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PAM-RTM 2014

User's Guide & Tutorials

PAM-RTM 2014

USER'S GUIDE & TUTORIALS

April 2014

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CONTENTS

INTRODUCTION

PRESENTATION OF LIQUID COMPOSITE MOLDING

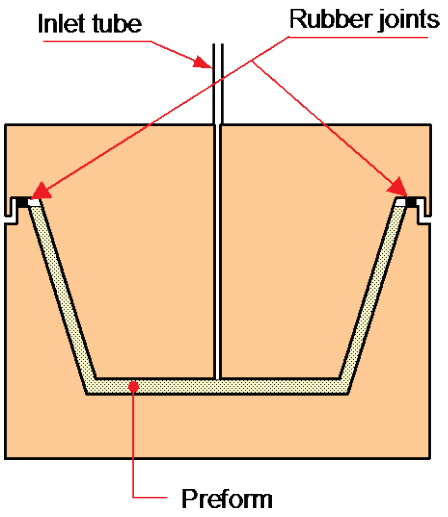
"*Liquid Composite Molding*" (**LCM**) is a generic term for a family of related processes in composite manufacturing, in which continuous fibers used as reinforcement are first placed in the bottom part of a mold, then a polymer matrix is injected as liquid resin into the cavity. After curing, the part is demolded. The resin impregnation of the preform is governed by Darcy's law, the general model describing fluid flows through porous media. Although **LCM** technologies are used mainly to manufacture composites with thermosetting resins, thermoplastic resins can also be processed under certain conditions.

The main **LCM** process variants are stated below:

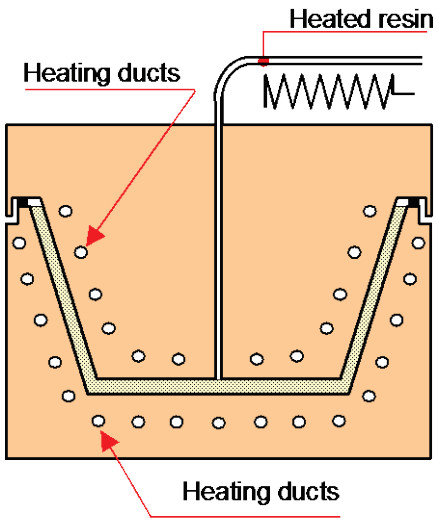
- **Standard or closed mold RTM** ("*Resin Transfer Molding*"): closed mold injection of resin that can be performed also after vacuum has been made in the mold. This latter alternative is often called "*Vacuum Assisted Resin Transfer Molding*" - **VARTM**).
- **Non isothermal RTM** . The mold and/or the resin are heated to facilitate the resin flow by decreasing resin viscosity.
- **Injection-compression** ("*Compression Resin Transfer Molding"* - **CRTM***)*. The top part of the mold is opened slightly during resin injection in order to increase the porosity of the reinforcement and facilitate mold filling. Transverse flow is considered as negligible for this process.
- **Vacuum Assisted Resin Infusion - VARI.** The reinforcement is covered by a flexible membrane, which is sealed and under which vacuum is done.
- **Liquid Resin Infusion – LRI.** Often, VARI is considered as a variant of LRI. What distinguishes LRI is a use of a highly permeable layer; it could be a net bleeder set over one side of the preform or an internal reinforcement layer. The resin flow is a combination of transverse flow and surface flow; transverse flow is significant for this process and can not be neglected. Note also that in a quite similar - and patented - process variant called **SCRIMP**, a flexible membrane is also used with vacuum together with a skin of much higher permeability on top of the reinforcement.
- **Resin Film Infusion - RFI**. A resin film is positioned on top of the reinforcement. Resin flow occurs through the thickness of the part, as the resin film is heated and compressed by a press.
- **Autoclave RTM**. This hybrid process variant uses an autoclave to control the pressure on top of a flexible membrane under which resin is injected. The

membrane is semi-permeable, in the sense that it allows air to be expelled during resin injection, but it is impermeable to resin.

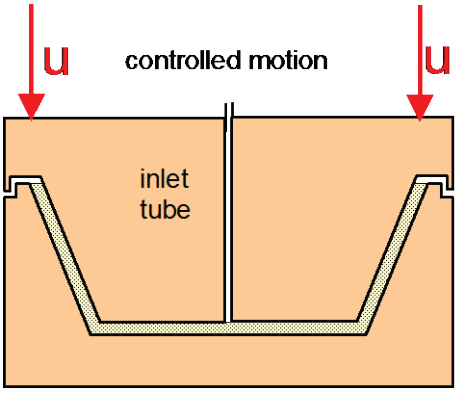
These **LCM** process variants are illustrated in the following figures:



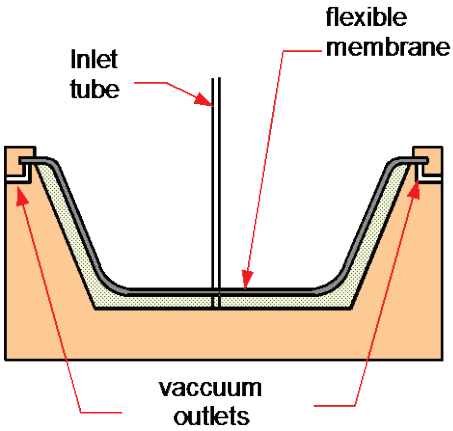
closed mold RTM



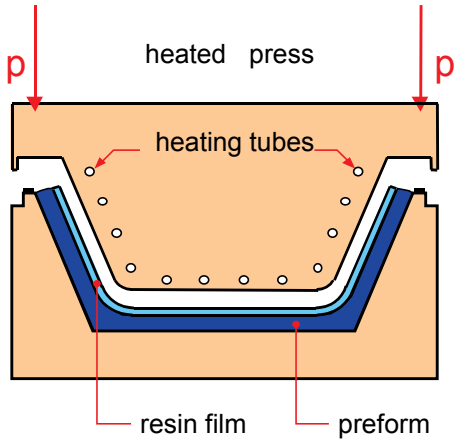
heated RTM



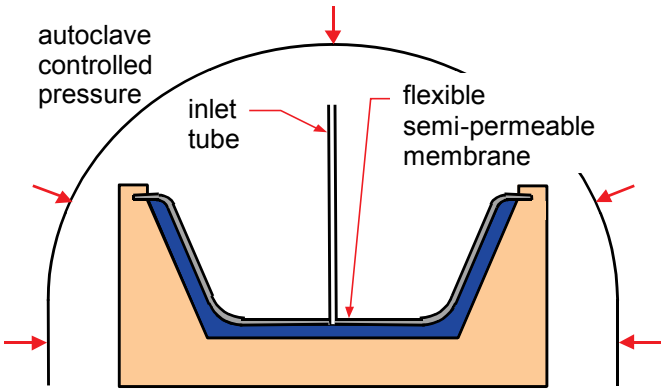
injection-compression (CRTM)



Vacuum Assisted Resin Infusion (VARI)



Resin Film Infusion (RFI)



Autoclave RTM

As there is a large number of **LCM** process variants currently in use or under development, it is not possible to describe all of them, nor even the details of the ones presented above. This information is usually part of the corporate know-how. Very often **LCM** simulations must be tailored to meet the diversity of injection processes.

RTM Process

The most frequently used resins are polyester, polyurethane, phenolic and epoxy systems. The reinforcements are made of glass, carbon or kevlar fibers. In the **RTM** process, resin is injected at a relatively weak pressure, usually less than 5 bars to prevent fiber washing by the resin flow. The injection can be performed using one or several injection ports, injection lines or a tree of injection channels. It is necessary to select a good configuration of injection ports and vents to avoid dry spots and minimize filling time. This is precisely the goal of numerical simulation.

Motivation of Filling Simulations

In numerous situations, numerical simulations of mold filling can be of great help to avoid problems such as resin rich areas, air bubbles, dry spots, zones of high porosity, as well as the formation of cracks following cure shrinkage. Most of the time, for large parts, and even for small parts with ribbed connections, it is advantageous to determine by simulation the optimal positions of injection ports and vents.

Simulation software has been developed in the last few years to assist in the design of **RTM** molds. It is more economic to perform simulations before construction of the mold than to modify an existing mold. The more complex is the mold, the more costly are mistakes in mold design. This is the reason why, even for small parts, it is useful to perform a preliminary study by simulation.

Modeling

The numerical simulation of the **RTM** process implies the modeling of three categories of physical phenomena: the resin flow through the fiber bed, the thermal analysis of heat exchanges in the part and with the mold, and finally, the chemical reaction of the resin.

Flow in a Porous Medium

In the **RTM** process, the resin flows through a fibrous reinforcement, which can be considered as a porous medium. In this case, the flow of resin is governed by Darcy's law, which states that the flow rate of resin per unit area is proportional to the pressure gradient and inversely proportional to the viscosity of the resin. The constant of proportionality is called the *permeability* of the porous medium. It is independent of the fluid, but it depends on the direction of the fibers which form the reinforcement (if the porous medium is no isotropic). The reinforcement is initially dry and the resin must fill the cavity. Capillary forces of attraction or repulsion act to the forehead of flow.

These forces, which depend on the surface tension of the resin and on its ability to adhere to the surface of fibers, have the effect of either reducing or increasing the effective pressure at the resin front. However, they are considered as sufficiently small in front of the pressure field in RTM to be neglected by numerical models.

Darcy's law states that the fluid velocity is proportional to the pressure gradient:

$$\vec{V} = -\frac{K}{\mu}\vec{\nabla}P$$

where:

- K : permeability tensor
- μ : viscosity of the resin
- V : Darcy's velocity
- P : pressure

In order to preserve the balance of resin mass, the velocity field must satisfy the divergence condition :

$$\nabla.\vec{V} = 0$$

By combining these two equations, we get

$$\nabla.\left(\frac{K}{\mu}\nabla P\right) = 0$$

If Ω denotes the cavity and dΩ its boundary, boundary conditions are necessary to solve the problem. These conditions can be of two types:

- **Dirichlet conditions**, or imposed pressure:

$$p = f(x, y, z)$$

This means that the pressure is specified on part of the boundary dΩ. This is also the case when the injection is made under vacuum; the pressure at the inlet gate is then simply the air pressure. At the inlet gates, the pressure is equal to the value fixed by the injection pump.

- **Neumann conditions,** or imposed flow rate at the inlet gates:

$$\vec{V}.\vec{n} = Q$$

An alternative to RTM is Vacuum Assisted Resin Infusion (VARI), which uses flexible covers instead. The VARI process inherits the basic principles from RTM, while requiring vacuum in the cavity where the reinforcement has to be placed. The vacuum is mainly intended to reduce voids formation and facilitate the transfer of the resin, which is injected at the ambient pressure.

However, in the case of deformable media, one has to derive the governing equations starting from the resin mass balance in order to ensure conservation. The continuity equation, considering the resin and the fibers material as incompressible, is expressed as:

$$div\left(\phi \cdot \vec{V}_r\right) = -div\left(\vec{V}_s\right)$$

Where ϕ is the porosity, V_r is the resin velocity and V_s is the solid velocity.

Finally, Darcy's law enables to write:

$$div\left(\frac{[\mathbf{K}]}{\mu}\langle \nabla P \rangle\right) = div\left(\vec{V}_s\right) = \frac{d\varepsilon}{dt}$$

where ε represents an infinitesimal deformation of the fiber bed.

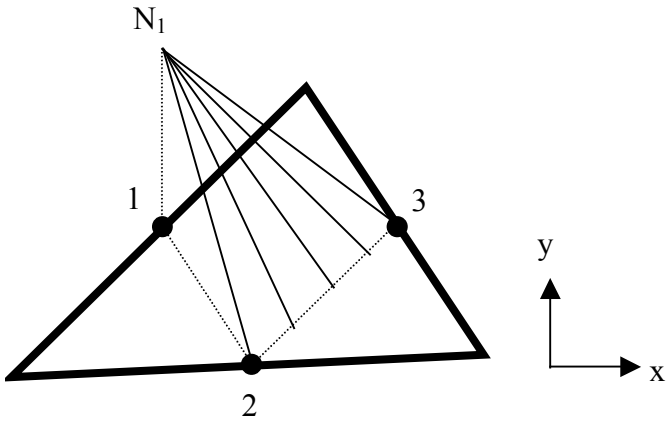
This equation is the general form of mass conservation for the consolidation problem and is often called the unified Darcy equation.

An additional equation is introduced to follow the deformation of the cover. A quasi-steady state is assumed to prevail at any point on the cover surface. In the present case, the sum of the compaction pressure (P_c) and the resin pressure (P_r) has to balance the external pressure (P_{ext}) acting on the cover surface. This can be formulated as:

$$P_c + P_r = P_{ext}$$

The knowledge of the resin pressure and the external pressure allows the user to obtain at each time step the thickness of the cavity from the compaction law of the reinforcement. Therefore, compaction curve plays a major role in this approach.

The flow is solved using a non-conforming finite element approximation. The pressure is discontinuous along the inter-element boundaries except at the middle nodes, as shown below for a triangular element. Contrary to conforming finite elements, the computed Darcy flow rates remain continuous across the boundary of elements. Instead of associating fill factors with the nodes of the mesh as in the conforming finite element, they are based on the elements of the mesh.



The pressure is interpolated using linear shape functions N_i as

$$p(x,y) = a + bx + cy = \sum_i P_i N_i(x,y)$$

and

$$N_i(x_j^*, y_j^*) = \delta_{ij} = \begin{cases} 0, & if \quad i \neq j \\ 1, & if \quad i = j \end{cases}$$

where (x_j^*, y_j^*) are the middle nodes at the element boundaries.

Permeability of the Reinforcement

The permeability characterizes the relative facility of a viscous liquid to impregnate a porous medium. This physical property of the porous medium (cloth, fabric, fiber mat, etc.) depends on the fiber volume fraction (degree of compaction) and on the draping of the plies. The permeability is usually denoted by K and its unit is m^2. The permeability of reinforcements in their principal directions is determined experimentally.

Thermal Phenomena

The part lies in the cavity of the mold. It consists of fibrous reinforcements and resin, which first fills up the mold and then becomes progressively polymerized. Heat transfer phenomena have a strong influence on mold filling and resin curing. Indeed, the temperature of the resin governs the reactivity of the polymerization reaction. Temperature also has an influence on mold filling, since the viscosity of the resin depends on temperature. Thermal simulations are therefore delicate to conduct because of all the related phenomena. Firstly, heat is transferred by conduction between the fibers and the resin. Secondly a convective transport of heat occurs during the filling of the cavity by the resin. Finally, heat is produced by the exothermic chemical reaction of resin polymerization. Some heat is also created by the viscous dissipation during the resin flow, but to a lesser degree than the heat originating from the chemical reaction.

The temperature field is governed by the general equation:

$$\rho C_p \frac{\partial T}{\partial t} + \rho_r c_{pr} \vec{V} \bullet \nabla T = \vec{\nabla} \bullet \{k \bullet \nabla T\} - \rho_r \Delta h \frac{D\alpha}{Dt}$$

where T denotes the temperature, t denotes the time, ρ is the density, C_p is the specific heat, k is the heat conduction coefficient tensor, the subscript r designates the resin, Δh is the total enthalpy of the polymerization of the resin, α is the resin cure.

There are three kinds of temperature boundary conditions:

- Prescribed temperature boundary condition: $T = T_0$

- Heat flux boundary condition: $\frac{\partial T}{\partial n} = q$

- Heat convection boundary condition: $\frac{\partial T}{\partial n} = h(T_\infty - T)$, where h is the heat convection coefficient, T_∞ is the environmental temperature.

This general equation permits to treat the steps of pre-heating, filling and curing.

During the filling step, it is used with effective properties:

- For non-impregnated fibers:

$$\rho C_p = \phi \rho_a C_{pa} + (1-\phi)\rho_f C_{pf}$$

$$k = \phi k_a + (1-\phi)k_f$$

- For impregnated fibers:

$$\rho C_p = \phi \rho_r C_{pr} + (1-\phi)\rho_f C_{pf}$$

$$k = k_e + k_D$$

where the subscript r stands for the resin, f for the fibers and a for the air. In general, thermal properties of the air are neglected. The effective conductivity tensor k_e of the composite is averaged in each direction. Like the permeability tensor K, the heat conduction coefficient tensor k reduces to a scalar for the isotropic fiber preform.

The coefficient k_D represents the thermal dispersion tensor arising from hydrodynamic dispersion. It can be evaluated as a function of Peclet number, but its influence is small as long as the fluid velocity is weak. However starting with **PAM-RTM™ 2008**, it is now possible to take into account thermal dispersion. The following paragraphs describe how it is modeled.

Experimental results showed that dispersion depends on Prandtl and Reynolds numbers and that Peclet number can approximate hydrodynamics and heat transfer phenomena at the pore level. Based on this, Delaunay et al. further extended this approach and showed experimentally that both transverse and axial dispersions can be modeled empirically using a mixing length approach, by correcting the components of the thermal conductivity with an expression that depends on Peclet number as follows:

$$\lambda_{trans} = \lambda_{stat}\left(1 + 0.1Pe\right)$$

$$\lambda_{axial} = \lambda_{stat}\left(1 + 0.8Pe\right)$$

Peclet number Pe is defined here as:

$$Pe = \frac{v_f l}{a}$$

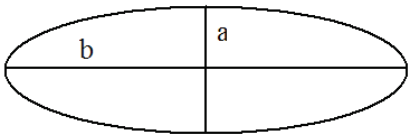
where,

v_f the observed velocity of the flow front (m/s), connected with Darcy velocity by the relation $v_f = \frac{v}{\phi}$ (ϕ denotes the porosity of the fibrous reinforcement)

l characteristic length (m)

a thermal diffusivity (m^2 /s)

The characteristic length is referred to as the characteristic scale of the elliptical shape of a compressed fiber tow,



In which case it is given by:

$$l = \sqrt{a\,b}$$

The following describes the thermal contact resistance. In a general way, when two solids (parts of a mold, reinforcement) are in contact, because of their roughness and the non-flatness of their surfaces, the contact is never carried out on all apparent surface. Between the zones of contact remains an interstitial space, which is a zone with low conductivity. The temperature field is thus considerably disturbed. The introduction of a thermal contact resistance R_{th} allows to neglect the thickness of the contact zone and to replace the abrupt variation in temperature by a true discontinuity.

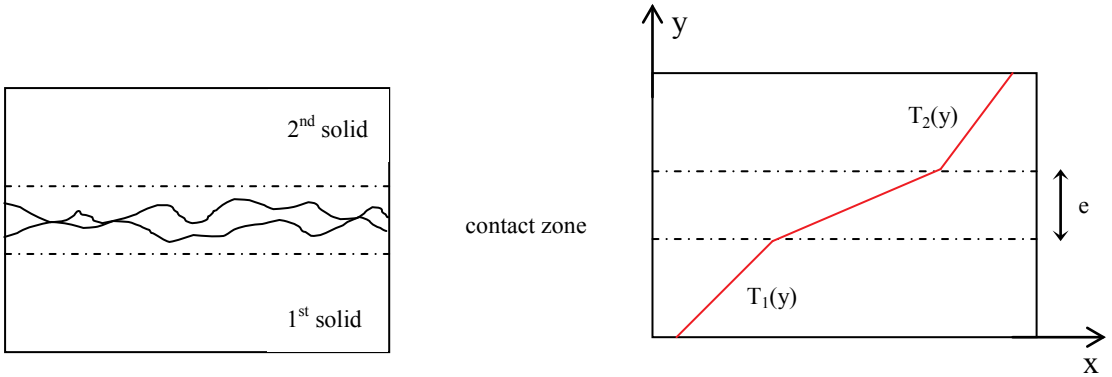


Illustration of the thermal contact resistance

The thermal contact resistance R_{th} is defined by $\varphi = \frac{T_1 - T_2}{R_{th}}$ where T_1 and T_2 are the contact temperatures on the interface and φ the heat transfer. Its surface value is determined by the following relation:

$$R_{th} = \frac{e}{k} \ (\mathrm{m^2W^{-1}K})$$

Where *e* is the thickness of the disturbed zone and *k* is often the thermal conductivity of the air.

Thus, we can consider gaps in the mold or ribs in the reinforcement, by affecting locally a value of thermal resistance.

The source term on the right side of the general equation of thermal phenomena accounts for the internal heat generated by the exothermic chemical reaction in thermoset resin system. This source term is usually assumed to be proportional to the reaction rate $\frac{D\alpha}{Dt}$.

Viscosity of the Resin

The viscosity of the resin depends on temperature and on the degree of conversion. The dependence on the degree of conversion is very strong, since it is usually assumed that viscosity reaches infinity when the resin comes to gelation.

The dependence of viscosity on temperature and the degree of conversion is modeled by a constitutive law. **PAM-RTM™** offers several options to model viscosity:

- Constant viscosity.
- Viscosity function of the temperature from a predefined model

$$\mu(T) = A \cdot \exp(B \cdot T)$$

  where *A* and *B* are two user specified constants.

- Viscosity function of temperature and of resin rate of conversion from a predefined model, where *A*, *B* and κ are characteristic constants of the resin:

$$\mu(T,\alpha) = A \cdot \exp\left(\frac{B}{T} + \kappa \cdot \alpha\right)$$

- Viscosity $\mu = f(T, \alpha)$ function of temperature and of the resin rate of conversion, such as in the following frequently used model:

$$\mu(T,\alpha) = B \cdot \exp\left(\frac{T_b}{T}\right) \cdot \left(\frac{\alpha_{gel}}{\alpha_{gel} - \alpha}\right)^{c_1 + c_2 \cdot \alpha}$$

  where *B*, T_b, α_{gel}, C_1 and C_2 are user defined characteristic constants of the resin.

Kinetics of Resin Polymerization

The software permits to define a kinetics of polymerization of the resin from the model of Kamal-Sourour. The general shape of the equation of Kamal-Sourour for a resin with *n* components is the following:

$$\alpha = \sum_{i=1}^{n} C_i \alpha_i$$

$$\frac{d\alpha_i}{dt} = K_i(T) \cdot \alpha_i^{m_i} \cdot (1-\alpha_i)^{p_i}$$

where $\frac{d\alpha_i}{dt}$ is the rate of reaction for the ith component in s^{-1}, the values of K_i are defined by the law of Arrhenius : $K_i=A_i exp(-E_i/RT)$

- A_i give the number of useful shocks to reactions,
- E_i are the energies of activation of the chemical reaction,
- m_i and p_i are exponents characterizing the sensitivity of each autocatalytic reaction,
- C_i are the weights of each reaction.

Coupling of Physical Phenomena

The following table presents a summary of the main phenomena that come into play in the **RTM** process. All these phenomena are strongly coupled and **PAM-RTM™** is able to simulate them.

Category	Phenomenon	Mathematical model
Rheologic	Resin flow in a porous medium Variations of viscosity	Darcy's law Constitutive law
Thermal	**Mold**: conduction, loss in surface **Part**: conduction, convection, generation of heat, superficial heat loss	Heat equation, transfer coefficient (convection-radiance) Equation of convection-diffusion with source term, model with one temperature
Chemical	Transport of chemical species, diffusion, polymerization	Equation of convection-diffusion with source term, kinetic model (Kamal-Sourour)
Mechanical	Mold deformation Variation of porosity and permeability	Newton's law Empirical models

CREDITS

A series of software modules developed by the Chair on Composites of High Performance (CCHP) at École Polytechnique de Montréal have been incorporated in **PAM-RTM™ 2008, 2009 and 2010**:

- Optimization of the void distribution in an RTM composite part through injection flow rate (VoidOpt module);
- Rapid RTM flow simulation (OneShot module);
- Conditional opening of injection ports and vents during resin injection (TriggerManager module);
- Incorporation of simultaneous filling and curing simulations including the overfilling phase and the evacuation of excess resin at the end of the filling cycle;
- Optimization using genetic algorithms of injection points locations minimizing fill time (GenPorts module);
- Compression RTM and Articulated Compression RTM (ACRTM).

Permeability tensor of the reinforcements is the main material data required for Liquid Composites Molding simulation. However, no normalization of the permeability measurements exists today and significant scatters in measured permeability values between laboratories are observed. In the first stage of an international benchmark exercise on the experimental determination of reinforcement permeability; 11 partners, implementing 16 different measurement techniques between them, compared in-plane permeability data for the examples of fabrics provided by HEXCEL. A second stage of this benchmark study is currently on-going; its purpose is to eliminate sources of scatter and lead to a standardization of measurement methods.

Andy Long's team especially Andreas Endruweit from Nottingham University who participates in that benchmark partnered with ESI Group composites team is sharing non-confidential permeability values measured these last years at the University. Few of these reinforcement data are in the PAM-RTM installation files. A more extensive database that is continuously improved and completed with new data is available on ESI customer portal "MyESI" (local ESI representative must be reached for more information).

There are currently no standards for permeability measurement to interpret the provided data; while observed trends (e.g. for the change in permeability as a function of the fiber volume fraction), are of general validity, application of different experimental methods may result in quantitative differences in absolute permeability values.

The main purpose of the database is to provide a starting point to PAM-RTM users.

PAM-RTM USER'S GUIDE

INTRODUCTION

To run a simulation with **PAM-RTM™**, it is necessary at least to have prepared a mesh of the part to inject using a commercial (GEOMESH, I-DEAS, PATRAN, CATIA) or public domain mesh generator. Whatever the mesh generator you choose, it should have the capability to export a mesh in one of the file formats supported by **PAM-RTM™**: **I-DEAS** *Universal*, **PATRAN** *Neutral*, **NASTRAN** or **PAM-SYSTEM**. Most commercial mesh generators can export a mesh in NASTRAN format, so it shouldn't be a problem to work with any mesh generator.

The important point is that you work in the CAD system you like to prepare the geometry for meshing, then you mesh in the mesh generator you like, and finally you export the mesh (*only nodes and elements, not the boundary conditions or physical properties*) in one of the formats supported by **PAM-RTM™**. The boundary conditions and physical properties are later specified in **PAM-RTM™**.

For simulations involving resolution of Darcy's equation (RTM, Heated RTM, VARI), **PAM-RTM™** uses non-conforming finite elements. Non-conforming finite elements are only available on triangles and tetrahedrons. This means that the cavity has to be meshed with 3 nodes triangles or 4 nodes tetrahedrons. For Heated RTM simulations, the mold could be meshed with 4 nodes quads or 8 nodes bricks. For simulations that don't solve Darcy's equation (preheating, curing), quads and bricks could be used to mesh the cavity.

In general, having a finite element mesh created by **I-DEAS** or **PATRAN** is not enough to launch a simulation with **PAM-RTM™**. Injection ports and vents have to be defined. In addition, the specification of fiber orientations is not always available in the mesh file. **PAM-RTM™** has some tools to specify material orientations and to modify the mesh for injection points and vents. Groups of nodes are created interactively in **PAM-RTM™** to be used in the specification of boundary conditions.

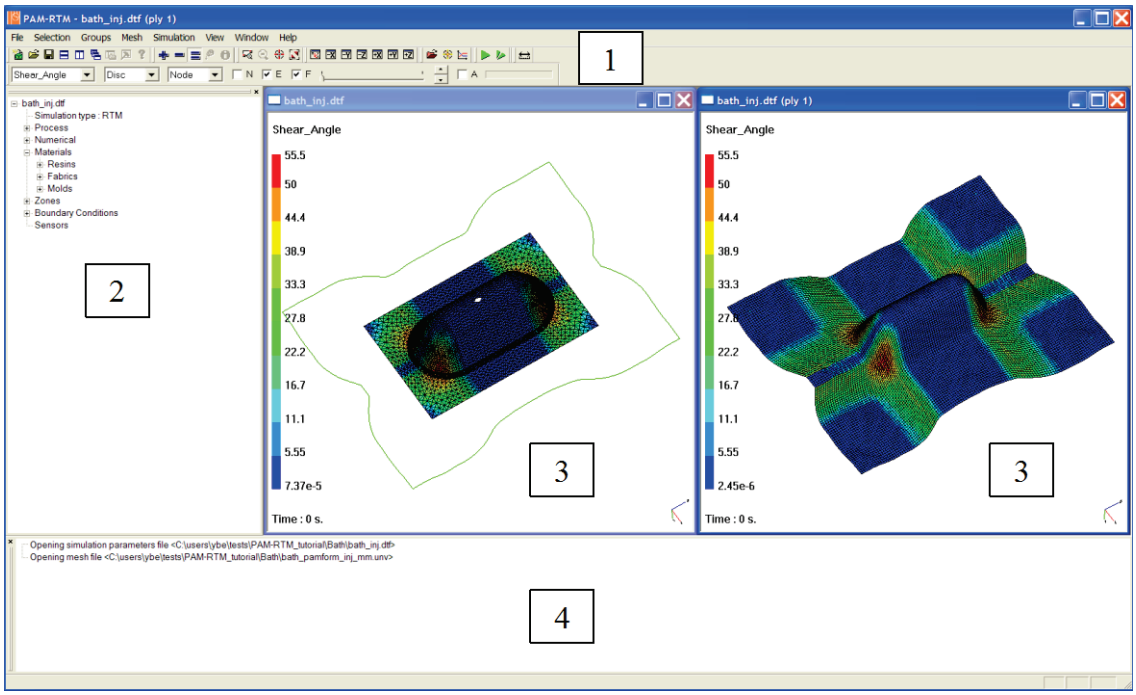
Once the model is completely specified (material properties, orientations, groups, boundary conditions, etc.), the simulation parameters file (`.dtf`) is saved and the simulation can be launched from the user interface or from a command window. The latter is mostly used to run the simulation on a Unix server (see chapter **Running the Simulation from a Command Window**).

When the simulation is done, the **PAM-RTM™** post-processing functionalities are used to visualize the simulation results. Alternatively, by using the appropriate output format, simulation results can be visualized in **I-DEAS** or **PATRAN**.

PRESENTATION OF THE USER INTERFACE

The main frame window of **PAM-RTM™** is made of 4 areas:

- toolbar area **[1]**
- model explorer **[2]**
- 3D graphics windows **[3]**
- message pane **[4]**



Overview of the PAM-RTM user interface

PAM-RTM™ is a multi-document, multi-view application, which means that many documents can be opened at the same time, and many views can be created on the same document. This is useful, for example, to visualize the resin pressure field in one view and the temperature field in another view. Or, as shown in the previous image, to visualize a mesh of the part to inject in one view, and a mesh of a ply with fiber orientations in another view.

To open a new view on the current document, use the **Window->New Window** command. When many windows are opened, you can use the **Window->Cascade**, **Window->Tile Horizontally** and **Window->Tile Vertically** commands to have automatic layout of the windows.

You can position toolbars in PAM-RTM toolbars any way you like. The recommended setup of toolbars is shown in the previous picture. To move a toolbar you have to click on the left double vertical bar, then drag the toolbar where you want, as shown in the

next picture. When the toolbar is floating, there is an **X** box that appears in the upper right corner of the window that allows to close it (in case you need more space or you never use some toolbars). To recover a toolbar you closed in such a way, there is a command in the **Window** menu to show or hide each of the **PAM-RTM™** toolbars (ex: **Window->Display Toolbar**, **Window->Selection Toolbar**, etc.).

Handle to move the toolbars

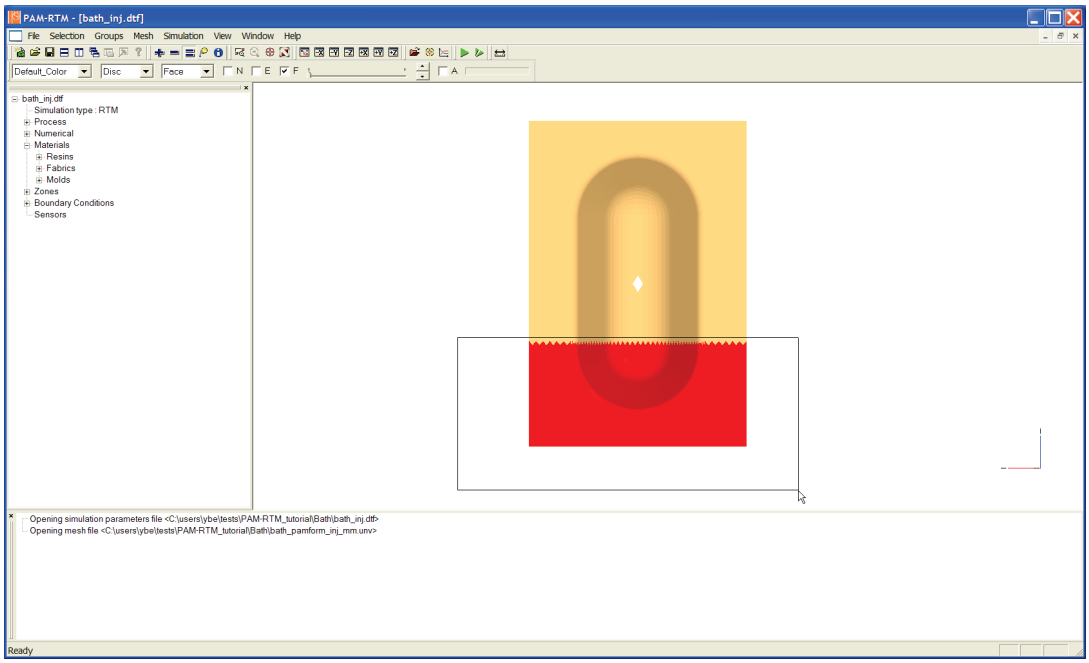
Floating toolbar

Interaction with the Mouse

The middle mouse button is reserved in **PAM-RTM™** to dynamically control the viewpoint:

- Middle button alone: rotate
- Ctrl + Middle button: pan
- Shift + Middle button : zoom

The left button is used for selection (picking or area). The selection filter (nodes, faces, elements) is available in the **Display** toolbar.



Selection of elements by area

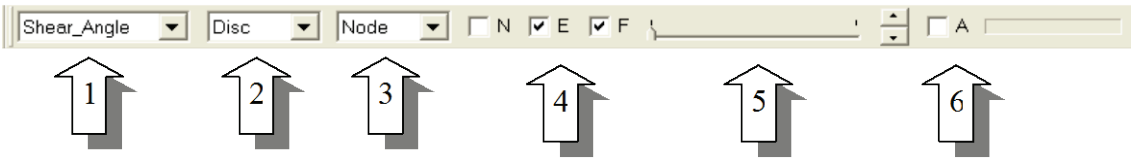
Toolbars

File Toolbar

File toolbar

This toolbar contains shortcuts to standard Windows commands (from left to right): **File->New, File->Open, File->Save, Window->Tile Horizontally, Window->Tile Vertically, Window->Cascade, Help->About**.

Display Toolbar

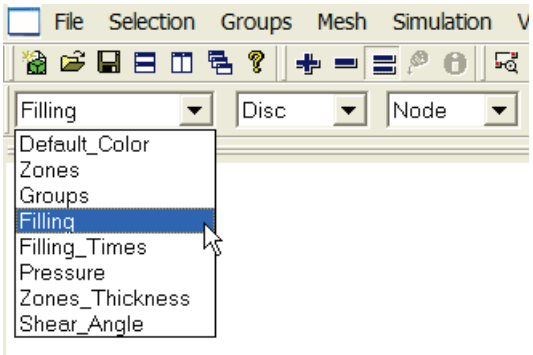


Display toolbar

There are basically 4 display modes in **PAM-RTM™** that affect the coloring of display entities:

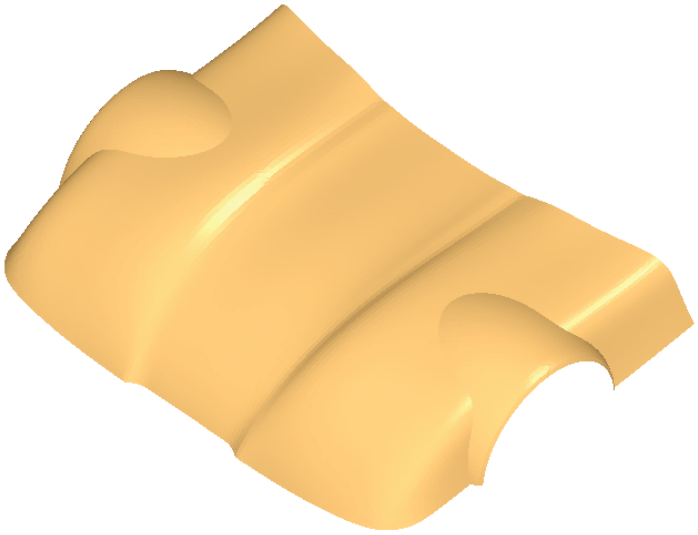
- *Default color*: in this mode, nodes, edges and faces are displayed using the default colors specified by the user in the **Color** tab of the **View->Options** dialog box.
- *Zones*: element faces are colored according to their zone ID.
- *Groups*: if a node or face is part of a group, it is colored according to the group ID.
- Scalar Field: faces are colored based on a scalar field value (for example temperature or pressure).

The 4 display modes are activated by selecting something in the scalar field roll-down list of the display toolbar **[1]**. Depending on the context, there will be more or less scalar fields to display. Here is an example.



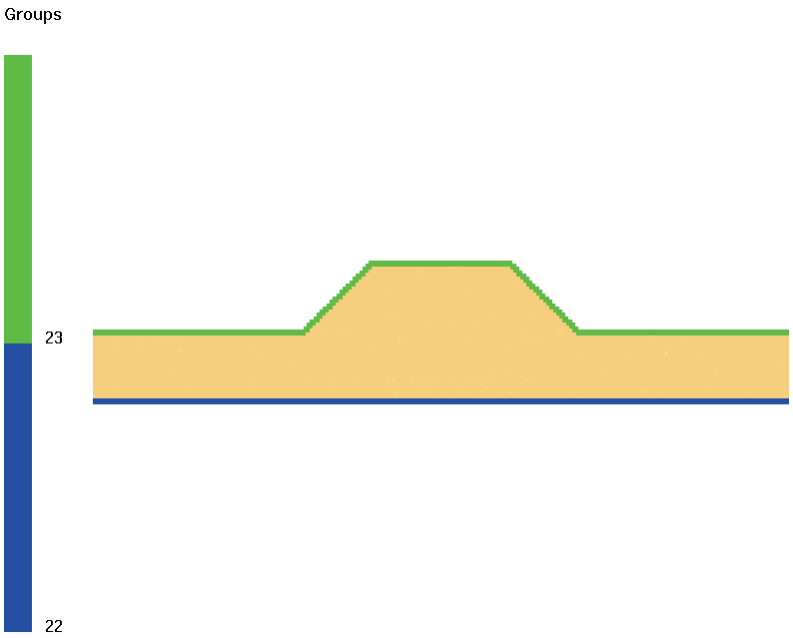
Scalar field list

Examples of the each display mode are shown in the following figures.

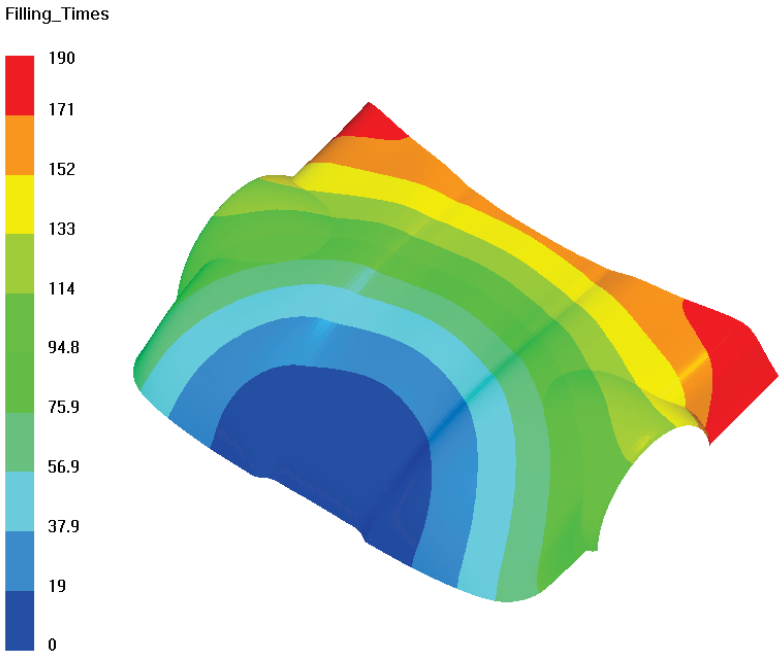


Surface mesh displayed in Default Color mode

Zones display



Groups display



Segmented filling scalar field display

Here is a description of the other controls available in the display toolbar.

- Plot type **[2]**: *Disc* or *Iso*. This parameter has an effect only when visualizing scalar fields.

  - *Disc* is used for example to display a scalar field that was computed at the nodes as a discontinuous fields averaged on each element.
  - *Iso* is used to display contours of the current scalar field. Note that if the original field was computed at elements (which is the case for instance for the filling factor), the values will be averaged at the nodes before contours can be generated, which can take a while depending on the mesh size and number of steps.

- Selection filter **[3]**: set the selection filter to *Node*, *Face* or *Element*. For example, use *Node* if you want to pick nodes, or *Element* if you want to pick elements.
- **N**, **E**, **F [4]:** check boxes to show or hide nodes, edges, faces.
- Time step **[5]**: drag this slider to visualize the current scalar field step by step.
- Animate **[6]**: starts/stops animation of the current scalar field. Use **View->Post-Processing** for animation parameters.

Selection Toolbar

This toolbar is used to control the behavior of the selection. For example, if the selection filter is *Node* and the **=** button is pushed when some nodes are selected by area, the current selection will be replaced by the new selection. When the **+** button is pushed, each new selection is added to the current selection. When the **–** button is pushed, the new selection is removed from the current selection set. Other buttons are available to clear the current selection (equivalent to **Selection->Unselect All (no filter)**), and to get information about the selected entities (equivalent to **Selection->Info Detailed**).

Selection toolbar (current selection empty)

Selection toolbar (non-empty selection)

Camera Toolbar

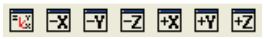
Camera toolbar

From left to right:

- Corner zoom: drag the mouse to define a rectangular area to zoom in.
- Zoom out: use after a corner zoom to restore the previous state.
- Rotation center: pick a point on the mesh to set the center for rotation and zoom.

- Fit: reset view so that the mesh is completely displayed, in the center of the graphics window.

Viewpoint Toolbar



Viewpoint toolbar

Choose one of the pre-defined viewpoints (along **-X** axis, **+X** axis, etc.).

Simulation Toolbar

Simulation toolbar

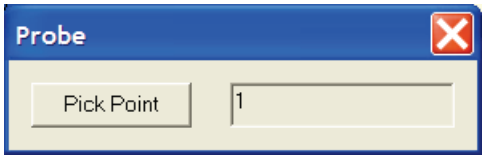
Start or restart the simulation. Restart is used when simulation was stopped with a CTRL-C and needs to be restarted.

Results Toolbar

Results toolbar

From left to right:

- Reload results: reloads all the results files that were generated for this simulation. This is the preferred way to load results in **PAM-RTM™**.
- Probe: opens the **Probe** dialog box, allowing the user to pick an arbitrary point on the mesh and display the value of the current scalar field for the current time step on that point.



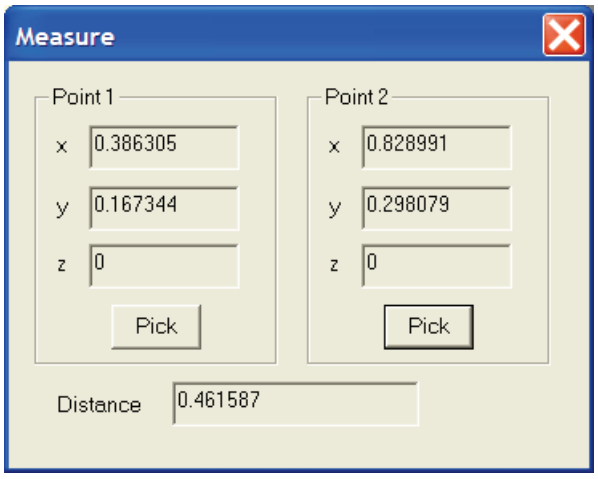
Probe dialog box

- Plot: allows the user to pick a point and automatically generate a plot of the scalar field value on that point as a function of time.

Tools Toolbar

Tools toolbar

There is only one tool currently available in this toolbar: the measure tool. Pushing this button opens the **Measure** dialog box, allowing the user to pick two arbitrary points on the mesh and get the distance between the points.

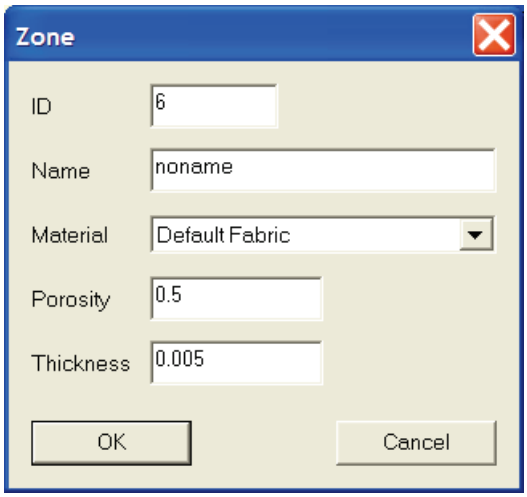


Measure tool

Model Explorer

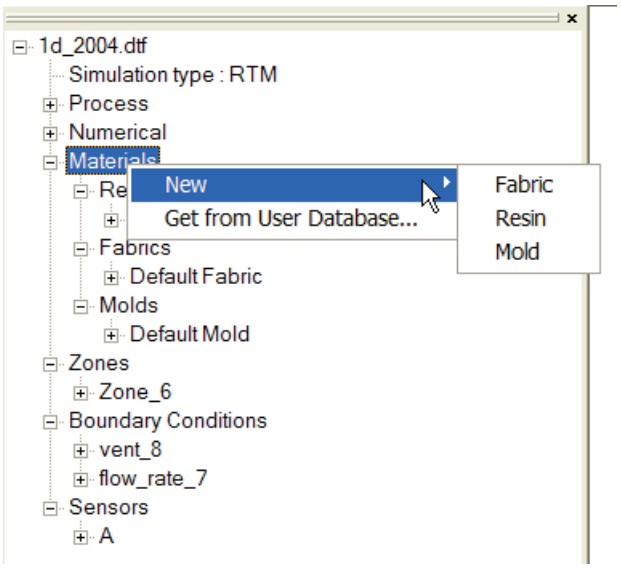
The model explorer displays information about open documents in a tree structure. The information displayed can be seen as a summary of open documents. Only the most useful information is displayed in the tree, depending on the type of simulation.

Double-clicking an item in the tree most of the time pops up a dialog box to edit the parameters related to the selected item. For example, double-clicking a zone opens the **Zone** dialog box.



Zone dialog box

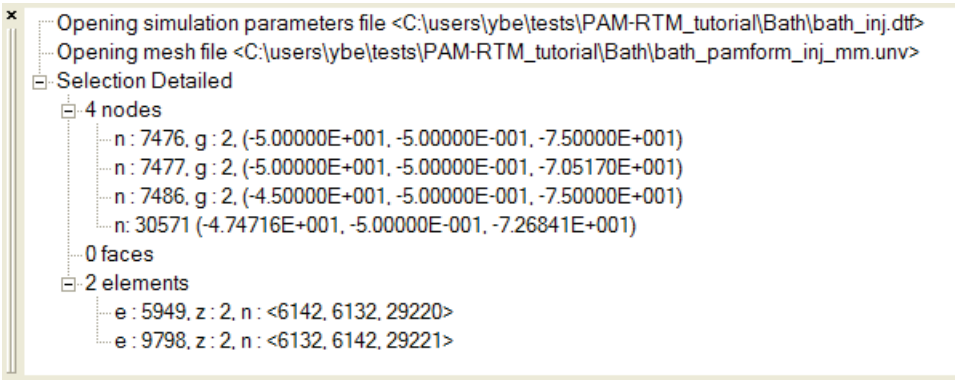
Right-clicking an item in the explorer will most probably popup a menu, depending on the item selected. In the following picture, the user right-clicked on the *Materials* item.



Right-click in the explorer window

Message Pane

The message pane is used to display messages to the user. A tree structure is used. For example, the **Selection->Info Detailed** command prints the following.



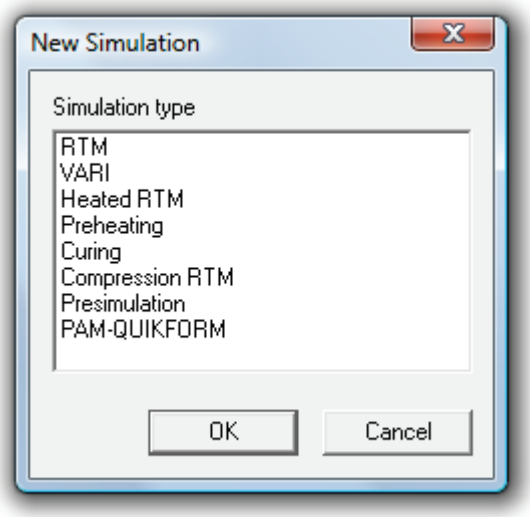
Message pane

FILE MENU

File > New

This is used to create a new simulation project. The supported simulation types are:

- **RTM**: classical isothermal closed mold RTM.
- **VARI**: Vacuum Assisted Resin Infusion. Isothermal injection under deformable plastic film. The thickness and permeability change of the fiber reinforcement is taken into account.
- **Heated RTM**: non-isothermal RTM. Heat exchanges between resin, fiber reinforcement and mold is taken into account. The effect of resin polymerization on viscosity and heat generation can also be taken into account.
- **Preheating**: heating of the mold and fiber reinforcement before filling. The possibly non-uniform temperature distribution at the end of preheating can be used to initialize Heated RTM simulation.
- **Curing**: post-filling resin cure. By default, assumes that the cavity is completely filled and the initial temperature and degree of cure is uniform. Otherwise the results of the Heated RTM simulation (filling factor, temperature, degree of cure) can be used to initialize the curing simulation.
- **Compression RTM**: simulates a process in which some amount of resin is injected first with a cavity thickness slightly higher than the targeted part thickness. This is done in order to facilitate impregnation since the permeability is higher. Once that amount of resin has been injected, the part is not completely filled yet. The inlet is closed, and the remaining dry areas are filled by a flow induced by compression of the preform. The compression direction can be normal to the part, or in a specified direction. This simulation is based on a 2.5D modeling where only the pseudo thickness of the shell element varies. Thus only meshes of triangles are supported.
- **Presimulation**: this simulation allows a first approximation of the filling time and flow behavior without solving Darcy's equation. That's why it is very fast. However it works only with constant flow rate injection.
- **PAM-QUIKFORM**: draping analysis of fiber reinforcements (bi-directional fabrics and unidirectional).



New Simulation dialog box

File > Open

This is used to open a project file *(*`.dtf`) or a mesh file. Most of the time this command is used to open a `.dtf` file, which contains the **PAM-RTM™** simulation parameters as well as links to external files such as mesh files. It can also be used to open directly a mesh file. In that case a default RTM simulation is automatically associated to the opened mesh file.

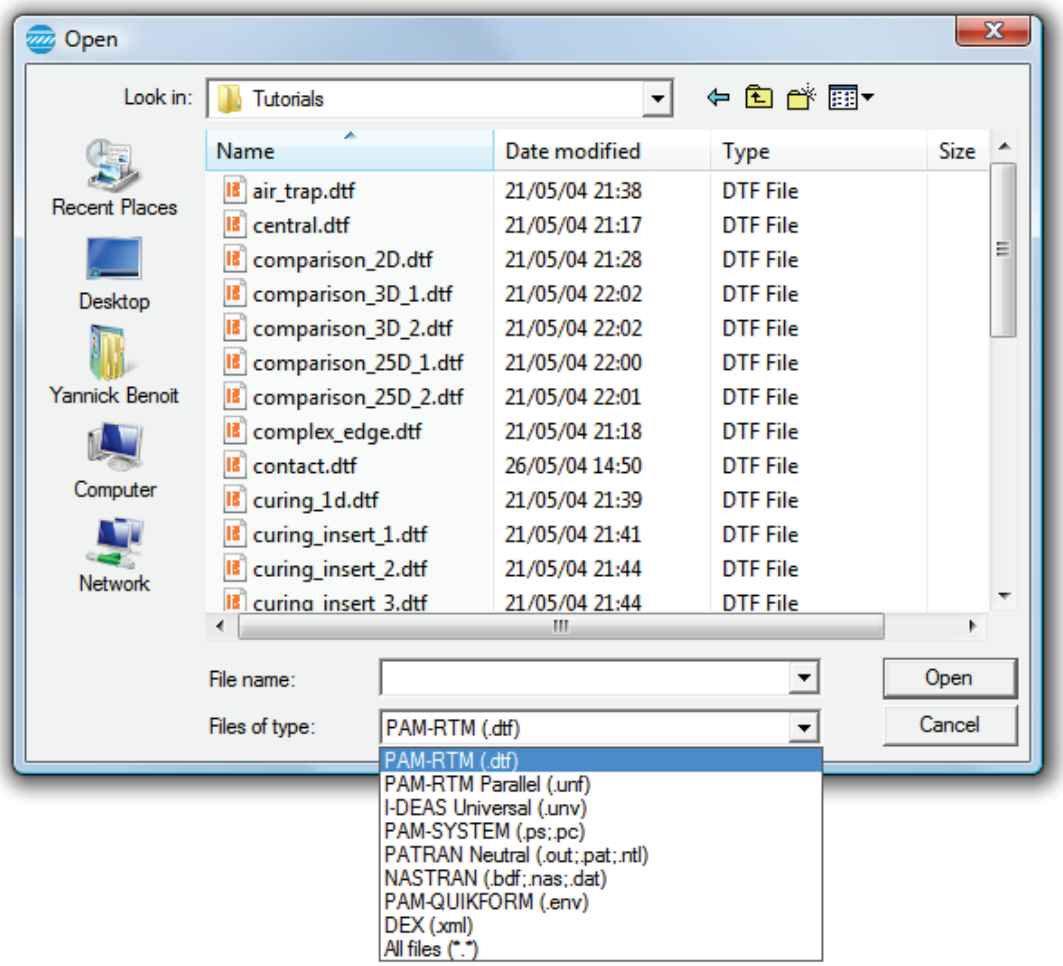
The option **PAM-RTM Parallel (.unf)** is to be used for post-processing of results generated by the new high performance parallel solver introduced in **PAM-RTM™ 2010**.

Note:

- *The .unf format is intended for post-processing only. All the pre-processing functionalities of the PAM-RTM GUI, such as creation of groups, specification of material orientations, etc., will be non-functional if such a document is loaded.*

The supported mesh file formats are:

- PAM-SYSTEM
- I-DEAS Universal
- PATRAN Neutral
- NASTRAN Bulk



File Open dialog box

File > Close

Closes the active document. If some modifications were done, the user is prompted to save the file before closing.

File > Save

Saves the `.dtf` file (simulation parameters) and the mesh file (`.unv`) in the directory where the `.dtf` file was opened. For example, if file `c:\rtm_tests\test.dtf` was opened, when the **File->Save** command is used, the file `c:\rtm_tests\test.dtf` will be overwritten and the associated mesh file `c:\rtm_tests\test.unv` will be generated.

File > Save As

Prompts the user to specify a new name and directory for the project. For example, if `c:\rtm_tests\test_2.dtf` is chosen, the current simulation parameters will be saved in `c:\rtm_tests\test_2.dtf` and an associated mesh file `c:\rtm_tests\test_2.unv` will be generated.

File > Import > Mesh

This is the command to use after a **File->New**, to import in the current document the mesh to use for the simulation. In some rare situations you could use this command to load many meshes in the current document, then merge them with **Mesh->Cleanup->Merge Coincident Nodes**. See **File->Open** for the supported mesh file formats.

File > Import > Scalar Fields

This command is used to import scalar fields (simulation results) into the currently active **PAM-RTM™** document for post-processing. These are the available file formats for scalar fields:

- I-DEAS Universal (extension: `.unv`)
- PAM-RTM Scalar Field (extension: `.sf`)
- PAM-RTM Filling Compact (extension: `.fil`)
- PAM-RTM Flow Front (extension: `.front`)
- Velocity Components Vx Vy Vz (I-DEAS format, extension .unv)

The PAM-RTM Filling Compact file contains the filling result of a **PAM-RTM™** simulation. The size of this file is much smaller than the same scalar field saved in a more general format like I-DEAS Universal.

The PAM-RTM Flow Front file contains the flow front position in time. This is the "raw" flow front position (not smoothed). It is made of line segments that define the saturated domain. The flow front position can be displayed on top of any scalar field in **PAM-RTM™**. This is useful to analyze, for example, temperature results.

Since **PAM-RTM™ 2008**, it is possible to display a vector field on top of a scalar field. This is generally used to display the resin velocity vector field on top of a pressure or temperature field, for instance. However any 3 components vector field could be displayed, as long as the 3 components are imported together with **File->Import->Scalar Fields->Velocity Components**. In general the user doesn't have to use this command, as the velocity components are imported automatically with the **Reload Results** button in the **Results Toolbar**, if the **Save Velocity** option was checked in the **Numerical Parameters**.

Note:

- *The preferred way to load simulation results in PAM-RTM™ is to use the button*  *in the Results Toolbar.*

File > Import > Draping Results

This menu is used to import draping analysis results files in the active document. Draping results are a set of meshes that define plies geometry (one mesh for each ply). Depending on the software that generated the laminate plies, material properties like fiber directions and thickness can be defined on each finite element of a ply. For example, the result of a **PAM-FORM™** simulation gives the fiber orientations and thickness on each element. However a **PAM-QUIKFORM™** simulation gives only the fiber directions, not the thickness.

These are the available interfaces to import draping results in **PAM-RTM™**:

- PAM-FORM
- PAM-QUIKFORM
- PATRAN Laminate Modeler
- FiberSIM XML

All these interfaces support local fiber directions specified on each element of each ply.

The PAM-FORM interface reads a **PAM-FORM™** results file (extension `.dsy`). A **PAM-FORM™** results file normally contains many states. **PAM-RTM™** assumes that it is only the last state that is interesting in the context of RTM simulation, so it loads in memory only the last state of the **PAM-FORM™** simulation.

There are two possibilities to import **PAM-QUIKFORM™** results. In case the PAM-QUIKFORM simulation was created and run in PAM-RTM (File->New->PAM-QUIKFORM), it is possible to import the PAM-QUIKFORM .dtf file, in which case higher level information such as materials used in the laminate definition is available. Otherwise it is also possible to import only the PAM-QUIKFORM generated mesh files (`.ps`, PAM-SYSTEM format). In that case, the user will have to associate materials to imported meshes by re-defining the laminate, if calculation of local permeability is needed.

The PATRAN Laminate Modeler interface reads a `.fmd` file, which contains a list of filenames that define the laminate. Each ply is a NASTRAN file with a special definition of the PCOMP section that allows the specification of 2 fiber directions on each element. One PCOMP section is specified for each element and each PCOMP section refers to 2 layers of UD.

The FiberSIM interface is used to import ply data generated by the FiberSIM software, in a special XML format.

File > Export > Mesh

This command is used to export the current mesh in one of the supported formats:

- PAM-SYSTEM
- I-DEAS Universal
- PATRAN Neutral

File > Export > PAM-RTM Scalar Field

This is used to export the currently displayed scalar field in a **PAM-RTM™** specific file format. This is used most of the time in the context of local permeability calculation, to export the `k1.sf`, `k2.sf`, `porosity.sf` and `thickness.sf` files needed to initialize a calculation that takes into account local permeability.

File > Clear > Scalar Fields

Clears from memory all the scalar fields that have been imported in the current document with the command **File->Import->Scalar Fields** or loaded with the  button.

File > Clear >Laminate

Clears from memory all the plies meshes that have been loaded by using **File->Import->Laminate**.

File > Save Image

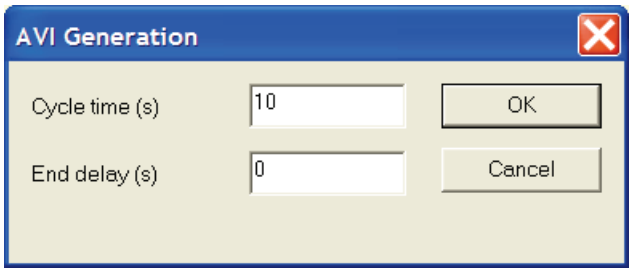
Saves the active 3D graphics window in one of the supported graphics file formats:

- PNG
- GIF
- TIFF
- JPEG

File > Generate AVI

Generates an animation file (`.avi`) from the currently visualized scalar field. The resulting `AVI` file can be visualized in Windows Media Player or integrated in PowerPoint presentations.

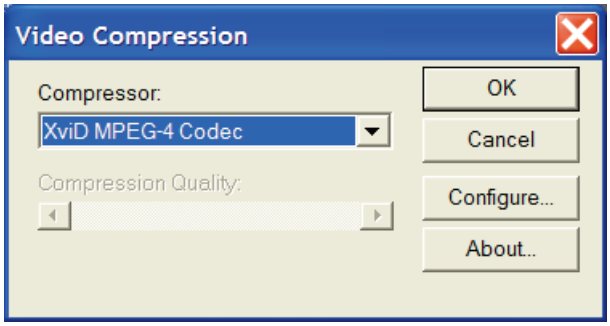
When the command is selected, the following dialog box pops-up, allowing the user to specify the cycle time, which is the time to display all the frames in the `AVI` file. The end delay is used to have the last frame displayed for some time. This can be useful for presentations.



AVI Generation

Then the user is asked to specify the name of the generated `AVI` file from the standard Windows file selection dialog.

Finally another dialog box pops up to select the "codec" to compress frames in the `AVI` file. This dialog box lists all the available codecs on the user machine. Since this list depends on other software installed on the machine, it is difficult to recommend the best codec. The **Cinepak** codec by Radius seems to be available on most machines and has given good results. However it is recommended to download from the internet the **XviD** MPEG-4 codec, which is open source and free. The **Full Frames** codec should be avoided as it generates huge files.



Selection of codec

Note:

- *Introduced in PAM-RTM™ 2008, the generated AVI can now take into account the Proportional animation option.*

File > Print

Prints the active 3D graphics window.

File > Print Preview

Gives a preview of the print command in the standard Windows print preview window.

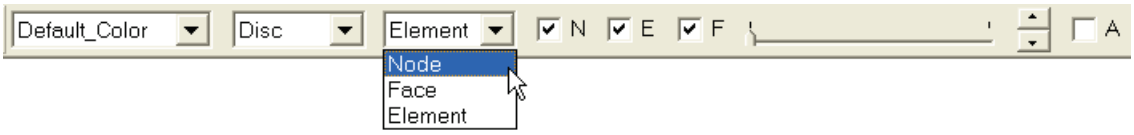
File > Print Setup

Opens the standard Windows dialog box to configure printing.

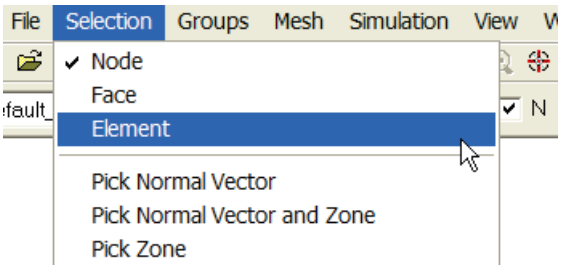
SELECTION MENU

Selection Filter

There are three types of geometrical entities that can be selected in **PAM-RTM™**: nodes, finite element faces, and finite elements. The selection filter is used to specify the type of entity to select. For example, if you want to pick some elements with the mouse, you have to set the selection filter to *Element*. If you want to select all the elements in a zone specified with an ID, you have to set the selection filter to *Element* before using the **Selection->Zone ID** command. The usual way to set the selection filter is using the *Display* toolbar. The **Selection->Node**, **Selection->Face**, and **Selection->Element** commands can also be used. A check mark is shown besides the currently active filter.



Selection filter in the Display toolbar

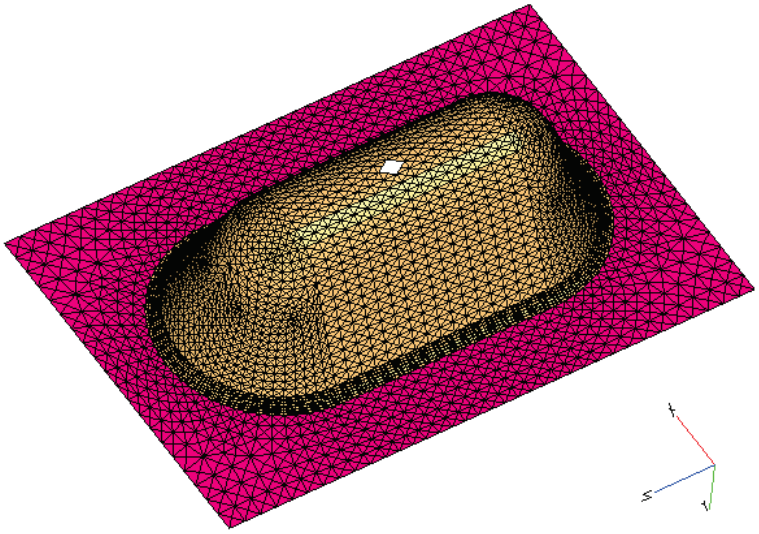


Selection filter in the Selection menu

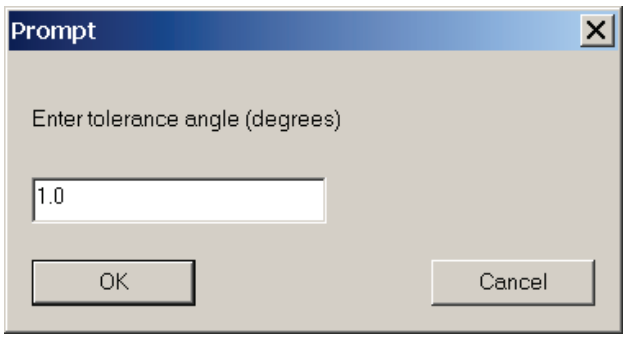
Selection > Pick Normal Vector

The **Pick Normal Vector** command is useful to select entities on the same planar surface (i.e. entities that have the same normal vector) in a single operation. For example, in the following image, all the faces in red were selected in a single click, while selection by area would have required many operations. When the **Pick Normal Vector** command is used, a dialog box pops up to prompt the user for a tolerance on the angle between two adjacent faces (angle between the 2 normal vectors). This is useful when the surface to select is not perfectly planar.

Note that nodes, faces and elements can be selected using this approach. When the selection filter is *Nodes*, all the nodes of all the faces that have the specified normal vector are selected.



Selection of faces with Pick Normal Vector



Tolerance angle for Pick Normal Vector

Selection > Pick Normal Vector and Zone

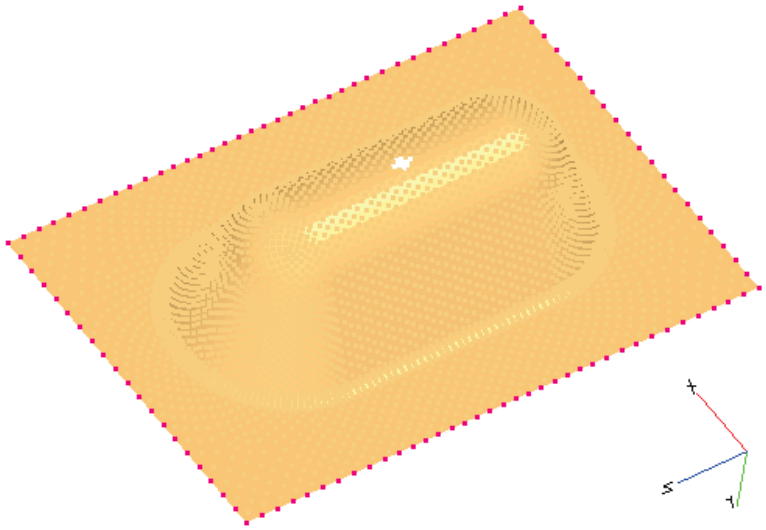
This command is basically the same as the previous one, except that it adds as a selection filter the zone ID of the face used to define the normal vector.

Selection > Pick Zone

This command allows selection of all the nodes, all the faces or all the elements in a zone picked by the user with the mouse. The user is first prompted to pick a face in the zone to select. Then all the entities are selected based on the current selection filter.

Selection > Pick Boundary

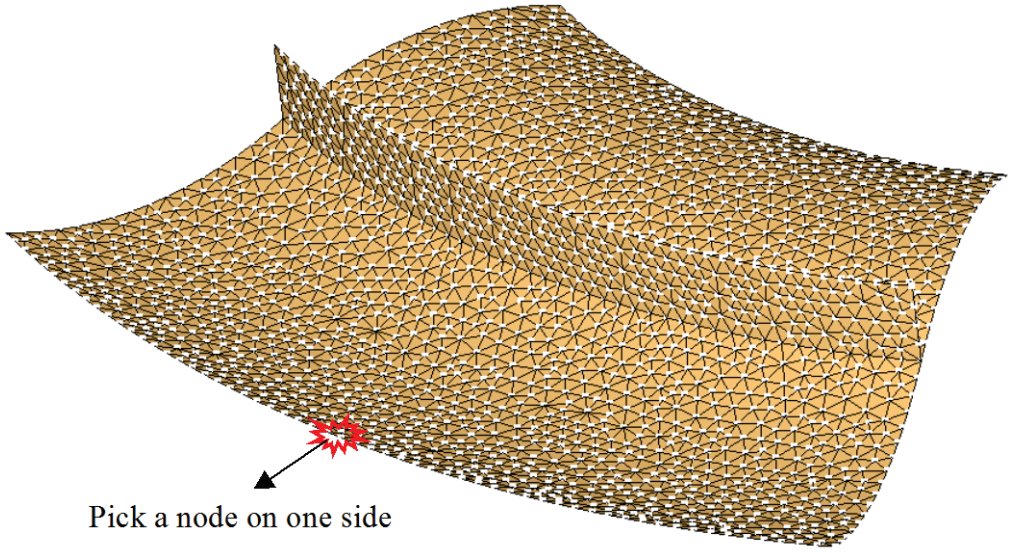
This command is useful to quickly select all the nodes on a boundary. The user is first prompted to pick the initial node that will be used in the algorithm to determine the boundary based on the neighbor elements of this node. Currently only boundary nodes, not elements, can be selected this way.

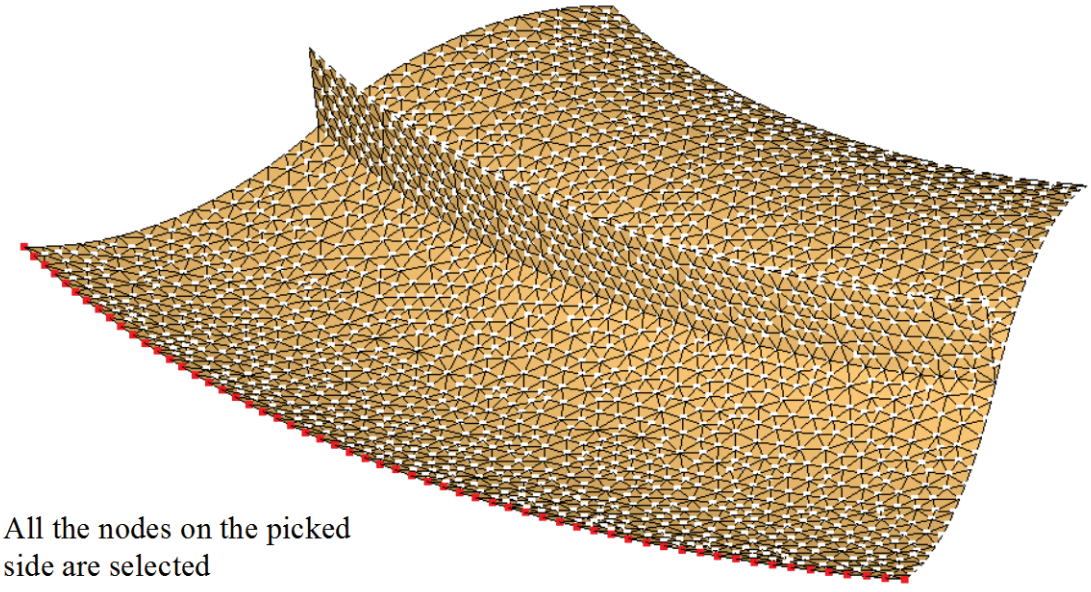


Selection -> Pick Boundary

Selection > Pick Free Edge

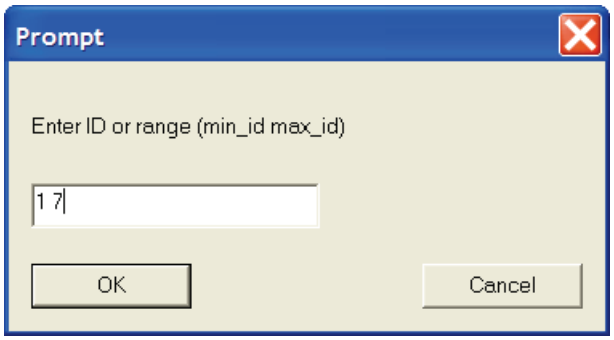
With this command, the user can select with a single click all the nodes along one side of the part. The identification of a part's side is done neighbor to neighbor starting from the picked node. The user is prompted to enter a tolerance to stop the propagation when the angle between two elements is larger than the tolerance value. Typically a tolerance value of 30 degrees could be used, to allow selection on a curved side and stop selection when a sharp corner is reached.





Selection > Zone ID

When the zone ID of the entities to select is known, the user can type it directly in the dialog box that pops up when the **Selection -> Zone ID** command is used. It is also possible to enter two values to specify a range. In the following image, the user enters *1* and *7* to select all the elements of all the zones in the range 1 to 7.



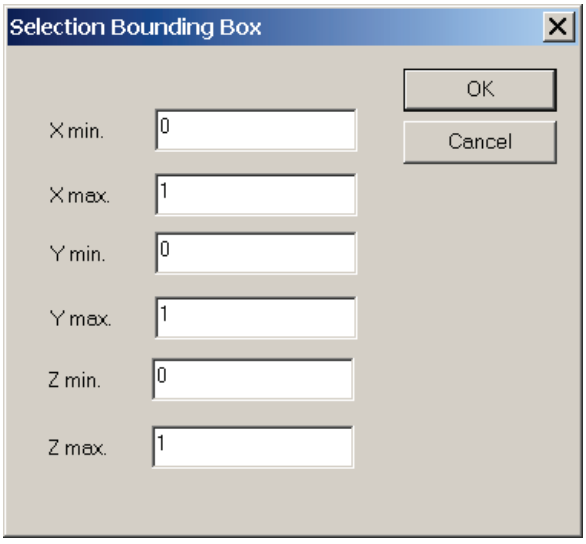
Selection with zone ID

Selection > Entity ID

This command is used to select an entity based on its ID. For example, it is possible to select the node with ID = *999* by entering this value in the selection dialog box. It is also possible to select all the nodes with IDs in the range 0 to 999 by entering the string "*0 999*" in the text field. This is the same behavior as **Selection->Zone ID**.

Selection > Bounding Box

This command opens a dialog box in which the user can specify the (*xmin*, *ymin*, *zmin*) and (*xmax*, *ymax*, *zmax*) coordinates of a bounding box. All the entities that fit in this bounding box are selected. For a face or an element, as soon as a node is inside the bounding box, the entity is selected.



Selection with bounding box

Selection > Select All

Selects all the entities based on the current selection filter. For example, if the selection filter is set to *Nodes*, all the nodes of the mesh are selected.

Selection > Unselect All (filter)

Unselects all the entities based on the current selection filter. For example, if the selection filter is set to *Nodes*, all the nodes are unselected. If faces or elements are selected, they stay selected.

Selection > Unselect All (no filter)

Completely clears the current selection (nodes, faces and elements) regardless of the selection filter. You can also use the **CTRL-U** keyboard shortcut or this button in the Selection toolbar to call this command.

Selection > Set Scalar Field Value

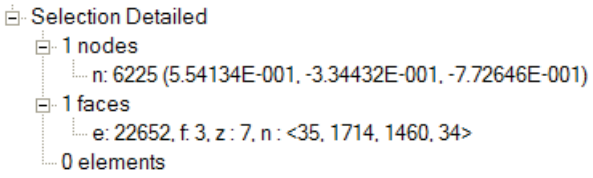
If you are currently visualizing a scalar field such as porosity or thickness, you can use this command to modify the scalar field values on the selected nodes or elements. This is sometimes useful to correct scalar fields after a **Compute Local Permeability**, when the mapping results are not very good because of complex geometry. The corrected scalar fields can be exported with **File->Export->PAM-RTM Scalar Field**.

Selection > Info Summary

Displays in the message window information about the current selection. The total number of nodes, faces and elements is displayed.

Selection > Info Detailed

Displays in the message window the details of the current selection. The ID of each selected entity is displayed. For example:



For selected faces, *e* means element ID, *f* means face index of the element (solid elements only), *z* means zone ID, and *n* is the connectivity of the element. For selected nodes, *n* means node ID, *g* is group ID (if the node is part of a group), and the (*x, y, z*) coordinates of the node are displayed.

GROUPS MENU

Groups of nodes or faces are created in PAM-RTM to be used as boundary conditions.

Groups > Create

Creates a new group with the currently selected entities. If nodes are currently selected, a new group of nodes is created. If faces are selected, a new group of faces is created. It is not possible to create a group of elements in PAM-RTM.

The ID of the new group is automatically assigned by PAM-RTM based on the largest ID of the groups currently defined. If the largest group ID is 99, the new group will have ID = 100. It is not possible to change the ID of a group after it has been created.

It is not possible to have nodes and faces in the same group.

Groups > Add To

This command is used to add nodes or faces to an existing group. The procedure is to select first some nodes or faces, then call the **Groups->Add To** command, and finally pick a node or face which is part of the group you want to modify.

Groups > Remove From

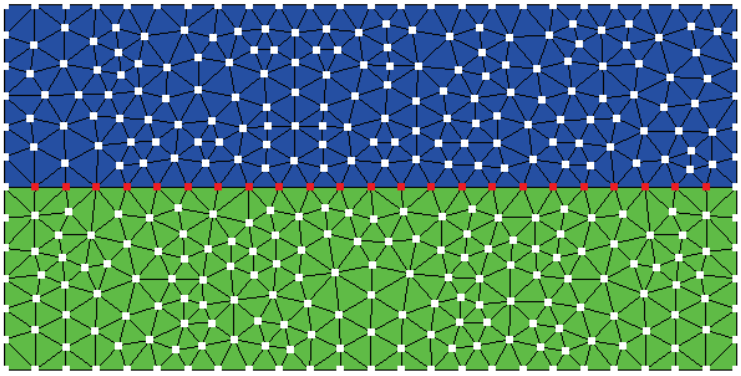
The procedure is to first select some nodes or faces, then call the **Groups->Remove From** command. The selected entities will be removed from all the groups they belong to. This means that if a node, for example, was part of 2 groups, it will be removed from the 2 groups.

Groups > Change ID

This command allows modification of a group ID. It asks the user the current ID of the group, and its new ID. If the specified new ID is already used, an error message is displayed.

Groups > Contact Interface

This command is used to create a special group that is currently used only for thermal contact resistance boundary condition. The elements are disconnected on the interface. This can be verified with the command **View->Outline->Free Edges**. A contact interface can only be created on the interface between two zones. The selection of nodes must be done with care. As shown in the following image, the two end points must not be selected. On a 3D mesh, it is recommended to work with a selection of faces.



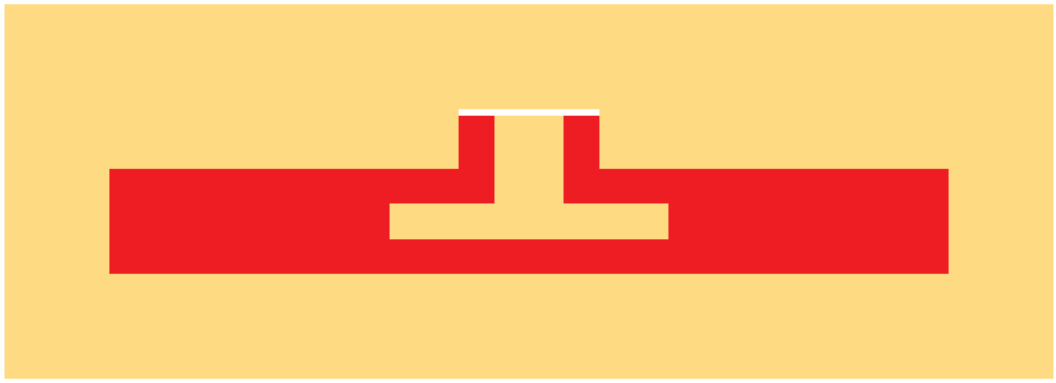
Nodes selection for contact interface

Free edges after creation of contact interface

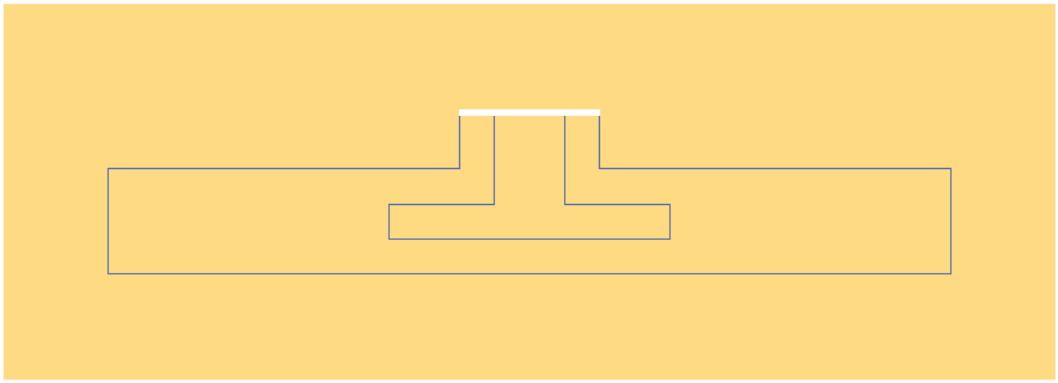
Groups > Mold/Cavity Interface

Automatically disconnects the elements on the mold/cavity interface for the whole mesh. The material type assigned elements through zones is used. Material type *solid* defines the mold area, and *reinforcement* the cavity area. A group of faces is automatically created, that can be referred by a *contact resistance* boundary condition. The following pictures show a cross section of a part with a metallic mold and insert. The first picture shows the solid material area (mold + insert), the second picture shows the reinforcement area, and the third picture shows the interface created by this command.

Solid material area (mold + insert)



Reinforcement material area



Interface created

Groups > Nodes to Faces

Convert a group of nodes to a group of faces. PAM-RTM prompts the user for the group ID to convert. Enter –1 to convert all groups.

Groups > Faces to Nodes

Convert a group of faces (for solid elements) or edges (for shell elements) to a group of nodes. PAM-RTM prompts the user for the group ID to convert. Enter –1 to convert all groups. This command is useful for example when you import a mesh generated in I-DEAS which contains groups of edges. PAM-RTM reads the group of edges from the I-DEAS file, but these groups can't be visualized or modified with the user interface. In such a case, this command should be used to convert all groups of edges to nodes.

Groups > Delete (Pick)

To delete a group, the user first calls this command, then picks a node or face in the group to delete.

Groups > Delete (ID)

Another way to delete a group is by entering its ID. Enter –1 to delete all groups.

Groups > Info Summary

Displays in the message window a short summary of the currently available groups. The ID of the group is listed, together with the total number of nodes or faces in the group.

Groups > Info Detailed

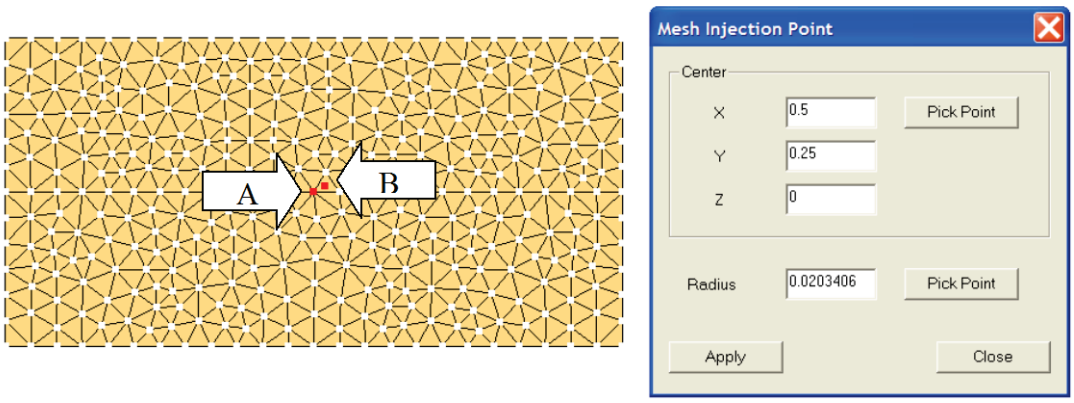
Lists in the message window all the node IDs and face IDs of all the groups.

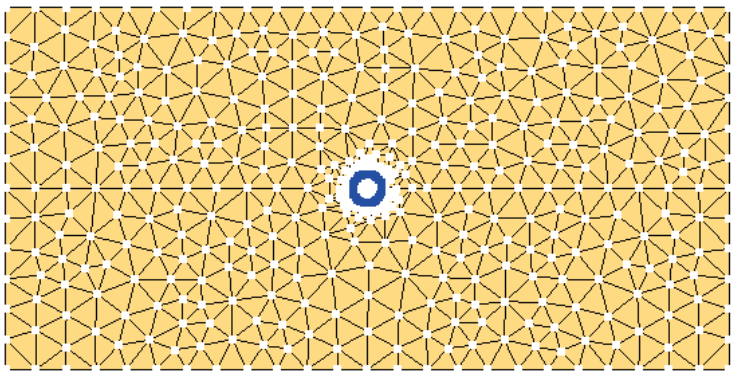
MESH MENU

Commands in the **Mesh** menu are used to make some modifications to a mesh, but most importantly to specify material orientations.

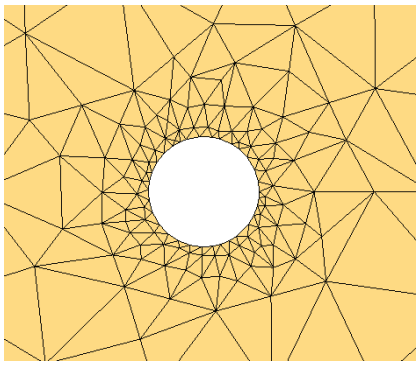
Mesh > Remesh > Injection Point

This command is used to create a hole in a shell mesh that can be used as an injection point. A group is automatically created within the nodes around the hole. The following image shows the **Mesh Injection Point** dialog box, together with the points that were picked for **Center** (**A**) and **Radius** (**B**).





Creation of a hole and a group



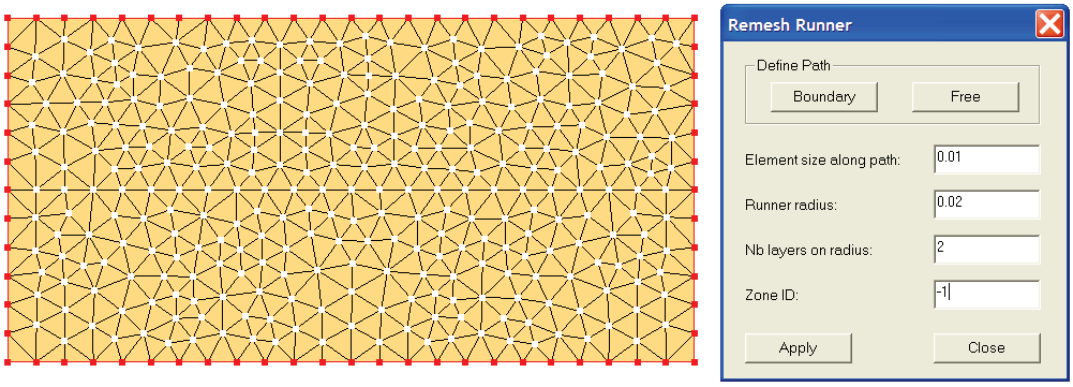
Mesh around the hole

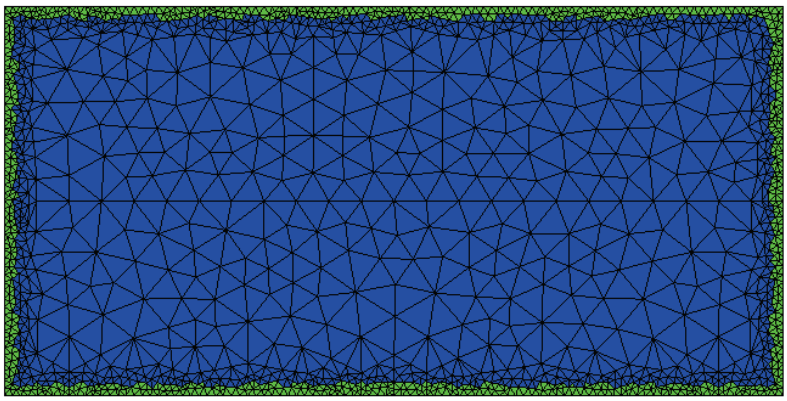
Mesh > Remesh > Runner

This command is used to create layers of thin elements that can be used to simulate runners or edge effects. The remeshed areas are most of the time on the part boundary, but they can also be internal to simulate special injection systems (for example injection tubes placed on top of the part). A distinct zone ID is automatically assigned to the elements in the remeshed zones.

You will most probably need the measure tool to use this command effectively.

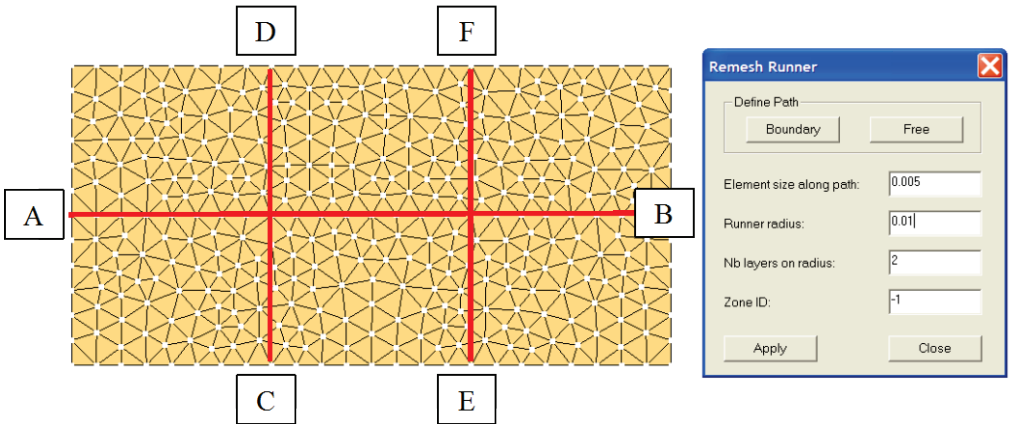
In the following image, a runner is created on the complete boundary of a rectangular part. To pick the full boundary, push the **Boundary** button, then pick any node on the boundary. The boundary is highlighted. Then you have to specify the size of elements along the path. The runner can be seen as a cylinder placed on top of the part. That's why it makes sense to talk about the runner *radius*. Specify the runner radius and the number of element layers you want on the runner radius. Use the measure tool to estimate the size of elements along the path and the runner radius. In this example the size of elements along the path was set to 0.01 m, the runner radius is 0.02 m and the number of layers on the radius is 2, which leads to elements with a good aspect ratio. As shown in the resulting mesh image, the runner is not a perfect straight line. However this should be good enough to simulate runners in PAM-RTM.

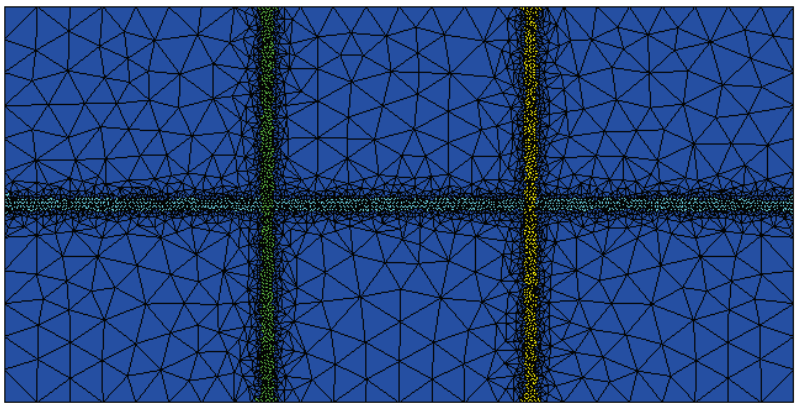




Creation of a runner on the boundary

It is also possible to create internal (not located on the boundary) free paths. Push the **Free** button, and then pick a sequence of nodes or points to define the path. The following images show how a branch like injection system can be created. First push the **Free** button, then pick nodes **A** and **B**. Enter the size parameters, then push the **Apply** button. Repeat the same procedure for the lines C-D and E-F.





Creation of a branch like injection system

Mesh > Orientations > K1

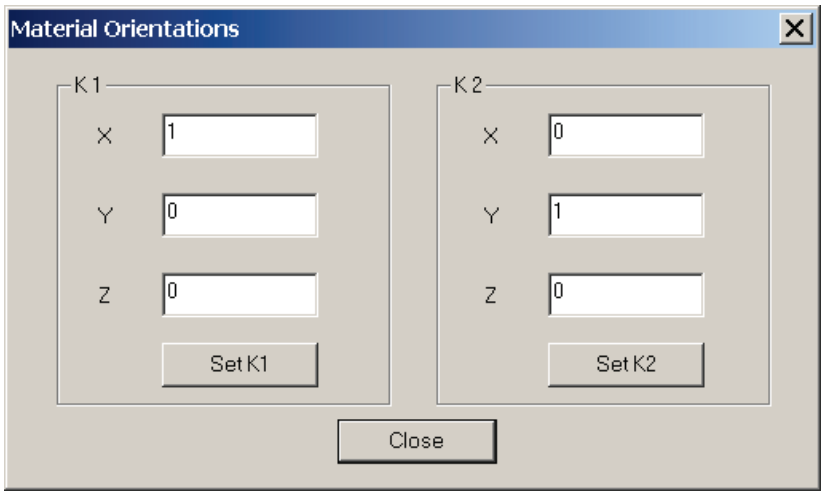
The **Mesh->Orientations->K1** and **Mesh->Orientations->K2** commands are used to set the current working direction. For example, a command like Set K Orthogonal needs to know if the direction to make orthogonal is K1 or K2. A check mark is displayed beside the current working direction.

Mesh > Orientations > Set Vectors

This command is used to set the direction vectors K1 and K2 by entering the 3 coordinates of vectors specified in the global coordinate system. After specifying the coordinates of K1 or K2, push the **Set K1** or **Set K2** button to apply the appropriate vector. The Set Vector command works on the currently selected faces or elements.

Mesh > Orientations > Project Vectors

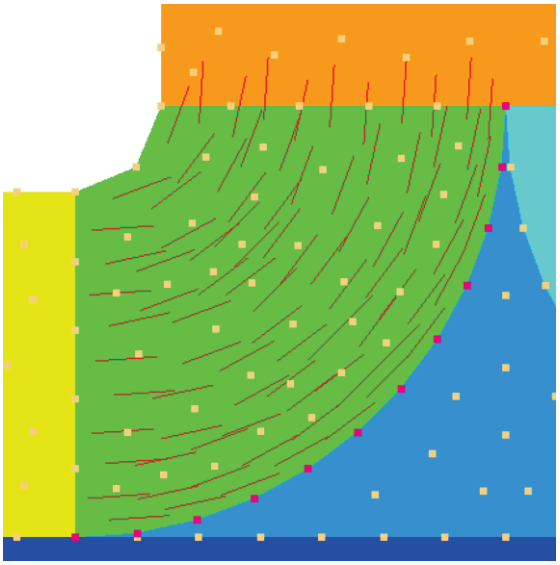
This command is the same as **Set Vectors** except that it does an orthogonal projection of the specified vectors on the selected elements.



Dialog box used by Set Vectors and Project Vectors

Mesh > Orientations > Set K from Selected Nodes

This command is used to specify material orientations in curved regions for which permeability directions can be described by a simple piecewise linear curve. For example, in the following image, K1 was specified by projecting the elements on the curve defined by the selected nodes. The tangent vector of the curve at the point of projection defines the K1 direction. Depending on the current working direction, K1 or K2 will be specified.



Setting material orientations in a curved region

The procedure to use this command is the following:

- Set the working direction (K1 or K2).
- Select faces or elements on which you want to specify the direction.
- Select nodes to define a piecewise linear curve. Nodes must be selected in a consistent order. For example in the previous image, nodes could be selected from bottom-left to top-right, or from top-right to bottom-left.
- Execute the **Mesh->Orientations->Set K from Selected Nodes** command.
- Verify the direction vectors with **View->Orientations->K1 Only** or **View->Orientations->K2 Only**.

Mesh > Orientations > Set K Orthogonal

This sets the orientation vectors in the current working direction as orthogonal to the other direction. For example, if the current working direction is K2 and this command is executed, the K2 direction of the selected elements will be made orthogonal to K1. Of course, in this example, K1 must be defined first.

Mesh > Orientations > Align Plies

This command is used to make material orientations consistent in plies. For example, after importing PAM-QUIKFORM plies, some direction vectors could be pointing in the X+ direction while other vectors in the same ply could be pointing in the X- direction. The goal of this command is to have all the elements in a ply oriented in the same global direction.

The algorithm currently implemented takes the first element of a ply and makes the directions consistent on the ply from neighbor to neighbor. This means that there is a risk that from ply to ply the directions could not be consistent. The user should always check the orientations on each ply after running this command. If a problem is found on a ply, the orientations on this ply can easily be reversed by selecting all the elements of the ply with **Selection->Select All**, then by reversing the orientations with **Mesh -> Orientations->Reverse**.

Mesh > Orientations > Reverse

This command reverses the current direction (K1 or K2) of the selected elements or faces. For example, if the current working direction is K1 and the command is executed on a set of elements with K1 pointing in the +X direction, the K1 direction will be reversed to -X.

Mesh > Orientations > Project on Skin

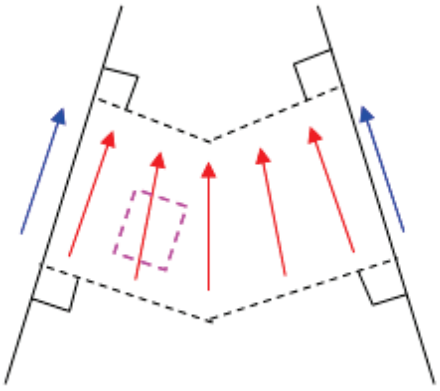
This command is used to project the orientation of an imported draping result on the mesh. It searches for each element in the mesh the closest element in the draping result and sets the direction K1 and K2 found on the draping result element on the mesh element.

Mesh > Orientations > Interpolate

This command works with two imported draping results, called skins. It will make an interpolation of the directions on each skin for the mesh.

The algorithm works that way:

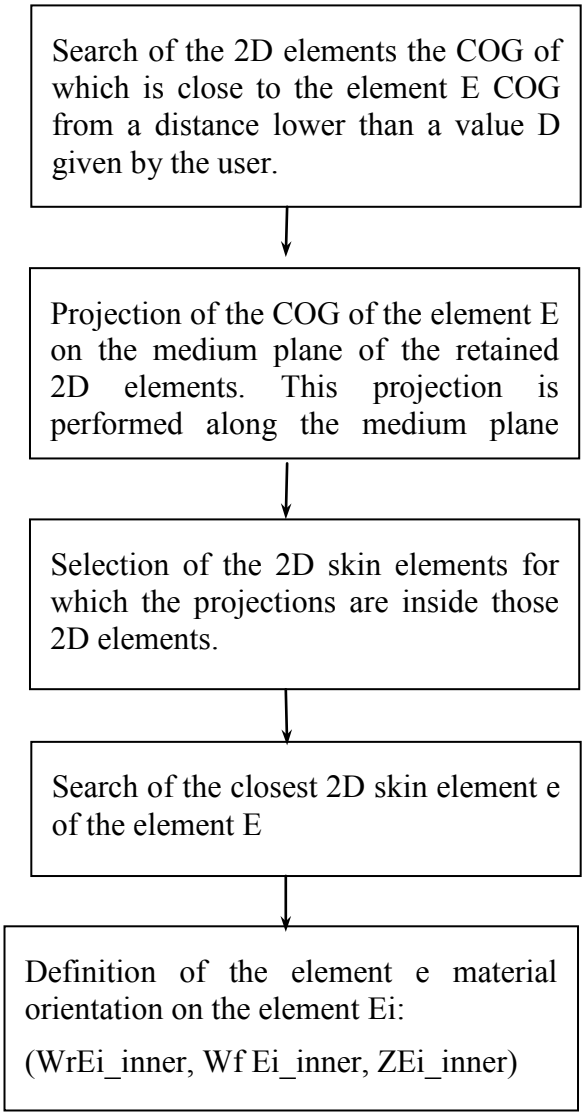
For each element of the mesh and each element of the skin, the coordinates of the centers of gravity (COG) are computed. If the distance between COG is inferior to the tolerance, it will try to project the cog on the skin element.



If no valid projection of the COG is found, the closest COG of the elements of skin mesh will be found, and the element will be selected.

For each skin, the direction of the weft and warp projection element will be saved, and the weft and warp direction of the element of the mesh to orient will be an interpolation of these two directions.

The used algorithm is the following.



Then the interpolation formula is

Interpolation formula :

$$Wr^{Ei} = d^{Ei\_outer} / (d^{Ei\_inner} + d^{Ei\_outer}) \times Wr^{Ei\_inner} + d^{Ei\_inner} / (d^{Ei\_inner} + d^{Ei\_outer}) \times Wr^{Ei\_outer}$$

$$Wf^{Ei} = d^{Ei\_outer} / (d^{Ei\_inner} + d^{Ei\_outer}) \times Wf^{Ei\_inner} + d^{Ei\_inner} / (d^{Ei\_inner} + d^{Ei\_outer}) \times Wf^{Ei\_outer}$$

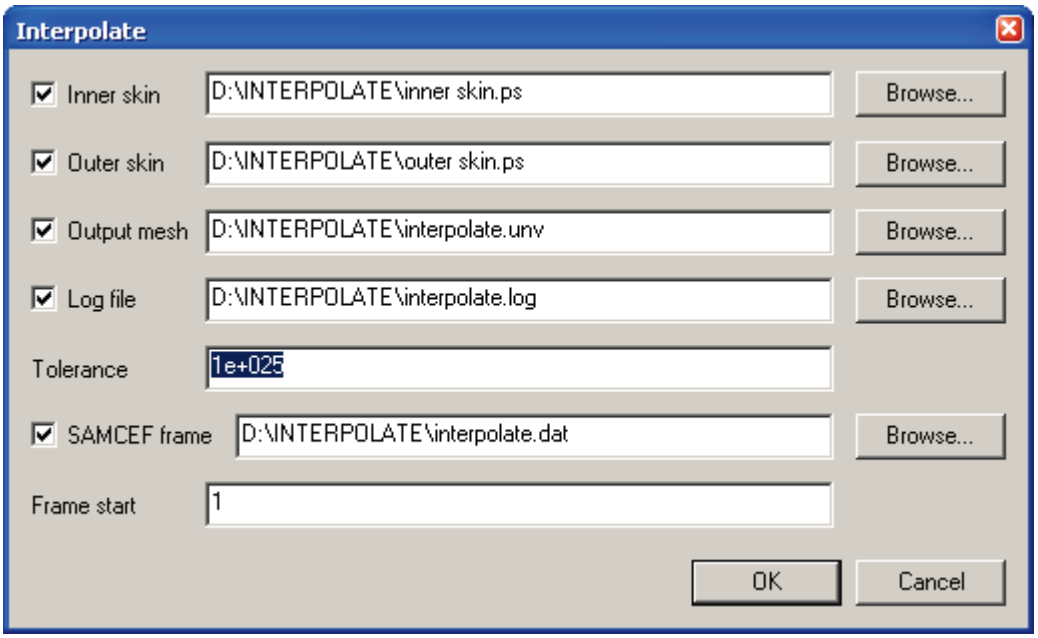
$$Z^{Ei} = Wr^{Ei} \Lambda Wf^{Ei}$$

Where:

- Wr and Wf are Weft and Warp directions,
- Z normal vector,
- Ei_outer is related to the outer skin and Ei_inner is related to the inner skin.

The function is used with this dialog box where the user can define or not define if the box is not checked:

- Path to the inner skin mesh file
- Path to the outer skin mesh file,
- Path to the output mesh in .unv format,
- Path to the log file,
- Tolerance value (mandatory),
- Path to the SAMCEF file,
- Number of the first frame in SAMCEF frame file.



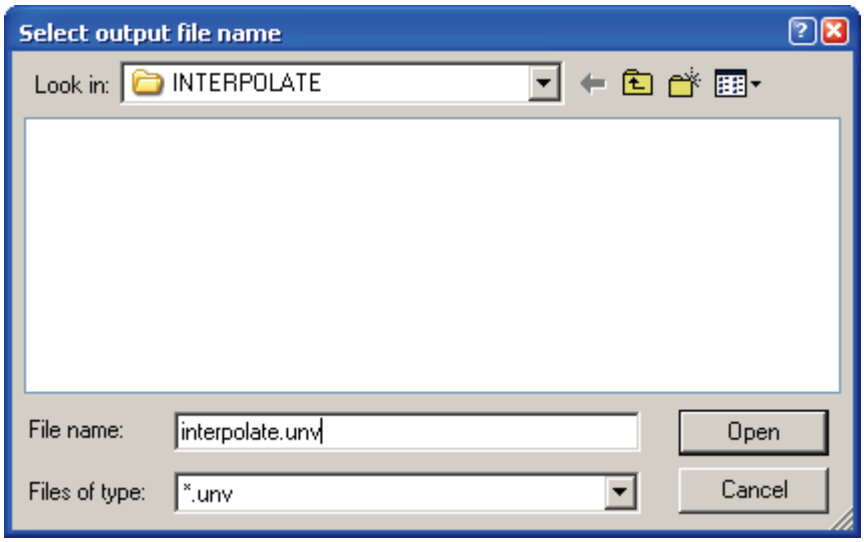
If the box for the inner and outer skin are not provided the interpolation will be made with draping results that would have been imported with the function *Mesh->import->draping results*. It will work only in the case when two draping results are already loaded. Otherwise an error message will be displayed.

If the box for the output mesh is not checked, the mesh will not be automatically exported. The user will have to export the mesh with *Mesh->export* or save the data.

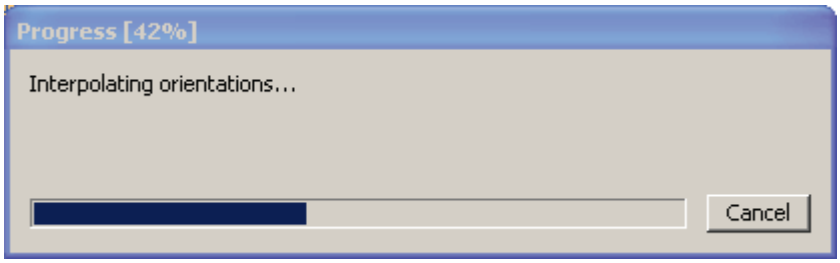
If the box for the log file is not checked, no log file is written.

If the box for the SAMCEF frame file is not checked, this file is not exported.

Every path selection will be made with windows explorer dialog box.



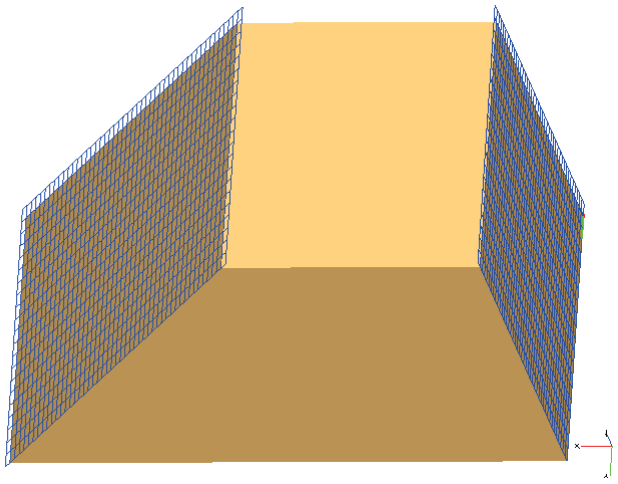
The user can follow the interpolation with a dialog box indicating the percentage made at any time. It is possible to stop calculation at any time by clicking on *Cancel* in this dialog box.



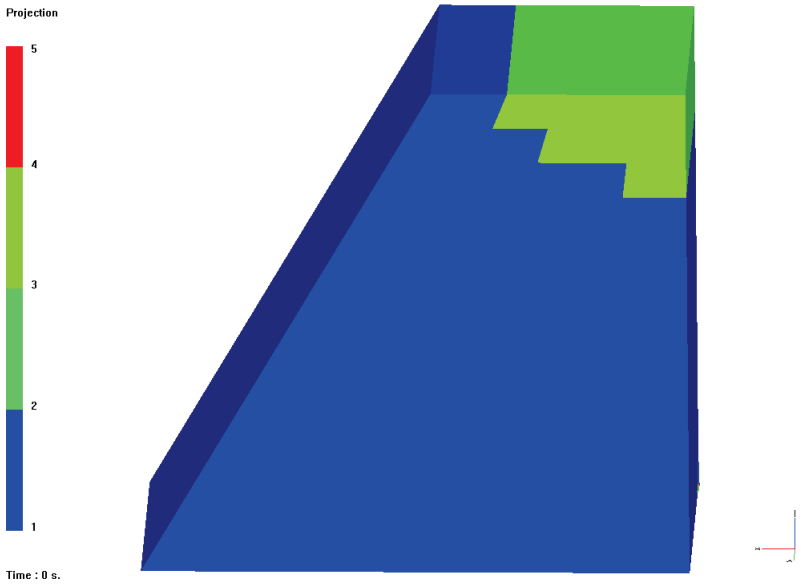
When interpolation is finished, a projection scalar field is displayed. The code for projection scalar field is:

- 1: projection worked on both skins,
- 2: projection didn't work on lower skin, the closest element is chosen,
- 3: projection didn't work on upper skin,
- 4: projection didn't work on both skins.

Below are showed one case where projection where some elements do not have a valid projection.



Trapezium volume mesh and skins to project



Trapezium projection results

The orientation can be displayed with the menu *View->Orientation*.

The .log file contains the following information:

- CPU time for the interpolation of the distance,
- Name of the exported files (.unv and .dat)
- For each element of the initial mesh:
  - Number of element
  - Number of the projection element on inner/outer skin or closest element id projection didn't work
  - Distance of projection
  - Weft/warp vector for inner/outer skin
  - Weft/warp vector for the element.

Examples of the content of the .log file are shown below in the cases where both projections worked and only the projection on outer skin worked.

```
elt: 790
proj inner: 381
dist: 4.57574E+000
i1: (-5.00006E-001, 0.00000E+000, 8.66022E-001)
i2: (0.00000E+000, -1.00000E+000, -3.81470E-007)
proj outer: 99
dist: 1.00389E+002
o1: (0.00000E+000, 3.81470E-007, 1.00000E+000)
o2: (0.00000E+000, -1.00000E+000, 3.81470E-007)
f1: (-4.78209E-001, 1.66294E-008, 8.71862E-001)
f2: (0.00000E+000, -1.00000E+000, -3.48211E-007)
```

```
elt: 1968
w1: no proj on inner, closest elt: 240
dist: 4.45928E+001
i1: (-4.99996E-001, -3.81470E-007, 8.66028E-001)
i2: (0.00000E+000, -1.00000E+000, 0.00000E+000)
proj outer: 401
dist: 9.04649E+000
o1: (0.00000E+000, 3.81470E-007, 1.00000E+000)
o2: (0.00000E+000, -1.00000E+000, 0.00000E+000)
f1: (-8.43264E-002, 2.52797E-007, 9.77405E-001)
f2: (0.00000E+000, -1.00000E+000, 0.00000E+000)
```

SAMCEF frame file contains for each element weft and warp vector using following format:

```
.FRAME   I 1000001  TYPE CARTESIAN ORIGIN 0. 0. 0.
             V1 0.234009  0.969422  -0.073899
             V2 -0.575535  0.046881  -0.816432
         I 1000002  TYPE CARTESIAN ORIGIN 0. 0. 0.
             V1 0.268795  0.955718  -0.119803
             V2 -0.617248  0.050841  -0.785124
         I 1000003  TYPE CARTESIAN ORIGIN 0. 0. 0.
             V1 0.209641  0.976123  -0.056876
             V2 -0.503107  0.036501  -0.863453
         I 1000004  TYPE CARTESIAN ORIGIN 0. 0. 0.
             V1 0.259903  0.962377  -0.079257
             V2 -0.545878  0.035112  -0.837129
         I 1000005  TYPE CARTESIAN ORIGIN 0. 0. 0.
             V1 0.187170  0.981582  -0.038255
             V2 -0.433344  0.029658  -0.900740

.AEL     I  12443   FRAME  1000001
         I  12444   FRAME  1000002
         I  12445   FRAME  1000003
         I  12446   FRAME  1000004
         I  12447   FRAME  1000005
```

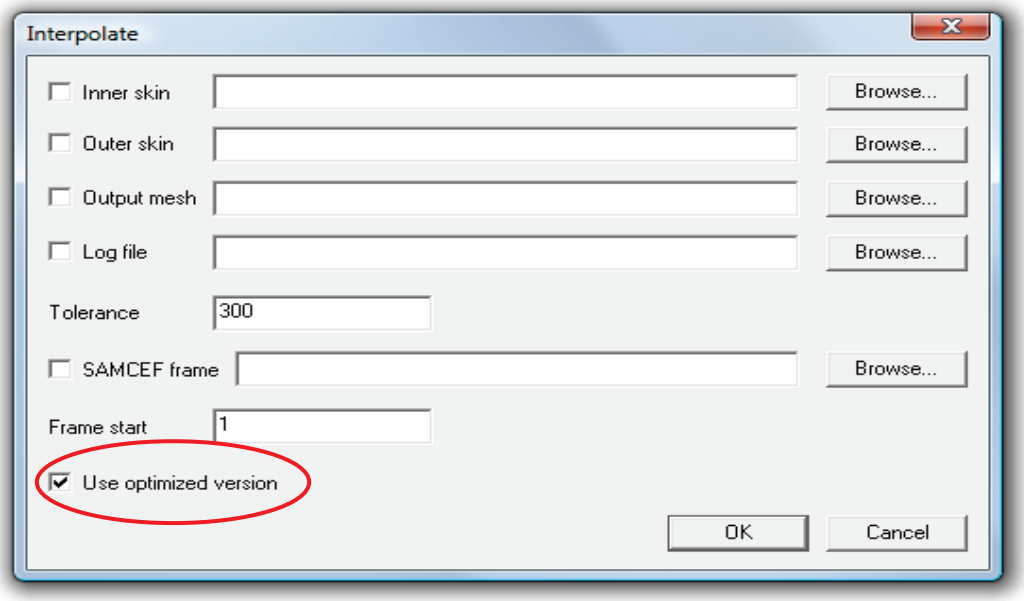
Frame number

Warp interpolated vector coordinates

Weft interpolated vector coordinates

Element number

Frame number



Introduced in PAM-RTM 2009 is a new optimized version of the method described above. To enable the optimized version, simply select **use optimized version**. The optimized version uses a completely different algorithm for the projection of the solid elements on the surface meshes. This algorithm is much faster but a little less accurate, so the non-optimized version should be used when accuracy is of primary concern compared to CPU time. However speedups of 30 were obtained with the optimized version, which makes it the version of choice for meshes of millions of elements. To get the best performance from this optimized version, the size of the surface elements should be at least 2 times smaller than the solid elements.

Mesh > Orientations > Map Draping Results

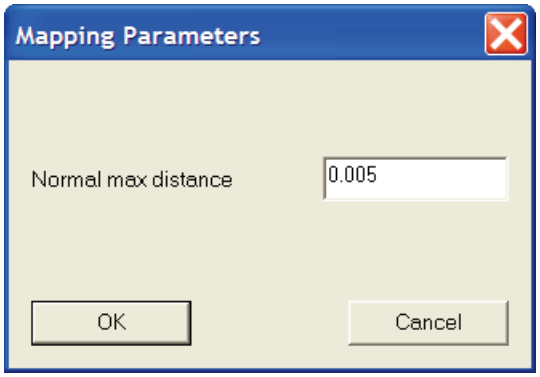
This command is used to project a stack of plies that have been imported with the command **File->Import->Draping Results**, on the mesh used for the injection simulation (the mesh that was loaded in **PAM-RTM™** with the command **File->Open** or **File->Import**). This is a CPU intensive geometrical calculation that tries to match elements of the injection mesh with elements in plies. The final goal is the calculation of the average local permeability on the injection mesh by taking into account the local fiber orientations in each ply.

Basically, what the algorithm does is the following:

- For each element of the injection mesh
  - Calculate the center of gravity (*C*) of the injection mesh element.
  - Define a ray *R* starting from *C*, with the direction of the normal vector of the injection mesh element.
  - For each ply mesh
    - Calculate the intersection of *R* with all the elements of the ply mesh
      - If an intersection is found within the *normal max distance* value, record the mapping of the element of the ply mesh with the element of the injection mesh.

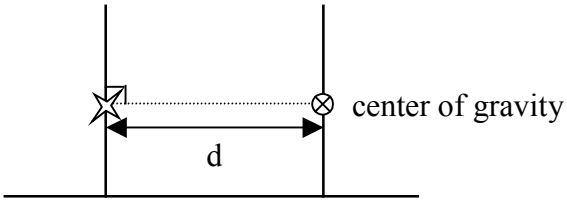
This is an exhaustive search through all the elements of all the plies.

The **Map Draping Results** command can work on the full injection mesh, or on the currently selected elements. If the current selection is empty, mapping is done on the full injection mesh. Otherwise, **PAM-RTM™** asks the user if he wants to do the mapping on the selected elements only, or the full injection mesh. **PAM-RTM™** then prompts the user for the *normal max distance* parameter, as shown in the following dialog box:



Mapping tolerance

- Normal max distance. Unit: length.



Valid projection discarded because d >max normal distance

The *max normal distance* is used to discard elements that have a valid projection, but the distance between the center of gravity of the injection element and the projected point is larger than the specified tolerance. This is useful in case of ribbed parts.

When the mapping calculation is done, it is always a good idea to verify the validity of the mapping with the *Nb_Plies* scalar field. This scalar field is automatically generated by **PAM-RTM™** after a *Map Draping Results* calculation. It shows the number of plies covering each element of the injection mesh. For example, if you drape 4 plies that cover completely the surface to drape, you should have *Nb_Plies* = 4 everywhere. If you find that some elements have different values, it means there was a problem with the mapping, and maybe you need to change the *max normal distance*.

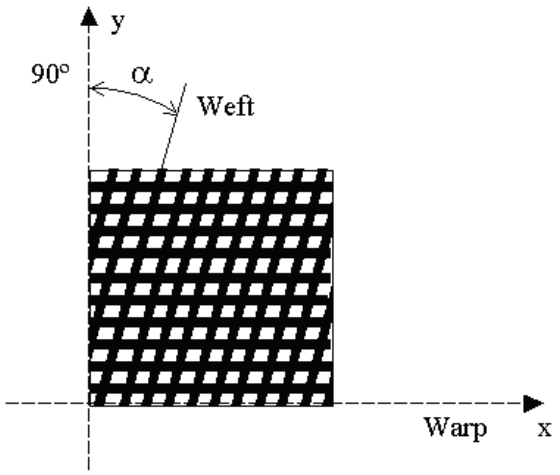
Mesh > Orientations > Compute Local Permeability on Shells

Before we describe the options to calculate the local permeability of a sheared fabric, some definitions are necessary.

A very important thing to understand is that when you visualize material orientations in **PAM-RTM™** with the **View->Orientations->K1** or **View->Orientations->K2** commands, these orientations can have a different meaning depending on the context. For example, when you visualize orientations on a ply imported with the PAM-FORM interface, the orientations should be seen as fiber directions, not permeability directions. However if you use **View->Orientations->K1** on the injection mesh after a *Compute Local Permeability*, the vectors you see are principal directions of the permeability tensor, not fiber directions.

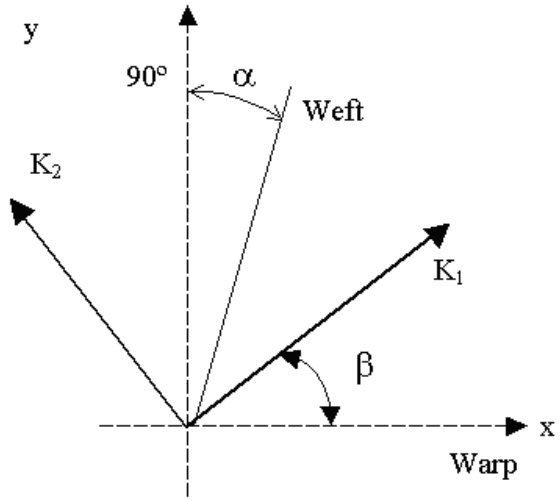
In the following text, we will refer to the direction visualized with **View->Orientations->K**1 in the context of fiber directions as f_1. The f_1 direction is also defined as the *warp* direction for fabrics. The f_2 direction is the *weft* direction for fabrics.

The shear angle α is defined as shown in the next figure: it is the angle between the weft direction and the direction orthogonal to the warp.



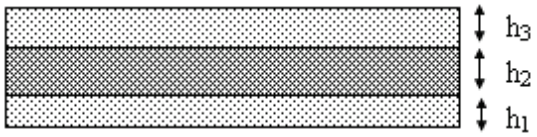
Definition of the shear angle α

When a fabric is sheared, the principal directions of the permeability tensor change as a function of the shear angle α. The principal permeability direction K_1 is defined with an angle β relative to the warp direction.



Rotation of the K_1 direction as a function of the shear angle α

In general, a laminate is made of many plies with different thickness and material properties.



A typical laminate made of many layers of different thickness and permeability

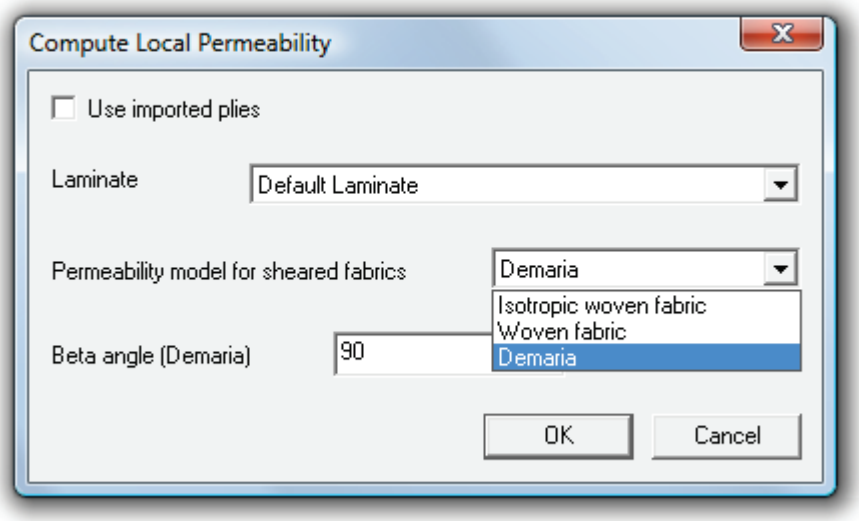
The average permeability calculation takes into account the thickness of each layer:

$$k_{avg} = \frac{\sum_{i=1}^{n} k_i h_i}{\sum_{i=1}^{n} h_i}$$

Since the permeability of each layer is actually a tensor, the permeability tensor of each layer is transformed in the referential given by the K_1 and K_2 directions of the first ply. The resulting non-diagonal tensor is then diagonalized and the final principal directions of the laminate are the eigenvectors of the non-diagonal tensor. The local permeability values k_1 and k_2 are the eigenvalues.

There are two ways to use the *Compute Local Permeability* command. The first one simply computes the average permeability, porosity and total thickness of a *laminate* material (found in the **Materials** folder of the document tree), and assigns these values to the current selection, or the whole mesh if nothing is selected. It uses the currently defined orientations on the mesh as the zero degree referential. The other approach uses the mapping computed by the *Map Draping Results* command to calculate the average local permeability of deformed plies. In that context, a *laminate* material still has to be defined by the user in order to link material properties to the imported plies. The number of layers of this laminate must match the number of imported plies. For example, if 4 draped plies were imported, a laminate material made of 4 layers must be defined. This is because **PAM-RTM™** needs to know the type of reinforcement and permeability model associated to each layer.

When the **Mesh->Orientations->Compute Local Permeability** command is called, **PAM-RTM™** opens the following dialog box. If draped plies, such as PAM-QUIKFORM results imported with **File>Import>Draping Results**, are to be used for the average permeability calculation, the user checks the **use imported plies** option. Otherwise, if that option is not checked, it means that one of the laminate materials currently defined will be used. The **laminate** combo lists the available laminate materials. In case sheared fabrics such as **PAM-QUIKFORM™** results are used, it is also necessary to specify the **permeability model for sheared fabrics**. Four models are currently supported and explained below: unidirectional, isotropic woven fabric, general woven fabric, and Demaria.



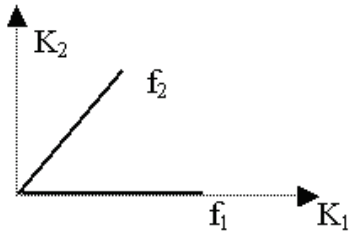
Available models to compute local permeability of fabrics

UD Model

When a layer is associated to a UD (unidirectional) reinforcement, the local K_1 principal permeability direction is automatically set in the same direction as the f_1 fiber direction. The f_2 direction is completely ignored (it is a UD, so the f_2 direction is meaningless), and K_2 is made orthogonal to K_1.

The permeability values assigned in the K_1 and K_2 directions are directly the values specified in the *Reinforcement* associated to each layer, without any local modification based on shearing.

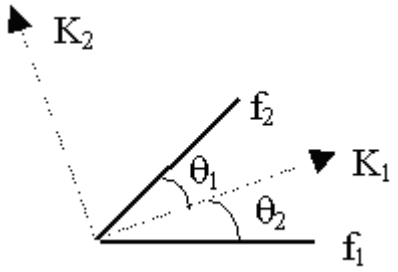
Referring to the figure ***Rotation of the K_1 direction as a function of the shear angle α***, the K_1 direction is given for this model by $\beta=0$.



Principal permeability K_1 for unidirectional

Isotropic Woven Fabric Model

With this model, which is valid only for fabrics with initially isotropic permeability (permeability of the fabric before shearing is isotropic), the principal permeability direction K_1 is calculated as the bisector of the angle between the warp and weft ($\theta_1 = \theta_2$ in the following figure).



Permeability directions calculated with the isotropic woven fabric model

Referring again to figure ***Rotation of the K_1 direction as a function of the shear angle α***, the angle β for this model is given by :

$$\beta = 45 - \frac{\alpha}{2}$$

The local fiber content (v_f) is calculated from the shear angle (α) and the initial fiber content of the ply, before deformation (v_{f0}) :

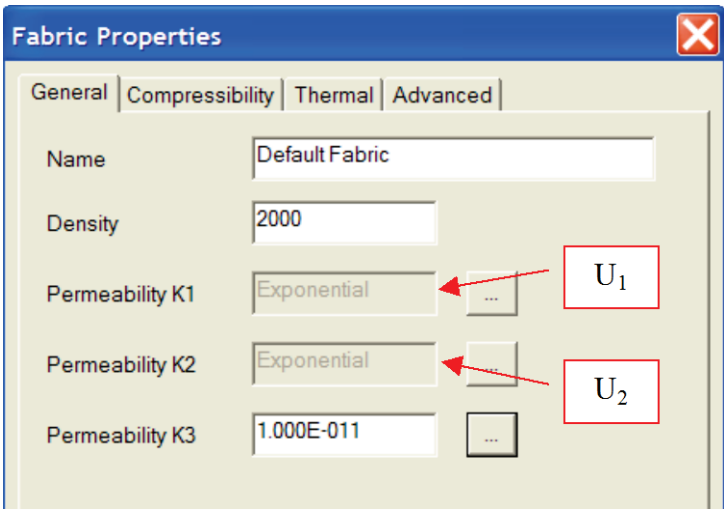
$$v_f = \frac{v_{f0}}{\cos\alpha}$$

The local permeability values in the principal directions are then computed using the permeability curves function of the fiber content specified in the *Fabric* associated to the ply (we call these curves U_1 and U_2 here) and an internal model that modifies these values as a function of the shear angle (M_1 and M_2) :

$$k_1 = U_1(v_f) * M_1(\alpha)$$

$$k_2 = U_2(v_f) * M_2(\alpha)$$

This means that to use this model, the user should ideally have access to experimental curves giving the permeability as a function of the fiber content. These curves are entered in the **Permeability K1** and **Permeability K2** fields of the fabric editor (next figure). The initial porosity required to calculate the local fiber content is specified for each layer of the laminate.



Specification of the permeability curves as a function of the fiber content in the Fabric Properties dialog

Woven Fabric Model

This empirical model uses the functions specified in the **Sheared Permeability K1**, **K2**, **K3** and **Sheared Rotation Angle** (β) fields of the fabric editor. These are functions of the shear angle and initial fiber content:

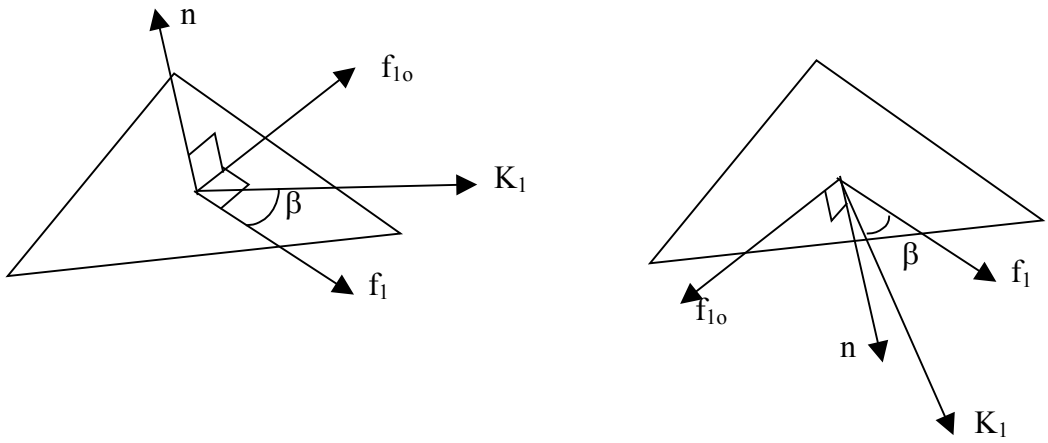
$$k_1 = f(\alpha, v_{f0})$$

$$k_2 = f(\alpha, v_{f0})$$

$$k_3 = f(\alpha, v_{f0})$$

$$\beta = f(\alpha, v_{f0})$$

The definition of the rotation angle β is the one shown in figure ***Rotation of the K_1 direction as a function of the shear angle α***. It is important to note that to calculate the K_1 direction with the angle β, **PAM-RTM™** constructs a right handed local coordinate system on an element of a ply with the f_1 direction, the normal vector of the element, and the direction orthogonal to f_1 and the normal vector (f_{1o}). If the user notices that K_1 is not rotated in the expected direction, he should verify normal vectors in each ply with **View->Normal Vector**, and then use the **Mesh->Cleanup->Reverse Normals** command if necessary to reverse the normal vectors of a ply.



The effect of the normal vector on the K_1 direction

The local fiber content (v_f) is calculated from the shear angle (α) and the initial fiber content of the ply, before deformation (v_{f0}):

$$v_f = \frac{v_{f0}}{\cos\alpha}$$

As an application example of the first approach (the one that works directly on a laminate without draping results), suppose you have a mesh already oriented and you want to rotate the orientations by 45 degrees. You could define a single layer laminate material, set the orientation angle of that layer to 45 degrees, run the **Compute Local Permeability** command and select the one layer laminate in the **laminate** dropdown list.

Demaria Model

The reference for this model is:

Demaria C, Ruiz E, Trochu F. *In-plane anisotropic permeability characterization of deformed woven fabrics by unidirectional injection. Part II: Prediction model and numerical simulations*. Polymer Composites, December 2007.

This model assumes that the principal permeabilities in the two principal directions can be expressed as follows:

$$K_{1,2}(\alpha) = K_{1,2}^{v_f}(\alpha) F_{geo}(\alpha) = K_{1,2}(\alpha = 0^\circ) F_{v_f}(\alpha) F_{geo}(\alpha)$$

Only the unsheared permeabilities $K_{1,2}(\alpha = 0^\circ)$ are needed to use this model. The $F_{v_f}(\alpha)$ term is derived from Kozeny-Carman, and the $F_{geo}(\alpha)$ term from the geometrical analysis of the deformation of a unit cell.

The $K_{1,2}(\alpha = 0^{\circ})$ permeabilities are simply the **Permeability K1** and **Permeability K2** parameters found in the **General** tab of the **Fabric Properties** dialog.

The parameter **beta angle** is available in the **Compute Local Permeability** dialog to specify the initial permeability angle with respect to the first fiber direction. It is equivalent to the angle β of the woven fabric model.

This model has been validated experimentally on a woven fabric, and should be applicable to any woven fabric.

The current implementation has an important limitation: the shear angle added to the initial permeability angle (*beta angle*) must remain in the X_+Y_+ quadrant, i.e. the final angle must be between zero and 90 degrees. For instance if the initial permeability angle is 60 degrees, a maximum negative shear deformation of 30 degrees is allowed, while a maximum positive shear deformation of 60 degrees is allowed. However it is better to stay away from these limits. The model will work better for instance with an initial permeability angle of 45 degrees and shear deformations in the range of +/- 30 degrees.

Mesh > Orientations > Compute Local Permeability on Solids

This command assumes that some orientations are already set on solid elements and represent fiber directions, potentially sheared (i.e. non-orthogonal). These orientations could have been transferred to the solid mesh with a command such as **Project on Skin**. This command is then used to compute from the draped fiber directions a permeability tensor on each solid element taking into account shearing.

If some elements are selected, the command will only compute permeability of those elements. Otherwise it will use the whole mesh.

When the command is launched, it opens a dialog box asking which draped permeability model to use. The options are:

- Isotropic woven fabric (bisector)
- Woven fabric

The first option is the simple bisector model, which doesn't need any material parameter.

The second option makes use of the "sheared" parameters of the **Advanced** tab of the reinforcement dialog box. In that case, the zone ID of each element is used to get the associated reinforcement.

There is actually a third option: if the zone refers to an unidirectional reinforcement, the first fiber direction f_1 will be kept as is and used as permeability direction K_1, then K_2

will be made orthogonal to K_1 in the plane of f_1 and f_2. The permeability value is directly the one specified on the reinforcement (in the **General** tab).

The local porosity is also calculated by the command.

The **Use local permeability files** and **Use local porosity file** options in the **Numerical Parameters > Local Variables** tab are automatically selected.

Mesh > Orientations > Compute Local Permeability from Zones

Starting with **PAM-RTM™ 2010**, it is now possible to assign laminate materials to zones. However the **PAM-RTM™** solver cannot run a flow simulation directly on the laminate materials. Instead the solver reads the local permeability, local porosity and local thickness files generated by the **PAM-RTM™ GUI** (.sf files).

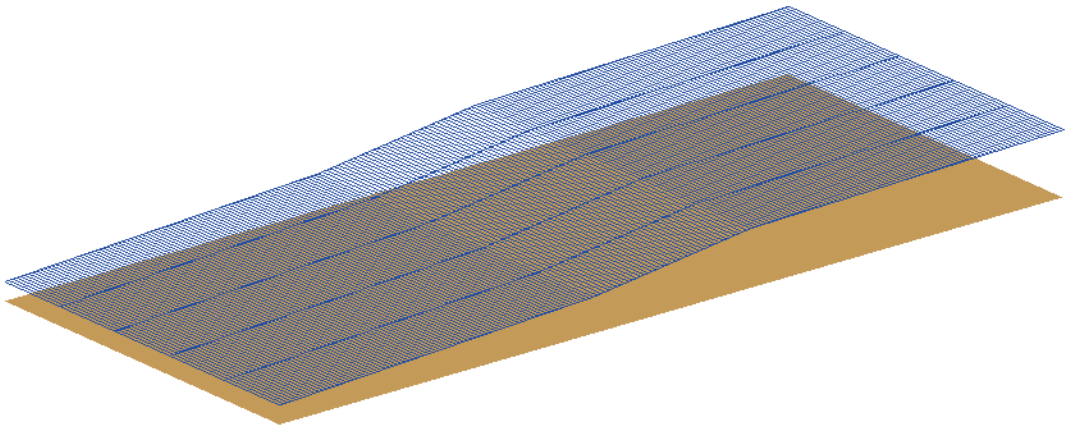
First the user assigns some laminates to zones. Then he launches the **Compute Local Permeability from Zones** command to generate the local permeability, local porosity and local thickness data. These can be checked graphically by choosing the appropriate entry in the dropdown list of the main toolbar (**K1** or **Plies_Thickness** for instance). The command will automatically turn on **use local permeability files**, **use local porosity file** and **use local thickness file** in the **Local Variables** tab of the **Numerical Parameters**. When the .dtf document will be saved, .sf files will be generated with names matching the .dtf name. This means the simulation is ready to run once the .dtf has been saved.

Note that it is not mandatory to assign a laminate to every zone to use that command. Some zones could be linked to a simple reinforcement, while others could be linked to laminates. In a case involving race tracking for instance, the high permeability zone could be linked to a simple reinforcement.

Mesh > Orientations > Compute Thickness from Skins

The goal of that command is to calculate the distance between a shell mesh (the reference mesh) and the top and bottom surfaces of a solid, then generate a local thickness field for the reference mesh. The mesh that was loaded in the **PAM-RTM™ GUI** with **File>Open** or **File>Import>Mesh** is the reference mesh. The command uses the draped plies meshes currently loaded (one or two) as skin information. In case a single draped mesh is available, the reference mesh is seen as the bottom skin of a solid, and the draped ply is the top skin of the solid. In case 2 draped plies are available, these are seen as the top and bottom skins of the solid, and the reference mesh is the mid-surface of the solid.

Below is an example where only the top surface of a solid was imported as a draped ply (**File>Import>Draping Results>PAM-QUIKFORM**). After running **Compute Thickness from Skins**, the **Mapped_Thickness** field is available in the dropdown list of the main toolbar.



To use that thickness field in a filling calculation, the user has to export the field first with **File>Export>PAM-RTM Scalar Field**. Assuming the case is called x.dtf, the exported scalar field file would be called x_thickness.sf. Then the option **use local thickness** has to be checked in the **Local Variables** tab of the **Numerical Parameters**.

Mesh > Orientations > Clear on Selection

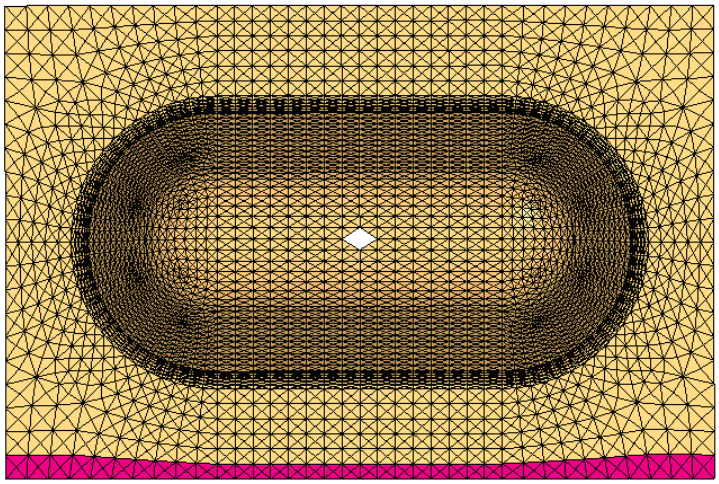
Removes any orientation specified on the currently selected elements.

Mesh > Orientations > Clear All

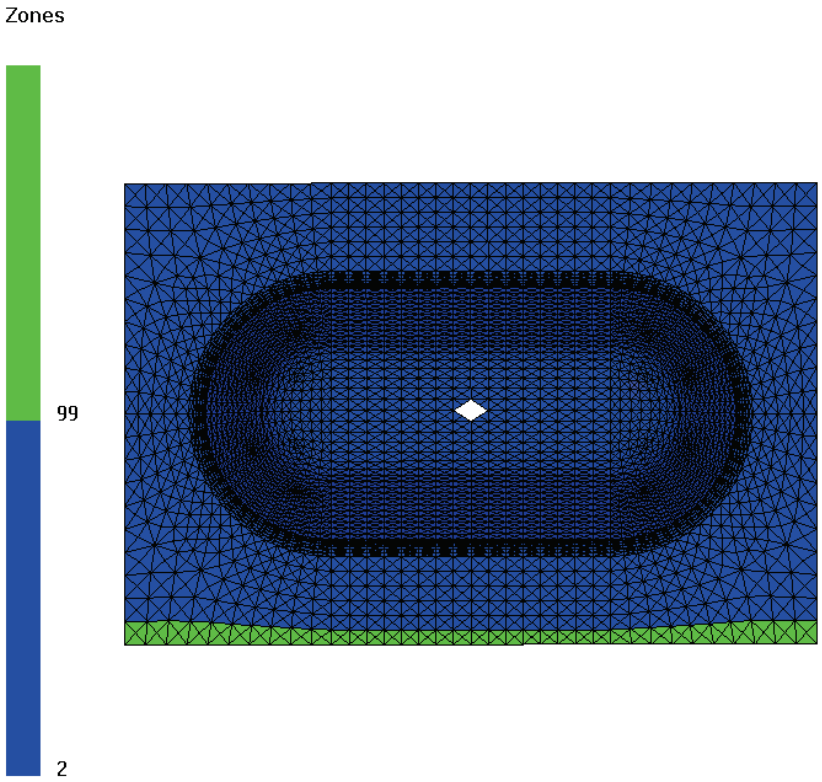
Removes any orientation specified on the whole mesh.

Mesh > Transform > Set Zone ID

This command is used to assign a different zone ID to the selected elements. This can be useful for example to create a runner (a zone with higher permeability).



Selection of elements on the edge of a part to create a runner with Set Zone ID



Assignment of zone ID 99 to the selected elements

Mesh > Transform > Offset Zone Ids

Adds a user specified value to the zone ID of each zone. For example if 10 zones are currently defined and numbered from 1 to 10, an offset of 100 will renumber zones from 101 to 110. This is useful in the context of local permeability calculation from imported plies. If there is a conflict between the zone IDs of the injection mesh and the plies IDs, the user can simply offset the zone IDs of the injection mesh.

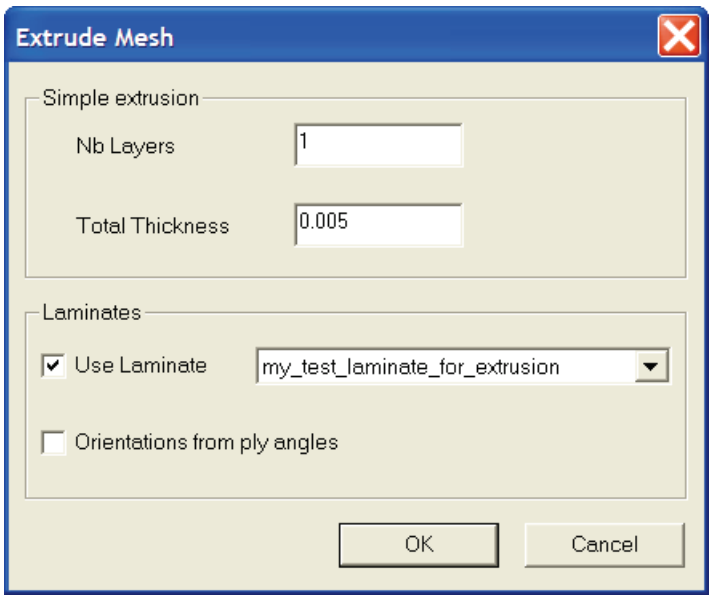
Mesh > Transform > Extrude

This command extrudes a mesh of shell elements to a mesh of solid elements. Triangle elements are transformed to 6-node prismatic elements, and 4-node quads are transformed to 8-node bricks.

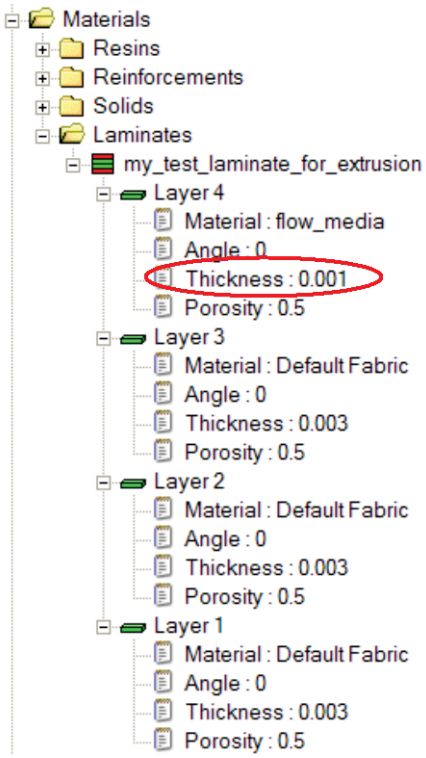
For simple extrusion, the user can specify the total thickness of the solid part and the number of layers. In that case all the layers will have the same thickness. A different zone ID is assigned to each layer so that it is easier later for the user to assign a different material to each layer.

For more advanced extrusion, it is possible to select a laminate material, so that the thickness of each layer of the laminate is used as the thickness of each layer of the extruded mesh. This process is shown below. Assuming the user already created a

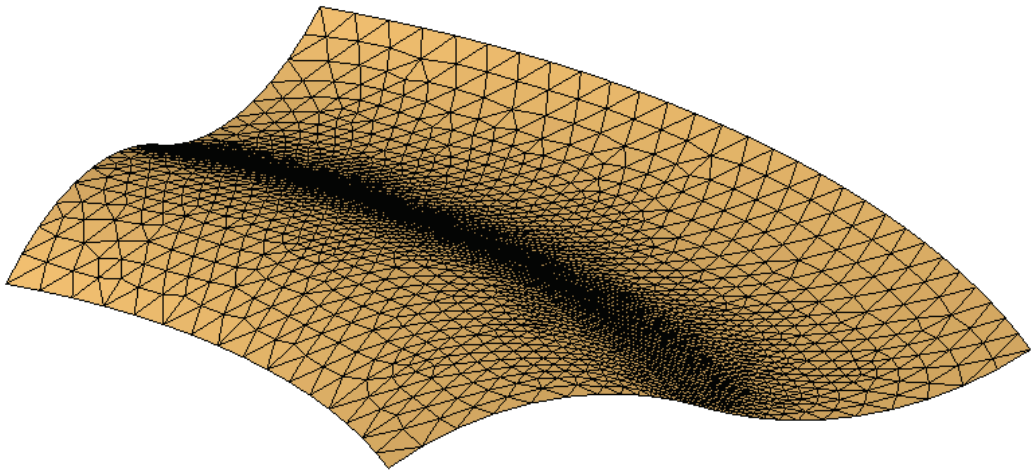
laminate material and specified the thickness of each layer, he checks the **Use laminate** option and selects the laminate previously created in the dropdown list. Note that if **Use laminate** is checked, the **Nb Layers** and **Total Thickness** parameters are completely ignored. It is also possible to have the elements of the extruded mesh automatically oriented if the **orientation from ply angles** option is checked. This assumes the user has specified the angle of each ply of the laminate, and that orientations are defined on the shell mesh. The orientations of the shell mesh correspond to zero degree ply angle. The final orientations are obtained by rotating those orientations by each ply's angle.



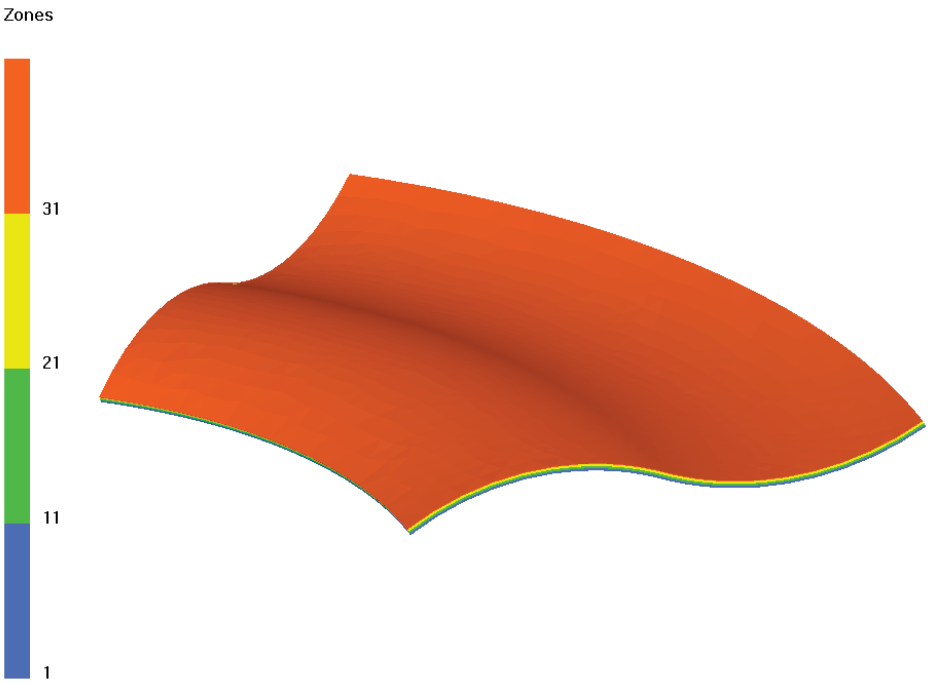
Extrude dialog box



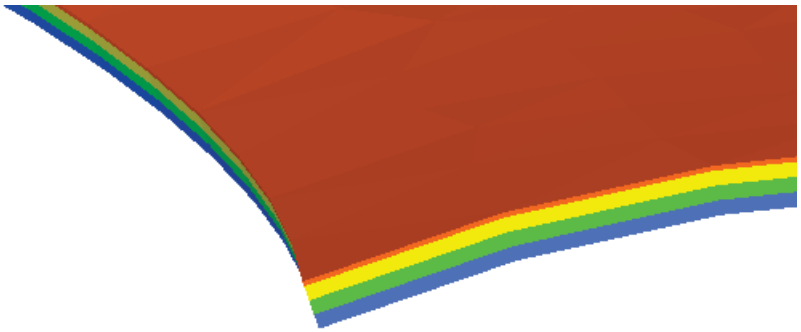
Definition of a 4 plies laminate, to be used for mesh extrusion. Notice the thickness of the 4th layer, much thinner.



Shell mesh to be extruded



Extruded 4 layers part



Notice the top layer, much thinner. Linked to a material with a much higher permeability, it could be used as a flow enhancing layer, for VARTM simulation for instance.

Mesh > Transform > Split Quads

Splits the 4 nodes quad elements into triangles. Each quad is split in 4 triangles, the barycenter of the quad being used as the common node of the 4 triangles.

This command is quite useful in PAM-RTM since quads are not allowed for filling simulations with Darcy. If the user has a mesh of quads that he would like to use for a

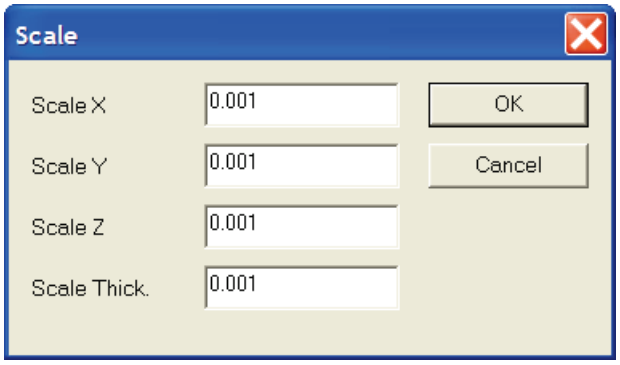
filling simulation, he can save a lot of time with this command instead of going back to his mesh generator.

Mesh > Transform > Split Solid Elements

The goal of this command is the same as the *Split Quads* command : since 6-node wedges and 8-node bricks are not allowed for PAM-RTM filling simulations with Darcy, this command can be used to split such elements into 4-nodes tetrahedra.

Mesh > Transform > Scale

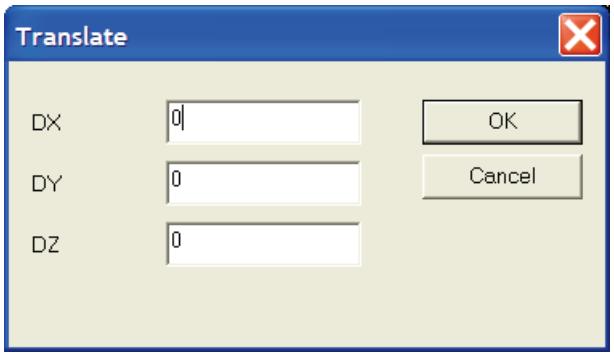
Used to apply a scale factor to the nodes of a mesh. This is useful for example to convert a mesh in millimeters to meters, since meters are used in PAM-RTM. It is also possible to apply a scale factor to the pseudo-thickness of a shell mesh.



Scale dialog box

Mesh > Transform > Translate

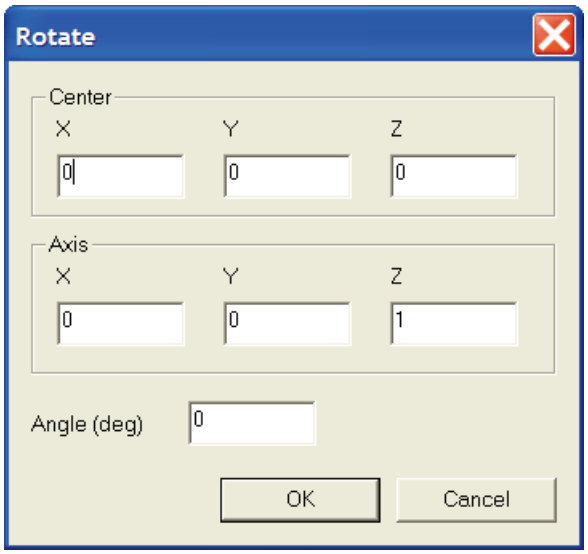
Applies a translation to all the nodes of a mesh, defined by the vector (DX, DY, DZ), in the global coordinate system.



Translate dialog box

Mesh > Transform > Rotate

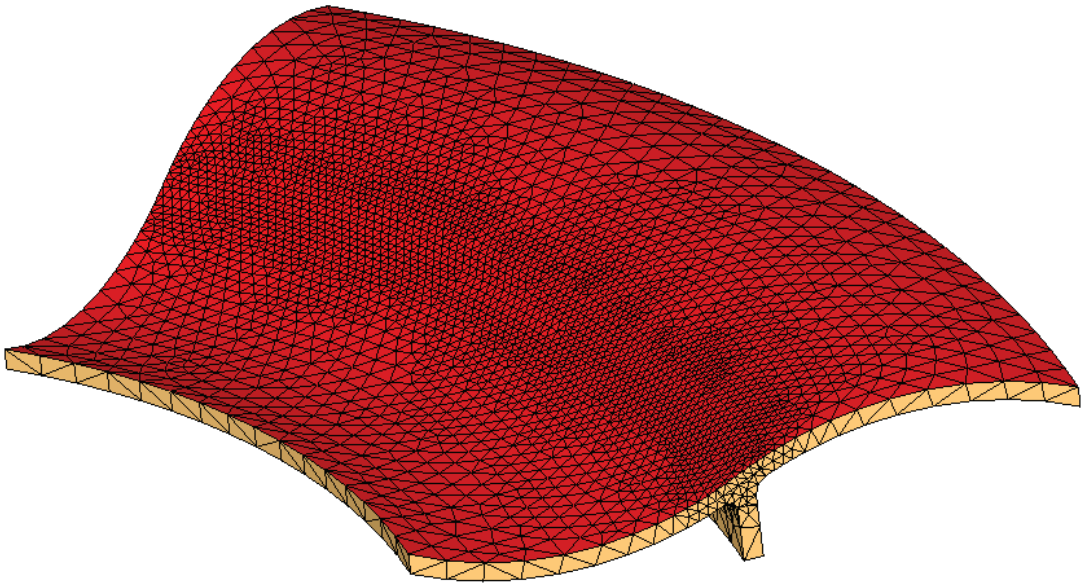
Rotates all the nodes of a mesh around a specified axis. The center of rotation can be specified. The rotation angle is entered in degrees.



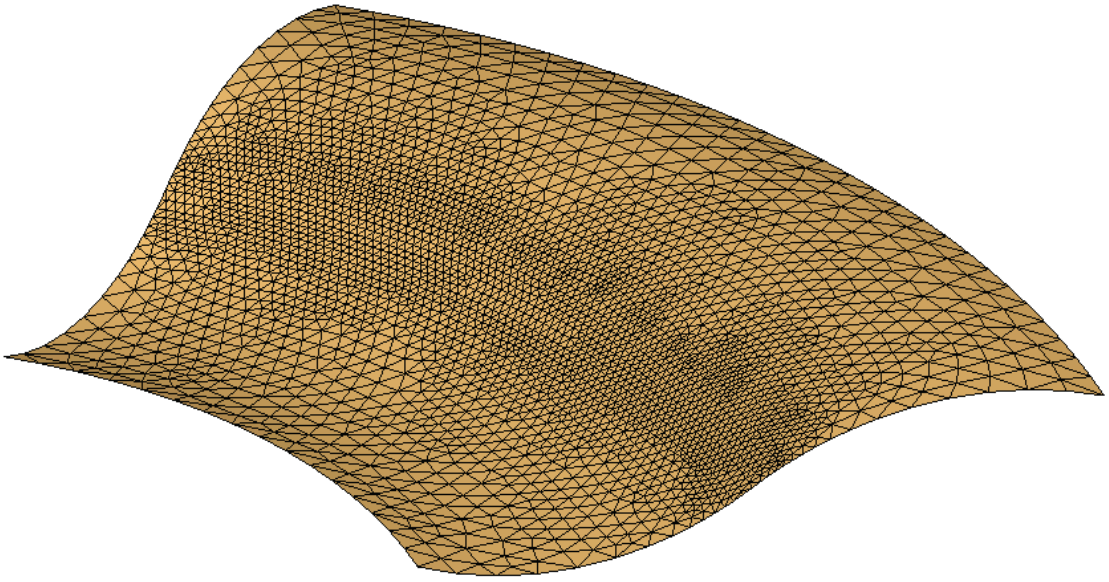
Rotate dialog box

Mesh > Transform > Extract Shell from Solid

Assuming some faces are selected on a solid mesh, this command generates a surface mesh from the selected faces. The current solid mesh in the document is replaced by the surface mesh. See images below.



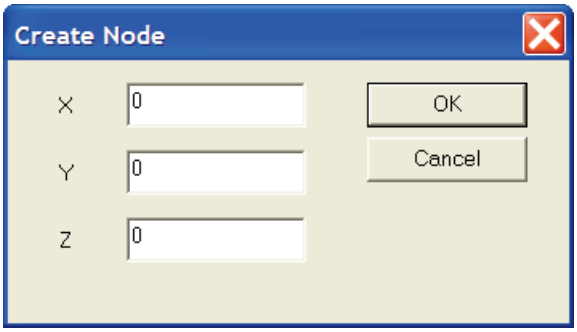
To extract a shell mesh from a solid mesh, first select some faces.



Extracted surface mesh

Mesh > Create > Node

Creates a new node with the specified (x, y, z) coordinates.



Create node dialog box

Mesh > Cleanup > Merge Coincident Nodes

It can sometimes happen that elements in a mesh are not connected, i.e. they have geometrically common nodes, but these nodes are actually different entities (they are nodes with different IDs but with the same coordinates). This problem can be fixed by PAM-RTM. The user enters a merge tolerance, i.e. the smallest allowable distance between 2 nodes. If 2 elements are closer than the specified distance, they will be considered the same node, and the elements connectivity will be modified accordingly.

Mesh > Cleanup > Reverse Normals (selection)

This command updates the nodes connectivity of the selected elements so that their normal vector points in the opposite direction.

Mesh > Cleanup > Align Normals (auto)

Automatically aligns the normal vectors based on the picked element. The picked element is used as the starting element in an algorithm that visits all the elements of the mesh from neighbor to neighbor, and changes nodes connectivity if needed to have the normal vector of an element pointing in the same direction as its neighbors.

Mesh > Cleanup > Delete Unreferenced Nodes

It is possible that some nodes in a mesh are not referenced by any element. This command is used to delete all the unreferenced nodes of the current mesh.

Mesh > Cleanup > Delete Selected Entities

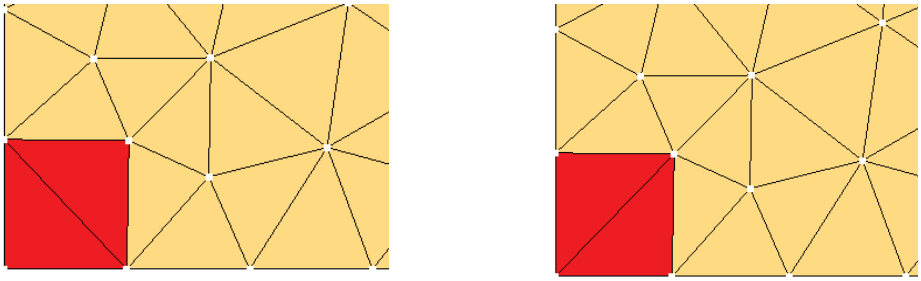
Deletes the selected nodes or elements. If nodes are deleted, the elements referring to these nodes will, of course, be deleted. Each time an entity is deleted, groups of nodes and groups of faces are also updated to make sure they don't refer to deleted entities.

Mesh > Cleanup > Delete Degenerate Elements

Deletes degenerate elements in a mesh, which are defined as elements referring more than once to the same node.

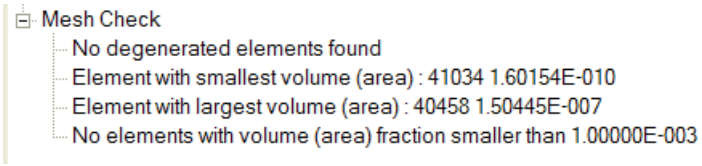
Mesh > Cleanup > Swap Diagonal

Modifies the connectivity table of 2 adjacent elements, so that their diagonal (common edge) is swapped.



Mesh > Check

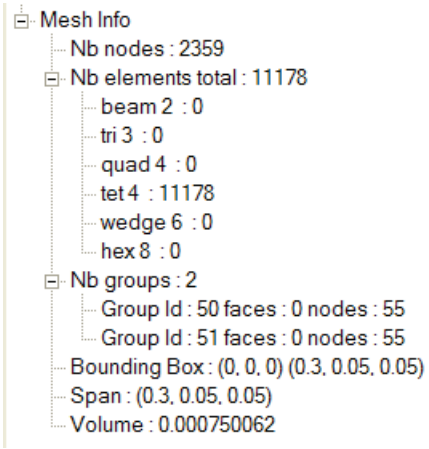
This command tries to find problems in a mesh. First it looks for degenerated elements, i.e. elements that have the same node ID appearing twice or more in their connectivity table. Then it outputs some information about the smallest and largest elements in the mesh, which can be useful for "debugging" a simulation. Finally it lists all the elements with a volume 1000 times smaller than the largest volume. This can also help to find problems, especially with volume meshes in which it can occur that very small elements are generated in the center of the part.



Output of the Mesh->Check command

Mesh > Info

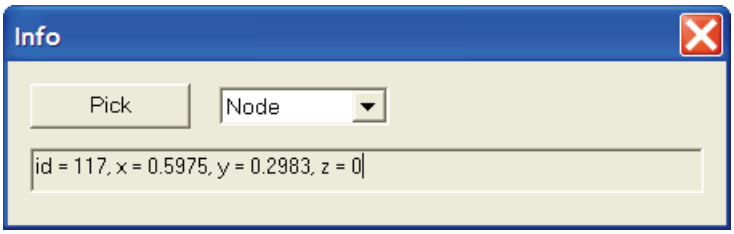
This command outputs some general information about a mesh, for example the number of elements of each type, the number of nodes, the group IDs, and some geometrical information like bounding box (min and max coordinates of a box containing all the nodes), span (size of the part in the x, y, z directions), and the volume of the mesh.



Output of the Mesh->Info command

Mesh > Info Pick

This command opens the following dialog box, which lets the user pick nodes or elements and get info on the picked entities.



Info Pick dialog box

VIEW MENU

View > Curve Viewer

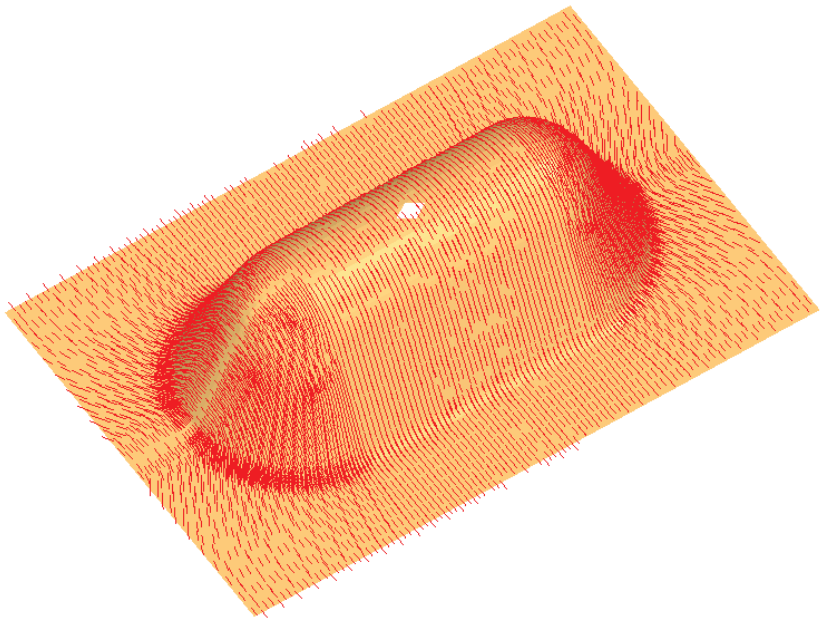
Opens the curve viewer dialog box. See section **Curve Viewer.**

View > Orientations > K1 Only

Used to visualize vectors in the K1 direction (see next figure).

Note

- *It is very important to understand the difference between the permeability directions and the fiber directions of a reinforcement. Most of the time, when you import a ply with* ***File->Import->Laminate****, the K1 and K2 directions are fiber directions, not permeability directions. The fiber directions are transformed to permeability directions with the* ***Mesh->Orientations->Compute Local Permeability*** *command. The same menu is used to visualize orientation vectors. Depending on the context, these vectors will be interpreted by the user as fiber directions or permeability directions.*



Visualization of the K1 direction (actually the f_1 direction or warp direction)

View > Orientations > K2 Only

Displays the K2 direction only.

View > Orientations > K1 and K2

Displays the K1 and K2 directions together.

View > Orientations > None

Clears the display of orientations.

View > Outline > Part

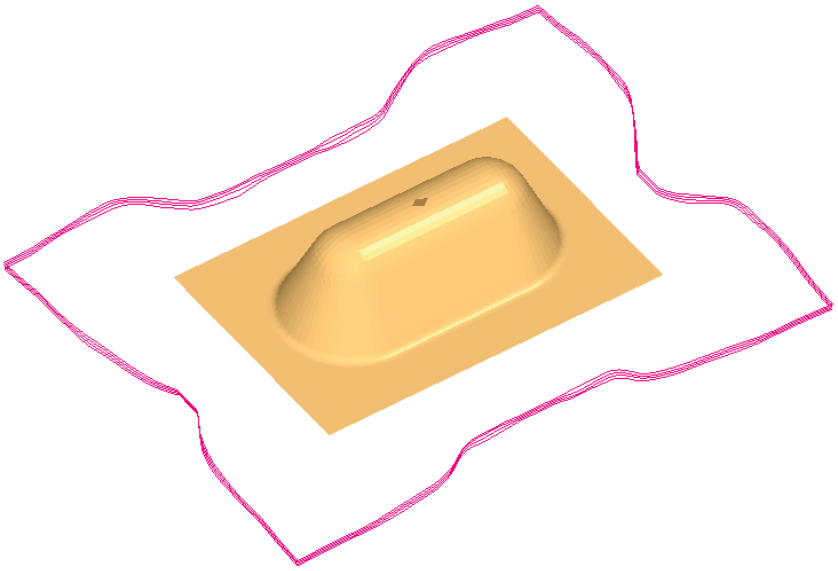
Plots the outline and the sharp edges of the mesh displayed in the current window (it can be the injection mesh or a ply mesh). The display of sharp edges is based on the *Outline Critical Angle* parameter available in the **View->Options->Display** dialog box. By default, this value is 40 degrees, which means that an edge common to two neighbor elements will be plotted if the angle between the two elements is greater than 40 degrees. A lower value would result in more line segments plotted.

View > Outline > Free Edges

This command plots free edges in a mesh of shell elements, i.e. edges that are not shared by more than one element. This is useful to find connectivity problems in a mesh.

View > Outline > Plies

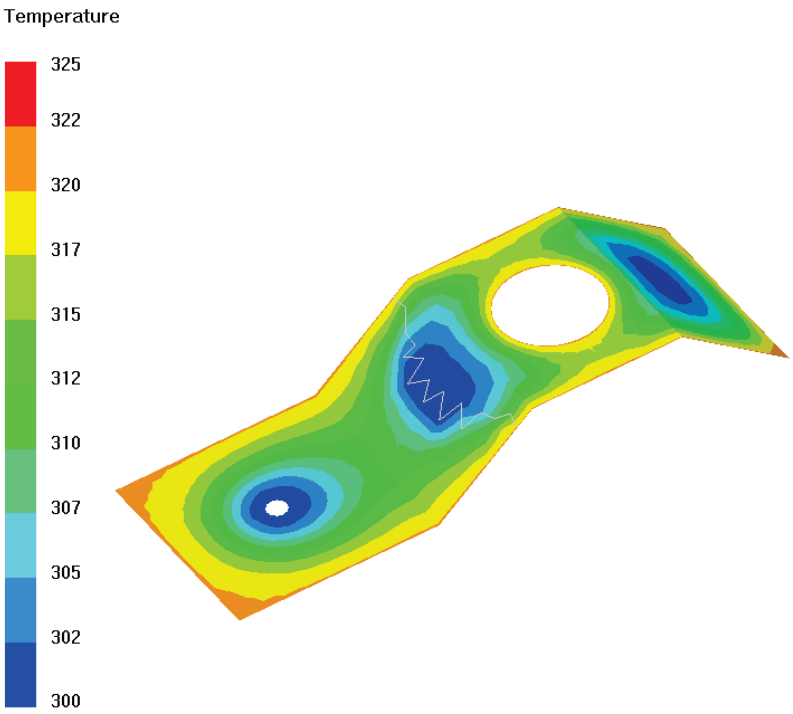
It is possible to have the outline of all the draped plies (imported through File->Import->Draping Results) plotted in the same window as the injection mesh, as shown in the next figure. This can be useful to analyze problems with *Map Draping Results*.



Visualization of plies outline with the injection mesh

View > Flow Front

The flow front position can be visualized on top of any scalar field. The user must import first the flow front file generated by the **PAM-RTM™** solver (extension `.front`), with **File->Import->Scalar Field->PAM-RTM Flow Front**.



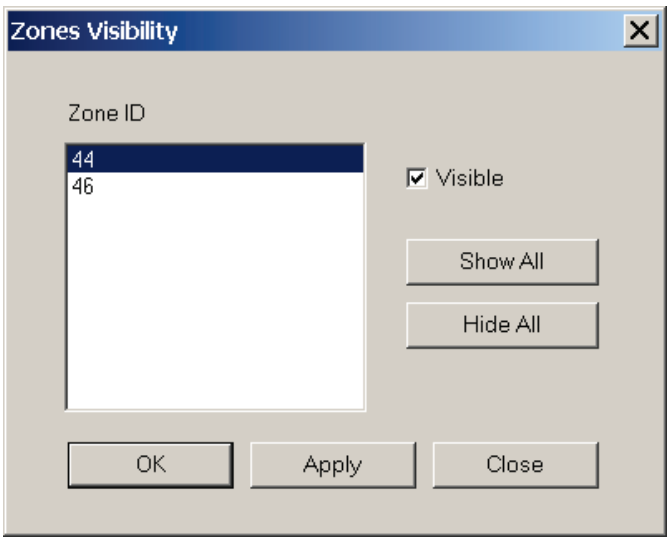
Flow front position (white line) on top of a temperature result

View > Normal Vectors

This command can be used to visualize normal vectors on shell elements or the external skin of a solid mesh.

View > Zones Visibility

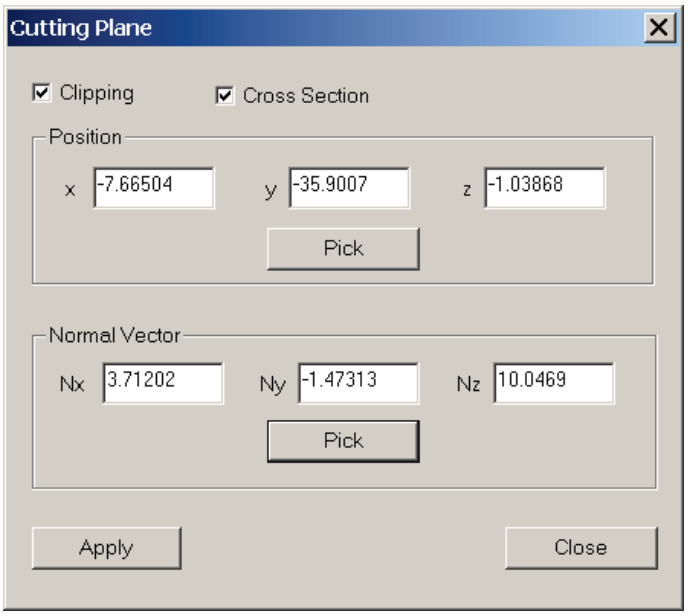
Opens the following dialog box, which is used to activate or deactivate the visualization of some zones. This can be useful to visualize results on internal zones completely surrounded by solid elements. This situation happens for example when the cavity and the mold are meshed with solid elements.



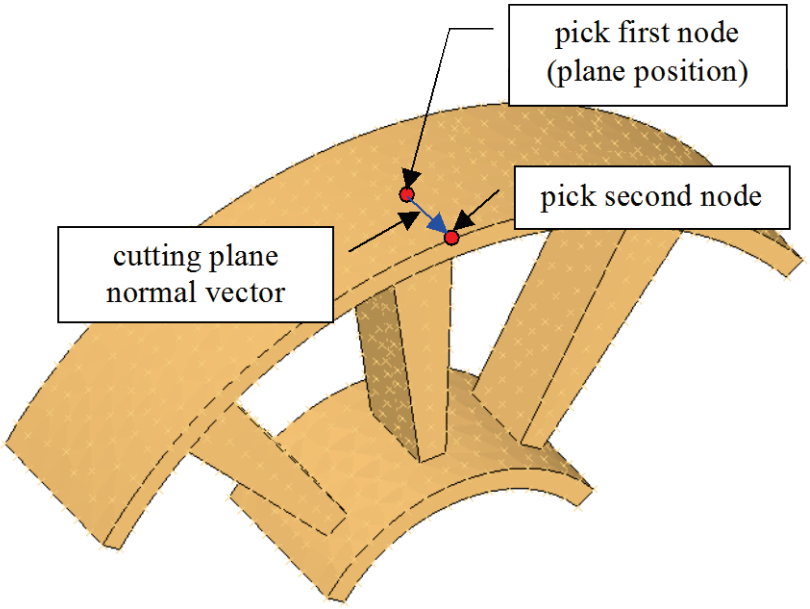
Zones visibility dialog box

View > Cutting Plane

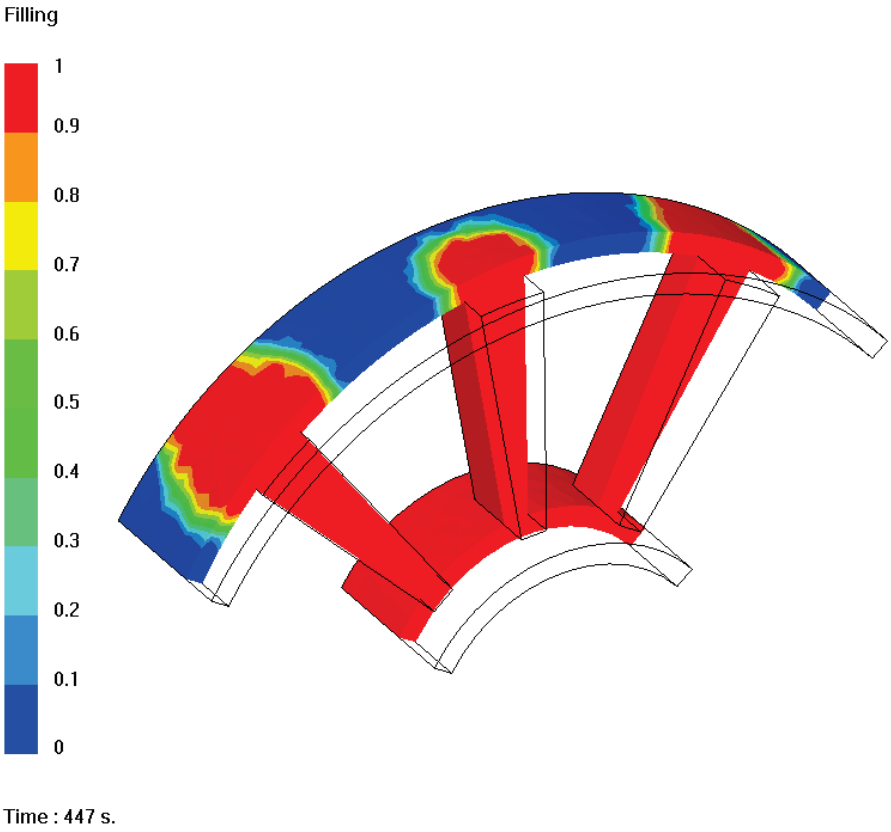
Opens the **Cutting Plane** dialog box, used to specify the parameters of a cutting plane. When **Clipping** is checked, visualization of graphics entities is disabled on one side of the plane. When **Cross Section** is checked, the intersection of the plane with a solid mesh is calculated and displayed. The plane is defined in space by entering the coordinates of a point and the normal vector of the plane. Coordinates can be specified exactly by the user. Otherwise, a node of the mesh can be picked with the mouse to define the plane's position. When the position is defined, another node can be picked to define the normal vector.



Cutting plane dialog box



Picking of nodes to define the cutting plane



Display of the filling factor with the cutting plane active

View > Post-Processing

This command opens the **Post-Processing** dialog box, used to set post-processing parameters.

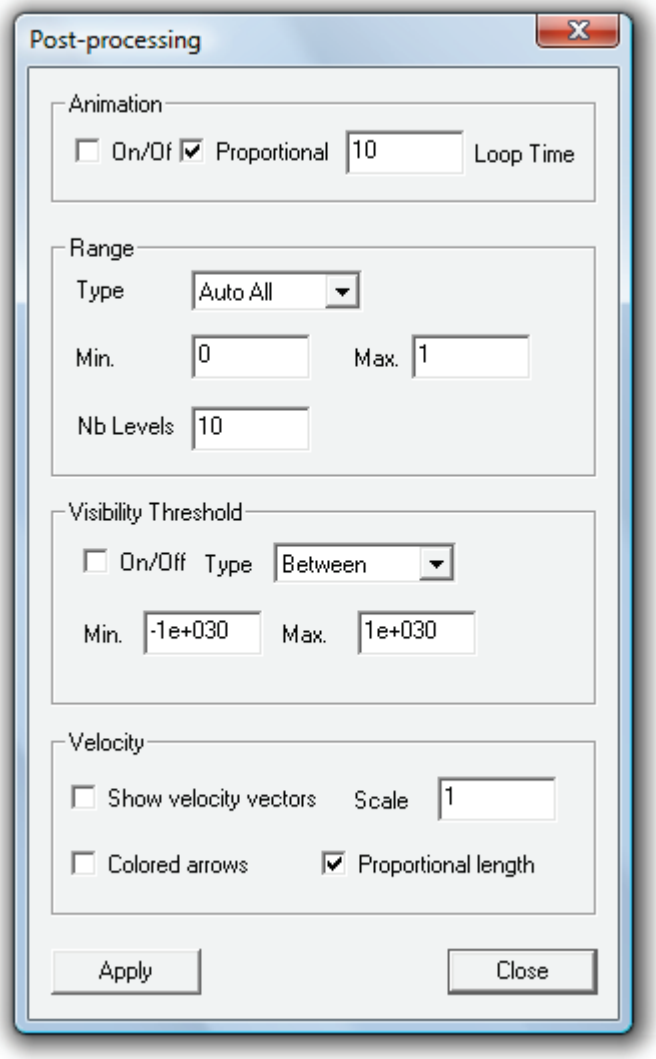
The first group of parameters is related to animation. Animation can be activated or stopped with the **On/Off** check box. When **Proportional** is checked, each animation frame is displayed for a time that depends on the simulated time and the **Loop Time**. The loop time specifies the total time to display all the frames. It is specified in seconds. For example, if a filling simulation generates output for times 1 s., 2 s., 5 s., 10 s., and if the loop time is set to 10 (s), the first frame would be displayed for 1 s., the second one for 3 s., the third one for 5 s. and the last frame is always displayed for some fixed time on which the user doesn't have control (2 s.). If proportional is not checked, each frame is displayed the same time. With the same example, since there are 4 frames to display in 10 seconds, each frame would be displayed for about 2.5 s. Note that there is nothing that warns the user if the computer is not able to achieve this frame rate.

The second set of post-processing parameters is related to the color scale. There are many options to control the range of the color scale :

- *Auto Step*: **PAM-RTM™** automatically adjusts the color scale based on the min and max values of each time step of the visualized scalar field.

- *Auto All*: the min and max values of all the time steps are used as the range of the color scale.
- *Fixed*: the values specified by the user in the **Min** and **Max** fields are used.
- *Min Fixed*: only the value specified in the **Min** field is fixed, the max value is automatically adjusted for each step.
- *Max Fixed*: only the value specified in the **Max** field is fixed, the min value is automatically adjusted for each step.

The number of color levels in the color scale is set with **Nb Levels**.



Post-processing parameters

The third set of parameters concerns the visibility of faces. If **On/Off** is checked, it means that some faces will be hidden. There are 4 options to control the visibility threshold:

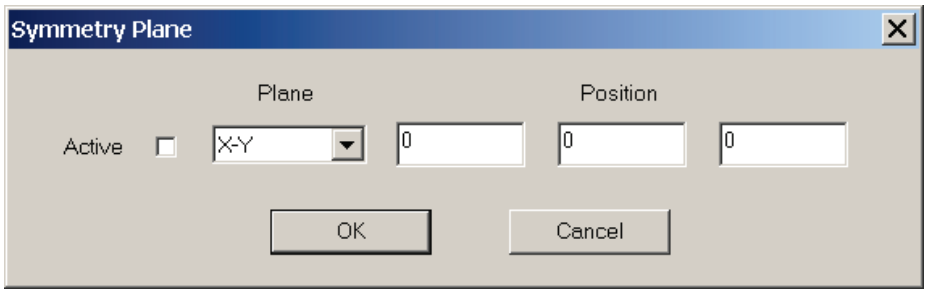
- *Under*: only faces with a scalar field value lower than the value specified in the **Min** field are displayed.
- *Between*: only faces with a scalar field value between the values specified in the **Min** and **Max** field will be displayed.
- *Not Between*: only faces with a scalar field value lower than the value specified in the **Min** field or greater than the value in the **Max** field will be displayed.
- *Above*: only faces with a scalar field value greater than the value specified in the **Max** field will be displayed.

Finally, the **Show velocity vectors** check box allows velocity vectors to be displayed on top of the currently visualized contour. For instance, it is possible to display velocity vectors on top of a temperature contour. The **Scale** value can be used to apply a scale factor to the velocity vectors, in case they are displayed too short or too long by default. The **colored arrows** option allows vectors to be colored based on their norm. The **proportional length** option, when active, displays arrows of size proportional to the norm of the vectors. Since velocity vectors close to the flow front are typically very small compared to vectors close to inlets, uncheck this option to visualize them correctly. These two last options are only available for post-processing of parallel solver results.

View > Symmetry

This command is useful when a simulation was run on mesh representing only half a part for symmetry reasons. It is possible using this command to recreate the complete mesh, to produce pictures for a report, for example.

The symmetry plane can be chosen as X-Y, Y-Z or X-Z. The position of the symmetry plane must also be specified by entering the 3 coordinates of a point in the **Position** text fields.



View->Symmetry dialog box

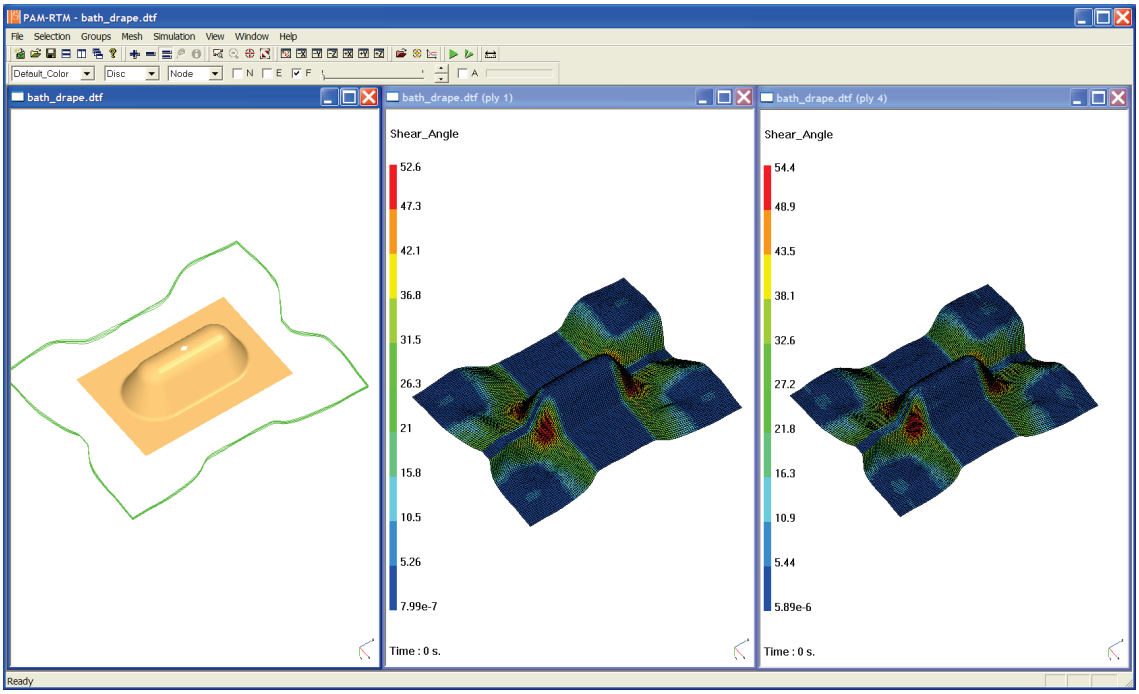
View > Delete N Last Steps

It sometimes happens that the last states of a filling calculation are not significant. For instance, depending on the outlet conditions, it could happen that only a few elements are filled in the last steps in a very long time. This command is used most of the time in

the context of the display of an animation, or for the generation of an AVI file. It allows exclusion of the *n* last steps from the animation. Of course this command doesn't delete anything in results files. It just prevents the last steps from being displayed.

View > Set Same Viewpoint

When many graphics windows are opened, it can be useful to set the same viewpoint (rotation) for all the views. This command sets the same viewpoint for all views of all open documents, based on the active view. Activate first the window that you want to use as the reference.

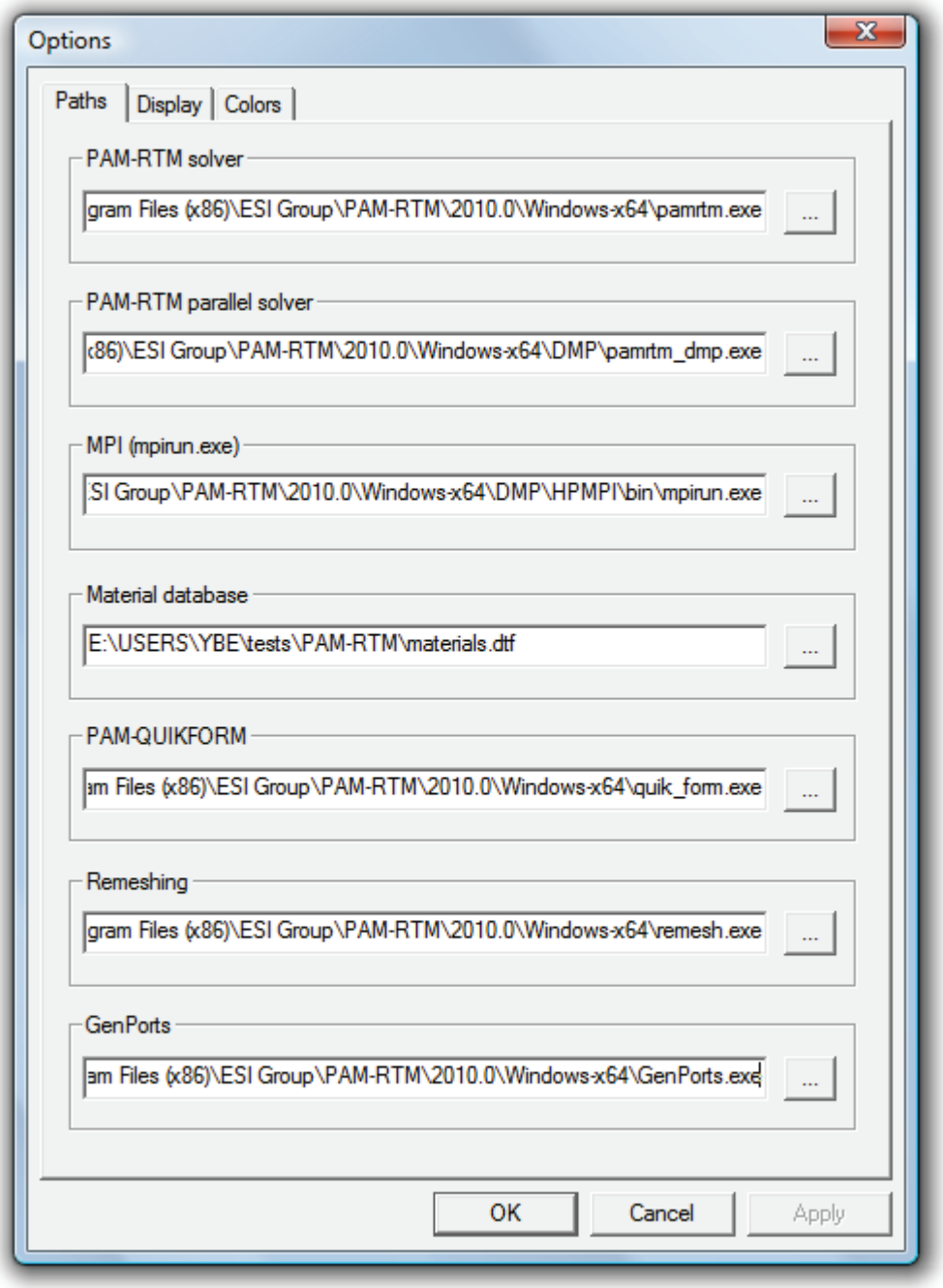


Result of the Set Same Viewpoint command. The active window is the left one.

View > Options > Paths

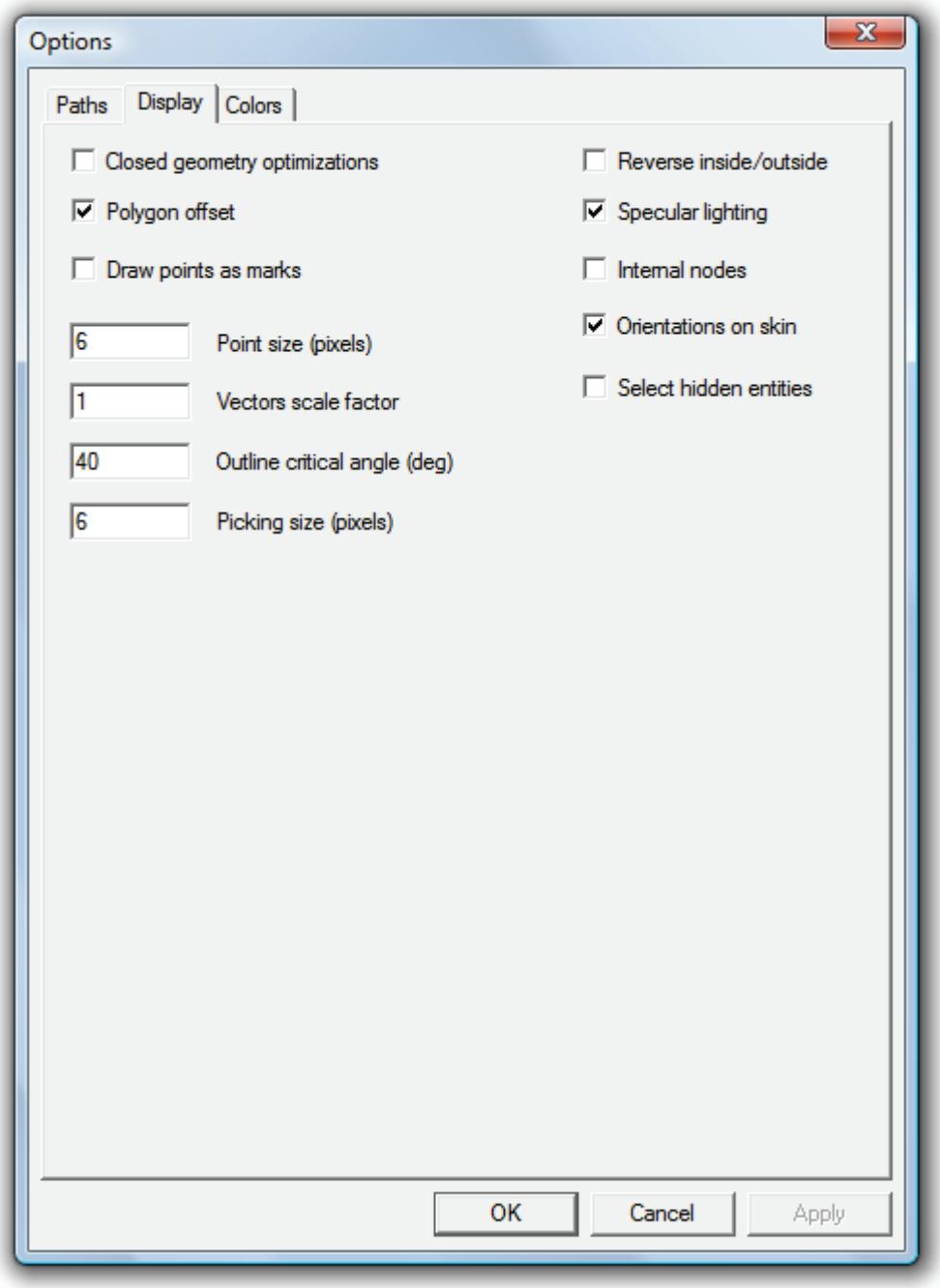
This tab is used to set the path to the **PAM-RTM™** standard solver executable (pamrtm.exe) and the parallel solver (pamrtm_dmp.exe). The PAM-QUIKFORM solver (quik_form.exe), MPI version used to run the parallel solver, and other executables are also specified in this tab. Normally these paths don't need to be changed. They are set by the InstallShield when **PAM-RTM™** is installed. However in some special situations like a minor **PAM-RTM™** update that doesn't ship with an InstallShield, the path could be changed manually by the user.

See section **Material Database** for information about the path to the material database.


Options
Paths
Display
Colors
PAM-RTM solver
gram Files (x86)\ESI Group\PAM-RTM\2010.0\Windows-x64\pamrtm.exe
PAM-RTM parallel solver
(86)\ESI Group\PAM-RTM\2010.0\Windows-x64\DMP\pamrtm_dmp.exe
MPI (mpirun.exe)
SI Group\PAM-RTM\2010.0\Windows-x64\DMP\HPMPI\bin\mpirun.exe
Material database
E:\USERS\YBE\tests\PAM-RTM\materials.dtf
PAM-QUIKFORM
m Files (x86)\ESI Group\PAM-RTM\2010.0\Windows-x64\quik_form.exe
Remeshing
gram Files (x86)\ESI Group\PAM-RTM\2010.0\Windows-x64\remesh.exe
GenPorts
m Files (x86)\ESI Group\PAM-RTM\2010.0\Windows-x64\GenPorts.exe
OK
Cancel
Apply

Paths tab

View > Options > Display



Display tab

There are many viewing parameters that can be set through the **Display** tab.

- **Closed geometry optimizations**: when it is checked, this parameter tells **PAM-RTM™** to turn on display optimizations relevant for closed geometry (usually

solids), such as culling (elimination at the first stage of the graphics pipeline of back facing polygons). If the user suspects rendering problems, for example faces that are not displayed, this optimization should be turned off.

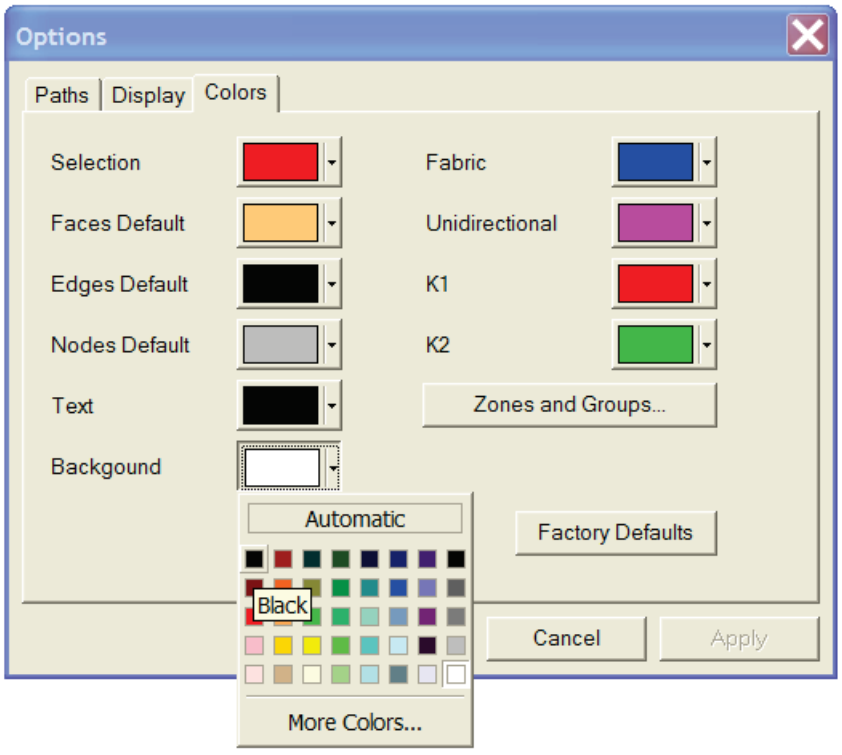
- If **Closed geometry optimizations** is active, so is culling, which means that the normal vector has an effect on the faces that will be displayed. By default, **PAM-RTM™** manages to have normal vector of the front facing polygons point in the direction of the viewer. However if the user notices some strange "inverse effects", for example when rotating the mesh it seems to turn in the inverse direction, the **Reverse inside/outside** parameter should be checked.
- The **Polygon Offset** flag is used to offset the element faces by some small distance so that the element edges can be displayed with better quality. Some graphics cards might not support this OpenGL feature very well, so it can be turned off if you suspect a problem.
- **Draw points as marks**: by default, nodes are displayed with OpenGL points. Problems with OpenGL points have been seen on some graphics cards. If the **Draw points as marks** check box is checked, nodes will be displayed as a small x instead of points.
- **Specular Lighting**: this flag is used to turn on or off specular lighting, i.e. the lighting that makes surfaces appear shiny. By default specular lighting is on.
- By default, only nodes on the external skin of solid meshes are displayed in **PAM-RTM™**. **Internal nodes** can be checked to visualize nodes inside solid meshes. This can be useful to create sensors by picking internal nodes.
- The **Point Size** parameter controls the half size of points, in pixels.
- **Vectors Scale Factor**: by default, **PAM-RTM™** calculates the length of vectors such that they have a reasonable size when projected in the graphics window. If the vectors appear too small or too large on screen, the user can apply a scale factor to the vectors. For example, if *0.5* is specified, the vectors will be *2* times smaller.
- **Outline Critical Angle**: this parameter controls drawing of sharp edges. **PAM-RTM™** determines sharp edges based on the angle between 2 adjacent faces. If too many sharp edges (false edges) are drawn, you should increase the value of this parameter. The maximum value is 90 degrees.
- **Picking Size**: this parameter can be used to modify the picking sensibility. It specifies the diameter of a circle (in pixels) around the point where the mouse button is clicked. The default value is 6 pixels. This means that to pick a node, for example, the user can click at most 3 pixels away from the node. If you think it's too difficult to pick nodes with the default settings, you should increase the value of this parameter.
- **Orientations on skin:** this option concerns solid meshes only. If the option is not checked, orientation vectors are displayed for all elements of the mesh, including internal elements. Orientation vectors are displayed with an arrow starting at the center of gravity of the element. If the option is checked, orientation vectors will only be displayed for elements on the skin of the solid (external boundary), thus

reducing the number of vectors displayed. Also, the center of gravity of the external face will be used as the origin for the display of orientation vectors, instead of the center of gravity of the element, which should lead to better visualization in general.

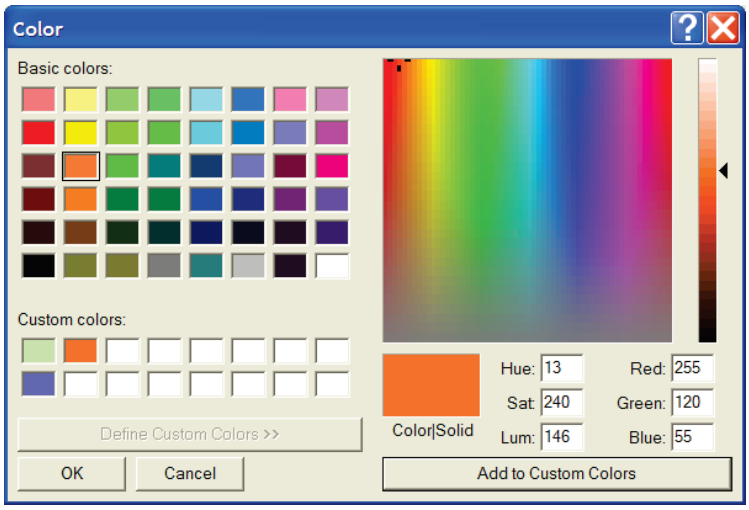
- **Select hidden entities:** by default, selection using a rectangular box only selects visible entities (nodes, faces, elements). It is sometimes useful, for instance when working on a solid model, to select entities located inside the solid. When this option is activated, all the entities that project inside the rectangle defined by the user will be selected, whether they are visible or not.

View > Options > Colors

The user can change the color of many graphics entities with the **Options->Color** tab. For example the default background color (white by default) can be changed by pushing the arrow on the **Background** button. This pops up a color chooser with a selection of pre-defined colors (see next figure). If the user doesn't find the color he wants in the pre-defined colors, he can use the **More Colors** button to popup the standard Windows Color Chooser. The default color of faces, nodes, etc., can also be changed. When the user changes one of these colors, the modified color settings are saved in the Windows registry. It is possible to come back to the original **PAM-RTM™** default values with the **Factory Defaults** button.

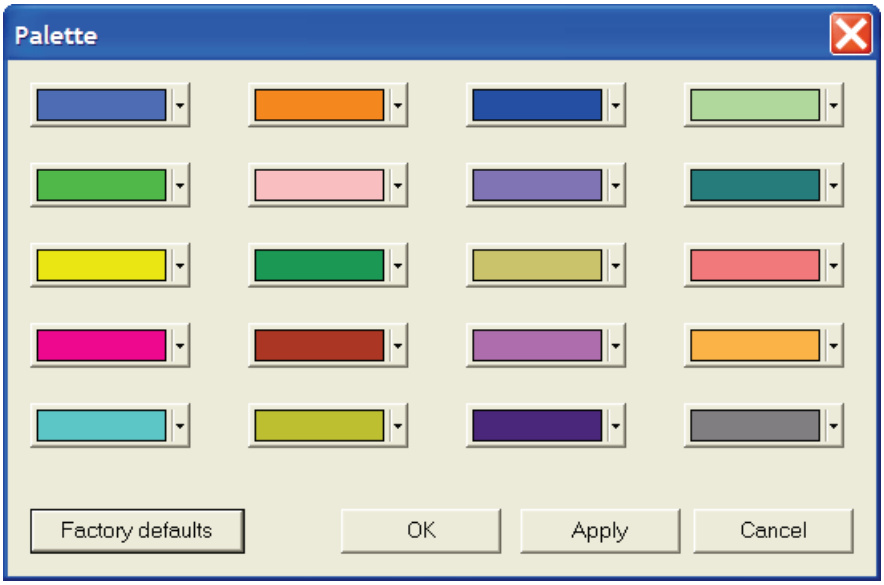


Colors tab



Standard Windows color chooser

The **Zones and Groups** button allows the user to customize the color scale used to display zones and groups. 20 colors are available for this color scale. If there are more than 20 groups or zones to display, the colors are re-used. Note that it is still possible to use the color scale that was used in version 2004 for groups and zones with **View->Color Scale->RGB**.



Default color palette used to display groups and zones

View > Color Scale

Enables the user to select the color space used to interpolate colors in the color scale. *RGB*, *HSV* and *GREY* color spaces are available.

View > Color Schemes

The user can select with this menu between a *Black Background* or *White Background* color scheme. For example, when the black background is selected, the color used for text is automatically set to white.

View > Lights

The **View->Lights** menu is used to turn on or off one of the 6 predefined lights.

View > Refresh

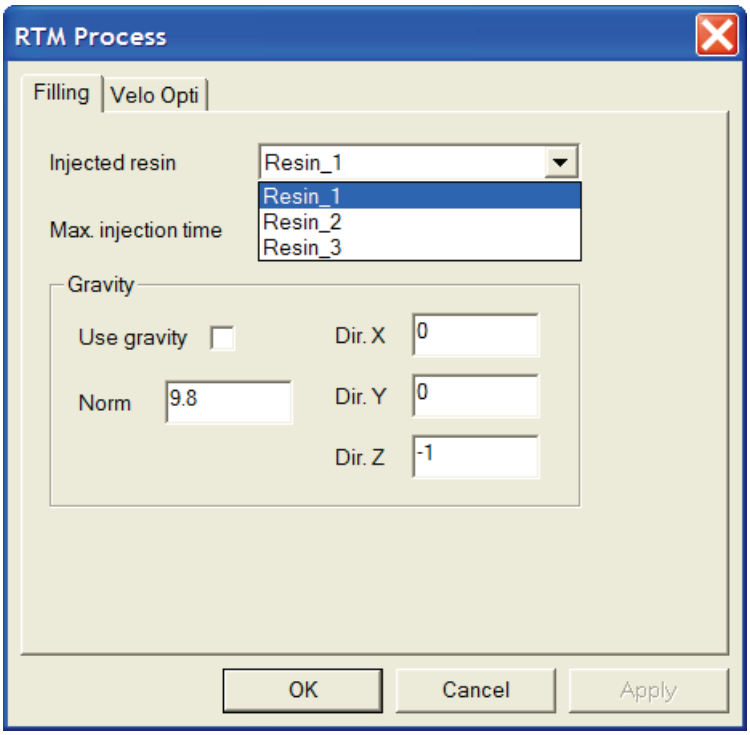
Forces the redraw of the active window. Use **CTRL-R** as a shortcut.

PROCESS PARAMETERS

The process parameters will be presented in the following sections for each simulation type. Many parameters are common to many simulation types, so instead of repeating text we refer to the section where the parameter was first described.

RTM Simulation

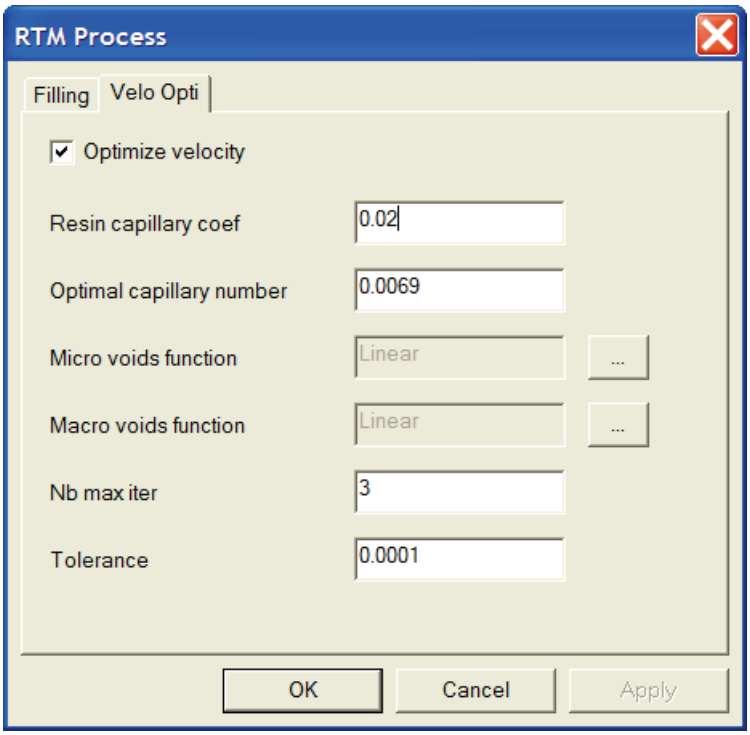
Filling Tab



RTM process parameters

- **Injected resin**: drop-down list allowing the user to select the resin to be injected. This list contains the names of all the resins currently defined in the model.
- **Max injection time**: the simulation will stop even if the part is not completely filled if the maximum injection time is reached.
- **Use gravity**: tells **PAM-RTM™** to take gravity into account when calculating the resin pressure field.
- **Gravity Norm**: gravitational acceleration. Unit: m/s^2.
- **Dir. X**, **Dir. Y**, **Dir. Z**: components of the gravity direction vector. By default gravity is in the negative Z direction.

Velo Opti Tab



The reference for the velocity optimization (voids minimization) functionality of **PAM-RTM™** is:
Ruiz E, Achim V, Soukane S, Trochu F, Bréard J. *Optimization of injection flow rate to minimize micro/macro-voids formation in resin transfer molded composites.* Composites Science and Technology 66 (2006) 475–486.

- **Optimize velocity**: tells **PAM-RTM™** to adjust the injection flow rate so that the voids percentage is minimal in the final part. Pressure controlled inlets are converted to flow rate controlled. If this parameter is not checked and the micro and macro voids functions are defined, **PAM-RTM™** won't optimize the velocity but will calculate the micro and macro void values. This is useful to have an idea of the void content that you would have at the end of the injection if you didn't control the flow rate.
- **Resin capillary coef**: the capillary number is defined as:

$$Ca^* = \frac{\mu v}{\gamma \cos\theta}$$

where μ is the fluid viscosity, v the superficial velocity, γ the surface tension, and θ the contact angle between the resin and the fibers. The **resin capillary coef** is the term $\gamma \cos\theta$.

- **Optimal capillary number**: the capillary number minimizing the void content.
- **Micro voids function**: the function describing the micro voids content, as un function of the capillary number.
- **Macro voids function**: the function describing the macro voids content, as un function of the capillary number.
- **Nb max iter**: the maximum number of Darcy's equation resolutions done each time step of filling to optimize the flow front velocity.
- **Tolerance**: the convergence error allowed in the optimization process.

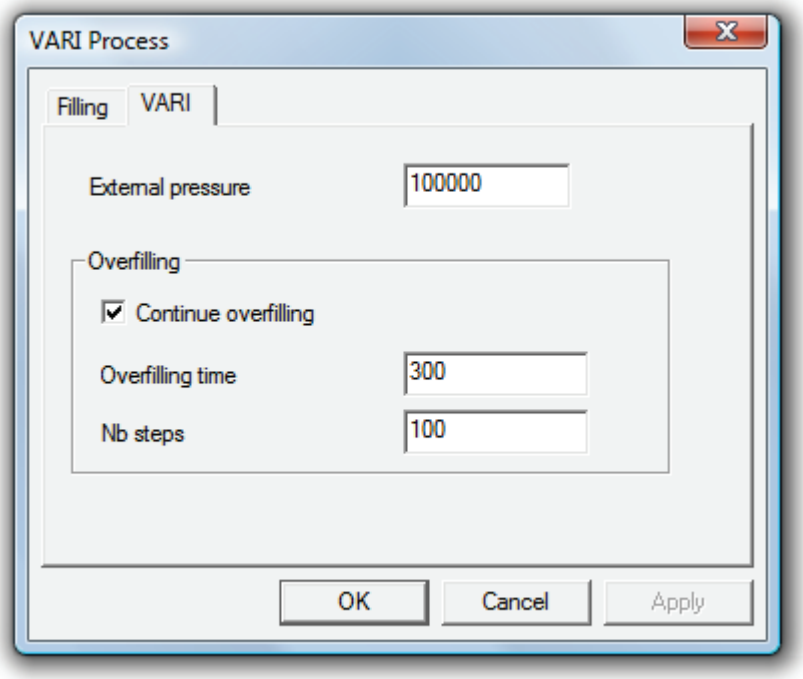
Please see the tutorial **Velocity Optimization** for more information.

VARI Simulation

Filling Tab

See RTM Simulation.

VARI Tab



VARI Process tab

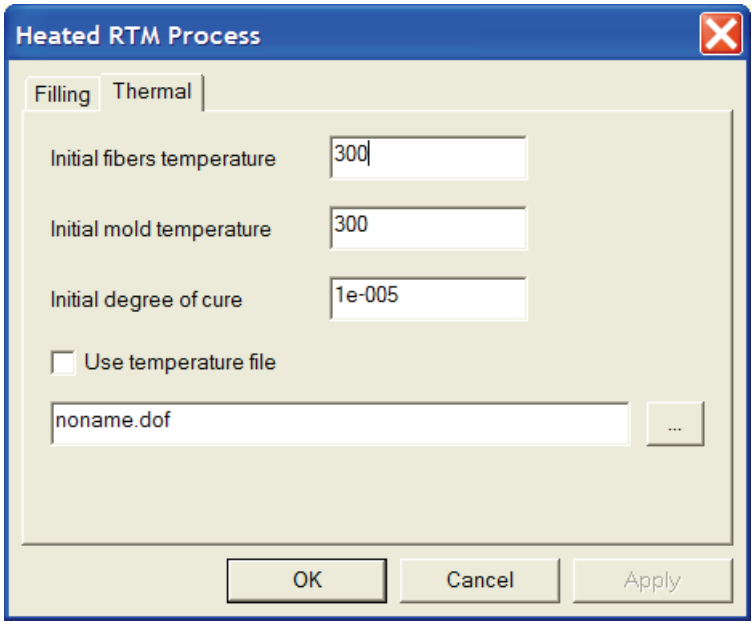
- **External pressure**: most of the time the default atmospheric pressure (100 000 Pa) is used, but if the infusion is done in an autoclave, a higher pressure could be specified.
- **Continue overfilling**: when checked, simulation will continue even if the part is filled. That allows the user to study the relaxation of the reinforcement after filling, and estimate how long it takes to reach thickness equilibrium. Different scenarios are possible. For instance the inlet could be kept on after filling is complete, or closed with the Trigger Manager.
- **Overfilling time**: the duration of the post-filling phase.
- **Nb steps**: the number of steps to compute for the post-filling phase. A constant time step is used, given by overfilling_time/nb_steps.

Heated RTM Simulation

Filling Tab

See RTM Simulation.

Thermal Tab



Heated RTM process parameters

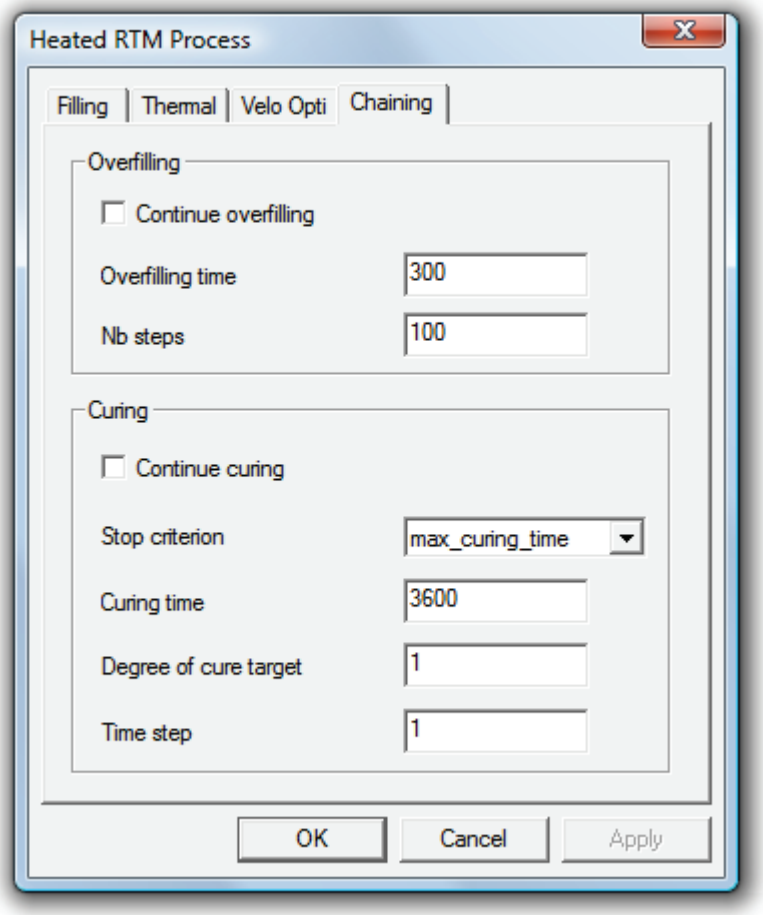
- **Initial fibers temperature**: initial temperature applied on the fibers just before the resin starts entering the cavity. This value is not used if **Use temperature file** is checked. Unit: degree Kelvin.

- **Initial mold temperature**: initial temperature of the mold. This value is not used if **Use temperature file** is checked. Unit: degree Kelvin.
- **Initial degree of cure**: degree of cure of the resin just before entering the cavity.
- **Use temperature file**: check this parameter if you want to initialize temperature in the mold and fibers with a non-uniform temperature field, result of a preheating simulation. Use the **...** button to browse to the file containing initial temperature. That file is `x_Thermal_p.dof` with the standard solver, `xt.unf` with the parallel solver, where x is the name of the preheating case.

Note:

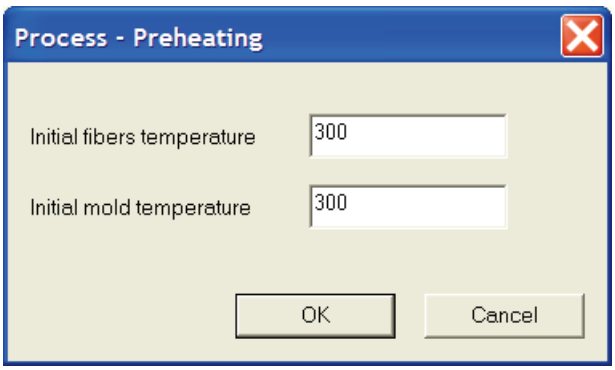
· It is also possible to specify initial temperature per zone. However zone temperature will be ignored if **use temperature file** is active.

Chaining Tab



- **Continue overfilling**: tells **PAM-RTM™** to perform overfilling, i.e. let the resin flow out of the vents for some time after the part is completely filled. This is useful to get a more uniform degree of cure distribution before starting the actual curing. The overfilling stage is optional. You could chain curing directly after filling, without overfilling.
- **Overfilling time**: the time allowed for the resin to flow out of the vents after filling. Unit: seconds.
- **Nb steps**: the number of steps of overfilling, i.e. the number of Darcy's resolutions after the part is filled.
- **Continue curing**: check this parameter if you want **PAM-RTM™** to continue with a curing simulation after filling or overfilling.
- **Stop criterion**: if **max_curing_time** is selected, the curing simulation will run until **curing_time** is reached. The **min_above** option will stop the simulation when all elements have at least the degree of cure specified in **degree of cure target**, while the **avg_above** option will stop the simulation when the average degree of cure on the mesh is above **degree of cure target**.
- **Curing time**: the time allowed for curing when the **max_curing_time** option is selected.
- **Degree of cure target**: the degree of cure to reach, when the **min_above** or **avg_above** options are selected.
- **Time step**: the time step for the curing simulation is explicitly set by the user. Unit: seconds.

Preheating Simulation



Preheating process parameters

- **Initial fibers temperature**: initial temperature of the fibers. Unit: degree Kelvin.
- **Initial mold temperature**: initial temperature of the mold. Unit: degree Kelvin.

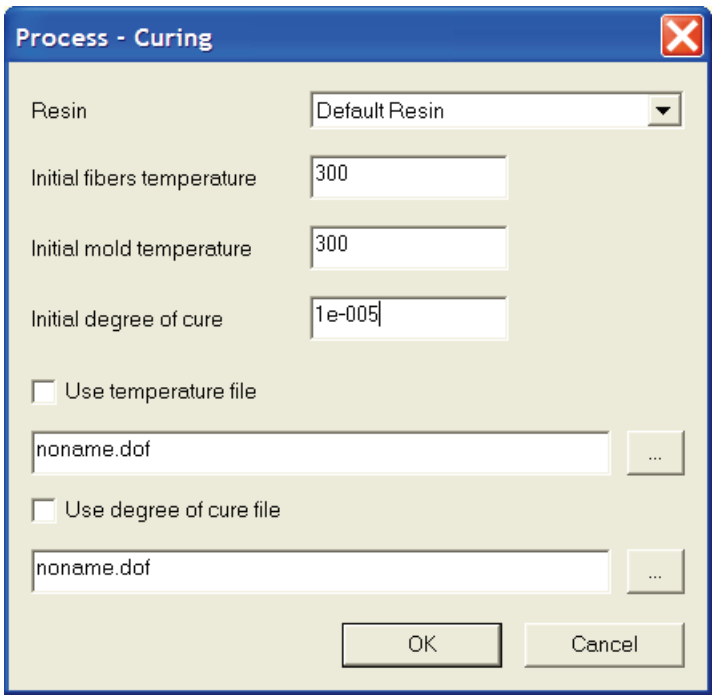
Note:

· *It is also possible to specify initial temperature per zone.*

Presimulation

No process parameters are available for presimulation.

Curing Simulation



Curing process parameters

- **Resin**: if many resins are defined in your document, you have to choose which resin to use for the curing simulation from this drop-down list.
- **Initial fibers temperature**: initial temperature in zones linked to fiber reinforcements. This parameter is not used if **Use temperature file** is checked. Unit: degree Kelvin.
- **Initial mold temperature**: initial temperature in zones linked to mold material. This parameter is not used if **Use temperature file** is checked. Unit: degree Kelvin.
- **Initial degree of cure**: initial degree of cure assigned to all the elements in the cavity. This parameter is not used if **Use degree of cure file** is checked. By default, the curing simulation assumes that the cavity is completely filled (filling factor is 1 everywhere in the cavity). The only way to take into account partially filled elements is with the degree of cure file.

- **Use temperature file**: check this option and browse to the `x_Thermal_f.dof` to initialize temperature with a non-uniform field resulting from the *Heated RTM* simulation. With the parallel solver the file to select is `xt.unf`.
- **Use degree of cure file**: check this option and browse to the `x_Curing_f.dof` to initialize the degree of cure with a non-uniform field resulting from the *Heated RTM* simulation. With the parallel solver the file to select is `xcr.unf`.

  Note:

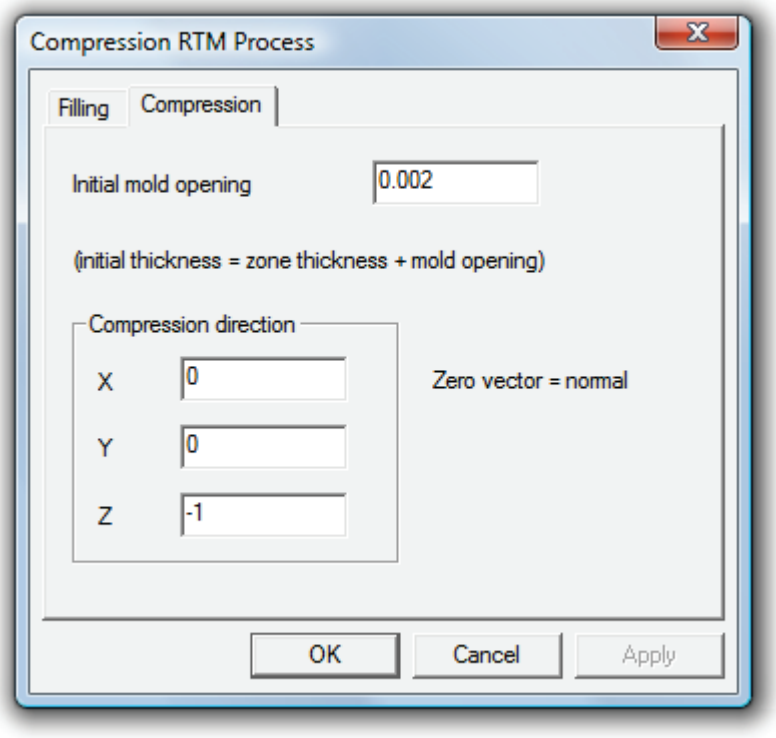
  · *It is also possible to specify initial temperature per zone. However zone temperature will be ignored if* ***use temperature file*** *is active.*

Compression RTM Simulation

Filling Tab

See RTM Simulation.

Compression Tab



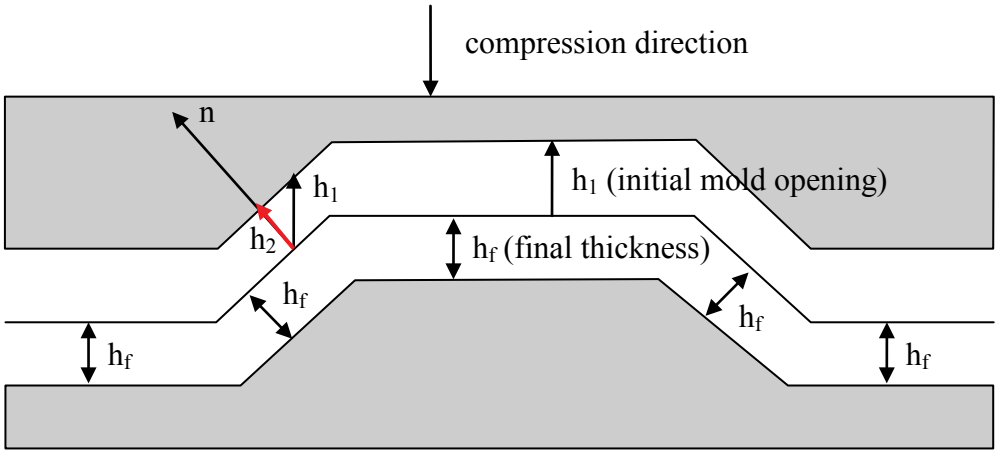
CRTM process parameters

- **Initial mold opening**: this is the thickness difference from start to end of compression (h_1 in the figure below). In case of a vertical mold displacement (compression direction –Z), the initial mold opening corresponds to the displacement of the tool.
- **Compression direction**: the vector in the global coordinate system defining the compression direction. If a zero length vector is specified, the normal vector of each element is used as the compression direction.

  Note:

  · *The initial mold opening doesn't correspond to an empty gap.* ***PAM-RTM™*** *modeling of CRTM assumes that the preform always fills completely the cavity.*

  · *The final thickness of the part is specified on zones. Even though in general the same final thickness will be specified on all the zones, it is possible to specify a different final thickness on each zone if needed. The initial thickness is automatically computed by* ***PAM-RTM™*** *so that at the end of compression the thickness matches the thickness of zones. This means the initial thickness could change from element to element, depending on the element's normal and the compression direction. The initial thickness is h_f+h_2, where h_2 is the projection of h_1 on the local normal vector.*



PAM-QUIKFORM Simulation

There are basically two process parameters for a PAM-QUIKFORM simulation: *axis* (also called draping referential) and *operation*. Even though axis do not appear in the

process folder of the explorer, they are clearly process parameters since they are used to specify contact point and draping direction.

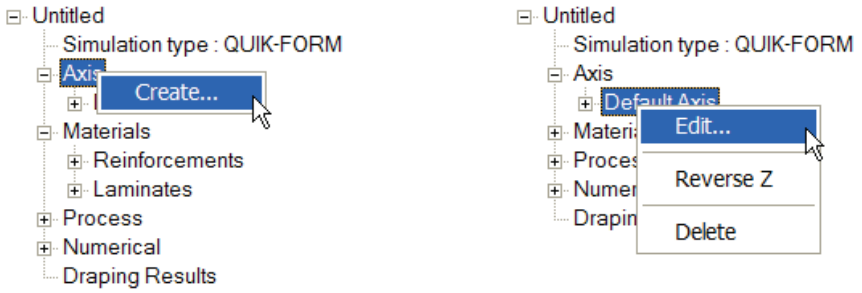
Another process parameter, used only in advanced applications, is the draping curve. It is possible to import a draping curve with the **Import Curves** command available in the popup menu associated to the *Process* item in the explorer. See description of the **curve** parameter in the PAM-QUIKFORM solver manual.

It is possible to create many axis in a PAM-QUIKFORM document. An axis is used as a referential on which a laminate is aligned before it is draped. The origin of the referential can be seen as the contact point, and the local X axis of the referential is the draping direction for a zero degree layer.

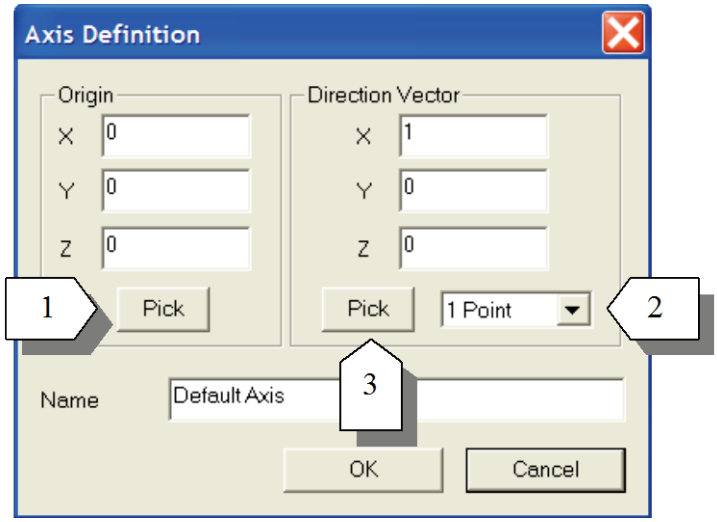
A draping operation is the association of a laminate, an axis and optionally a geometrical support (a selection of elements of the tool mesh). If the geometrical support is not specified, it is assumed that a layer is to be draped on the complete tool mesh. A laminate part is defined by specifying a sequence of draping operations. For example:

- Drape laminate 1 from axis 1.
- Drape laminate 2 on axis 2.
- etc.

Axis Definition

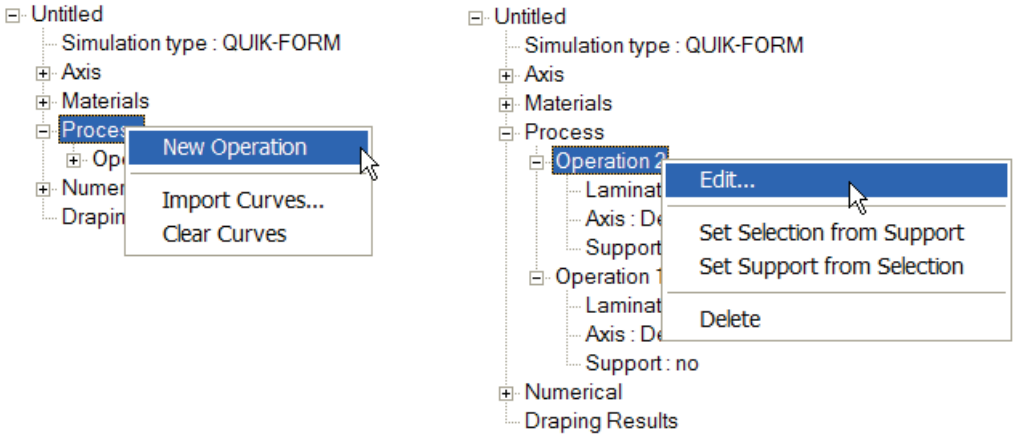


To create an axis, right-click the *axis* item in the explorer and choose **Create**. To edit an axis, double-click it in the explorer, or choose **Edit** in the axis popup menu. This opens the **Axis Definition** dialog.



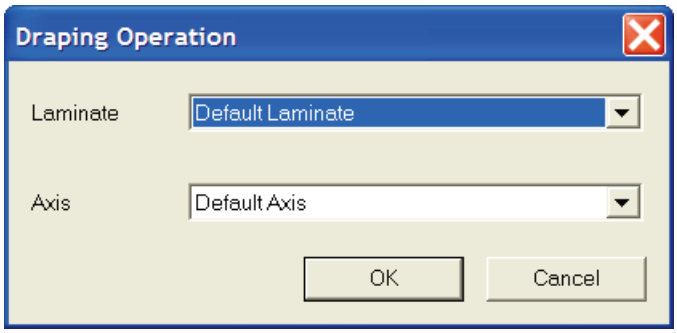
The coordinates of the origin can be entered manually, or an arbitrary point can be picked on the tool mesh with the **Pick** button **[1]**. The direction vector (local X axis of the referential) can also be entered manually, or interactively by picking points. First choose *1 Point* or *2 Points* option **[2]**. If *1 Point* is chosen, push the **Pick** button **[3]** and pick one point. The direction vector is then defined from the origin to the picked point. If *2 Points* is used, push the **Pick** button **[3]**, then pick two points on the tool mesh. The direction vector is then defined from the first picked point to the second.

Draping Sequence

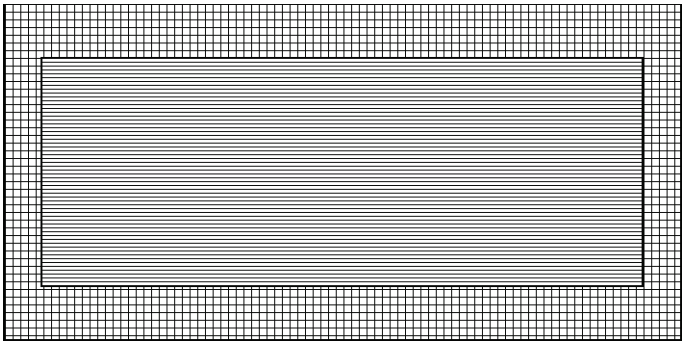


Before the sequence of draping operations can be specified, some axis and laminates must be defined (see chapter *Laminates*). To create a new operation, use the **New Operation** command in the *Process* popup menu. To edit an operation, double-click it in the explorer, or choose **Edit** in the popup menu. New operations are always added at the end of the operation sequence. It is not possible to move an operation in the sequence once it is created.

Editing an operation pops up the following dialog box, where the laminate to drape and the associated axis can be selected from the list of available entities.

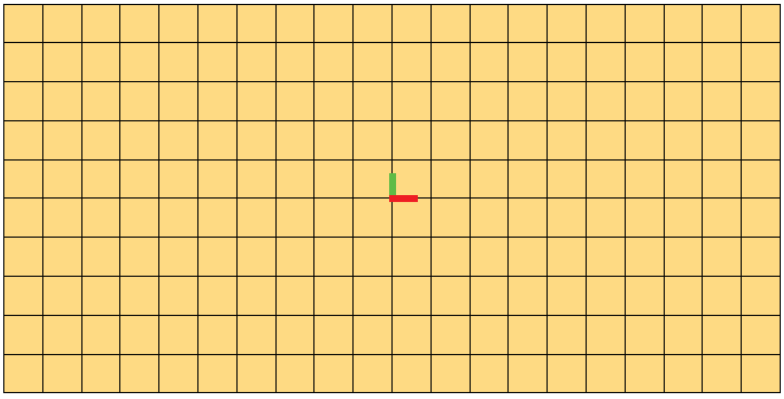


Optionally, it is possible to set a geometrical support to an operation. The use of supports will be demonstrated with the following example.



A rectangular surface is to be draped first with a layer of fabric. Then a layer of UD is draped on top of the fabric. The UD layer doesn't cover the surface completely.

The mesh used in this example is the following.

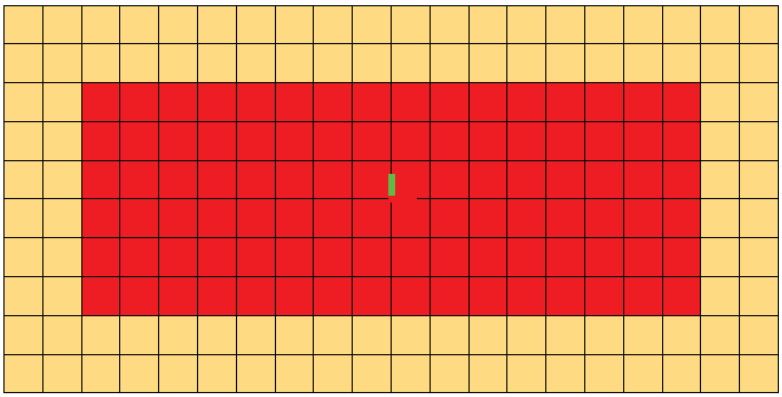


First we set the draping referential to the center of the part. When using supports, it is important that the referential used in a draping operation be located on the support.

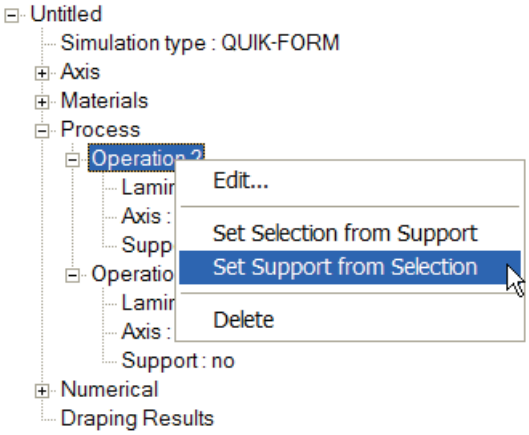
Then we create 2 laminates: one for the fabric layer, and one for the UD layer.

The next step is to create 2 operations. The first one is associated to the fabric layer, the second one to the UD layer.

Finally we set the support of the UD operation. Set the selection filter to *Element* then select elements like this.



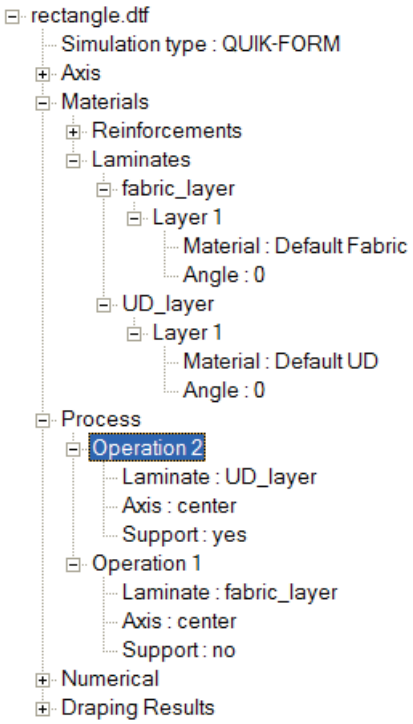
Use the **Set Support From Selection** command, available in the operation popup menu, to set the support of operation 2.



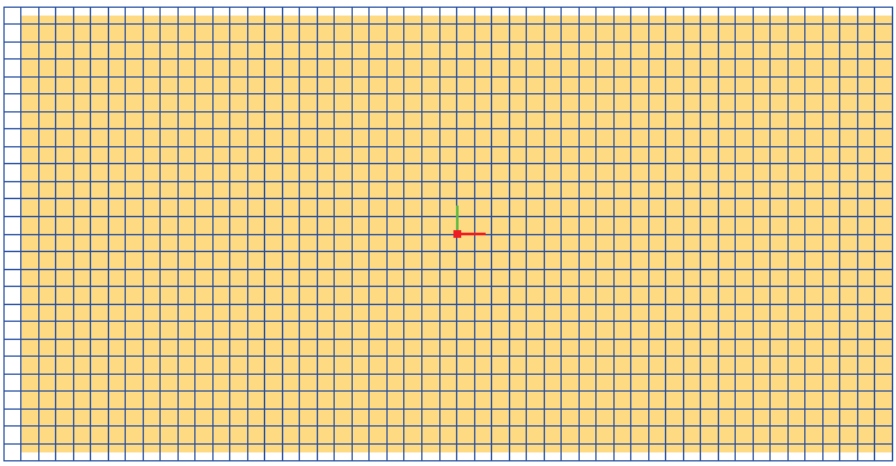
To visualize later the support of an operation, use the **Set Selection from Support** command.

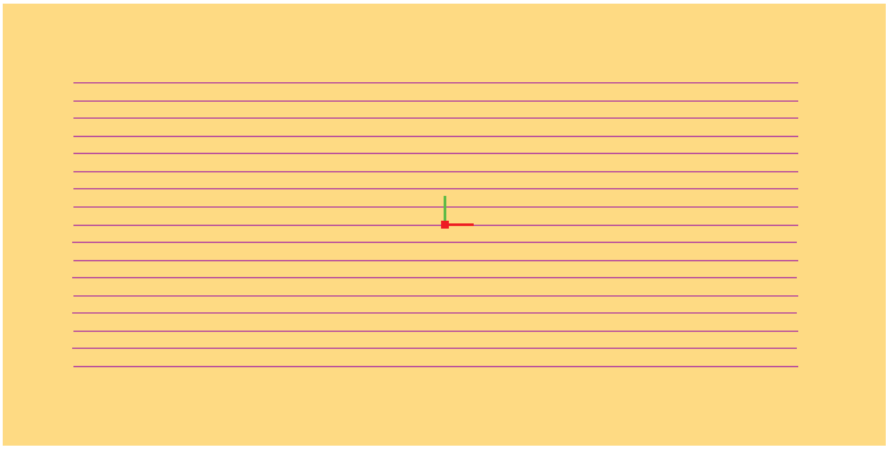
To modify a support, first use **Set Selection from Support** to clear the current selection and set it to the elements of the support, then modify selection (use these buttons  to replace, add to, or remove from selection), and finally set the support with **Set Selection from Support**.

At this point the explorer looks like this.



Running the simulation, we get the following results. The fabric layer covers the surface completely, while the UD layer is restricted to elements of the support.



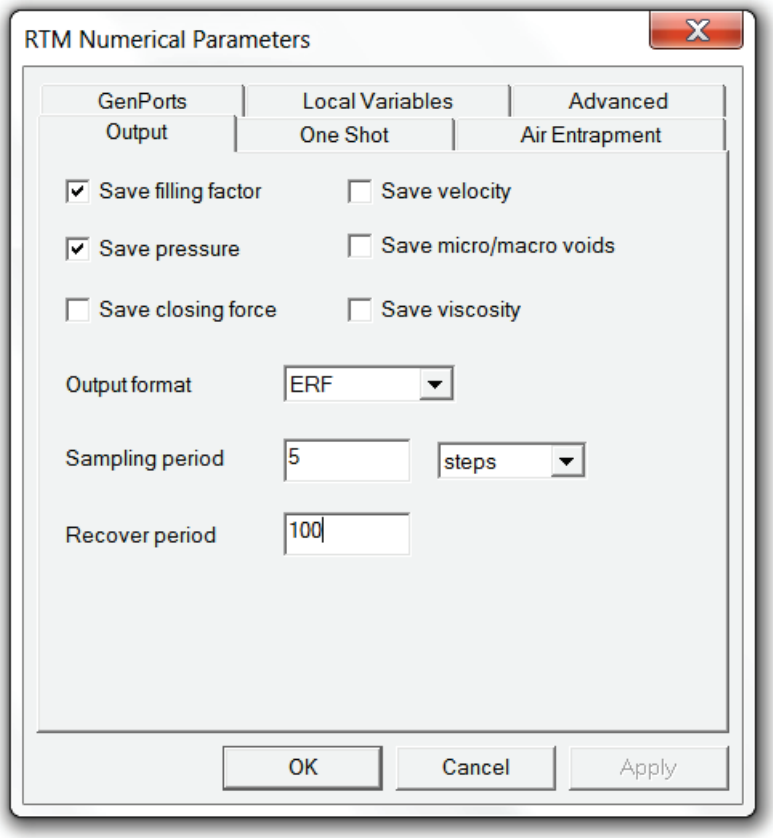


NUMERICAL PARAMETERS

The numerical parameters will be presented in the following sections for each simulation type. Many parameters are common to many simulation types, so instead of repeating text we refer to the section where the parameter was first described.

RTM Simulation

Output Tab



RTM Output tab

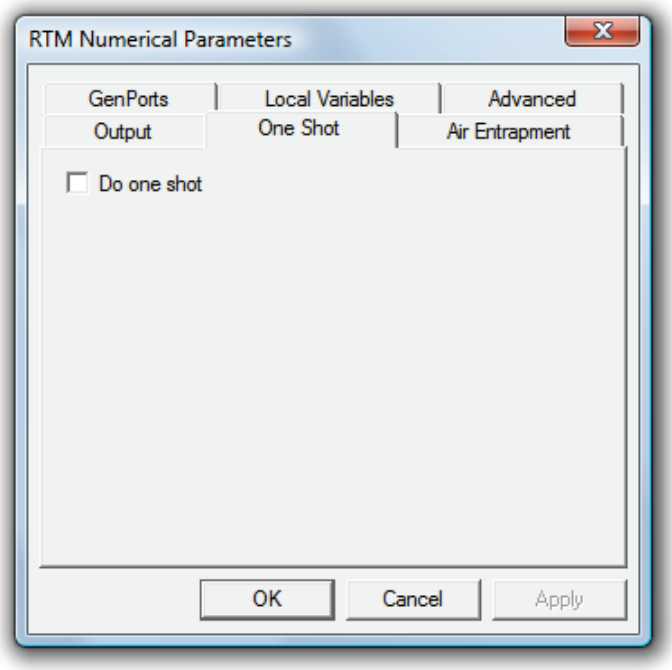
- **Save Filling Factor**: tells **PAM-RTM™** to generate result file for filling factor.
- **Save Pressure**: save pressure result file.
- **Save Velocity**: save resin velocity results files.

- **Save capillary numbers**: saves the capillary number, micro void, macro void, total void files. This option is useless if the micro and macro voids functions in the **Velo Opti** tab of the **Process Parameters** are not defined.
- **Save closing force**: writes a 5 columns text file, giving the components of the force vector in time, as well as norm of the force vector.
- **Save viscosity**: save resin viscosity. This is useful in the isothermal RTM context for viscosity function of time.
- **Output format**: **I-DEAS Universal** is the default format used by **PAM-RTM™** to write simulation results. The new **ESI Group** format called **ERF** is also available to perform post-processing in **Visual-Viewer™** (version 5.5 or later). **Visual-Viewer™** has more advanced post-processing capabilities than the standard **PAM-RTM™** viewer.
- **Sampling period**: store results in output files each *n* time step. By default *n*=10, which means that 1/10 steps will be saved. This parameter is useful to minimize the size of results files. Other options (parallel solver only):
  - **seconds**: saves results approximately each *x* seconds of simulated time
  - **fill %**: saves results approximately each *y* percentage of filling
- **Recover period**: (standard solver only) this parameter is useful in case you need to stop the simulation (**CTRL-C**) and restart it later. The default value is 500, which means that if you need to stop the simulation, you will have 500 steps to recalculate if you do a *restart*. Since a restart is considered an exceptional event, the default value is relatively large so that the simulation doesn't waste time writing unnecessary files. If you expect a simulation to run many days, you should maybe consider decreasing the recover sampling period.

Notes:

- *The "save" options (save filling, save pressure, etc.) only apply to the standard solver. The parallel solver writes systematically all the results files, regardless of that selection.*
- *One exception is the "save micro/macro voids" option that must be selected in order to have the parallel solver compute the micro and macro voids.*
- *The **seconds** and **fill percentage** sampling period options might not be respected, depending on the time step. For example, with a sampling period of 4 seconds and a time step of 5 seconds, results would be saved at t=0, t=5, t=10, instead of t=0, t=4, t=8, etc. From the time of the last save, the specified period is added, and the first step computed with a time greater or equal to that time generates a save. Of course with a small time step, the actual sampling period will be closer to the specified value.*
- *The parallel solver can be restarted from any time. It will actually restart from the closest time in the results files (depends on the sampling period).*

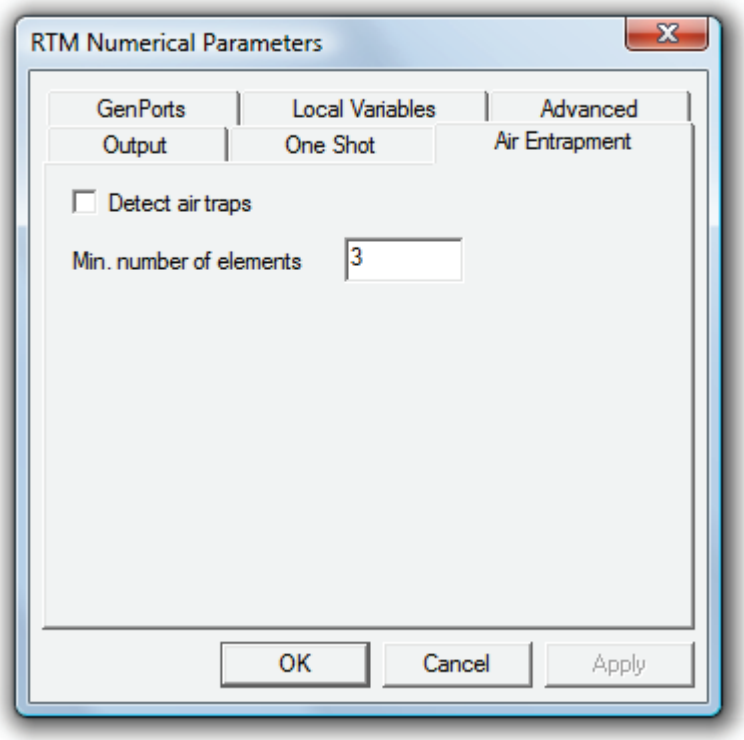
One Shot Tab



RTM One Shot tab

- **Do one shot**: (standard solver only) tells **PAM-RTM™** to perform a "one shot" simulation, i.e. solve in a single step to get the last points filled. This simulation is orders of magnitude faster than a standard filling simulation. Only pressure and flow rate boundary conditions are taken into account. There can be many inlets specified, but all must be of the same type (pressure or flow rare). Vents are ignored, as the goal of this simulation is to help find the best location for vents.

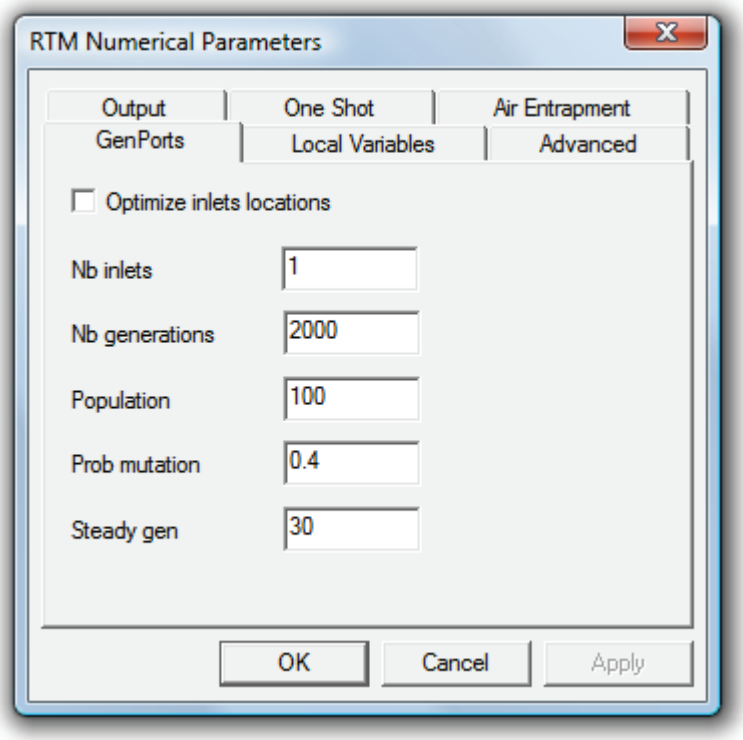
Air Entrapment Tab



RTM Air Entrapment tab

- **Detect air traps**: tells **PAM-RTM™** to detect air traps and take into account the pressure inside the air trap when solving the resin pressure field. An air trap is defined as a closed region of empty or partially filled elements not connected to an open vent.
- **Min. number of elements**: this parameter is used to avoid false air traps to be detected. The default value is 3, which means that if a small air trap of one or two elements pops up from nowhere, it won't be considered a real air trap and the cavity pressure still applies in this area (no pressure calculation based on the volume of the air trap). This doesn't mean that an air trap can never be smaller than 3 elements. Actually a large air trap is allowed to shrink below the **min number of elements** parameter.

GenPorts tab

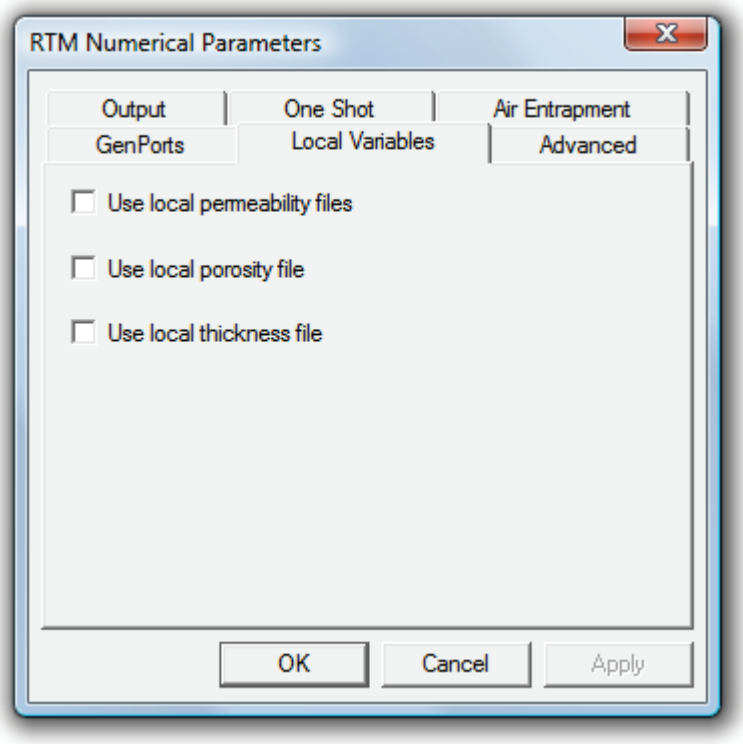


- **Optimize inlets locations**: if this box is checked, the **GenPorts** optimization module will be called to find the optimal injection ports locations minimizing fill time, instead of the standard RTM filling calculation.
- **Nb inlets**: number of injection ports to use.
- **Nb generations**: number of generations to be calculated by the genetic algorithm engine.
- **Population:** the number of individuals for each generation. An individual is actually an injection configuration, which is made of the number of injection points specified in **nb inlets**.
- **Prob mutation:** this is the probability that a major change occurs in a child with respect to his parents. For instance if a child is normally generated on the "line" connecting his 2 parents, a mutation could be to choose randomly a node of the mesh instead of one of the parents.
- **Steady gen:** if the calculation engine doesn't detect a significant change in the solution for that number of successive generations, it will assume convergence has been reached and will stop the calculation.

More information can be found in the **GenPorts** tutorial.

Note that **GenPorts** is not supported by the parallel solver.

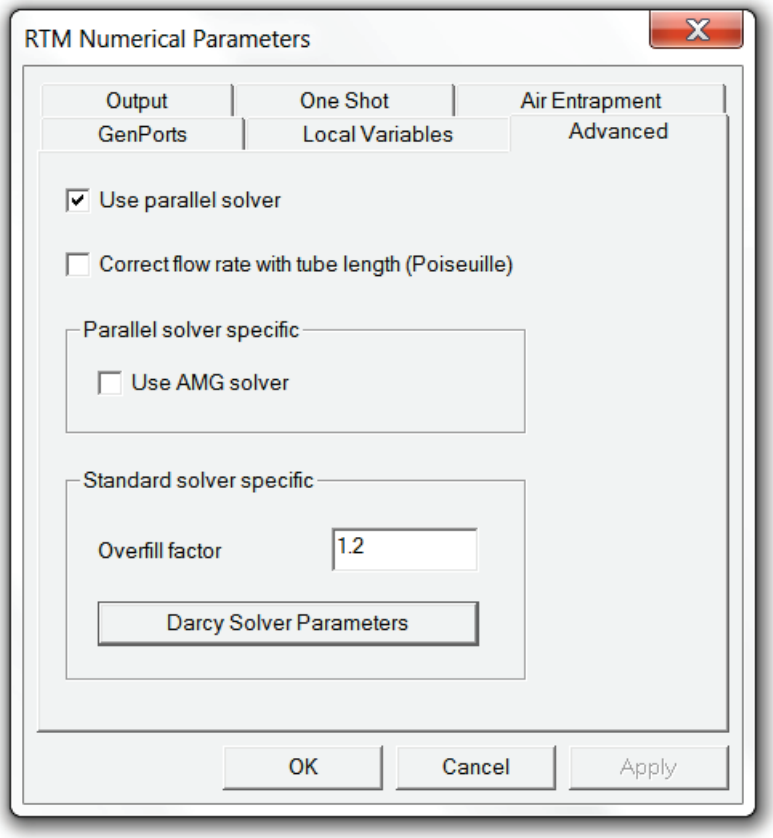
Local Variables Tab



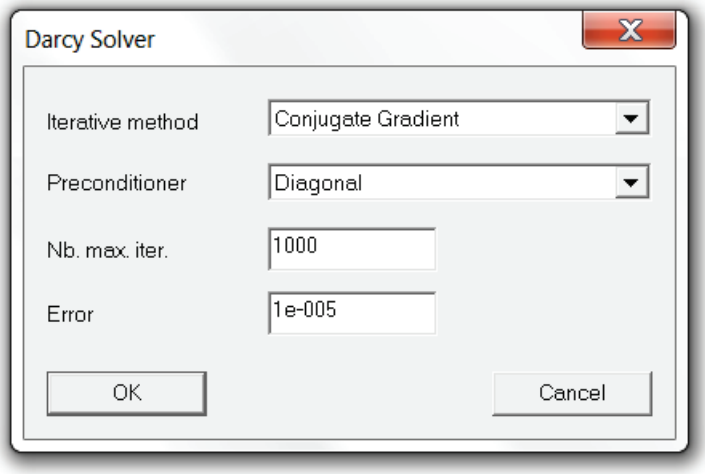
RTM Local Variables tab

- **Use local permeability files**: tells the **PAM-RTM™** solver to initialize local permeability (one permeability value for each element) from the `x_k1.sf`, `x_k2.sf` and optionally `x_k3.sf` (for solid elements) that have been generated as a result of *Compute Local Permeability*. For example if you do *Compute Local Permeability* and save your **PAM-RTM™** project as `test.dtf`, the files `test_k1.sf` and `test_k2.sf` will be generated in the same directory. You have to check **Use local permeability files** to initialize local permeability from these files. Otherwise the permeability of the material associated to each zone will be used.
- **Use local porosity file**: tells **PAM-RTM™** to use the local porosity file (`x_porosity.sf`) resulting from *Compute Local Permeability* to initialize the porosity of each element.
- **Use local thickness file**: the same principle applies to the thickness of shell elements.

Advanced Numerical Parameters



RTM Numerical Parameters - Advanced tab



Advanced Darcy solver parameters

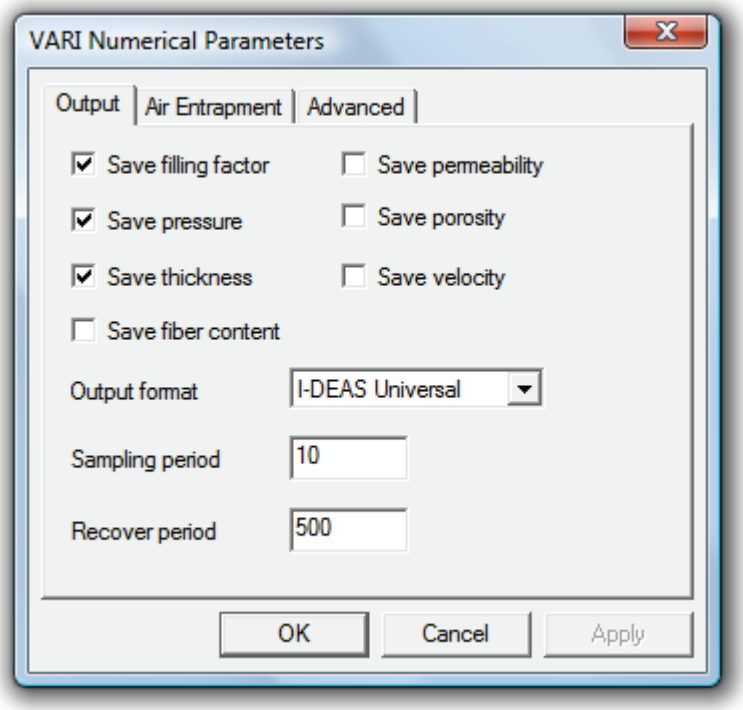
- **Use parallel solver**: if this box is checked, the new high performance parallel solver introduced in **PAM-RTM™ 2010** will be called instead of the standard solver. Before the calculation is launched, a dialog box is posted, asking how many processors are to be used. It is possible to enter 1 if the calculation is to be run on a single processor system, such as a laptop. In that case, the calculation will still be much faster than the standard solver, as the parallel solver uses a completely different code architecture, highly optimized. The memory used will also be much smaller than the standard solver. Once the calculation is done, the results have to be loaded for post-processing with **File > Open > PAM-RTM Parallel (.unf)**. Note that not all the functionalities of the standard solver are currently supported by the parallel solver. Please see the **PAM-RTM™ Release Notes** for the complete list of features supported or not supported.
- **Correct flow rate with tube length (Poiseuille)**: (parallel solver only) for pressure driven inlets, the corresponding flow rate on each inlet is computed and compared to the theoretical flow rate that would be obtained using Poiseuille formula (i.e. taking into account the tube length and radius specified on the boundary condition). If the flow rate on the inlet is found to be greater than that value, the inlet is switched to a flow rate controlled inlet with the flow rate set as the Poiseuille value.
- **Use AMG solver**: (parallel solver only) new high performance multi-grid solver used to solve Darcy's equation. Experimental (use with care).
- **Overfill factor**: (standard solver only) used to speed up the filling calculation by allowing more elements to be filled at each iteration, thus reducing the total number of Darcy solutions needed to fill the cavity (in **PAM-RTM™** most of the time is spent solving Darcy's equation). The idea is to allow an element to be oversaturated, i.e. to contain more resin than it can actually contain. The excess of resin of an element is distributed to its neighbors. The default value is 1.2, meaning that an element can be oversaturated by 20%.
- **Darcy solver parameters** (standard solver only):
  - **Iterative method**: the method used to solve the linear system $Ax=b$. *Conjugate gradient* should be used for Darcy. Advanced users can evaluate the performance of other supported methods:
    - *Bi-conjugate gradient*
    - *Bi-conjugate gradient stabilized*
    - *Conjugate gradient squared*
    - *Chebyshev iteration*
    - *Generalized Minimum Residual (GMRES)*
    - *Richardson iteration*
    - *Quasi-minimal residual*
    - *Conjugate gradient 2002*
    - *Conjugate gradient 2004*
    - *Conjugate gradient 2008*

Notes:

- *A new conjugate gradient implementation (**conjugate gradient 2008**) is introduced in PAM- RTM™ 2008. The meaning of the **conjugate gradient** option without version specification depends on the platform. For instance, on Windows 32-bit, **conjugate gradient** actually means **conjugate gradient 2004**. On Windows 64-bit, **conjugate gradient** means **conjugate gradient 2008**. The 2008 implementation was introduced mainly for porting reasons. Unfortunately the 2004 implementation, which is still the fastest of all implementations, makes use of advanced libraries which are not available on Windows 64-bit and Linux. We recommend keeping the default generic* **conjugate gradient** *option, so that the PAM-RTM solver automatically chooses the best implementation for a platform.*
- **Preconditioner**: *diagonal* should be used for Darcy. Other choices for advanced users are:
  - *Incomplete Cholesky*
  - *Incomplete LU*
- **Nb max iter**: maximum number of iterations to solve the linear system.
- **Error**: The residual is defined as $r_i = b - A * x_i$. The stopping criterion of the iterative method is $\frac{\|r_i\|_2}{\|b\|_2} \leq \varepsilon$, where ε is the specified error.

VARI Simulation (standard solver only)

The VARI simulation shares many of its numerical parameters with the RTM simulation. In the following sections, we list only the VARI specific parameters. The user should refer to the section *RTM Simulation* for a description of other parameters.



VARI output parameters

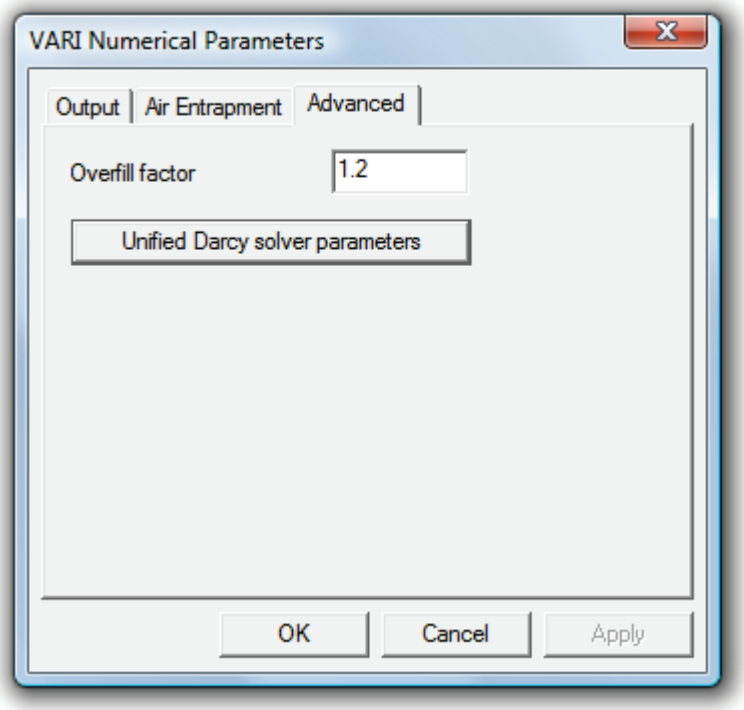
Output Tab

Since VARI simulation involves local change of thickness, fiber content (porosity) and permeability, these variables can be saved in results files. See *RTM Simulation* for other parameters.

Air Entrapment Tab

See *RTM simulation*.

Advanced Tab

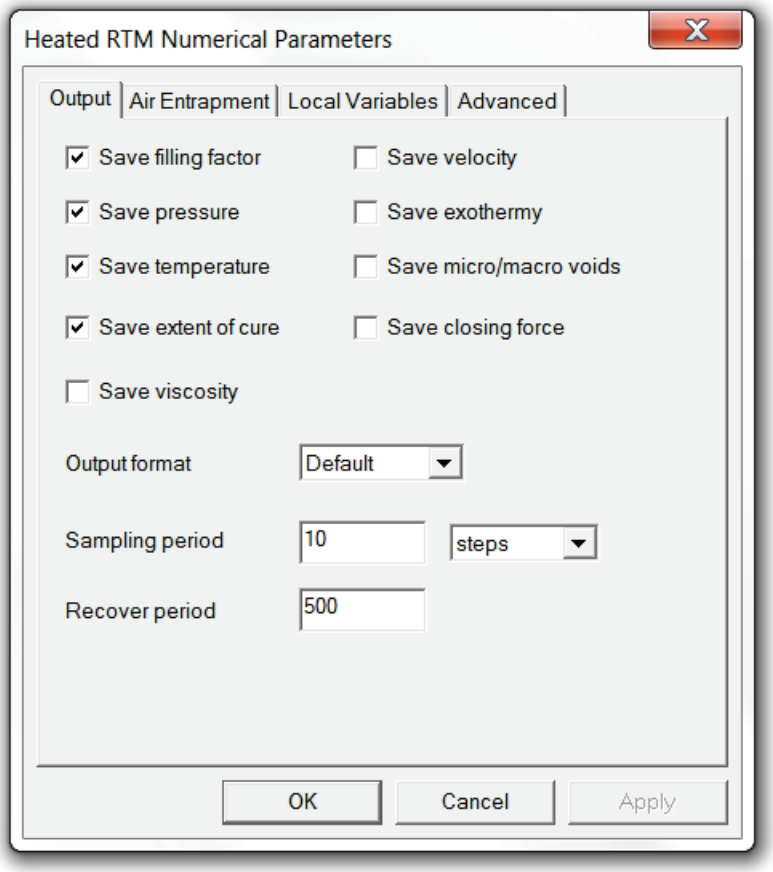


VARI advanced numerical parameters

- **Overfill factor**: see *RTM simulation.*
- **Unified Darcy solver parameters**: these are specific settings to solve the unified Darcy equation. The default settings are *GMRES* with *ILU* preconditioner.

Heated RTM Simulation

Output Tab



Heated RTM output tab

- **Save filling factor, Save pressure, Save temperature, Save extent of cure, Save exothermy, Save velocity, Save micro/macro voids, Save viscosity**: (standard solver only) check boxes to specify the variables to save in results files.
- **Save closing force**: writes a 5 columns text file, giving the components of the force vector in time, as well as norm of the force vector.
- **Output format**: see RTM simulation.
- **Sampling period**: see RTM simulation.
- **Recover period**: see RTM simulation.

Note:

- *The exothermy output of the standard solver is replaced by the rate of reaction (dα/dt) in the parallel solver.*

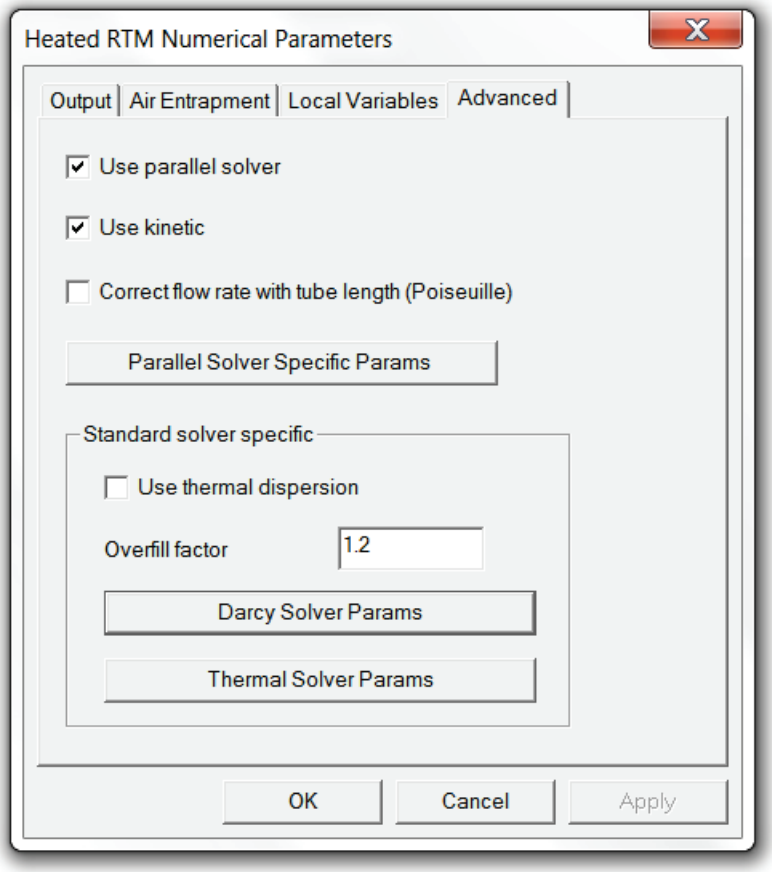
Air Entrapment Tab

The air entrapment option can be used with non-isothermal filling, however the current implementation doesn't take into account the effect of temperature on the pressure inside air traps. See *RTM Simulation* for a description of the parameters.

Local Variables Tab

See RTM simulation.

Advanced Tab



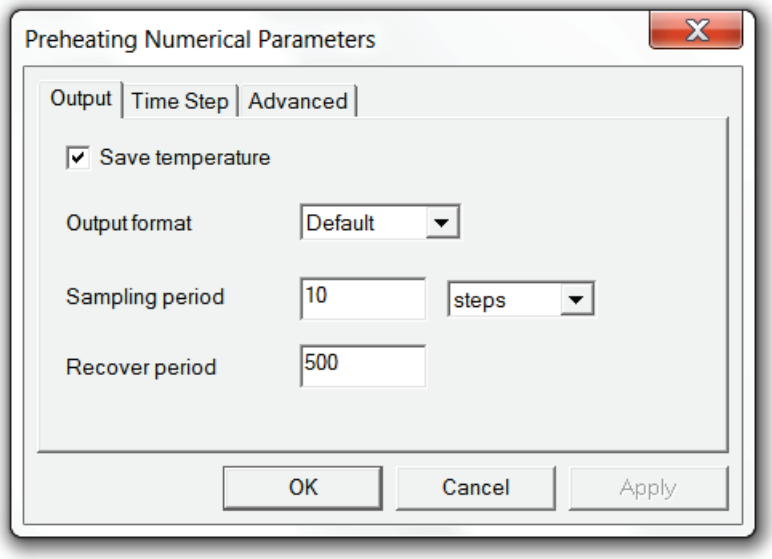
Heated RTM advanced parameters

- **Use parallel solver**: see RTM simulation. Thermal analysis with the parallel solver was introduced in **PAM-RTM™ 2011.**
- **Use kinetic**: uncheck this parameter when resin cure and its effects on viscosity and temperature are negligible during the filling phase, to avoid solving the transport equation for chemical species and reduce CPU time.
- **Correct flow rate with tube length (Poiseuille)**: see RTM simulation.
- **Use thermal dispersion**: (standard solver only) check this parameter to have **PAM-RTM™** take into account thermal dispersion, which is basically a correction to the thermal conductivity used in the saturated region. The corrected conductivity depends on the resin velocity. For more details, see the description of the **characteristic length** parameter, in the section on the thermal properties of the fiber reinforcements.
- **Overfill factor**: see RTM simulation.
- **Parallel Solver Specific Params**: these parameters are only used if **use parallel solver** is checked.
  - **Automatically generate mold/preform interface:** with the parallel solver, it is mandatory to specify a heat transfer coefficient for the mold/preform interface, as opposed to the standard solver for which it is optional. Since it can be a lot of work to generate that interface manually with the usual **Groups>Contact Interface** command, this option is checked by default, meaning the elements will be automatically disconnected on that interface for the whole mesh at calculation launch. In some special situations the user might need to specify different coefficients for different areas of the mold/preform interface. In that case, the user has to create interfaces manually; using contact resistances (see tutorial *Thermal Contact Resistance*). Be careful that the units of the contact resistance are the reciprocal of the mold/preform interface coefficient. This option must be unchecked if some contact resistances are to be defined manually on the mold/preform interface. In that case it is mandatory that all the faces of the mold/preform interface be part of a contact resistance. **PAM-RTM™** won't create automatically the remaining interfaces if the contact resistances cover only a subset of the mold/preform interface. Note that this doesn't apply to mold/mold interfaces. It is thus possible to have **automatically generate mold/preform interface** checked, while contact resistances for mold/mold interfaces are defined
  - **Mold/preform interface coefficient:** heat transfer coefficient (conductance) used on the whole mold/preform interface when the **automatically generate mold/preform interface** option is checked. Be careful that the units (W/m^2K) are the reciprocal of a thermal resistance.
  - **Use AMG solver**: (parallel solver only) new high performance multi-grid solver used to solve Darcy's equation. Experimental (use with care).

- **Darcy Solver Params**: see RTM simulation. These parameters are only used by the standard solver (i.e. if **use parallel solver** is unchecked).
- **Thermal Solver Params**: default is *GMRES* with *ILU* preconditioner. These parameters are only used by the standard solver (i.e. if **use parallel solver** is unchecked).

Preheating Simulation

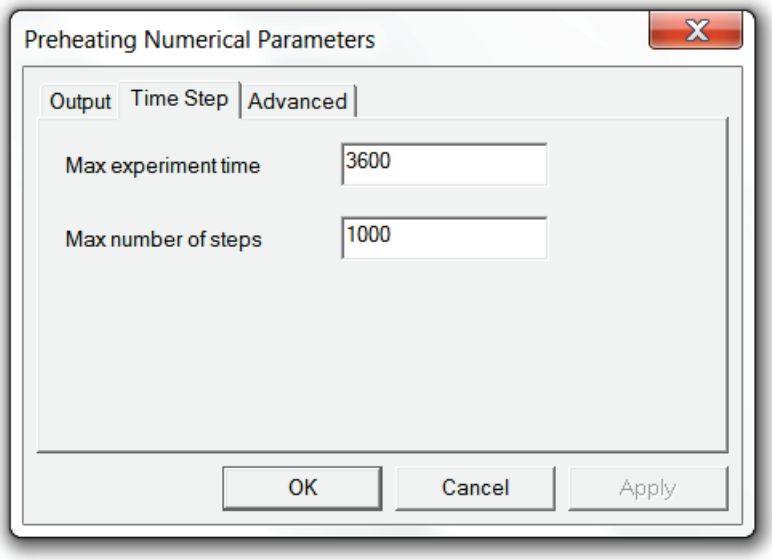
Output Tab



Preheating output tab

- **Save temperature**: this is the only variable that can be saved for a preheating simulation.
- **Output format**: see *RTM simulation*.
- **Sampling period**: see *RTM simulation*.
- **Recover period**: see *RTM simulation*.

Time Step Tab



Preheating time step tab

With the standard solver, the preheating simulation works with a constant time step calculated as:

$$dt = Max\ experiment\ time/Max\ number\ of\ steps$$

- **Max experiment time**: the total heating time of the mold and fibers. Unit: seconds.
- **Max number of steps**: the number of time steps for the calculation.

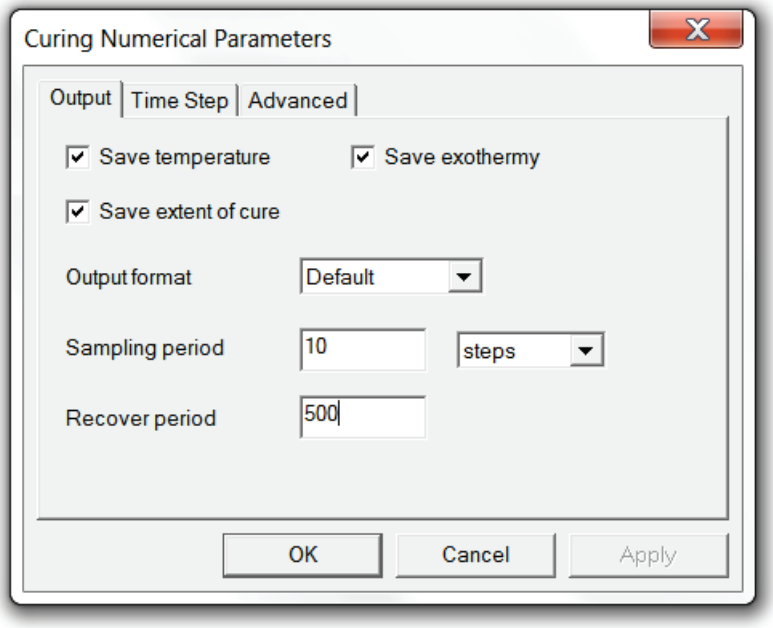
The parallel solver uses an adaptive time step, meaning it changes in time to respect convergence criteria. The *dt* formula above corresponds to the maximum time step.

Advanced Tab

See *Heated RTM*.

Curing Simulation

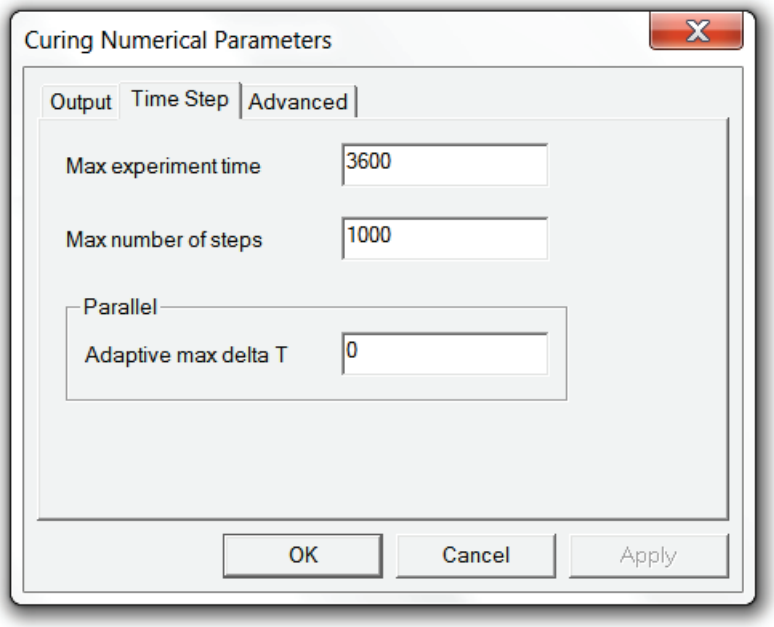
Output Tab



Curing output tab

- Variables available for saving in results files are: *temperature, extent of cure* and *exothermy*.
- **Output format**: see *RTM simulation*.
- **Sampling period**: see *RTM simulation*.
- **Recover period**: see *RTM simulation*.

Time Step Tab



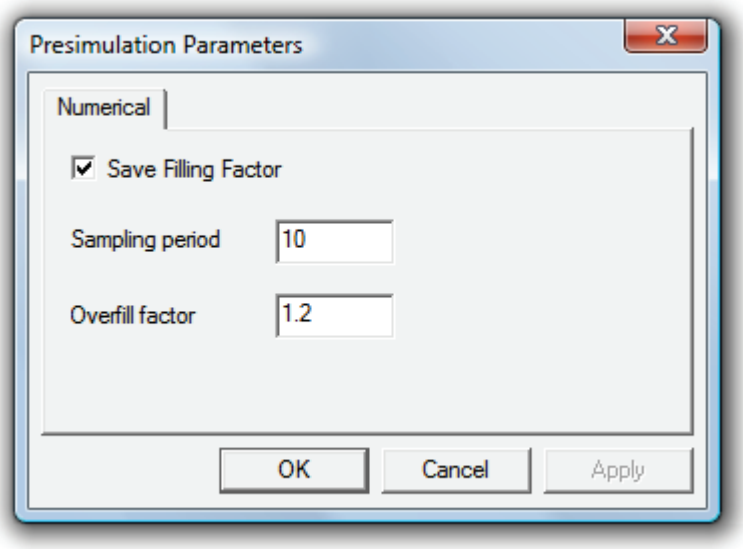
Curing time step tab

- **Max experiment time**: see *Preheating simulation*.
- **Max number of steps**: see *Preheating simulation*.
- **Adaptive max delta T**: (parallel only) in order to capture the high temperature peak typical of curing reactions, it is sometimes necessary to use this parameter to further control the time step. It specifies the maximum absolute temperature variation allowed on the whole domain between two steps. If the variation is higher, the time step will be decreased (divided by two), until the condition is respected. Then the time step will increase again as long as the condition is respected (up to the maximum time step *dt = max_experiment_time/max_number_of_steps*). The default value is zero, meaning the parameter has no effect.

Advanced Tab

See Heated RTM simulation.

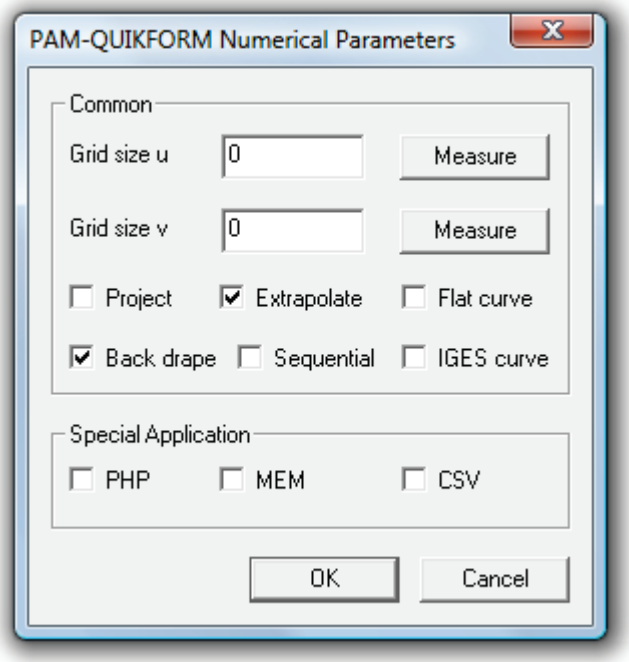
Presimulation (standard solver only)



Presimulation numerical parameters

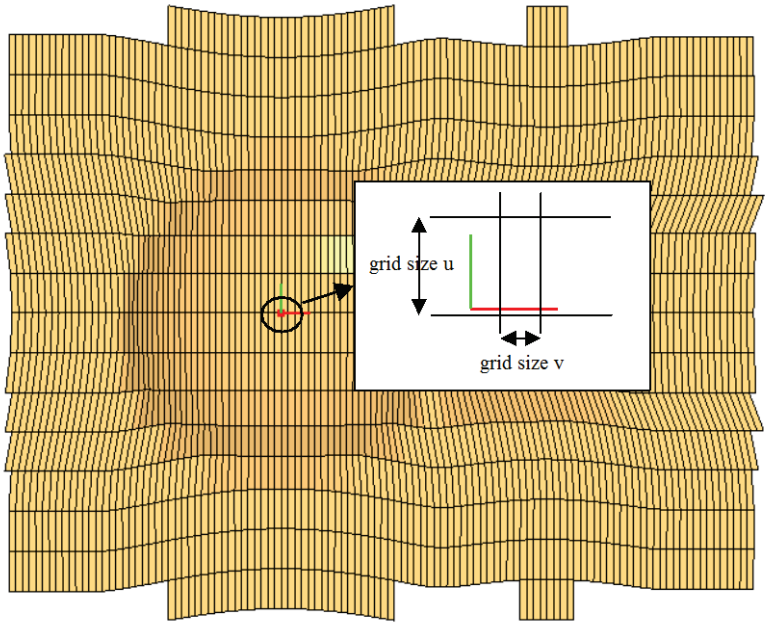
- **Save filling factor**: there is no pressure calculation involved in presimulation, so filling factor is the only variable available for output.
- **Sampling period**: see *RTM simulation*.
- **Overfill factor**: see advanced numerical parameters of *RTM simulation*.

PAM-QUIKFORM Simulation

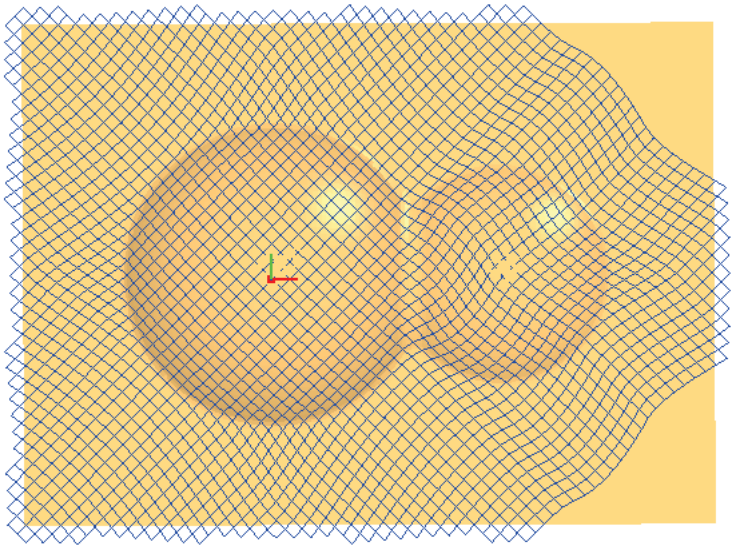


- **Grid size u**: size of the elements along the local Y axis of the draping referential (see figure below). For fabrics, *grid size v* is not used. Only *grid size u* is used for both directions. The UD algorithm supports different sizes for u and v.
- **Grid size v**: size of the elements along the local X axis of the draping referential. This value is not used for fabrics.
- **Project**: if this option is checked, the fiber orientations are projected by PAM-QUIKFORM on the tool mesh, and instead of writing mesh files of the 3D draped plies, the tool mesh is copied for each ply, with additional information for fiber orientations. See description of the *initial* parameter in the PAM-QUIKFORM solver documentation.
- **Extrapolate:** also called "manual draping", this option is used by PAM-QUIKFORM to cover a surface as much as possible by extrapolation. Without this option, draping will cover at most a quadrangle defined by the size of the two axes first draped. See example below.
- **Back drape:** activates the possibility of draping in back direction. The basic algorithm of PAM-QUIKFORM drapes from the starting point, increasing weft and warp directions. Due to the geometry of some parts, the basic algorithm might not be able to cover some areas without the back drape option. See example below.
- **Flat curve:** if this option is active, PAM-QUIKFORM projects the boundary of the tool on the mesh of the 3D draped ply in order to get a more accurate representation of the 2D flat pattern.

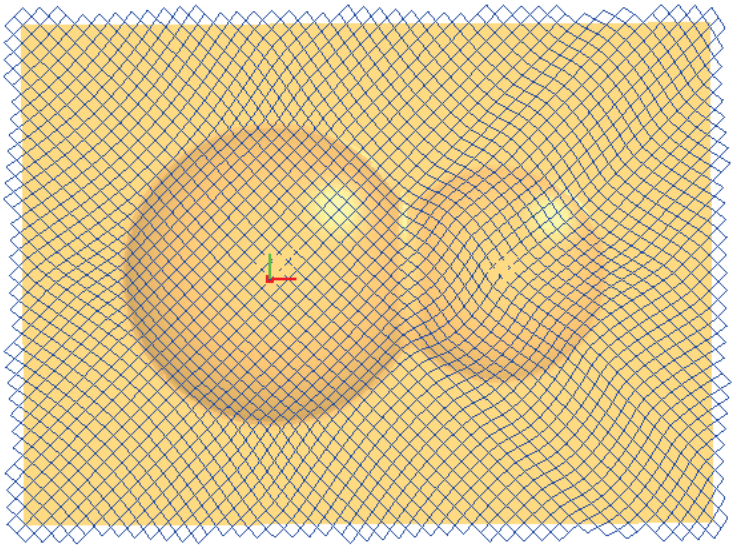
- **IGES Curve:** if the *flat curve* option is active, the flat curve is written in IGES format.
- **Sequential:** if this option is active, PAM-QUIKFORM will drape sequentially by zones, which must be numbered sequentially from 1 to *n*. The origin of the draping referential must be located in zone 1.
- **PHP, MEM, CSV:** special application flags. See PAM-QUIKFORM solver documentation.



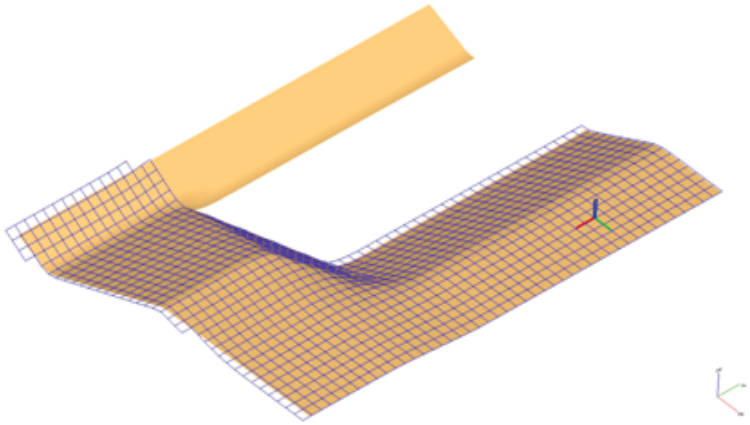
PAM-QUIKFORM grid size u and v parameters



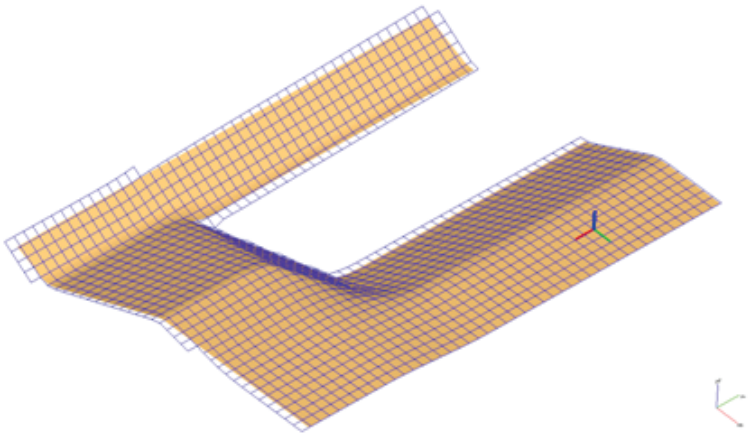
Draping without the extrapolate option



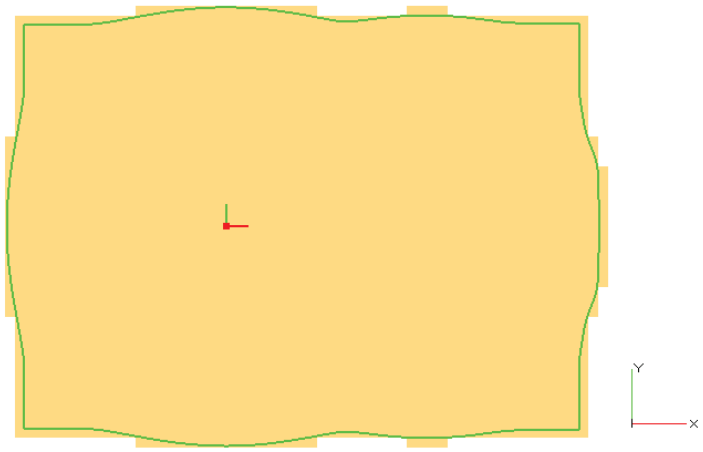
Draping with the extrapolate option



Draping without the "back drape" option



Draping with the "back drape" option



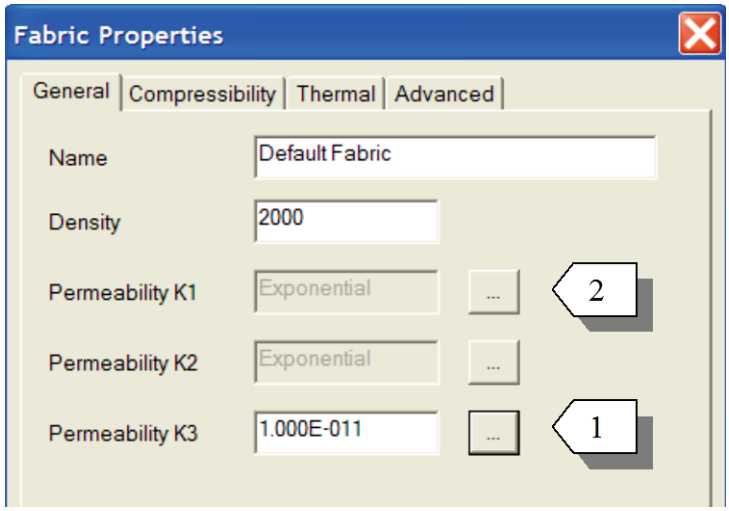
Flat curve

FUNCTION EDITOR

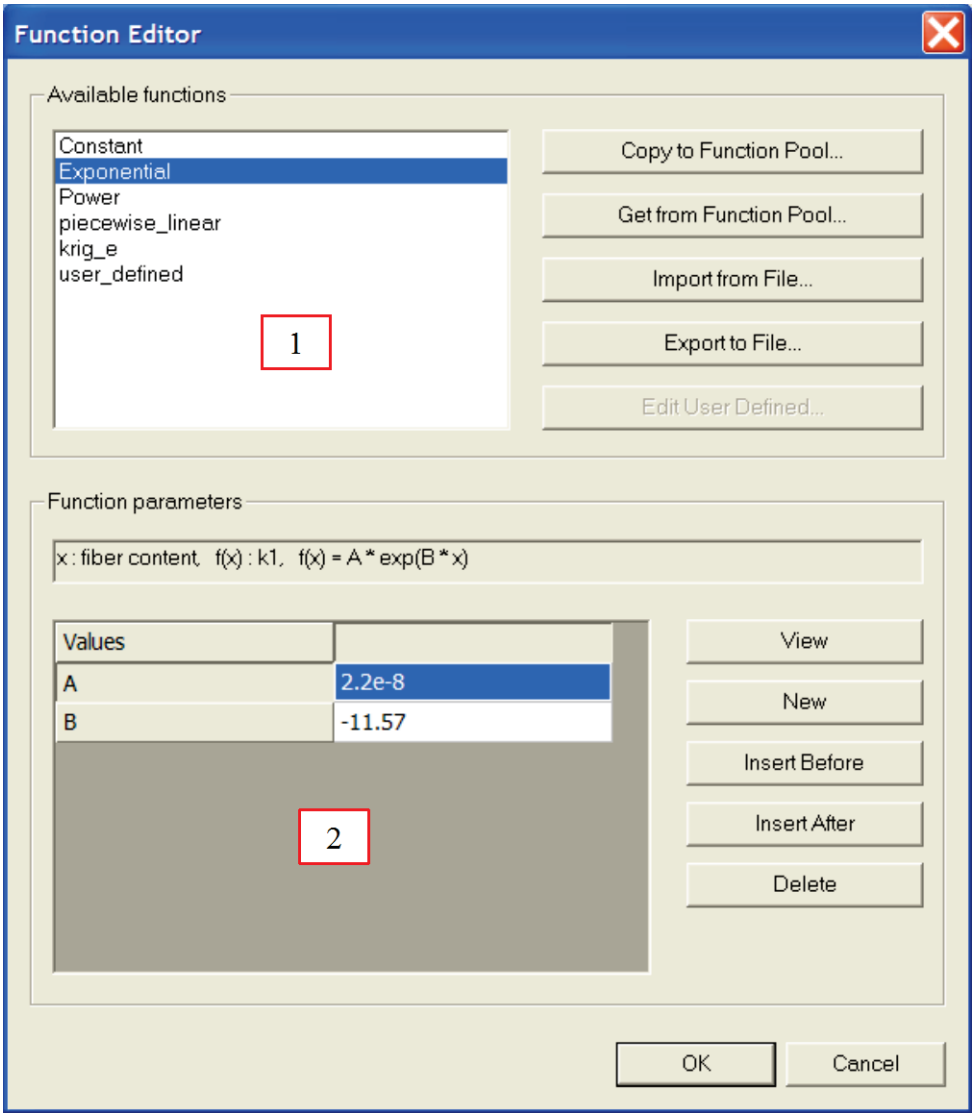
Many simulation parameters in **PAM-RTM™** use curves or mathematical functions of 2 variables. This chapter describes the function editor, a dialog box used to edit these mathematical functions.

Overview

This button ... is used in **PAM-RTM™** wherever a mathematical function can be assigned to a simulation parameter. The following image shows the **General** tab of the **Fabric Properties** dialog. In this example, *Permeability K3* **[1]** is a constant value, so its value can be entered directly in the text field. *Permeability K1* **[2]** has an exponential curve assigned to it. The text field is used to display the type of the function, the text field is disabled, and the user has to push the ... button to modify the parameters of the exponential curve. This opens the **Function Editor** dialog.



General tab of the Fabric Properties



Function editor dialog

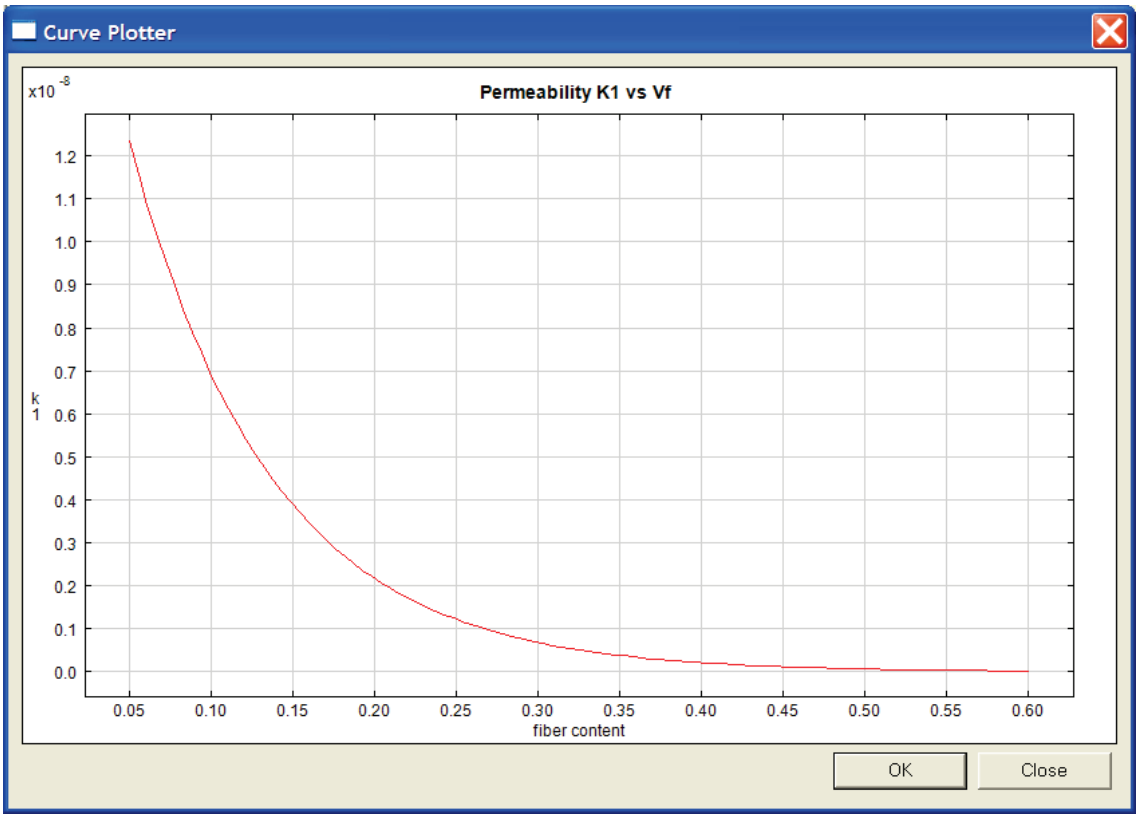
In this example, an exponential curve $f(x) = A \cdot e^{B \cdot x}$ with *A=2.2E-8* and *B=-11.57* is assigned to *Permeability K1*. The user can select other functions from the list of predefined functions **[1]**. Selecting a function displays either the function parameters such as *A* and *B* in this example, or the coordinates of the control points if the function is defined by a set of control points (*piecewise_linear* or *krig_e*). In any case, the user can click on a value and enter text to modify it.

A *user_defined* function is always available in the list of functions. The same exponential curve as shown above could be defined with the *user_defined* function by pushing the **Edit User Defined** button and entering the character string:

```
2.2E-8*exp(-11.57*x)
```

The curve is the same, however the evaluation of the curve costs more CPU time.

The curve can be visualized by pushing the **View** button. This opens the following **Curve Plotter**.



Permeability K1 as a function of fiber content

User Defined Functions

The parser recognizes the following operators:

+, -, *, /, ^ (exponent)

as well as the following functions:

H, abs, exp, ceil, floor, log, sqrt, sin, cos, tan, asin, acos, atan, sinh, cosh, tanh.

Note that the non-standard function *H* is the Heavyside step function, defined as:

$$H(x) = 0, x < 0$$
$$H(x) = 1, x \geq 1$$

As an example, the function *Kinetic_01* defined as:

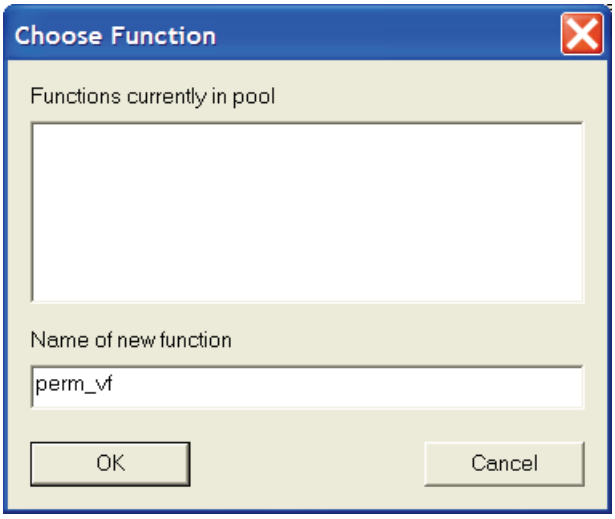
$$f(x,y) = A \cdot y^m \cdot (1-y)^p \cdot e^{\left(\frac{-E}{x}\right)}$$

with *A=9.17E+6*, *E=7304*, *m=0.7* and *p=1.3* would be defined as a *user_defined* function with the character string:

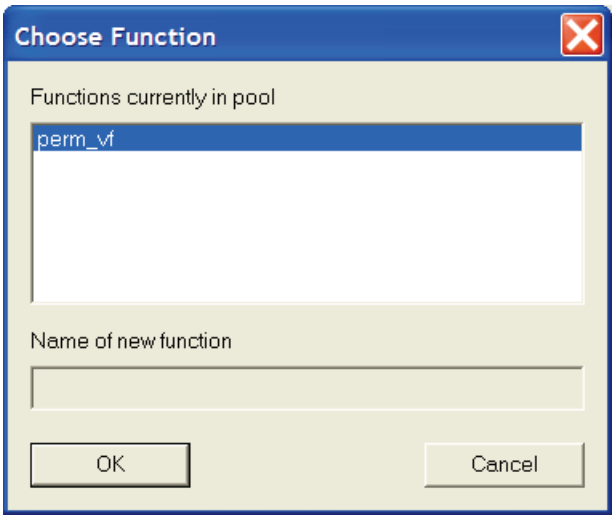
```
9.17E6*(y^0.7)*((1-y)^1.3)*exp(-7304/x)
```

Function Pool

The function pool can be seen as some kind of copy/paste functionality for mathematical functions. This is useful when the same function is assigned to many parameters. In that case, the user defines the function once, then push the **Copy to Function Pool** button, which pops up the following dialog box. A name must be given to the function before it is copied in the function pool. The function can be retrieved later by its name with **Get from Function Pool**. Note that the function pool is shared by all open documents and is available until **PAM-RTM™** is closed.



Copy to function pool dialog



Get from function pool dialog

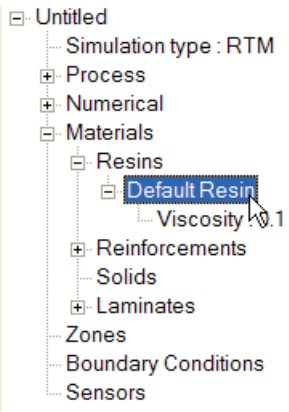
Import/Export

Depending on the context (edition of a function of 1 or 2 variables), it is possible to import in **PAM-RTM™** a 2 columns text file (curve) or a 3 columns text file (function of 2 variables). The columns can be separated with any combination of white space, tab or comma. If a 2 columns file is imported, a *piecewise_linear* curve is automatically created. For 3 columns text files, a *krig_e* function is created.

The set of control points associated to piecewise linear or kriged functions can also be exported in 2 or 3 columns text files.

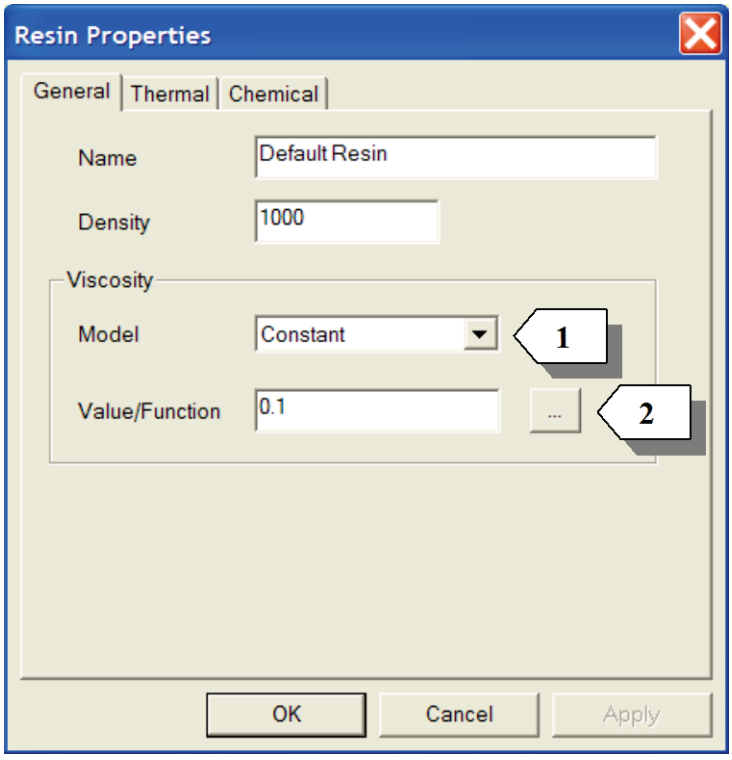
MATERIAL PROPERTIES OF THE RESIN

The **Resin Properties** dialog box is opened by double-clicking a resin in the model explorer.



The following dialog box is used to specify resin properties such as viscosity, chemical reaction model, thermal conductivity and specific heat.

General Tab



Name

Enter a text description to fully identify the resin. It is sometimes useful to include in this description the validity domain of the associated viscosity and kinetics models, such as "*My resin with kinetics 350 < T < 400*".

Density

Density of the resin. Unit: kg/m^3.

Viscosity

Unit: ***Pa.s***. Several models are available:

- Constant
- Function of temperature **f(temperature)**
  - Constant
  - Exponential: $f(x) = A \cdot \exp(B \cdot x)$
  - Piecewise linear function
  - User defined
  - User DLL
- Function of temperature and degree of cure **f(temperature, alpha)**
  - Constant
  - Viscosity_01 (see reference **[R.1]** at the end of this chapter):

$$f(T,\alpha) = A \cdot \exp\left(\frac{B}{T} + C \cdot \alpha\right)$$

  - Viscosity_02 (Castro-Macosko **[R.2]**):

$$f(T,\alpha) = c_0 \cdot \exp\left(\frac{c_1}{T}\right) \cdot \left(\frac{c_2}{c_2 - \alpha}\right)^{c_3 + c_4 \cdot \alpha}$$

  - Viscosity_03:

$$f(T,\alpha) = c_1 \cdot \exp(\frac{c_2}{T}) \cdot \exp\left(\frac{c_3}{c_4 - \alpha} - c_5\right)$$

  - Viscosity_04:

$$f(T,\alpha) = c_0 \cdot \exp\left(\frac{c_1}{T - c_1}\right) \cdot \left(\frac{c_2}{c_2 - \alpha}\right)^{\left(\frac{c_3}{T - c_4} \cdot \alpha\right)}$$

  - Viscosity_05:

$$f(T,\alpha) = A \cdot \exp(\frac{B}{T} + c_0 + c_1\alpha + c_2\alpha^2 + ... + c_6\alpha^6)$$

- Viscosity_06 (**[R.3]**):

$$f(T,\alpha) = h_u \cdot \exp\left(\frac{T_{rheo}}{T - T_m} + C \cdot \alpha\right)$$

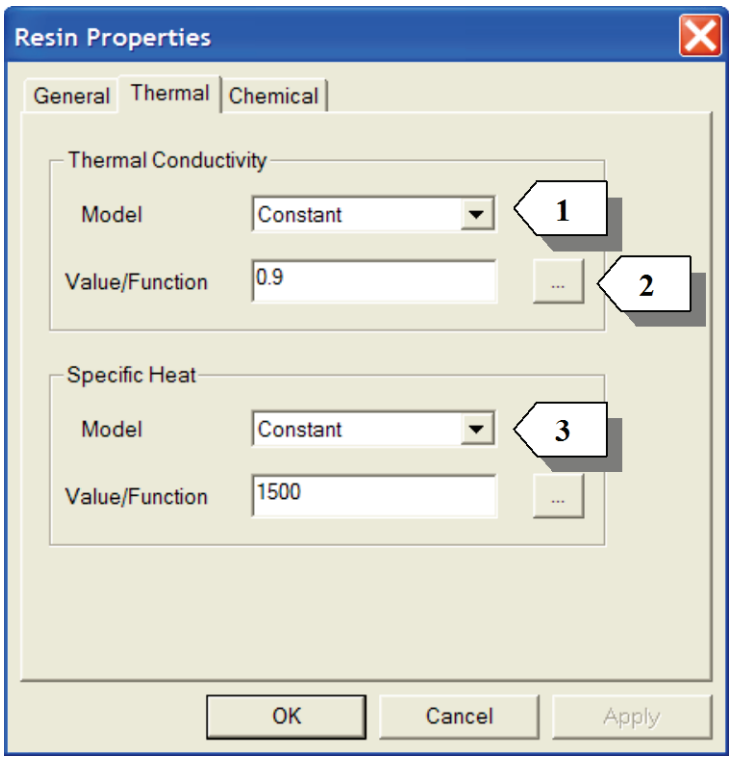
- Kriged function
- User defined
- User DLL

- Function of time **f(global_time)**
  - Constant
  - Piecewise linear function
  - User defined
  - User DLL
- Function of time **f(material_age)**
  - Constant
  - Piecewise linear function
  - User defined
  - User DLL

Note:

- *The **user_dll** type is only supported by the parallel solver. See tutorial **User defined functions**.*
- *The time variable used for the evaluation of viscosity **f(global_time)** is the time since beginning of injection. At a given time, the viscosity is uniform on the saturated domain.*
- *For **f(material_age)**, the time variable corresponds to the time since a resin particle entered the mold. Viscosity is thus non-uniform on the saturated domain, and higher close to the resin front.*
- *The **f(material_age)** model is only supported by the parallel solver.*
- *The viscosity model is selected with the **Model** dropdown list**[1]**. In case of a constant viscosity, the value can be entered directly in the **Value** field. Otherwise the user has to go through the function editor **[2]** to enter the coefficients of the selected function (see section **Function Editor**).*

Thermal Tab



Thermal Conductivity

Unit: W/m.K.

Available models are: constant, function of temperature, or function of temperature and degree of cure **[1]**.

Once again, in case of a constant model, the value can be entered directly in the text field **[2]**. Otherwise use the **...** button to open the function editor.

Specific Heat

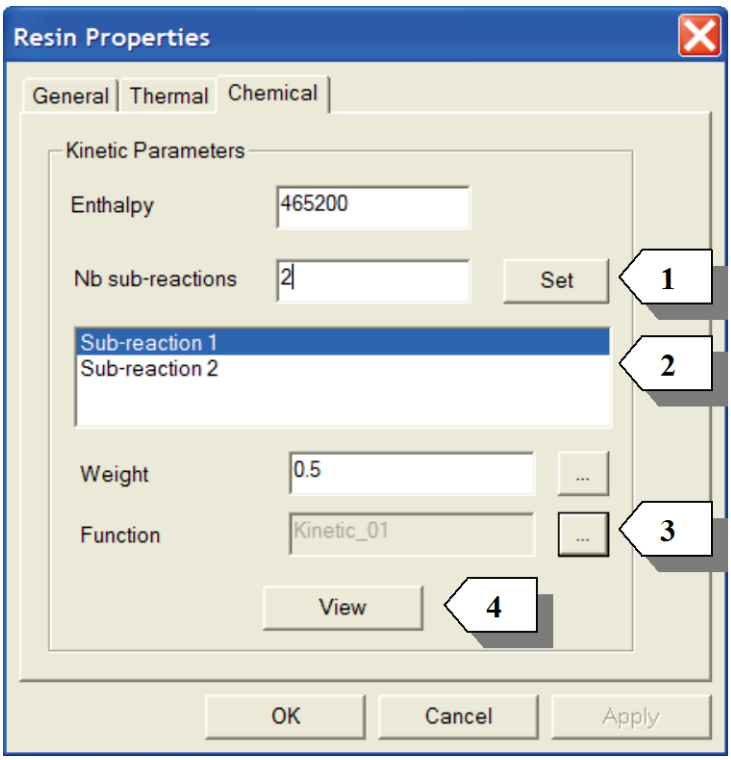
Unit: J/Kg.K.

Available models are: constant, function of temperature, or function of temperature and degree of cure **[3]**.

Note

- *When using the parallel solver, if specific heat f(temperature, alpha) is needed, it has to be specified with a user_dll function (i.e. C-language code written by the user). See tutorial User Defined Functions.*

Chemical Tab



Enthalpy

Unit: J/Kg.

The heat generated by the full resin polymerization per unit mass.

Reaction model

The resin kinetics model is defined as a weighted summation of sub-reactions:

$$\frac{d\alpha}{dt} = \sum_{i=1}^{n} w_i(t) \cdot f_i(T, \alpha)$$

The number of sub-reactions *n* must be specified first in the **Nb sub-reactions** field. Then the user pushes the **Set** button **[1]**, which actually generates the sub-reactions listed in **[2]**. Select a sub-reaction, then edit the associated weight function and kinetics function **[3]**. The weight is function of time, while the kinetics function is function of temperature and degree of cure.

Available functions for kinetics are:

- Kinetic_01 (autocatalytic **[R.4]**):

$$f(T, \alpha) = A \cdot \alpha^m \cdot (1 - \alpha)^p \cdot \exp\left(\frac{-E}{T}\right)$$

- Kinetic_02 (Kamal-Sourour **[R.5]**):

$$f(T,\alpha)=\left(A_1\cdot\exp\left(\frac{E_1}{T}\right)+A_2\cdot\exp\left(\frac{E_2}{T}\right)\cdot\alpha^m\right)\cdot(B-\alpha)^n$$

- Kinetic_03 (modified Kamal-Sourour):

$$f(T,\alpha)=\left(A_1\cdot\exp\left(\frac{E_1}{T}\right)+A_2\cdot\exp\left(\frac{E_2}{T}\right)\cdot\alpha^{m(T)}\right)\cdot(B(T)-\alpha)^{n(T)}$$

$$B(T)=b_0+b_1\cdot T+b_2\cdot T^2$$
$$m(T)=m_0+m_1\cdot T+m_2\cdot T^2$$
$$n(T)=n_0+n_1\cdot T+n_2\cdot T^2$$

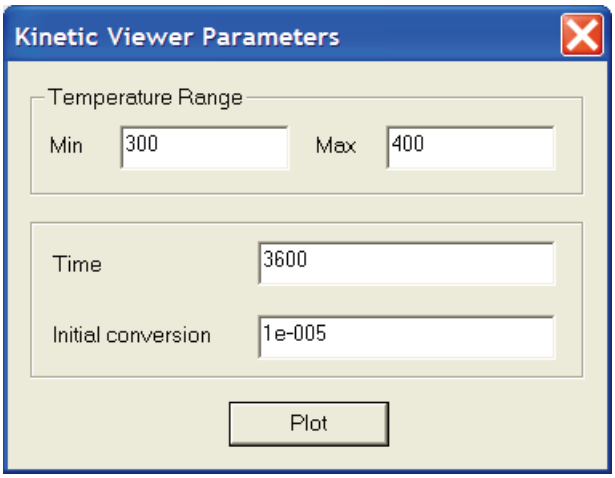
- Kinetic_04 **[R.3]**:

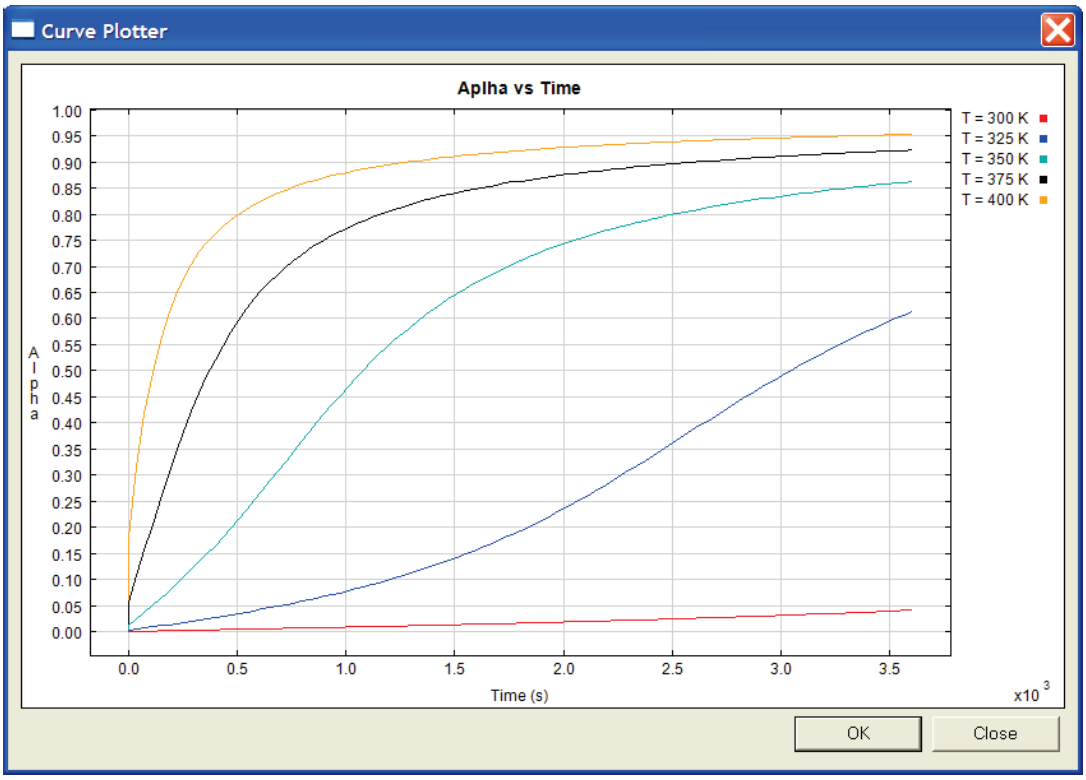
$$f(T,\alpha)=A\cdot\exp\left(\frac{-T_{kin}}{\alpha-T_m}\right)\cdot\left[ramp\left(1-\exp\left(-B\cdot(T-T_m)\right)-\alpha\right)\right]^m\cdot\alpha^n$$

$$ramp(x)=x, x\geq 0$$
$$ramp(x)=0, x<0$$

- Kriged function: interpolation function constructed from a set of data points.
- User defined
- User DLL (parallel solver only, see tutorial *User defined functions*)

The **View** button **[4]** opens the **Kinetic Viewer Parameters** dialog, used to specify a temperature and time range. Then pushing the **Plot** button plots isothermal conversion curves, as shown below. This is actually the time integration of $\frac{d\alpha}{dt}$ for different temperatures. This viewer is useful to quickly evaluate how long it takes to fully cure the resin at a given temperature.





Kinetic Viewer

References

[R.1] A.M. Stolin, A.G. Merzhanov, A.Y. Malkin, Polymer Engineering and Science; 1979, 19, 1074

[R.2] J.M. Castro, C.W. Macosko, Studies of mold filling and curing in the reaction injection molding process, AIChE J., 1982, 28, 250

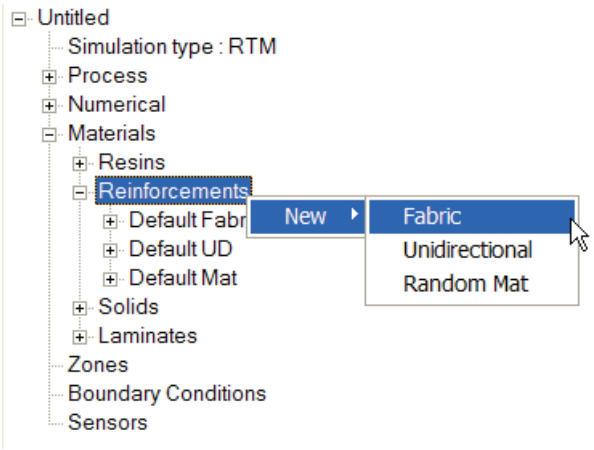
[R.3] M. Henne, C. Breyer, M. Niedermeier, P. Ermanni, A new kinetic and viscosity model for liquid composite molding simulations in an industrial environment, Polymer Composites, 2004, 25, 3

[R.4] A.M. Clayton, Epoxy Resins, Engineered Material Handbook: Composites, ASM International, 1998

[R.5] M.R. Kamal, S. Sourour, Kinetics and thermal characterisation of thermoset cure, Polymer Engineering and Science, January 1973, Vol. 13, No. 1

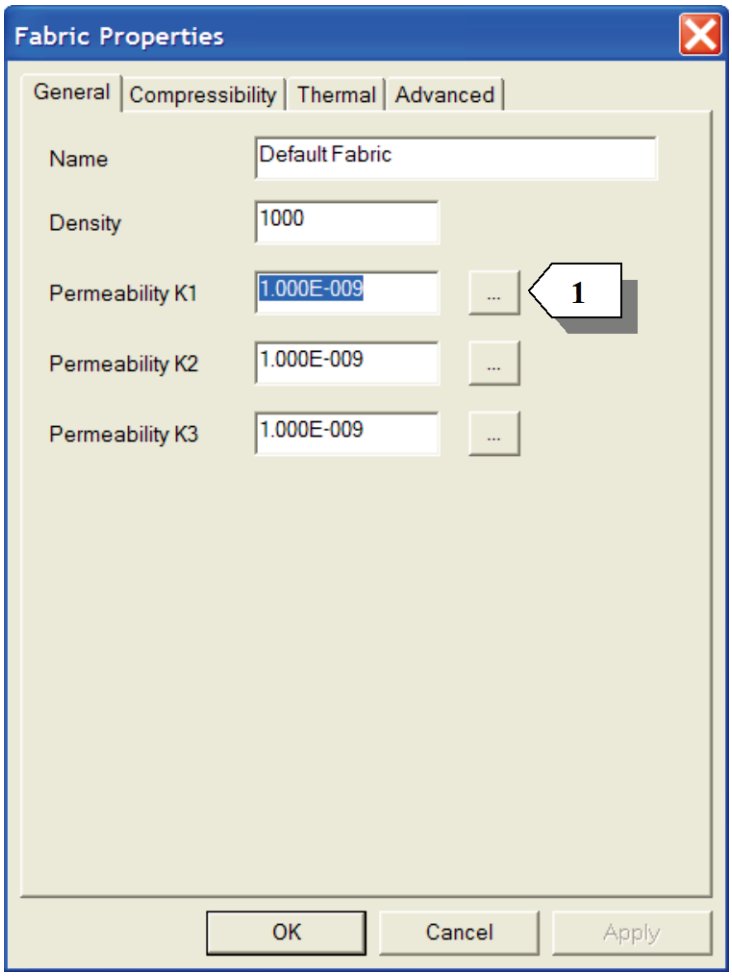
MATERIAL PROPERTIES OF THE FIBER REINFORCEMENTS

Three types of fiber reinforcements can be created in **PAM-RTM™**: fabric, unidirectional, and random mat. Right-click the *Reinforcements* item in the explorer to create new instances of reinforcements.



To edit a fiber reinforcement, double-click it in the model explorer. The *General*, *Thermal* and *Compressibility* tabs are shared by all reinforcements. An *Advanced* tab is available on the fabric to specify permeability as a function of shear angle. A *Draping* tab is available in the context of a PAM-QUIKFORM simulation.

General Tab



Name

Enter a text description to fully identify the fiber reinforcement.

Density

Unit: kg/m^3

Density of the "solid" fiber material, i.e. density for 100% fiber volume fraction. For example density of pure glass, if the reinforcement is made of glass fibers.

Permeability K_1, K_2, K_3

Unit: m^2

Permeability in the 3 principal directions of the permeability tensor, i.e. the directions in which the tensor is diagonal. K_1, K_2 and K_3 are the values on the principal diagonal.

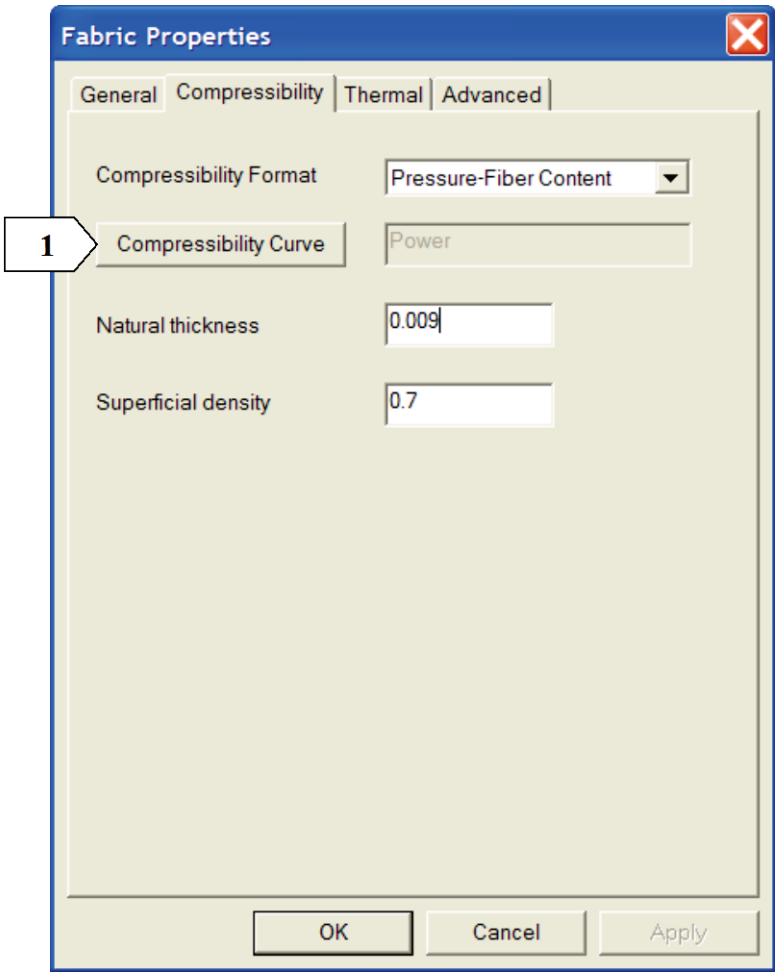
The in-plane principal permeability components K_1, K_2 and through-thickness permeability K_3 are most of the time specified as constant values for a given fiber volume fraction (v_f). They can also be specified as functions of v_f. It is important for VARI simulation to specify permeability as a function of v_f.

The models available for permeability as a function of v_f, which can be selected through the *function editor* **[1]**, are:

- Exponential: $f(x) = A \cdot \exp(B \cdot x)$
- Power: $f(x) = A \cdot x^B$
- Piecewise linear
- Kriged (interpolation of experimental data points)
- User defined

Compressibility Tab

The parameters in this tab are currently only used for VARI simulation.



Compressibility format

The format of the compressibility curve, which can be specified as one of the following:

- Pressure as a function of fiber content (v_f),

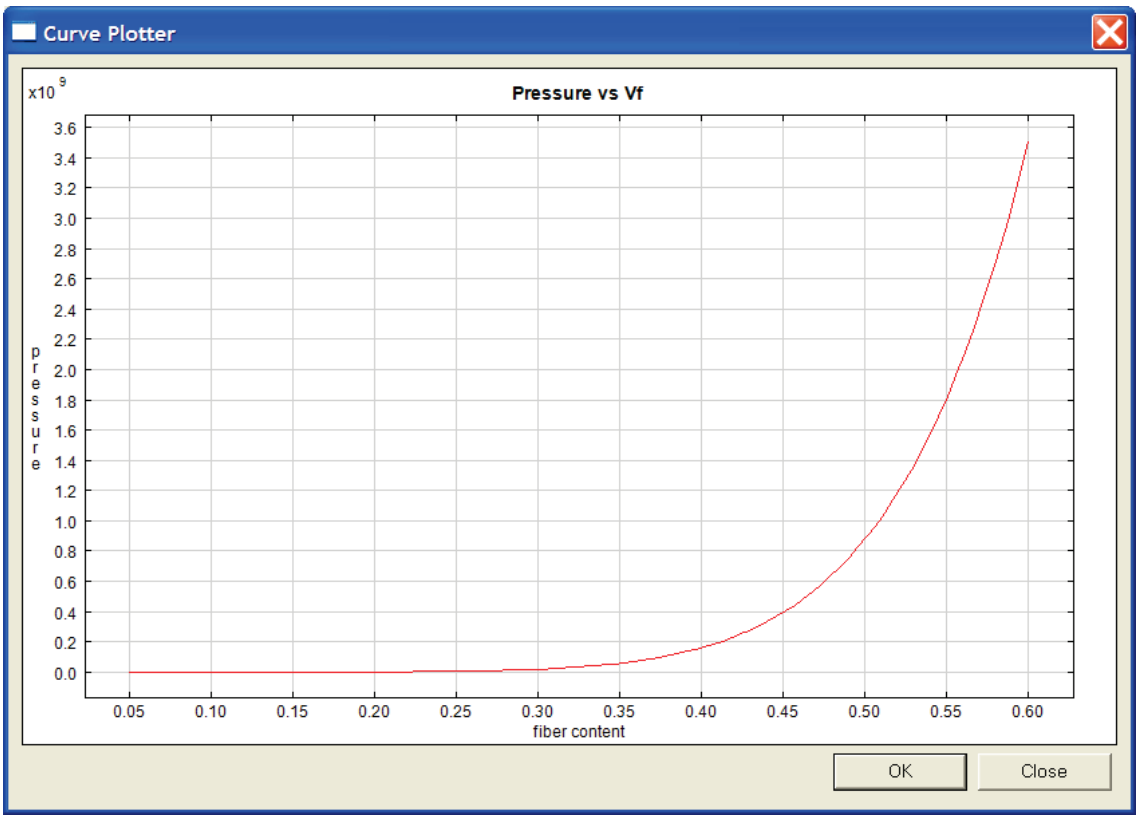
- Stress as a function of strain. Strain is defined between -1 and 0. Zero strain corresponds to natural thickness.

Compressibility curve

Here is the list of functions that can be selected in the function editor, opened by pushing the **Compressibility Curve** button **[1]**:

- Power: $f(x) = A \cdot x^B$
- Piecewise linear
- Kriged (interpolation of experimental data points)
- User defined

Here is an example of a compressibility curve specified as Pressure-V_f. A power law is used with $A = 1.7E+11$ and $B = 7.6$.



Natural thickness

Unit: m

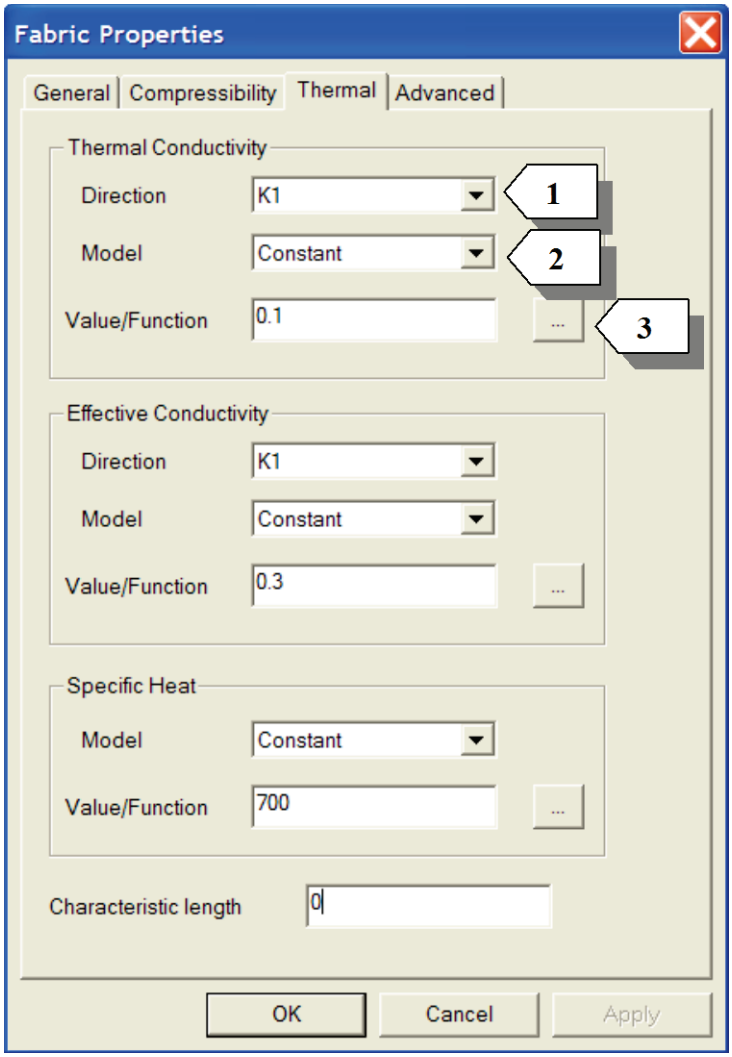
This is the thickness of the reinforcement at ambient pressure.

Superficial density

Unit: Kg/m^2

The superficial density of a single layer of reinforcement or a ply.

Thermal Tab



Thermal conductivity K_1, K_2, K_3

Unit: W/m.K

This is the thermal conductivity of the "solid" fiber material, as if the reinforcement had a fiber volume fraction of 100%. For example for a glass fiber reinforcement, the thermal conductivity of pure glass would be specified. It is only used in the dry area. In the wet area the effective conductivity is used (see below). It can be specified as orthotropic, in which case principal directions need to be set.

Use the **Direction** dropdown list **[1]** to set the current direction (K_1, K_2 or K_3), then choose the **Model [2]** which can be *constant* or *f(temperature)*. If *f(temperature)* is specified, use the function editor **[3]** to define the conductivity curves. A different curve can be assigned to K_1, K_2 and K_3.

Note

- *The principal directions of the permeability and conductivity tensor are assumed to be the same. It is not possible in the current version of **PAM-RTM™** to specify different directions for permeability and conductivity.*
- *When using the old solver, the thermal conductivity values have to be multiplied by porosity.*

Effective conductivity K_1, K_2, K_3

Unit: W/m.K

This is the conductivity of the mixture of resin and fibers that **PAM-RTM™** uses in the saturated region. In general the user could use the rule of mixture ($k_{eff} = v_f.k_f + (1-v_f).k_r$) to calculate the effective conductivity, but in some cases a modified value could be used to take into account thermal dispersion for instance.

The effective conductivity can be specified orthotropic. It can be modeled as *constant*, *f(temperature)* or *f(temperature, alpha)*.

Note

- *When using the parallel solver, if effective conductivity f(temperature, alpha) is needed, it has to be specified with a user_dll function (i.e. C-language code written by the user). See tutorial User Defined Functions.*

Specific heat

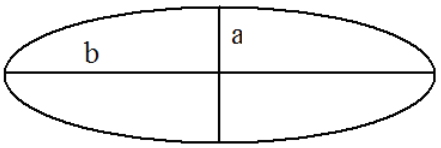
Unit: J/Kg.K

The specific heat of the "solid" fiber material, i.e. 100% fiber volume fraction.

Characteristic length

Unit: m

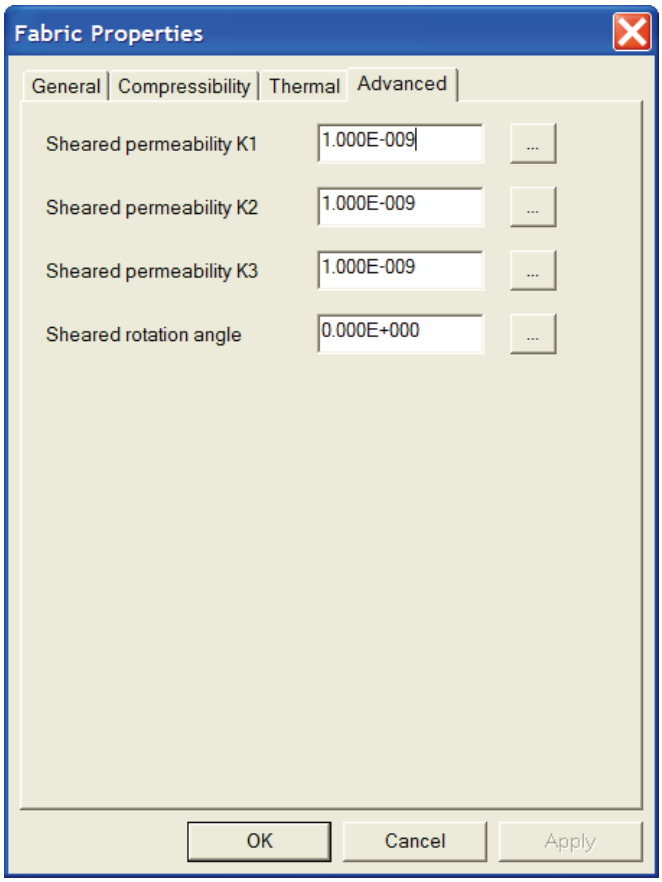
The characteristic length is referred to as the characteristic scale of the elliptical shape of a compressed fiber tow



in which case it is given by $l = \sqrt{a\,b}$. This parameter is used in the context of thermal dispersion modeling. It doesn't have any effect in the calculation if **use thermal dispersion** in the advanced numerical parameters is not checked. Please see the introduction chapter of this user's manual for details on thermal dispersion modeling.

Advanced Tab (Fabrics)

The parameters in this tab are currently only used in the context of a local permeability calculation taking into account fiber directions of a draped fabric. See **Mesh->Compute Local Permeability**.



Sheared permeability K_1, K_2, K_3

Unit: m^2

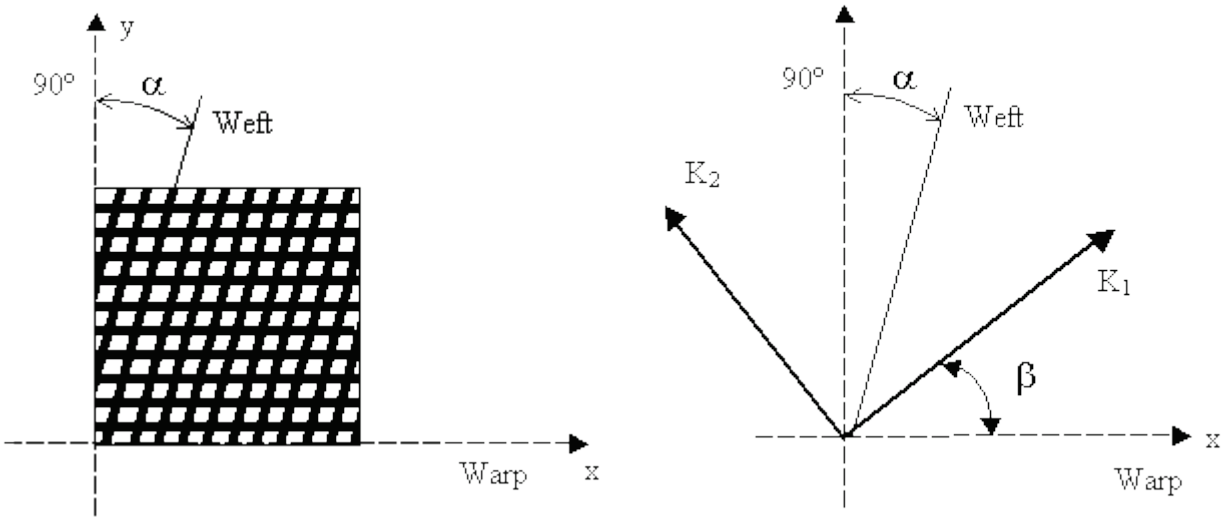
Allows the specification of permeability as a function of the shearing angle and initial fiber content.

Sheared rotation angle

Unit: angle (degree)

Allows the specification of the rotation angle of the K_1 principal permeability direction relative to the weft as a function of the shearing angle and initial fiber content.

The following pictures explain the rotation of the principal permeability directions when a fabric is sheared by an angle α relative to the weft. The principal direction K_1 is rotated by an angle β relative to the warp.



Draping Tab

The parameters in this tab are currently only used in the context of a PAM-QUIKFORM simulation.

Fabric

Locking angle

Unit: degree.

This is the maximum shearing of the fabric before wrinkles occur. PAM-QUIKFORM will stop calculation in areas where the locking angle is reached. Default value is 90 degrees. Validity range is between zero and 90 degrees.

Unidirectional

Grid stretch

Unit: no unit, percentage.

In areas of high curvature, the PAM-QUIKFORM UD algorithm can increase the distance between fibers (parameter *grid size u* in the PAM-QUIKFORM numerical parameters), up to the *grid stretch* percentage, in order to respect the *grid shear* criteria below. Default value: 200 %.

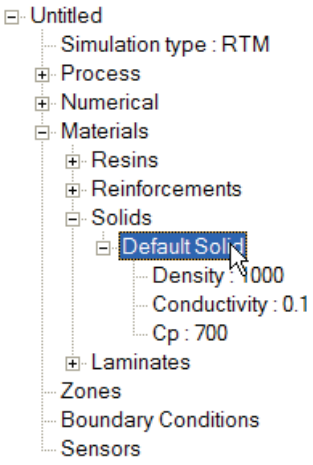
Grid shear

Unit: degree.

Maximum allowable shear angle of the unidirectional.

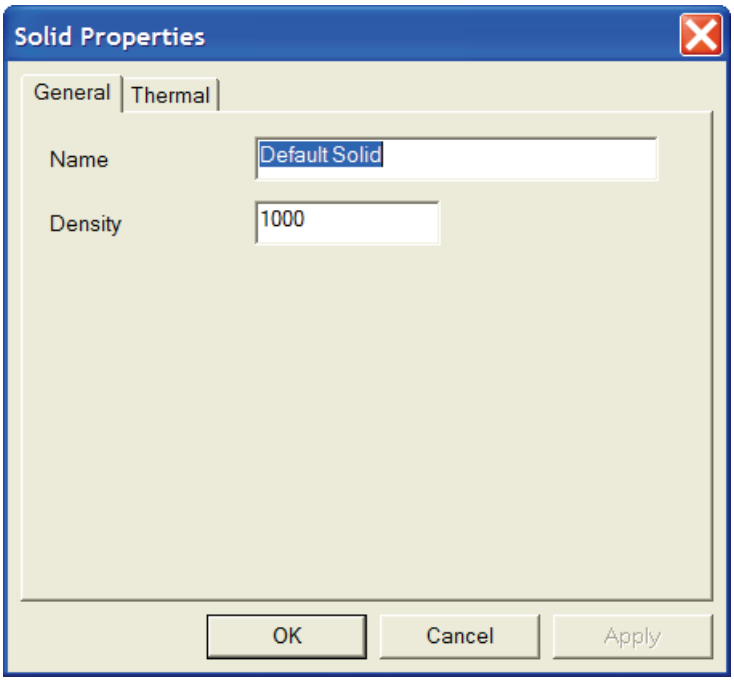
MATERIAL PROPERTIES OF SOLIDS

The material called *solid* in **PAM-RTM™** should be used to specify any non-permeable material such as foam or metallic inserts.



The **Solid Properties** dialog box is opened by double-clicking a "solid" in the model explorer.

General Tab



Name

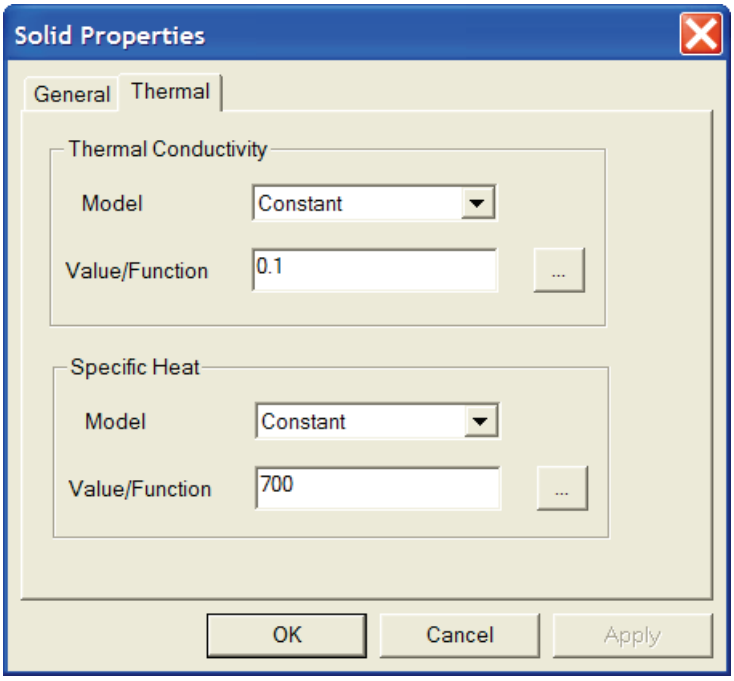
Enter a text description to fully identify the material.

Density

Unit: kg/m^3

Density of the material.

Thermal Tab



Thermal Conductivity

Unit: W/m.K

Can be specified as constant or function of temperature.

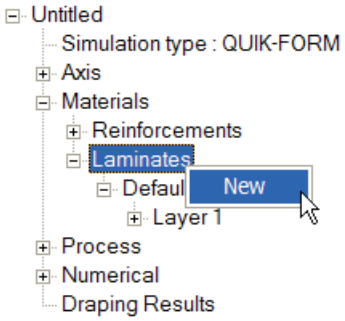
Specific Heat

Unit: J/Kg.K

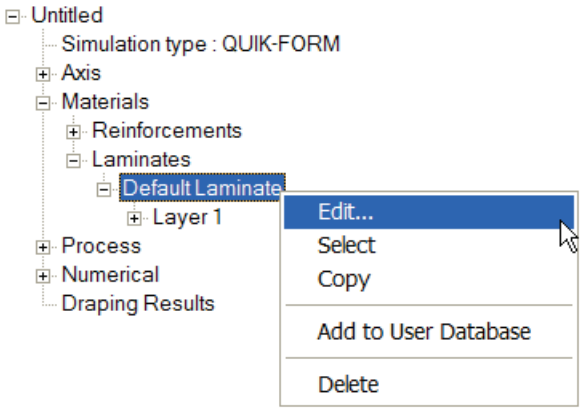
Constant or function of temperature.

LAMINATES

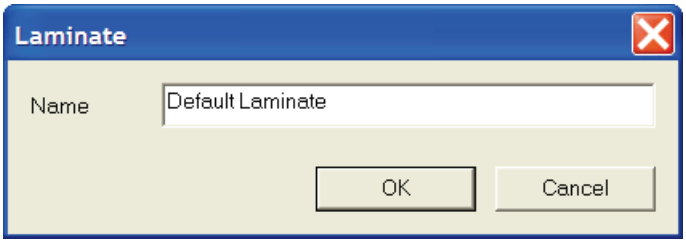
Laminate materials are made of layers of fiber reinforcements or solids. Currently laminates are used in **PAM-RTM™** in the context of a **PAM--QUIKFORM™** simulation, and also in the context of local permeability calculation, to link reinforcements to imported draped plies.

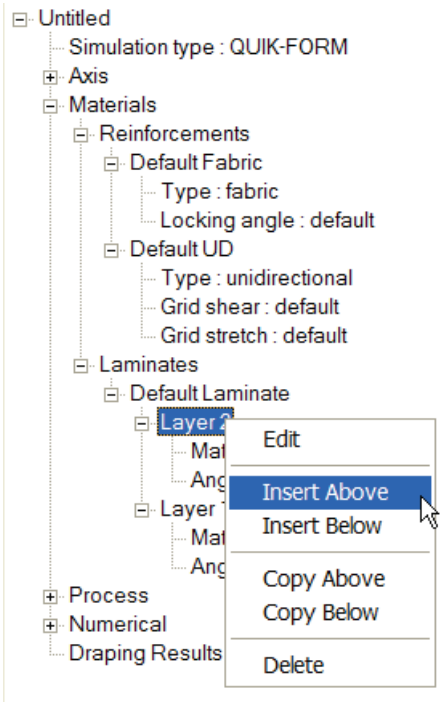


A new laminate is created by right-clicking the *Laminates* item in the explorer, and choosing the *New* command.



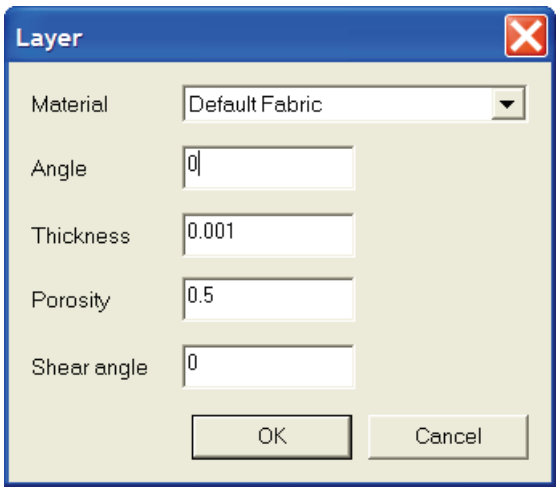
Right-clicking a laminate's top level item gives access to the popup menu common to all materials. The *Edit* command pops up a dialog box, which currently only allows modification of the material name.





It is possible to insert, copy, delete layers by right-clicking one layer in the explorer.

Editing a layer opens the following dialog box, used to associate a reinforcement or solid to this layer.



Material

Choose the material to link to this layer from the roll-down list. All currently defined reinforcements and solids are listed.

Angle

Unit: degree

Angle of the layer in the laminate referential (α in the figure below).

Thickness

Unit: meters

Thickness of the layer.

Porosity

Unit: no unit, percentage expressed as a value between zero and one.

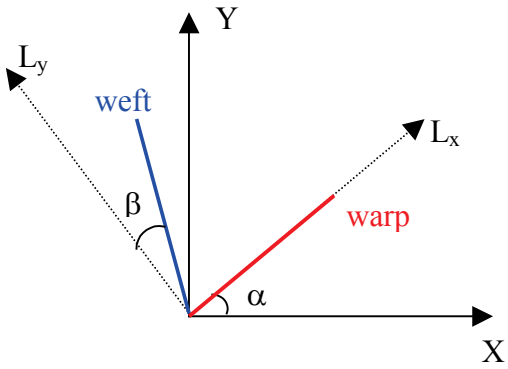
Initial porosity of the layer (before shearing in case of fabrics).

Shear Angle

Unit: degree

Initial shearing of the layer (fabrics only, β in the figure below).

In the following figure a layer's referential (L_x-L_y) was rotated by an angle α relative to the laminate's referential (X-Y). The layer's x axis defines the warp direction of a fabric, and the layer's y axis is the weft direction. A non-zero initial shear angle β was specified.



MATERIAL DATABASE

The user can create his own material database with the materials he/she uses most often.

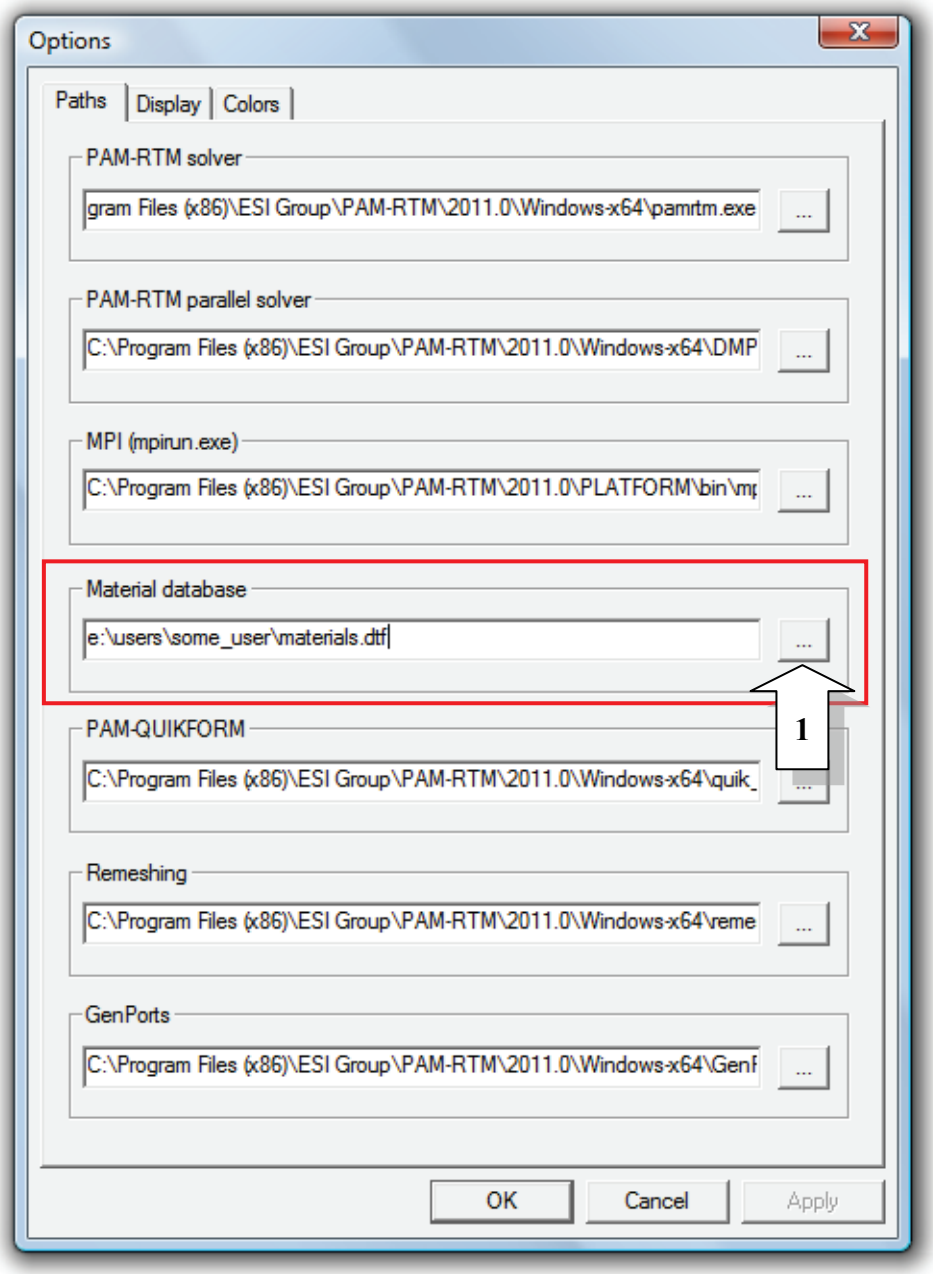
Creation of the Material Database

This is the procedure to create the material database the first time **PAM-RTM™** is run.

The path to the material database has to be specified in the **Paths** tab of the **Options** dialog box (**View->Options**). Before the path is explicitly set by the user, it is blank in the **Options** dialog.

To set the path, the user pushes the browse button (see **[1]** in image below) which opens the standard Windows file browser. Then the user is asked to select an existing `.dtf` file. Since the first time the software is used that `.dtf` file doesn't exist, the user has to create first an empty `.dtf` file with a text editor. That file could be named for example `materials.dtf`. Note that the material database is actually a subset of the **PAM-RTM™** input file, so it has the same extension `.dtf`.

The path to the material database is a *current user* setting, which means that all **PAM-RTM™** users working on the same computer have to set it. If many users need to share the same material database, the `materials.dtf` file could be placed in a directory where all users have read and write permissions.

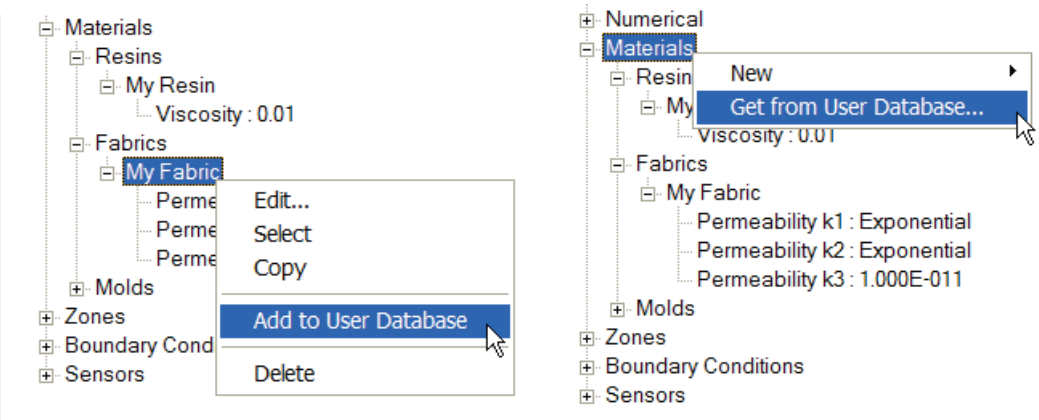


Paths tab of the Options dialog box

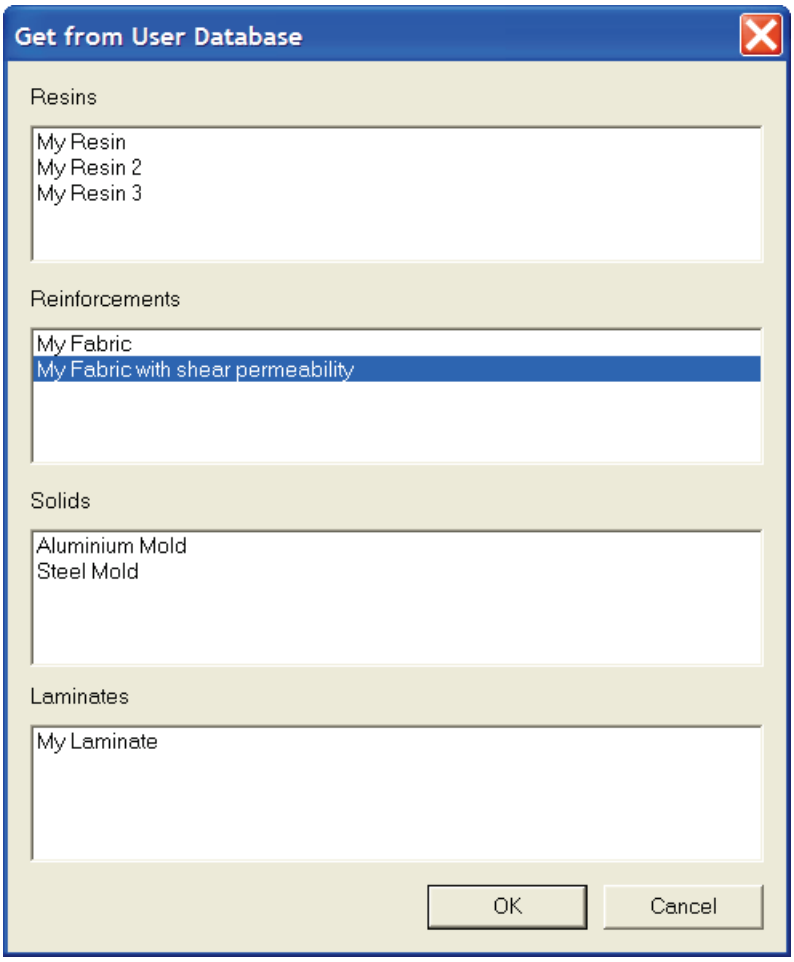
Using the Material Database

Once the initial empty `materials.dtf` file has been created and the path set, you can start building the database. First completely define your material with the **Reinforcement**, **Resin** or **Solid** editors of **PAM-RTM™**. Once you are satisfied with the

material definition, right-click the material in the explorer and choose *Add to User Database*.



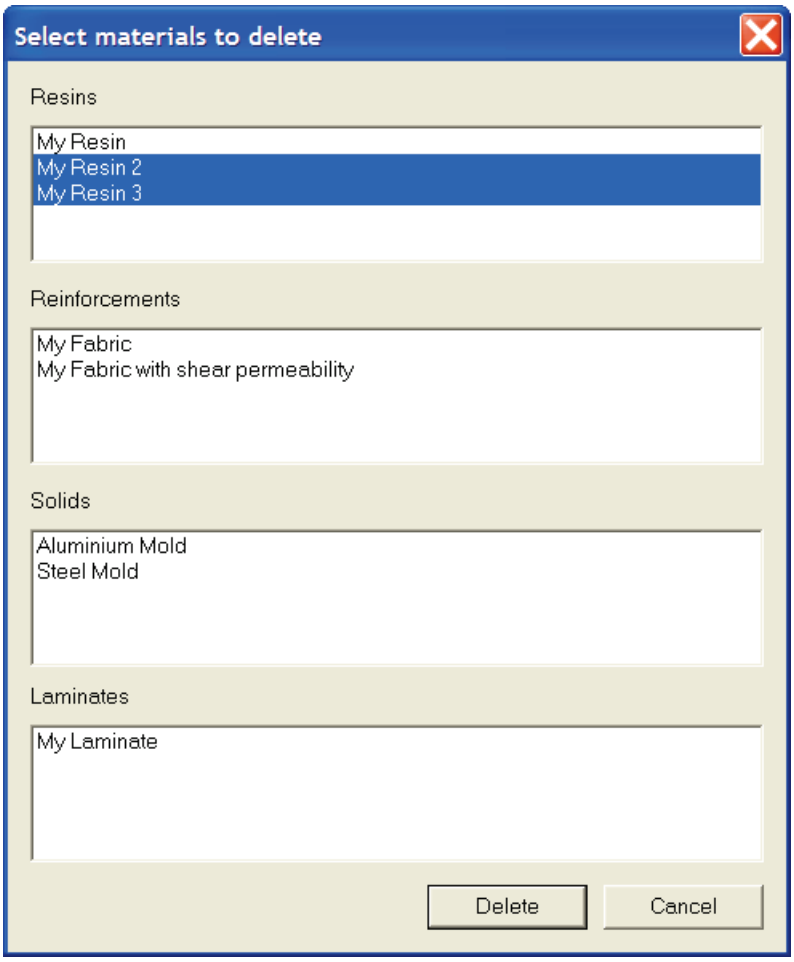
Later if you want to reuse the same material in another simulation, you can retrieve materials from the database by right-clicking the **Materials** item in the explorer and choosing *Get from User Database*. This opens the following dialog box, which lists all the materials available in the database. Choose one or more materials you want to copy in your current model. If there is a material with the same name in the current document, **PAM-RTM™** asks for a confirmation that you want to replace it with the version stored in the material database. It is important to understand that when retrieving a laminate from the material database, **PAM-RTM™** retrieves also all the materials used in the definition of the laminate.



Get from User Database dialog

If you need to make some changes to one of the materials of the database, you have to retrieve it first from the database into the current model. Then edit the material and send it back to the database with *Add to User Database*. If you didn't modify the material name, **PAM-RTM™** detects that a material with the same name already exists in the database and asks if you want to replace it. Answer *Yes*.

The command **Simulation->Manage User Database** opens the following dialog box, which is actually almost the same as the previous one, except that there is a **Delete** button that allows the user to remove the unwanted materials from the database. This is the only database management functionality currently available.

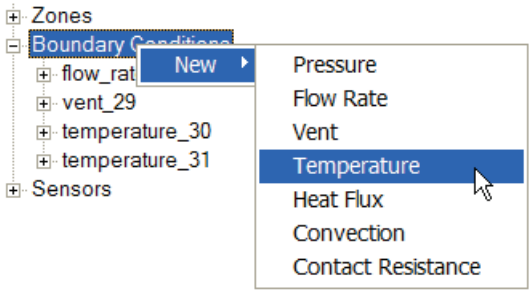


Manage User Database dialog

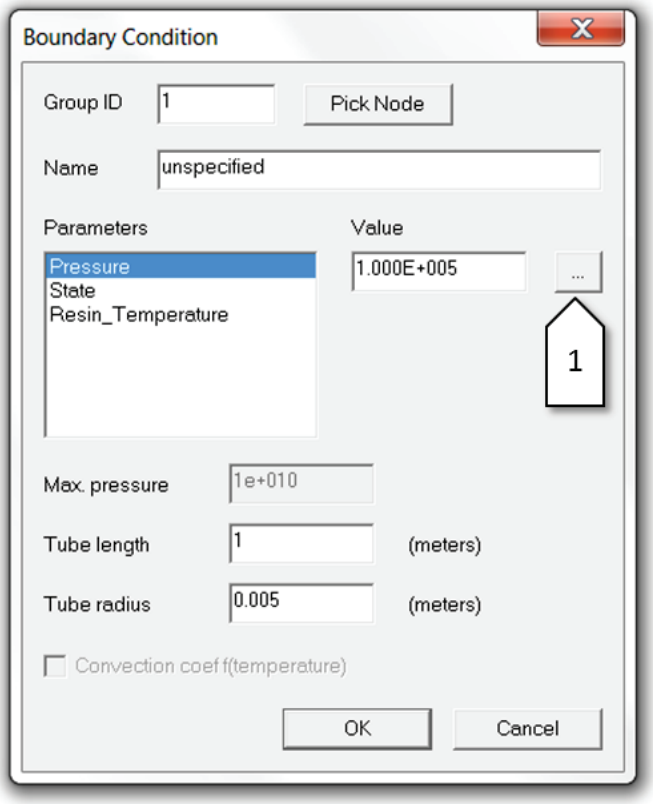
BOUNDARY CONDITIONS

Boundary conditions in **PAM-RTM™** are associated to groups of nodes or groups of faces as their geometrical support. So the first step is to create a group to define where a boundary condition is applied, then create the actual boundary condition which refers to the group through its ID.

To create a boundary condition, right-click the **Boundary Conditions** item in the model explorer. The types of boundary conditions that can be created depend on the simulation type.



The newly created boundary condition is not assigned to any group. Double-click the new boundary condition in the explorer to set its parameters. This opens the **Boundary Condition** dialog box.



The first parameter to specify is the group ID to which this boundary condition refers. If there are many groups, it can be difficult to identify a group with the color bars, so simply push the **Pick Node** button and pick a node that belongs to the group.

The **Parameters** area contains the list of parameters associated to this boundary condition. For instance, all the boundary conditions have a *State* parameter which allows to activate or deactivate the boundary conditions as a function of time. To use the state parameter, simply create a piecewise linear curve. When the value is >= 0.5 the boundary condition is active, otherwise it is disabled.

Actually all the parameters of boundary conditions are functions of time. For example, the *Flow Rate* boundary condition contains three parameters: *flow_rate*, *resin_temperature* and *state*. All three parameters can be functions of time. Use the ... button to open the function editor **[1]**.

The only exception is the convection coefficient, which is by default a function of time, but can be made a function of temperature if the **convection coef f(temperature)** option is checked at the bottom of the dialog box. This check box is only available when a convection boundary condition is edited.

Here's a list of all boundary conditions with the simulation types that support them.

- **Pressure**
  - Description: pressure controlled inlet.
  - Simulations: RTM, VARI, Heated RTM.
  - Parameters:
    - *Pressure*. Inlet pressure. Unit: Pa.
    - *Resin_Temperature.* Resin temperature when it enters the cavity. This parameter is used most of the time for *Heated RTM* simulations, but it makes sense to use it also for isothermal simulations, for example to have **PAM-RTM™** calculate the viscosity from a viscosity curve. Unit: degree Kelvin.
    - *State*
    - *Tube length.* The length of the tube between the pressurized resin pot and the mold. Only used when the Poiseuille correction is activated in the advanced numerical parameters. Unit: m.
    - *Tube radius*. Also only used with the Poiseuille correction. Unit: m.
- **Flow Rate**
  - Description: flow rate controlled inlet.
  - Simulations: RTM, VARI, Heated RTM, Presimulation.
  - Parameters:
    - *Flow_Rate*. Unit: m^3/s .
    - *Resin_Temperature*. Unit: Kelvin
    - *State*
    - *Max Pressure*. The flow rate inlet supports a special parameter to specify the maximum pressure that can be reached by the injection machine. This parameter is not a function of time.
- **Vent**
  - Description: resin outlet.
  - Simulations: RTM, VARI, Heated RTM, Presimulation.
  - Parameters:
    - *Pressure*. The pressure on the vent. Unit: Pa.
    - *State.* Useful to "program" a vent opening and closing sequence.
- **Temperature**
  - Description: fixed temperature, i.e. Dirichlet boundary condition in the heat transfer equation.
  - Simulations: Heated RTM, Preheating, Curing.
  - Parameters:

- *Temperature*. Unit: Kelvin.
- *State.*

- **Heat Flux**
  - Description: imposed heat flux, i.e. Neumann boundary condition in the heat transfer equation.
  - Simulations: Heated RTM, Preheating, Curing.
  - Parameters:
    - *Heat_Flux*. $\frac{\partial T}{\partial n} = q$. Unit: W/m^2.
    - *State.*

- **Convection**
  - Description: $\frac{\partial T}{\partial n} = h(T_\infty - T)$
  - Simulations: Heated RTM, Preheating, Curing.
  - *Convection coef f(temperature)*: check to make the convection coefficient a function of temperature instead of time.
  - Parameters:
    - *Reference_Temperature*. T_∞ in the equation above. Unit: Kelvin.
    - *Convection_Coefficient*. *h* coefficient. Unit : W/m^2.K
    - *State.*

- **Contact Resistance**
  - Description: used to model the heat transfer on the interface between two solids in contact.
  - Simulations: Heated RTM, Preheating, Curing.
  - Parameters:
    - *Contact_Resistance*. R_{th} in equation $\varphi = \frac{T_1 - T_2}{R_{th}}$, where T_1 and T_2 are the temperatures on both sides of the interface. Unit: m^{2}W^{-1}K
    - *State.*

- **Thickness**
  - Description: prescribed thickness on the part boundary.
  - Simulations: VARI.
  - Parameters:
    - *Thickness*. Unit: m.
    - *State.*

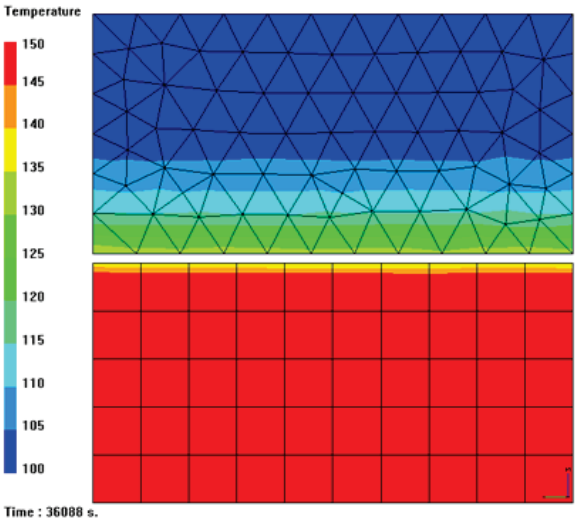
- **Compression**
  - Description: used in the context of Compression RTM simulation, to specify the upper mold closing velocity and the compression direction.
  - Simulations: Compression RTM.
  - Parameters:
    - *Velocity_Norm*. The upper mold closing velocity. Unit: m/s.
    - *Final_Thickness*. The targeted final thickness of the part. This is only used as a hint for the Compression RTM simulation to determine the time step, it is not a stopping criteria. Unit: m.
    - *Dir_x, Dir_y, Dir_z*. The components of the direction vector for compression. If the direction to be used is normal to each element, the three components must be set to zero. Unit: none.
    - *State.*

Notes:

- **Max pressure** *only applies to flow rate inlets.*
- **Tube length** *and* **tube radius** *only apply to pressure inlets.*
- **Convection coef f(temperature)** *only applies to convection boundary conditions.*

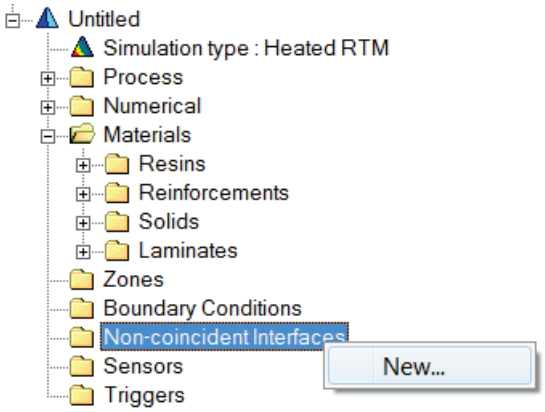
NON-COINCIDENT INTERFACES

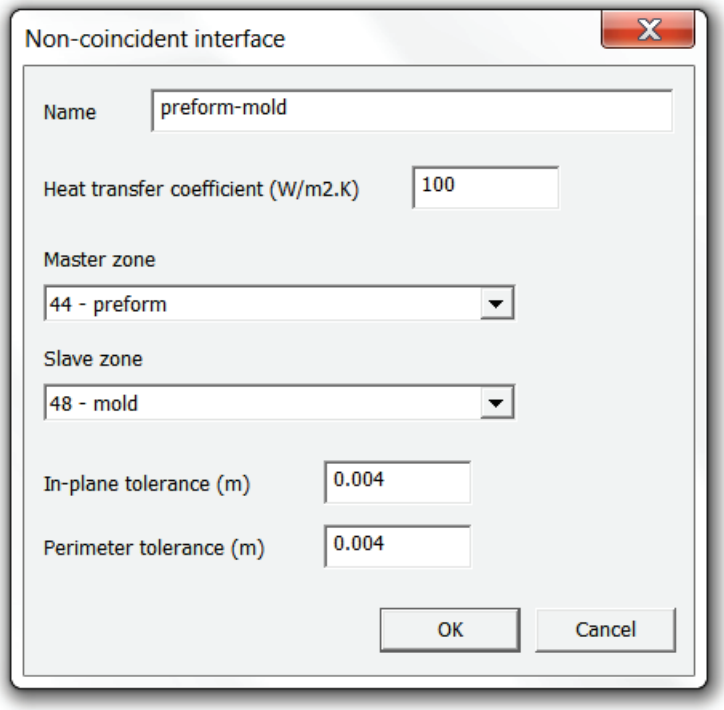
Non-coincident interfaces allow disconnected meshes to be used for thermal calculations. Typically they allow different meshing parameters to be used for the preform area and the mold. For instance the preform could be meshed with tetrahedral, while the mold is meshed with bricks. Also the size of the elements can be different on both sides of the interface. An example is shown below.



A folder **non-coincident interfaces** is available for thermal calculations (preheating, heated RTM, curing).

To create a non-coincident interface, right-click on the **non-coincident interfaces** item, then **New**, which opens the non-coincident interface dialog box.





The main parameters to specify are the two zone IDs involved in the interface. In general the master zone is the preform, and the slave zone is the mold. The **master zone** and **slave zone** dropdown lists allow selection of one of the zones currently defined in the model. It is recommended to assign meaningful names to zones before defining interfaces, to make that selection easier.

The **heat transfer coefficient** is a parameter specific to each interface, meaning it is possible to have in the same model many interfaces with different heat transfer coefficients.

The **in-plane tolerance** corresponds to the maximum distance around an element of the master surface where a node of the slave surface can be found.

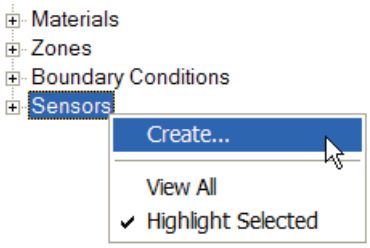
The **perimeter tolerance** corresponds to the maximum distance between the two surfaces in order to have a contact (distance normal to the plane of the interface).

In general, a good tolerance value should be about half the size of the elements on the preform side, and it is recommended to use the same value for in-plane and perimeter tolerances. However if the mesh has a quite heterogeneous mesh size, these tolerances may be too small (and thus, there will be "no contact", and thus no heat transfer at these non-coincident interfaces). If such a case occurs, one can change (i.e. increase) these tolerances. One should however be careful not to use too large tolerances so that nodes beyond the opposite surface would be taken into account.

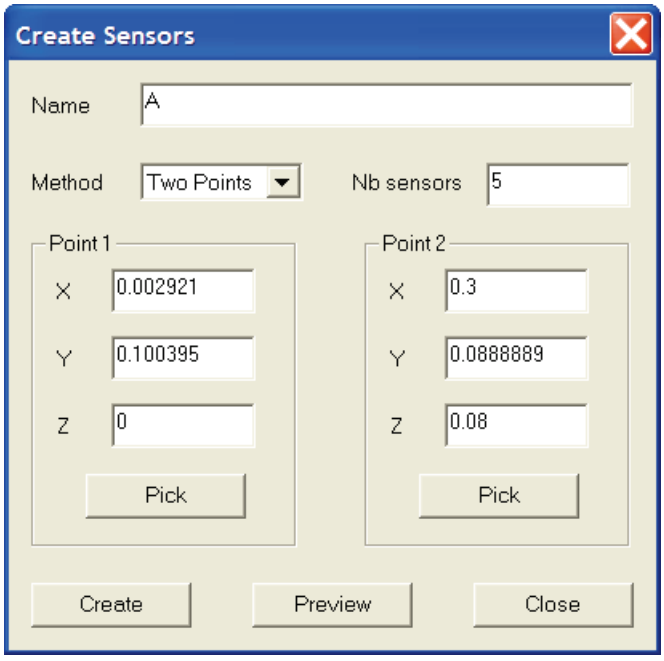
SENSORS

Creating Sensors

Sensors are used in **PAM-RTM™** to sample results on specific points in order to plot curves.



To create sensors, open the **Create Sensors** dialog box, either by right-clicking the **Sensors** item in the explorer, or by using the **Simulation->Create Sensors** command, which pops up the following dialog box.



First give a *name* to the sensor, so you can identify it easily. However try to give a short name because this name will be used in the graph legend when results are plotted.

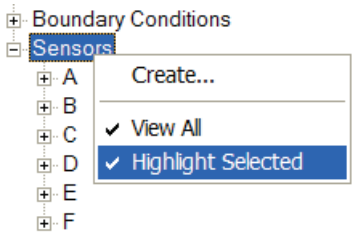
There are two methods to create sensors: *one point* and *two points*. With the *one point* method, the user either enters the coordinates of the sensor directly, or pushes the **Pick** button to pick with the mouse an arbitrary point on the mesh. Then the user pushes the **Create** button to actually create the sensor.

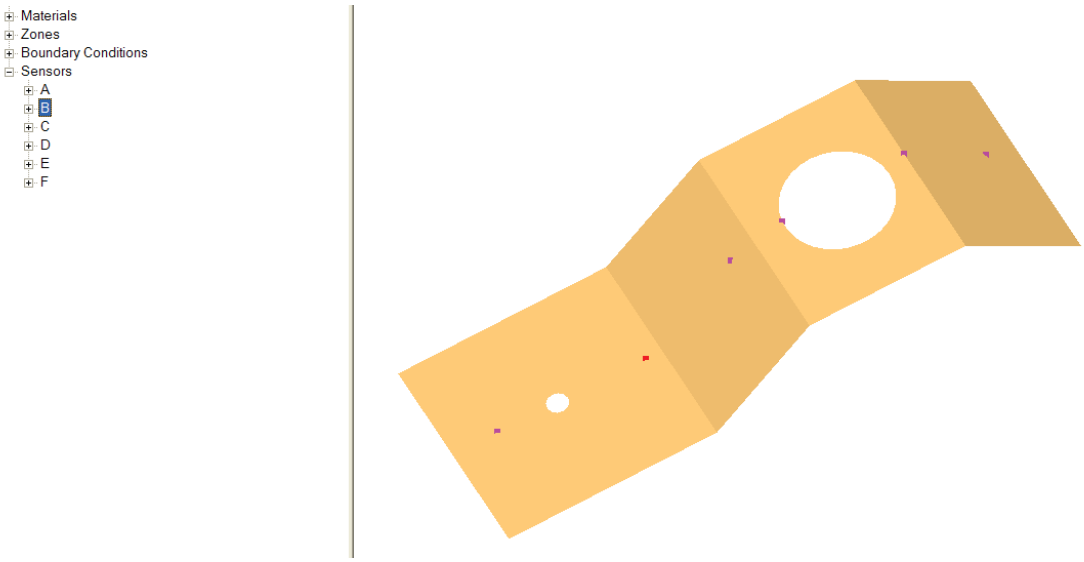
With the *two points* method, the user specifies two points that define the end-points of a line segment. The idea is to have **PAM-RTM™** generate automatically a specified number of sensors on that line. The two end-points can be specified by entering the coordinates or by picking with the mouse. The line segment doesn't have to lie on the surface. In case of curved geometry, **PAM-RTM™** projects the sensors on the surface.

A **Preview** button is available to visualize the approximate position of the sensors, before they are projected.

When the *two points* method is used, the name of the sensor is used as a root name, and a number is automatically added to this name. For example, if the user specifies the name as *s* and 3 sensors are created, they will be called *s_1*, *s_2*, *s_3*. The names can be modified later.

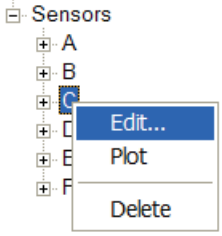
As shown below, the created sensors are listed in the explorer under the **Sensors** item. Selecting a sensor in the explorer highlights it in the graphics window. This behavior is controlled by the **Highlight Selected** command available in the popup menu on the **Sensors** item. It is also possible with the **View All** command to turn on or off the visualization of all sensors in the graphics window.



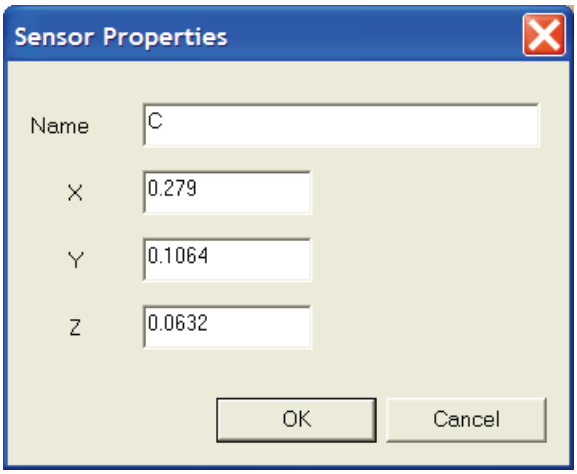


Editing Sensors

Once they have been created, it is possible to modify attributes of a sensor by double-clicking it in the explorer, or by using the menu that pops up when a sensor is right-clicked in the explorer.



The edit command opens the **Sensor Properties** dialog box.



With this dialog box the user can change the name of the sensor and its coordinates.

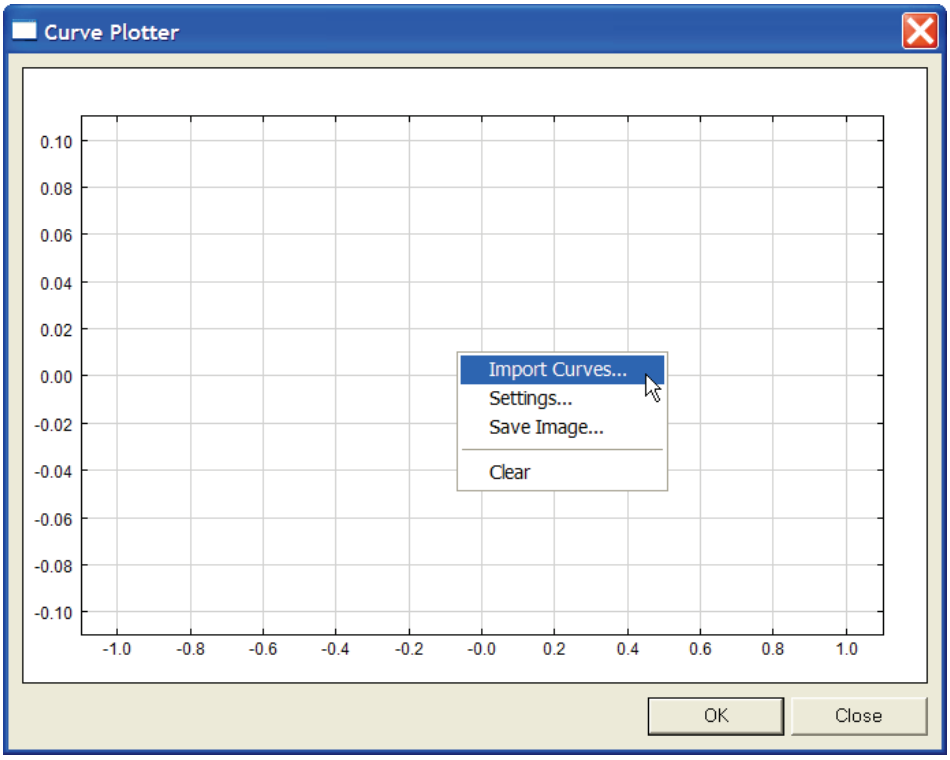
A sensor can be deleted by selecting it in the explorer and by choosing **Delete** in its popup menu.

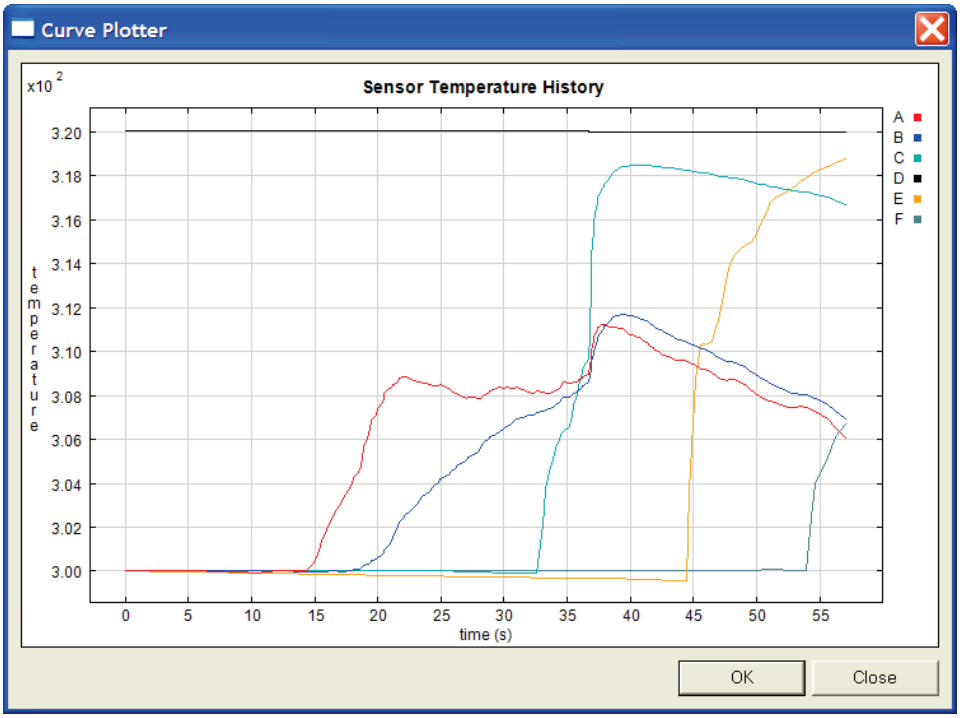
Plotting sensors

There are two ways to plot curves on sensors. The simplest one is by using the **Plot** command available in the sensor popup menu. This command samples the currently visualized scalar field on the sensor position, then opens the curve viewer and adds a new curve to it. So to use this command, activate first visualization of a scalar field such as pressure or temperature.

Another way is to open first the curve viewer with **View->Curve Viewer**. Then use the **Import Curves** command of the curve viewer popup menu, available by right-clicking in the curve viewer graphics window, as shown below. Select one of the sensor results files generated by the solver (for example `x_Temperature_Filling_Sensors.dat`). This loads all the curves available in the file in the curve viewer.

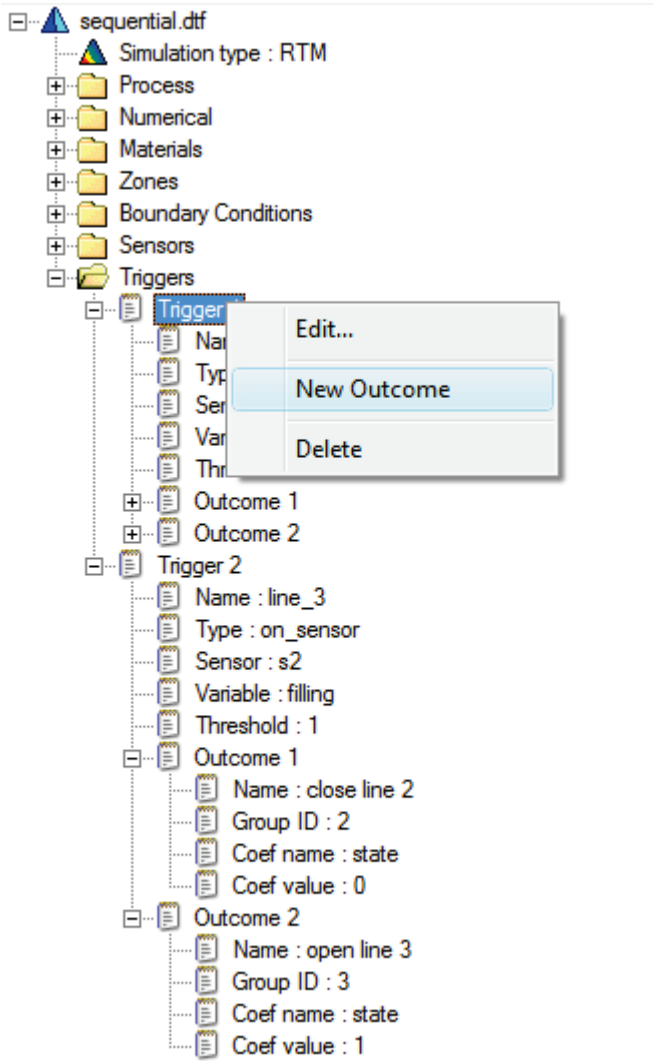
While the first approach is more convenient because you don't have to import a file in the curve viewer, the second approach is more accurate. This is because with the first approach, the number of values plotted depend on the *sampling period* parameter, while in sensor results files all the time steps are saved.





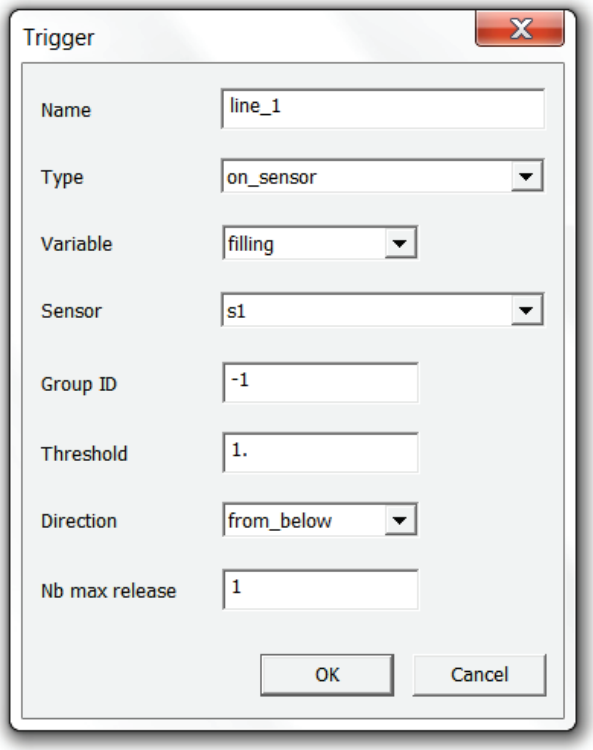
TRIGGER MANAGER

The *trigger manager* is a module allowing easier control of opening and closing of injection ports and vents. The user defines *triggers* and *outcomes*. A trigger specifies a condition such as "filling factor on sensor *x* equals 1", actually meaning "the resin has reached sensor *x*". Associated to a trigger is a list of outcomes, i.e. events that are generated when the condition is met. For instance, an outcome could be "set the state coefficient of injection port *y* to 1", actually meaning "open injection port *y*". This allows easy definition of sequential injection used for large parts, in which injection ports are successively opened and closed. Running such simulations with earlier versions of **PAM-RTM™** was possible, but required more work as the user had to run many simulations to estimate the time of arrival of the resin on a given point. With the trigger manager a single run is required. Note that many outcomes can be associated to a trigger, such as "closing vent *x*" and "opening injection port *y*". Also conditions on the volume of resin injected or lost are available on triggers, i.e. the user could define conditions such as "when a volume *x* of resin has been lost on vent *y*, close vent *y* and open injection port *z*".



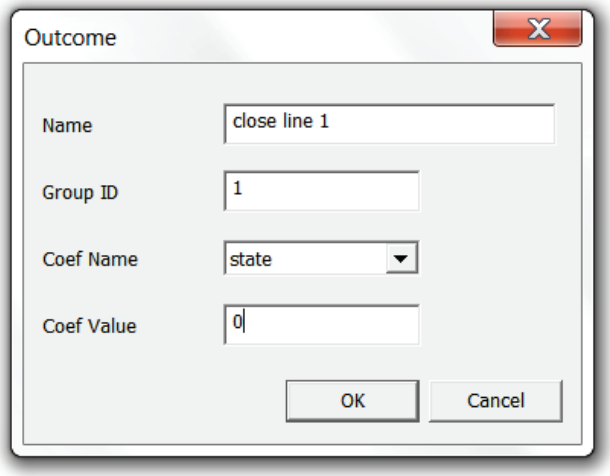
A folder **Triggers** is available in the document's tree. Right-clicking the **Triggers** folder gives access to the **New** command to create triggers. To create outcomes, the user right-clicks a trigger and selects **New Outcome**.

Double-clicking a trigger or an outcome in the document's tree opens a dialog box for edition of the entity. These dialog boxes are described below.



- **Name**: name of the trigger.
- **Type**: the following types are currently supported:
  - **on_sensor:** the trigger is associated to a sensor, which must be selected in the **sensor** combo below.
  - **injected_volume:** the trigger is based on the injected volume for a specific injection port. The injection port ID is specified in the **group ID** field below.
  - **lost_volume:** the trigger is based on the lost volume for a specific vent. The vent ID is specified in the **group ID** field below.
  - **global_injected_volume:** the trigger is based on the injected volume of all the injection ports.
  - **global_lost_volume:** the trigger is based on the lost volume of all the outlets.
- **Variable:** this parameter is only meaningful for **on_sensor** type.
  - **pressure:** the resin pressure is sampled on the sensor.
  - **filling:** the filling factor (value between 0 and 1), is sampled on the sensor.
  - **thickness:** thickness is sampled on the sensor (standard solver only).
  - **temperature:** temperature is sampled on the sensor (parallel solver only).
- **Sensor:** the list of sensors currently defined in the document. Sensors should be created before defining triggers.

- **Group ID:** only meaningful for the **injected_volume** and **lost_volume** types. The ID of the group defining the injection port or vent.
- **Threshold:** the critical value that will fire outcomes. It could be a pressure value or a filling factor value, depending on the **variable** selected. For instance, if **filling** is selected and a value of 1 is entered as **threshold**, it means that outcomes will be fired when the element on which the sensor is located is completely filled. If a pressure value of 10 000 Pa is entered, it means that outcomes will be fired when the resin pressure on the sensor becomes larger than 10 000 Pa.
- **Direction:** indicates if the trigger is to be fired when the threshold is crossed **from_below** (positive slope), **from_above** (negative slope), or **from_all** (every time the threshold is crossed, regardless of the direction).
- **Nb max release:** the maximum number of times that the outcomes can be fired. For instance, if a pressure trigger is defined, it is possible that the pressure will increase above the threshold, which will fire the outcomes a first time, then decrease, and increase again to the threshold, firing the outcomes a second time. To avoid that enter a value of 1 for **nb max release**.



- **Name**: give a meaningful name to the outcome, such as "close line 1".
- **Group ID**: the group (boundary condition) on which the coefficient will be set.
- **Coef name**:
  - **state:** most of the time you will work with the state coefficient, allowing opening (**coef value** = 1) and closing (**coef value** = 0) of inlets and outlets.
  - **pressure:** forces the pressure value on an inlet (standard solver only).
  - **flow_rate:** forces the flow rate on an inlet (standard solver only).
- **Coef value:** the value that will be set on a coefficient as the result of an outcome being fired.

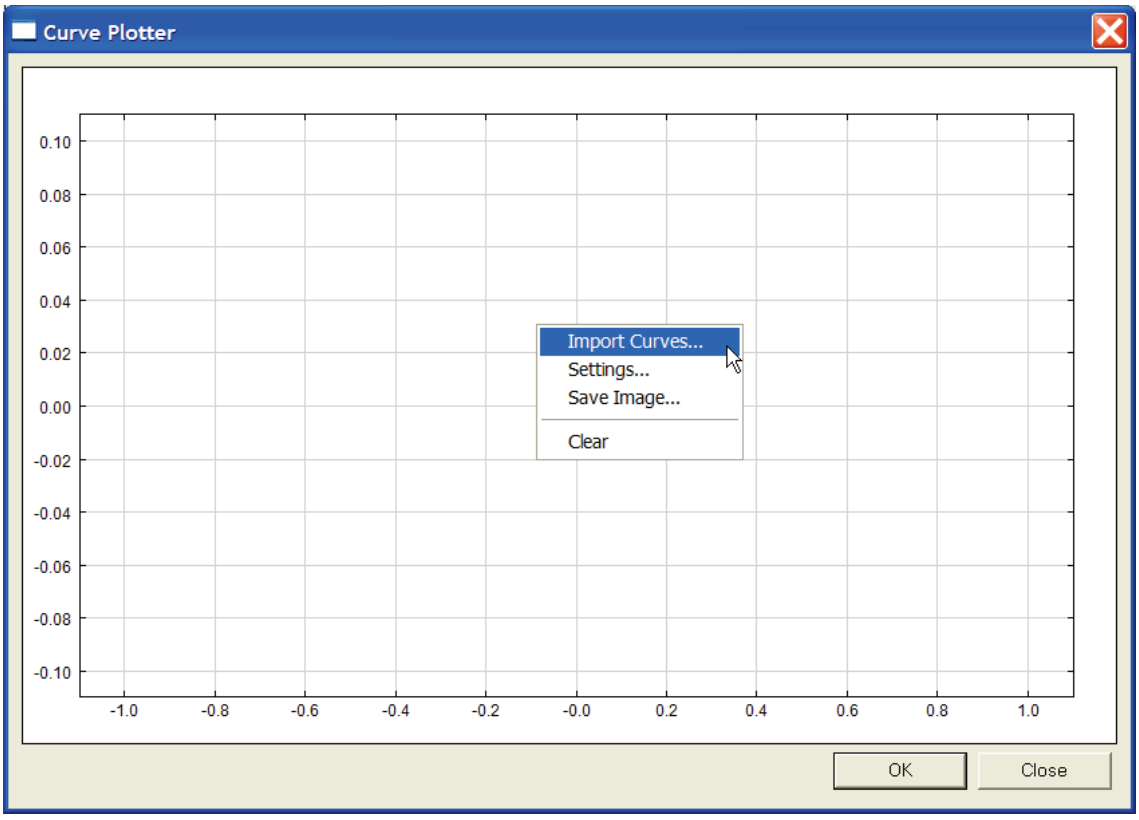
CURVE VIEWER

The curve viewer is used to visualize simulation results on sensors. It is also used to visualize mathematical functions associated to simulation parameters, such as viscosity as a function of temperature, or the reaction rate $\frac{d\alpha}{dt}$ as a function of temperature and degree of cure. Depending on the context, the curve viewer will be used to visualize functions of one or two independent variables.

Importing Curves

The curve viewer is opened with the **View->Curve Viewer** command.

Notice that there is a popup menu available by right-clicking in the graphics area.

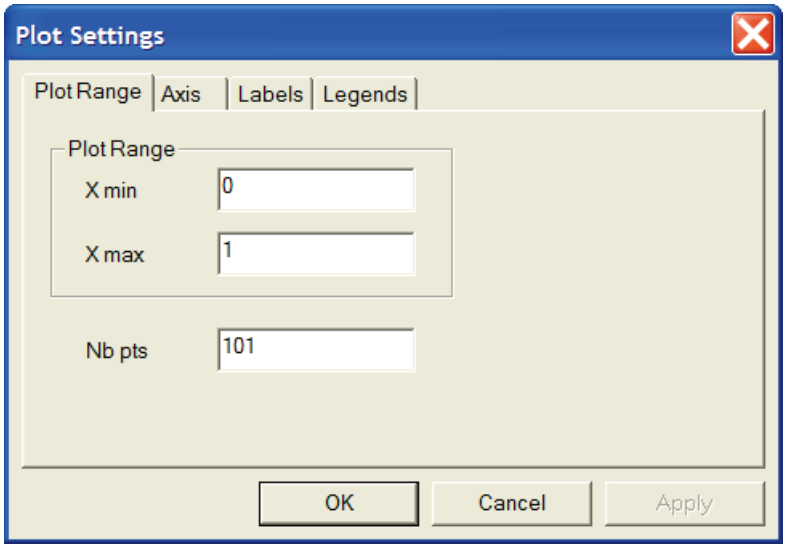


Curve viewer's popup menu

Curves can be imported in the curve viewer with the **Import Curves** command of the popup menu. In general curves imported that way are sensor results files (see section **Sensors**).

Settings

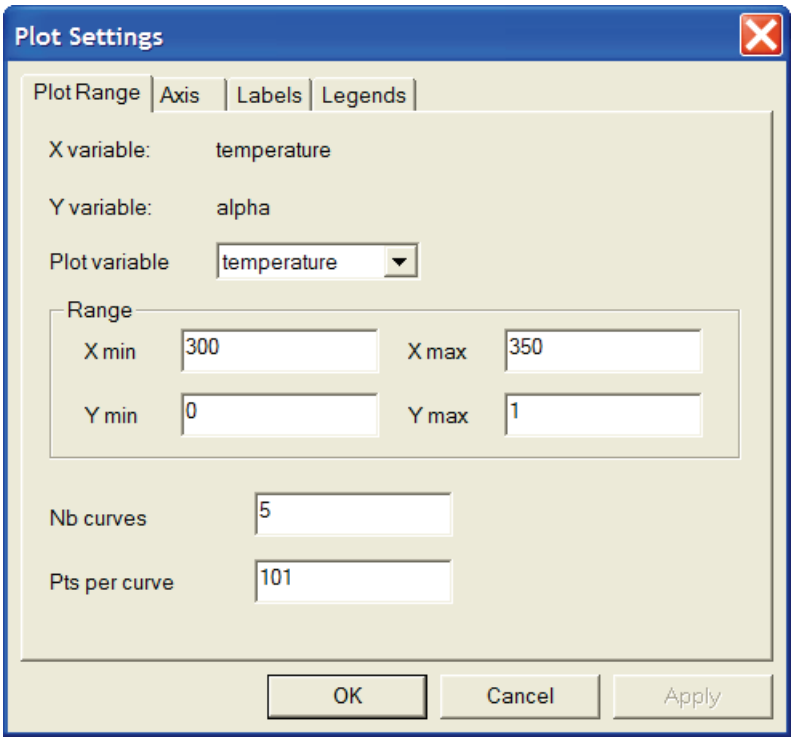
Plot range



Plot range for a function of one variable

The **Plot Range** tab is used to specify the range that the user wants to plot. For example, if the currently visualized function is viscosity with respect to temperature, changing the **X min** and **X max** values means changing the temperature range to visualize. **PAM-RTM™** will re-evaluate the function on **Nb pts** equally spaced in the new range and update the graph accordingly.

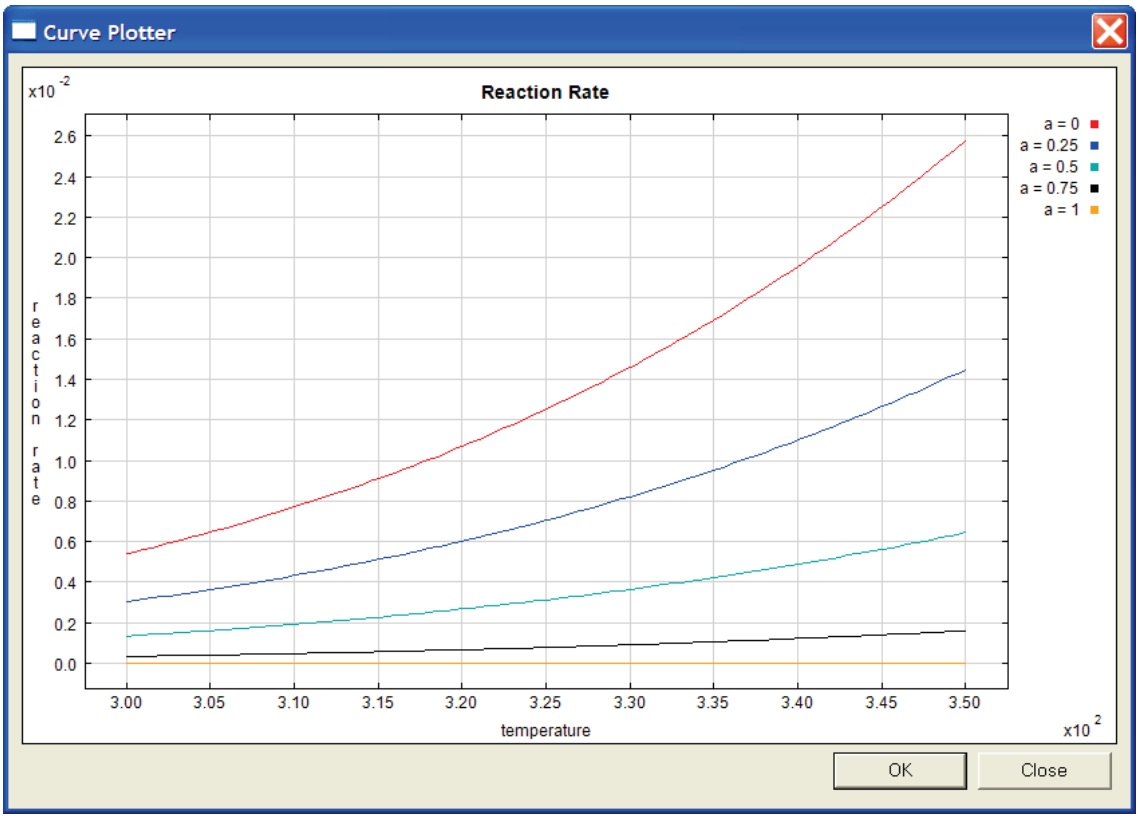
When functions of two variables are visualized, such as the rate of reaction $\frac{d\alpha}{dt}$ with respect to temperature and degree of cure, the **Plot Range** tab has more parameters, as shown below.



Plot range for a function of two variables

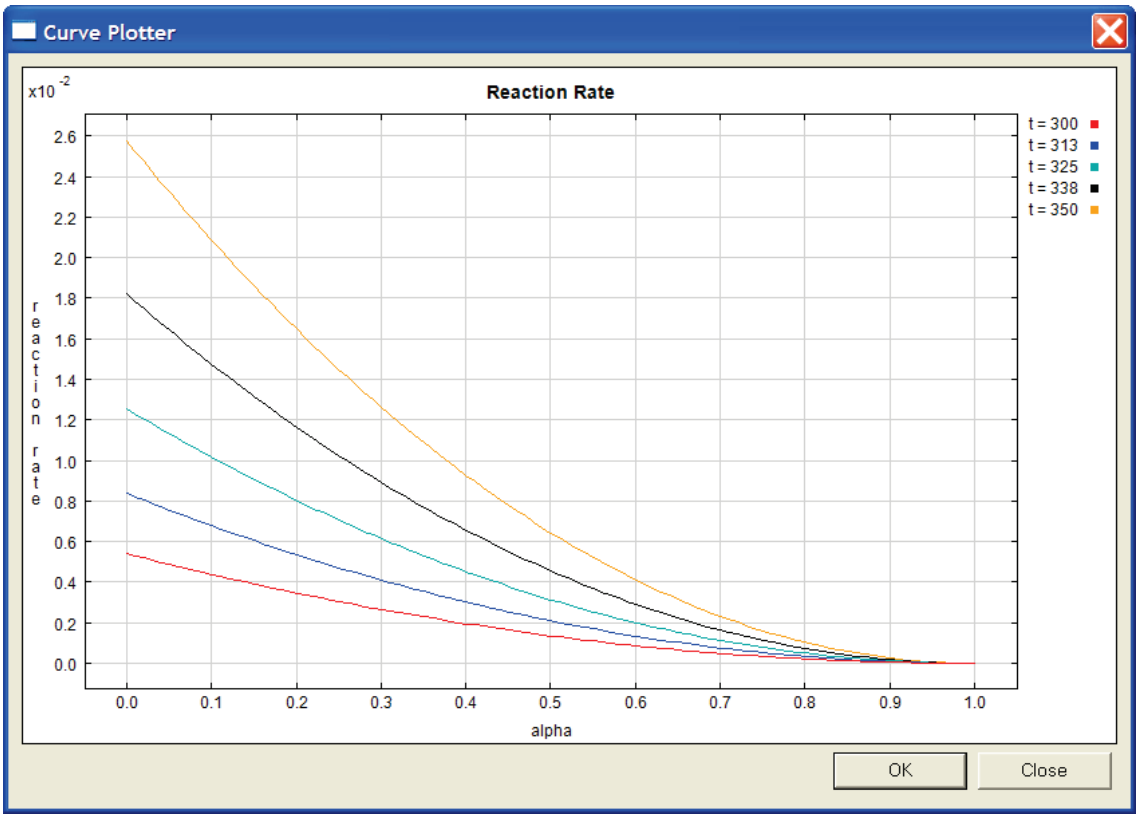
Here we see that the **X variable** is temperature and the **Y variable** is alpha (degree of cure).

The **Plot variable** dropdown list is used to select the variable displayed on the X axis of the graph. In this example, the X axis is temperature, which varies between 300 and 350 Kelvin, and five iso-alpha curves are plotted (see graph below).



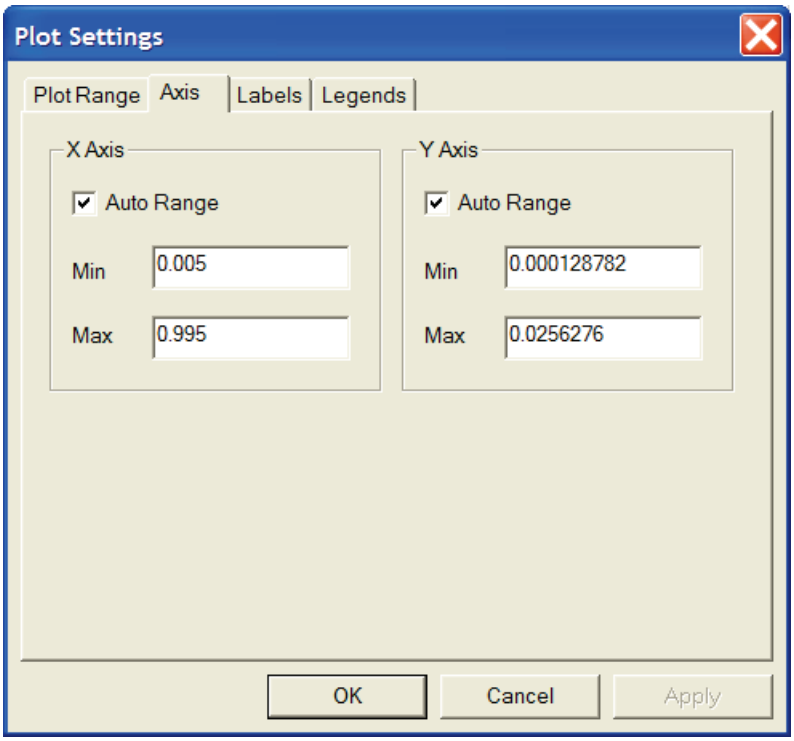
Iso-alpha curves

Changing the **Plot variable** to alpha instead of temperature would lead to the following iso-temperature curves.



Iso-temperature curves

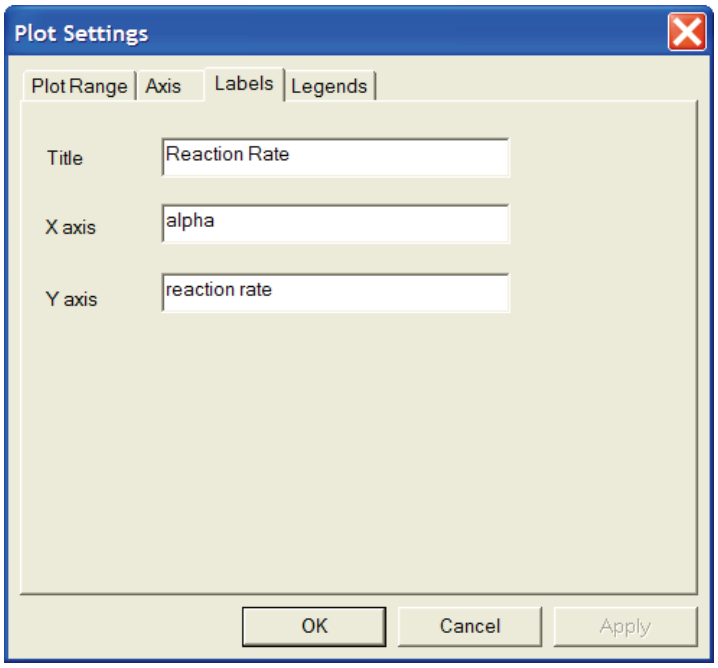
Axis Settings



Axis settings

In general the X and Y axis ranges are automatically calculated from the data points to fit entirely the curves. In some situations the user may want to restrict the view, so the **Auto Range** parameter can be unchecked and a different range specified. Note that this changes only the viewing range, not the plot range, which means that the function is not re-evaluated. If you want to re-evaluate the function on a different range, use the **Plot Range** tab.

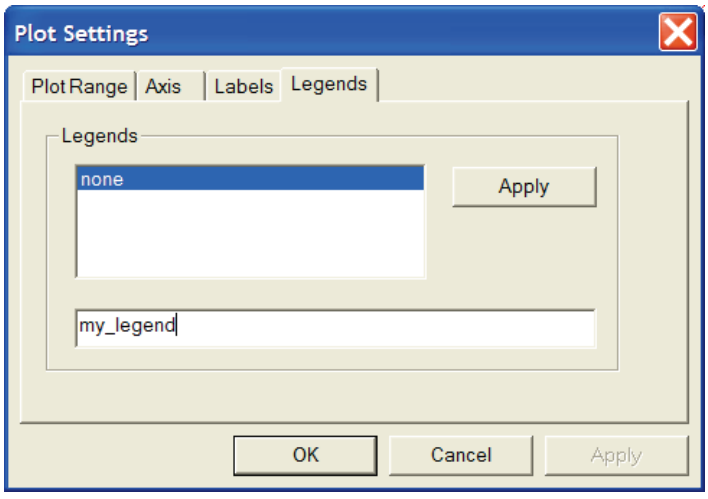
Labels



Labels

Graph title and labels for the X and Y axis are automatically assigned by **PAM-RTM™** depending on the context. If the user doesn't like the default labels, he can modify them with the **Labels** tab. This is useful for example if a screen capture of the curve viewer is needed to be included in a report and the labels are not explicit enough.

Legends



Legends tab

It is possible to modify the graph legends. First select the legend to be modified in the list, then enter the new text in the text field, and finally push the **Apply** button.

Saving Images

The curve viewer graphics area can be saved in an image file, which can be included later in reports.

The supported image file formats are:

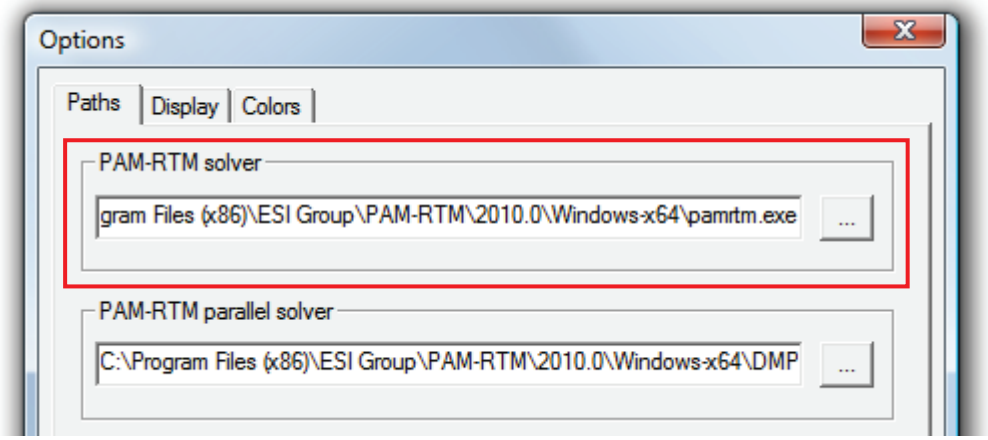
- PNG
- GIF
- TIFF
- JPEG
- It is recommended to use the PNG format.

RUNNING THE SIMULATION FROM A COMMAND WINDOW

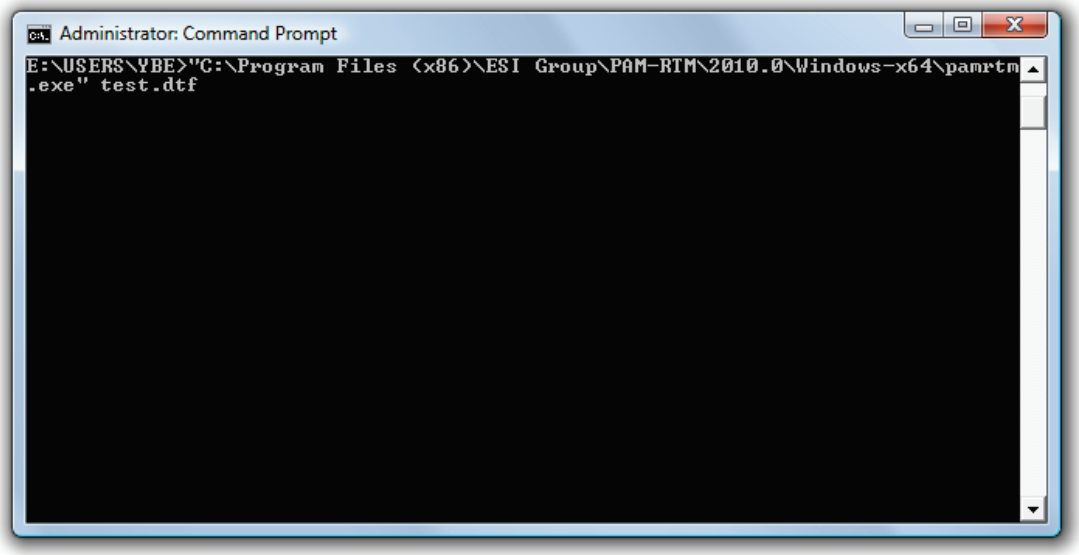
Windows

Most of the time the **PAM-RTM™** solver is launched from the user interface with the start button in the *simulation* toolbar. In some situations however it can be useful to launch the simulation from a command window. For example you might want to launch many simulations from a batch program on your PC to have them running during the week-end. Or you might want to run a big simulation on a Linux workstation.

On Windows, you will need first to identify the directory where the solver executable file `pamrtm.exe` is located. This can be done with the **Options->Paths** tab.



Then open a **Command Prompt** window with **Start->All Programs->Accessories->Command Prompt**. Change directory to where the **PAM-RTM™** input file (`.dtf`) is located, then launch the simulation by typing the full path to `pamrtm.exe` between quotes, as shown below.



Calculations using the parallel solver are also normally launched with the start button in the *simulation* toolbar. However if for some reason the user wants to launch a calculation from outside the user interface, the file *xxx_dmp.bat* can be used. You need to launch the calculation at least once from the user interface to have that file generated. To launch the calculation, simply double-click that file in the Windows Explorer, or enter "*xxx_dmp.bat*" in a command prompt window. That file could be easily edited to run many cases consecutively.

Linux

To run a simulation on Linux with the standard solver, the input files have to be prepared first with the user interface on Windows, because only the solver is available on Linux. Save the project with **File->Save**. Then upload the `.dtf` file and matching `.unv` file (mesh file) by `FTP` to your Linux workstation. Use `telnet` or an equivalent to connect to the Linux workstation.

Type "`pamrtm xxx.dtf`" to launch the simulation. When it is done, download the results files `x_*.unv` to the PC and go back to the **PAM-RTM™** user interface for post-processing.

To run a simulation on Linux with the parallel solver, do the same as described above to transfer the files. Then type "`pamrtmdmp xxx.dtf`". Here are optional parameters that can be passed to `pamrtmdmp`.

```
pamrtmdmp [-np <#>] [-host <hostfile>] [-restart] [-mpiext "<mpi-
args>"] <input-file>
```

```
      -np <#>: specifies the number of processors to use on a single
host. This option must not be used if a cluster configuration file is
specified (see -host option).

      -host <hostfile>: specifies the name of a cluster file
configuration for applications running on multiple hosts within
distributed memory environment (MPI). A cluster file configuration
simply lists a series of hostnames, one per line, followed by the
number of processors to use on each host.

      -mpiext "<mpi-args>": pass optional arguments to mpirun program.
See HP-MPI manual for the list of mpirun arguments.

      -restart: this option must be specified when a restart of a
calculation is needed. The user must first edit file xxxp.dat and
change the value of INILEV to the step number from where the
calculation will restart.

      <input-file>: input file name (.dtf).
```

Typical commands:

- `pamrtmdmp –np 2 test.dtf`
- `pamrtmdmp –host clusterfile test.dtf`

Here is an example of cluster file:

```
host1 2
host2 2
host3 4
host4 6
```

TUTORIALS

CENTRAL INJECTION

The files related to this example are:

- ***central_start.unv*** (starting mesh)
- ***central.dtf + central.unv*** (solution)

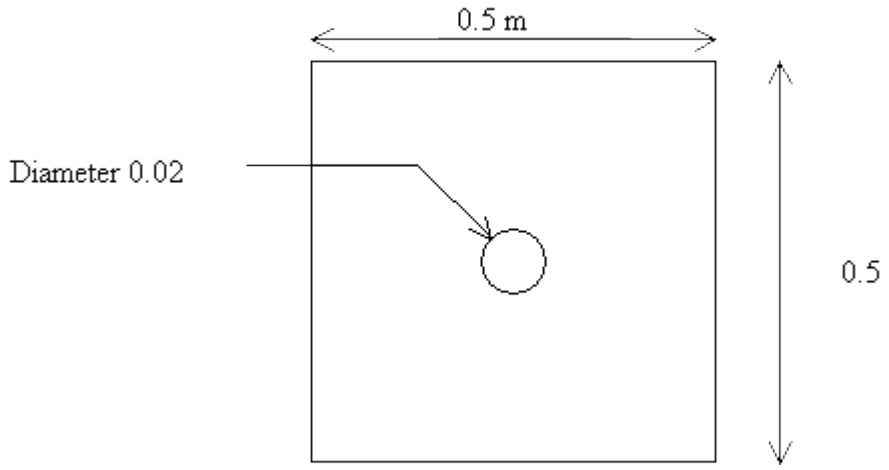
Objective

This example on central injection will show you how to:

- create a simulation project,
- import a mesh to create groups of nodes for boundary conditions,
- visualize the zones,
- specify the simulation parameters for an injection based on Darcy's law,
- display the filling pattern in the cavity and the pressure field in time.

Model of the Part and Physical Parameters

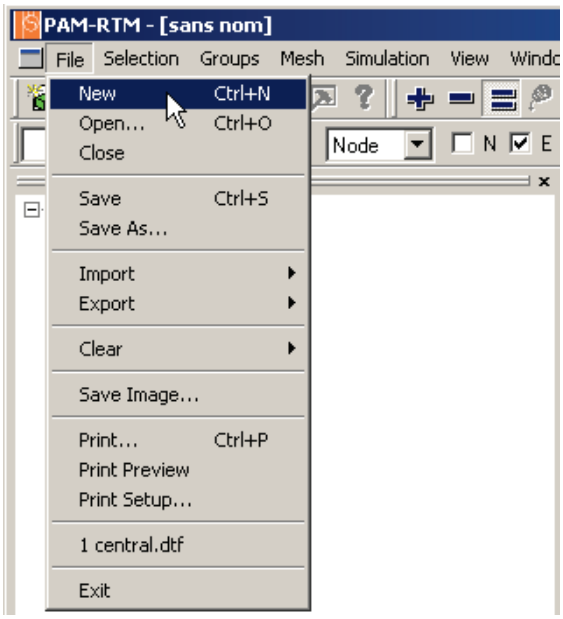
The part analyzed here is a square plate of length 0.5 *m* and thickness 0.005 *m* with a hole of radius 0.01 *m* in the center, through which a resin of viscosity 0.1 *Pa.s* is injected. The reinforcement is isotropic. The permeability is $K_1 = K_2 = K_3 =$ 1E-9 m^2, and the porosity 0.7.

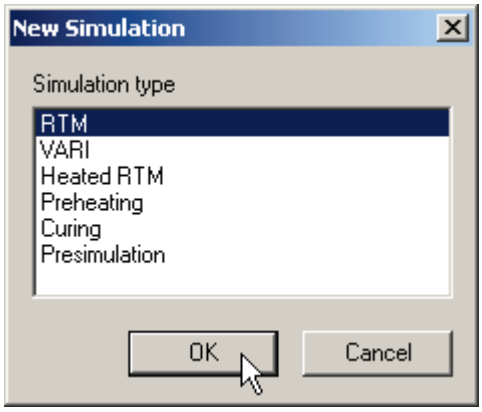


Mesh Import and Visualization of the Zones

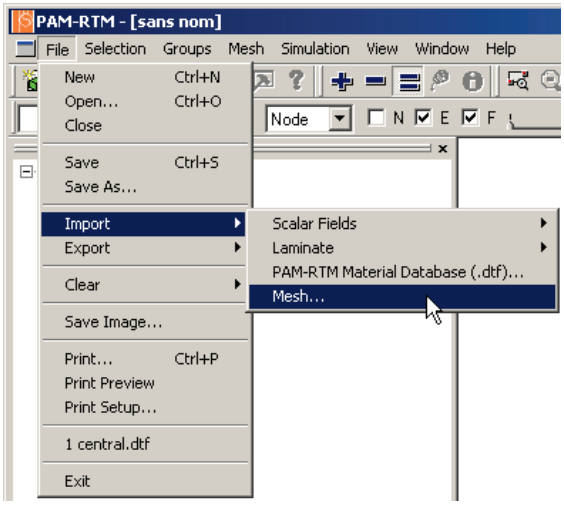
To launch **PAM-RTM™**, double-click the shortcut on the desktop, or use the shortcut in the Windows start menu (**Start->Programs->PAM-SYSTEM->PAM-RTM->version->PAM-RTM**).

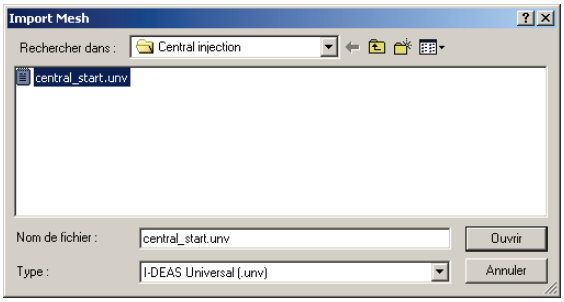
To create a new simulation, use the **File->New** command. This pops up the simulation type box, choose the RTM simulation type.



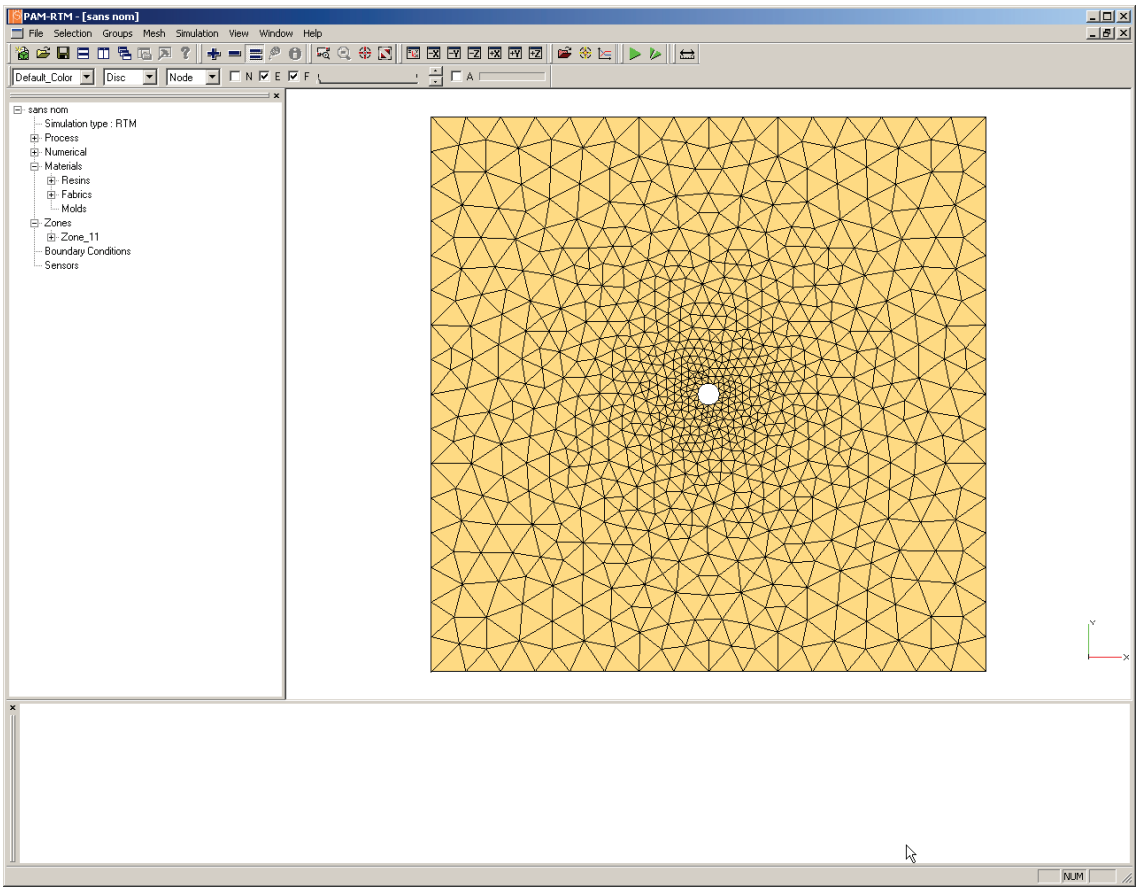


To load the mesh provided for this example, use the **File->Import->Mesh** command. This pops up the **Import Mesh** dialog box, in which you can choose the format of the mesh file. For this example, the mesh provided is an I-DEAS Universal file.

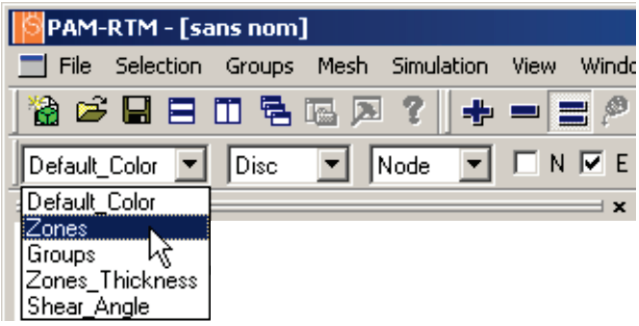




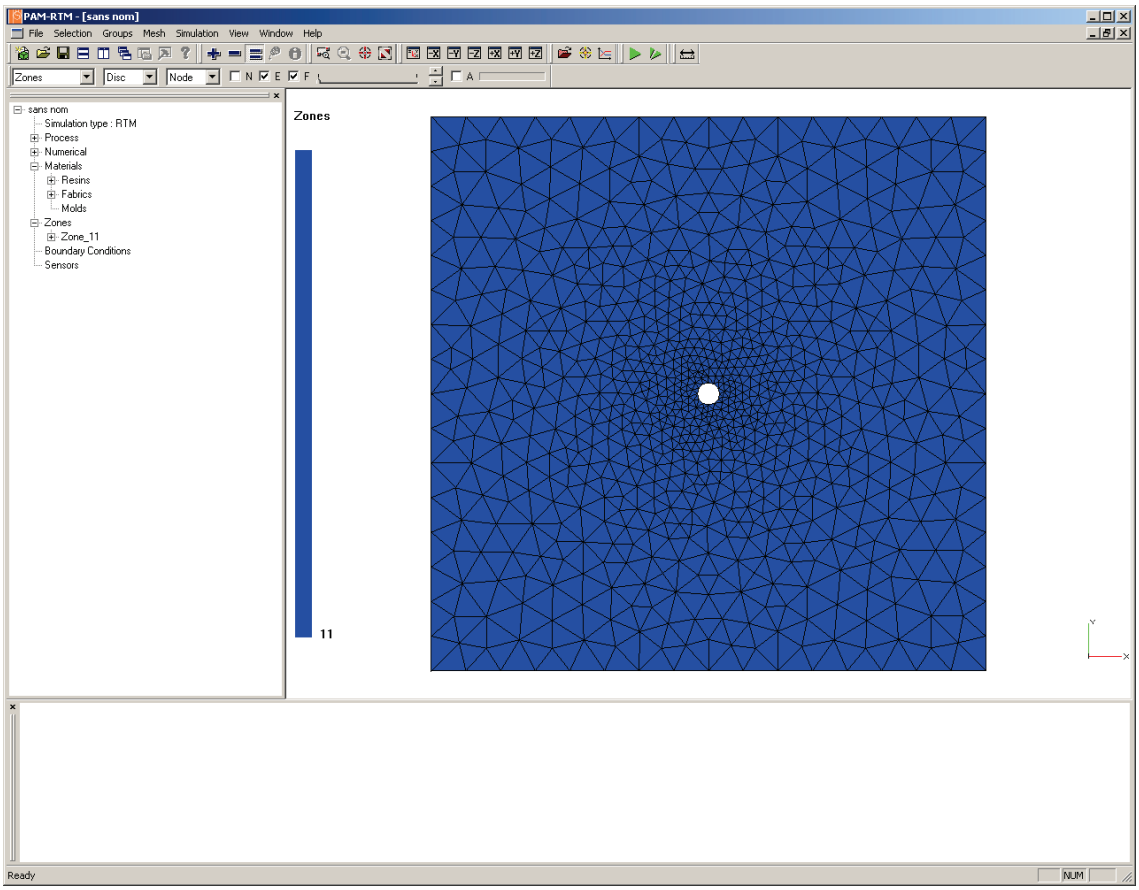
After opening the file, you should see the following:



The zones are groups of finite elements used to assign different material properties to different regions of the mesh. To visualize the zones defined in a mesh, select *Zones* in the display toolbar.



This leads to the following picture, in which we can see that all the elements in this mesh are part of zone 11.



Creation of Groups

Groups of nodes or groups of faces are used to specify boundary conditions. To visualize the groups defined in a mesh, select *Groups* in the display toolbar.

Since currently there are no groups defined in this mesh, you see nothing special. The fact that there is no color scale displayed at the left of the window is an indication that there is no group currently defined in the mesh. You can also verify this with the **Groups->Info** command.

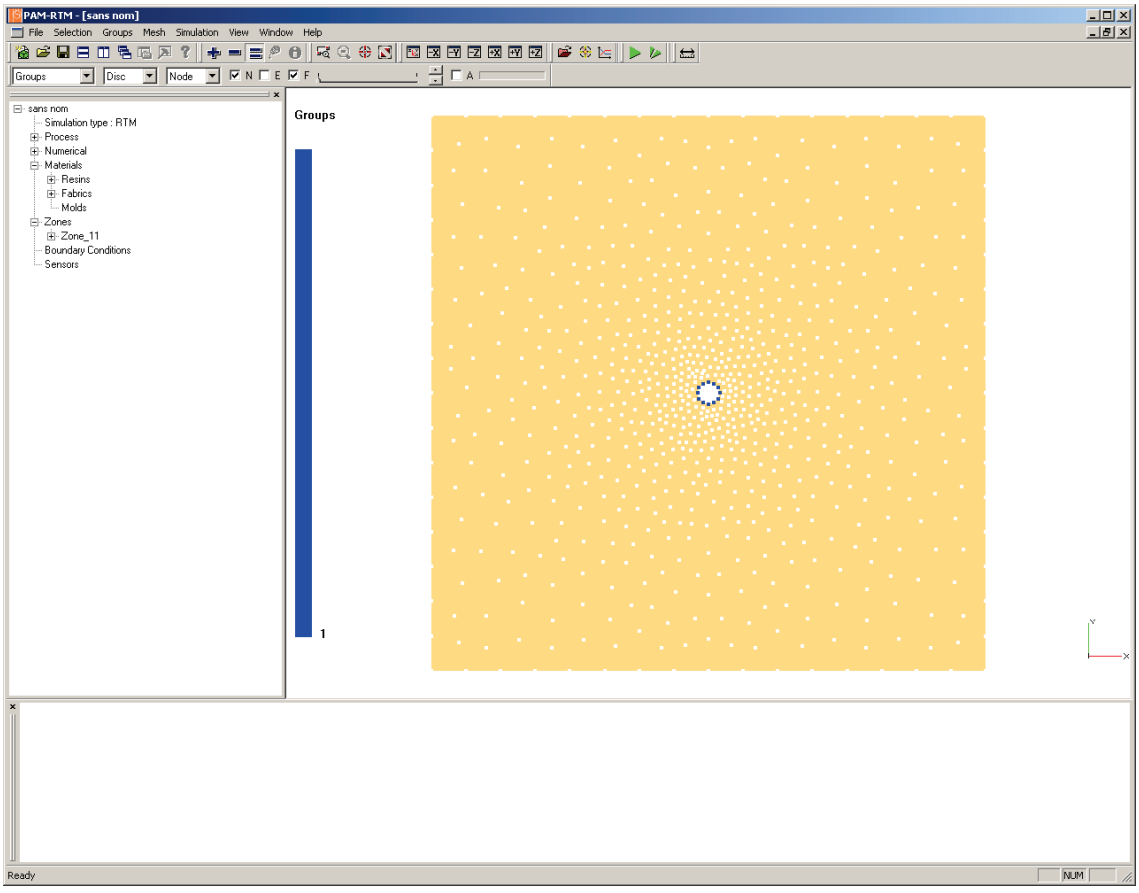
To create a group of nodes, you must first select some nodes. Turn on visualization of nodes by clicking the *N* checkbox in the toolbar. To select nodes more easily and to see more easily the groups, you might have to turn off visualization of edges (*E*).

Activate multiple picking mode with the + button in the toolbar. If you want to remove a selected node to your selection, you can activate the – button by clicking on it.

Then select all the nodes around the injection hole. There is an useful command that allows you to do that in a single click on **Selection->Pick Boundary**, then pick one of the nodes around the injection hole. All the nodes are automatically selected.

Once the nodes are selected, you can create a group with the **Groups->Create** command.

If you are not currently in Groups visualization mode, choose *Groups* from the toolbar combo box to visualize the new group. You should have the following display.

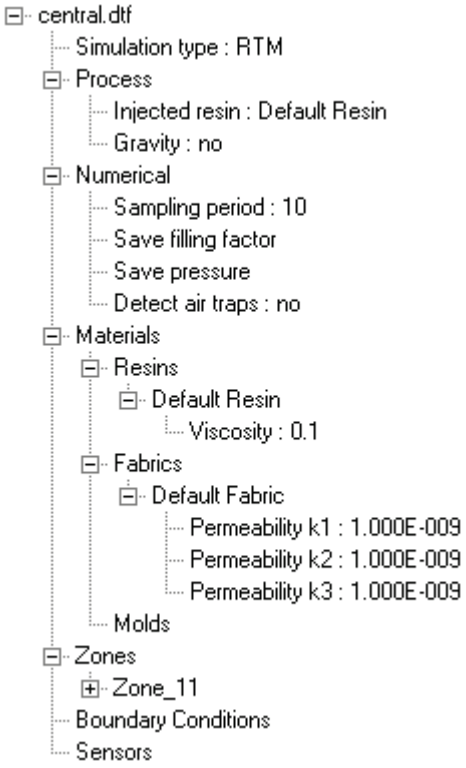


Save the project with the modified mesh with the **File->Save As** command. Give the file a different name so that you don't overwrite the original mesh. If your `.dtf` file is called for example `test.dtf`, a mesh file called `test.unv` will be automatically saved in the same directory as the `.dtf` file.

Simulation

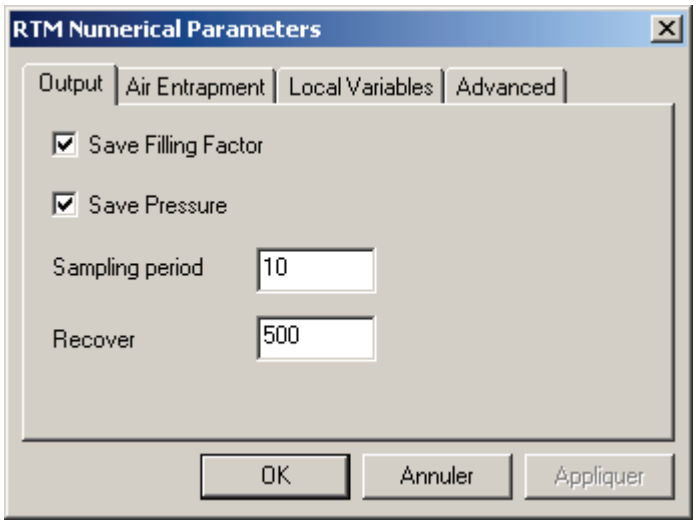
For this example, only the parameters that should be changed from their default value will be pointed out.

In the left column, you can find all the parameters necessary for the simulation.



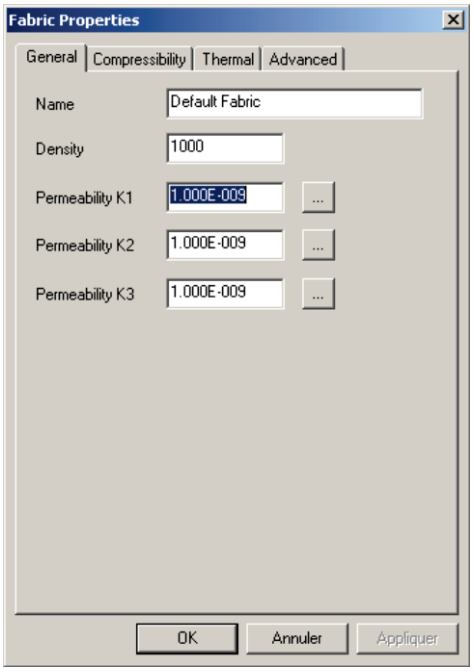
These parameters are divided into six categories, namely: **Process**, **Numerical**, **Materials**, **Zones**, **Boundary Conditions** and **Sensors**.

Double-click on **Numerical** to open the **RTM Numerical Parameters** dialog box.



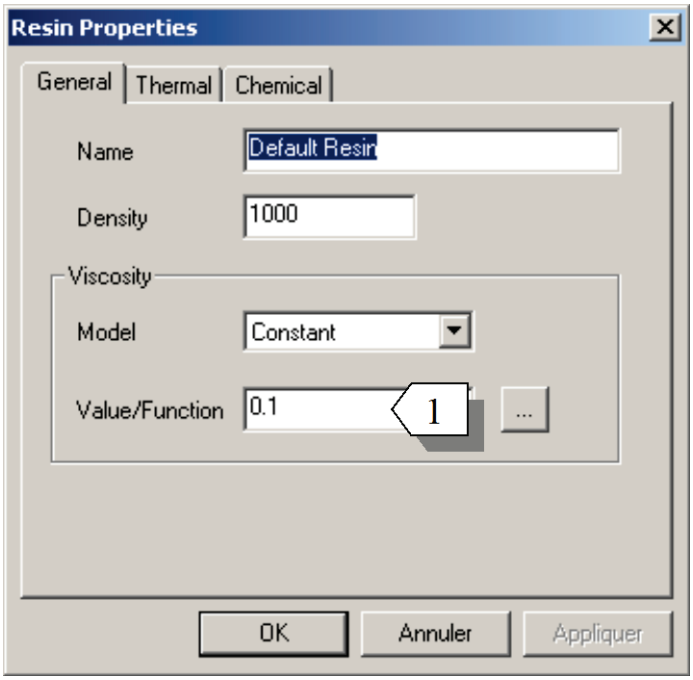
Verify that **Save Filling Factor** and **Save Pressure** are active.

Double-click **Default Fabric**. The following dialog box pops up.

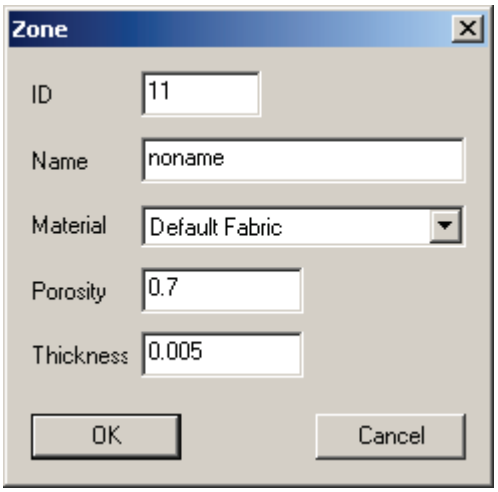


Enter an isotropic permeability of 1.10^{-9} m^2 for K1, K2 and K3.

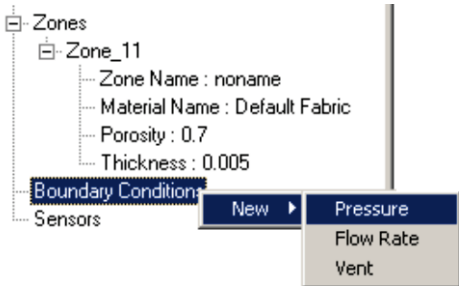
Now, double-click **Default Resin**. The resin properties will appear. Set a constant viscosity of 0.1 Pa.s **[1]**.

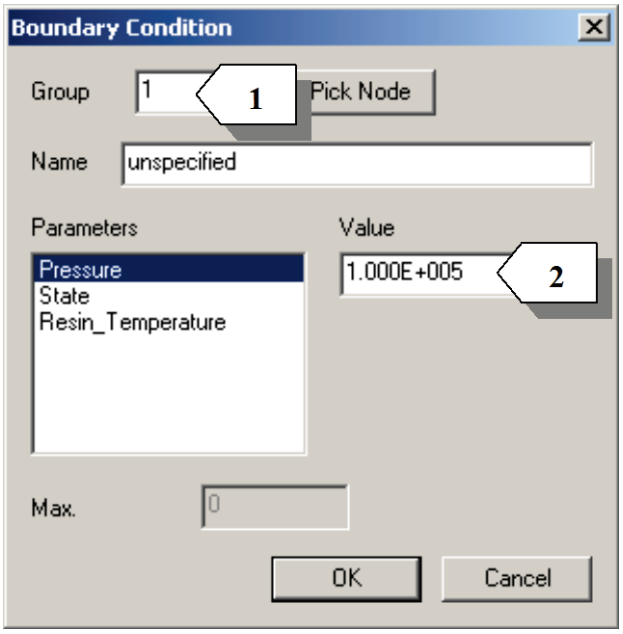


Double-click on *Zone 11*. Make sure that Default Fabric is assigned to it, the porosity is 0.7 and the shell thickness is 0.005 m.

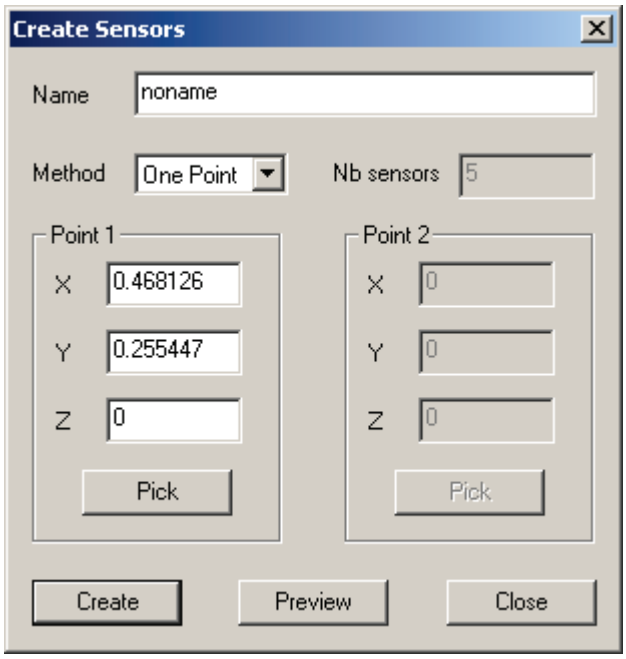


Right-click **Boundary Conditions**, select **New->Pressure** as type of boundary condition. Then, double-click *pressure_-1*. Enter the ID of the group **[1]** and the value of the injection pressure **[2]**. In this example, 1E+5 *Pascals* is used, so the pressure is constant and equal to one bar. Note that it is also possible to choose a piecewise linear curve in the function editor to simulate a time dependent injection pressure.

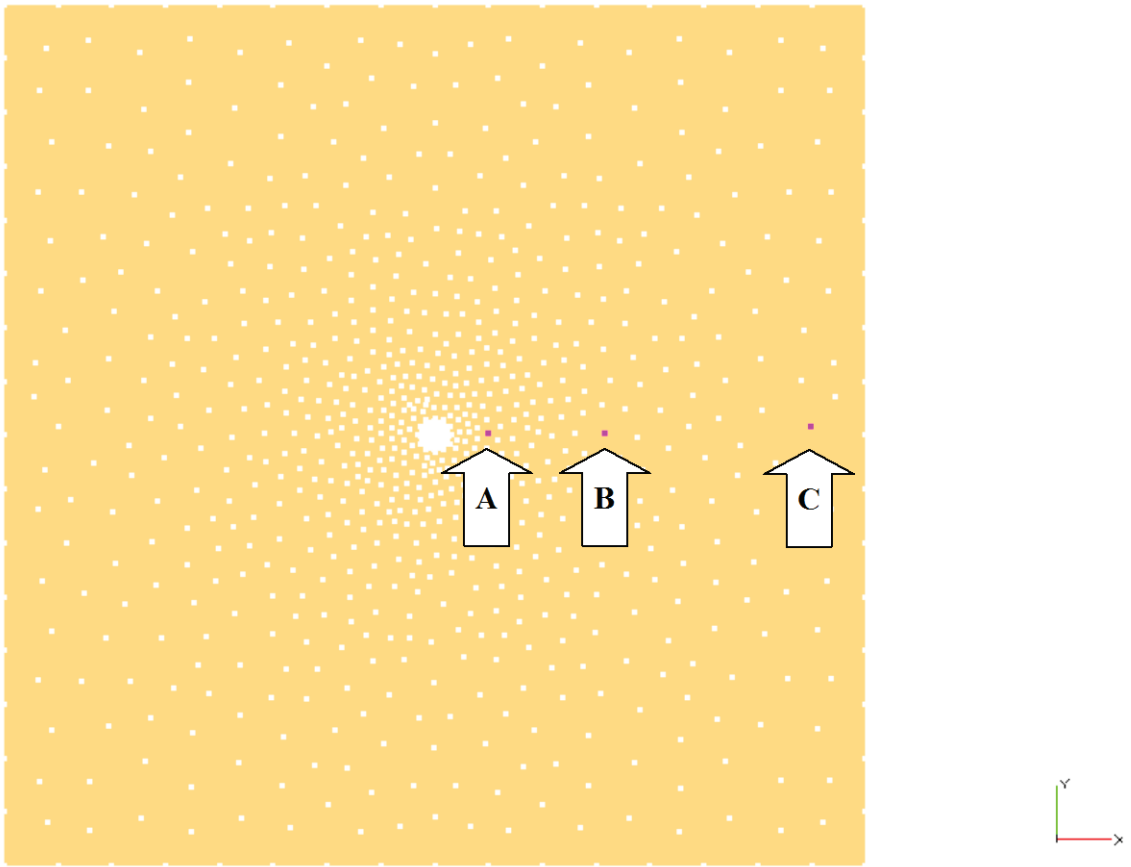




It is sometimes useful to define sensors at specific locations in the cavity to sample pressure or temperature. Right-click **Sensors**, select *Create* and the dialog box **Create Sensors** appears.



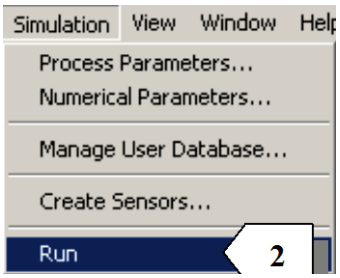
Select 3 nodes (A, B and C) as shown in the following picture. You can enter directly the position of the sensor or you can select it with the Pick function. Then you click on the **Create** button.



Finally, save the simulation parameters with **File->Save**.

Note :

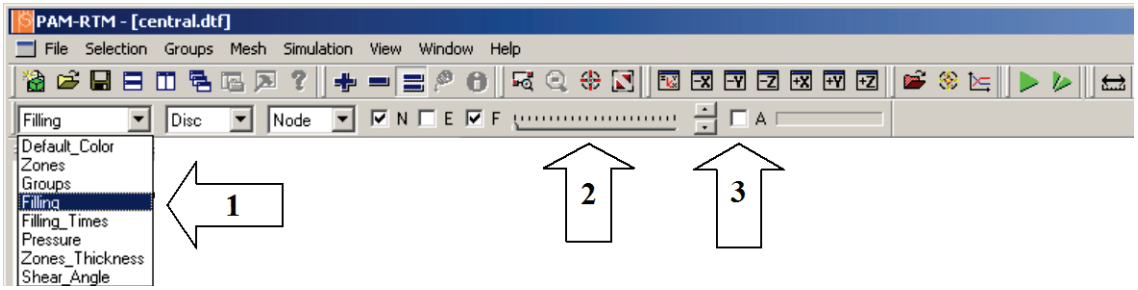
- *Whenever simulation parameters are modified, it is important to save the file before launching a new simulation (otherwise the simulation will be executed with the old set of parameters).*
- *The simulation can be launched by clicking on the **Start** button **[1]** or by selecting **Simulation->Run [2].***



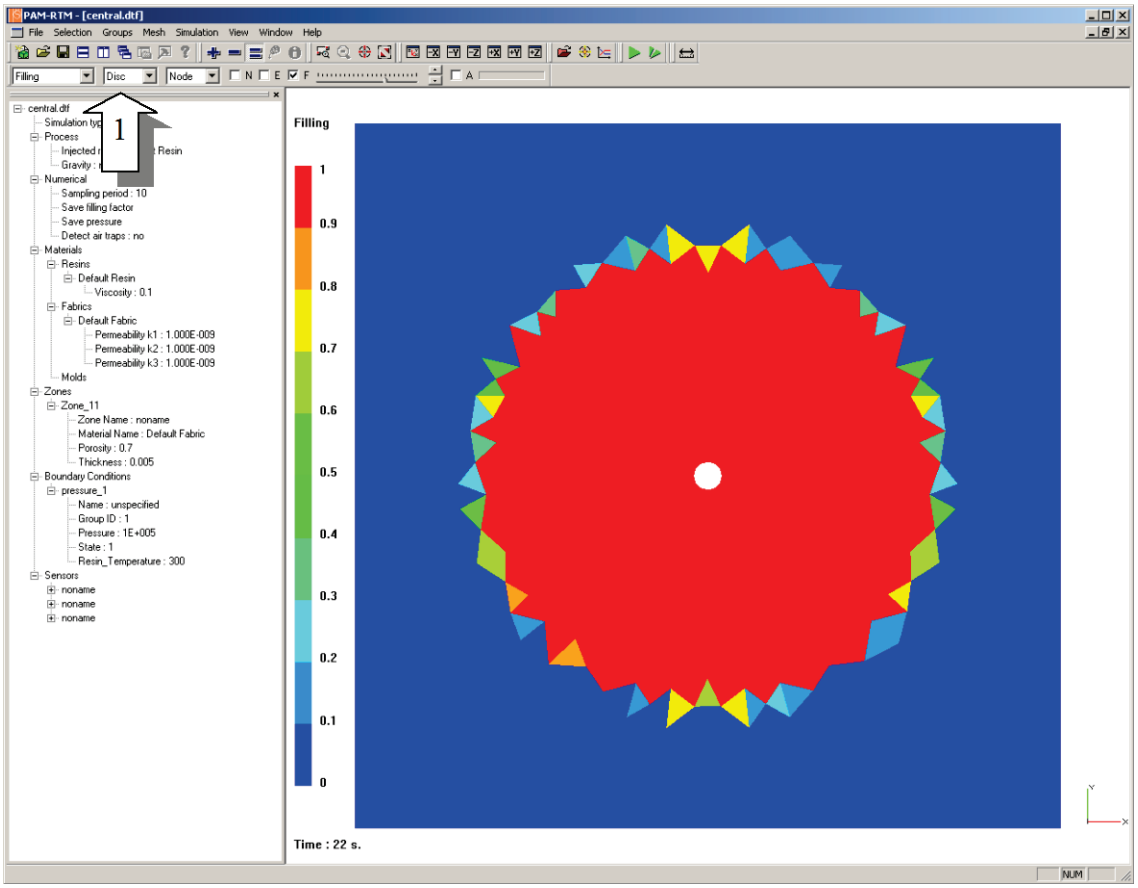
Post-Processing the Results

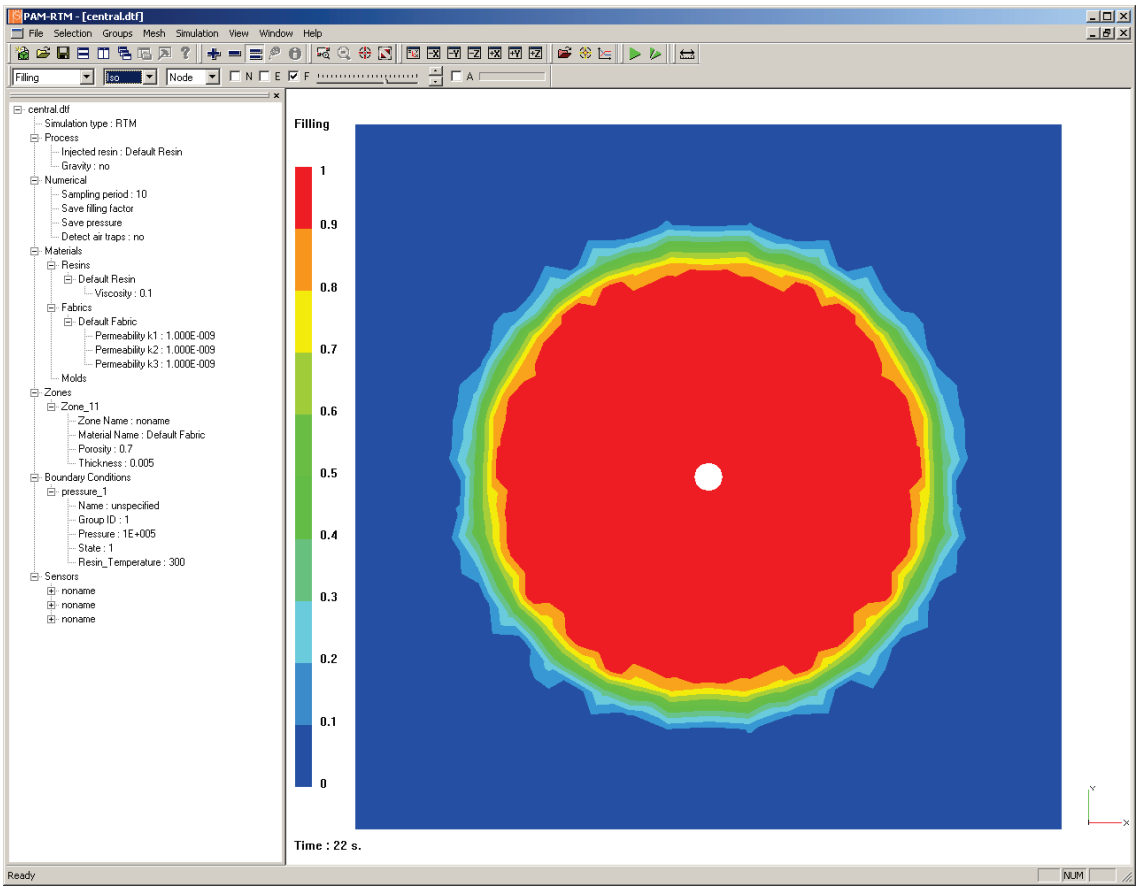
To import the filling results, click on the **Reload Results** button **[1]**. It is possible to load results during the calculation.

After importing scalar fields, they become available in the scalar field combo box **[1]**. Select *Filling*, then drag the time step scroll bar to visualize the filling factor step by step **[2]**. Alternatively you can use the arrows to visualize a scalar field step by step. You can also launch an animation by clicking the **A** check box **[3]**.

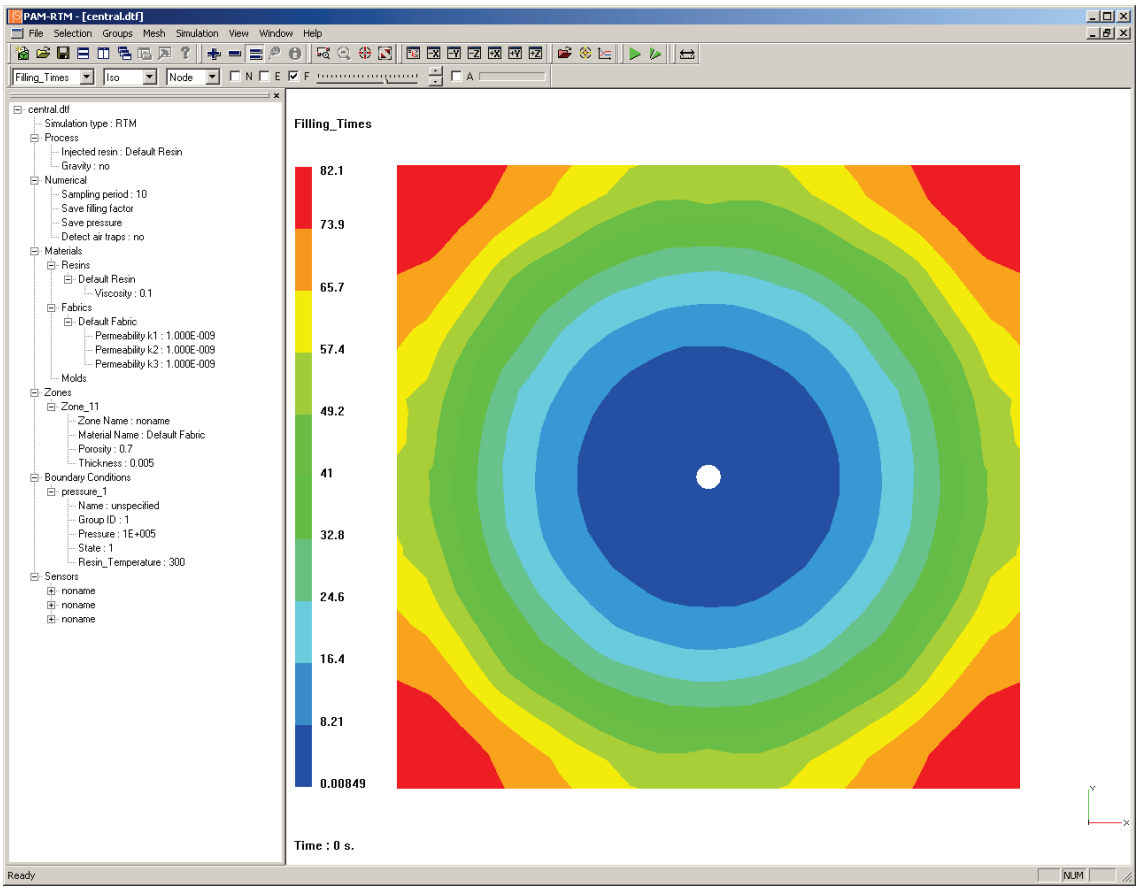


Now you should have the following picture. This is the "raw" filling result of the **PAM-RTM™** simulation (the filling factor is calculated in **PAM-RTM™** as a constant per element scalar field). You can improve the display of the filling factor by selecting *Iso* in the display toolbar **[1]**. This will give you a smoothed scalar field.

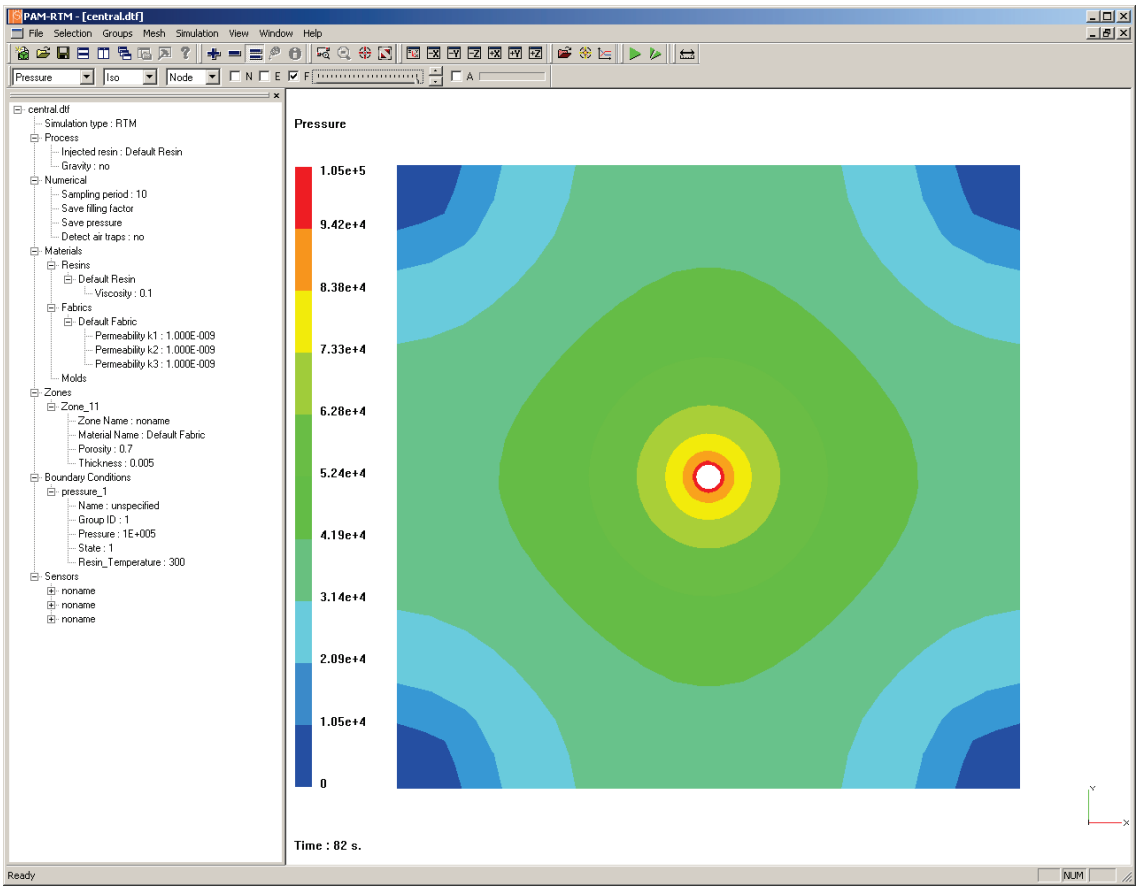

PAM-RTM - [central.dtf]
File Selection Groups Mesh Simulation View Window Help
Filling
Disc
Node
central.dtf
Process
Numerical
Sampling period : 10
Save filling factor
Save pressure
Detect air traps : no
Materials
Resins
Default Resin
Viscosity : 0.1
Fabrics
Default Fabric
Permeability k1 : 1.000E-009
Permeability k2 : 1.000E-009
Permeability k3 : 1.000E-009
Molds
Zones
Zone_11
Zone Name : noname
Material Name : Default Fabric
Porosity : 0.7
Thickness : 0.005
Boundary Conditions
pressure_1
Name : unspecified
Group ID : 1
Pressure : 1E+005
State : 1
Resin_Temperature : 300
Sensors
noname
noname
noname
1
Filling
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time : 22 s.
NUM



Another useful scalar field to visualize is *Filling Times*. This scalar field is used to visualize the successive positions of the flow front in time in a single picture.

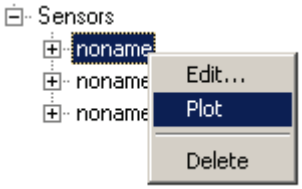


Finally, we can have a look at the pressure field at the end of the injection, when the cavity is completely filled.

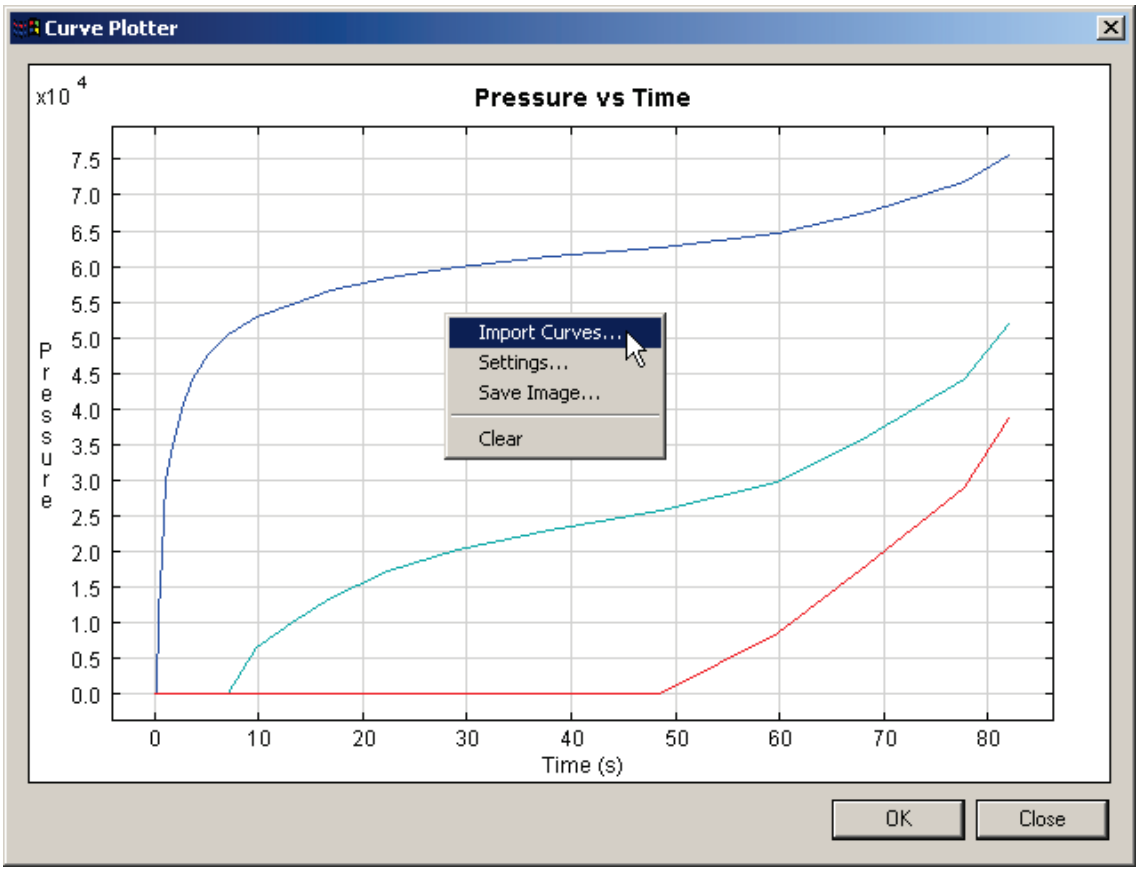


It is important to understand in this example that, even if no vents were specified, **PAM-RTM™** is able to fill completely the cavity. This is because it assumes that when no vent is specified, the injection is performed under perfect vacuum.

The sensors defined are important tools to study the results. They enable the display of pressure curves in time. Right-click on the name of the sensor and select *Plot*.



Each time you select *Plot* on a sensor, a curve is added to the curve viewer. This is useful to compare curves. To clear the curves currently displayed in the curve viewer, right-click in the drawing area and choose Clear.


Curve Plotter
Pressure vs Time
x10 4
Pressure
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
60
70
80
Time (s)
Import Curves...
Settings...
Save Image...
Clear
OK
Close

EDGE EFFECTS – RECTANGULAR PLATE

The files related to this example are:

- ***rect_edge_start.unv*** (starting mesh)
- ***rect_edge.dtf*** + ***rect_edge.unv*** (solution)

Objective

In this example, a rectangular plate is injected from one side. The plate contains a special zone along one edge, in which the resin flows more quickly. This phenomenon, quite common in RTM, is called *race tracking*.

Creation of Groups and Visualization of Zones

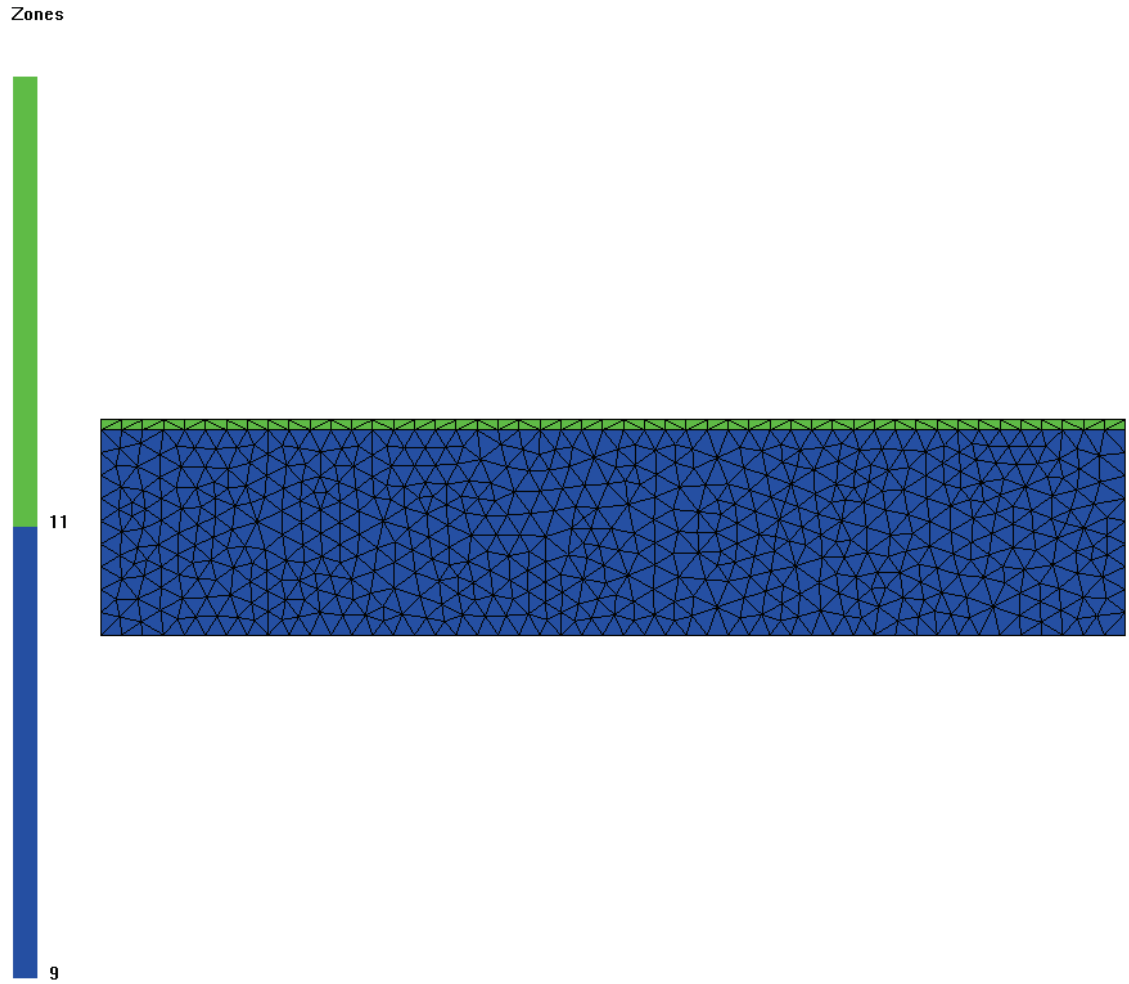
Create a new simulation , use **File ->New** command and choose the RTM simulation type.

The mesh provided for this tutorial doesn't contain any group, so the first step is to define groups of nodes for the injection and vent boundary conditions.

Import the file `rect_edge_start.unv` with the menu **File->Import->Mesh**.

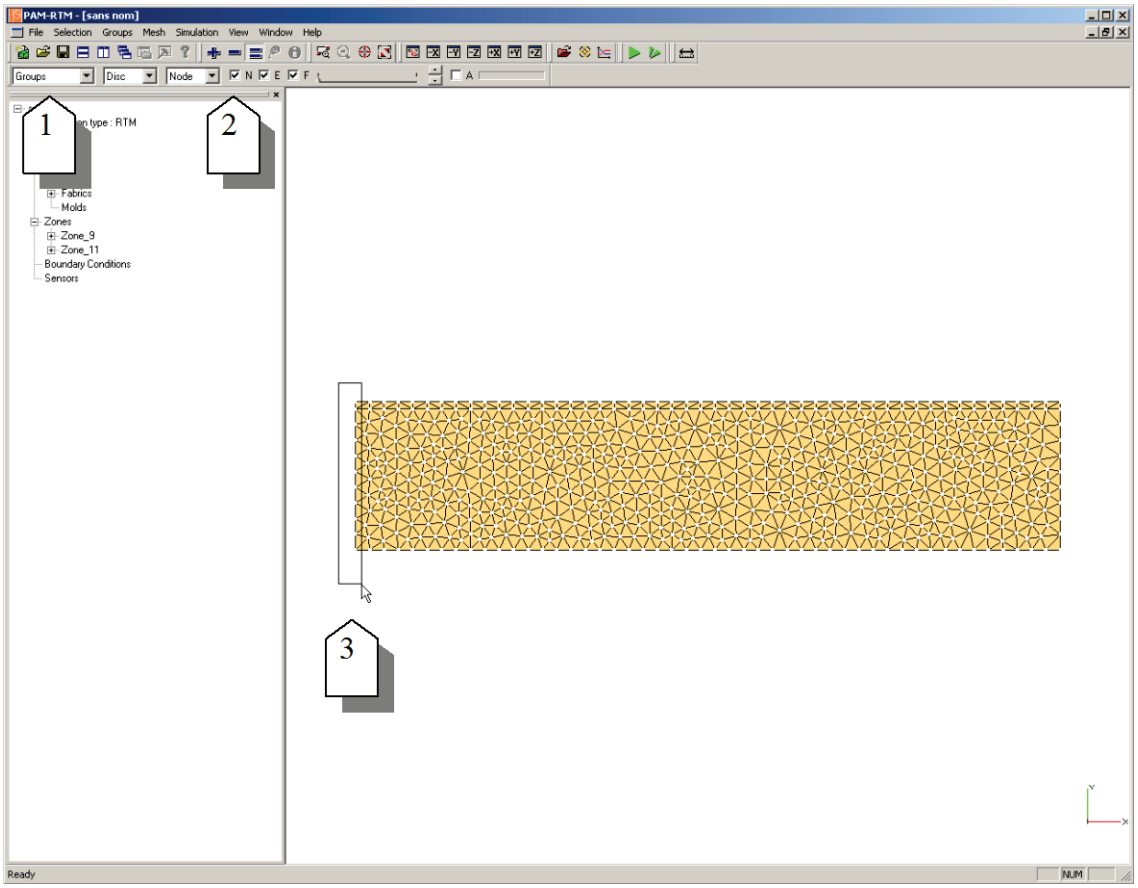
Select Zones in the scalar field combo box **[1]**.

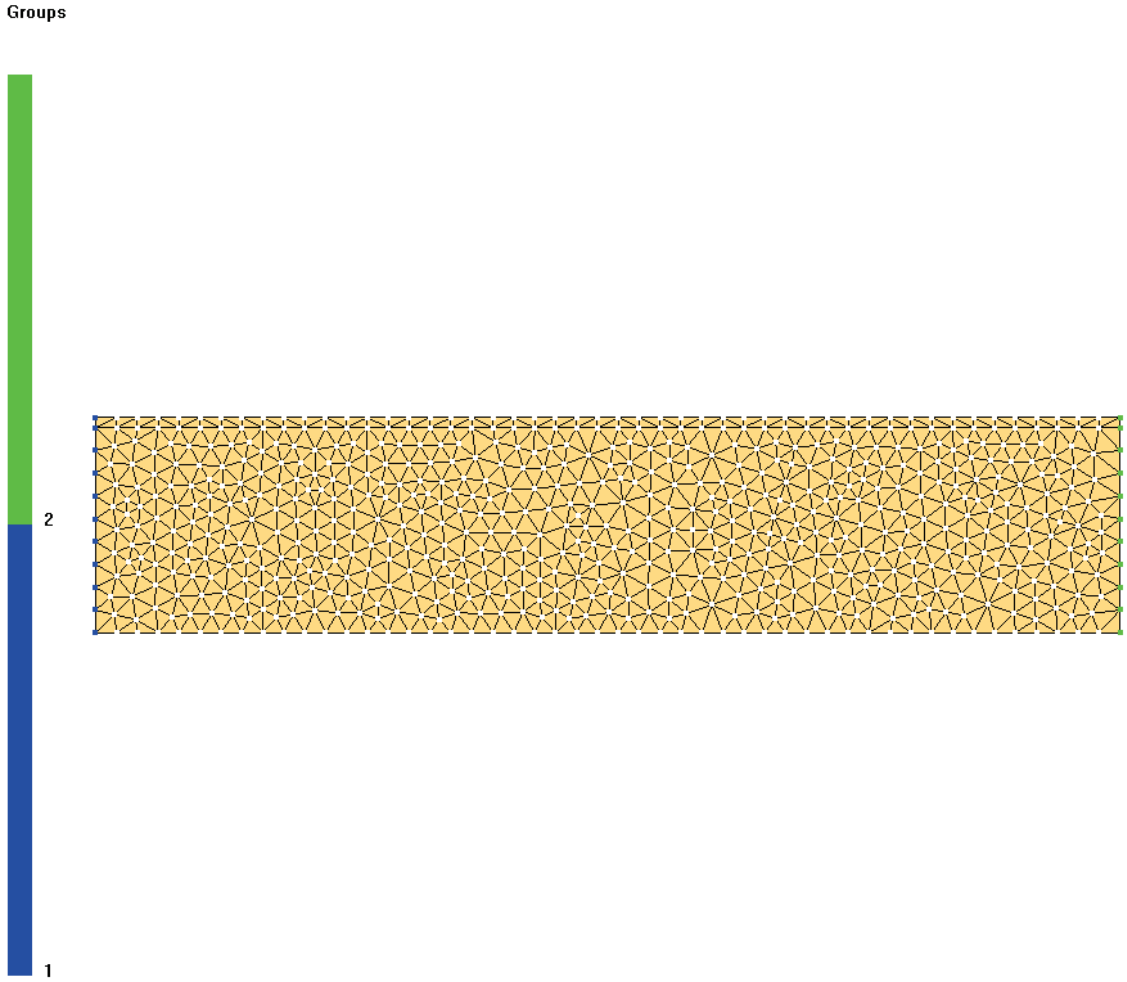
Notice in the zones image that 2 zones are defined. Zone number 11 will be used for race tracking. We will assign it a material with higher permeability than the permeability of zone 9.



Now we will create 2 groups of nodes, one for the pressure boundary condition on the left side of the rectangle, and one for the vent on the right side.

- Click on **N** to activate visualization of nodes **[1]**.
- Select *Groups* in the scalar field combo box to view nodes colored according to the group ID **[2]**.
- Drag the mouse to select the nodes on the left **[3]**.
- Choose **Groups->Create**. This creates a group with ID = 1.
- Select the nodes on the right.
- Choose **Groups->Create**. A group with ID = 2 is created.


PAM-RTM - [sans nom]
File Selection Groups Mesh Simulation View Window Help
Groups
Disc
Node
Fabrics
Molds
Zones
Zone_9
Zone_11
Boundary Conditions
Sensors
1
2
3
Ready
NUM

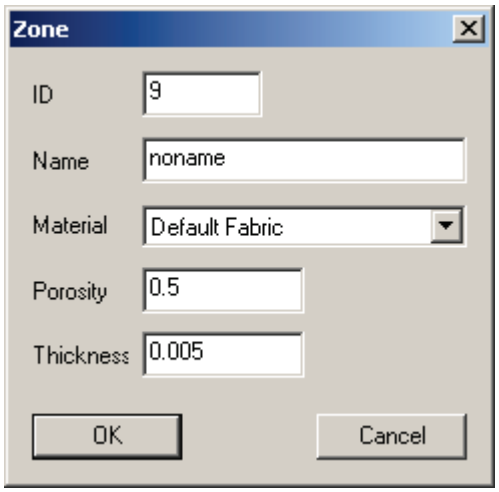


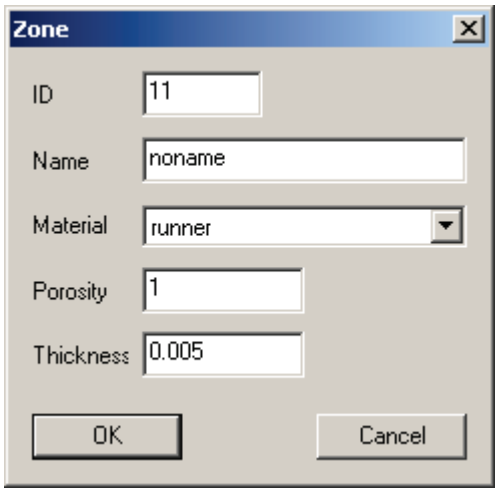
Simulation

Double–click on **Default Fabric** and give the value 1.10^{-10} m^2 to the components of the permeability tensor K_1, K_2, K_3.

Create a new reinforcement (of type *fabric*). Name it *Runner* and define its permeability to 1.10^{-9} m^2, so the permeability of this zone will be ten times larger than the rest of the cavity.

Click on **Zones**, verify that the material assigned to zone 9 is *Default Fabric* with a porosity of 0.5 and that the material of zone 11 is *Runner*. Give the value of 1 to the porosity of zone 11. This means that this region doesn't contain any fibers.





Note:

- *Zones used for race tracking have a porosity of 1. However a reinforcement has to be assigned to these zones even if they don't contain any fibers.*

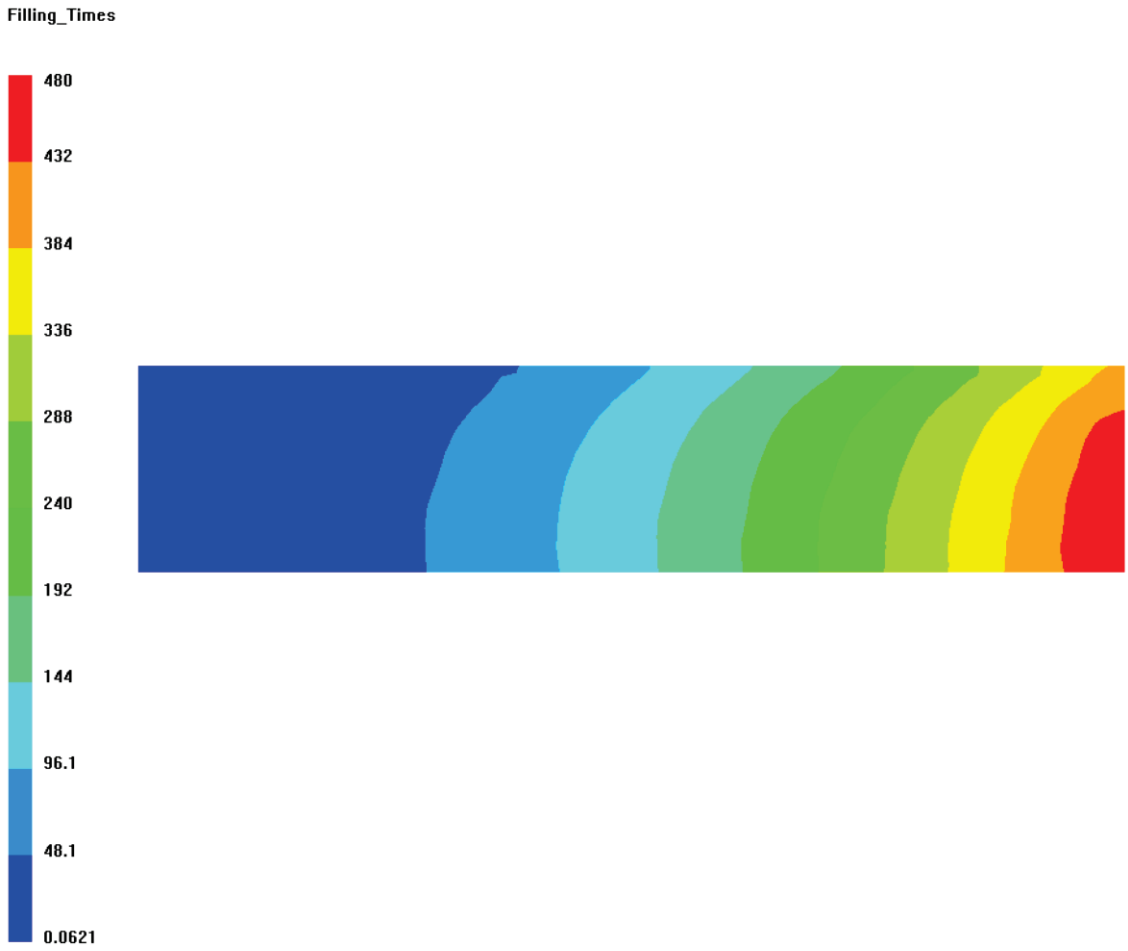
Right-click on **Boundary Conditions**, select *Pressure* as type of boundary condition. Enter the number of the group 1 and set a constant injection pressure of 1.10^5 Pa. Set group 2 to type *Vent* and set its pressure to zero.

Save the simulation parameters file with **File->Save** and give it the name `my_edge.dtf`. Launch the simulation with the **Start** button.

Visualization of Results

Import the filling results by clicking on **Reload Results** button. Choose Filling in the scalar field toolbar and click on the *A* check box to animate the filling results. Then have a look at the pressure field.

An interesting visualization feature is the *Filling_Times* scalar field which shows in only one picture the evolution of the resin front during the injection. You should have the following picture. Notice how the resin flows more easily along the top edge.


Filling_Times
480
432
384
336
288
240
192
144
96.1
48.1
0.0621

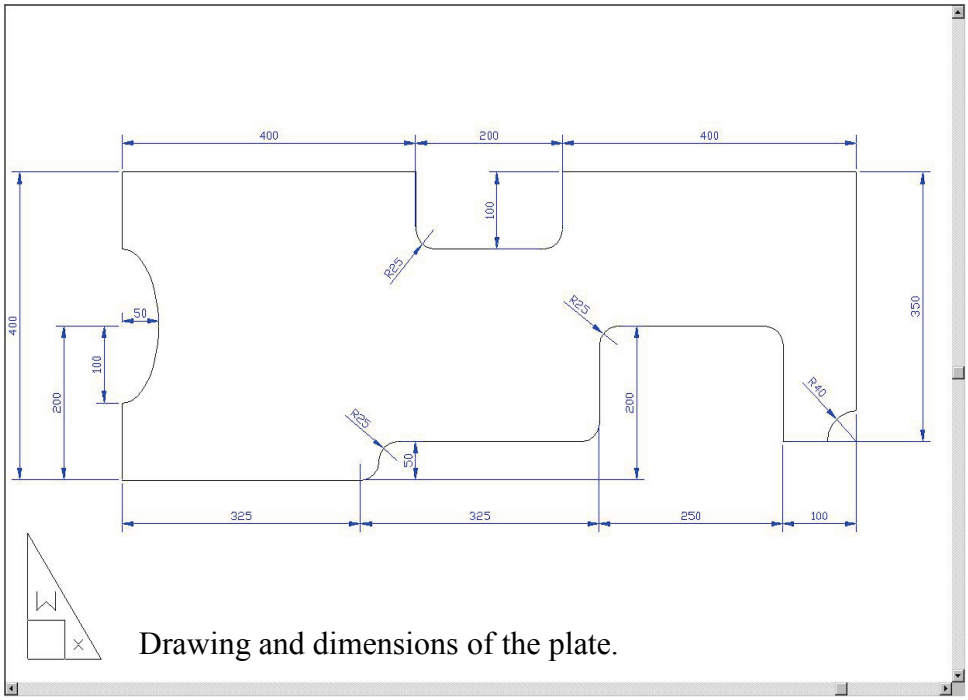
EDGE EFFECTS – COMPLEX SHAPE

The files related to this example are:

- ***complex_edge_start.unv*** (starting mesh)
- ***complex_edge.dtf*** + ***complex_edge.unv*** (solution)

Objective

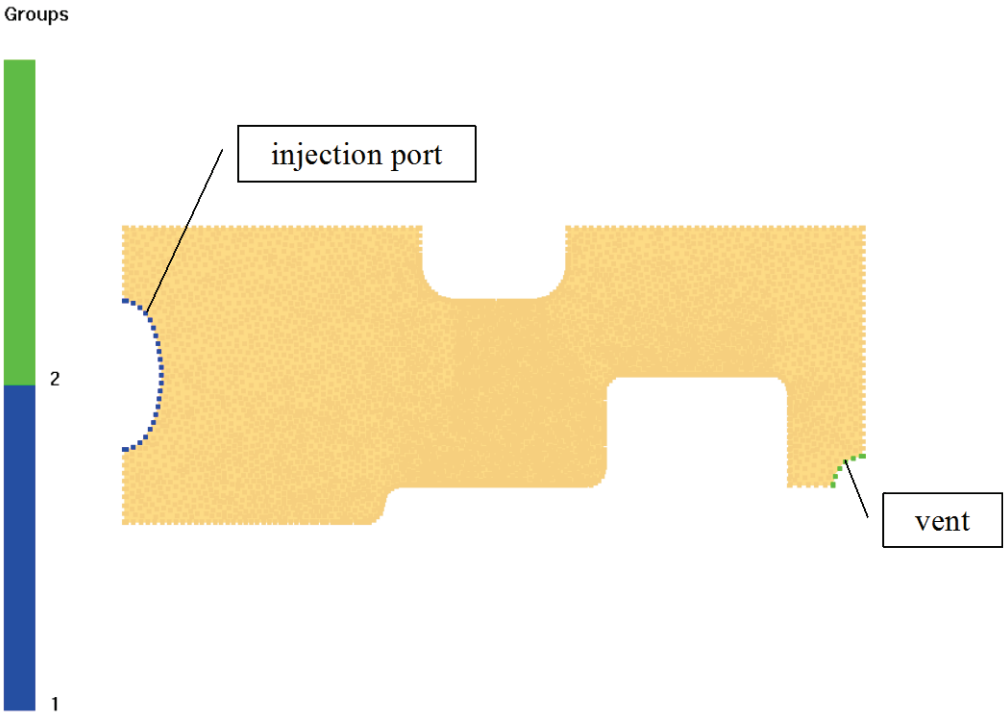
This example is an extension of the previous case. The mesh provided with this example was created from the drawing below. We don't give the details of how to create such a geometry. We assume that the **PAM-RTM™** user already knows a CAD software and mesh generator. The most time consuming task in creating this geometry is the definition of the race tracking zones. A thin zone of two millimeters width must be added along the edges of the cavity, in which the resin will flow more quickly.

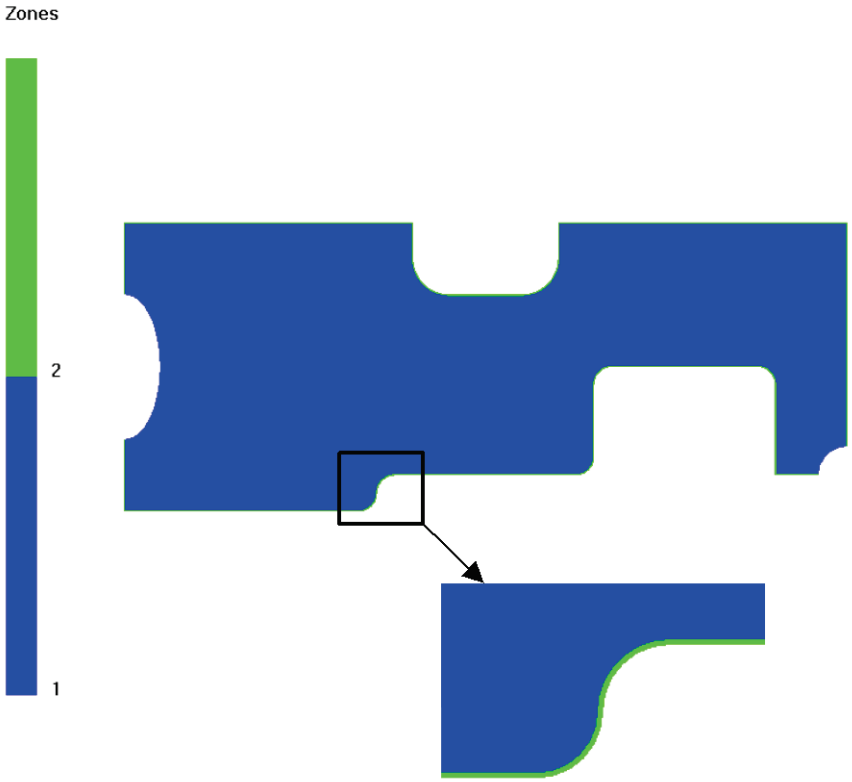


Drawing and dimensions of the plate.

Visualization of Groups and Zones

The pictures below show the groups and the zones defined in the mesh file.


Groups
injection port
vent
2
1


Zones
2
1

Simulation

This section describes the parameters required to carry out this simulation:

General Simulation Parameters

Simulation type: **RTM**

Geometry file: `complex_edge_start.unv`

Materials

The equivalent permeability of an empty channel of diameter *D* for a Poiseuille flow is:

$$K = D^2/12$$

$$K_{runner} = (2mm)^2/12 = 3{,}3\ 10^{-7}\ m^2$$

This is the permeability we will use here for the runner all around the part.

Set the following properties :

- *Resin*: constant viscosity at 0.2 *Pa.s*
- *Default fabric*: $K_1 = K_2 = 3\ 10^{-9}\ m^2$, $K_3 = 1\ 10^{-9}\ m^2$
- *Runner*: $K_1 = K_2 = K_3 = 3{,}3\ 10^{-7}\ m^2$

Zones

Define the central zone (the one with the largest area) with the *Default Fabric*. Its porosity is 0.6 and thickness 0.003 *m*. For zone 2, the material to select is *Runner* with a thickness of 0.003 *m* and a porosity of 1.

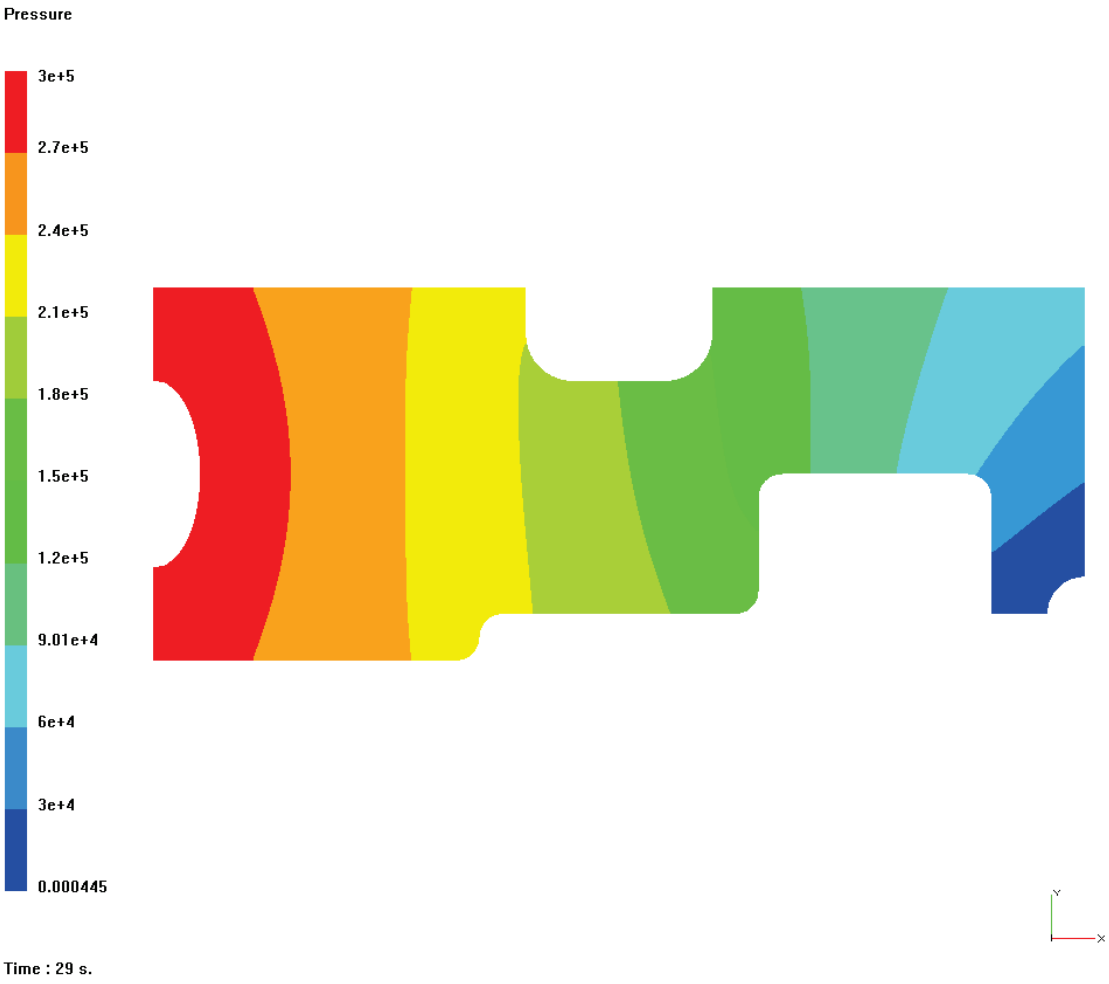
Boundary Conditions

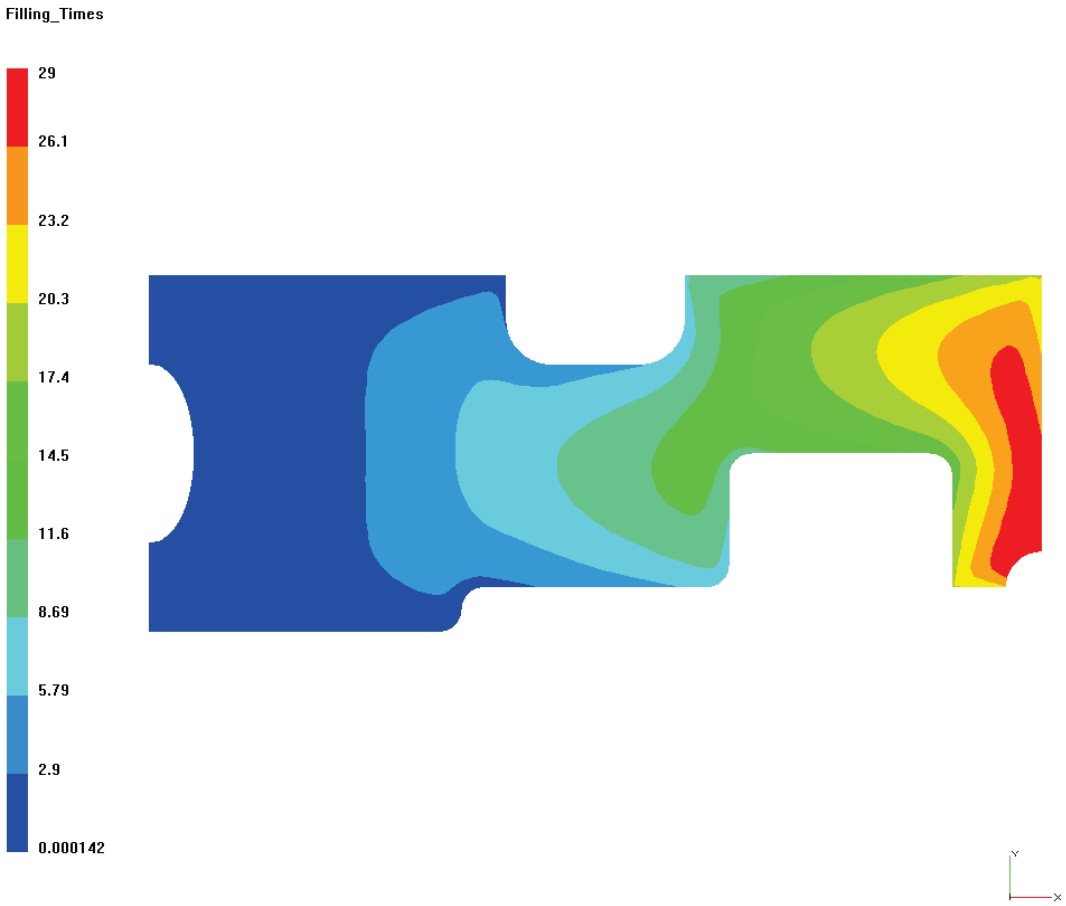
Define group 1 as an injection boundary condition of type *Pressure* with a constant injection pressure of $3\ 10^5$ *Pa*. Define group 2 as a vent.

Simulation

Save the simulation parameters file under the name `my_complex_edge.dtf` and launch the simulation.

Here are the filling and pressure results at the end of injection.


Pressure
3e+5
2.7e+5
2.4e+5
2.1e+5
1.8e+5
1.5e+5
1.2e+5
9.01e+4
6e+4
3e+4
0.000445
Time : 29 s.



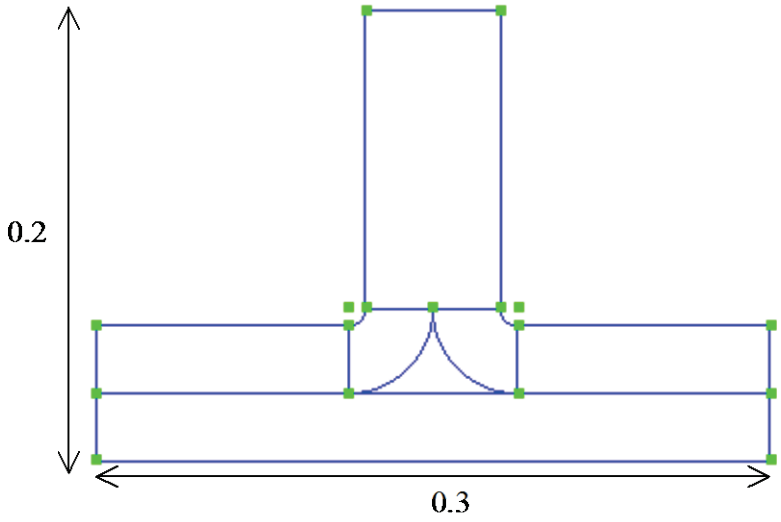
FIBER ORIENTATIONS

The following files will be used:

- ***deltoid_start.unv*** (starting mesh)
- ***deltoid.dtf*** + ***deltoid.unv*** (solution)

Objective

This tutorial shows how to specify fiber orientations in a T-junction.



Test Part

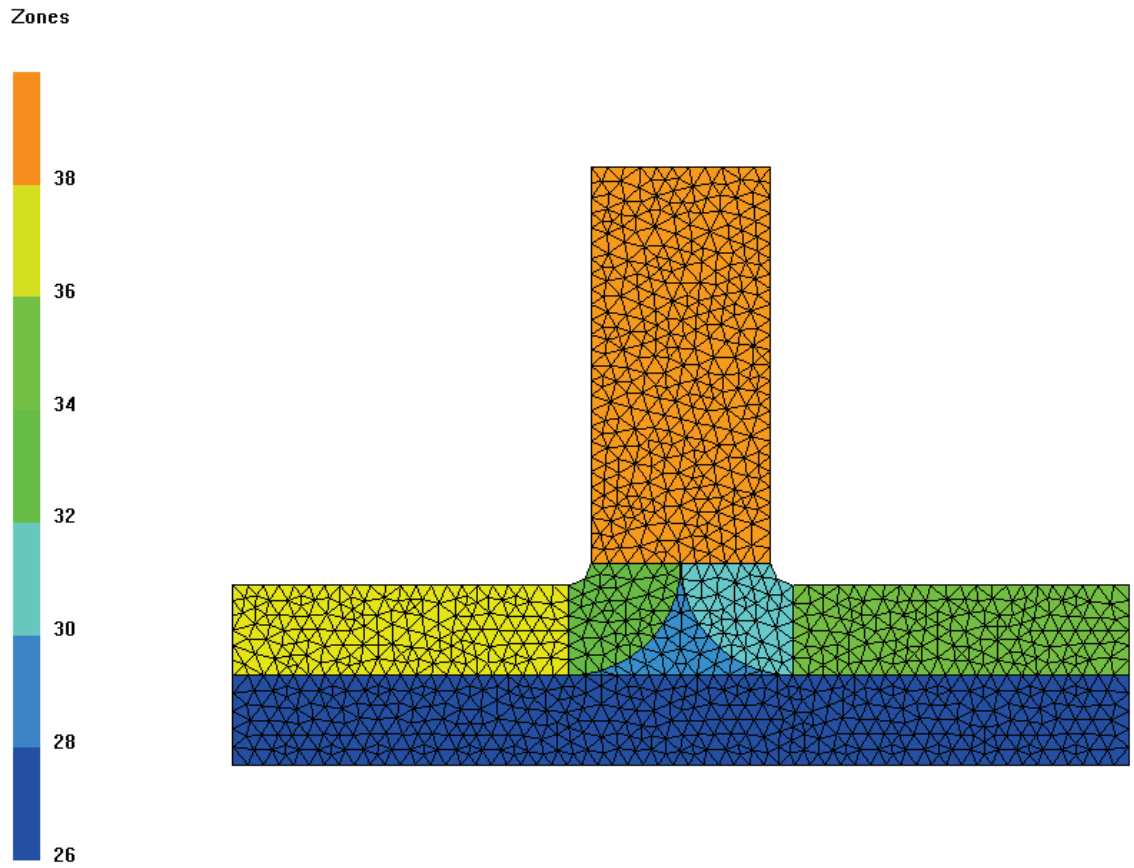
The length of the part is 0.3 *m*. Two layers of reinforcement of thicknesses t_1 and t_2 are considered. The total height is h=0.2 *m*. The injection is performed through the left wall with a resin of viscosity 0.02 *Pa.s*. Special attention should be paid to the permeability values in the three directions K_1, K_2 and K_3. Two materials will be used: one fabric in the deltoid zone with a lower isotropic permeability, and another fabric in the other zones.

Fiber Orientations

Begin by creating a new RTM simulation and import the mesh file `deltoid_start.unv`.

The orientations of the permeability tensor can now be defined. To do so, it is important to visualize the different zones. In the display toolbar, select **Zones**, activate **Edges** and **Faces**, deactivate **Nodes**.

Here is what will appear on the screen:



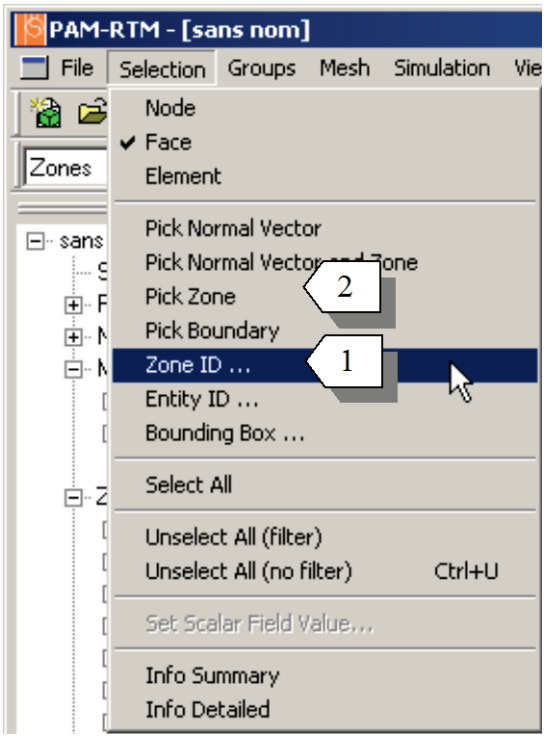
The fiber orientations must be specified in every zone, except in zone 28 (middle zone of the deltoid), where it is not necessary since permeability is isotropic in this region. The simpler zones, where the fibers are oriented along x and y as principal axes, will be defined first.

We will first select the elements on which we want to specify orientations using zone selection.

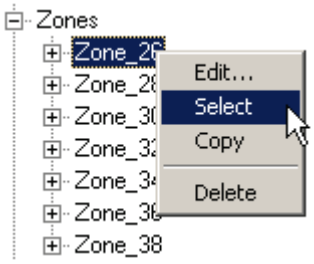
Set the selection filter in the main toolbar to *Face* (or use **Selection->Face** from the menu).

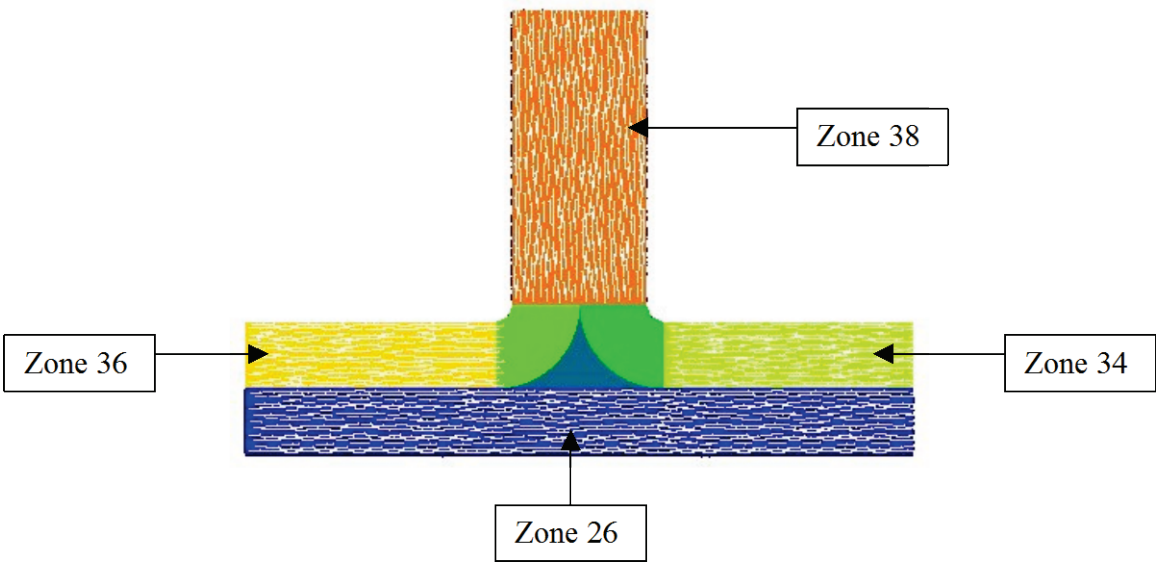
There are several ways to select a zone :

- Click **Selection->Zone ID [1],** a dialog box pops up enabling to enter the zone ID.

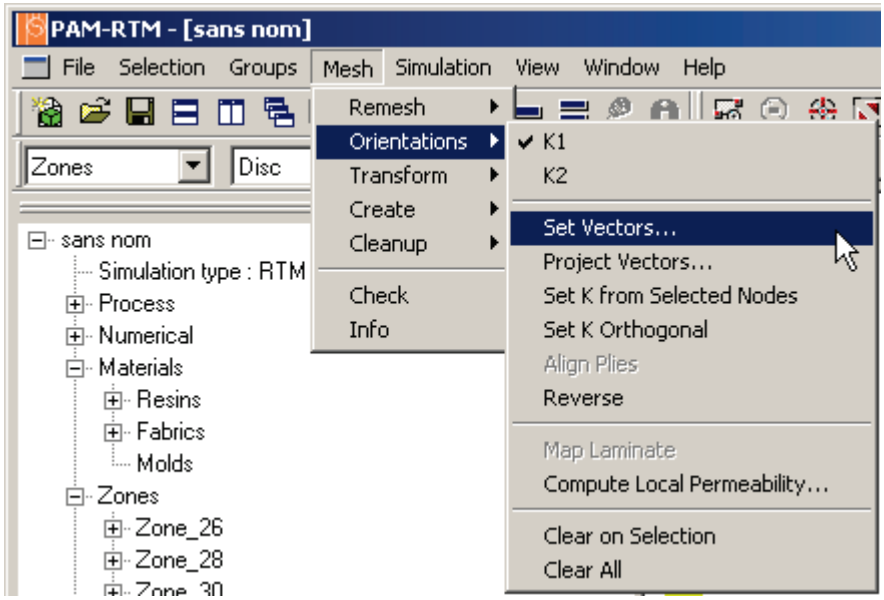


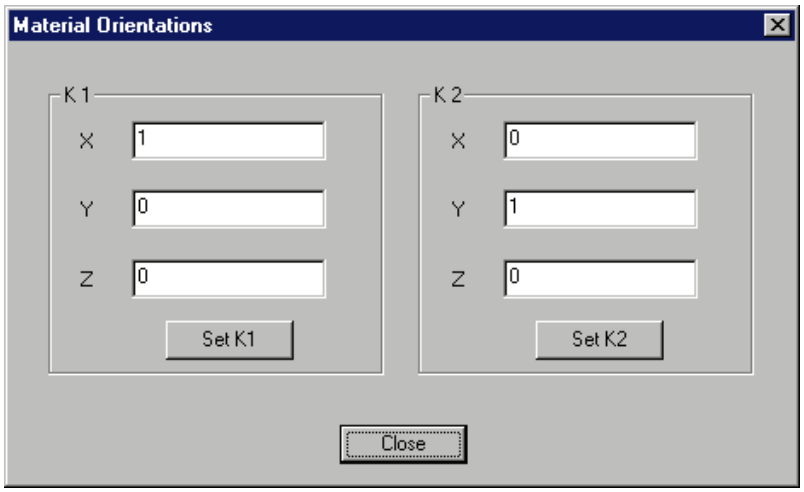
- Click **Selection-> Pick zone [2]** and pick one element of the zone to select.
- Right-click on zone_ID and choose *Select.*



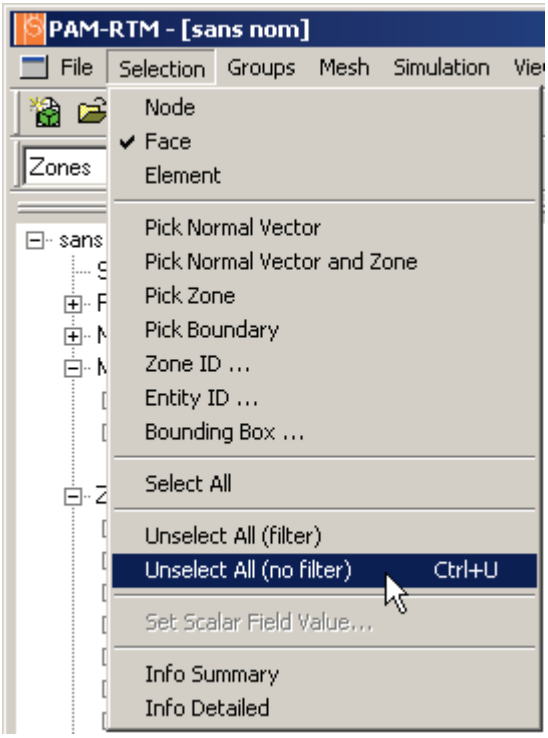


Select elements in zones 26, 34 and 36 (horizontal parts). Then, open the **Material Orientations** dialog box (***Mesh->Orientations->Set Vectors***).





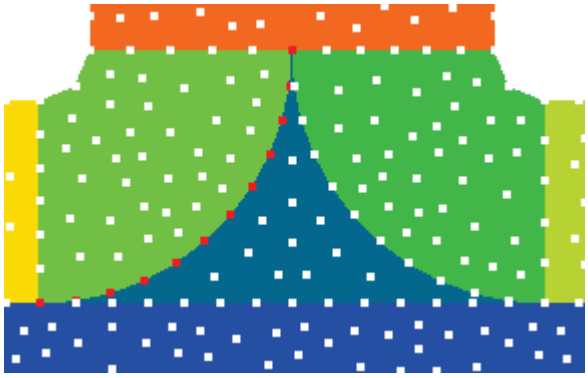
Define K_1 (1,0,0) and click the **Set K1** button. This permeability will be defined for each of the selected zones. Define K_2 (0,1,0) and click the **Set K2** button. Close the window by clicking the **Close** button. Then clear the current selection (**Selection->Unselect All**).



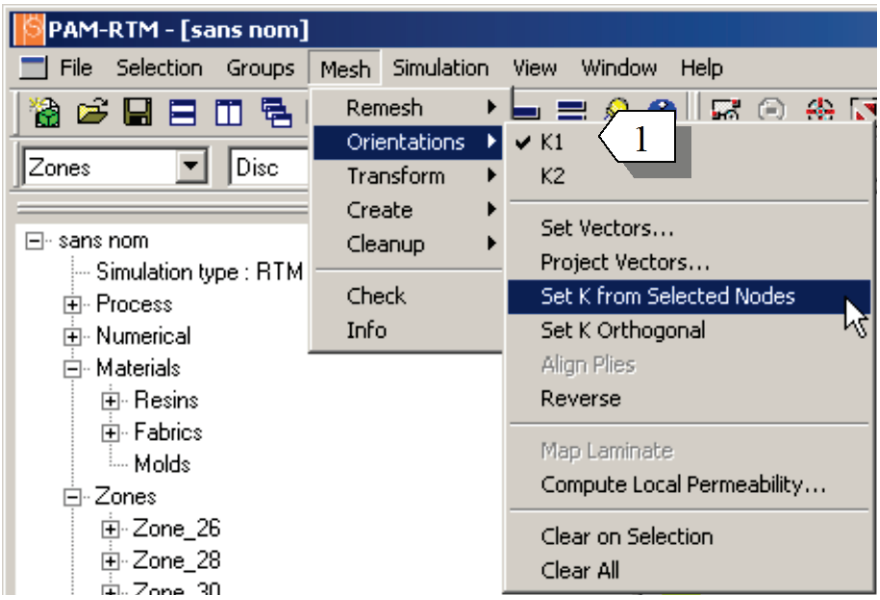
In the same way, select the elements in zone 38 (vertical part). Open the **Materials Orientations** dialog box and define K_1 (0,1,0) and K_2 (1,0,0).

We are now ready to work on the two curved sections. Clear all the selections with **Selection->Unselect All**. Select the desired zone, say zone 32 (one of the two curved zones). Then in the display toolbar, click the **N** button to activate node display. Next, in the **Selection** menu, choose **Nodes.**

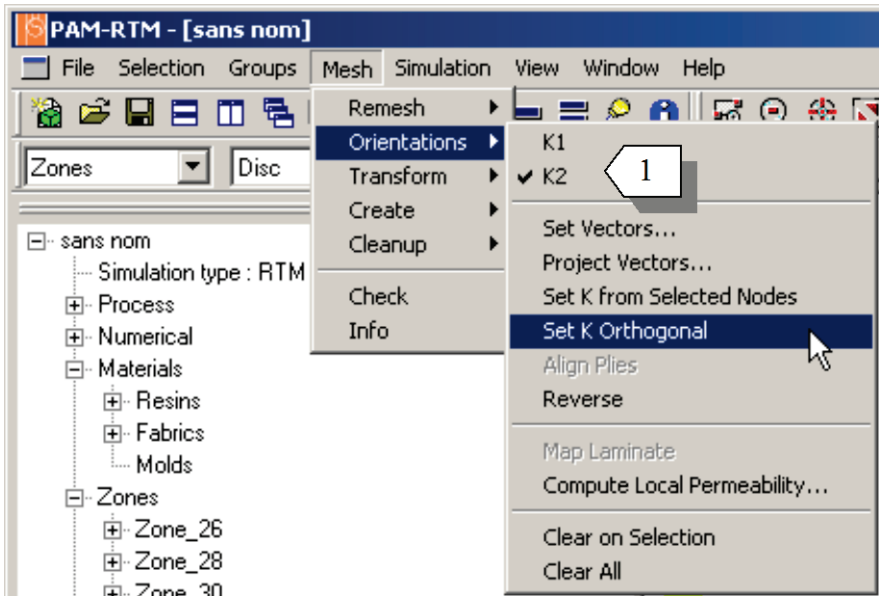
Using the mouse and clicking on the nodes of interest, you can select the nodes that will define the orientation of the fibers. They will appear in red once the selection is made. The order of selection is important. Select them from left to right or from right to left.



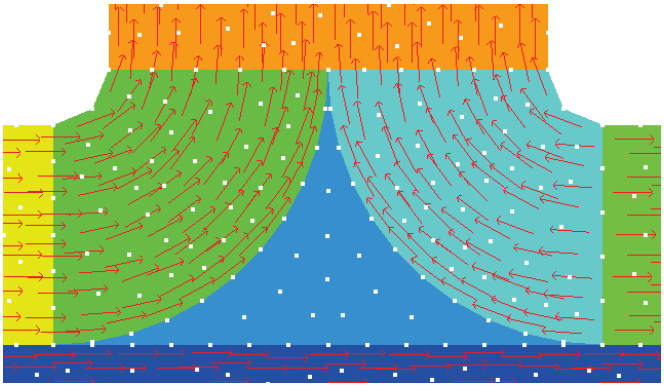
As soon as this step is completed, the fiber orientations can be defined. First of all, in the selection menu, choose Face, and select zone 32. Set the current working direction as K1 with **Mesh->Orientations->K1 [1]**. From the same menu, select **Set K From Selected Nodes** (this should be understood as *Set K1 From Selected Nodes)*.



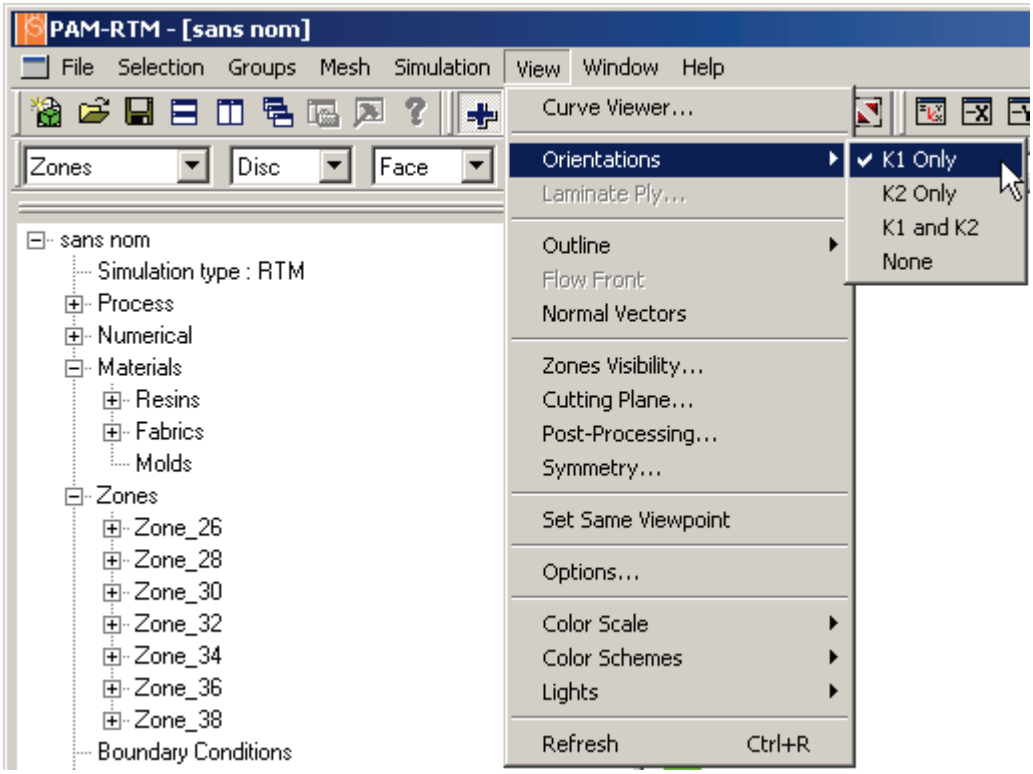
The selected elements are projected on a curve constructed from the selected nodes. The tangent vector at the projected point indicates the orientation of the fibers. Permeability K_1 is now defined in zone 32. Permeability K_2 remains to be specified from the menu **Mesh->Orientations**. After having selected **K2 [1]**, choose the submenu **Set K Orthogonal** (meaning *Set K2 Orthogonal to K1*).



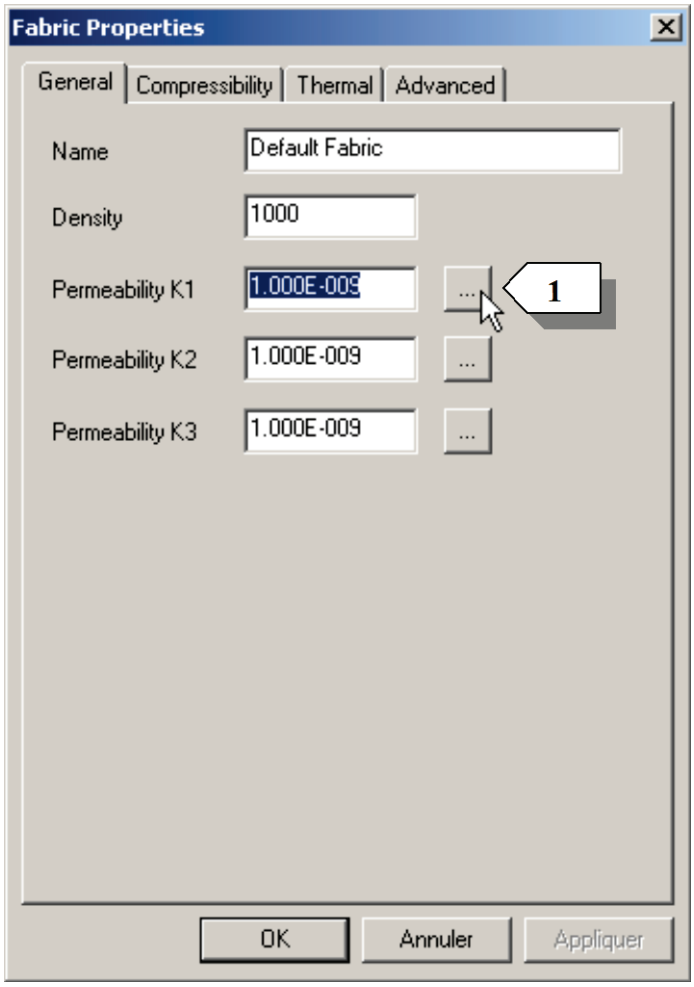
Clear all current selections and restart the same procedure with elements of zone 30. Once completed, the orientations of the fibers appear as follows:

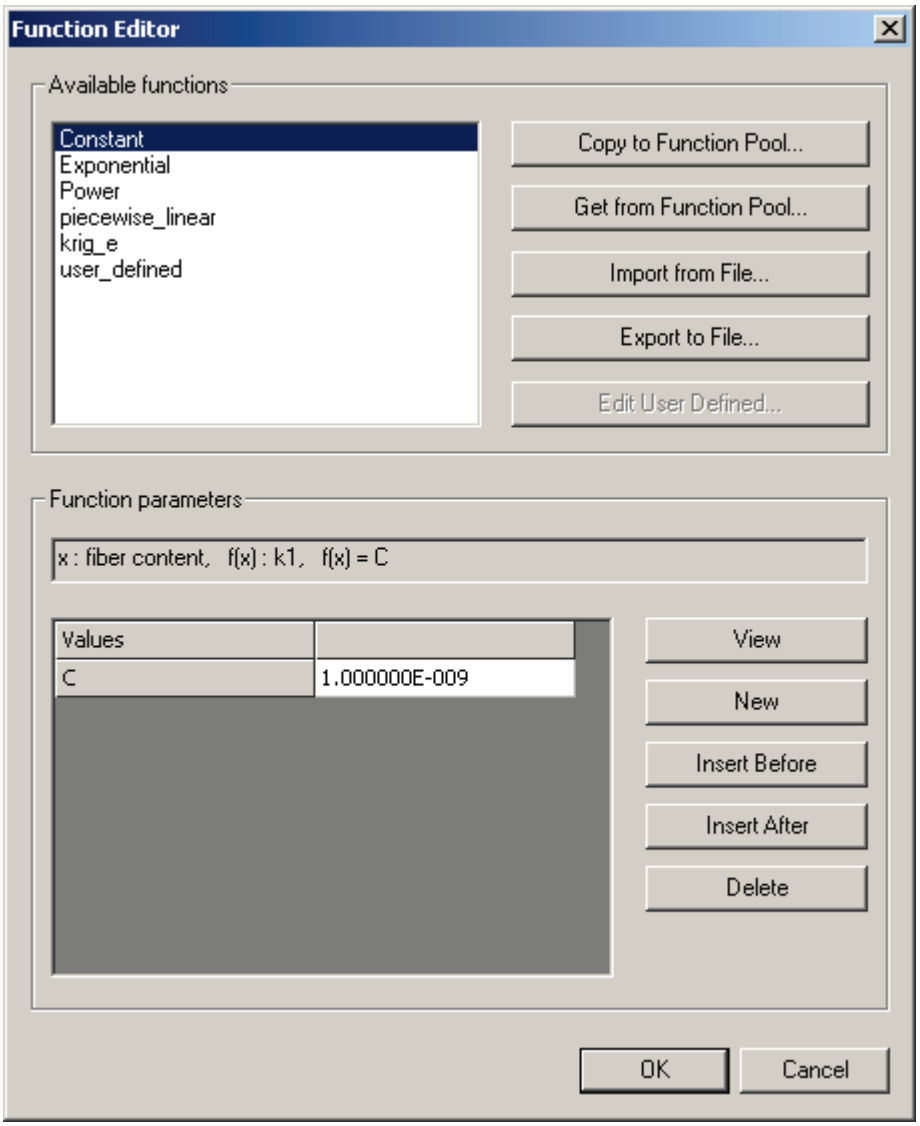


To view orientations, select **View->Orientations->K1 Only**.



Now, set the permeability of the reinforcement. Double-click on **default Fabric** and click on the **...** button **[1]**. This opens the **Function Editor** dialog box, which lets you assign a curve or a constant value to the parameter:

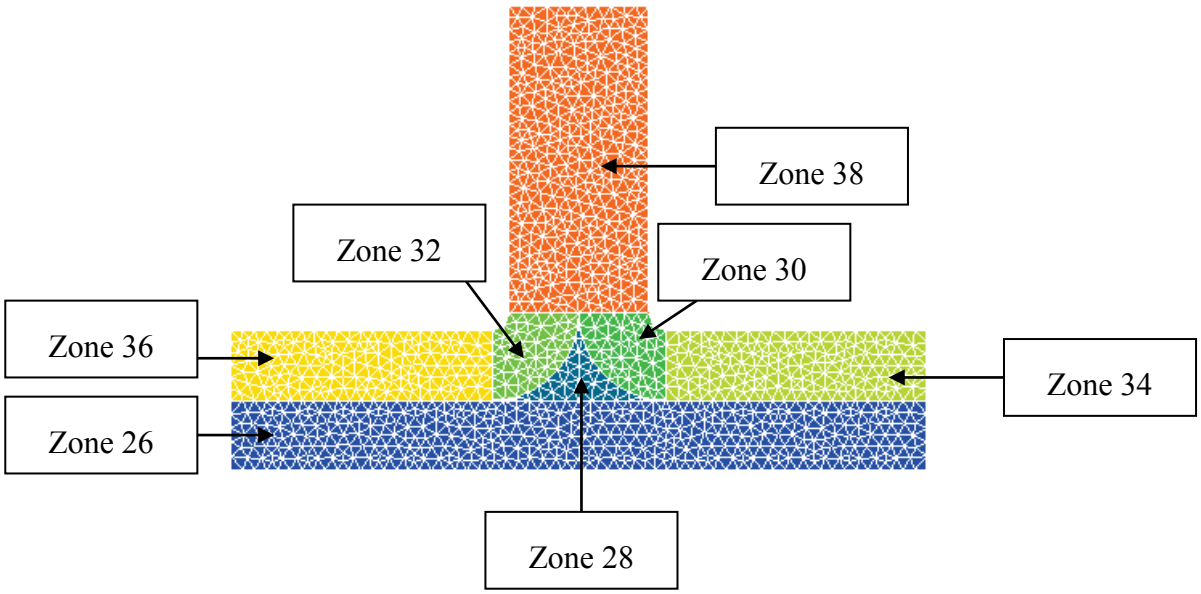

Fabric Properties
General
Compressibility
Thermal
Advanced
Name
Default Fabric
Density
1000
Permeability K1
1.000E-009
Permeability K2
1.000E-009
Permeability K3
1.000E-009
1
OK
Annuler
Appliquer



Set the permeability for the Default Fabric to K1=1 10^{-11} K2=1 10^{-12} K3=1 10^{-11}

Create a new Fabric *(***Material->New->Fabric**), name it deltoid and set the isotropic permeability to K1=K2=K3=1 10^{-13}

The following table summarizes the permeability assigned to each zone.



Zone N°	Material	K_1	K_2	K_3	Porosity
26	Default fabric	1^E-11	1^E-12	1^E-11	0.5
28	Deltoid	1^E-13	1^E-13	1^E-13	0.4
30	Default fabric	1^E-11	1^E-12	1^E-11	0.5
32	Default fabric	1^E-11	1^E-12	1^E-11	0.5
34	Default fabric	1^E-11	1^E-12	1^E-11	0.5
36	Default fabric	1^E-11	1^E-12	1^E-11	0.5
38	Default fabric	1^E-11	1^E-12	1^E-11	0.5

For every zone, you must also specify the porosity of the reinforcement (see previous table) and its thickness (0.005 m).

Define properties of the resin, set a constant viscosity of 0.02 *Pa.s*.

The boundary conditions still remain to be defined. Three groups are available. Assign Pressure to the one that corresponds to the injection line (left side). Enter a constant pressure value of 2 10^5 *Pa*. Then, define the other two lines as vents.

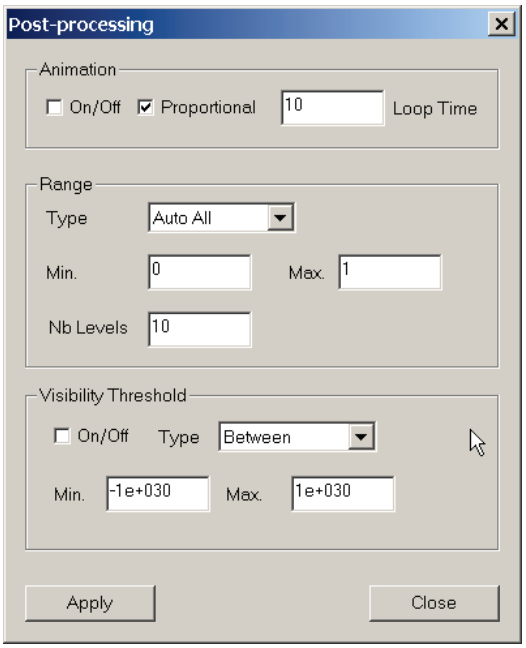
Now choose **File->Save** and run the simulation.

Note:

- *It is important to save this file before launching a simulation, otherwise the changes you made to the simulation parameters won't be used in the simulation.*

Visualizing the Simulation Results

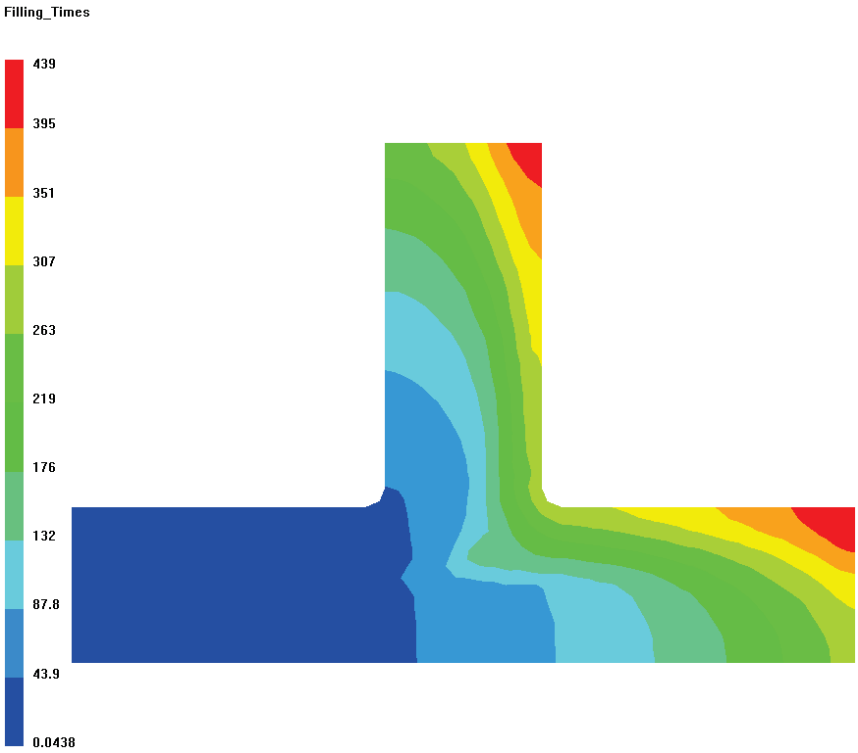
Many post-processing parameters can be changed in the **Post-processing** dialog box by selecting **View –> Post-Processing**.



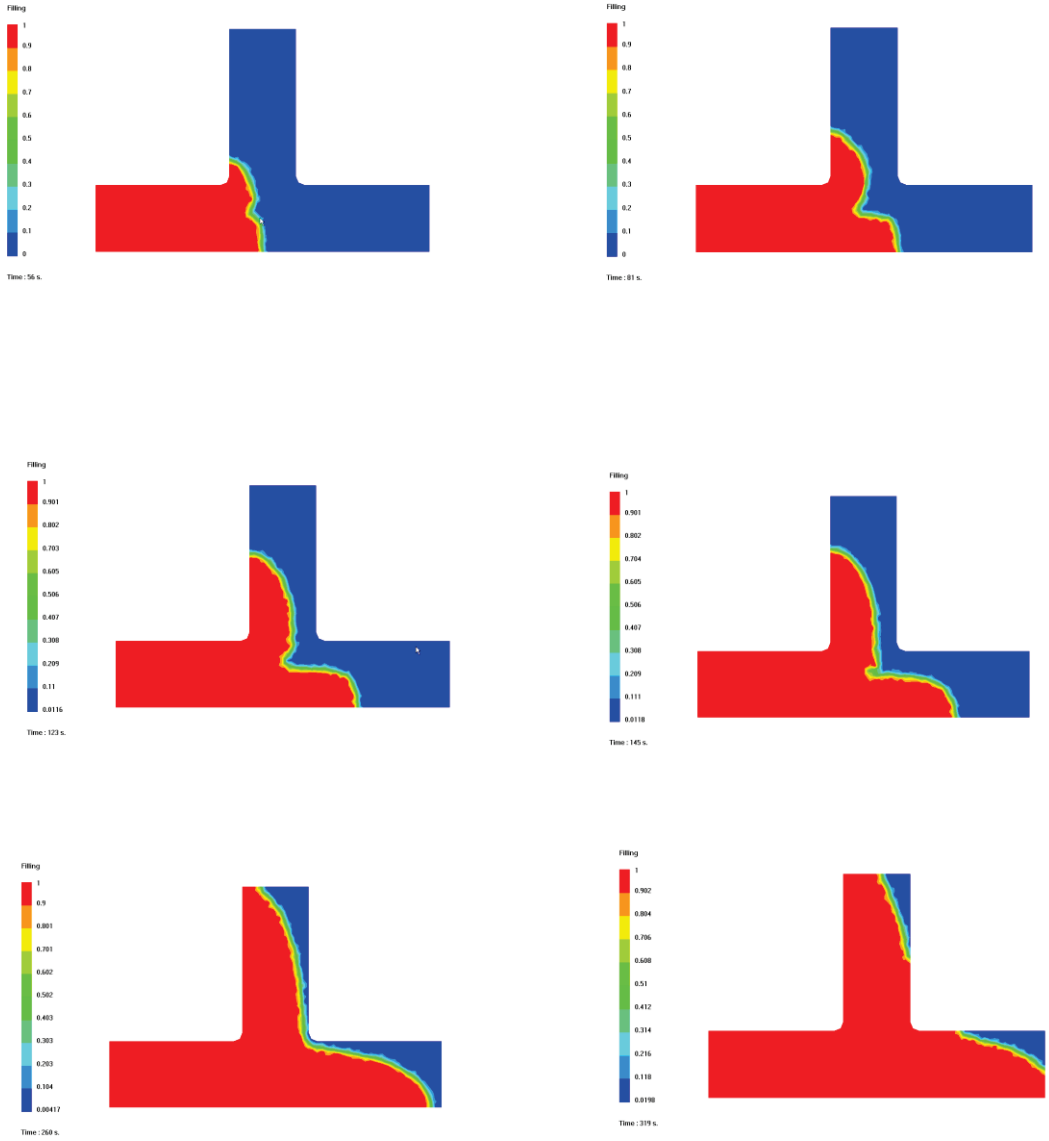
After loading the simulation results, choose the *Filling* option in the drop-down list to visualize the evolution of injection. Then by sliding the Time Step control arrow in the tool bar, the filling of the mold is displayed in time. By clicking on the button A (animation), an animated display of mold filling is activated. The animation speed can be modified by changing the **Loop Time** field in the **Post-processing** dialog box.

To get a smooth injection flow front**,** select the Type *Iso* in the drop-down list. The number of colors may be modified in the *Nb levels* field in the Post-processing dialog box.

The figure below shows the different positions of the flow front in time in the part.



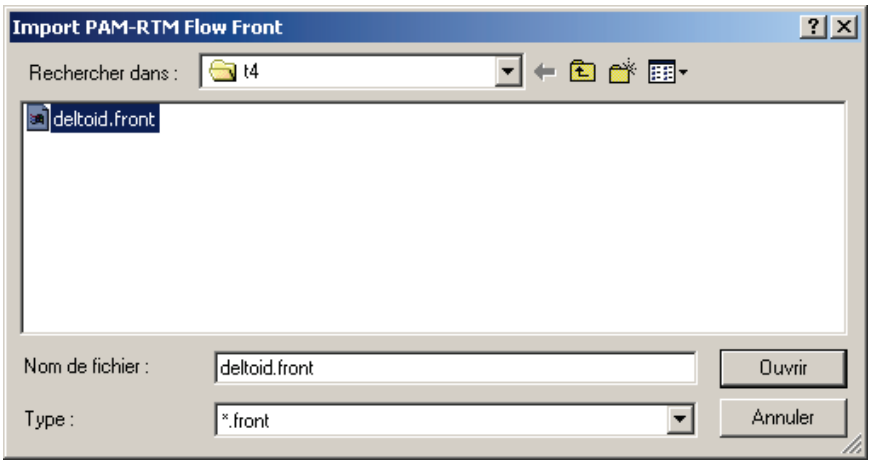
The following figures show sequentially how the mold is filled:



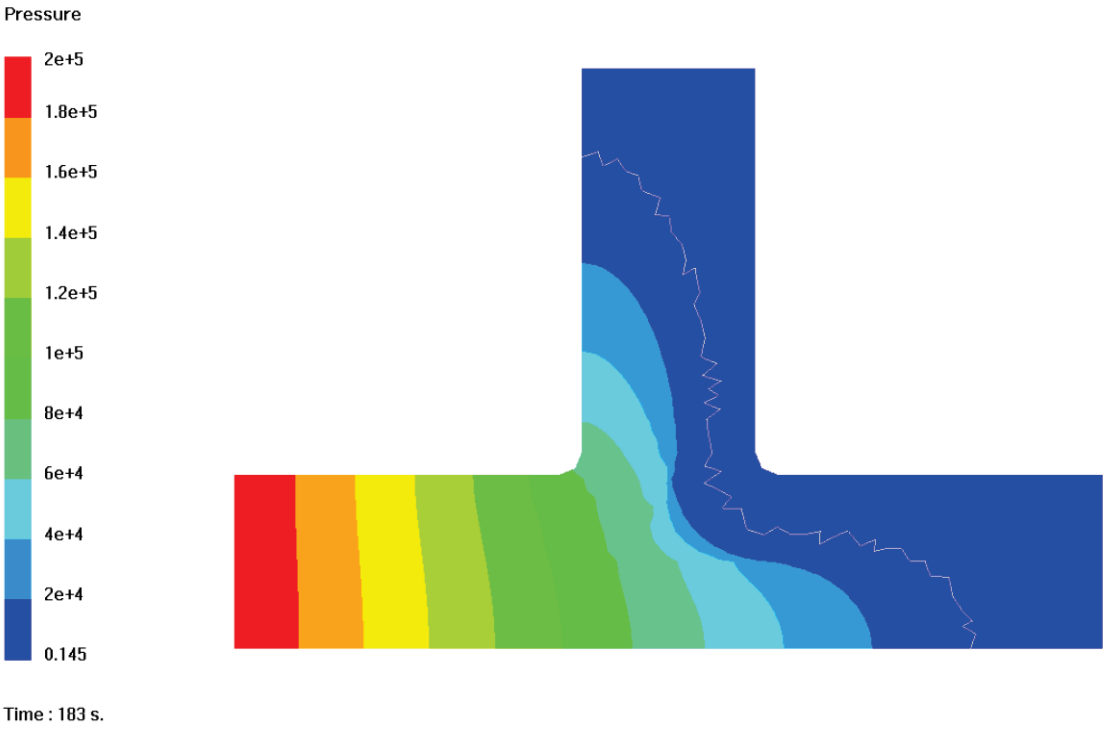
The injection is performed from the left side of the part. The lower permeability in the central zone of the junction delays the flow front in that zone.

The pressure field can also be visualized during the injection. Select *Pressure* in the drop-down list in the display toolbar.

It is sometimes useful to visualize the resin front on top of another scalar field such as the pressure or temperature field. To do so, select **File–> Import–> Scalar Fields –> PAM-RTM Flow Front (.front)… ,** then under the **Import PAM-RTM Flow Front** dialog box, select the flow front file and click **Open**.



The following image is displayed, in which the flow front appears as a white line. This is the raw position of the flow front, without any smoothing. On one side of the flow front, the elements are completely saturated (filling factor = 1), while on the other side elements are partially saturated or empty (0 <= filling factor < 1).



COMPARISON 2D – 2.5D – 3D

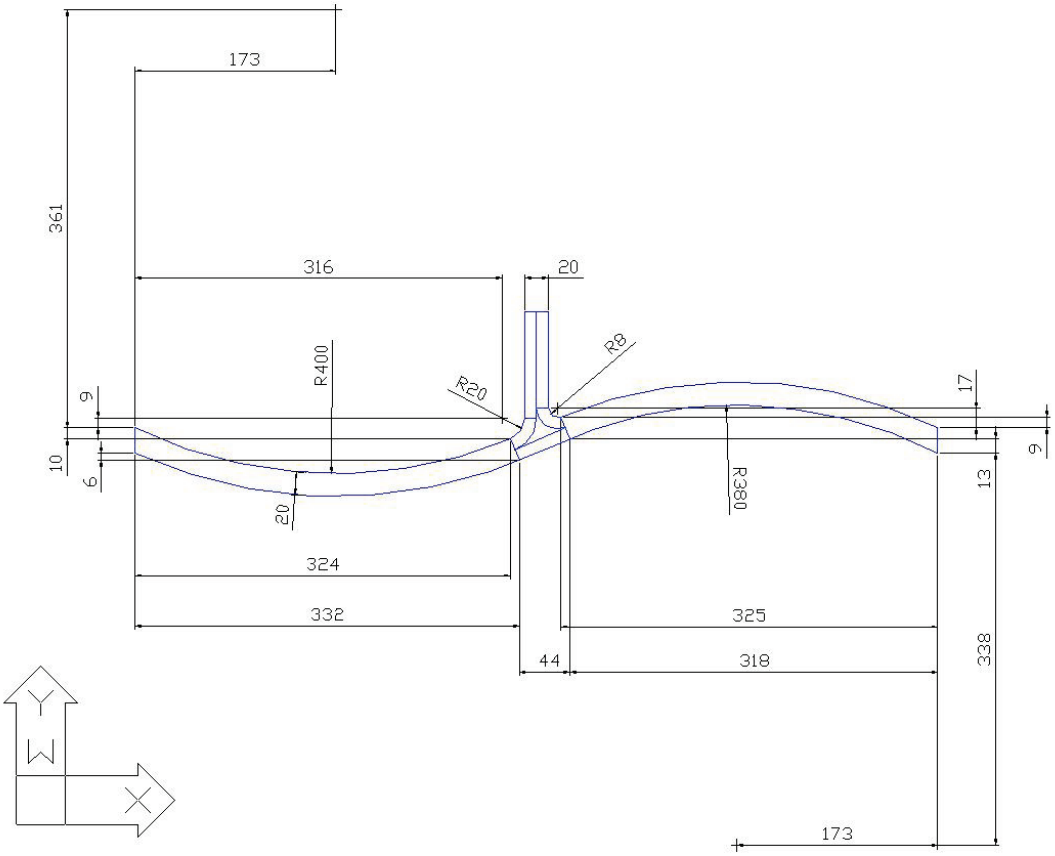
The following files are used in this example.

- ***comparison_2D_start.unv***, ***comparison_25D_start.unv***, ***comparison_3D_start.unv*** (starting mesh)
- ***comparison_2D.dtf*** + ***comparison_2D.unv*** (solution for 2D)
- ***comparison_25D_1.dtf***, ***comparison_25D_2.dtf***, + ***comparison_25D.unv*** (solution for 2.5D)
- ***comparison_3D_1.dtf***, ***comparison_3D_2.dtf***, + ***comparison_3D.unv*** (solution for 3D)

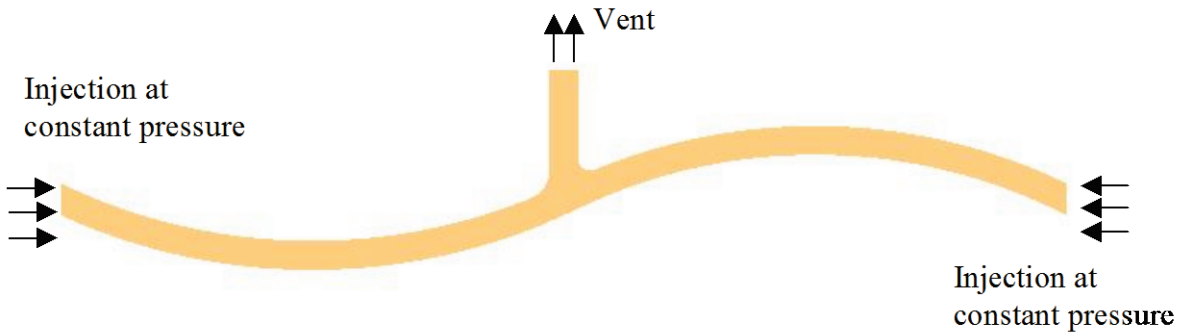
Introduction

Description of the Part

This example describes the results obtained for a part whose dimensions are specified in the figure below:



The injection is performed at a constant pressure of 2 *bars* from each extremity of the part as illustrated on the figure below:

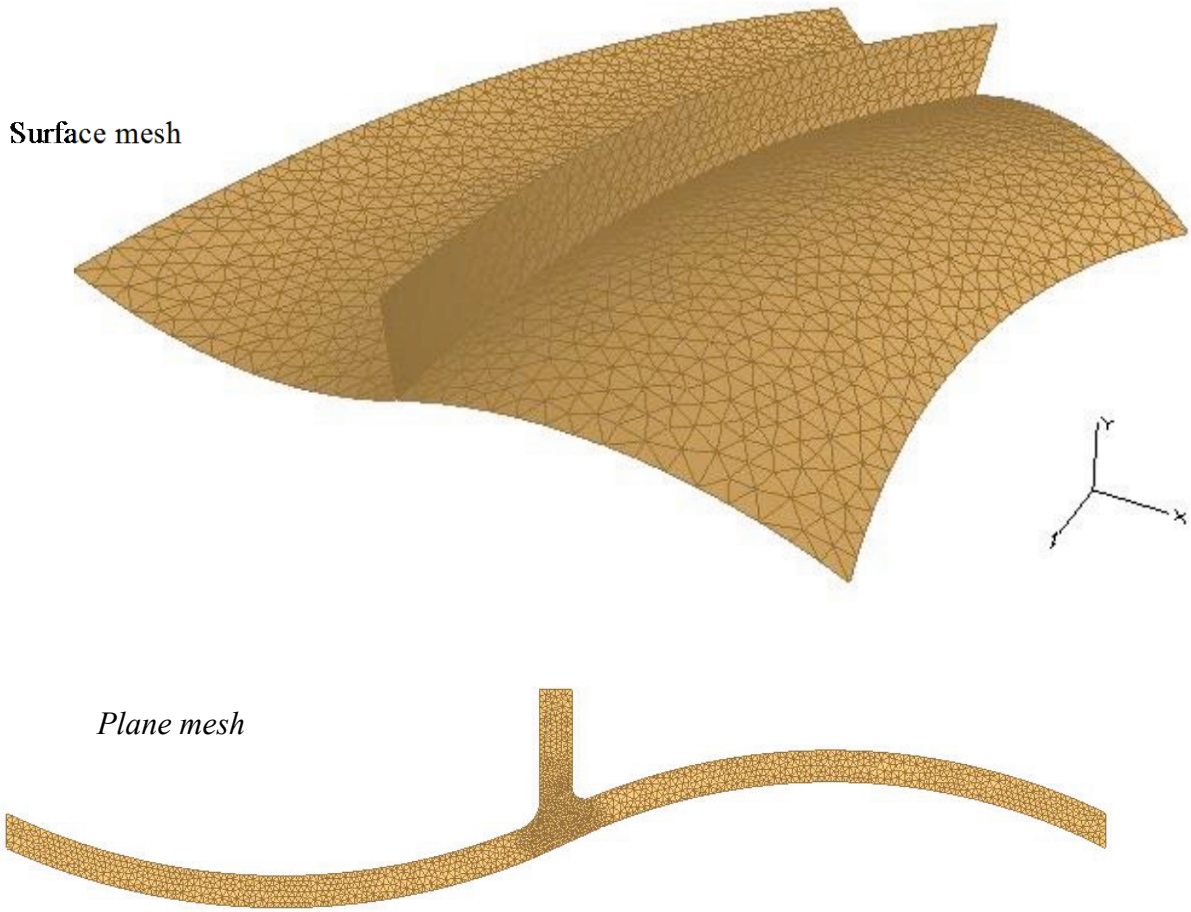


Objectives of the Analysis

The objectives of this analysis is to study the position of the resin front and to compare the results obtained from three types of mesh:

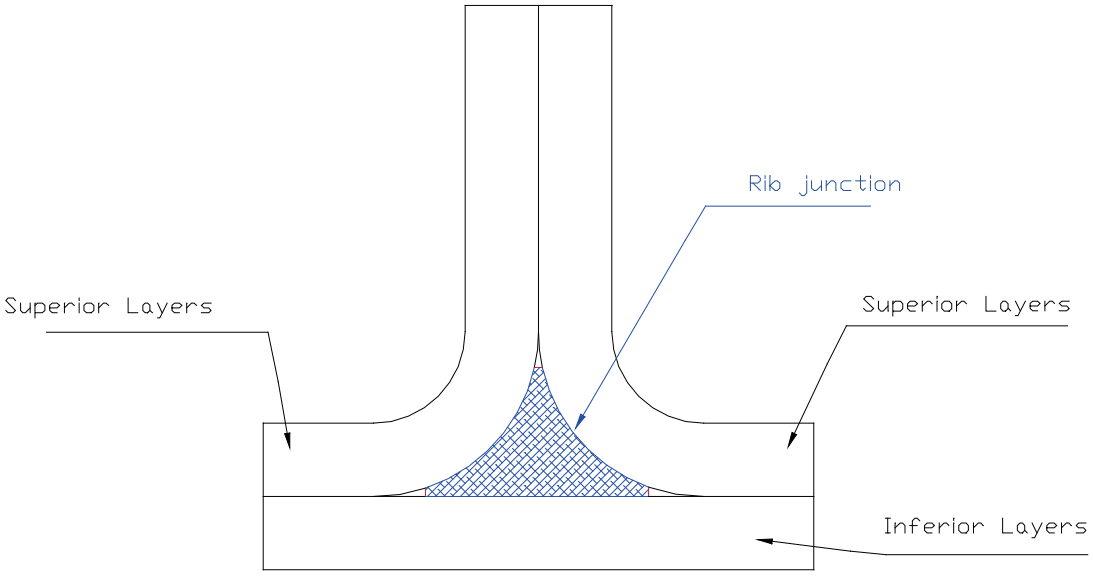
- 2D plane mesh of triangles
- 2.5D surface mesh (thin shell) with triangular shell elements
- 3D solid mesh of tetrahedrons

Solid mesh



Description of a Typical Rib Junction

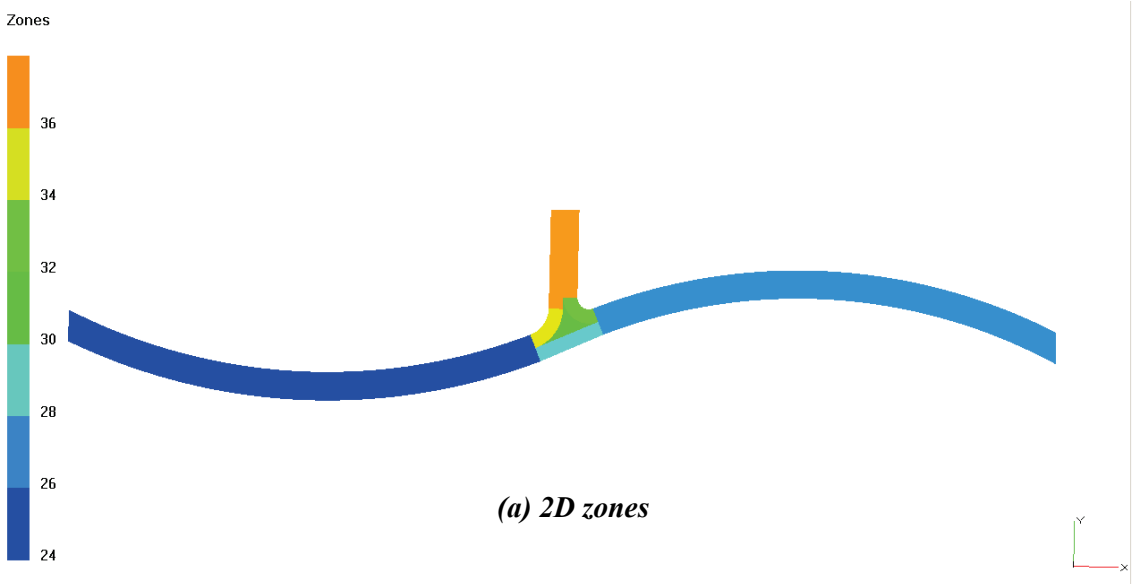
The permeability of the reinforcement is $K_1 = K_2 = K_3 = 1.10^{-9}$ m^2 and the porosity is $\phi = 0.5$. The rib junction is constructed with unidirectional fibers to fill the internal volume between the two top folded plies and the inferior layers in order to create the T shape. The permeability of the reinforcement in the rib junction (shaded area in the figure below) is $K_1 = K_2 = K_3 = 1.10^{-10}$ m^2.



Typical rib junction (T shape)

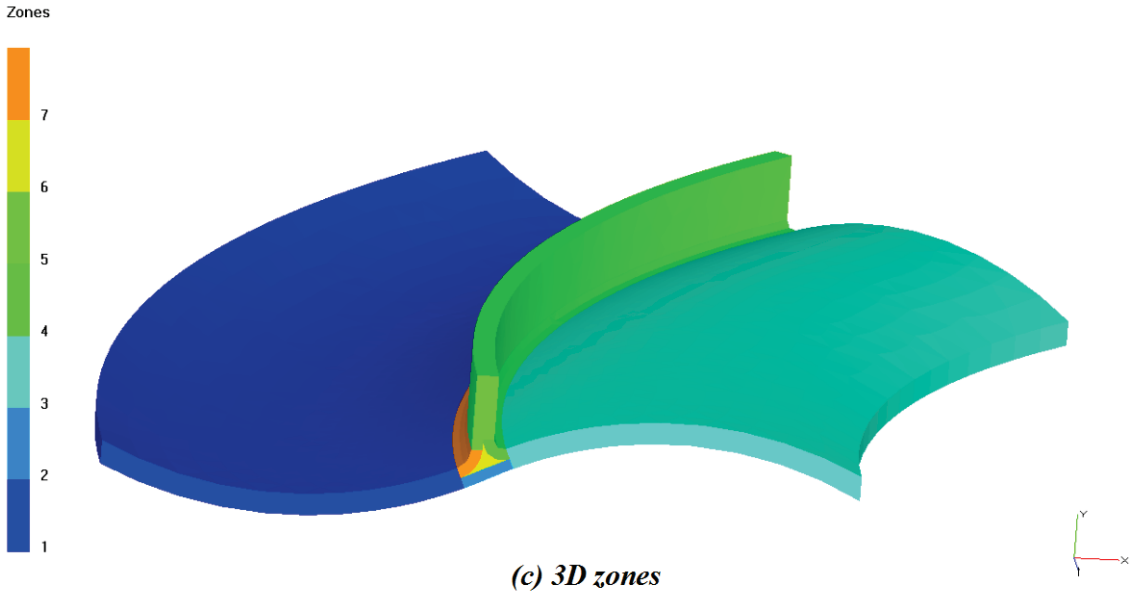
Zones of the Part

The analysis was carried out in order to compare the results between a 2D simulation with analyses performed with shell (2.5D) and solid (3D) elements. The following figures show the different permeability zones for each type of simulation.



(a) 2D zones

(b) 2.5D zones



(c) 3D zones

Zones for the three types of mesh:

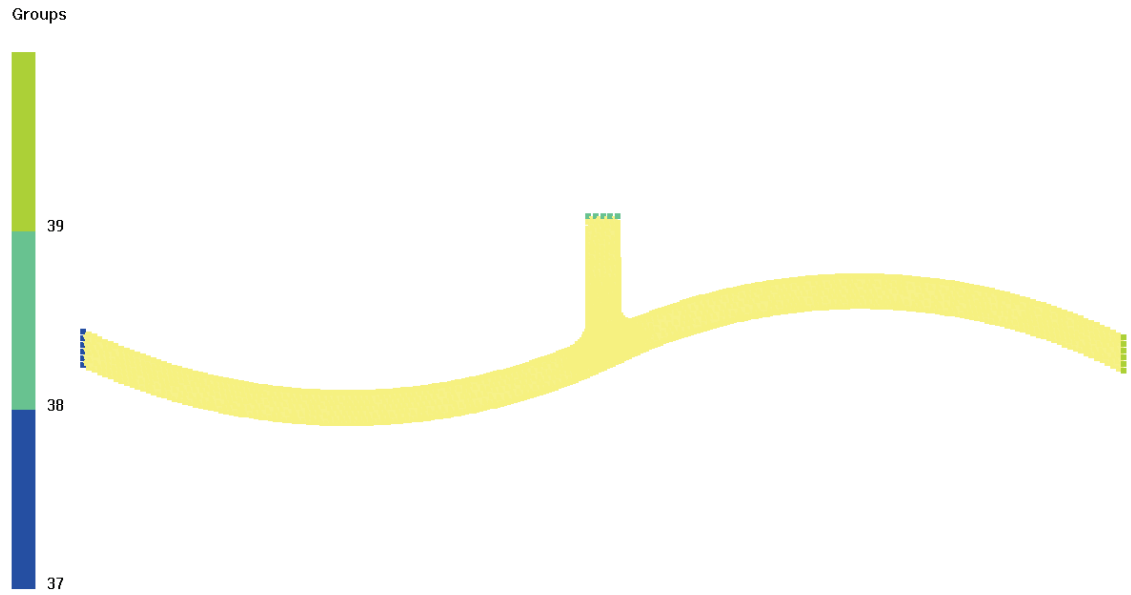
We can immediately notice several differences. Indeed, in the surface simulation, there is no central zone at the junction. The zones used in the 2D simulation do not consider the curvature of the part. These topics will be discussed later.

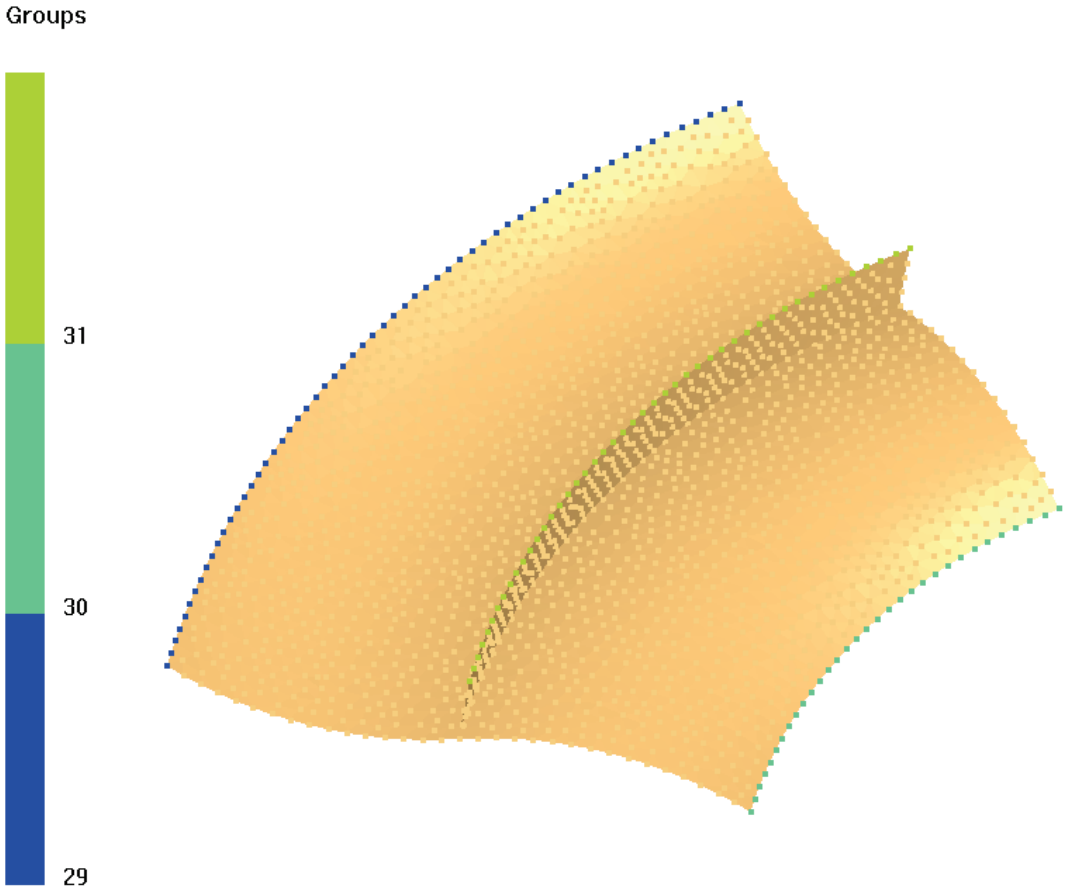
Injection Strategies

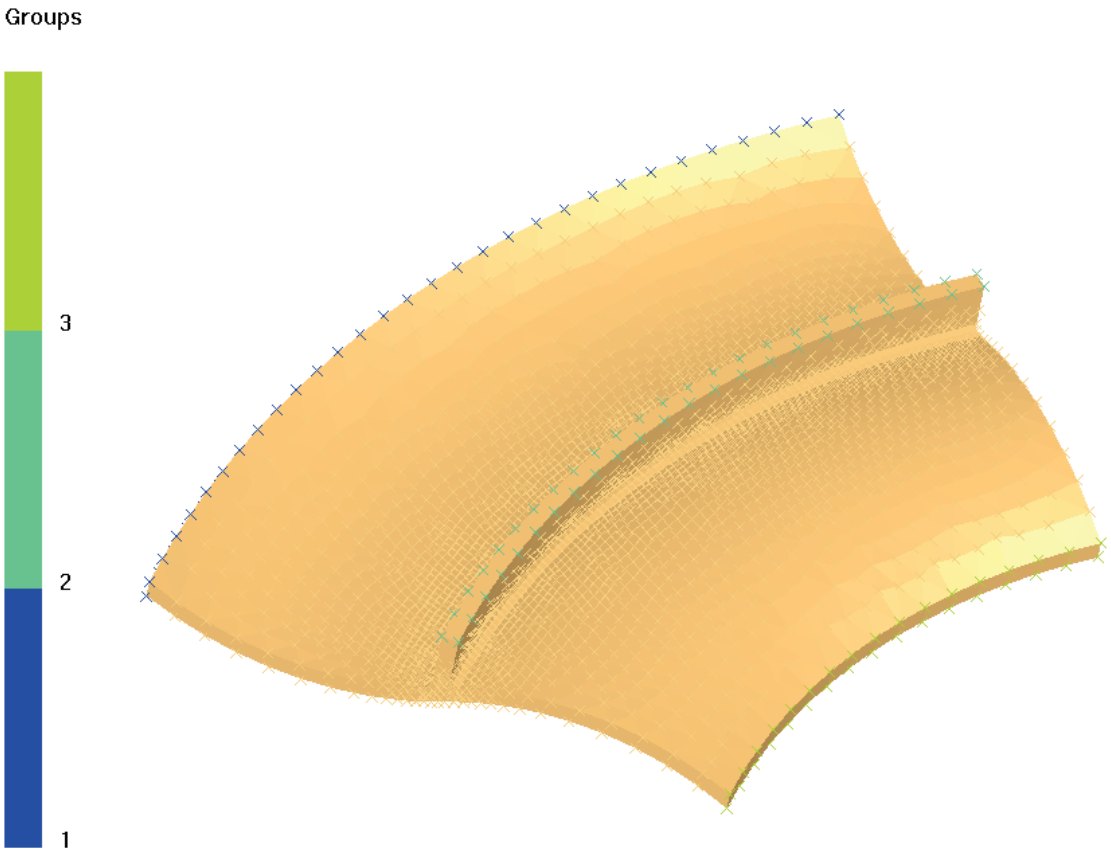
The following table indicates the injection pressure used for each experiment.

Simulation	P_{inj} 1	P_{inj} 2
2D	2 *bars*	2 *bars*
2.5 D/1	2 *bars*	2 *bars*
2.5 D/2	2 *bars*	2.3 *bars*
3 D	2 *bars*	2 *bars*

The following figures show the groups of nodes that define the injection boundary conditions:



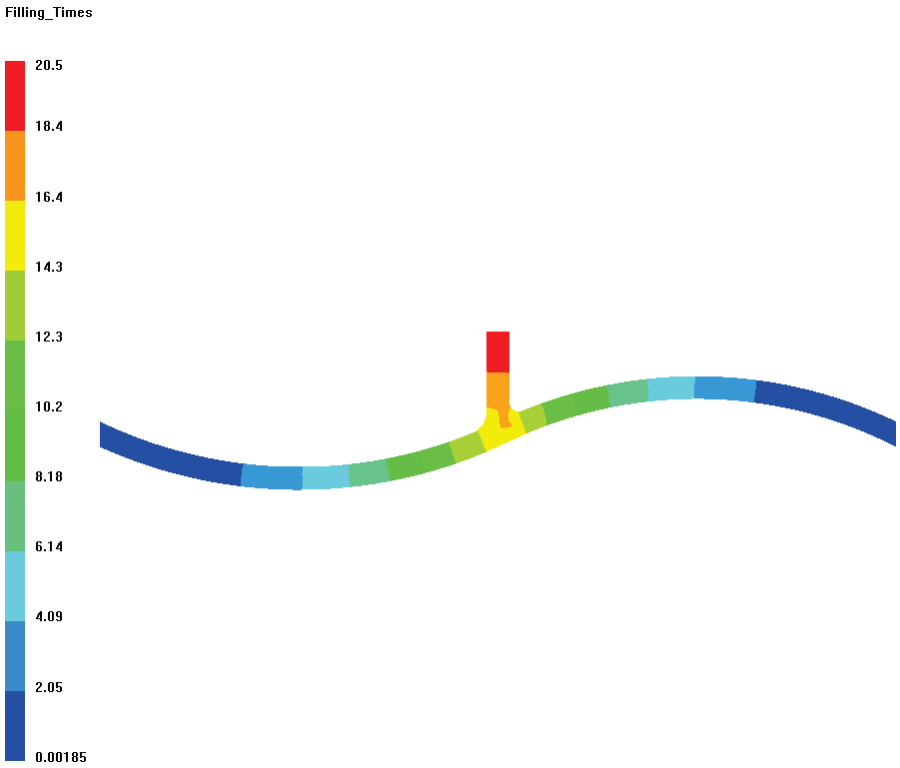

Groups
31
30
29

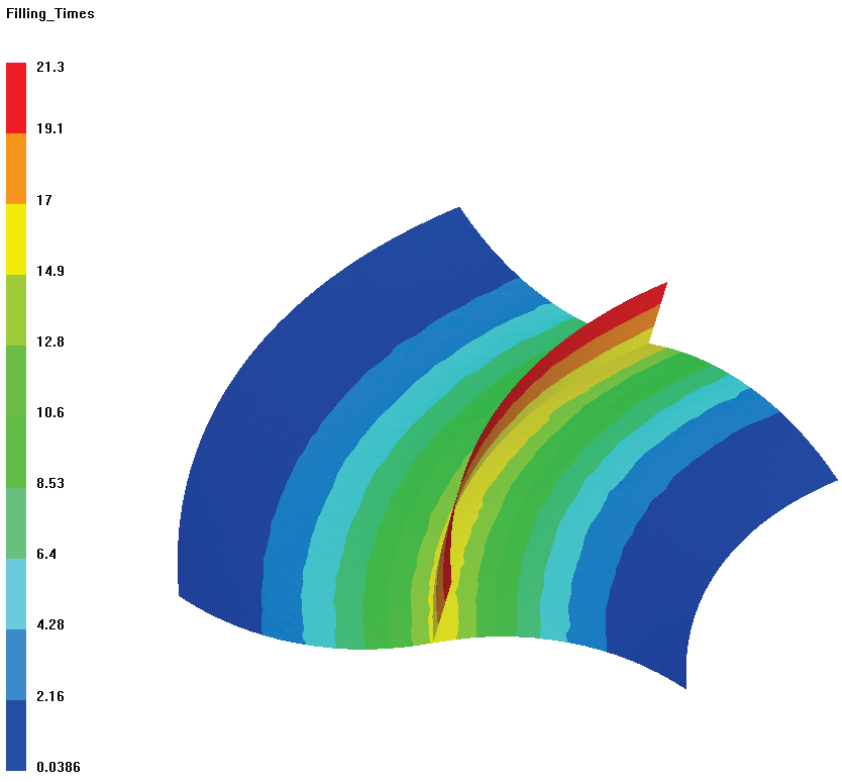


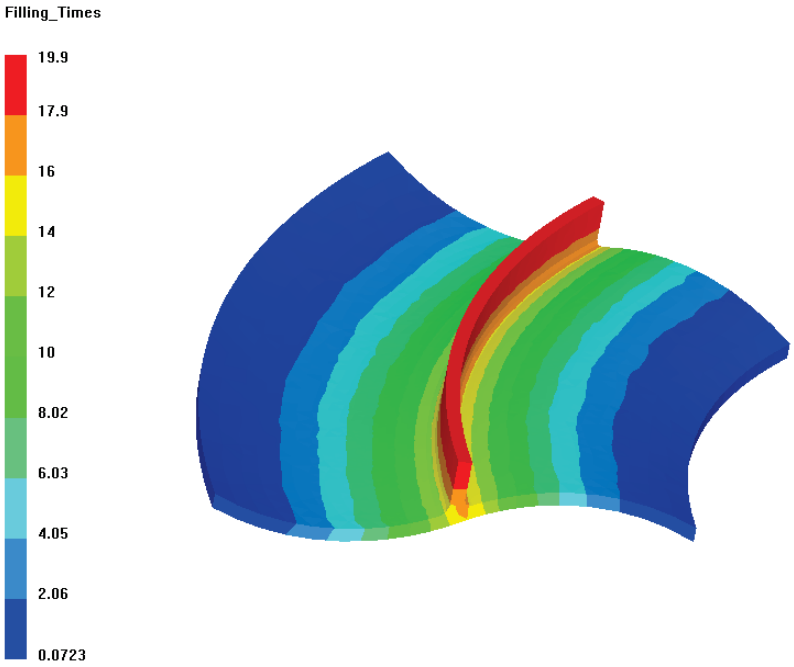
Simulation Results

Filling Times

The first interesting point to verify here is the injection time required to fill the mold for each type of analysis. The filling times are in fact very similar, between 19.9 and 21.3 *seconds* for the three simulations. This demonstrates the consistency between the different options offered by the software.

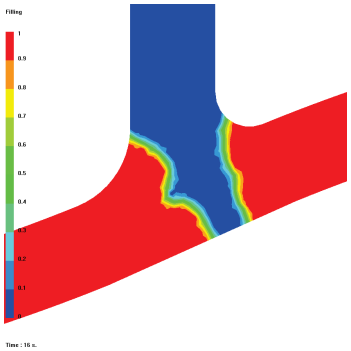

Filling_Times
20.5
18.4
16.4
14.3
12.3
10.2
8.18
6.14
4.09
2.05
0.00185

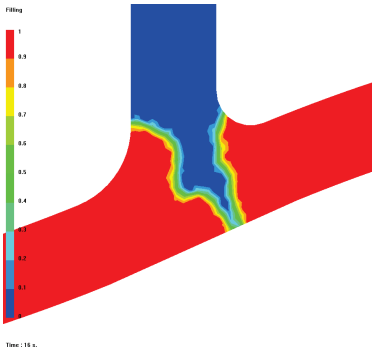

Filling_Times
21.3
19.1
17
14.9
12.8
10.6
8.53
6.4
4.28
2.16
0.0386

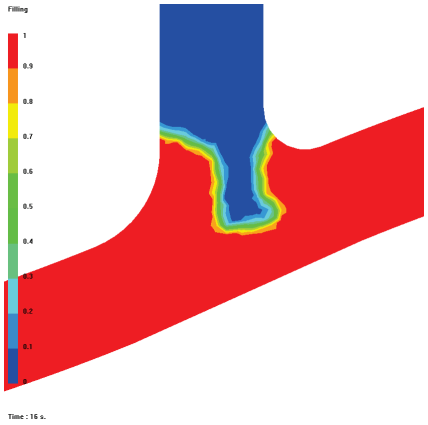


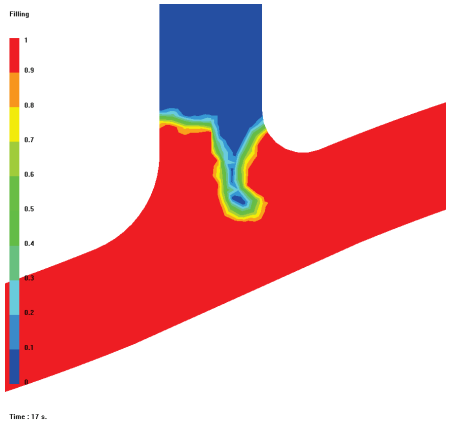
Special Effects in the Rib Junction

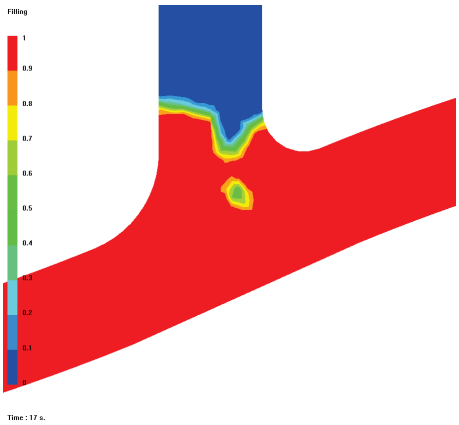
However, several differences exist between the different types of simulation. The 2D simulation shows the details of the filling in the T junction, which is naturally not possible with the 2.5D results. An air bubble is formed in the T junction as illustrated below by a series of filling results at different injection times. Although a 2D simulation allows observation of local effects, it does not give a 3D picture of mold filling. As a matter of fact, the whole geometry of the part has an influence on the filling pattern.







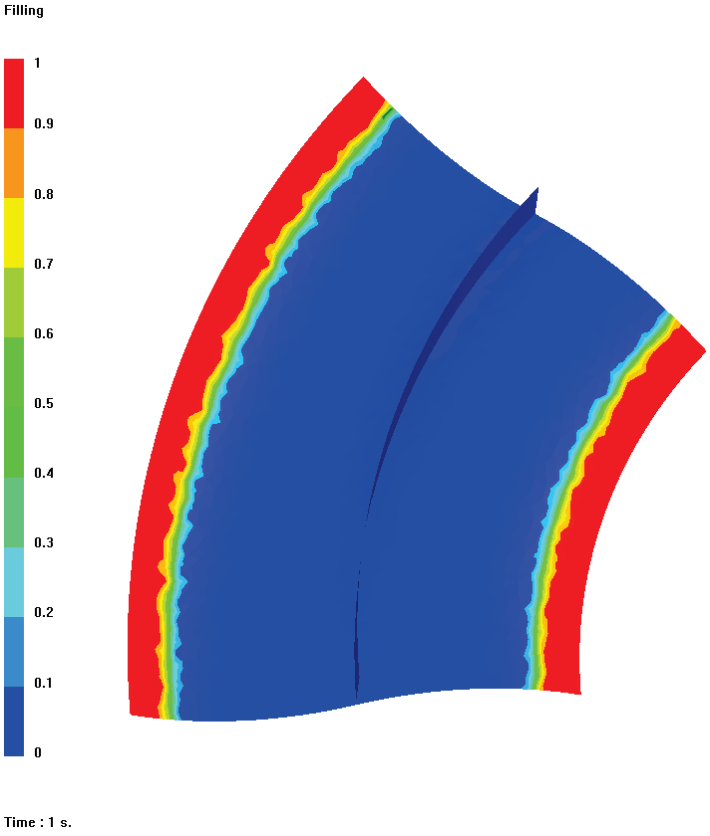


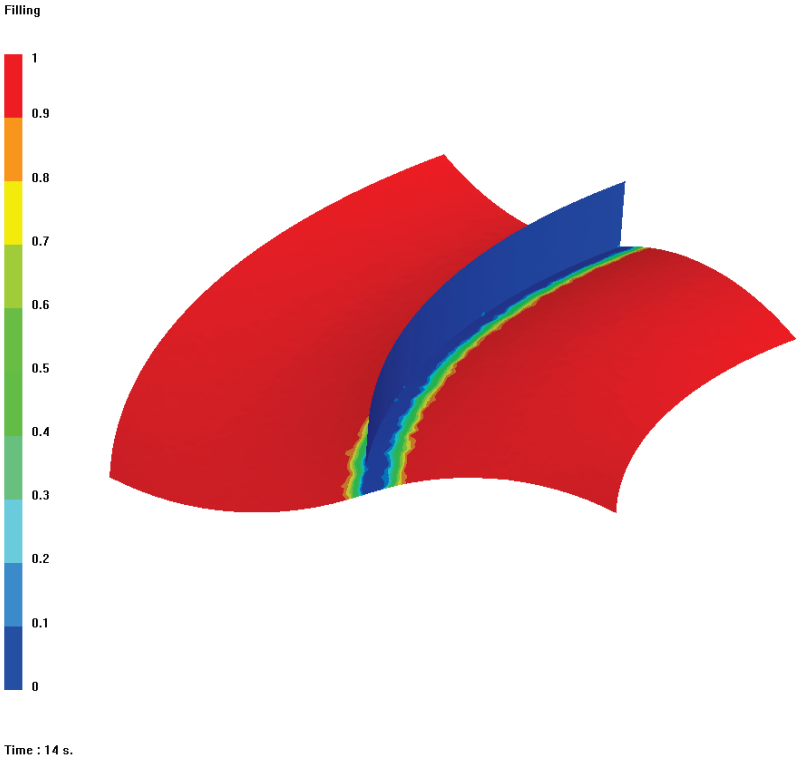


This air bubble could possibly be removed by the pressure field up to the vent. Note that this is no longer a problem if the injection is performed under vacuum.

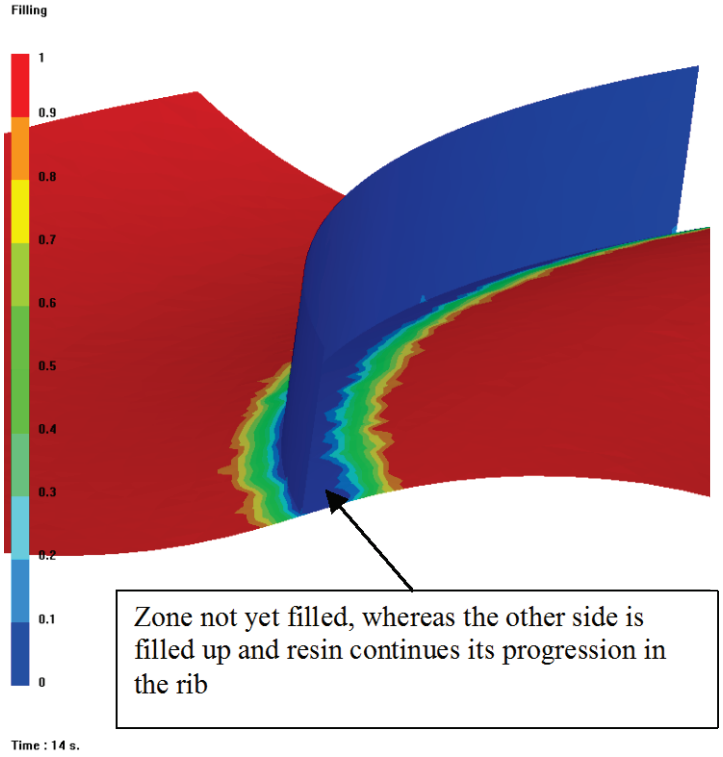
Convergent and Divergent Flows

A surface simulation (2.5D) allows to compare the injection pressure with a 2D analysis. Note that the resin front does not merge near the rib like in the 2D analysis, but on the right panel, where the flow is divergent. As a matter of fact, the resin flow converges in the left panel and diverges in the right panel. This difference in geometry accelerates the resin flow in the convergent geometry as shown in the figure below:


Filling
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time : 1 s.

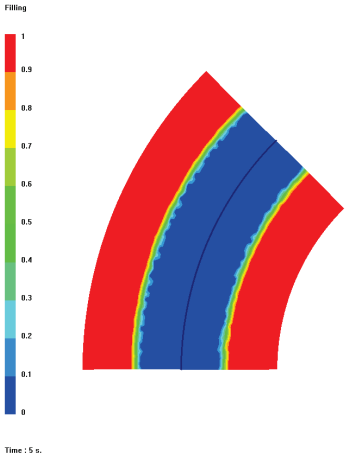

Filling
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time : 14 s.

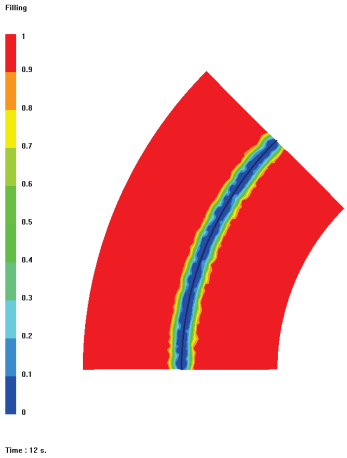
Although the injection pressure is the same on both sides, the left panel fills up faster than the right one. The surface simulation, and not the plane simulation, could show this phenomenon, which is due to resin flows in convergent versus divergent geometries.

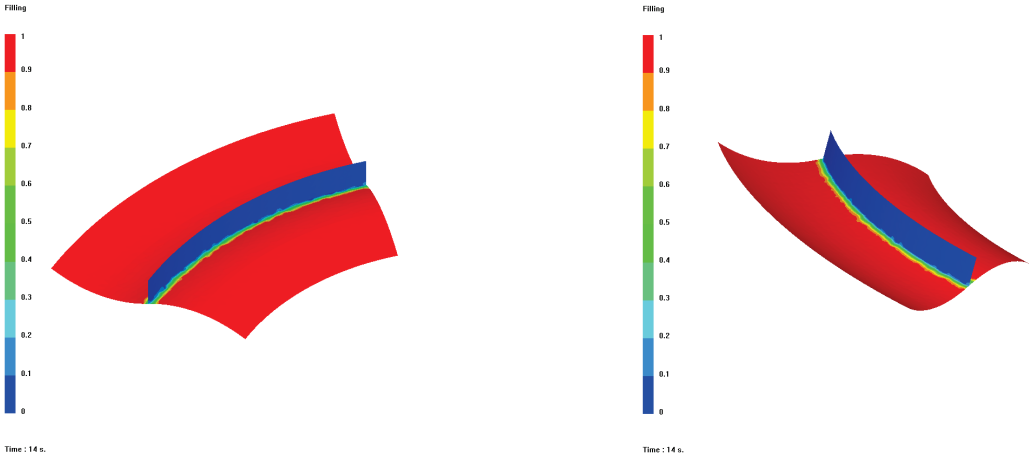


Modification of the Injection Pressure on one Side

In order to merge the two resin fronts in the center of the part, it is possible to inject from one side at 2 *bars* and from the other at 2.3 *bars*. The flow fronts merge then right in the middle of the part at the rib connection as illustrated in the figures below:





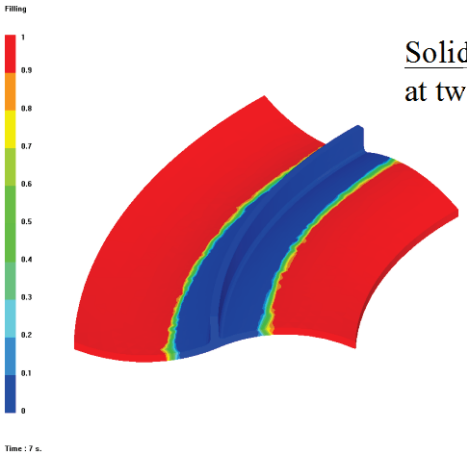


The selection of two different injection pressures permits to merge the resin fronts in the center of the part, i.e., directly at the rib junction

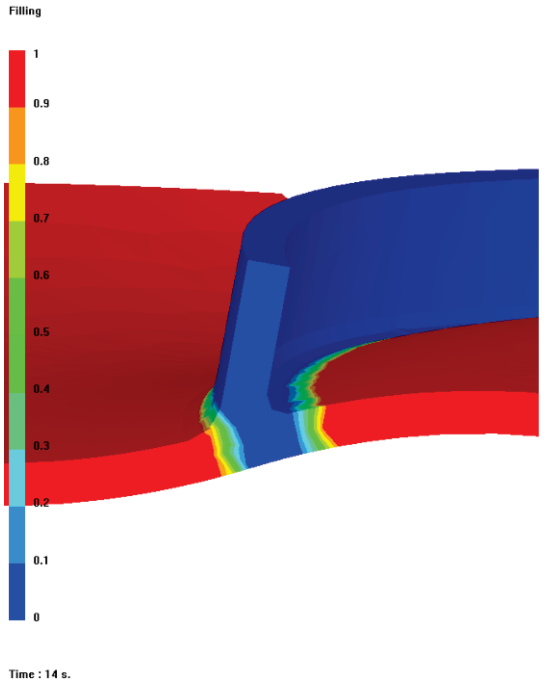
The need to inject with two different pressures would not have appeared without performing a surface simulation.

3D Solid Simulations

Although surface simulations (2.5D analysis) provide a global vision on the filling of the part, no local effects are shown such as how the two incoming resin fronts merge in the T junction for example (where it was seen that air bubbles form). 3D solid simulations visualize such problems. Both global and local effects will appear at the same time: convergent and divergent flux phenomena, as well as air bubbles in the rib junction. However, the time required to model the geometry of the part, generate the 3D mesh and especially, the calculation time to simulate the injection, becomes much more important.



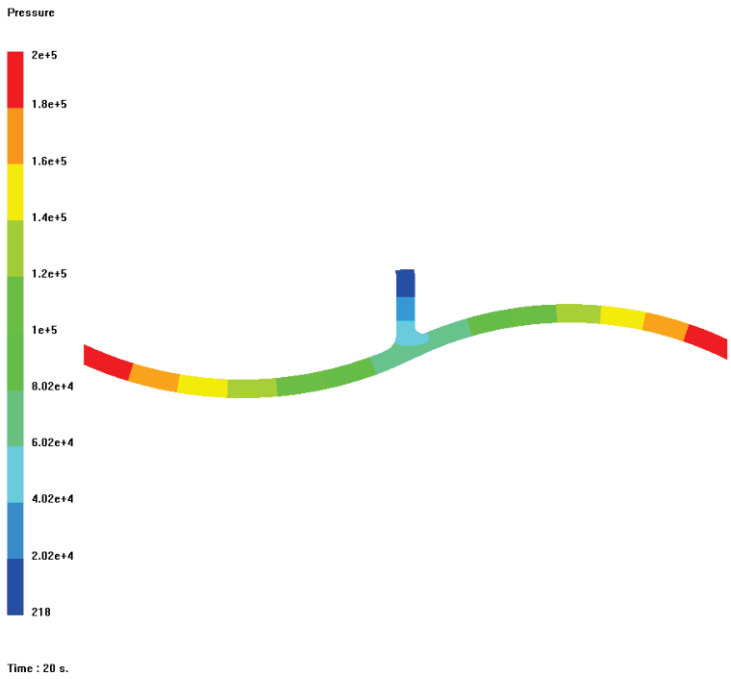
Solid simulation: injection
at two bars from each side



Geometry related effects can be studied with a 3D simulation, which provide a **global vision**. As shown in the figure on the left, it is necessary to inject at a higher pressure so that the resin fronts will merge at the center of the part.

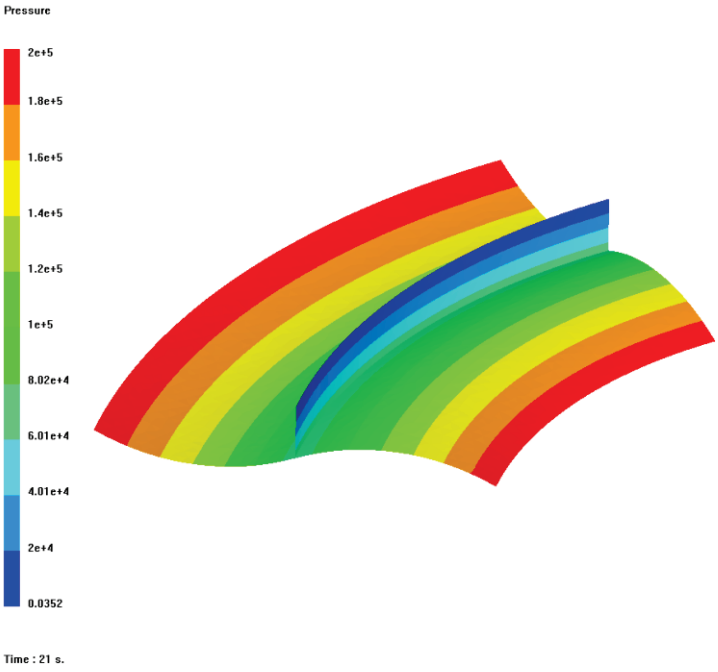
Pressure Field in the Cavity

Finally, as illustrated by the images of next page, the analysis of the pressure field in the cavity during the injection does not show much difference between the three types of simulations considered here.

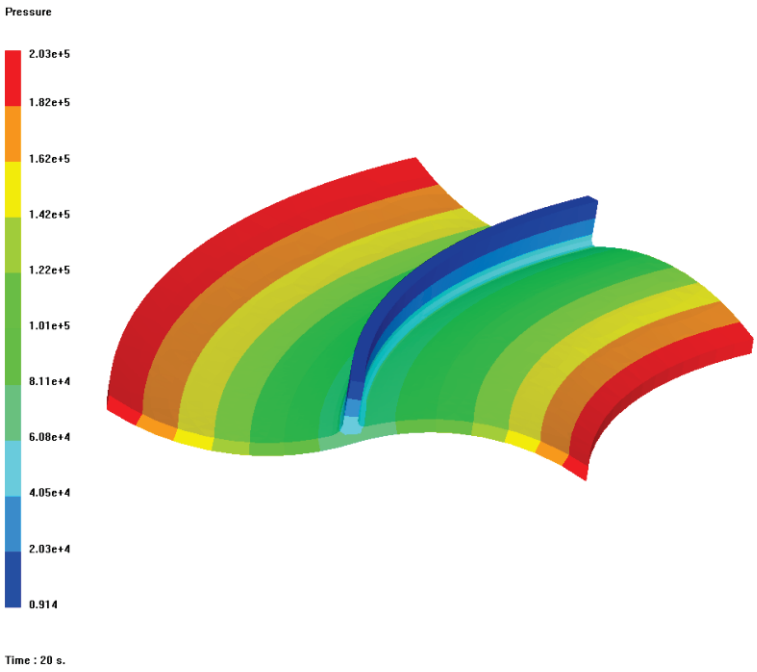


Pressure field for a 2D simulation

Pressure field for a surface simulation



Pressure field for a 3D simulation



Conclusion

In conclusion, a 3D simulation with solid elements allows observation of global and local effects related to the geometry of the part. A surface simulation (2.5D) provides a global vision at a reduced cost while a 2D simulation in a section of the part shows only local effects. The advantage of a 2D simulation is the much reduced calculation time.

3D simulations require a much larger number of elements to perform the calculations, which causes the calculation times to increase dramatically.

The following table compares the numbers of elements used in this example with the corresponding calculation times. The simulations were run on a dual processor Pentium 3 700 MHz PC.

Simulation	Number of elements	Simulation time
2D	3084 triangles	5 min., 8 s.
2.5D	3979 triangles	1 min, 25 s.
3D	35137 tetrahedrons	100 min.

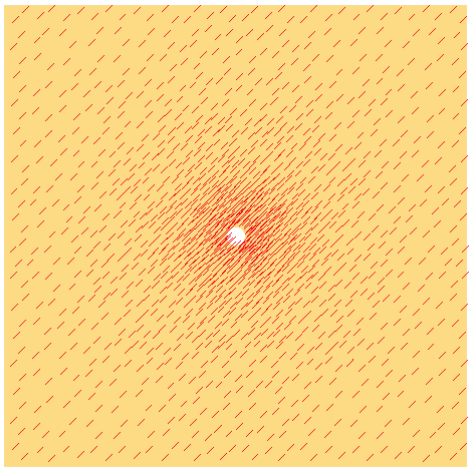
AIR ENTRAPMENT

The files related to this example are:

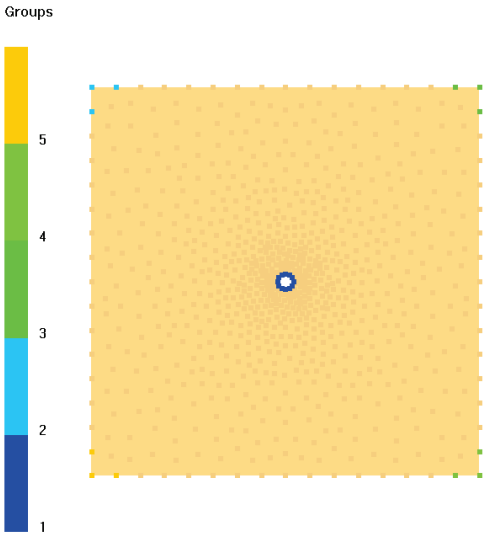
- ***air_trap_start.unv*** (starting mesh)
- ***air_trap.dtf + air_trap.unv*** (solution)

Visualization of Groups and Orientations

In this tutorial, we do a central injection in a fabric with anisotropic permeability. Here is a picture of the K_1 principal permeability direction.

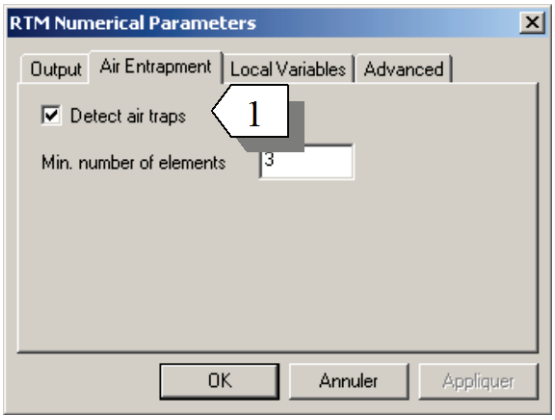


We use this simple example to demonstrate the air entrapment feature of **PAM-RTM™**. We want to force creation of an air trap in the bottom right corner by closing vents shortly after beginning of injection. Only the top left vent stays open during the complete simulation.



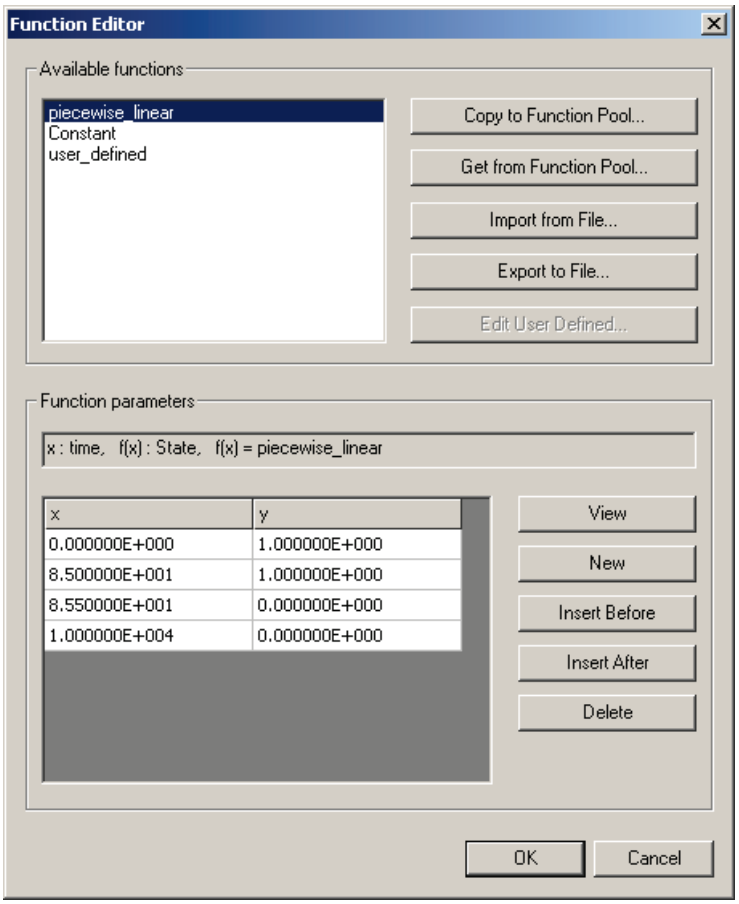
These are the parameters that were used for this simulation:

- Input geometry file: air_trap_start.unv
- Simulation type: RTM
- Air entrapment: active **[1]**

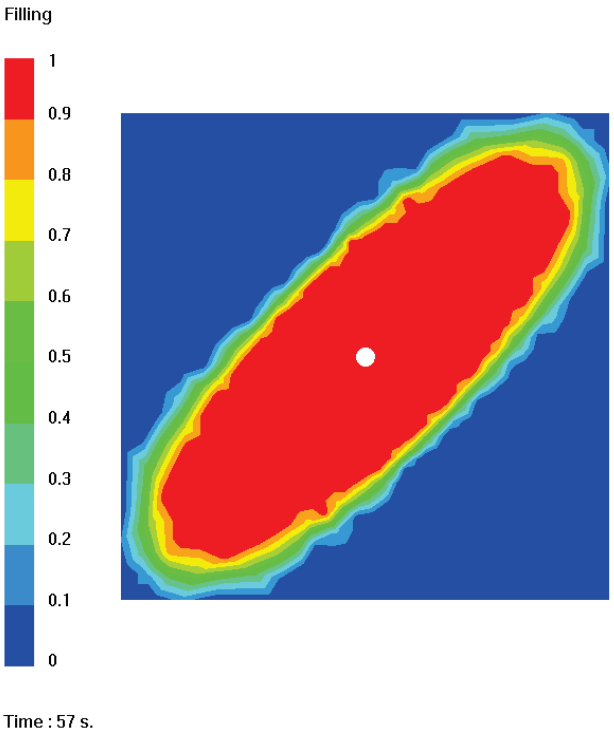


- Resin viscosity: 0.1 Pa.s
- Permeability: K1 = 1E-9 m^2, K2 = 1E-10 m^2
- Porosity: 0.5
- Injection pressure: 2E5 Pa
- Vents' pressure: 1E5 Pa
- Vent 2 stays open during the complete simulation (State = 1)
- Vents 3 and 5 closed at 85 s.
- Vent 4 closed at 120 s

To close a vent at a given time, open the **Function Editor** dialog box for the *state* parameter of the boundary condition, and define a piecewise linear function as shown below:

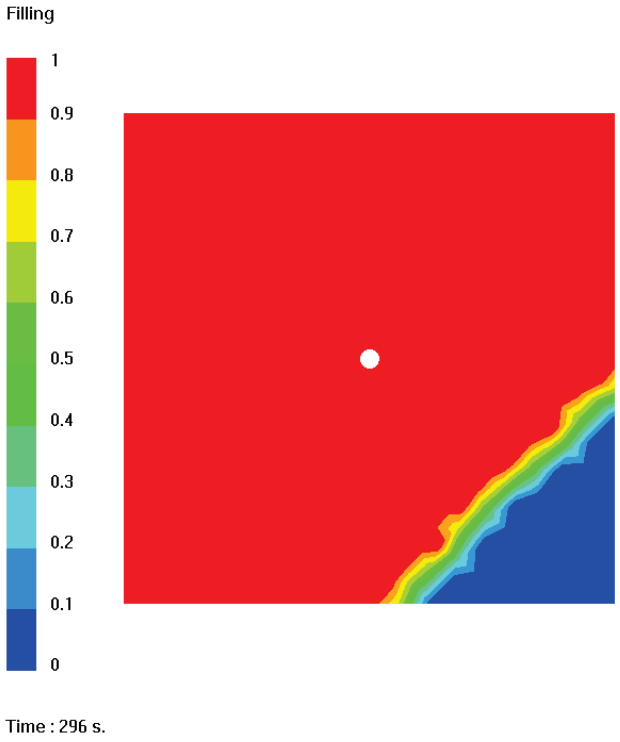


The anisotropic fabric leads to an elliptical flow front.



To avoid air traps in the bottom left and top right corners, the vents are closed a short time after the resin reaches them (t = 85 s.). The bottom right vent is kept open a little longer. When it is closed (t = 120 s.), an air trap is detected by **PAM-RTM™**. The top left vent stays open during the complete simulation, that's why there is only one air trap detected.

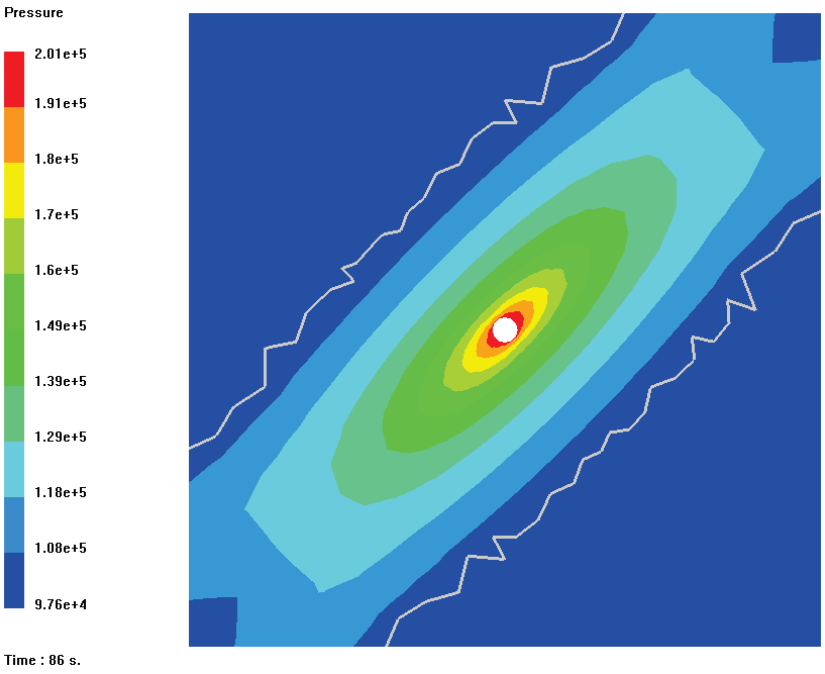
As soon as the air trap is detected, the pressure starts to increase in it. The law of perfect gases *Pressure * Volume = constant* is used to manage the pressure increase as the volume of the air trap changes. After some time, the pressure in the air trap becomes very close to the injection pressure, which means that the pressure gradient is very small and the resin can't move. The simulation stops with some elements that are not filled.

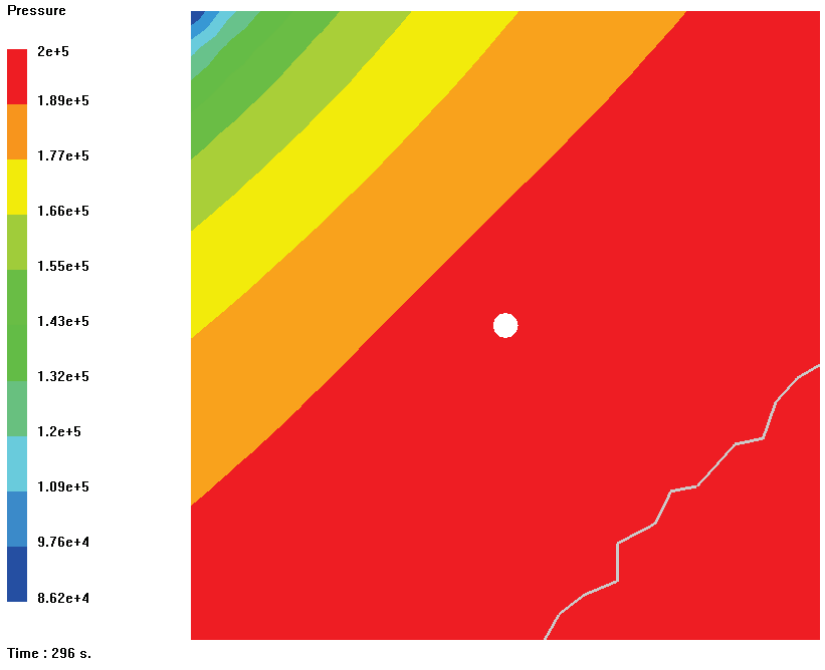


The pressure specified in **PAM-RTM™** is absolute pressure. For the air entrapment option to work correctly, the vent pressure must be positive and not zero. In this example, the vent is initially open and its pressure is 1E5 Pa (1 bar). The injection pressure is 2 bars, so there is 1 bar pressure difference between the injection point and the flow front. When the air trap is detected, its pressure is the same as the initial cavity pressure (pressure on the vent), and it will rise as the air trap gets smaller.

You can visualize the flow front position on top of any scalar field by loading the flow front file (extension .front) with **File->Import->Scalar Fields->PAM-RTM Flow Front**. The flow front is displayed as a white line in the following pressure images.

Notice the pressure at the bottom left and top right corners. This "strange" pressure field comes from the fact that the resin has reached the top left corner where the vent is still open, so the pressure stays fixed at 1 bar. The last pressure image shows that the pressure in the air trap at the end of the simulation is the same as the injection pressure.


Pressure
2.01e+5
1.91e+5
1.8e+5
1.7e+5
1.6e+5
1.49e+5
1.39e+5
1.29e+5
1.18e+5
1.08e+5
9.76e+4
Time : 86 s.


Pressure
2e+5
1.89e+5
1.77e+5
1.66e+5
1.55e+5
1.43e+5
1.32e+5
1.2e+5
1.09e+5
9.76e+4
8.62e+4
Time : 296 s.

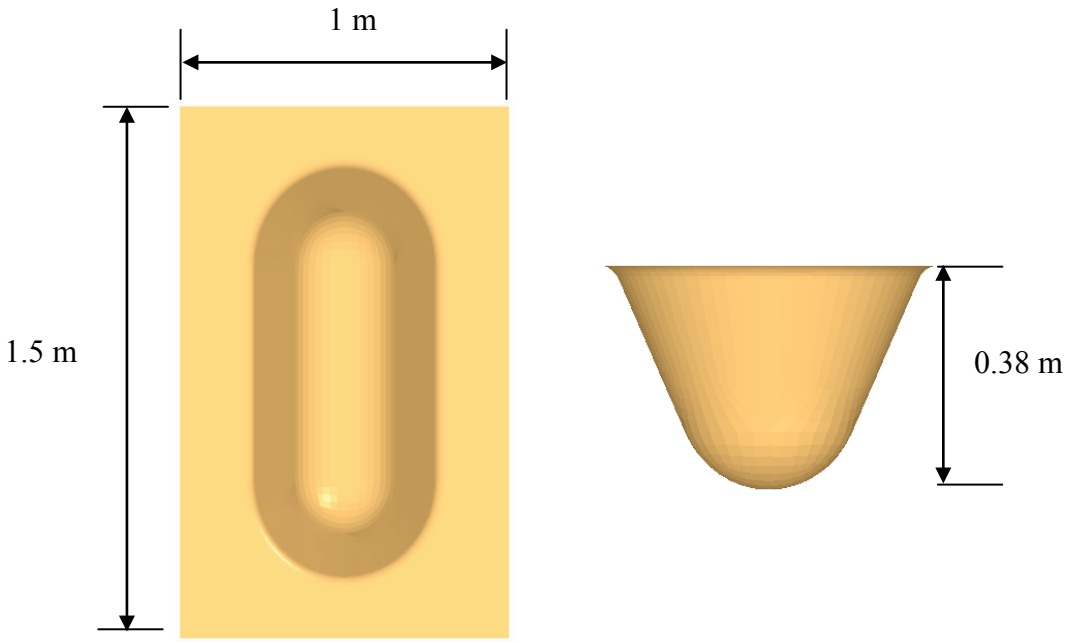
VACUUM ASSISTED RESIN INFUSION (VARI)

The following files will be used:

- ***vari_start.unv*** (starting mesh)
- ***vari.dtf + vari.unv*** (solution)

Objectives

This tutorial shows how to specify the parameters for a VARI simulation. The post-filling, leading to the final thickness of the part calculation, after the injection port has been closed will also be simulated. Two cases will be run, one where vents will stay open, and the other one where vents will be closed.



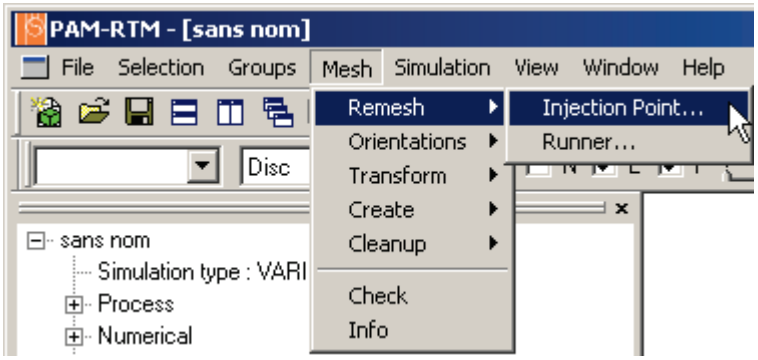
Top View ***Side View***

Mesh Modification

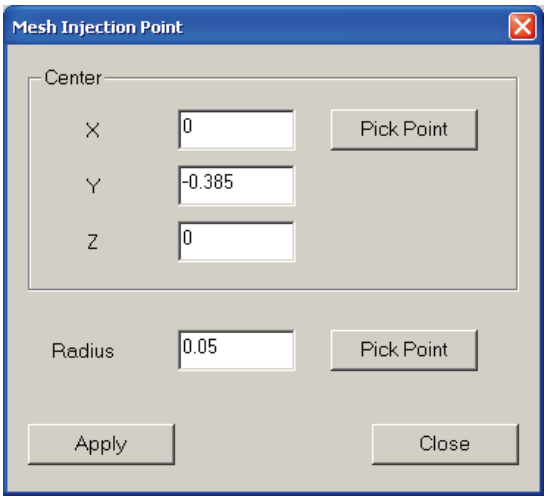
Create a new *VARI* simulation with **File->New** and import the mesh file `vari_start.unv`.

The mesh provided for this tutorial does not have an injection point. We will create one for central injection.

To define an injection point, open the **Mesh Injection Point** dialog box (**Mesh -> Remesh ->Injection Point**).

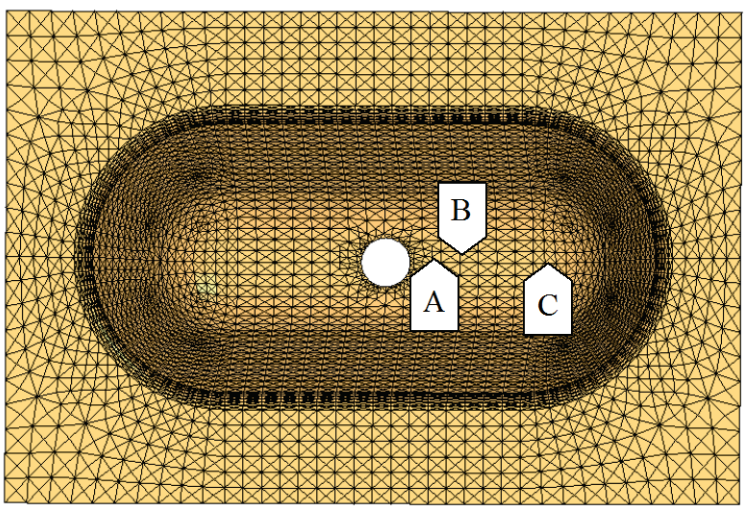


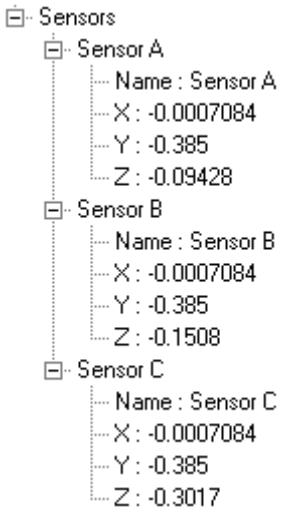
PAM-RTM™ asks if you want to split quads into triangles. Choose *yes*. The remeshing tools work only on mesh of triangles.



Enter the coordinates of the center point (0, -0.385, 0) and set the radius at 0.05, then **apply** and close the window.

The modified mesh appears as follows:





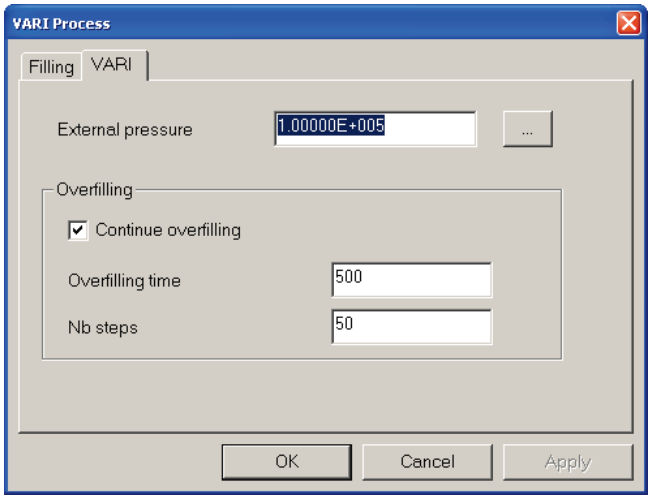
Create three sensors by picking approximately points **A**, **B** and **C**, or enter the exact coordinates of the sensors as shown above.

Simulation

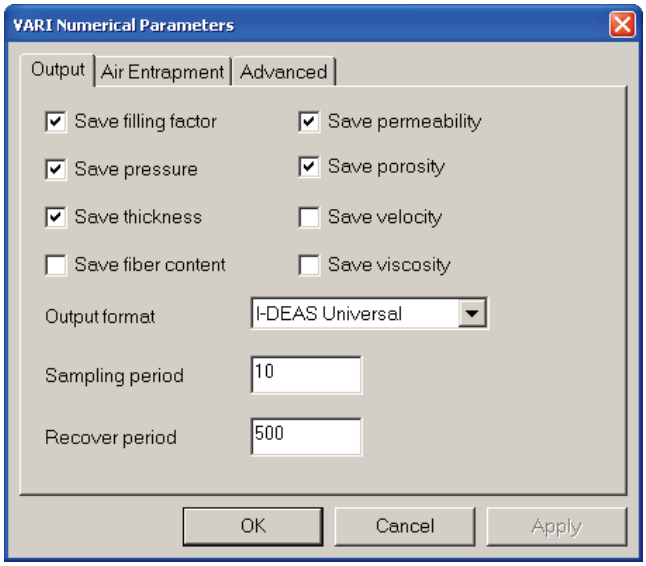
This section describes the parameters required to carry out this simulation:

Double-click on **Process** in the model explorer to open the **VARI Process** dialog box. In the **VARI** tab, set the **External pressure** at 1.10^5 Pa.

Overfilling is activated by checking **Continue overfilling** box, and the duration of Overfilling is set to 500s. The number of numerical steps is set to 50. That will allow the simulation to continue after complete filling of the part until reaching a mechanical equilibrium.

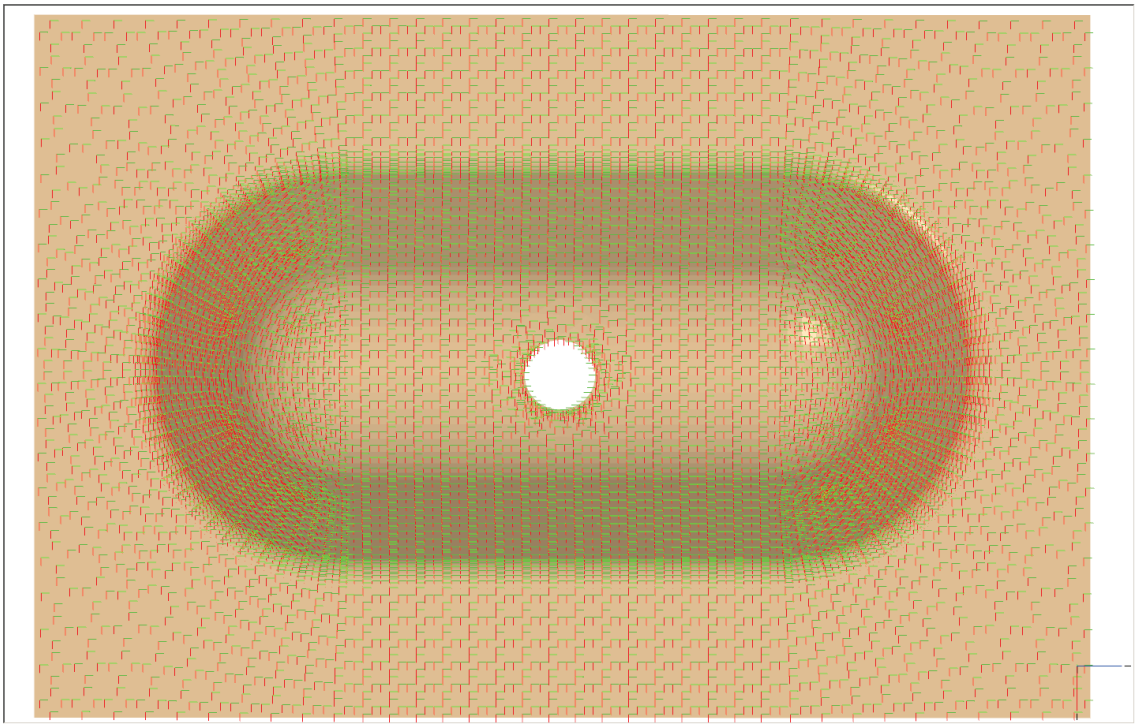


In the explorer, double-click on **Numerical** to open the **VARI Numerical Parameters** dialog box and be sure that **Save filling factor**, **Save pressure**, **Save thickness**, **Save permeability** and **Save porosity** are active.



Orientation

No orientation is defined on the mesh. It will be defined with **projection** method. First select all the elements, then use *Mesh->Orientation->Project Vectors* to project X as K1. Then set, K2 orthogonal to K1, *Mesh->Orientation->Set K Orthogonal*.



Materials

Set the resin and the fabric properties as shown below.

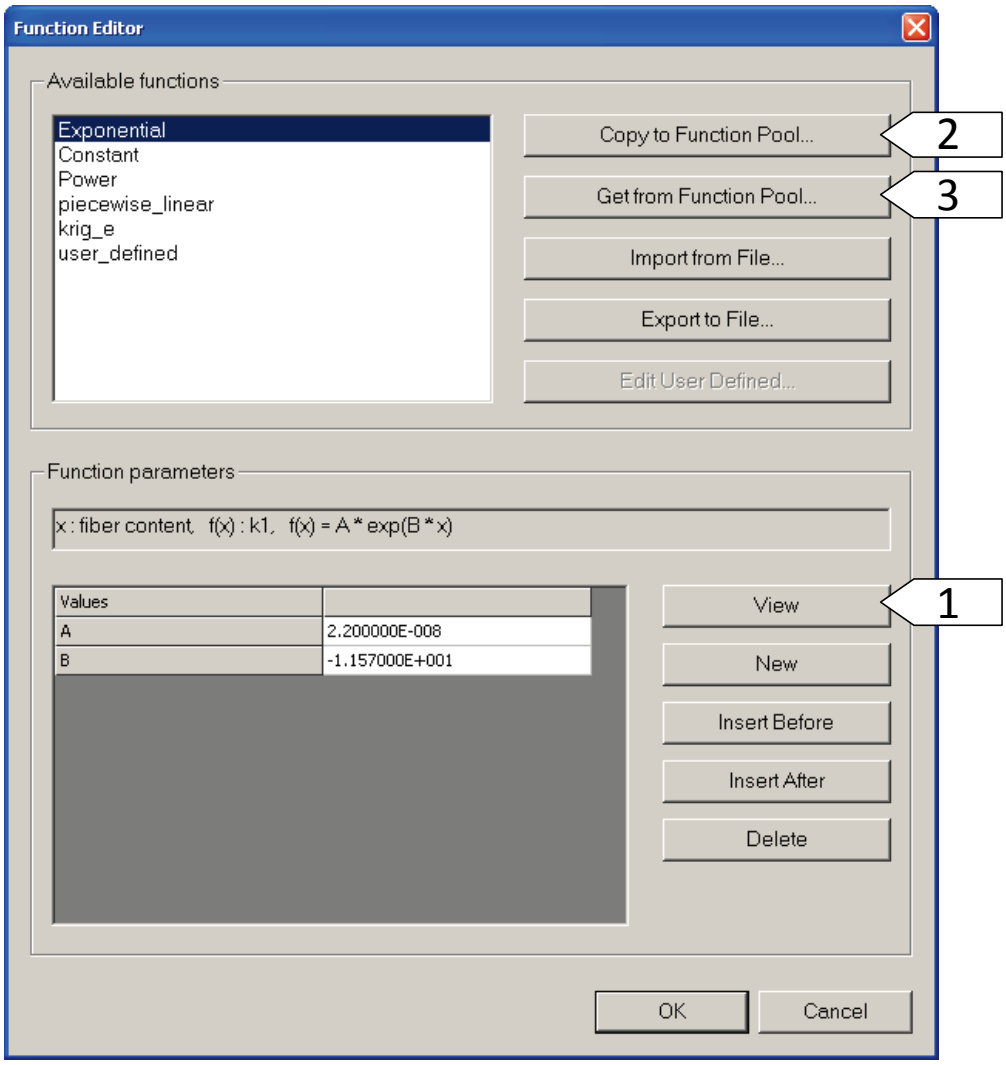
Resin

- Constant viscosity = 0.1 *Pa.s*
- Density = 1083 kg/m^3

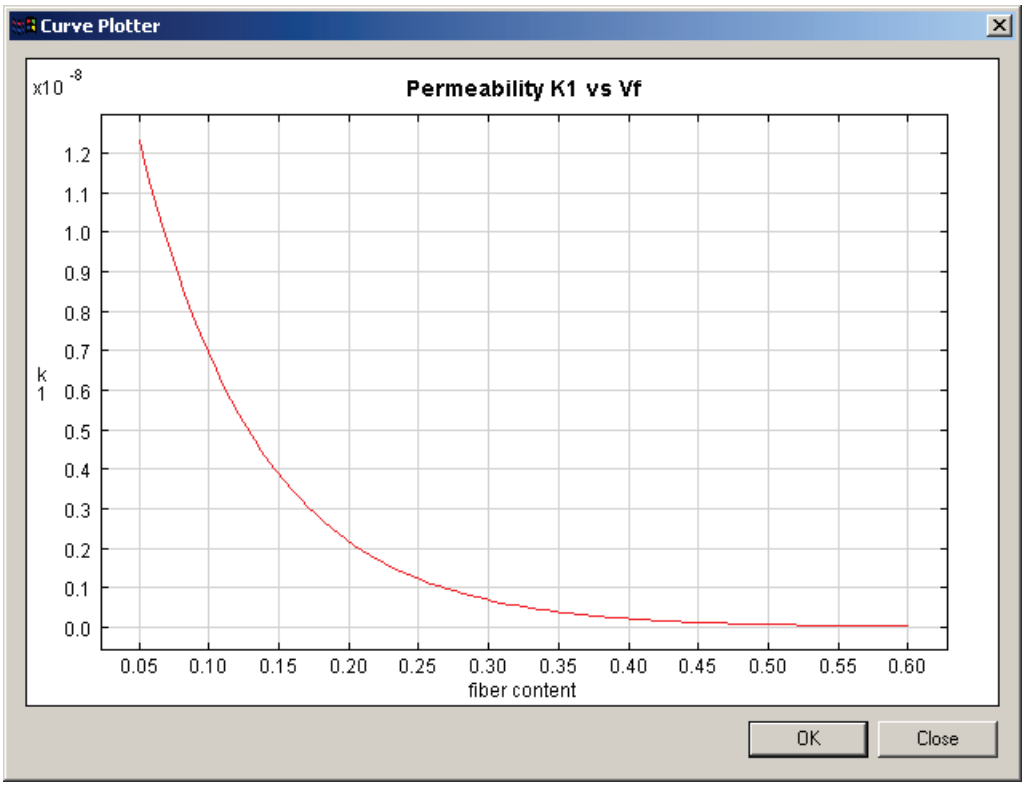
Fabric

Double-click the **Default Fabric** in the explorer to open the **Fabric Properties** dialog box.

To set the permeability K1, open the **Function Editor** by clicking the ... button beside **K1**. Select the **Exponential** function, then set A = 2.2 10^{-8} and B = -11.57.

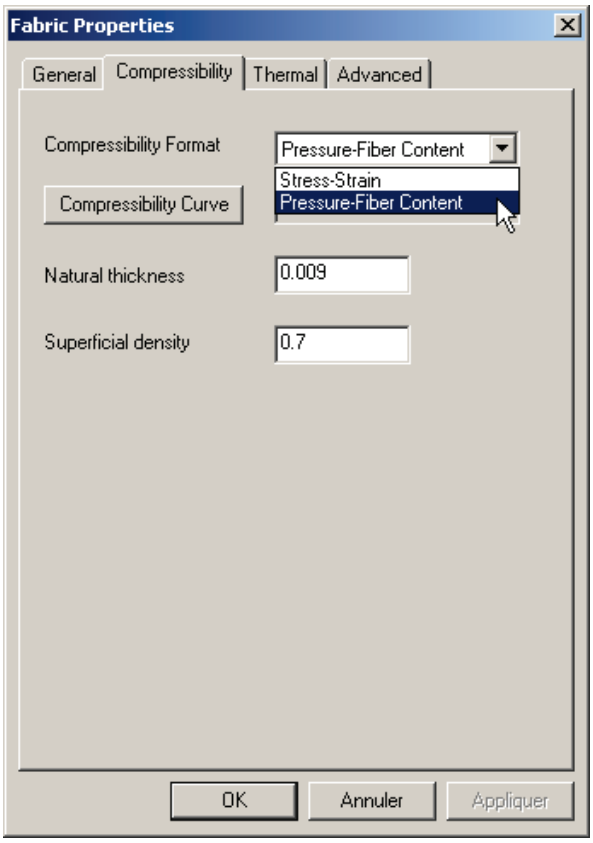


The permeability curve can be visualized by pushing the **View** button **[1]**.

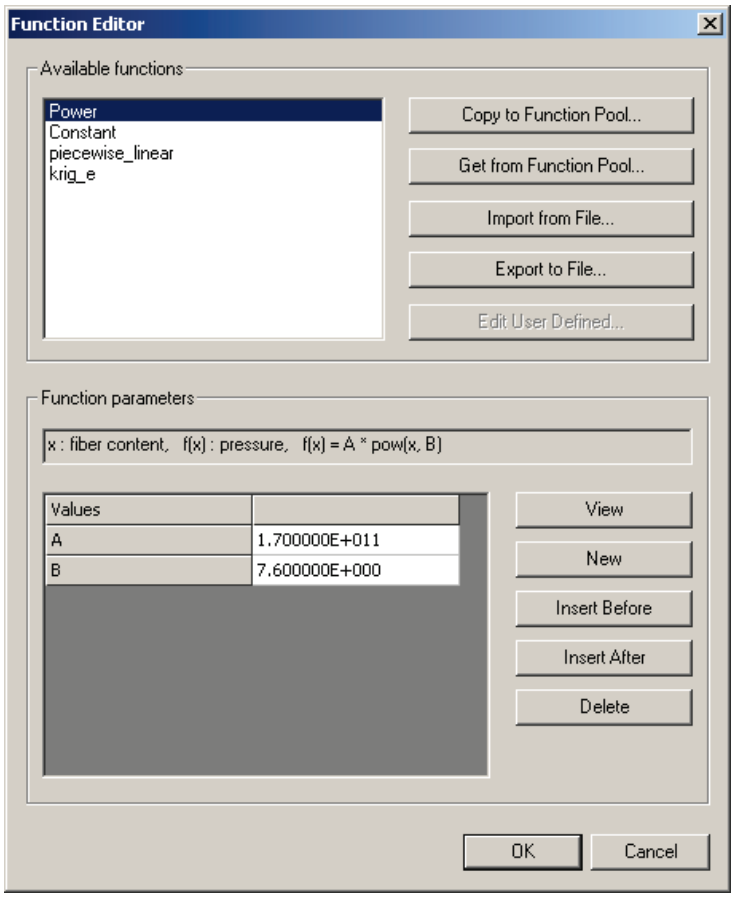


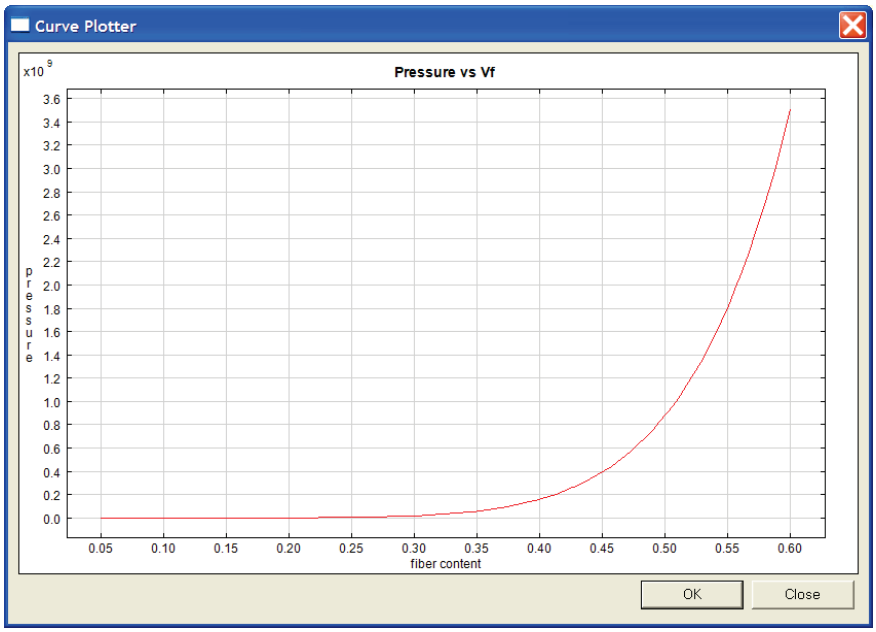
Instead of entering the coefficients of the exponential curve again for K2, you can use the **Copy to Function Pool** functionality. Push the **Copy to Function Pool button [2]**, and then give a name to the curve, such as `perm_vf`. Next in the function editor of *Permeability K2*, you just have to click on **Get From Function Pool [3]** and select `perm_vf` to get the curve that was defined for K1. Note that the functions stored in the function pool are available until you close **PAM-RTM™**. The function pool is shared by all open documents.

One of the most important parameters for VARI simulation is the compressibility curve of the reinforcement. Double-click **Default Fabric** in the explorer. In the **Compressibility** tab, choose the **Pressure-Fiber Content** curve format in the drop-down list.



Push the **Compressibility Curve** button to define the curve. Choose a power law and set $A = 1.7\ 10^{11}$ and $B = 7.6$ in the **Function Editor** dialog box. The compressibility curve is shown below.

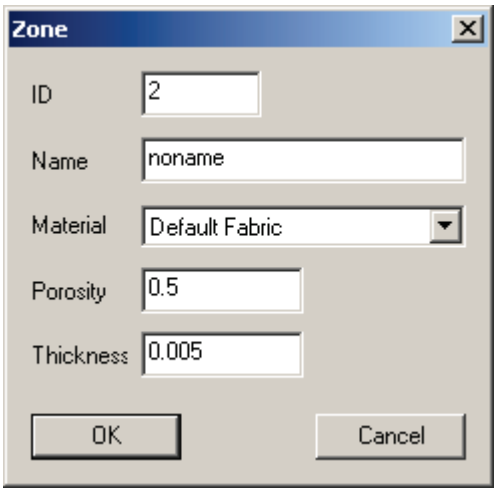




Finally set **natural thickness** to 0.009 m and **superficial density** to 0.7 $kg.m^{-2}$ in the **Fabric Properties** dialog box. The natural thickness of the fabric corresponds to the zero pressure in the compressibility curve.

Zones

There is only one zone defined in this mesh. Double-click **Zone_2** in the explorer, associate *Default Fabric* to it and set its porosity as 0.5 and its thickness as 0.005 *m*.



Note

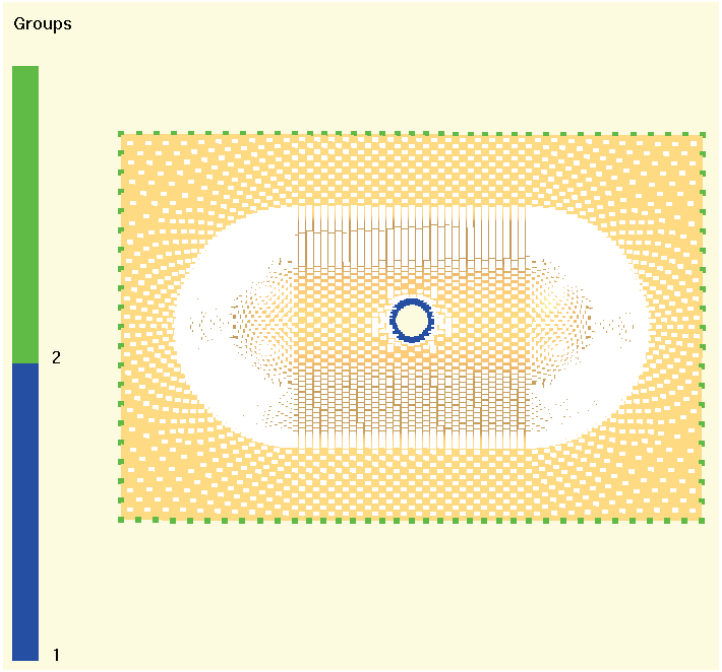
- *The thickness value specified in the zone is only used to initialize the calculation.* ***PAM-RTM™*** *will calculate the actual thickness from the compressibility curve and the external pressure. It is important to set the initial thickness of zones to some value inside the definition range of the compressibility curve. Normally half the natural thickness of the reinforcement should be a good initial thickness.*
- *If the specified material and process parameters are such that at some point in the simulation the thickness of the reinforcement becomes larger than its natural thickness, the simulation is not valid.*

Boundary Conditions

When the injection point was created with the remeshing tool, a group was automatically created (ID=1) with the nodes around the injection hole. Now you need to associate a boundary condition to this group. Click on **Boundary Conditions** in the explorer with the right mouse button and choose **New->Pressure.** Verify that the injection pressure is 1.10^5 *Pa*.

The full boundary of the injected part will be specified as a vent. You can easily select all the nodes on the boundary. Use **Selection->Pick Boundary**, then pick a node on the boundary you want to select. Use **Groups->Create** to create a group with the selected nodes. Associate a *Vent* boundary condition to this group and make sure that the vent pressure is zero. The groups are shown below.

Save the **PAM-RTM™** document and launch the simulation.

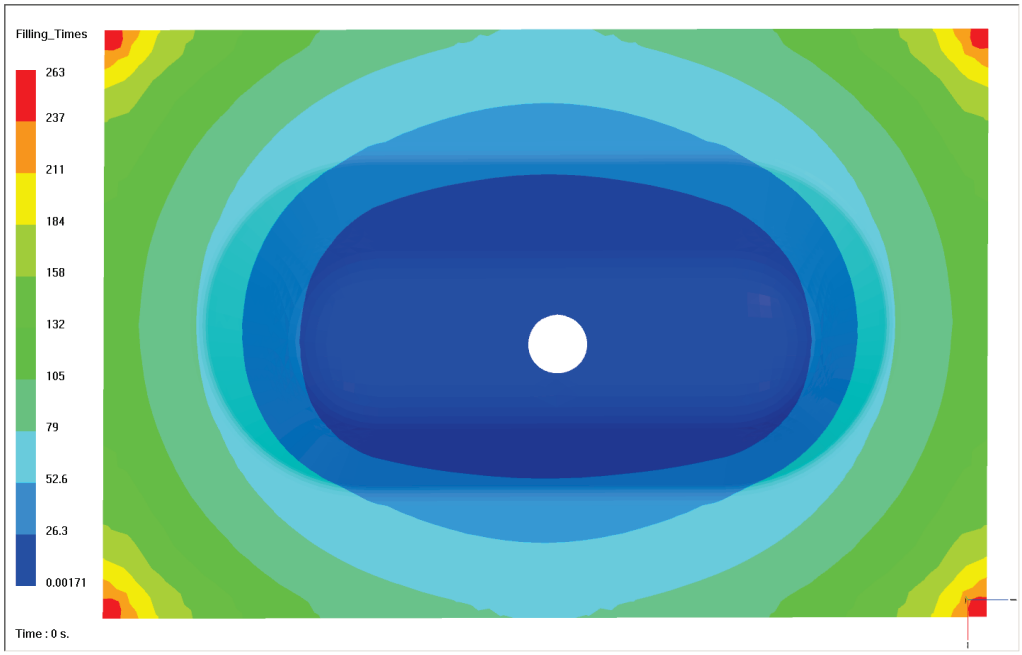


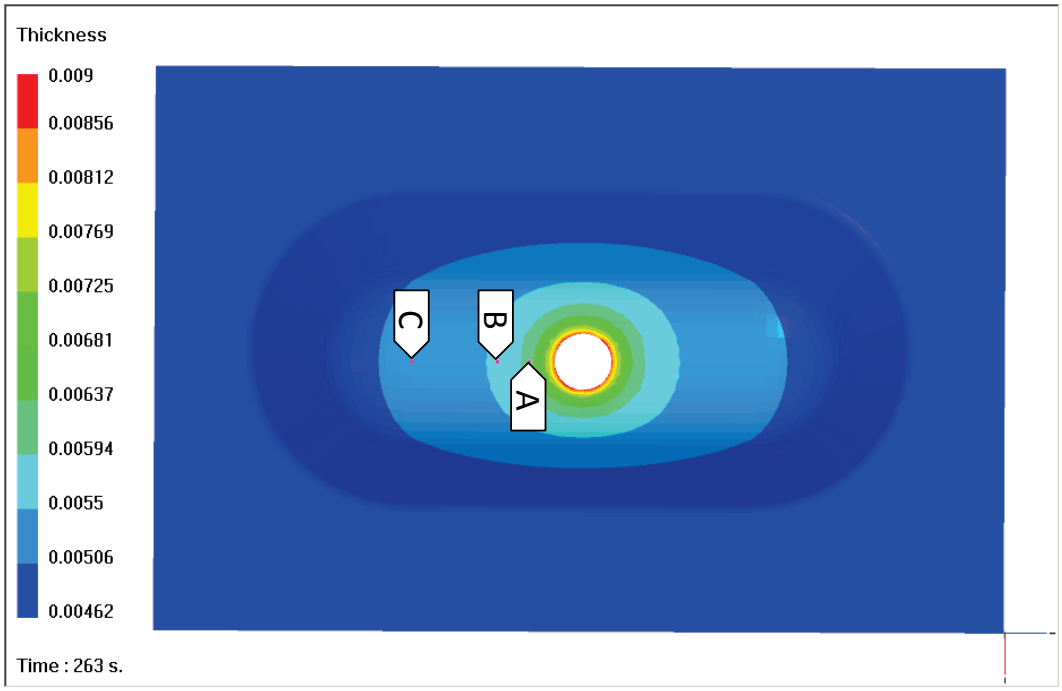
Post-Processing

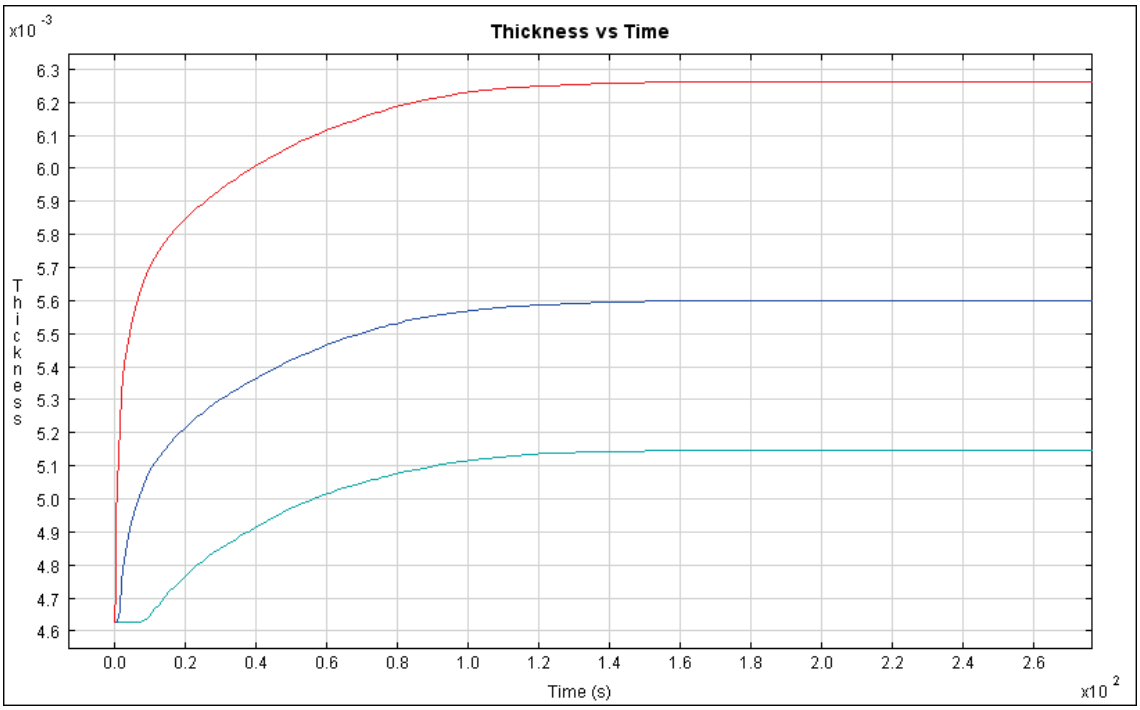
It can be seen in log file that the simulation is split in two phases: filling then overfilling.

```
=> 763    time=2.26128E+002   filled=10808 +8    99 %
=> 764    time=2.63163E+002   filled=10816 +8    100 %
=> 765    time=2.63173E+002   filled=10816 +0    100 %
Start of overfilling phase
=> 766    time=2.73173E+002   filled=10816 +0    100 %
=> 767    time=2.83173E+002   filled=10816 +0    100 %
=> 768    time=2.93173E+002   filled=10816 +0    100 %
```

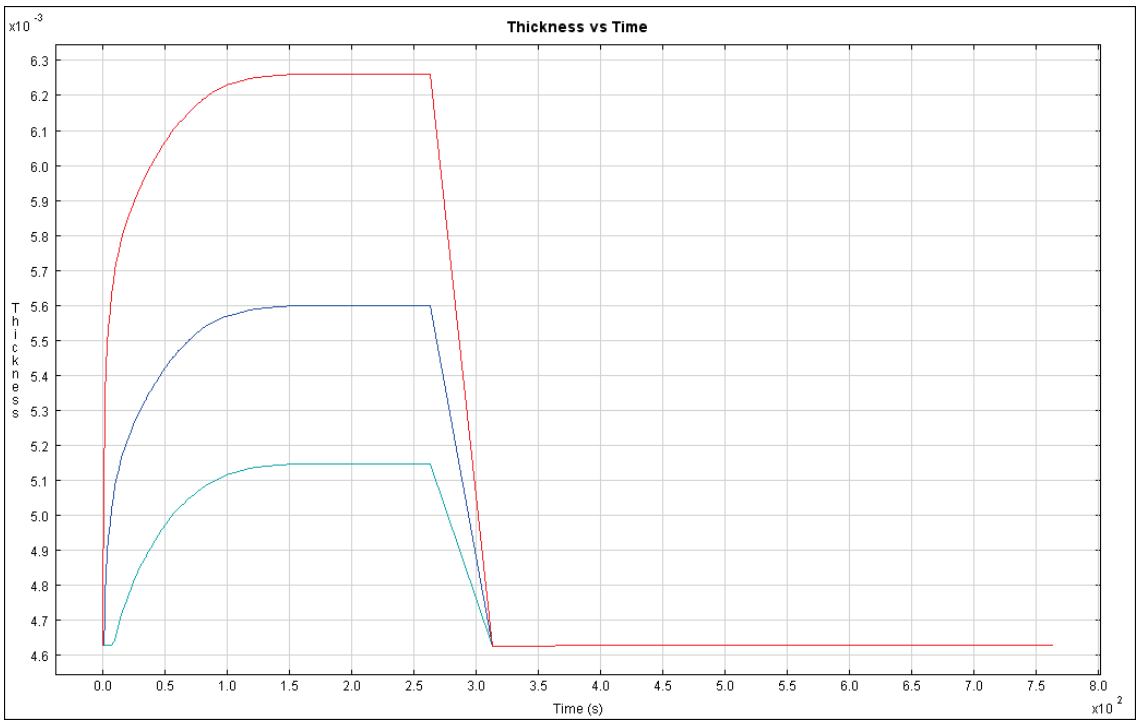
The images below show the segmented filling patterns and the thickness field at the end of filling. The thickness evolution in time was plotted on the 3 sensors at positions A,B and C on picture below.







Thickness evolution during filling

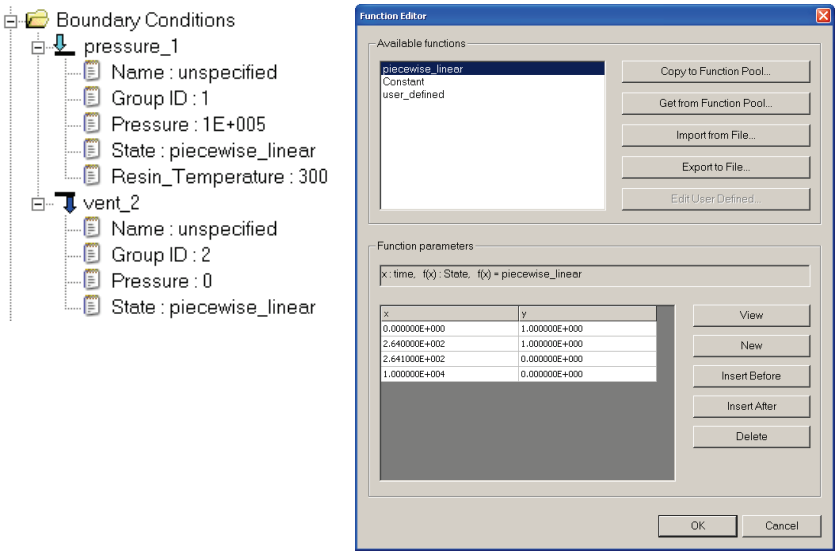


Thickness evolution after filling

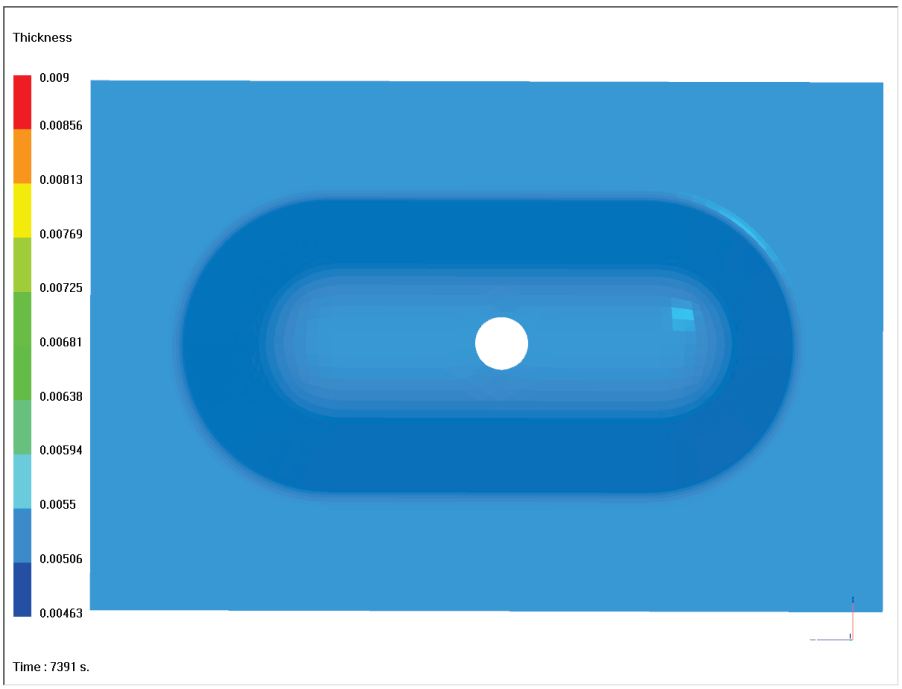
Second case with closing of the vent

A modification of the set-up is made so that vent is closed at the end of the filling, in the same time as injection stops.

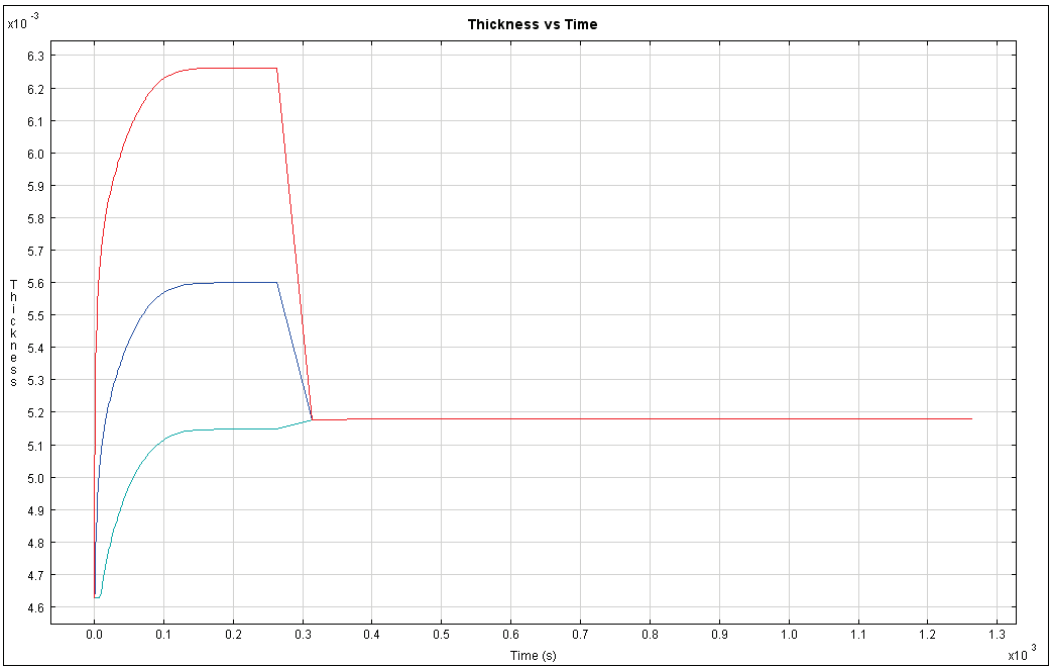
The first simulation showed that filling lasts 263s. The modification of set-up is so that injection port and vent are closed after 264s. State functions for each boundary condition are set like the function below.



Behavior is modified after the end of filling as the thickness value at the end of the post-filling and thickness curve show.



Thickness at the end of over-filling phase.



Thickness evolution after filling

Final thickness is 5.46mm compared to 4.6mm in the case of opened vent.

Conclusion

This tutorial showed the set-up of infusion simulation (VARI model), and the computation of final thickness after the complete filling of the part and mechanical equilibrium is reached.

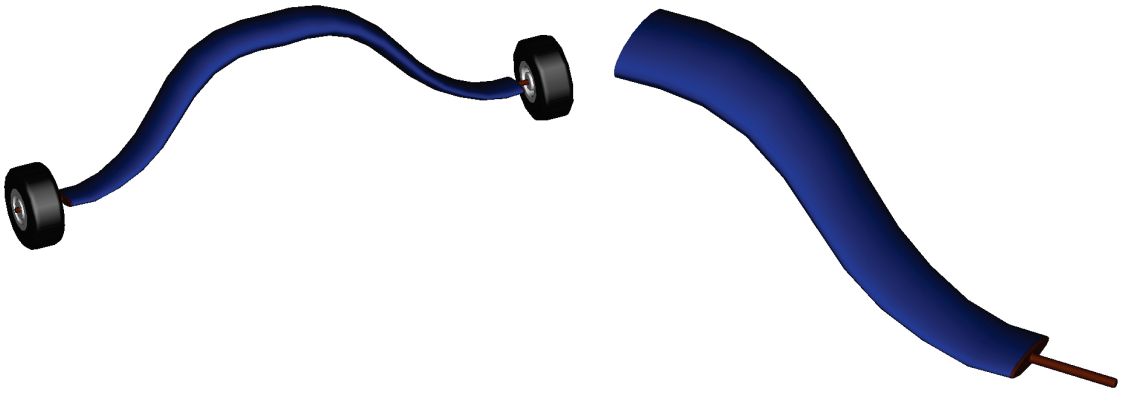
LANDING GEAR

The following files are used in this example.

- ***landing_start.unv*** (starting mesh)
- ***landing_1.dtf***, ***landing_2.dtf***; + ***landing.unv*** (solution)

Introduction

In **PAM-RTM™** simulations, complex parts can be modeled with shell or solid elements. Different zones must be defined, the type of materials contained in the cavity must be specified (metallic insert, foam…) as well as the properties of the fibrous reinforcement (orientations and values of the permeability tensor). Numerical simulation aims to assist users to understand the progression of the resin flow during the injection. It helps to avoid problems such as air entrapments. It allows also to compare different injection strategies in order to find the best one, for example the one with the shortest cycle time. Non isothermal simulations study the coupling between the resin flow, temperature and curing.



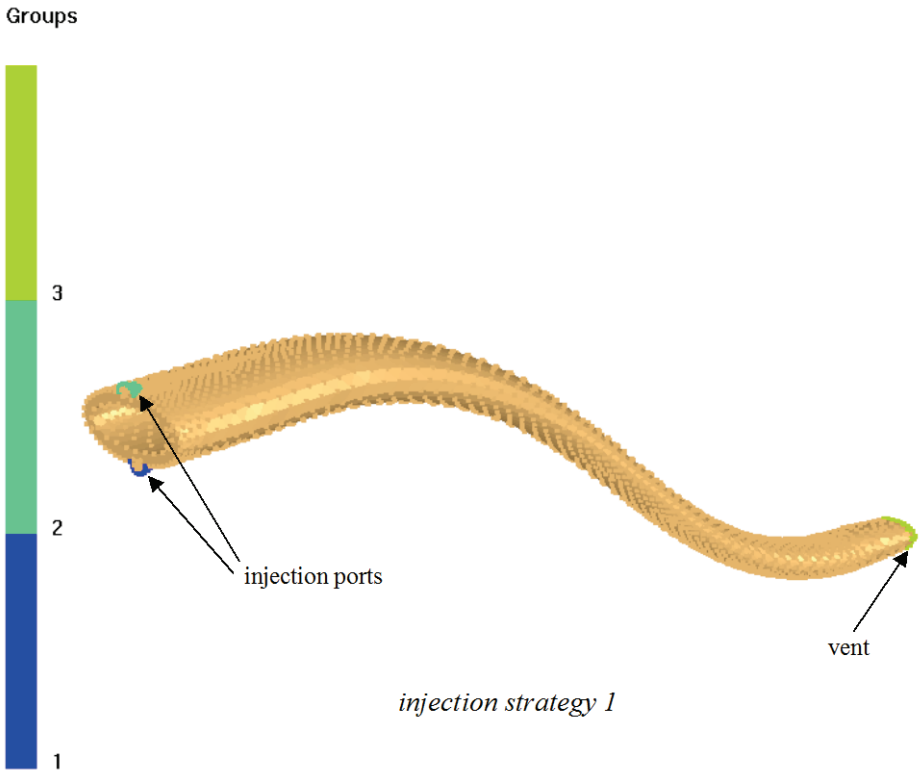
Landing gear

Analysis of a Landing Gear

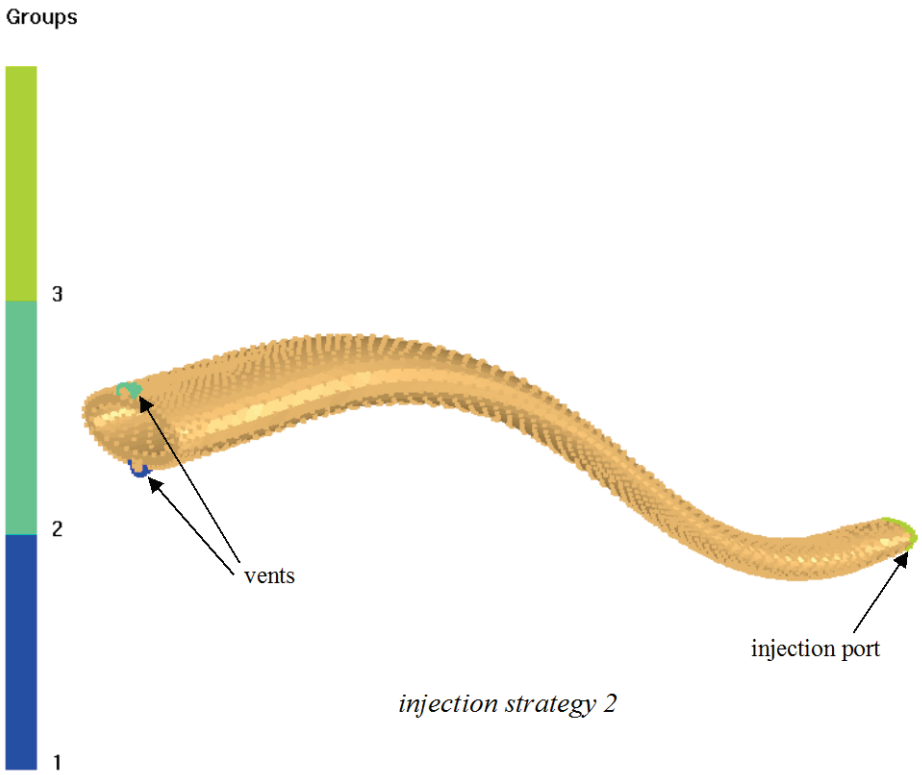
The landing gear of a small touring airplane is analyzed in this example. As demonstrated on the picture, the landing gear is located on the front part of the airplane and is symmetric along its central axis. If the injection is performed from the center or from the two extremities, because of the symmetry only half of the part needs to be simulated. This example is important because it compares the effect of convergent versus divergent flows and illustrates how convergent resin flows are systematically accelerated in restrictions.

Two injection scenarios at constant pressure will be considered here for half of the part. The first test consists of injecting the resin from two injection ports located at the center of the part as shown in the figure below. The vents are located at both extremities at the positions of the wheels.

In the second test, the resin is injected from both extremities, the vents being located in the center of the part.



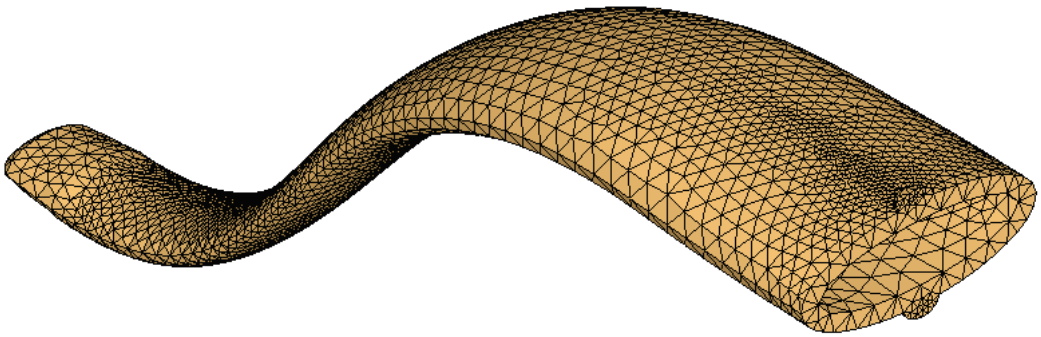
injection strategy 1



injection strategy 2

This composite part is normally made of several materials. It contains a metallic insert at its extremities for the installation of the wheels. The center of the part is an impermeable foam. Since these are non-permeable inserts and since we are only doing an isothermal simulation, it is not necessary to mesh these inserts. It is important to note that if you decide to mesh the non-permeable zones, the *mold* material of **PAM-RTM™** must be assigned to these zones.

The mesh has been generated with **I-DEAS**. It is shown below.

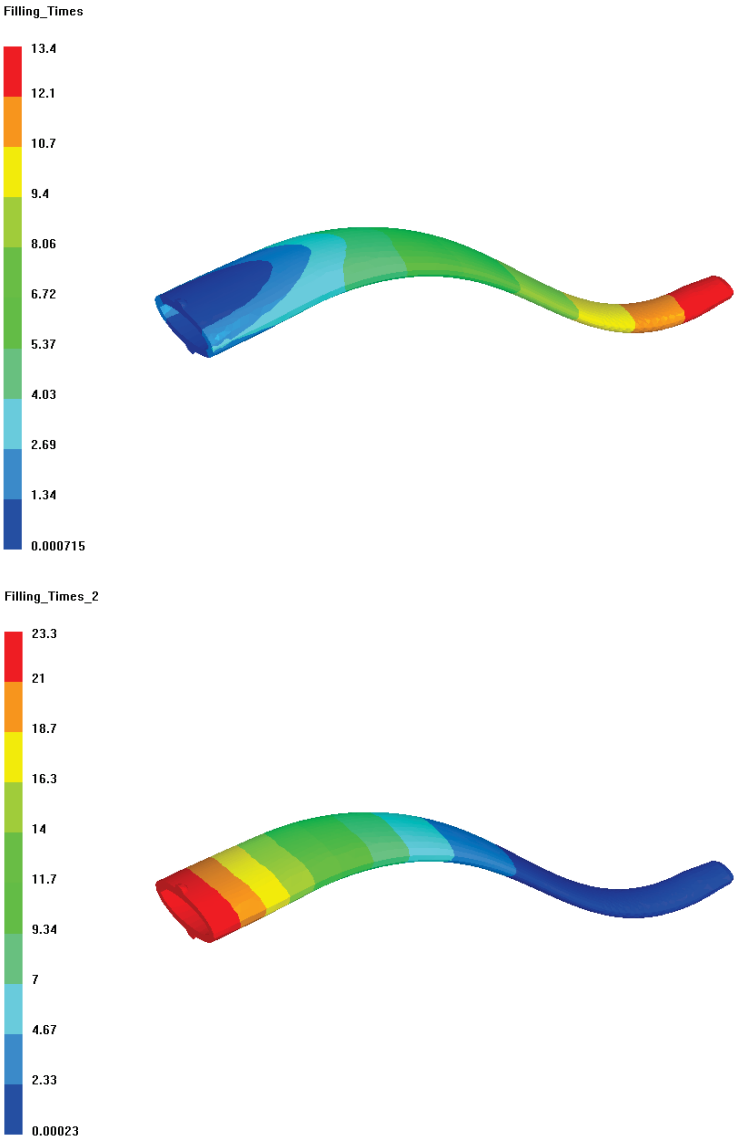


Analysis of Simulation Results

The landing gear has been simulated for both injection scenarios. The two injections were performed at constant pressure from the two extremities (case 1) or from the center of the part (case 2). The goal is to determine the best injection strategy to produce the part and avoid errors in the design of the mold.

Let us examine the injection process in more detail. When the injection is performed from the center (first strategy), no particular difficulties appear. However when the part is injected with the second strategy, an air trap appears near the vents. This shows that the air vents are not correctly positioned. In order to correct the problem, the air vents should be positioned on the side of the part, exactly where the air traps appear. The air trap is created in this example because of the divergent flux during the injection.

This phenomenon (divergent flux) does not only create an unwanted air bubble, but it also increases the injection time significantly. The successive positions of the resin front in time are displayed next for the two injection strategies considered. For a constant pressure injection, the first injection strategy gives a much lower injection time compared to the second. Indeed, the first strategy enables to fill the mold in 134 seconds, while it takes 234 seconds for the second strategy. This difference is caused by the shape of the part. In the first case, the resin flux is convergent, which has the effect of accelerating the displacement velocity of the resin in the restriction, whereas in the second case a divergent flux is obtained.



Conclusion

The landing gear design information is a good example that demonstrates the importance of numerical simulation, appropriately provided to mold designers. Note that mistakes can be very expensive to repair once the mold is made. The simulation permits to predict where air bubbles might be created, which has a direct effect on the mechanical properties of the part. It is possible to prevent the formation of air entrapments by changing the position of the vents. In this particular case, the vents will be placed on the side of the part and not on top of it. Finally, the simulation allows to optimize the cycle time. Thus, in this analysis, the first strategy of injection proves to be the best since it allows to shorten the filling cycle and avoid the creation of air entrapments. In conclusion, numerical simulation allows to design a mold rapidly and efficiently while avoiding some expensive modifications once the mold is built.

MESH EXTRUSION

The following files are used in this example.

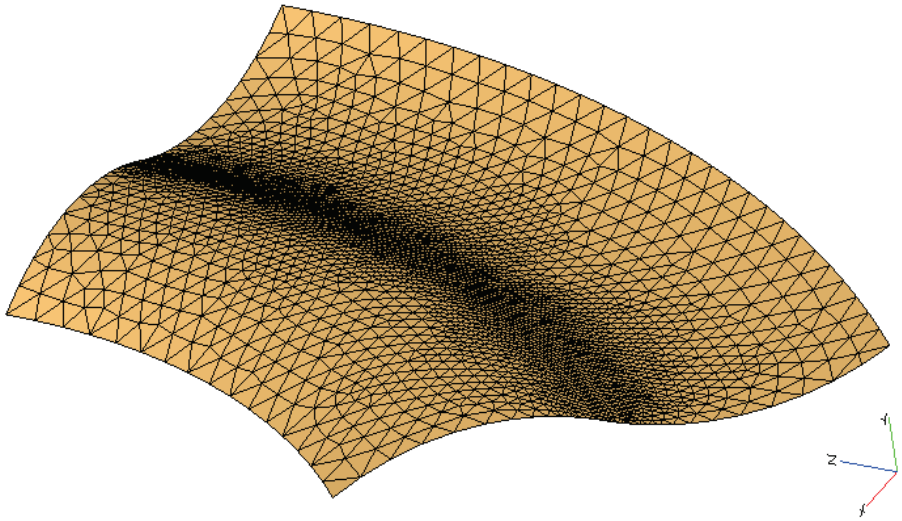
- ***extrude_start.unv*** (starting mesh)
- ***extrude.dtf* + *extrude.unv*** (solution)

Objectives

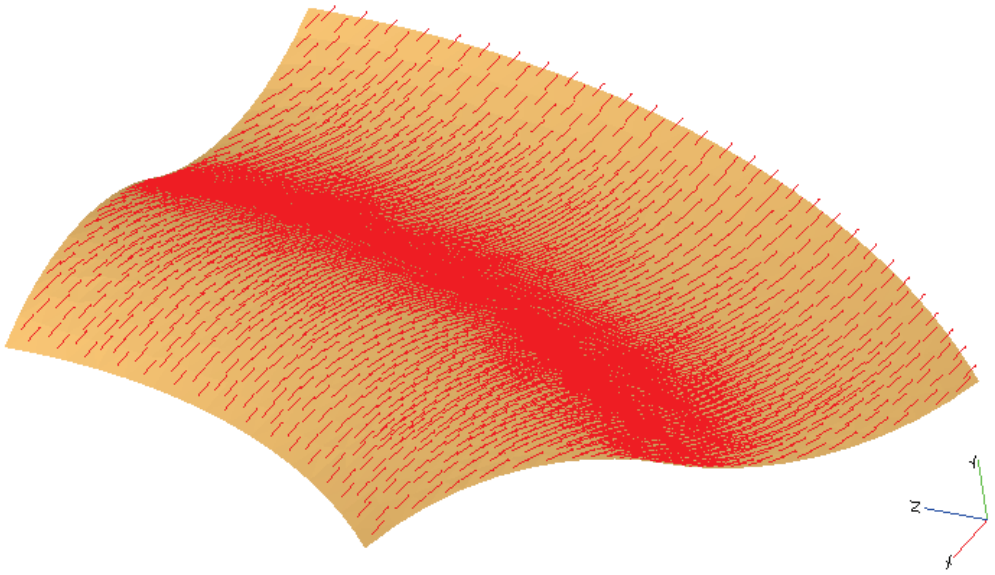
The goal of this tutorial is to show how a surface mesh can be extruded with layers of different thickness and materials. A flow enhancing layer, such as the one found in the VARTM process, is used on top of the fiber preform. The new prismatic element is used directly to avoid splitting into tetrahedra.

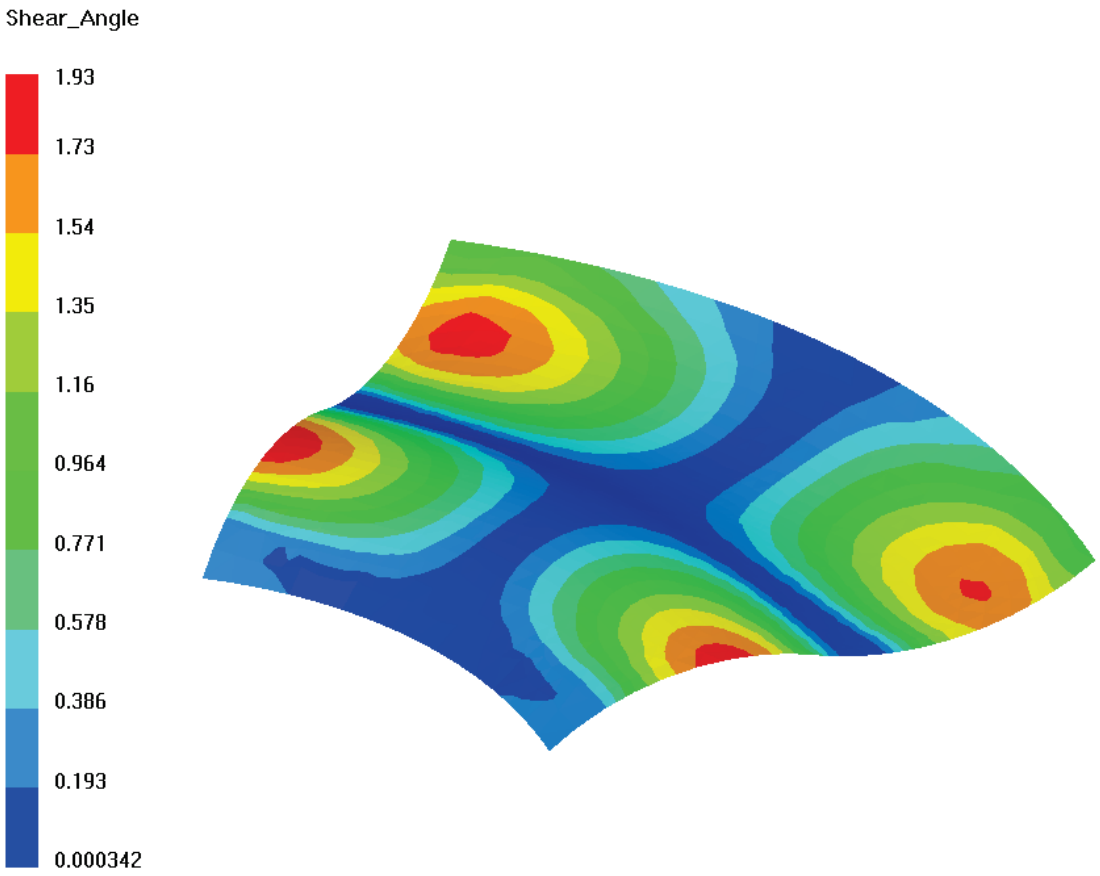
Mesh Extrusion

Begin by creating a new **RTM** simulation, then import the mesh file *extrude_start.unv*. You should have the following.

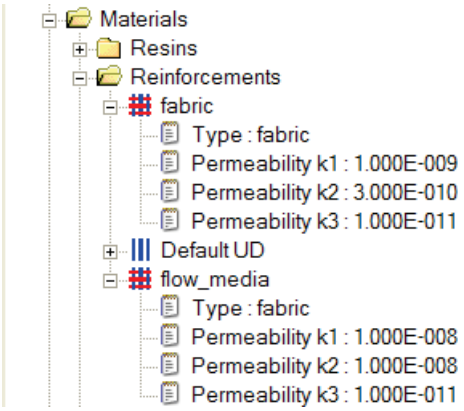


Verify that this mesh contains orientations with **View > Orientations > K1 Only**. Notice that the fiber directions F1 and F2 (actually K1 and K2) are not perfectly orthogonal. This can be seen by activating the **Shear_Angle** in the main toolbar, which shows angles of about 2 degrees. This mesh was actually oriented using PAM-QUIKFORM.



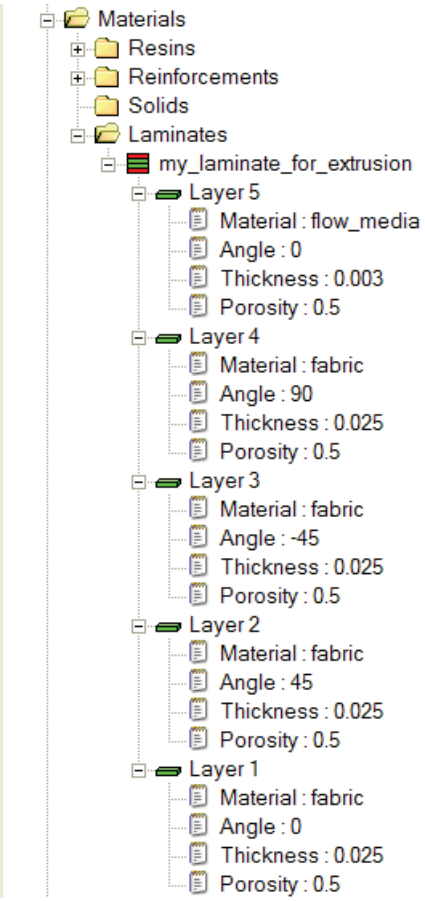

Shear_Angle
1.93
1.73
1.54
1.35
1.16
0.964
0.771
0.578
0.386
0.193
0.000342

The goal is to generate a solid mesh made of 5 layers: 0, +45, -45, 90, and a flow media on top. The first step is to create materials for the fiber reinforcement and the flow media. The same material will be used for the 4 plies. The fiber reinforcement has k1 three times larger than k2. The permeability of the flow media is ten times larger than k1. After creating the materials, you should have the following in the document's tree.

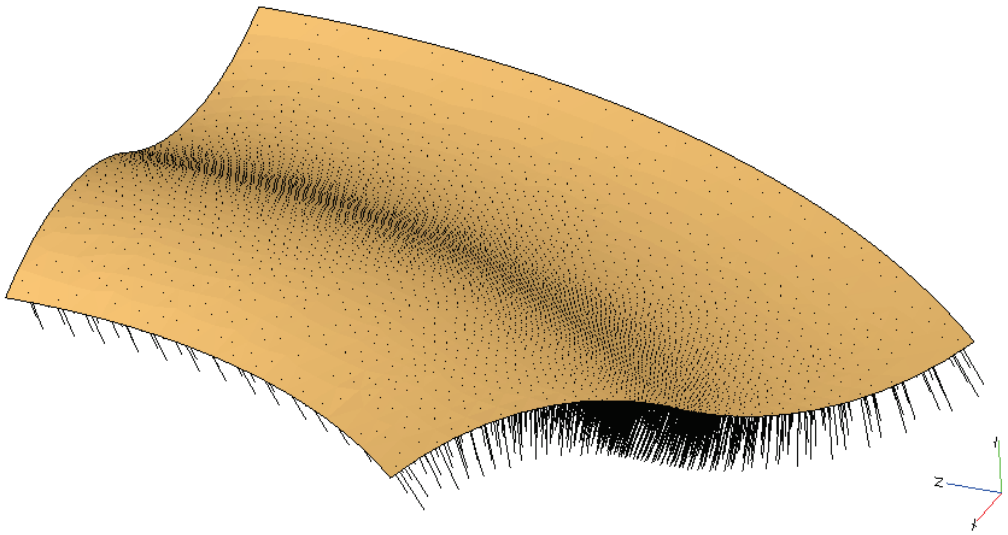


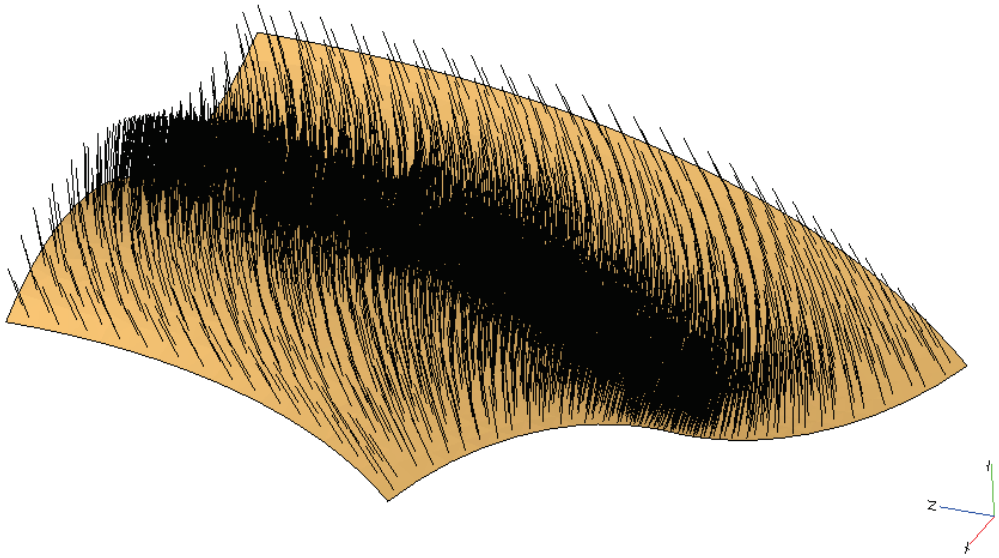
Notice that we use the same permeability k3 for the reinforcement and the flow media. This is important to avoid numerical problems.

The thickness of the plies is set to 0.025 m. It is exaggerated for the purpose of this tutorial, to see the flow better through thickness. The thickness of the flow media is much thinner, 0.003 m. Don't forget to set the angle of each ply. The angle of the flow media is not important since its planar permeability is isotropic. After creating the laminate, you should have the following.

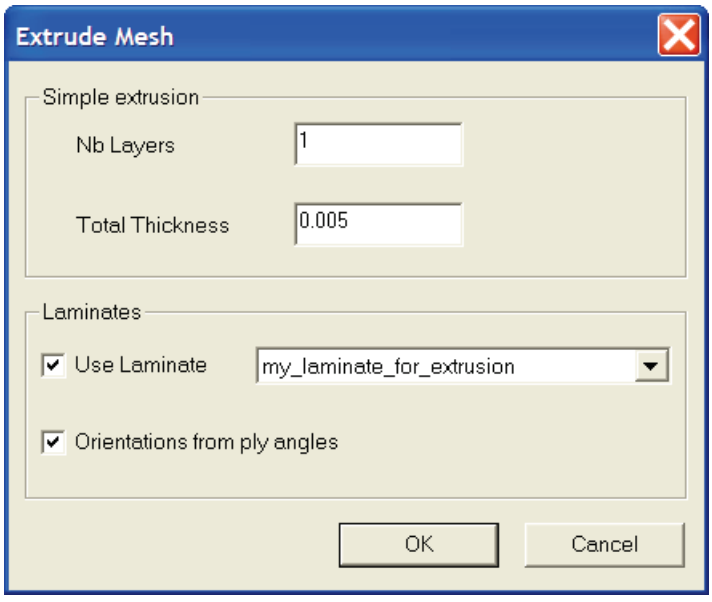


Before performing extrusion, it is important to verify that the normal vectors a pointing in the right direction (**View > Normal Vectors**). Here we would like the mesh to be extruded in the opposite direction. To reverse the normal vectors, we first select all the elements with **Selection > Element** and **Selection > Select All**. Then we use **Mesh > Cleanup > Reverse Normals**.

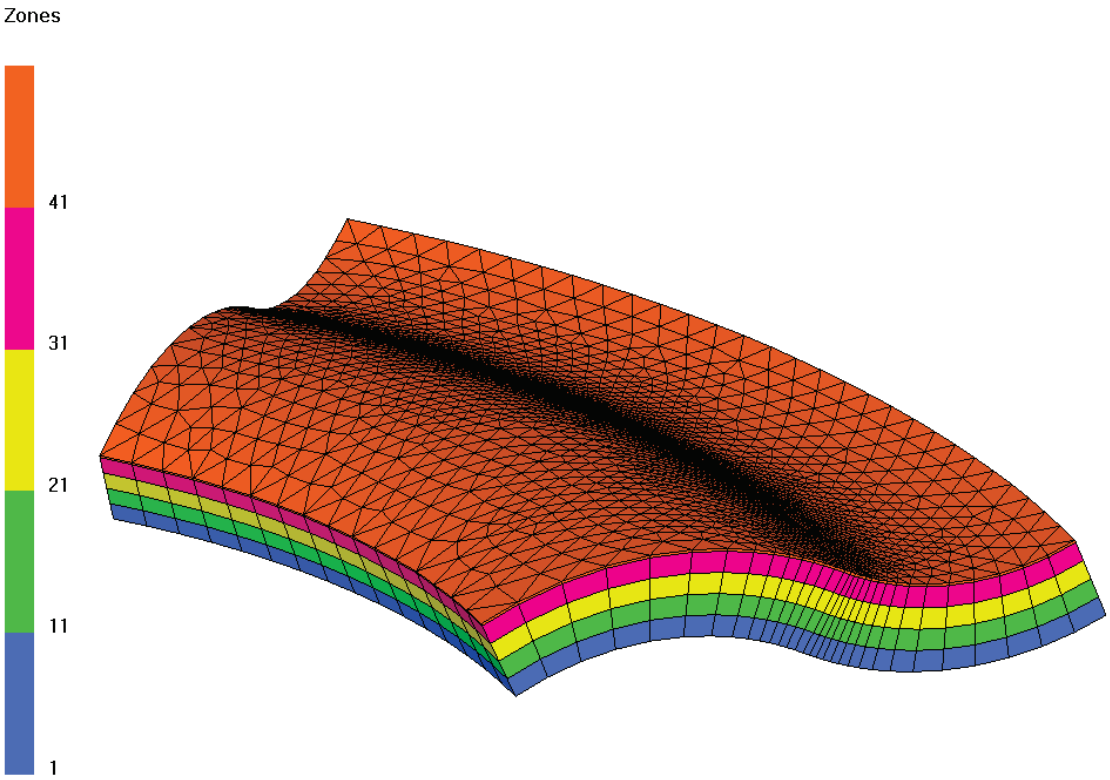




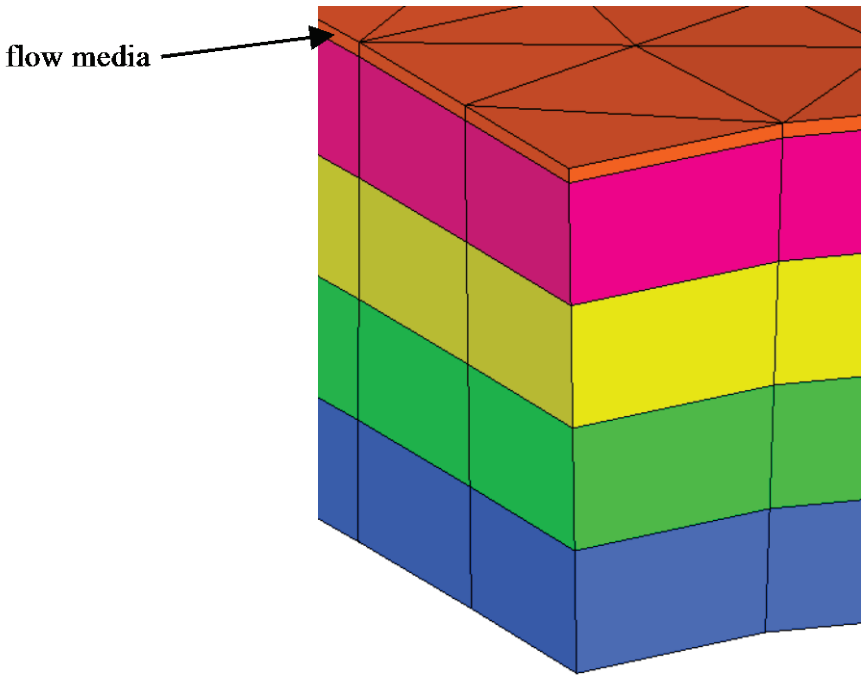
Once the normal vectors have been reversed, open the mesh extrusion dialog box with Mesh > Transform > Extrude. Check the **Use laminate** option (meaning that parameters in the **Simple extrusion** area are completely ignored), select your laminate in the dropdown list, and select **Orientation from ply angles** so that the orientation of each element is set as the orientation of the corresponding element in the first layer, rotated by the ply's angle. The **Extrude Mesh** dialog box is shown below.



Push the OK button to launch mesh generation. You should have the following. Notice the top layer, very thin compared to the other layers. This is the layer used as the flow media.

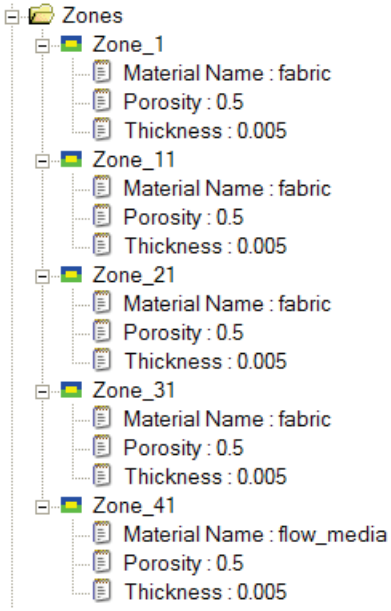


Extruded mesh

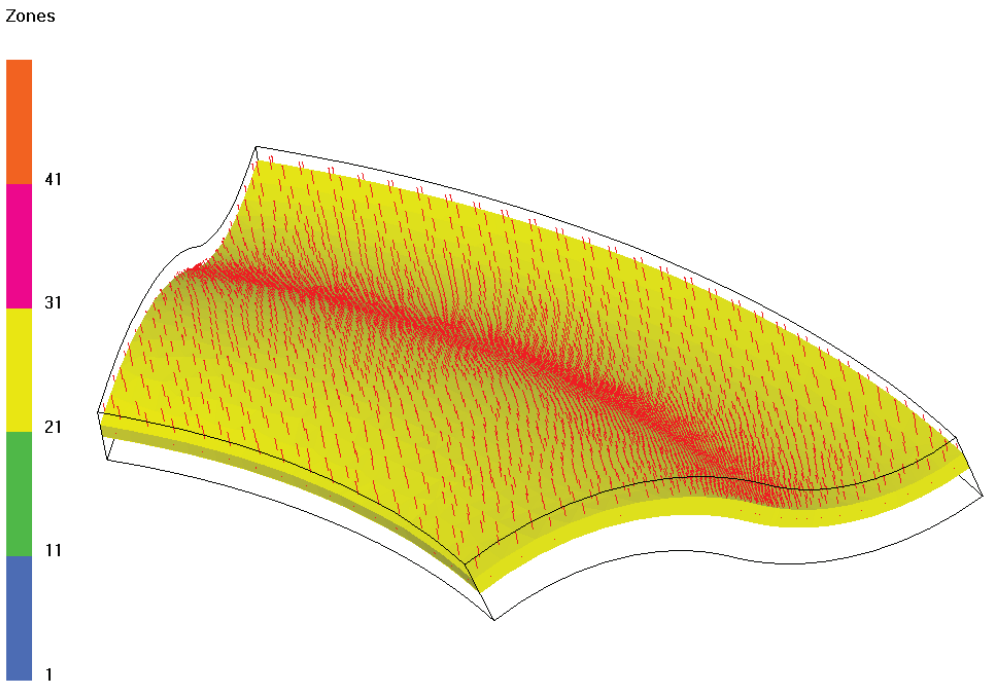


Zoom on the layers

The extrusion command automatically generates a zone for each layer in the document's tree. Each zone is linked to the corresponding ply material. The thickness of each zone is not important since we are working with solid elements. The porosity of each zone is also set from the plies.

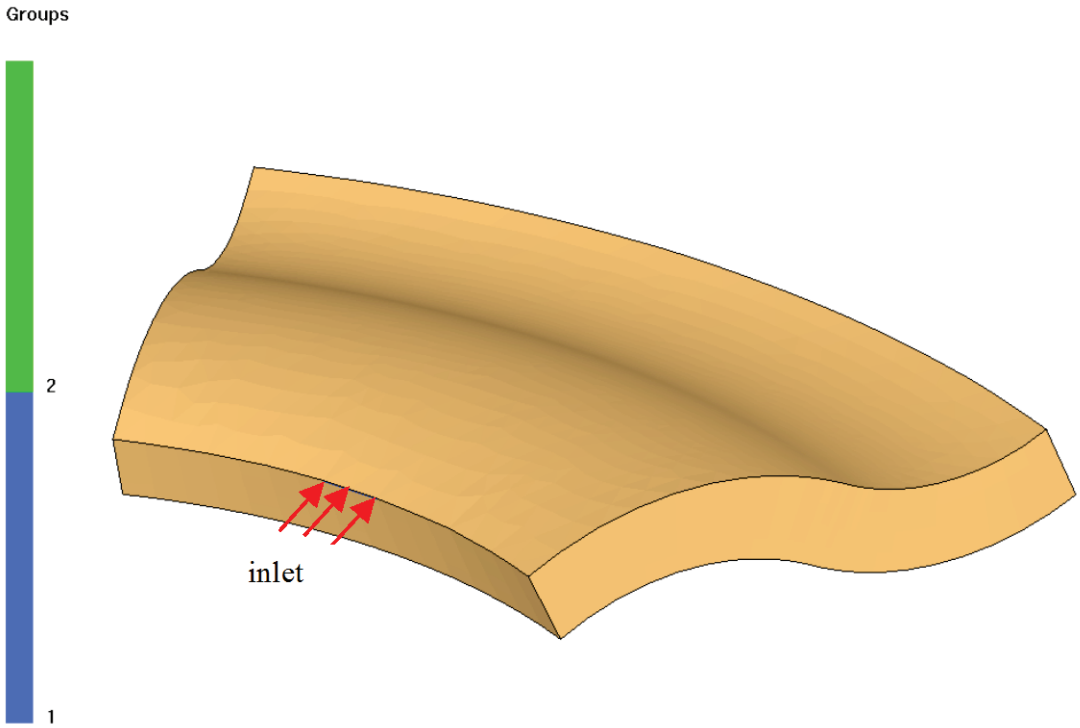


To verify that the orientations are correctly set, use the **View > Zones Visibility** command. For example, hide all layers and show only zone 21. Then show K1 vectors with **View > Orientations > K1 Only**. You should have the following picture, correctly showing orientation vectors at –45 degrees.

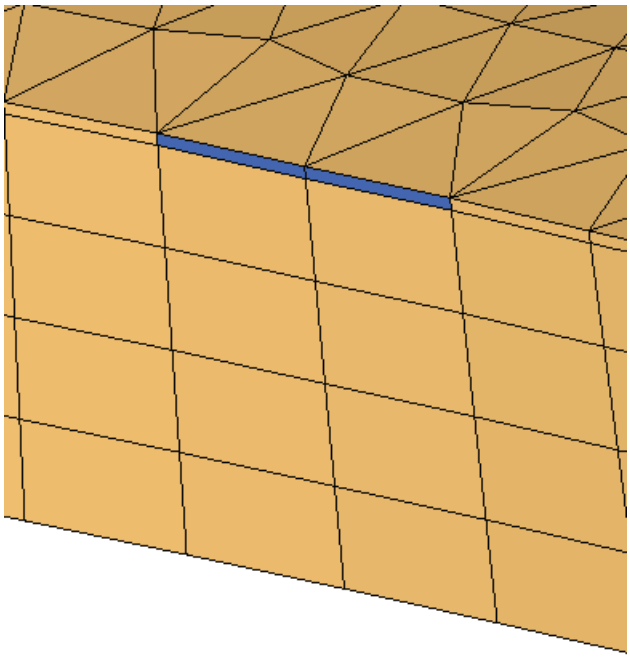


Process and Numerical Parameters

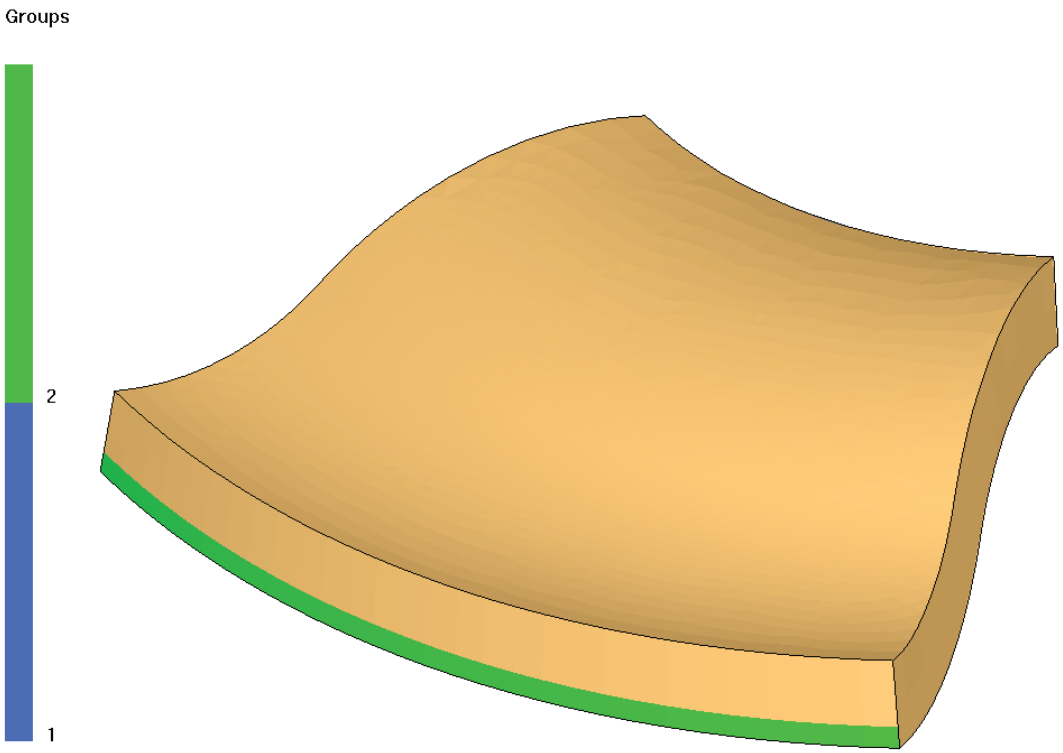
For the boundary conditions, create groups of faces as shown below. We inject from 2 faces directly in the high permeability layer. The vent is at the bottom of the opposite side. Set the injection pressure to 1 bar, and keep the default zero bar on the vent.



Location of the inlet



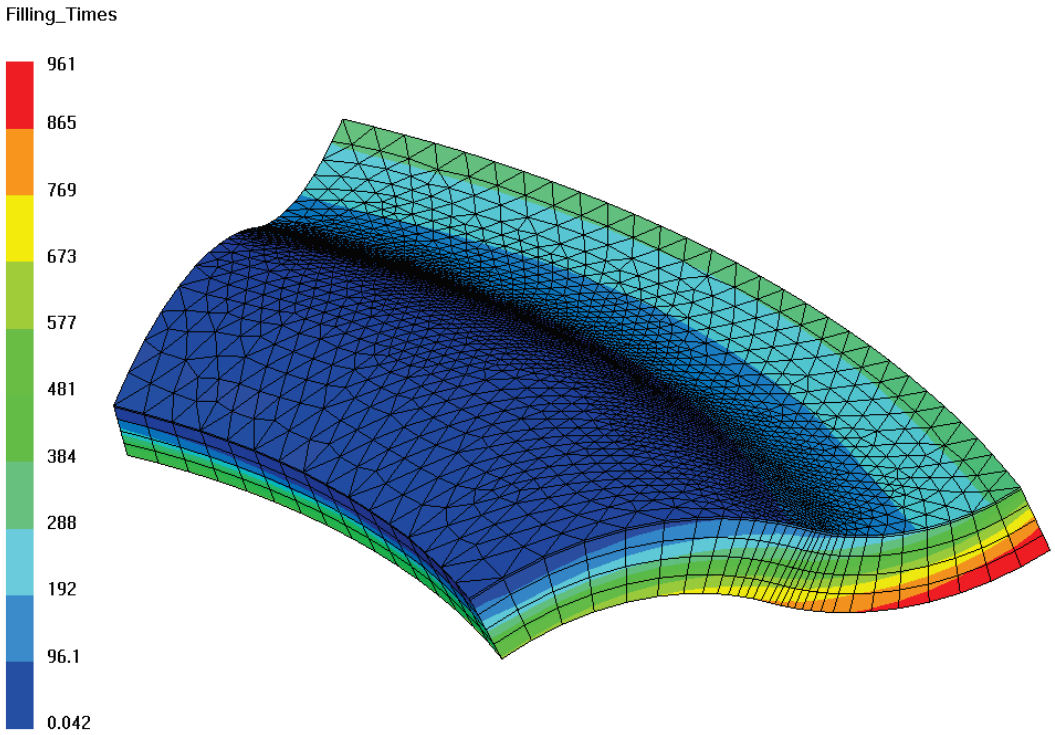
Group of faces for the inlet



Group of faces for the outlet

Launching the Simulation and Post-Processing

Save the document with **File->Save** and launch the simulation.



Segmented filling result

The segmented filling image clearly shows the effect of the flow media. Since the permeability of that layer is much higher, the resin almost completely fills that layer before starting to flow through the thickness of the part.

NON-ISOTHERMAL INJECTION

The files related to this example are:

- ***non_iso_fil_start.unv*** (starting mesh)
- ***non_iso_fil_1.dtf***, ***non_iso_fil_2.dtf***, ***non_iso_fil_3.dtf***, + ***non_iso_fil.unv*** (solution)

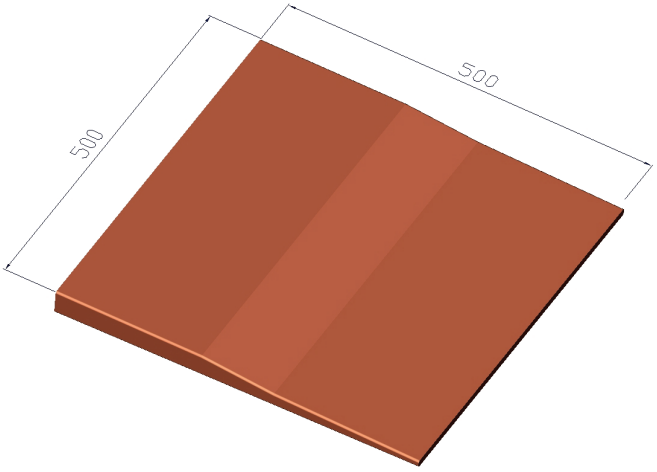
Objective of the Analysis

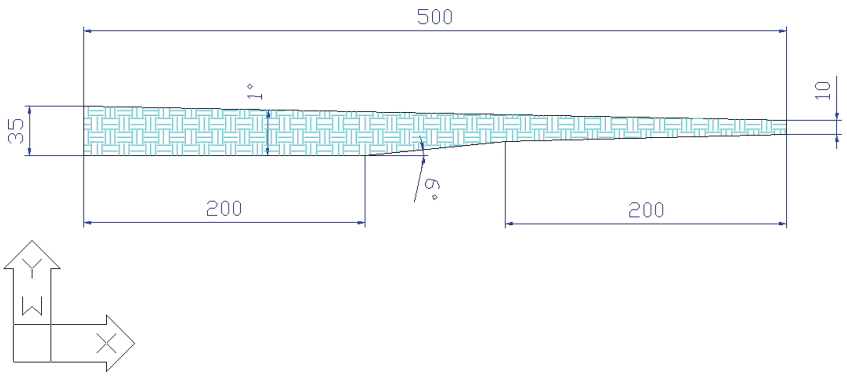
This example will show you how to:

- Perform a non-isothermal filling simulation,
- Study the effects of temperature on the injection of resin.

Geometry Description

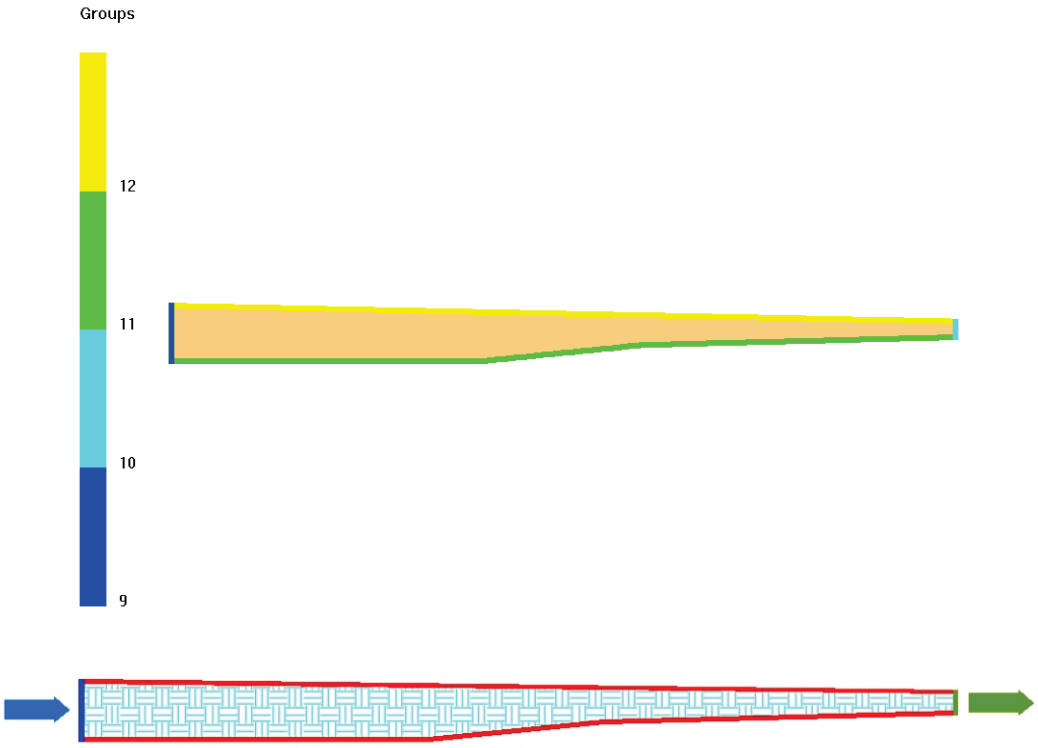
It is possible with **PAM-RTM™** to simulate the injection and at the same time take into account thermal effects. The part that will be simulated in this example is shown below. It is an extruded panel of variable thickness.





Visualization of Groups

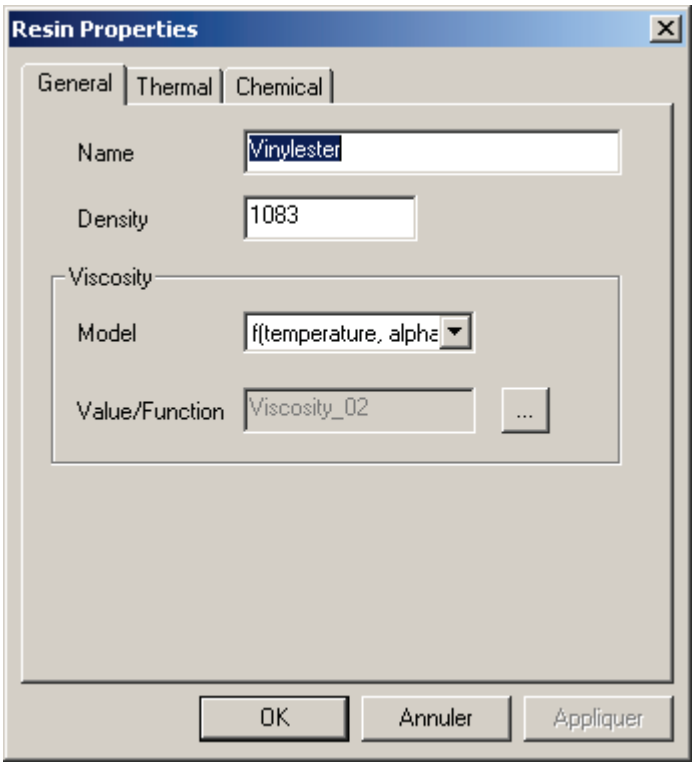
Create a new simulation of type Heated RTM (**File->New**) and import the mesh file `non_iso_fil_start.unv`. Then visualize groups of nodes. Groups at the extremity of the part will model the injection port (dark blue) and vent (light blue), groups on the top and bottom of the part (11 and 12) will be used to set the heating boundary conditions on temperature.



Simulation Parameters

Open the **Resin Properties** dialog box (doucle-click on **Default Resin**).

Enter the resin parameters as shown below:



- Resin Name: **Vinylester**
- Density = 1083 Kg/m^3
- Viscosity: a viscosity function relates viscosity with temperature and the degree of cure. Select the *Viscosity_02* model:

$$f(x,y) = c_0 e^{C_1/x} \times \left(\frac{c_2}{c_2 - y}\right)^{C_3 + C_4 \times y}$$

$C_0 = 1 \cdot 10^{-7}$

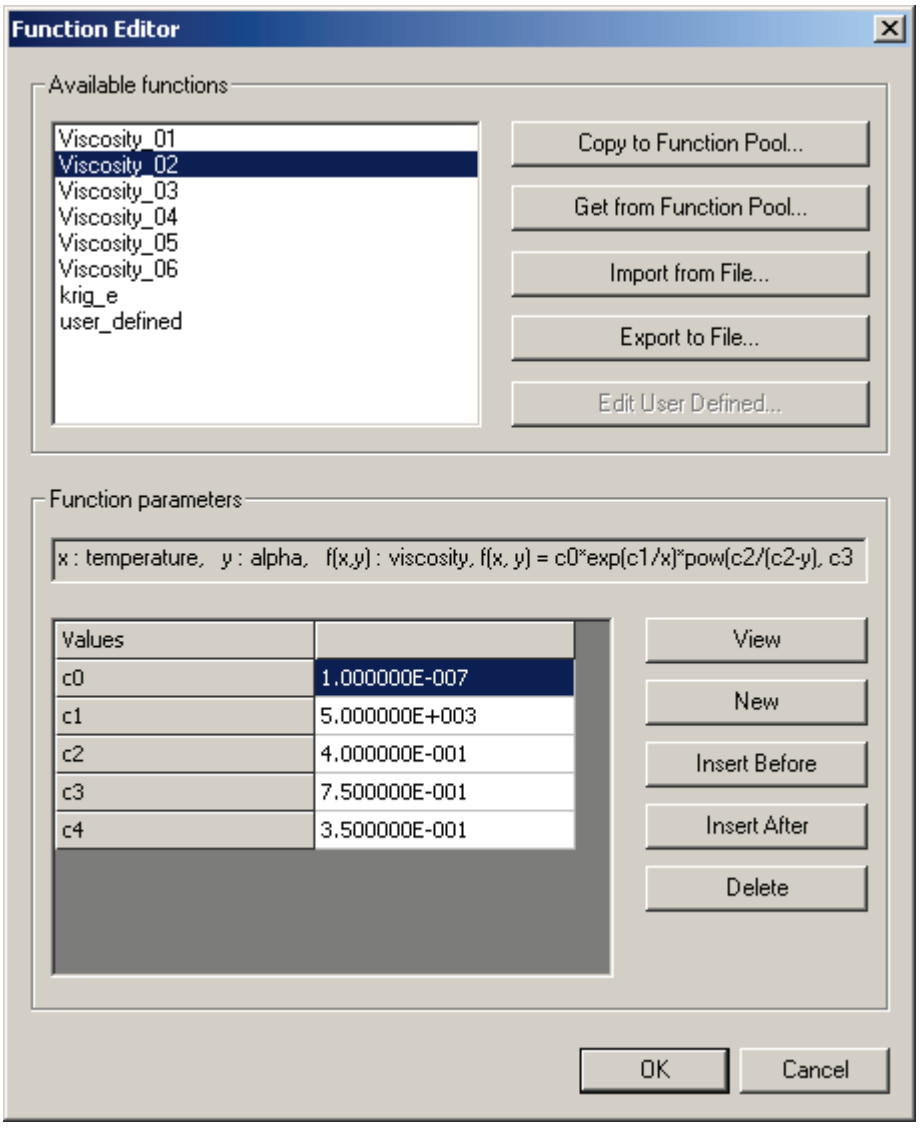
$C_1 = 5000$

$C_2 = 0.4$

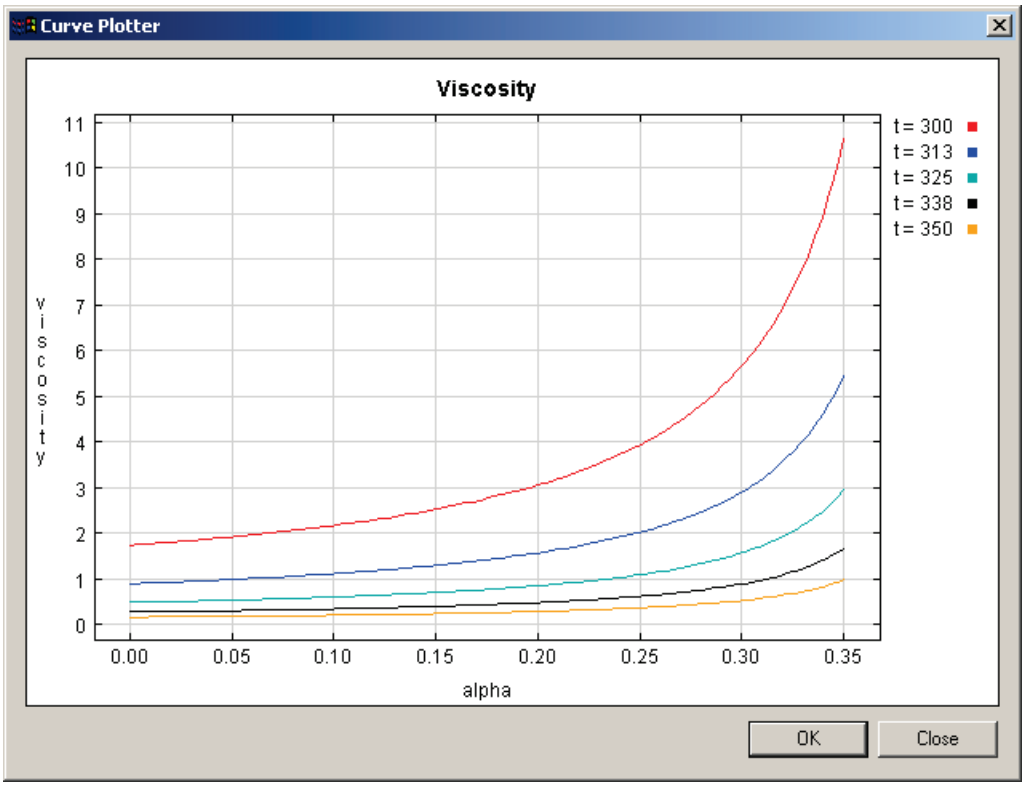
$C_3 = 0.75$

$C_4 = 0.35$

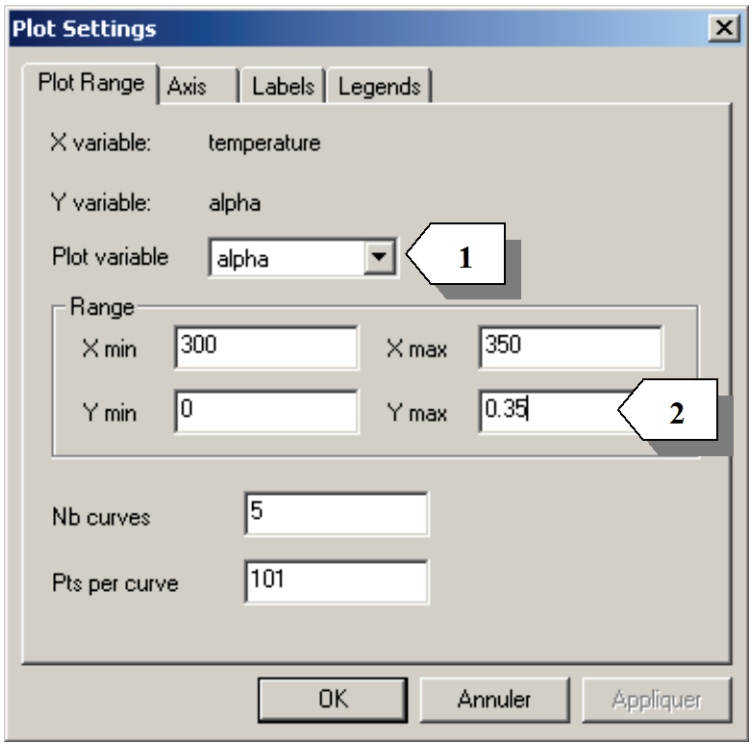
Choose in the Model drop down list *f(temperature, alpha)* and open the **Function Editor** (click on the **...** button), select the function *Viscosity_02* and set its parameters.



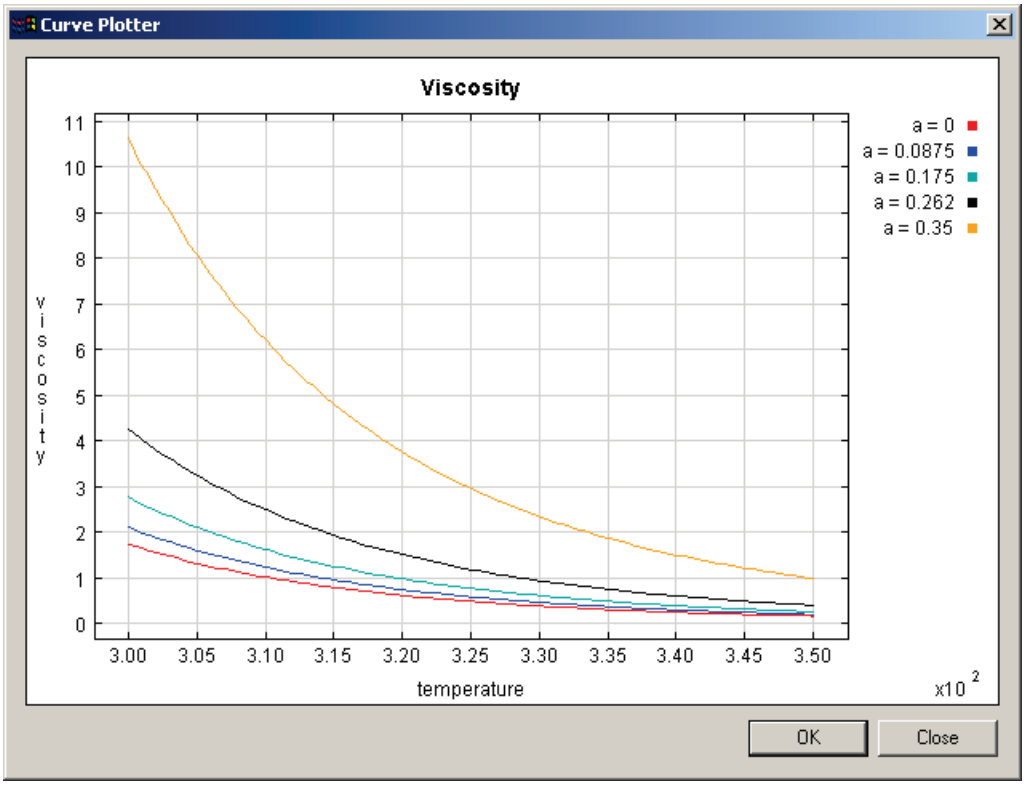
To visualize the viscosity function, push the **View** button. By default, curves are plotted for the viscosity as a function of alpha for fixed temperatures. In this example, a temperature range of 300 to 350°K was chosen. The maximum allowable value of alpha is 0.4 (the viscosity tends to infinity at 0.4), that's why the alpha max value was set to 0.35.



Right-click in the **Curve Plotter** window to open the **Plot Settings** dialog box. The range parameters are found in the **Plot Range** tab. In this context (viscosity as a function of temperature and alpha), X means temperature, Y means alpha.

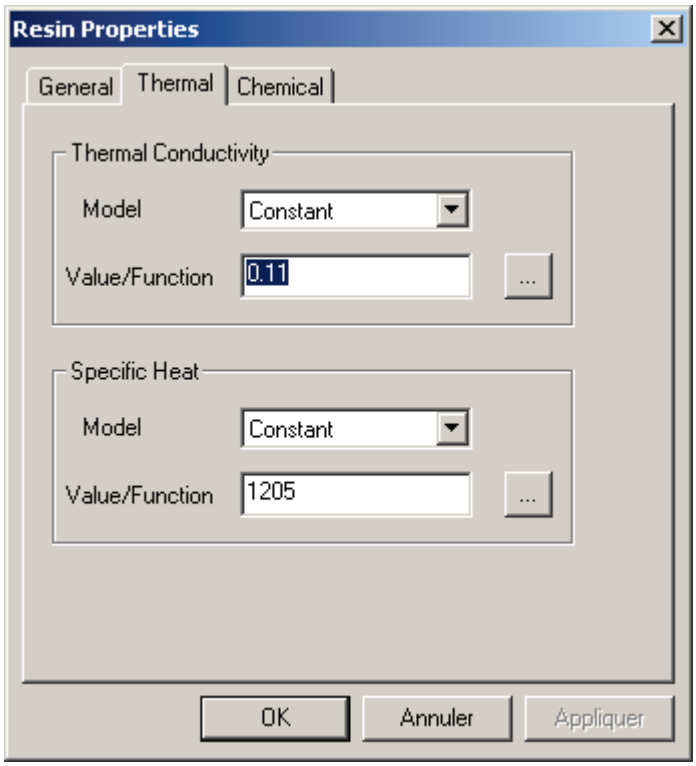


Choose alpha in the **Plot Variable** drop-down list **[1]** and set Y_{max} at 0.35 to avoid undefined viscosity function when alpha = 0.4 **[2]**.

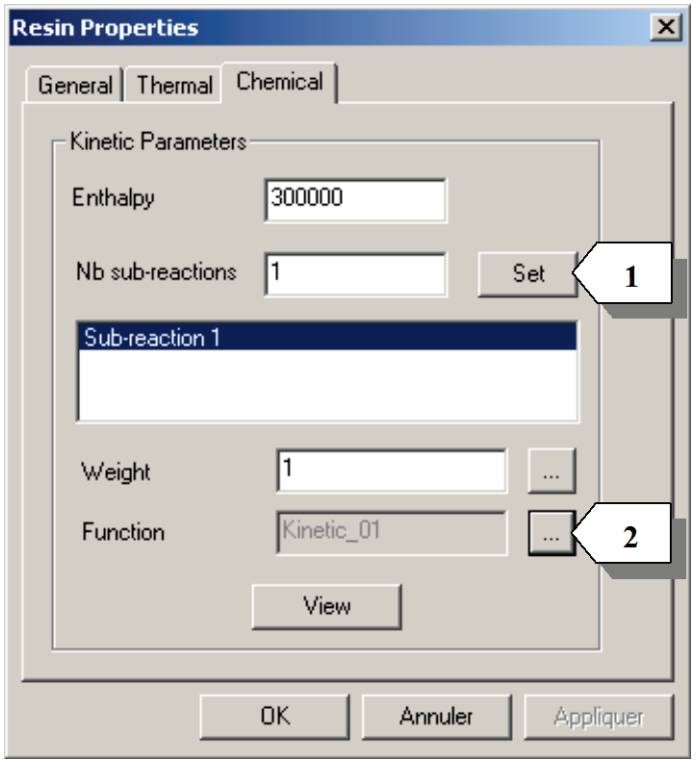


In the **Resin Properties**, select the **Thermal** tab to enter the thermal conductivity and the specific heat.

- Thermal conductivity = 0.11 W/m.K
- Specific heat = 1205 J/Kg.K



In the **Resin Properties** dialog box, select the **Chemical** tab and enter the kinetic parameters.



Set the Reaction Enthalpy at 3.10^5 J/kg.

Type 1 in the **Nb Sub-reactions** text field, then click the **Set** button **[1]**. This creates one sub-reaction. Then select *sub-reaction 1* and push the **...** button **[2]** to choose the resin kinetics model.

In the **Function Editor**, select *Kinetic_01* for the following resin kinetics model:

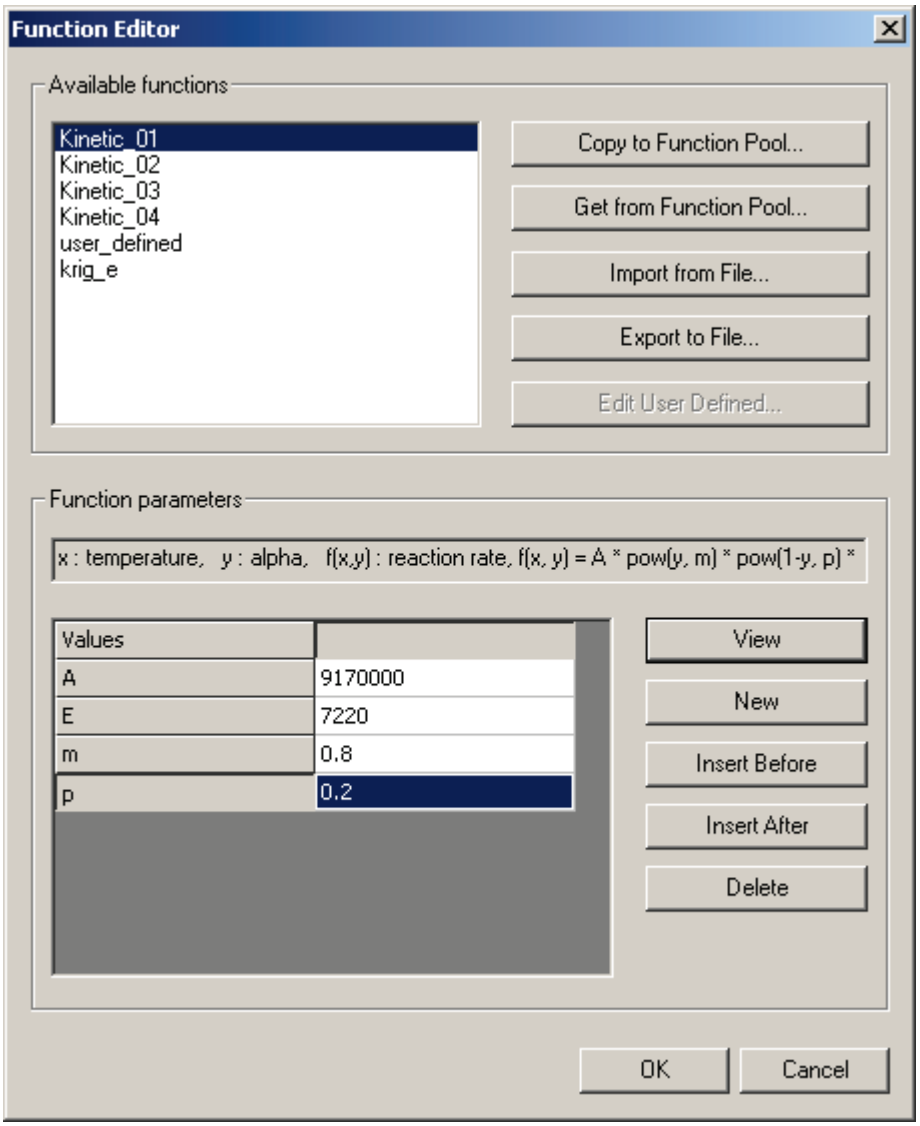
$$f(x,y) = A \times y^m \times (1-y)^p \times e^{-E/x}$$

A = 9170000

E = 7220

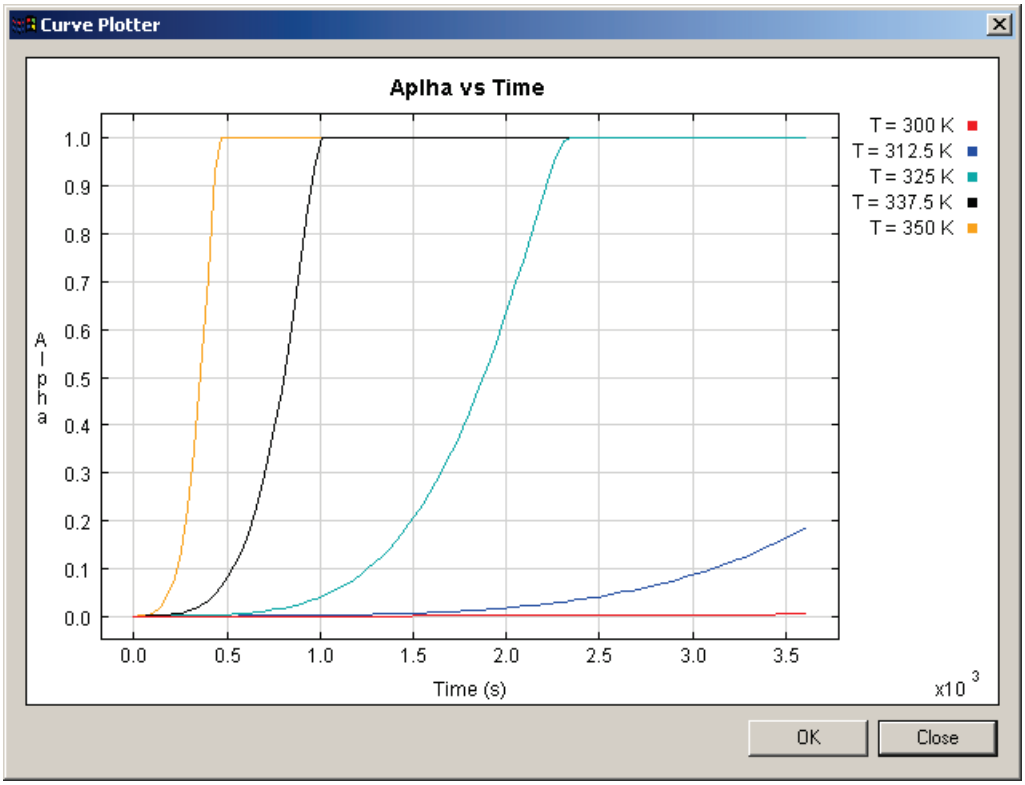
m = 0.8

p = 0.2



After defining the chemical reaction, it is possible to view the conversion curves in time for different temperatures. Push the **View** button in the **Chemical** tab of the **Resin Editor**

to open the **Kinetics Viewer** dialog. Set the appropriate temperature and time range, then push the **Plot** button.



This viewer is useful to know quickly how the resin behaves at different temperatures. For example, since we know that the viscosity becomes very large when alpha is near 0.4, we should try to avoid alpha values larger than, say, 0.1 with a good safety margin. This means that the part must be filled in about 250 s. if the temperature is 350 K.

Now set the properties of the reinforcement as follows :

- Density: 2565 kg/m^3
- Thermal conductivity: 0.2 W/m.K
- Specific heat: 1205 J/Kg.K
- Effective conductivity: 0.3 W/m.K
- Permeability: K1=K2=K3=1.5 10^{-10} m^2

And the parameters of the zone:

- Porosity: 0.5
- Thickness: 0.005 m

Define the boundary conditions.

- Injection pressure (Group 9) = 2.10^5 Pa.
- Vent pressure (Group 10) = 0 Pa.

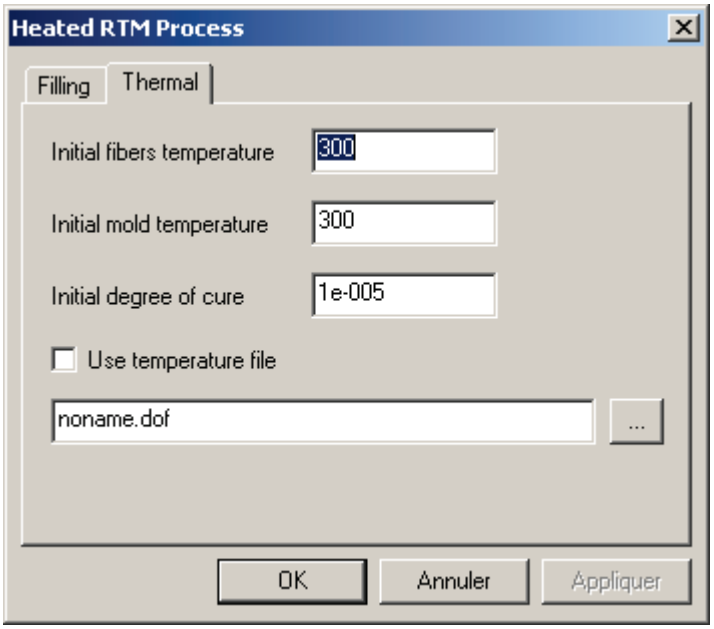
Simulation Cases

Case 1

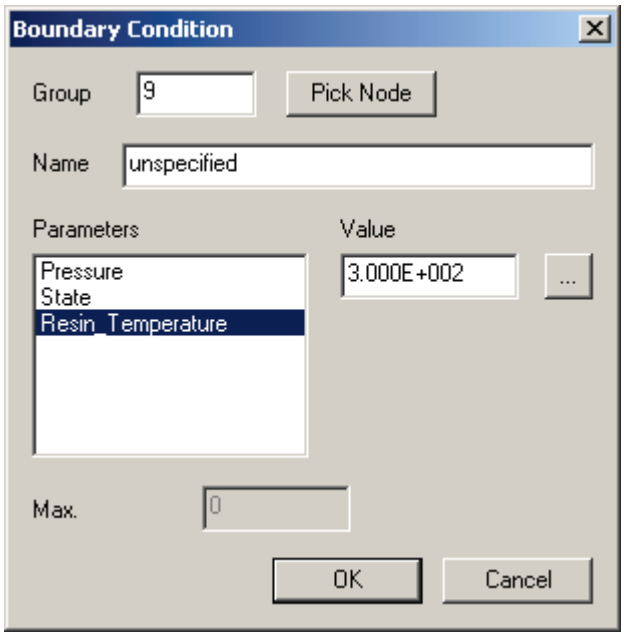
The first case is carried out with the following conditions:

- Initial temperature of the mold and fibers: 300 degrees K
- Temperature of the injected resin: 300 degrees K
- Temperature of the mold walls: 350 degrees K

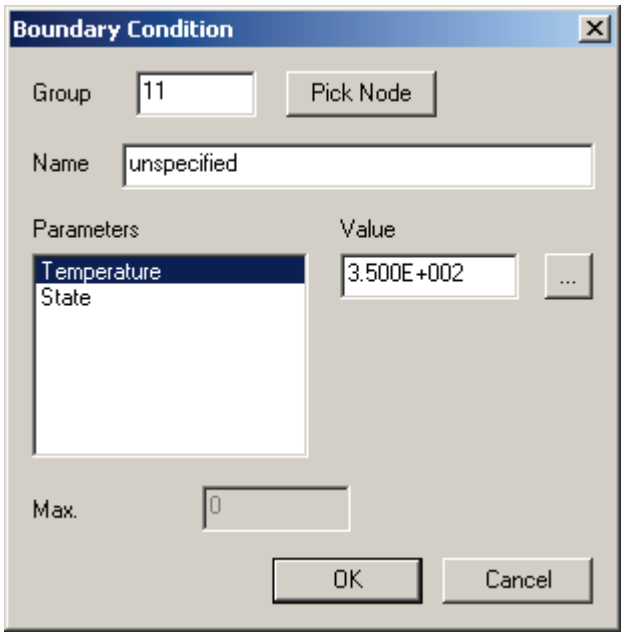
To set the *Initial fibers* and *mold temperature*, double-click on **Process** and select the **Thermal** tab.



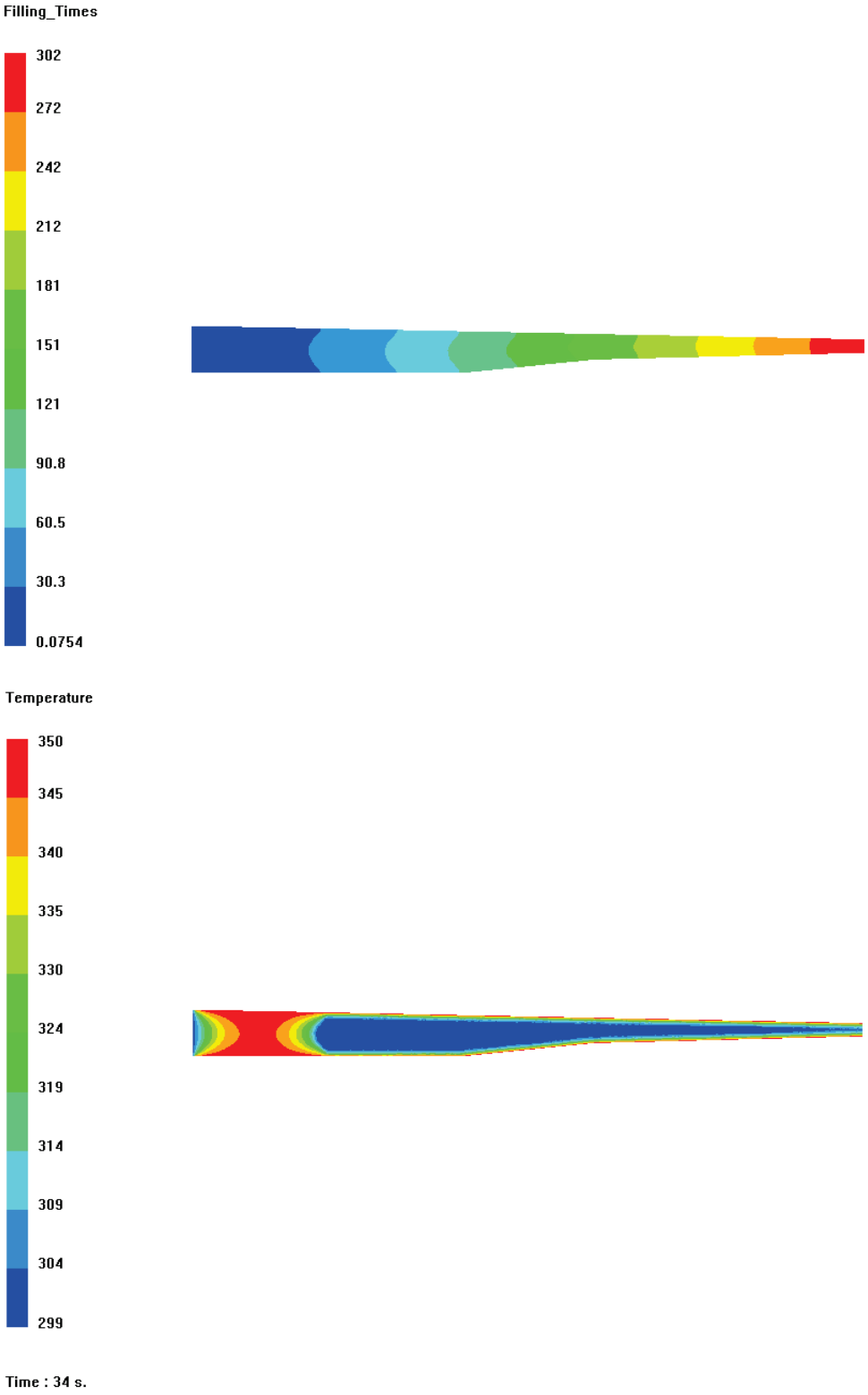
The temperature of the resin is specified in the injection port parameters:

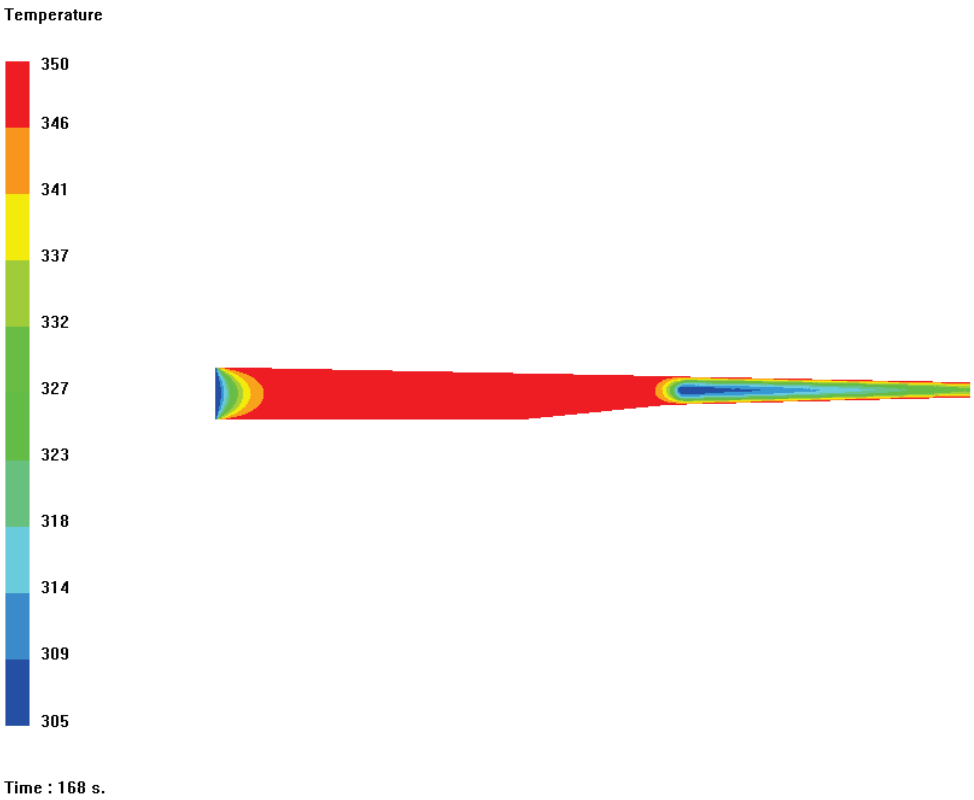


To define the thermal boundary conditions, right-click on **Boundary Conditions** and click on **New->Temperature**, then double-click on **Temperature_-1** to open the **Boundary Condition** dialog box.



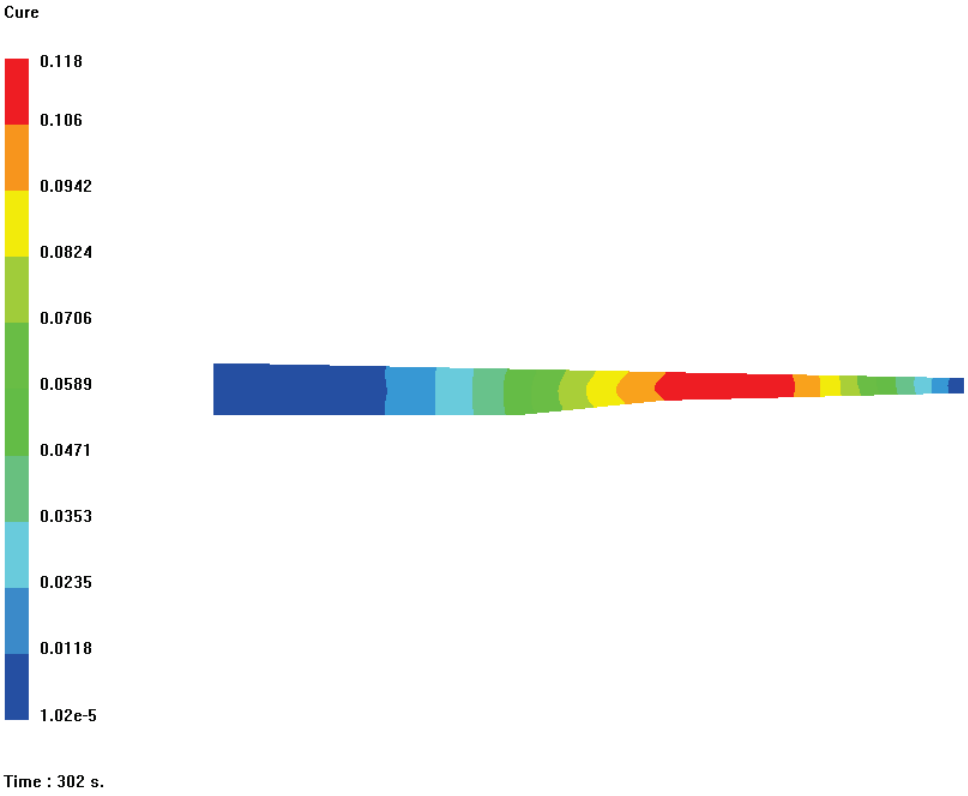
The resin is injected at 300 degrees K in the mold cavity. Since the upper and lower mold walls are heated at 350 degrees K, the resin temperature increases close to the mold walls. This reduces the viscosity of the resin and tends to accelerate the resin flow along the top and bottom walls of the mold as illustrated below.


Filling_Times
302
272
242
212
181
151
121
90.8
60.5
30.3
0.0754
Temperature
350
345
340
335
330
324
319
314
309
304
299
Time : 34 s.



Note that the flow front is not only accelerated on the top and bottom mold walls because of a lower resin viscosity, but also in the center as a result of the convergent geometry of the part. When the resin has reached the thinner section on the right, the flow front has become straight.

As the temperature in the cavity increases, the resin viscosity decreases, and the curing reaction begins to solidify the resin. The figure below shows the degree of cure at the end of the filling:



Case 2

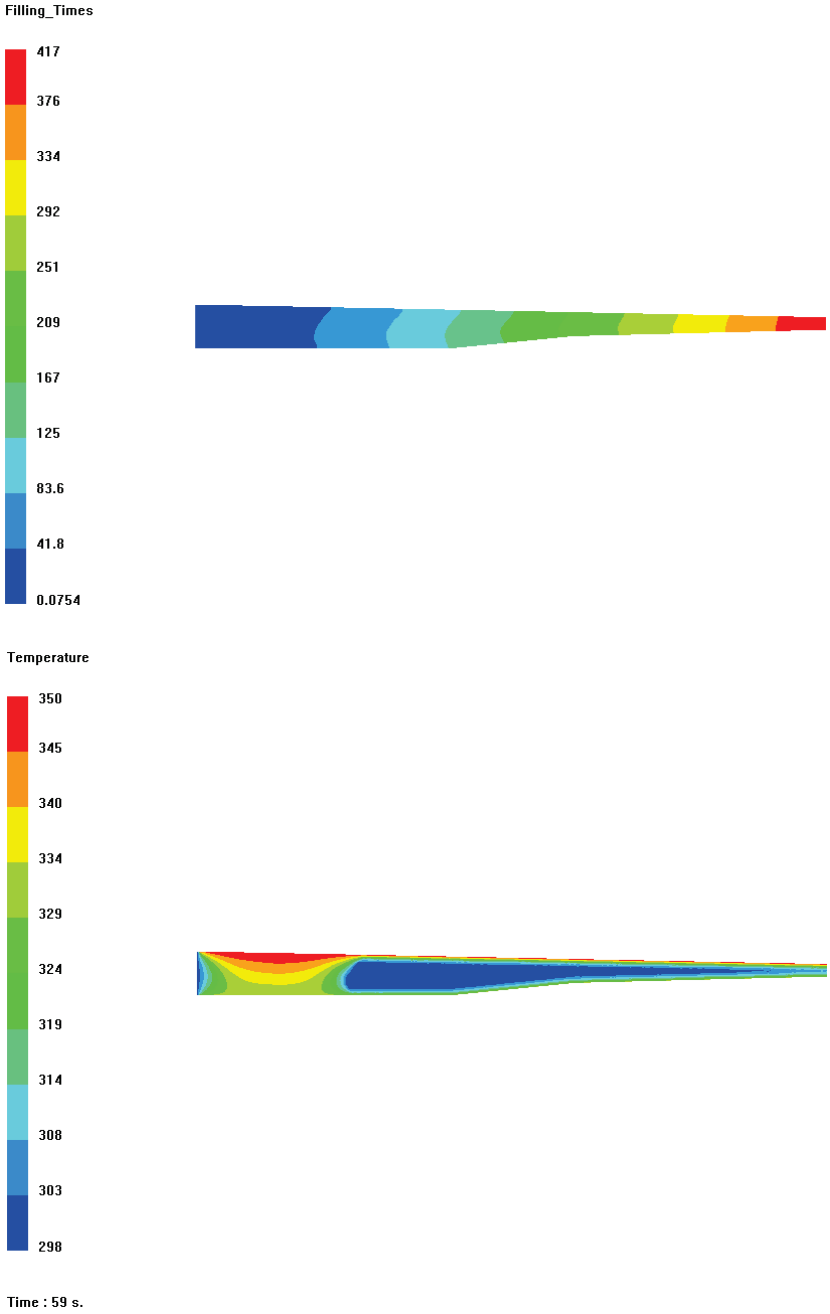
In this second test, the boundary conditions are slightly different :

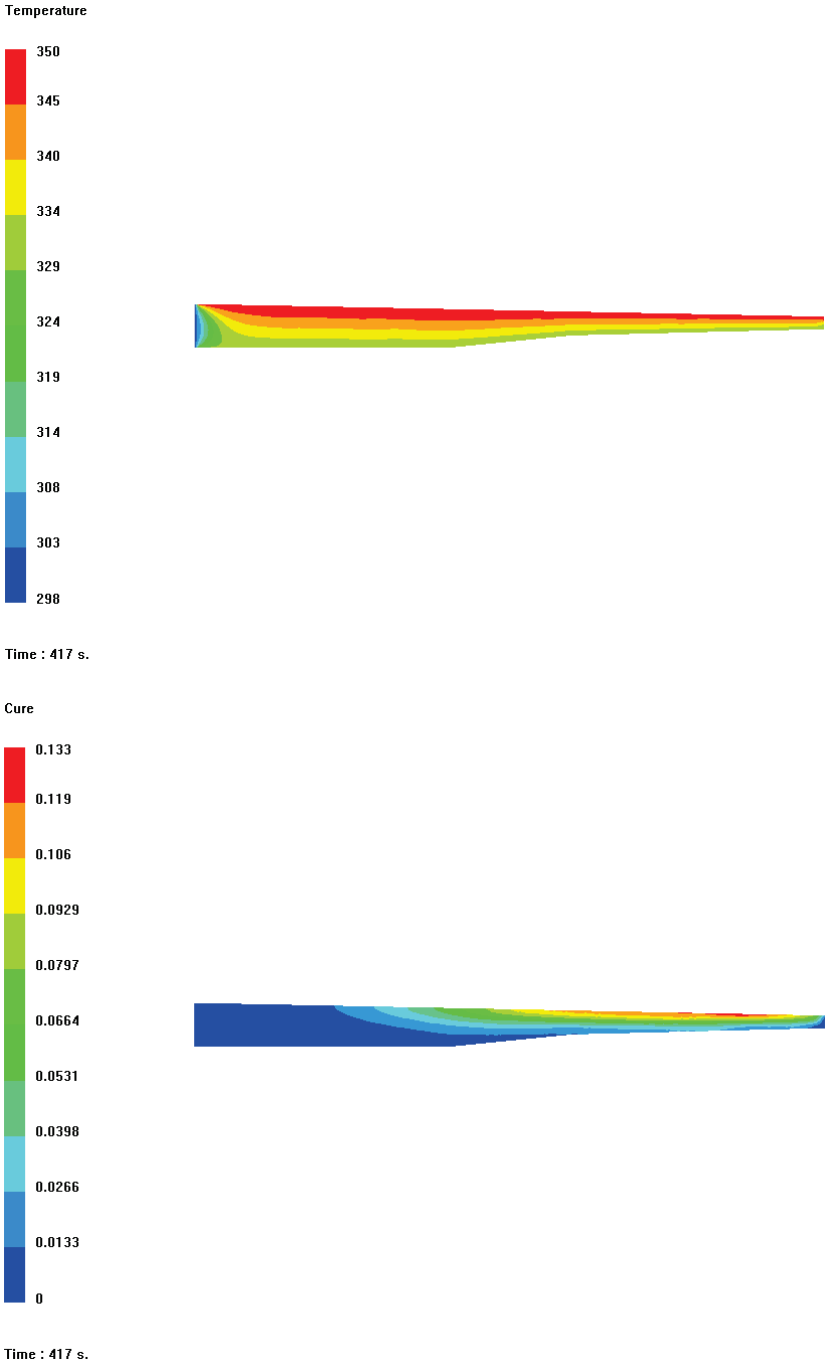
- Initial temperature of the mold and fibers: 300 degrees K
- Temperature of the injected resin: 300 degrees K
- Temperature of mold walls : 350 degree K on top and 330 degree K on bottom

In this case, the resin viscosity is not uniformly distributed through the thickness because the temperature of the top mold wall is higher than that of the lower wall. Therefore, the resin flow is faster near the upper mold wall at the beginning of the injection. However because of the combined effects of the temperature, degree of cure and convergent geometry, the flow front is almost straight at the end of filling.

The degree of cure distribution at the end of the injection is not very interesting. The cycle time will be longer than in the previous case. The degree of cure of the part is also not uniform. So the mechanical properties of the part will vary in each section. This can be disastrous when the part will be used.

The figures below show the segmented filling patterns, the temperature field at the end of the injection and the degree of cure at the end of the injection.


Filling_Times
417
376
334
292
251
209
167
125
83.6
41.8
0.0754
Temperature
350
345
340
334
329
324
319
314
308
303
298
Time : 59 s.

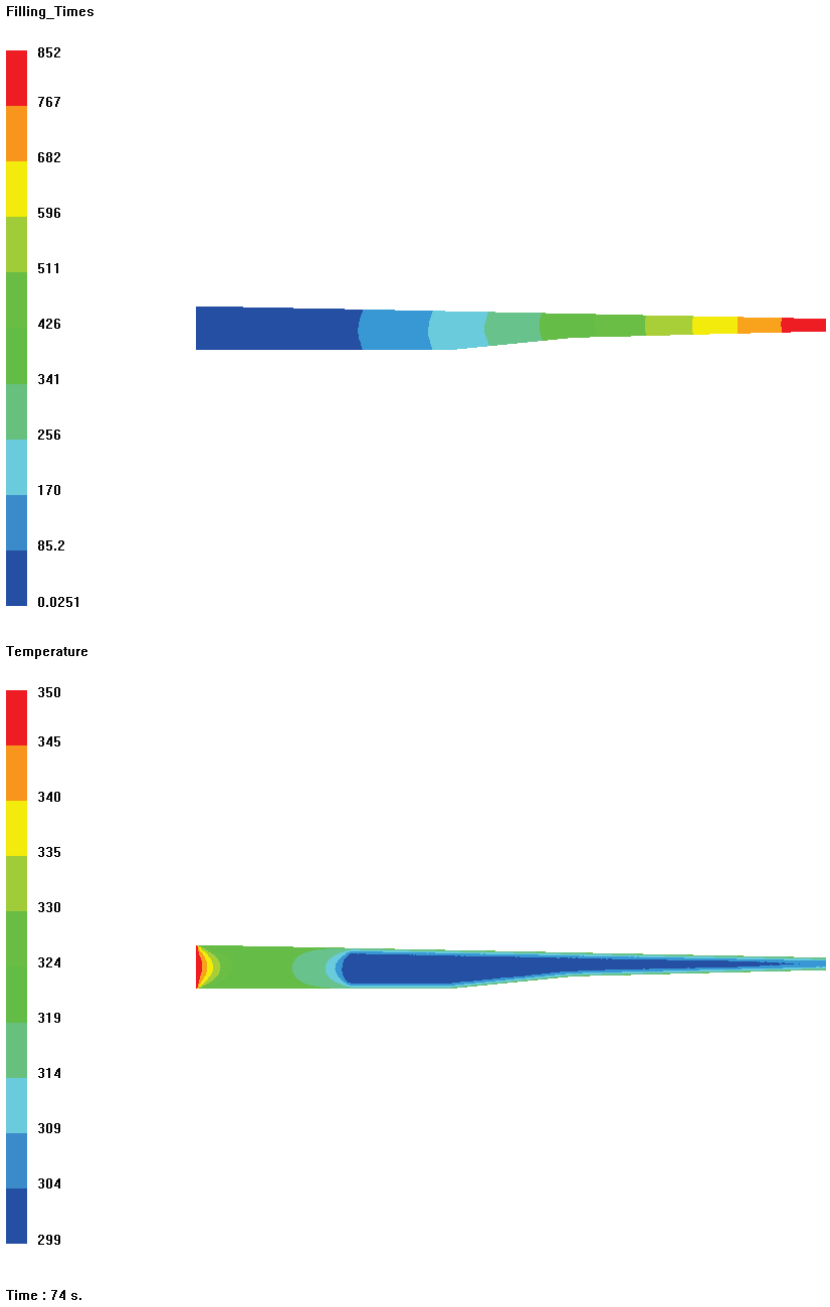


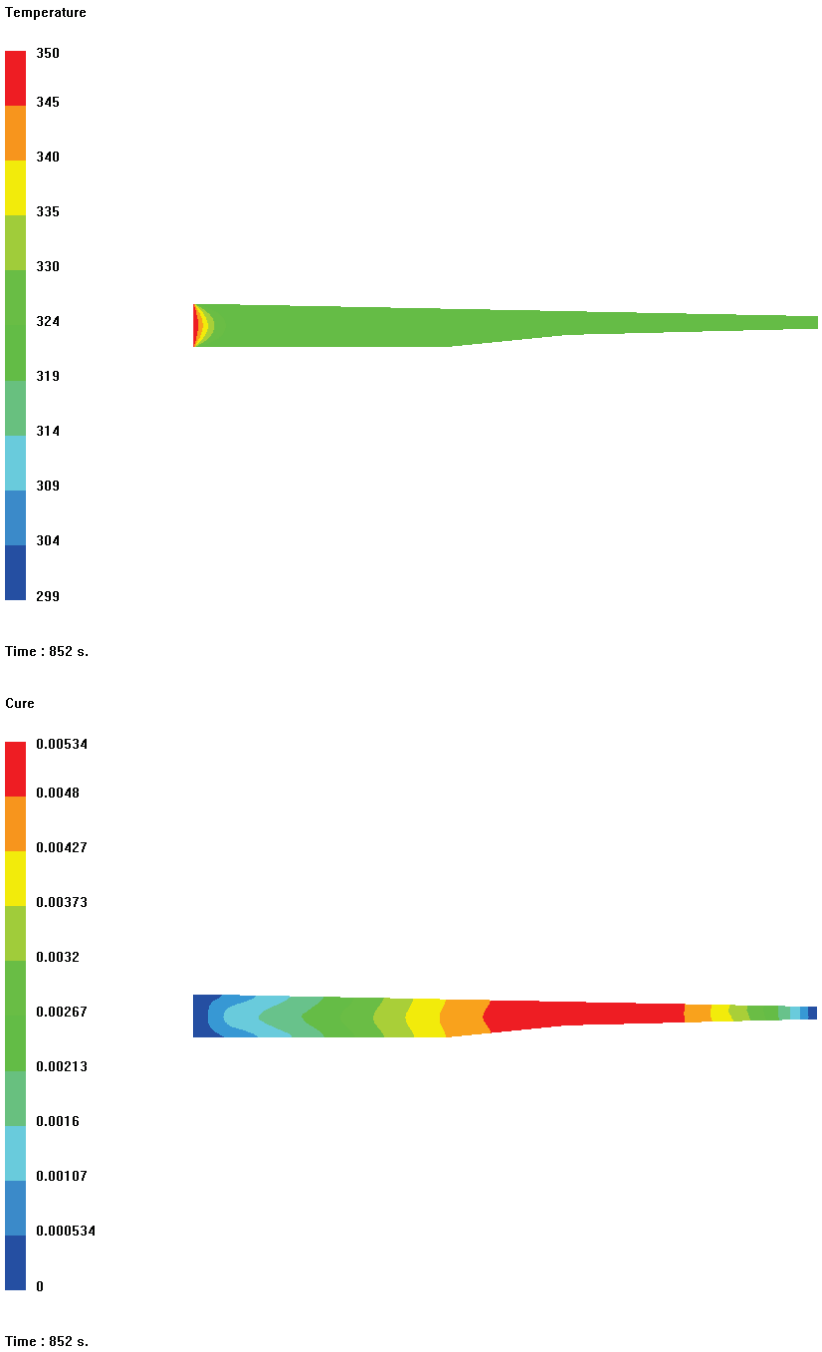
Case 3

The temperature boundary conditions of the third case are the following:

- Initial temperature of the mold and fibers: 300 *degrees K*
- Temperature of the injected resin: 350 *degrees K*
- Temperature of mold walls: 320 *degrees K*

For this case, the temperature of the resin is larger than the temperature of the mold. This has several consequences. First of all, the figures below show that resin is cooled down by the mold when it enters the cavity. At the end of the filling, the temperature is almost uniform in the part. Secondly, the resin front is not distorted and remains nearly straight. Finally, because the temperature of the resin stays much lower, the degree of cure at the end of the injection is very small (0.005). The major problem in this case is that the filling time is very long (about 850 s. compared to 300 s. for the first case), because the viscosity is higher.




Temperature
350
345
340
335
330
324
319
314
309
304
299
Time : 852 s.
Cure
0.00534
0.0048
0.00427
0.00373
0.0032
0.00267
0.00213
0.0016
0.00107
0.000534
0
Time : 852 s.

CURING OF A PLATE

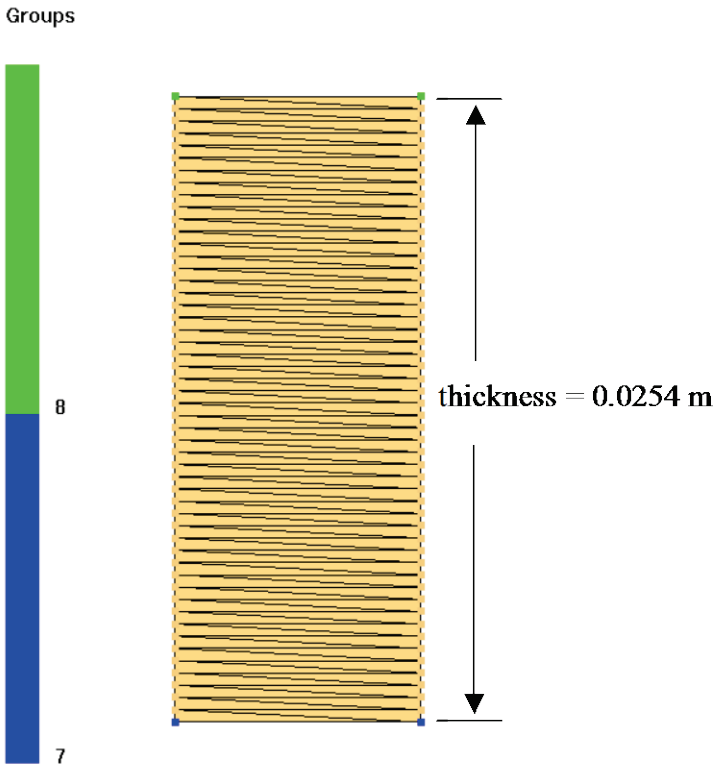
The files related to this example are:

- ***curing_1d_start.unv*** (starting mesh)
- ***curing_1d.dtf*** + ***curing_1d.unv*** (solution)

Visualization of the Mesh and Groups

Begin by creating a new *Curing* simulation with **File->New** and import the mesh file `curing_1d_start.unv`.

Visualize the mesh and groups of nodes. You should have the following:



This simplified problem should be seen as a cross section in a thick rectangular plate, on which the temperature is fixed on top and bottom and the heat flux is zero all around the part. This leads to a 1D heat transfer problem through the thickness of the part.

Simulation Parameters

Numerical Parameters

Use **Simulation->Numerical Parameters** to open the **Curing Numerical Parameters** dialog box, select the **Time Step** tab and set the following parameters:

- Max. Experiment Time: 3600
- Max. Number of Steps: 1000

Notes:

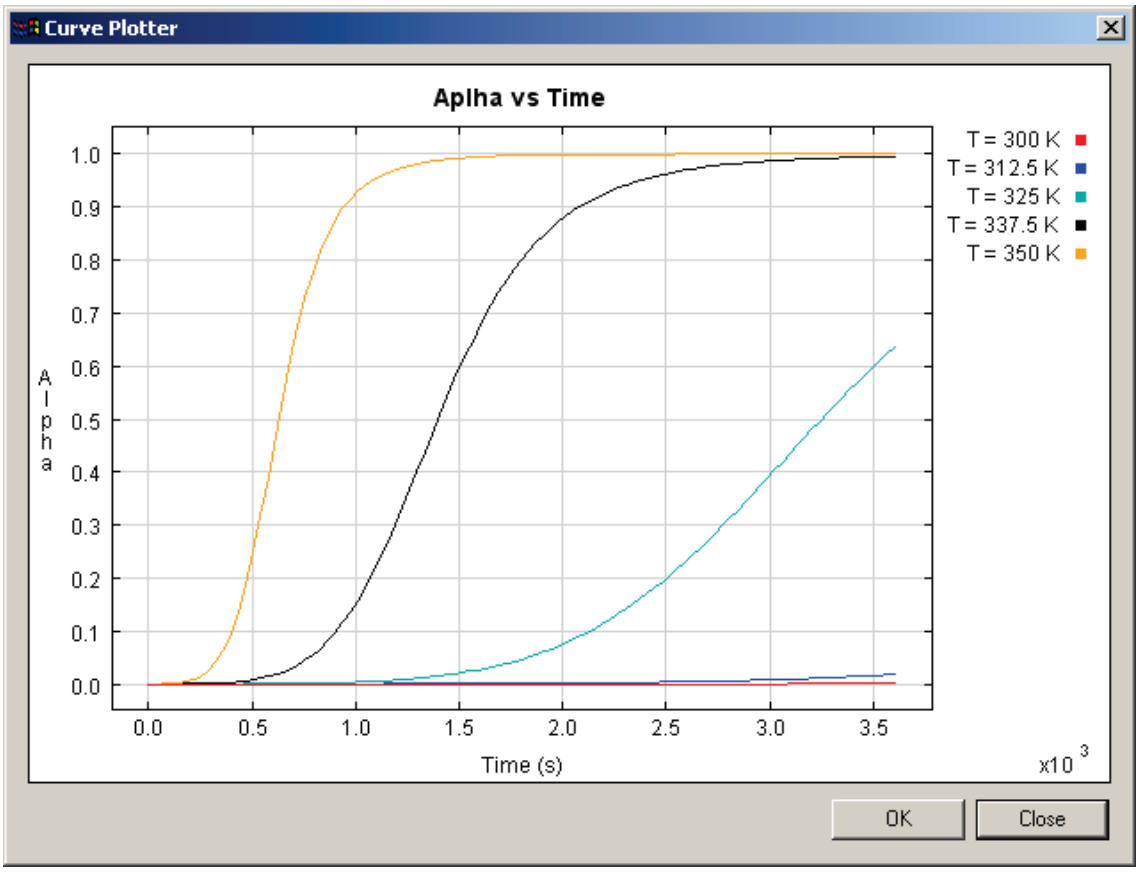
- *For a curing and preheating simulation, the time step is fixed and is calculated as:*
  dt = Max. experiment time/Max. number of steps

Resin Parameters

Open the **Resin Properties** dialog box and set the following parameters:

- Resin Name: Vinylester
- Density: 1083 kg/m^3
- Specific Heat: 1205 J/Kg.K
- Enthalpy: 266342 J/Kg
- Add a new reaction, open the **Function Editor** and select Kamal-Sourour model (Kinetic_01) with A=9.17E6, E=7289, m=0.85 and p=1.15

Use the **View** button to verify the chemical model. As illustrated in the figure below, this function allows visualizing resin conversion curves, i.e., the evolution of the degree of polymerization (alpha) in time for different processing temperatures.



On these curves of isothermal conversion, the value of 1 means that the resin has been cured completely. Curves with a smaller slope are obtained for lower temperatures. Change the processing temperature and the time scale to visualize the effect of temperature on the curing time.

Fiber Parameters

Enter the following parameters.

- Name: **Glass**
- Density: 2565 Kg/m^3
- Specific Heat: 1205 J/Kg.K
- Effective Conductivity of the saturated reinforcement (for each direction: K_1, K_2, K_3): 0.25 W/m.K

  Note:

  · *For curing simulations, it is not necessary to specify the conductivity of the dry fibers nor the conductivity of the resin. The single conductivity value that will be used is the effective conductivity, which is the conductivity of the composite.*

Zones

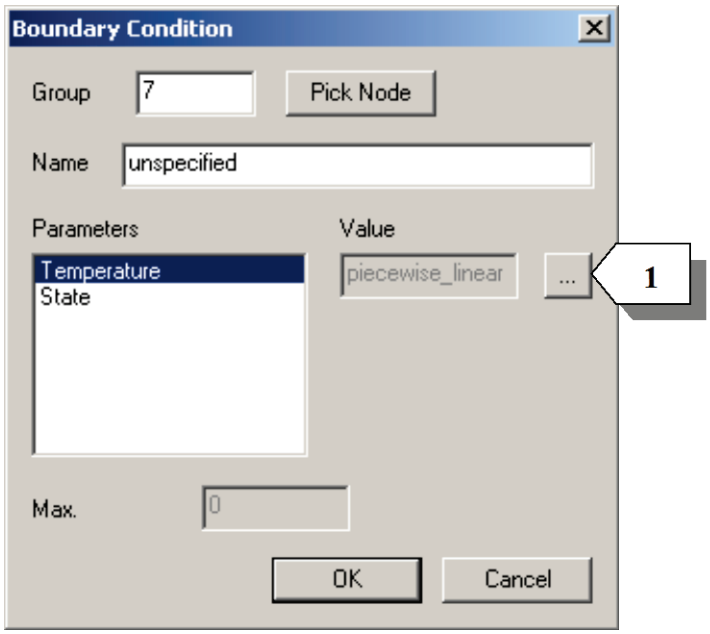
Assign the material *Glass* to the zone 6. Choose a porosity of 0.57, i.e., the fiber volume fraction is 43%.

Note:

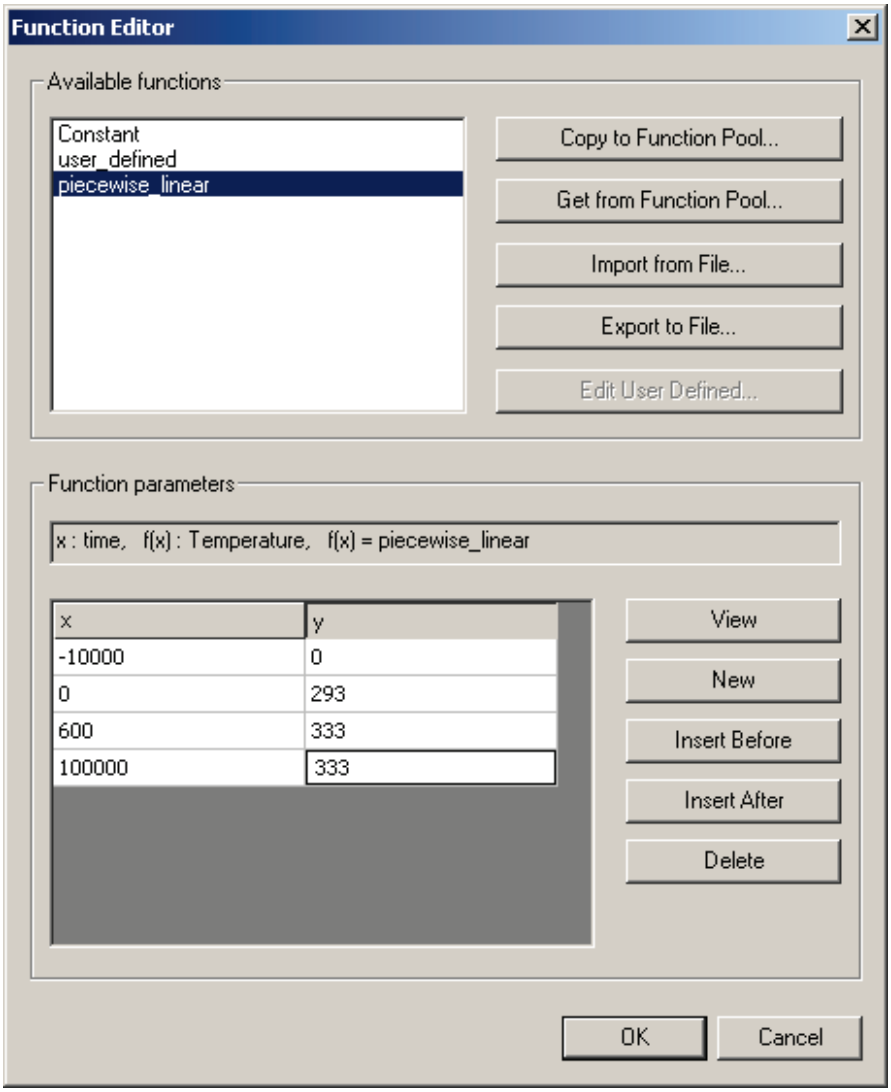
- *For a curing simulation, the meaning of porosity is the same as in the simulation of injection. Porosity is equal to 1-V_f, where V_f is the volume fraction of fibers.*

Boundary Conditions

Create a new Temperature boundary conditions.



Open the **Function Editor [1]** to define a curve of the temperature vs. time.



Choose piecewise_linear and enter the points in the following sequence (the order is very important):

- (-10000, 0)
- (0, 293)
- (600, 333)
- (10000, 333)

The first point is used to avoid problems in case there would be slightly negative time values generated during the simulation. The last point tells the software to keep the temperature constant to 333 degrees after 600 seconds of curing. Otherwise, the software would extrapolate using the slope defined by the two last points.

Repeat this procedure now for the second boundary condition (group 8).

Sensors

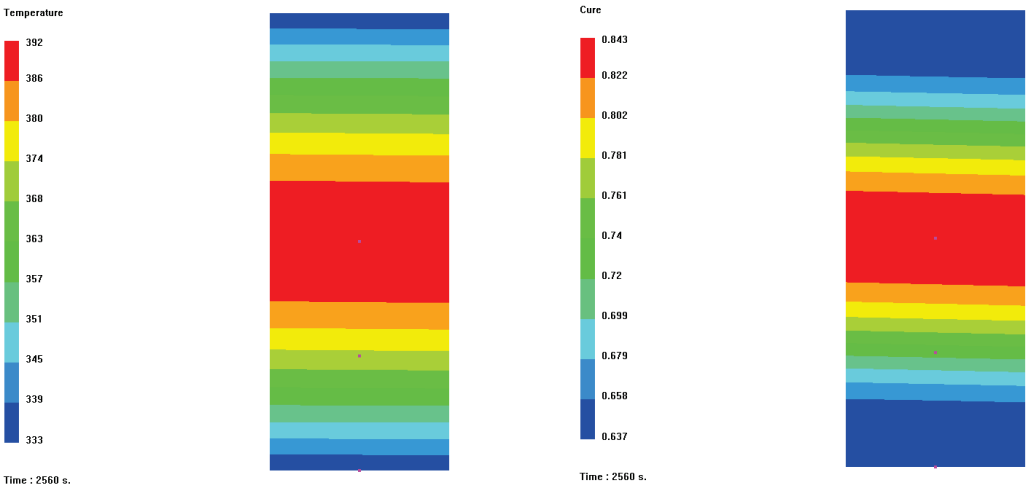
In order to get curves of temperature in time, three sensors are set in the cavity. Define the sensors as *Points* and set the following coordinates:

- (0.005, 0.00635, 0.) (lower quarter)
- (0.005, 0.0127, 0.) (middle)
- (0.005, 0., 0.) (boundary condition)

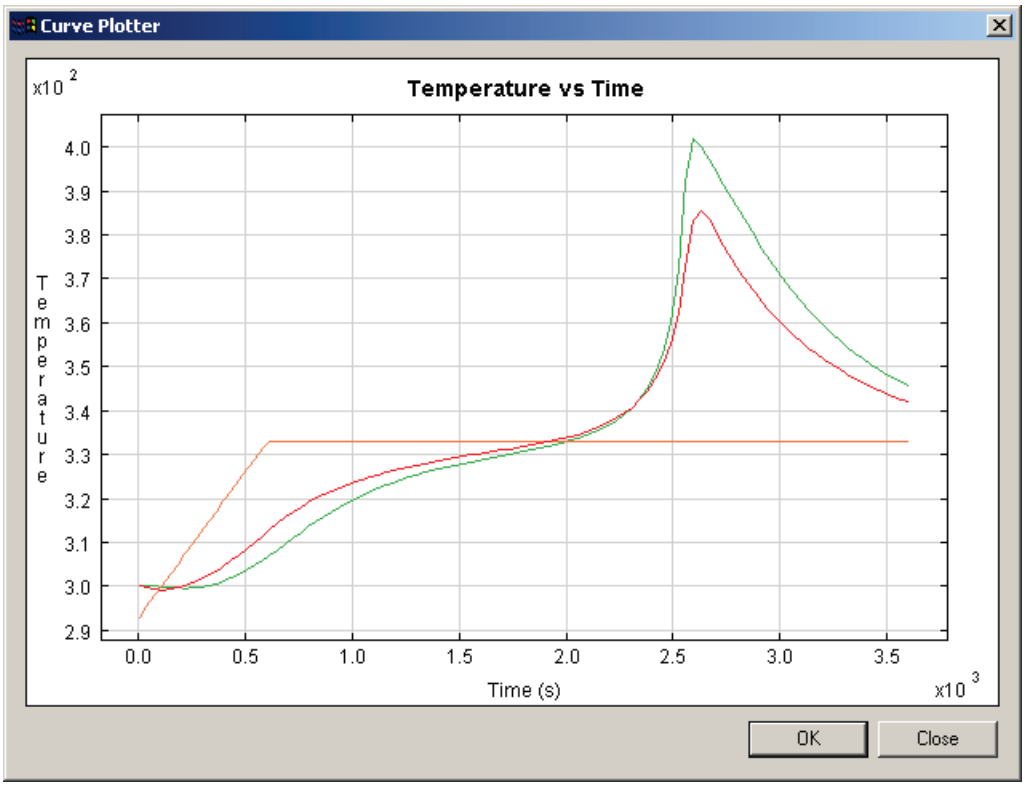
Simulation Results

Save the *.dtf* file and launch the simulation.

Select *Temperature* and *Cure* scalar fields in the display toolbar. You should have the following. Note on the Cure picture that it begins in the center of the part and ends up on the top and bottom faces. This is important to avoid a build up of residual stresses in the part.



The curve viewer can be used to display the following curves. In the explorer, right-click each sensor and choose **Plot**.



Note that sensor values are saved in text files so that you can import them later in more advanced plotting software like Microsoft Excel or GNUPLOT. In this example, a file named *curing1d_Temperature_Curing_sensors.dat* is generated for temperature values on sensors, and a file named *curing1d_Cure_sensors.dat* contains the extent of cure values on each sensor. The format of these files is simple. The first column represents time, the next ones contain the scalar field value for each sensor. These files can easily be imported in plotting software.

CURING OF A PART WITH AN INSERT

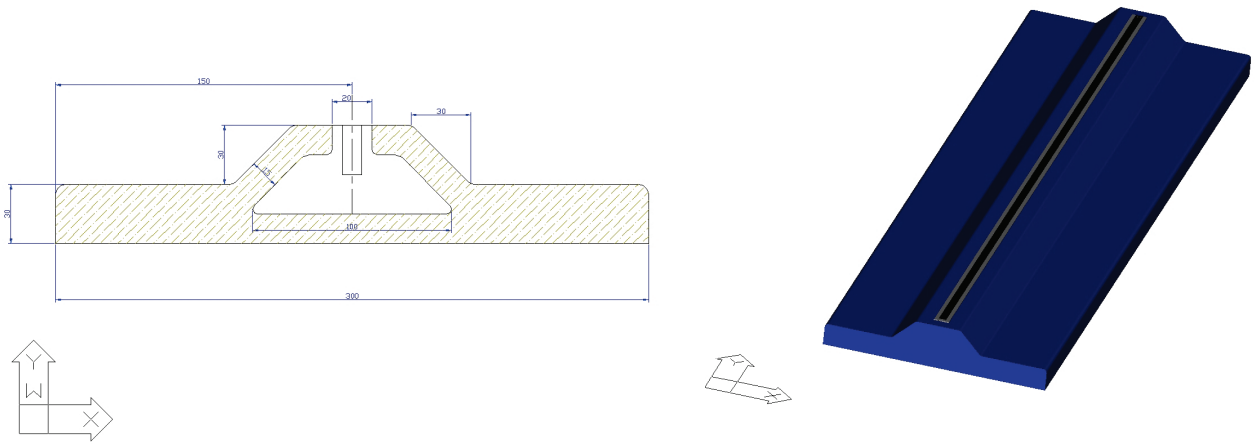
The files related to this example are:

- ***curing_insert.unv*** (starting mesh)
- ***curing_insert_1.dtf***, ***curing_insert_2.dtf***, ***curing_insert_3.dtf***, + ***curing_insert.unv*** (solution)

Objectives of the Analysis

This example will show you how to:

- Perform an analysis of the curing process on a part containing a steel insert,
- Use sensors.



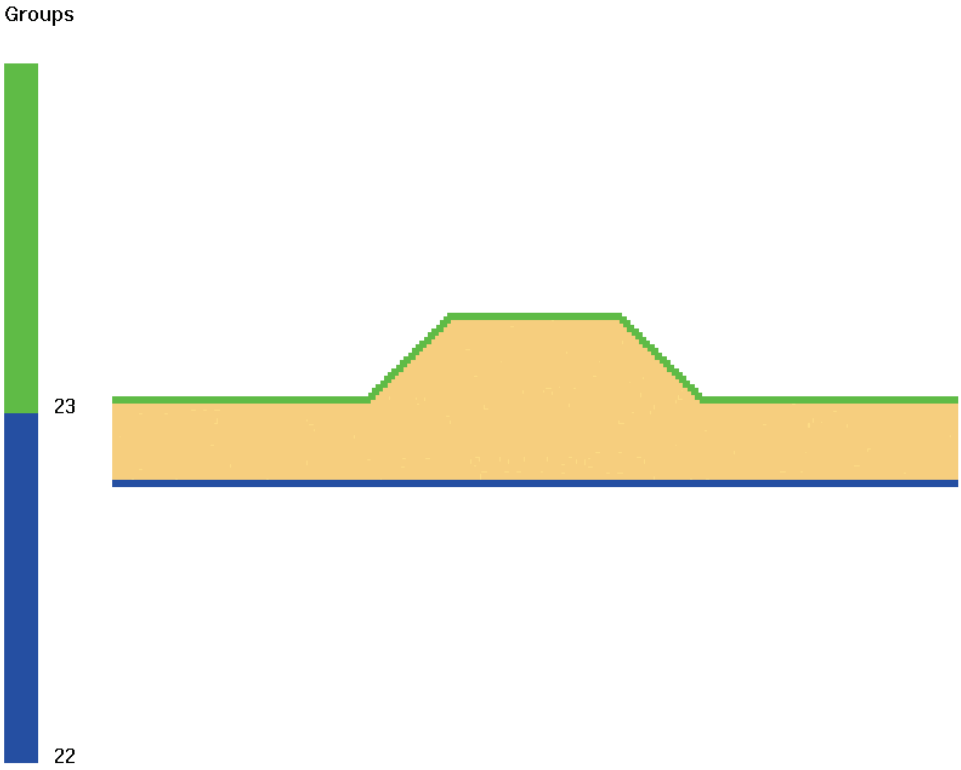
Visualization of Groups and Zones

The part simulated in this example contains a metallic insert, which has an influence on the curing of the composite. The geometry of the complete part is extruded from the section shown below, so a two-dimensional analysis is appropriate here.

Create a new *Curing* simulation with **File->New**. Import the mesh file `curing_insert_start.unv`.

Visualize the zones and groups of nodes. You should have the following display. Zone number 21 will be used for the metallic insert, and zone 19 for the fiber preform. Group number 22 and 23 are used for temperature boundary conditions.

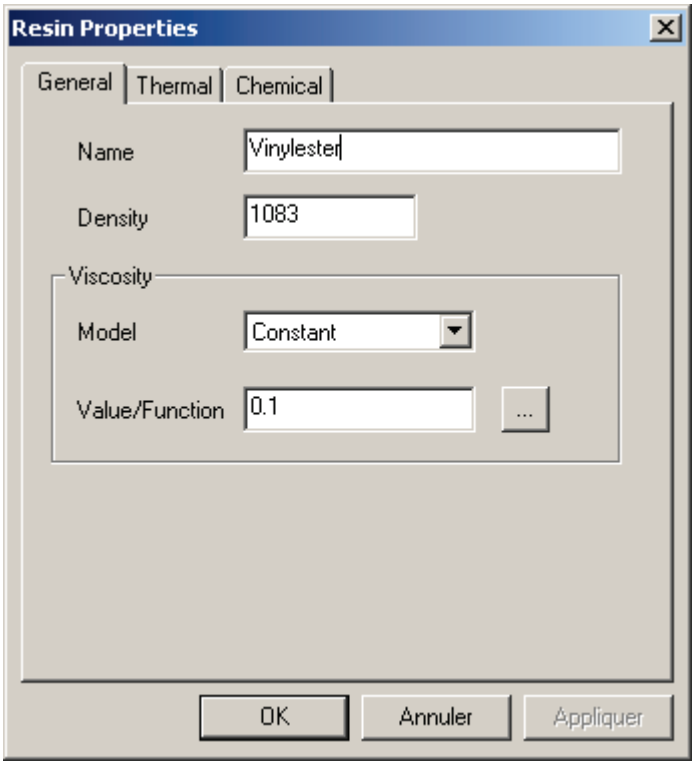

Zones
21
19


Groups
23
22

Simulation Parameters

Set the *Max. experiment time* to 2000 s. and the *Max. number of steps* to 500, which leads to a constant time step of 4 s.

Open the **Resin Properties** dialog box.



To simulate the resin cure, the following parameters that describe the resin must be specified:

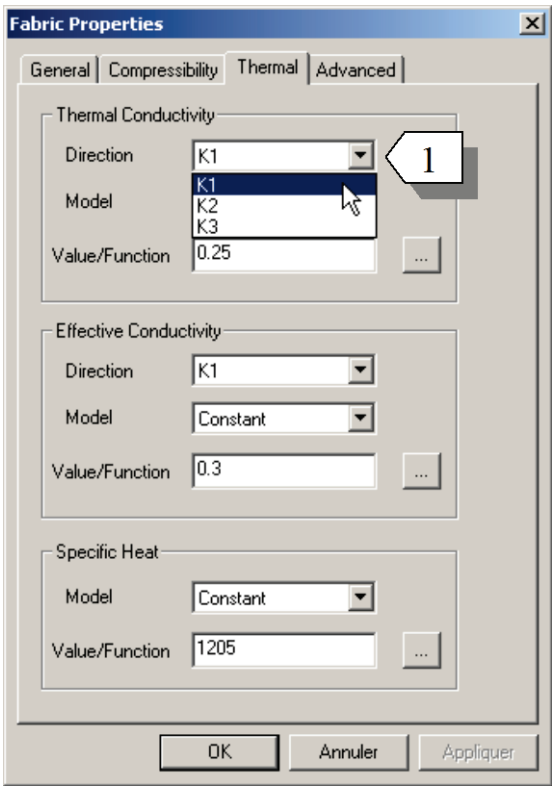
- Name: Vinylester
- Density: 1083 Kg/m^3
- Thermal Conductivity: 0.25 *W/(m.K)*
- Specific Heat: 1205 *J/(Kg.K)*
- Reaction Enthalpy: 300000 *J/Kg*
- Add a new reaction, open the **Function Editor** and select Kamal-Sourour model (*Kinetic_01*) with A=9.17E6, E=7289, m=0.85 and p=1.15.

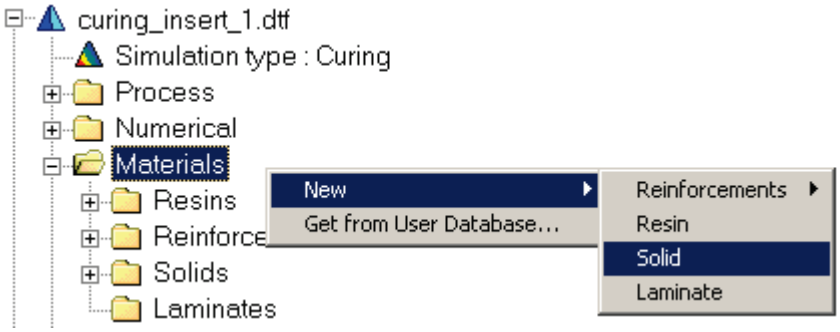
Double click now on the reinforcement. In this analysis, it is not necessary to enter the permeability of the reinforcement since there is no flow involved in curing simulation. However, for the thermal analysis, some parameters need to be specified in the **Fabric Properties**. Enter the following parameters:

- Density: 2565 Kg/m^3
- Specific Heat: 1205 *J/(Kg.K)*

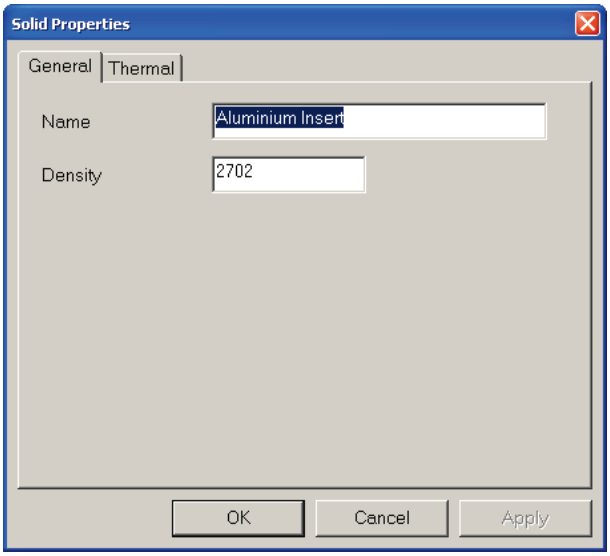
- Thermal Conductivity: 0.25 *W/(m.K)*
- Effective Conductivity: 0.3 *W/(m.K)*

Set isotropic thermal conductivity (K_1=K_2=K_3=0.25*W/(m.K)*). Use the **Direction** drop-down list **[1]** to select the direction to set. For constant conductivity, the value is updated each time a character is typed in the text field (no need to **Apply**). To specify conductivity as a function of temperature, you would choose *f(temperature)* in the **Model** drop-down list, then click the **...** button to select a function.





Finally, the aluminum insert must be created. Create a new *Solid* material by right-clicking the **Materials** item in the explorer, then choose **New->Solid**, as shown in the figure above. Open the **Solid Properties** dialog box by double-clicking the new solid. Note that there are no specific materials for inserts in **PAM-RTM™**. The *Solid* material type must be used when you need to specify a non-permeable material such as metallic or foam inserts.

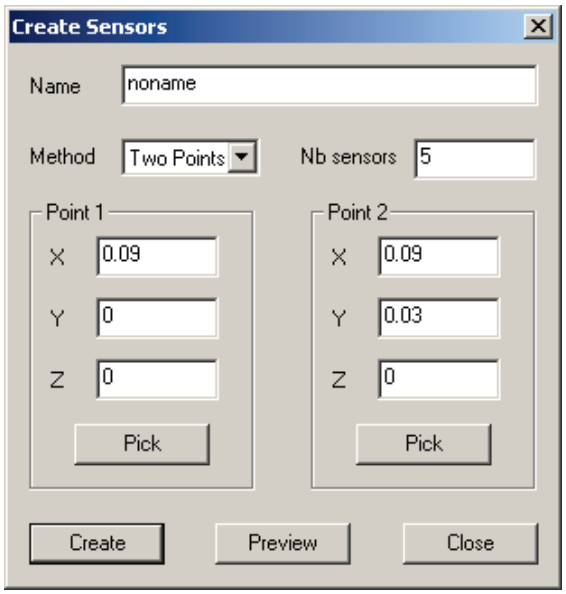


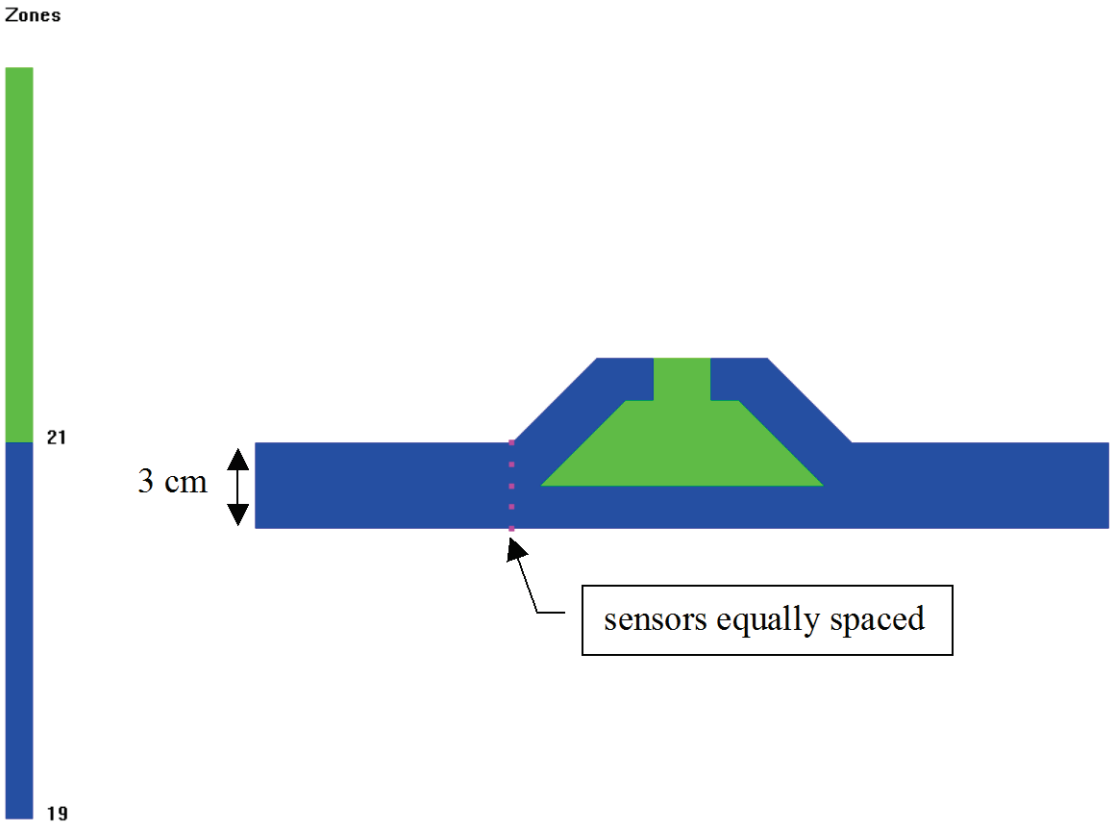
The following parameters for the aluminum insert must be specified:

- Density: 2702 *Kg/m*^{3}
- Specific Heat: 900 *J/(Kg.K)*
- Thermal Conductivity: 2.165 *W/(m.K)*

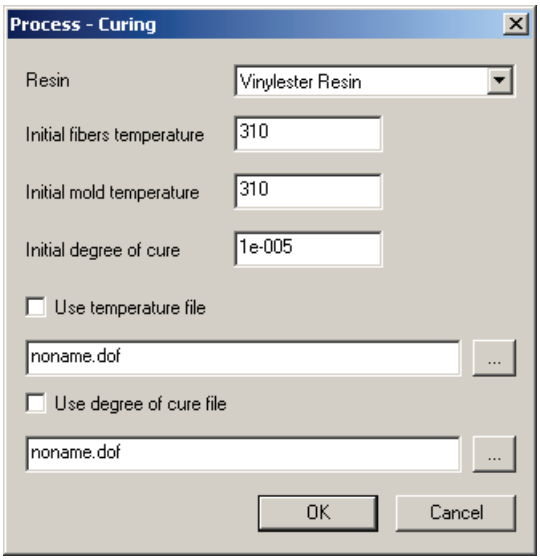
Before launching the actual simulation, it is necessary to assign the appropriate material to each zone and to set the boundary conditions. Assign the aluminum insert to zone 21 and the default fabric to zone 19. The porosity of zone 2 (insert) should be set to zero for consistency. However if you forget to do so **PAM-RTM™** automatically assigns a zero porosity to solid-type materials.

To facilitate the analysis, sensors will now be defined with the **Create Sensors** dialog box (**Simulation->Create Sensors)**. In the **Method** drop-down list, choose *two points* and set the number of sensors to 5. Enter the coordinates of Point 1 (0.09, 0., 0.) and Point 2 (0.09, 0.03, 0.) and click the **Create** button.





The initial temperature of the fibers and the mold is 310°K (to be set in the **Process Curing** dialog box).



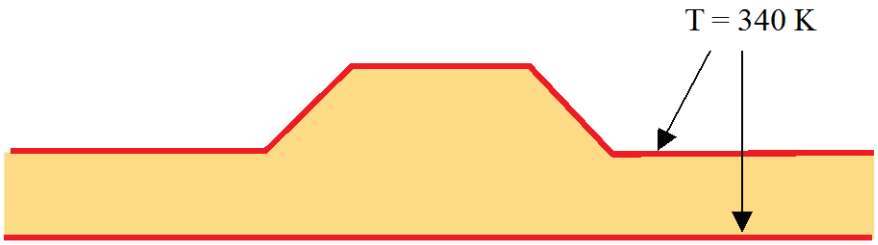
Three cases corresponding to three different curing strategies will be analyzed:

1. Mold wall at 340°K.
2. Lower mold wall at 350°K and upper mold wall at 330°K.
3. Mold walls initially at 310°K with a linear temperature variation in time up to 340°K.

Curing Simulations

Case 1 (mold walls at 340°K)

Create the temperature boundary conditions for the group 22 and 23, and set the temperature at 340. Save and launch the simulation. The figure below shows the temperature boundary conditions. Heating is performed from the outside on the top and bottom surfaces of the part.



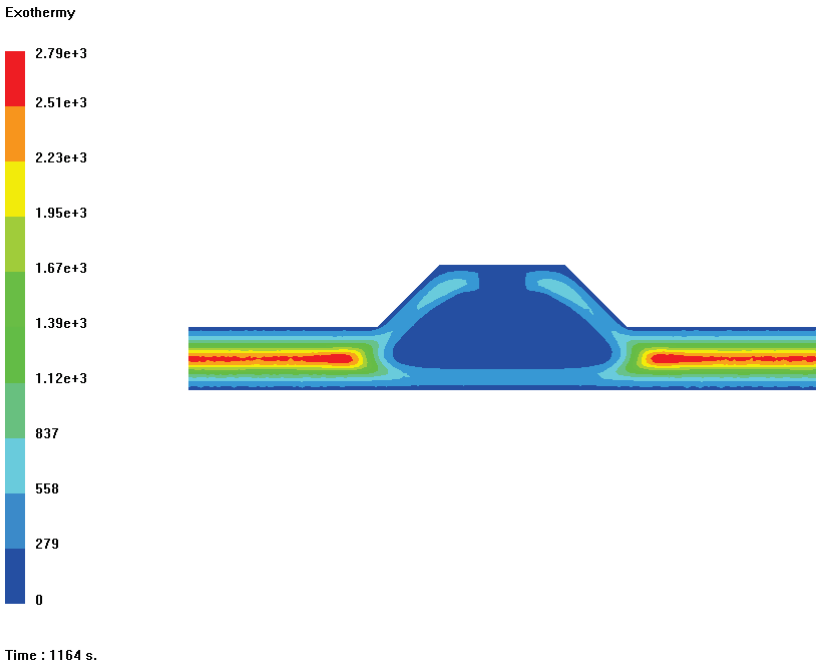
The first parameter to verify in the simulation results is resin conversion. The results below show that curing begins on the sides. Therefore the solidification of the resin begins close to the mold walls, i.e., on the outside of the part. Because of the heat

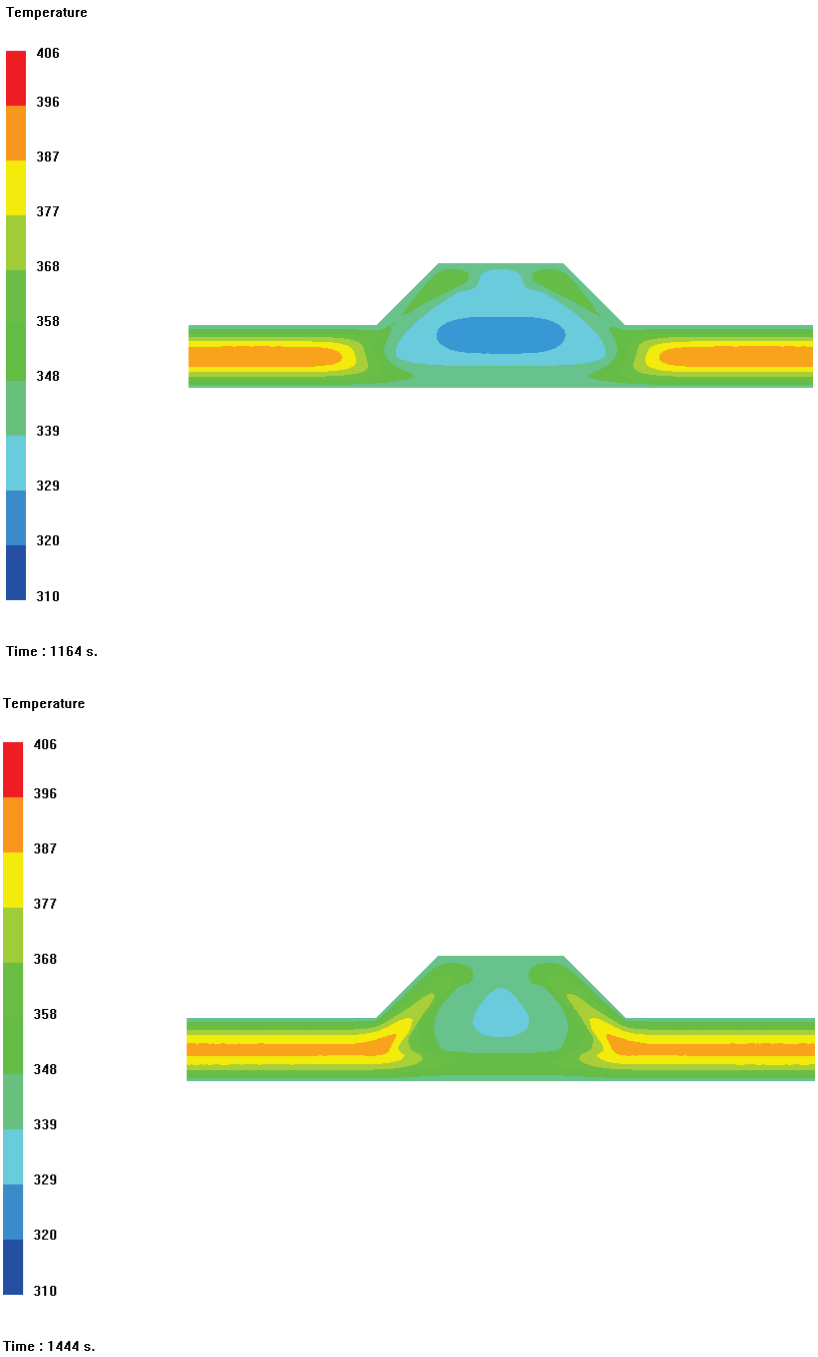
generated by the exothermic chemical reaction, the solidification moves then towards the center of the part. Resin conversion reaches then its peak at the center of the part.

Note that the metallic insert remains at a nearly constant temperature of 320°K. This means that its temperature is lower than the extremities of the mold. So the curing rate of the resin is minimal near the insert.

This type of curing from outside to inside will have several effects on the part. First of all, as the solidification of the resin begins on the outside of the part, this means that shrinkage will occur first on the outside. This is usually one cause of poor surface finish. Obviously, this approach cannot be used if a **class A** surface is required. Another problem is related to the **thermal residual stresses**, which result from a delayed cure in the center of the part while the outside has already become rigid. This can affect considerably the mechanical properties of the part. Finally, the slow cure rate near the insert can cause a problem, if the resin is not sufficiently cured. The region located near the insert will have a weaker mechanical resistance. As the insert is usually connected to another part, it will be submitted to significant loadings that might create delaminations in the composite.

The figures below show the evolution of cure in time in the part. The evolution of this parameter is closely connected to temperature. Indeed, the heat generated by the exothermic chemical reaction will cause a temperature increase. On the other side, the numerical results show that the chemical reaction is accelerated when the temperature reaches its peak. Note the temperature peaks at the center of the part. This is also where most of the heat is liberated by the exothermic chemical reaction. Temperature is smaller near the insert, which acts as a heat sink. This causes a slower cure of the resin in this region and may reduce locally the mechanical properties of the composite.





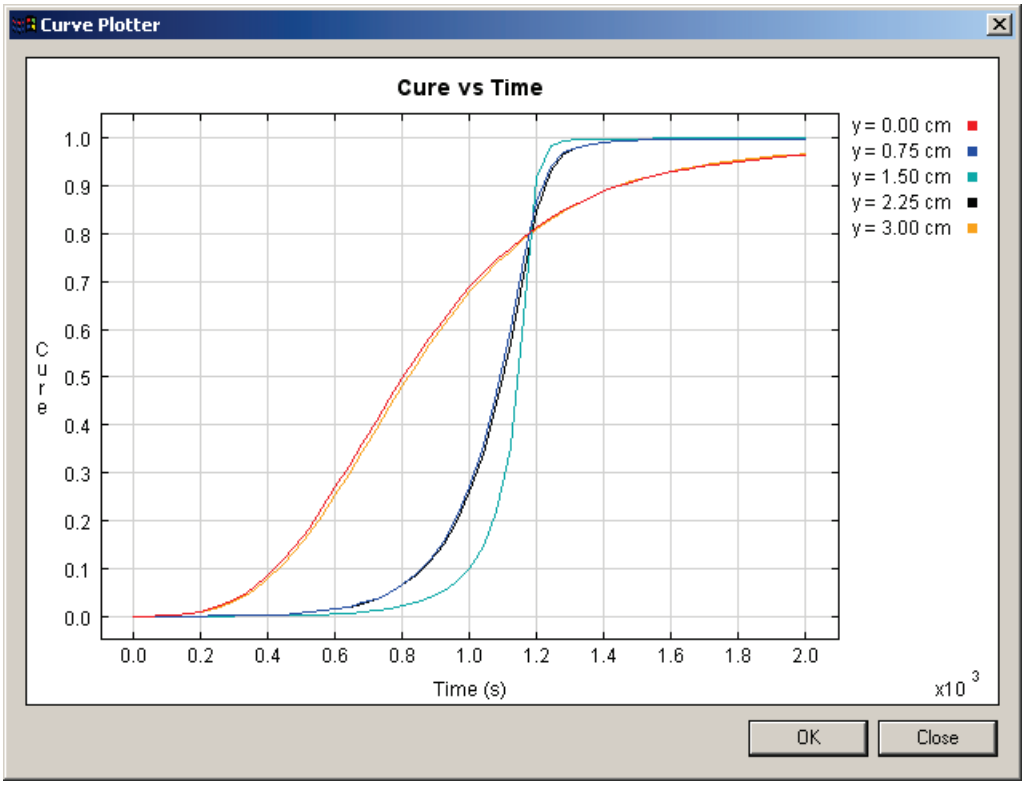
The exothermic reaction caused the part's temperature to increase significantly. The temperature peaked in the center of the part at about 405°K.

This curing strategy from outside to inside is certainly not the best one. As a matter of fact, a series of problems is associated with this approach:

- Shrinkage and surface finish
- Thermal residual stress
- High temperatures in the center of the part

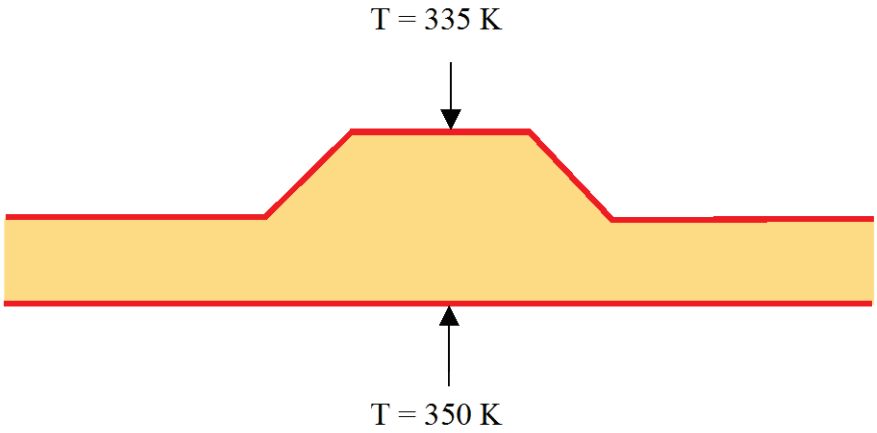
- Weak curing rate near the insert

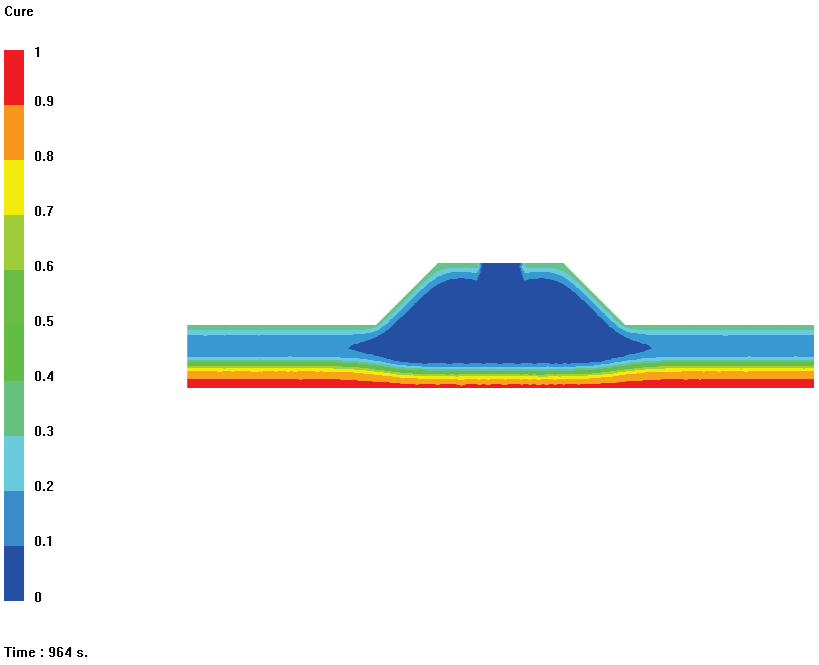
The analysis of the sensor recordings leads to the same conclusion. Sensor 1 is positioned on the bottom surface of the mold (y = 0 cm). Then, starting from the lower surface, sensor 2 is located at a quarter position into the part, sensor 3 halfway and sensor 4 three quarters into the part. The extent of cure curves recorded by the sensors show that the center of the part reaches a critical degree of cure (0.7) faster than the outside region. This can lead to problems in the final part.

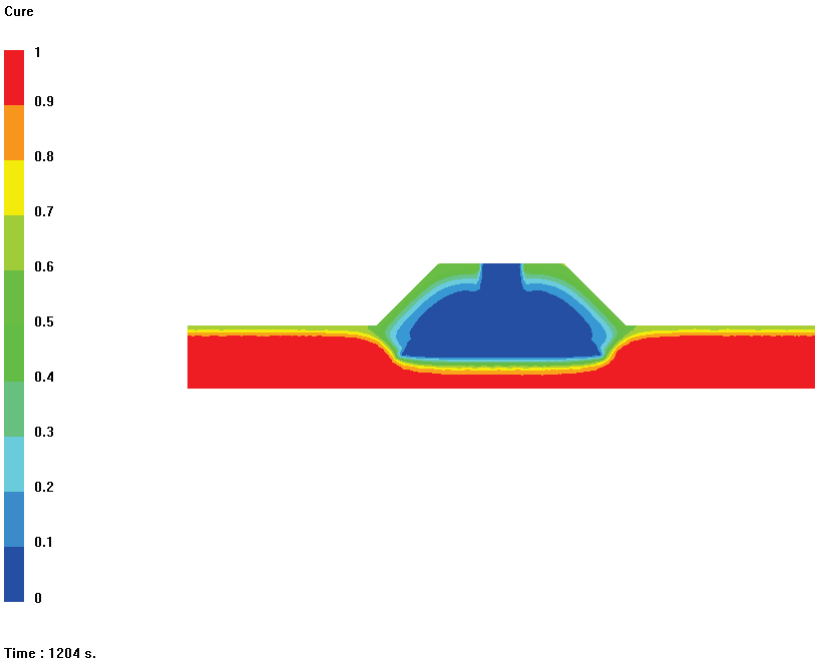


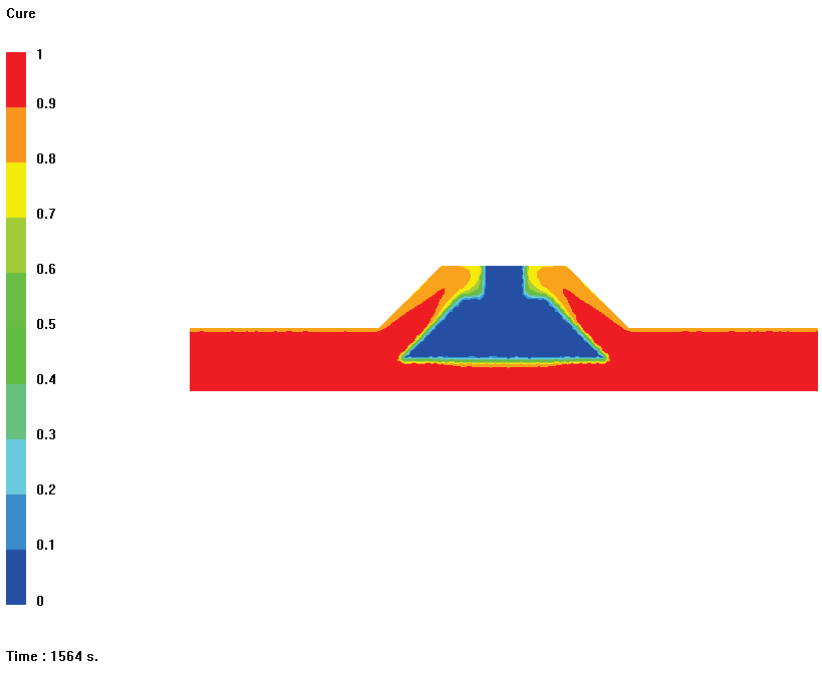
Case 2 (bottom mold wall at 350°K and top wall at 335°K)

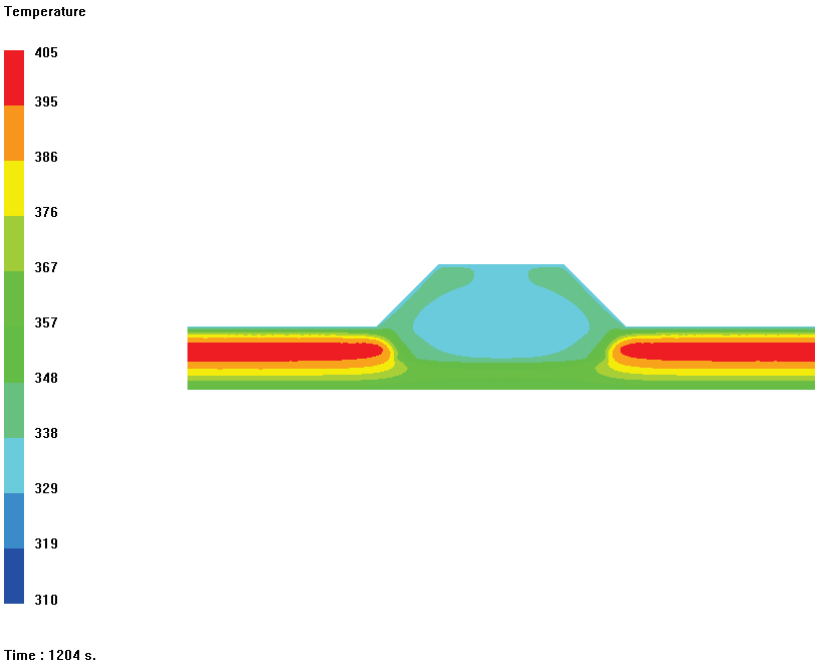
This curing strategy heats up the composite from one side. Simulation results show that the solidification of the resin begins on the lower surface of the part. Then a curing front progresses through the part, beginning from the highest temperature at the bottom of the part up to the upper surface where the temperature is the smallest.

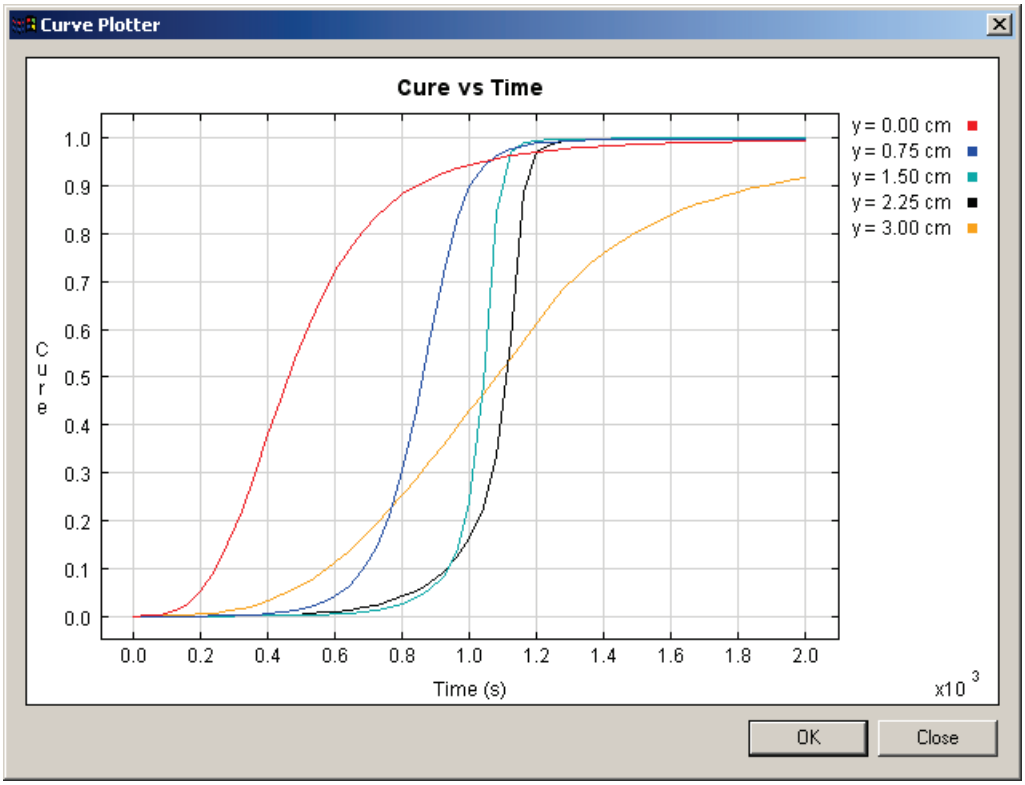

T = 335 K
T = 350 K


Cure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time : 964 s.


Cure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time : 1204 s.


Cure
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Time : 1564 s.





This type of curing has several effects on the quality of the final part. First of all, as the resin at the bottom solidifies and the curing front moves toward the top surface of the part, problems related to shrinkage are no longer present. Therefore the surface finish will be good on the lower surface. If the objective is to obtain a class A finish on one side, only this method will lead to acceptable results. Indeed, although the lower surface

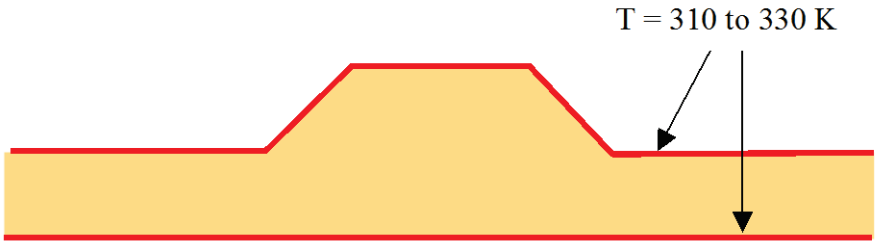
will have an improved finish, the upper face will show some imperfections. Because the resin is solidifying uniformly from the bottom towards the unconstrained top of the part, there will not be any thermal residual stresses in the composite.

The temperature increases with time as the curing front advances until it reaches three quarters of the part. The exothermic chemical reaction of the resin increases significantly the temperature of the part. The maximum temperature reached at three quarters through the thickness is 405°K. Such a high temperature can spoil the resin and decrease its mechanical properties.

This type of curing produces better results than the first strategy from outside to inside. In particular, it leads to a better surface finish. However, it is necessary to pay attention to the high temperatures that can be reached. Because of the heat generated during resin cure especially in thick composite parts, it can cause the resin to degrade.

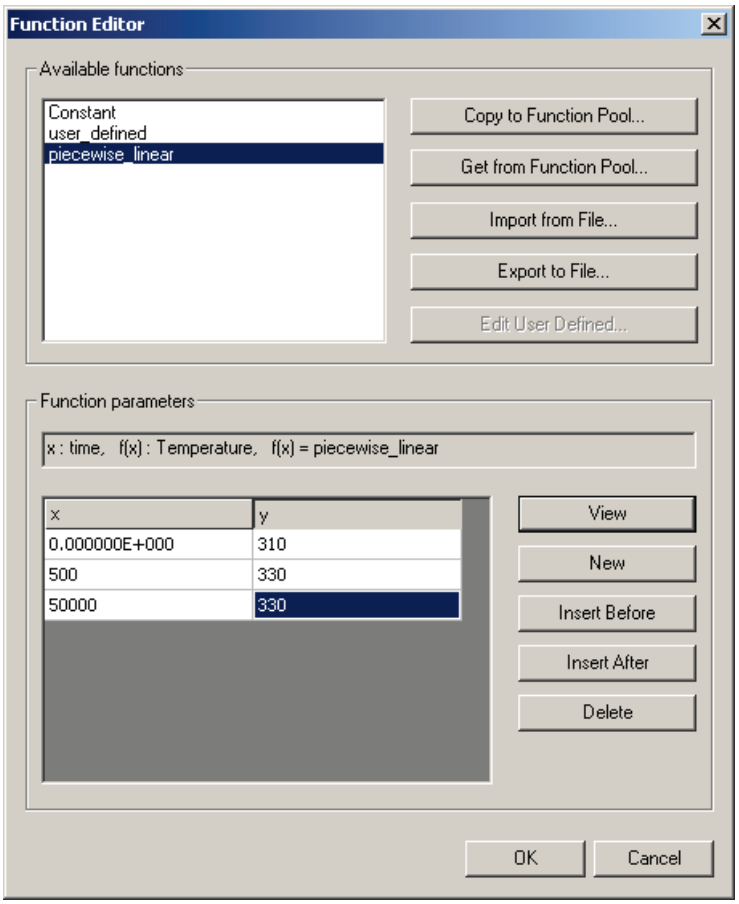
The analysis of the sensor curves confirms these results. Indeed, according to the position of the sensors, resin cure does not begin at the same moment and as the temperature increases, the chemical reaction becomes faster.

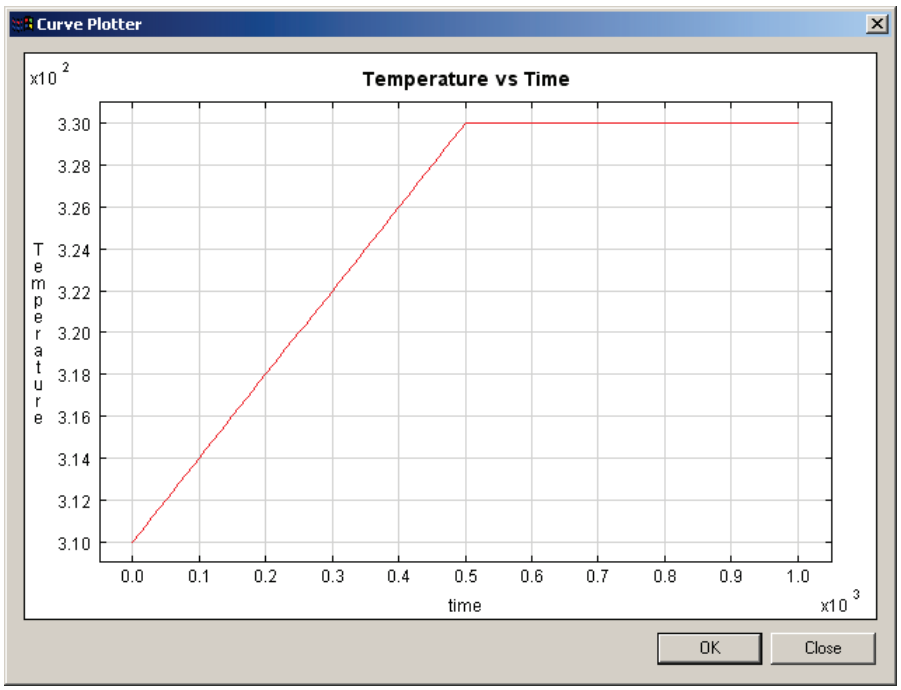
Case 3 (linear heating from 310°K to 330°K)



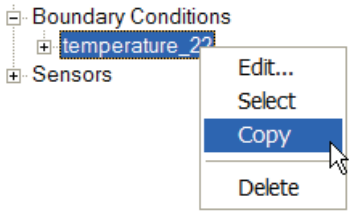
For this simulation the *Max. experiment time* is set to 3000 s. and the *Max. number of steps* is left to 500.

Create a temperature boundary condition, then specify temperature as a Piecewise_Linear function as shown in the **Function Editor** dialog below.

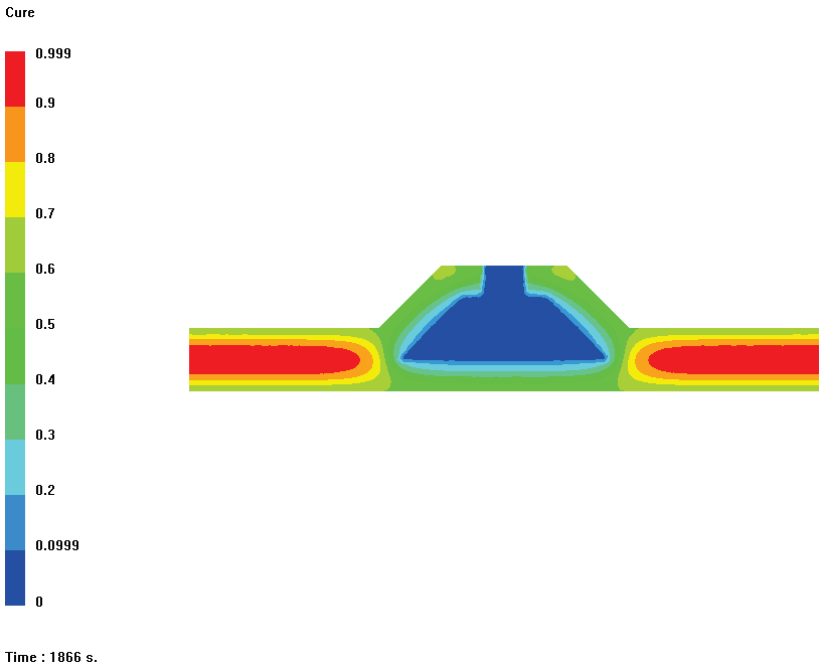


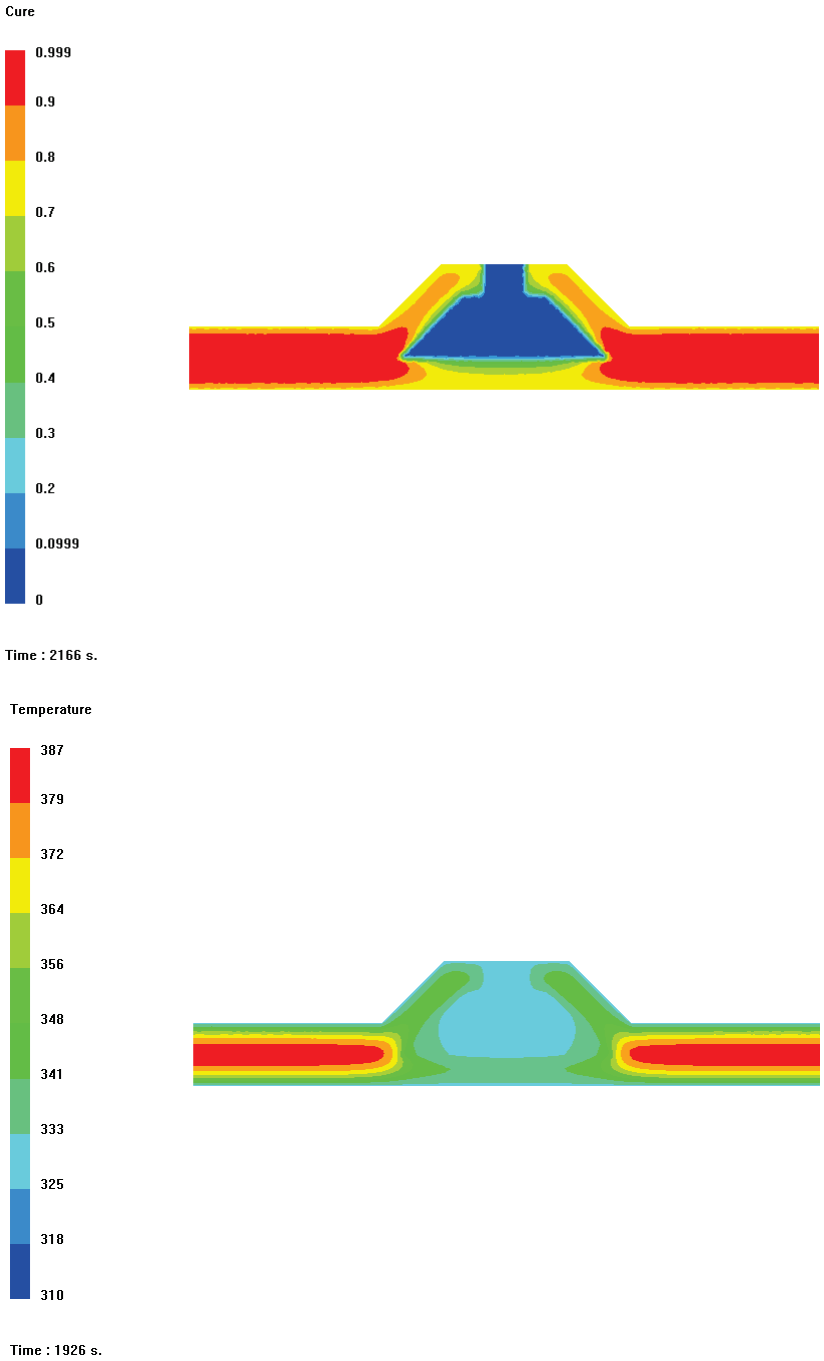


Use the Copy command available when you right-click on a boundary condition to avoid entering the control points of the piecewise linear curve twice.



The figures below show the resin conversion at 1866 *s*, 2166 *s* and 1926 *s*. With this type of heating, curing slowly begins on the sides of the part, then the center catches up and the exothermic reaction begins to solidify the center and then moves towards the sides.



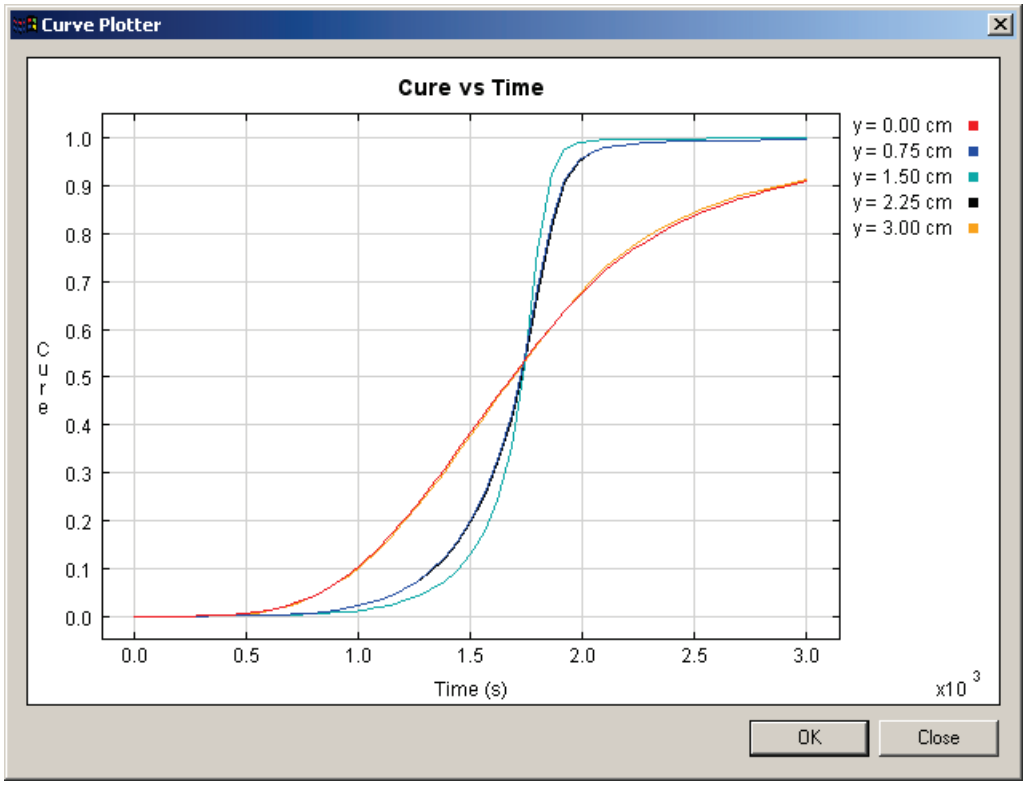


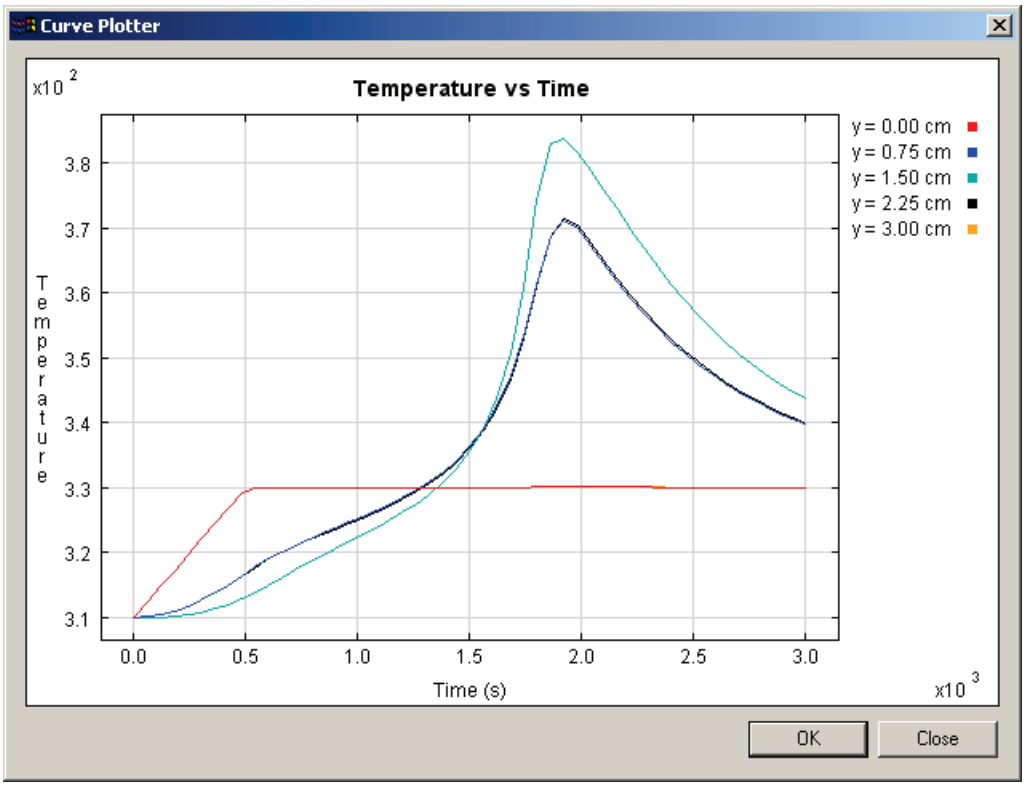
This method presents several advantages. There is no thermal residual stress in the part if the lower and upper surfaces of the part remain unconstrained. The shrinkage of the resin due to curing will not create problems in the part and conditions are met to obtain a good surface finish.

The temperatures analysis demonstrates that the temperature peaks at the center of the part are about 20°K lower than the two other cases. This reduces the possibility of spoiling the resin because of overheating.

However, there is one major drawback with this method of curing a thick composite part: curing cycles take a much longer time to be completed.

The results of the sensors next page show that the temperature peak is reached at the center of the part.





Conclusion

The three curing examples analyzed here highlight the importance of selecting the best curing strategy. Indeed, it all depends on the objective (good surface finish on one or both surfaces). The numerical simulation can help to understand and predict the curing behavior and hence, avoid numerous and costly trial and errors testing.

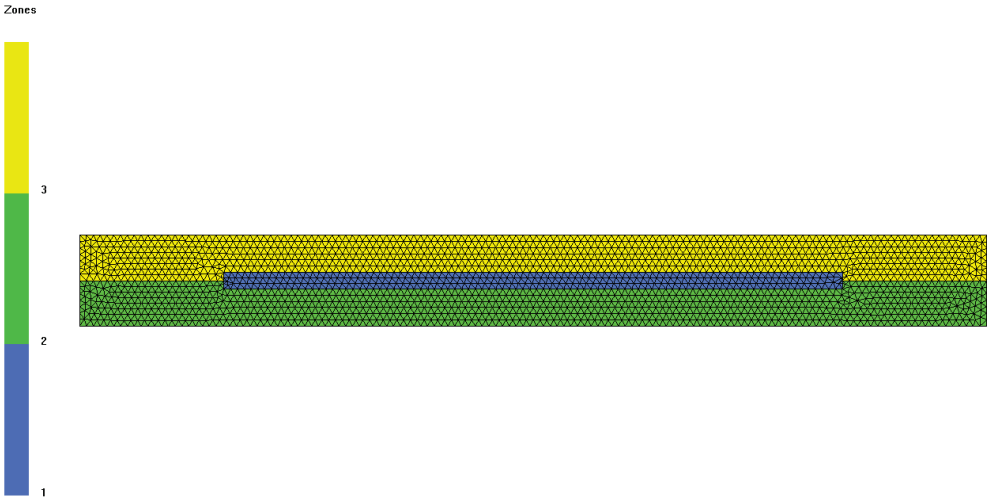
THERMAL CONTACT RESISTANCE

The following files will be used:

- ***contact_start.unv*** (starting mesh)
- ***contact.dtf + contact.unv*** (solution)

Objectives

This tutorial shows how to specify parameters for a preheating simulation, taking into account a thermal contact resistance.



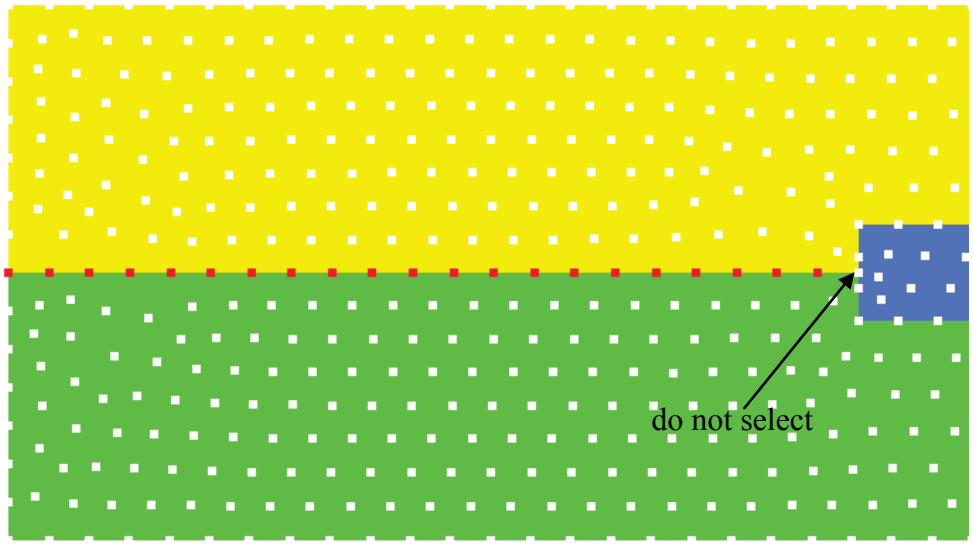
Previously quads and bricks were allowed for preheating and curing simulations with the old solver, but this is no more the case with the parallel solver, which only supports triangles and tetrahedra.

Creation of Groups

Use **File->New** to create a new preheating simulation, and then import the mesh file `contact_start.unv`.

The different zones represent a fiber preform (zone 1) in a mold (zone 2 and 3).

First create a group of nodes at the bottom of the mold, then another group on top of the mold. These will be used for imposed temperature boundary conditions.



A contact interface will then be created at the interface of the bottom and top mold. First select nodes as shown above. Notice that the node common to the top mold, bottom mold, and preform (shown with an arrow in the figure above) was not selected. This is necessary otherwise a free edge would be generated on the mold/preform interface, which would be in conflict with the automatic mold/preform interface. Select nodes the same way on the right side of the part (add the nodes to the same selection). In this example a single group is created containing nodes on both sides of the part, but of course it would be possible to create two groups.

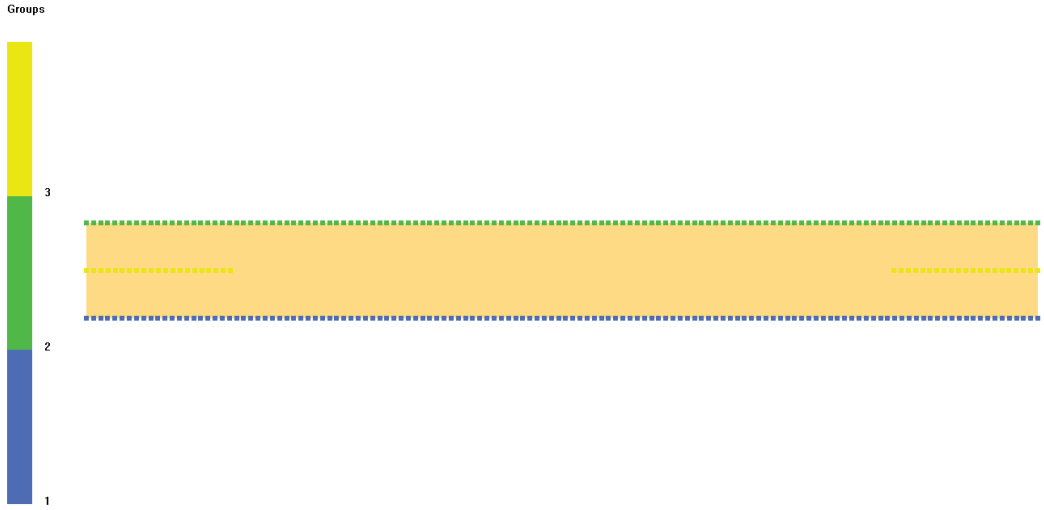
Notes:

- *The contact interface can only be created at the interface between two zones.*
- *If we were working on a 3D mesh, we would select element faces instead of nodes.*

Once the selection is done, choose **Groups->Contact Interface.**

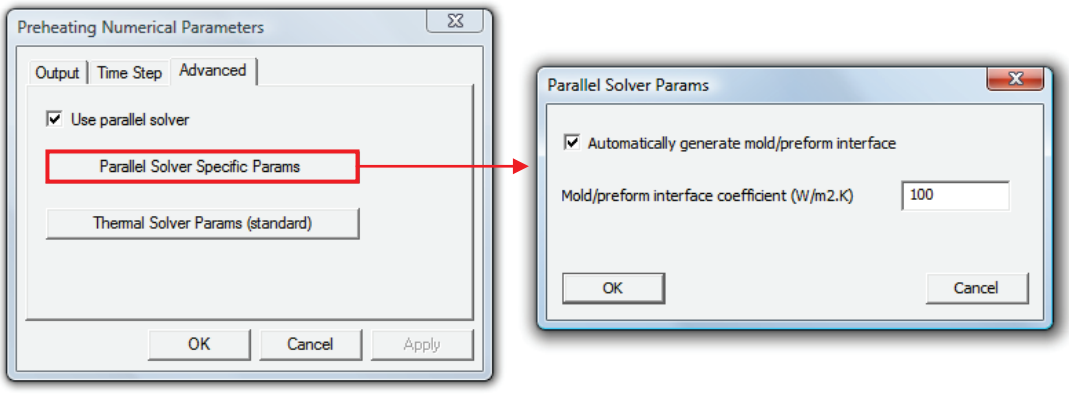
The creation of a contact interface modifies the mesh. Coincident nodes are created on the interface and elements are disconnected. Choose **View->Outline->Free Edges** to verify the interface. The red line in the next figure shows that the elements have been correctly disconnected.

The three groups are shown below.



Simulation

With the parallel solver, a thermal contact interface is automatically generated between the mold and the preform. The conductance value (reciprocal of the resistance) used on that automatic interface is found by pushing the **Parallel Solver Specific Params** button in the **Advanced Numerical Parameters**. For this example we will keep the default conductance of 100 W/m^2.K.



Also in the **Advanced** tab, select *use parallel solver*.

In the **Time Step** tab, set *max experiment time* = 1800 s and *max number of steps* = 50.

In the **Process** parameters, check that the initial temperature of the fibers and the mold is 300 K.

Materials

For the fabric:

- Density = 2565 Kg/m³
- Thermal conductivity k1 = k2 = k3 = 0.5 W/m.K
- Specific Heat = 1205 J/Kg.K

For the mold (create a new material of type *solid*):

- Density = 2707 Kg/m³
- Thermal conductivity = 150 W/m.K
- Specific Heat = 900 J/Kg.K

Zones

Associate zone 1 with the *Default Fabric* and zones 2 and 3 with the *Default Mold*. Porosity of zone 1 is kept to 0.5, while the porosity of zones 2 and 3 doesn't really matter as it will be forced to zero by the solver. However it is a good habit to set it to zero.

Boundary Conditions

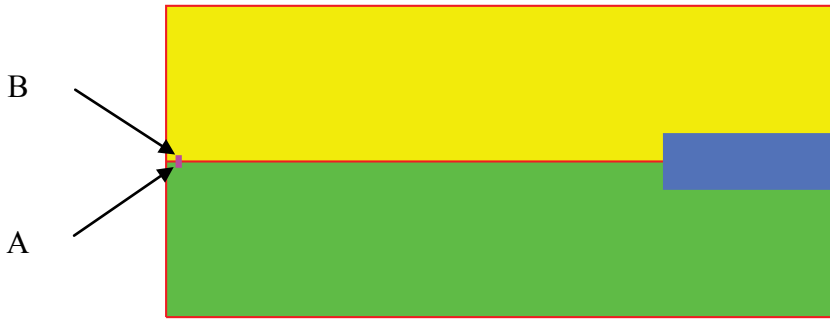
Create two temperature boundary conditions. The first is associated with lower mold wall at 310 K and the second with the upper mold wall at 350 K.

Create a new *contact resistance* boundary condition associated with group 3, and set the value of the thermal contact resistance to 0.001 m²K/W. A second simulation will be run with a contact resistance value of 0.01 m²K/W, and a third one with 0.1 m²K/W.

Sensors

Create the following sensors:

- A (0.04, 0.49, 0)
- B (0.04, 0.51, 0)

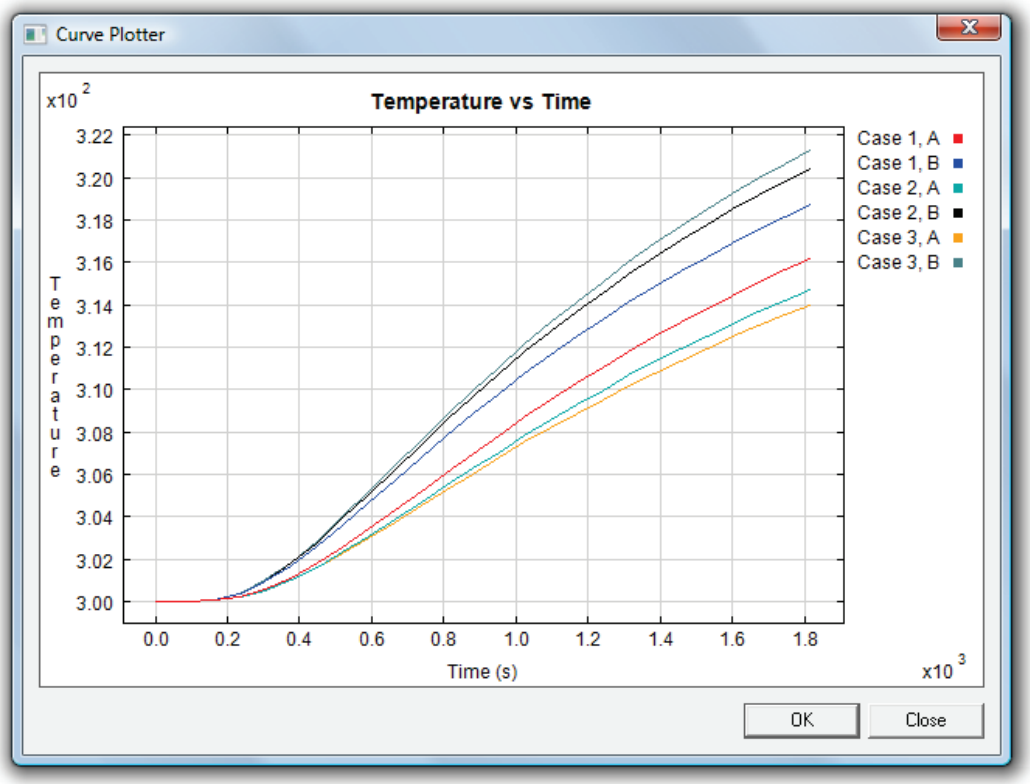


Post-Processing the Results

The temperature contour obtained after 1800 sec. is shown below for the third case corresponding to a contact resistance of 0.1 m²K/W.

By using sensors **A, B** near the interface between the two parts of the mold, we can observe the influence of the thermal contact resistance.

Temperature curves for cases 1, 2 and 3, corresponding respectively to a contact resistance of 0.001, 0.01 and 0.1 m²K/W are plotted below. For case 3 we can see that there is a non-negligible difference of about 7 degrees on both sides of the interface after 1800 sec.



NON-ISOTHERMAL 3D – FIBERS ORIENTATION

This case is a chaining analysis (preheating, heated RTM and curing) for a 3D part with orientations. The following files will be used:

- ***Insert_3D.unv*** (starting mesh)
- ***Insert_3D_Preheating.dtf*** + ***Insert_3D_Preheating.unv*** (solution)
  Insert_3D_Heatedfilling.dtf + ***Insert_3D_Heatedfilling.unv*** (solution)
  Insert_3D_Curing.dtf + ***Insert_3D_Curing.unv*** (solution)

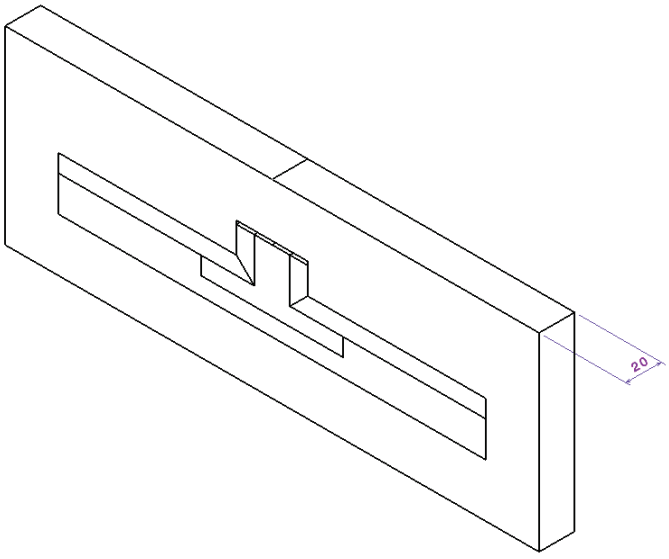
Objective of the Analysis

This tutorial will show you how to simulate a chained RTM process stage by stage (preheating -> heated filling -> curing). Data transfer between each stage is explained, for instance how to use the temperature distribution at the end of the preheating analysis to initialize the temperature for filling.

Material characteristics and some set-up steps like orientation, and material assignment are common to each step and are described prior to the description of each step.

Geometry Description

The geometry (***Insert_3D.unv***) is composed of several 3d parts that have been defined in order to split the insert, the preform and the mold volume which do not have the same physical properties.

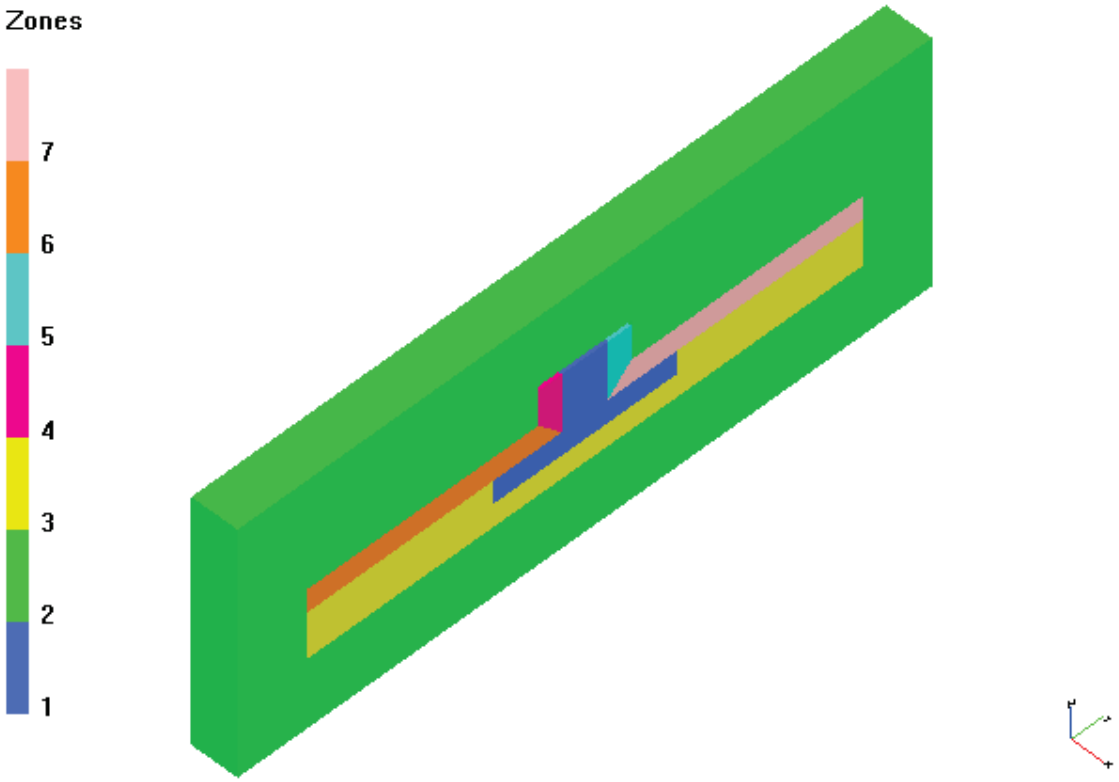


Part geometry

Zones of the Part

The zone IDs corresponding to each material are shown below:

- Insert: zone ID 1
- Mold: zone ID 2
- Reinforcement: zone IDs 3 to7

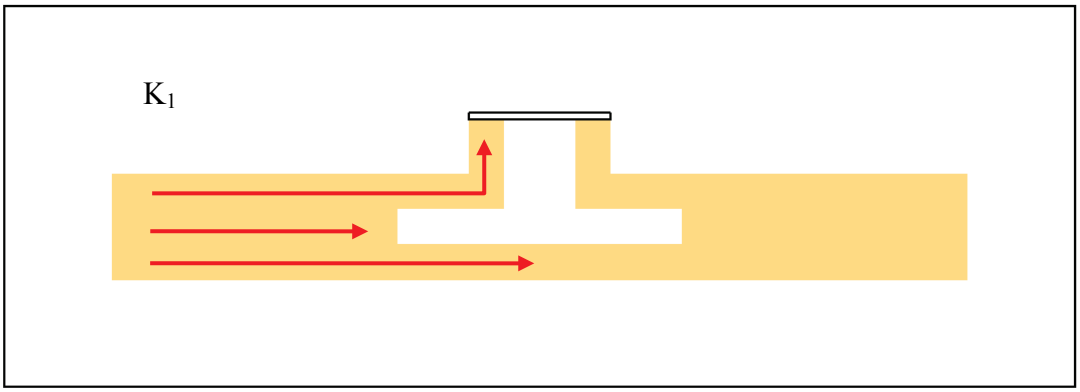


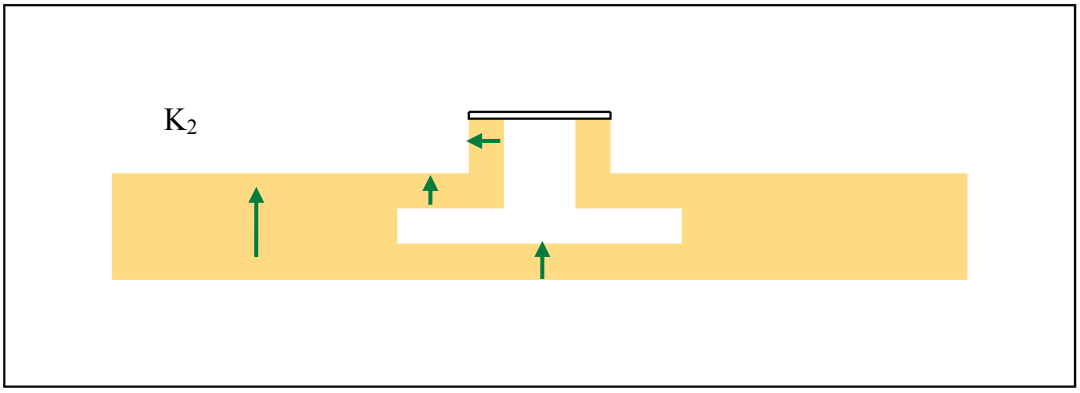
Zones

Fiber Orientations

The orientation of the preform (Zone IDs 3 to7) must be defined as shown below;

- K1 is parallel to Y and K2 to Z for zones 3,6 and 7;
- K1 is parallel to Z and K2 to Y for zones 4 and 5.





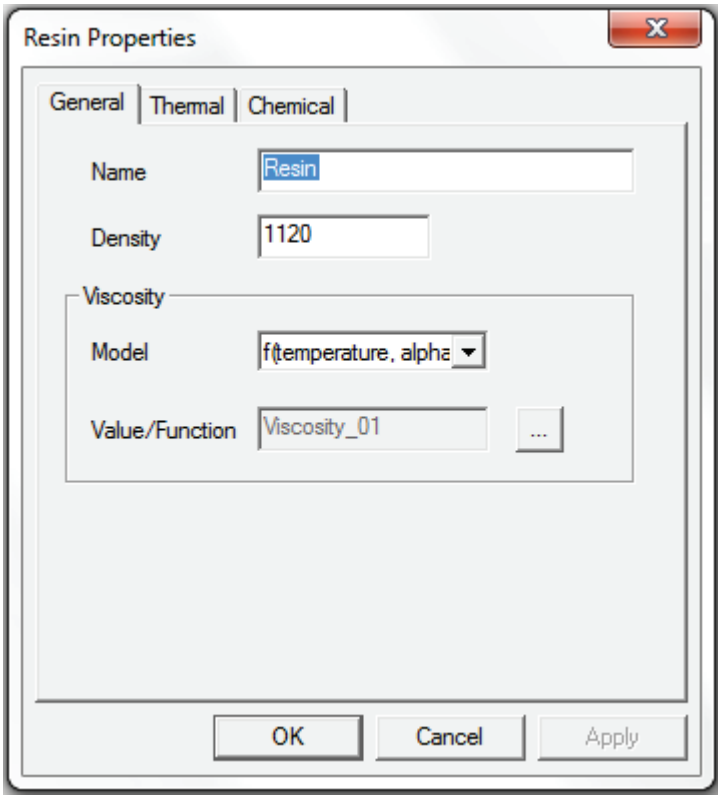
Material parameters

The resin parameters

To simulate the resin cure, the following parameters must be specified.

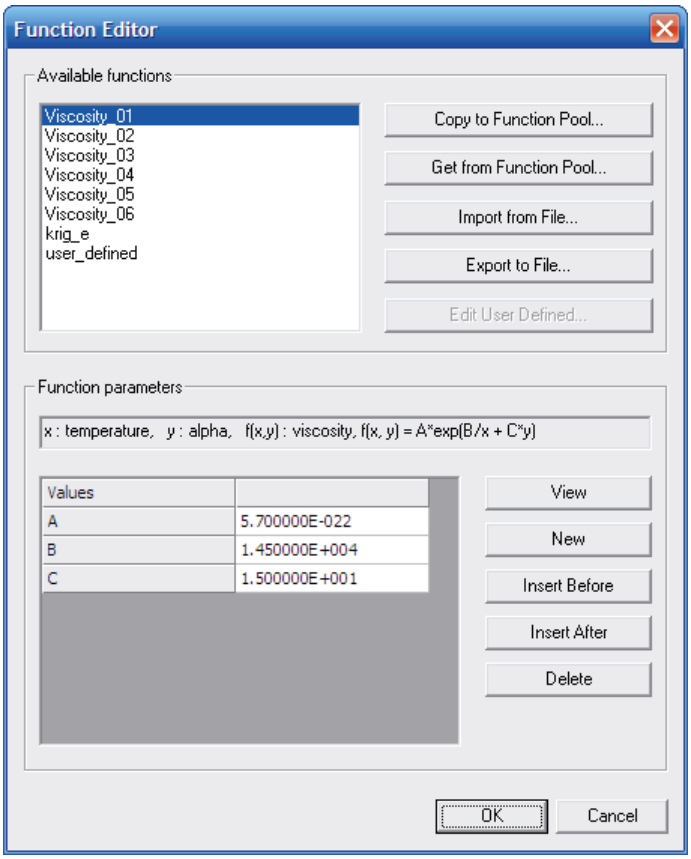
In the general tab:

- **Density**: 1120 Kg/m3
- **Viscosity**: a viscosity function relates viscosity with temperature and the degree of cure.



Resin general sub-section dialog box

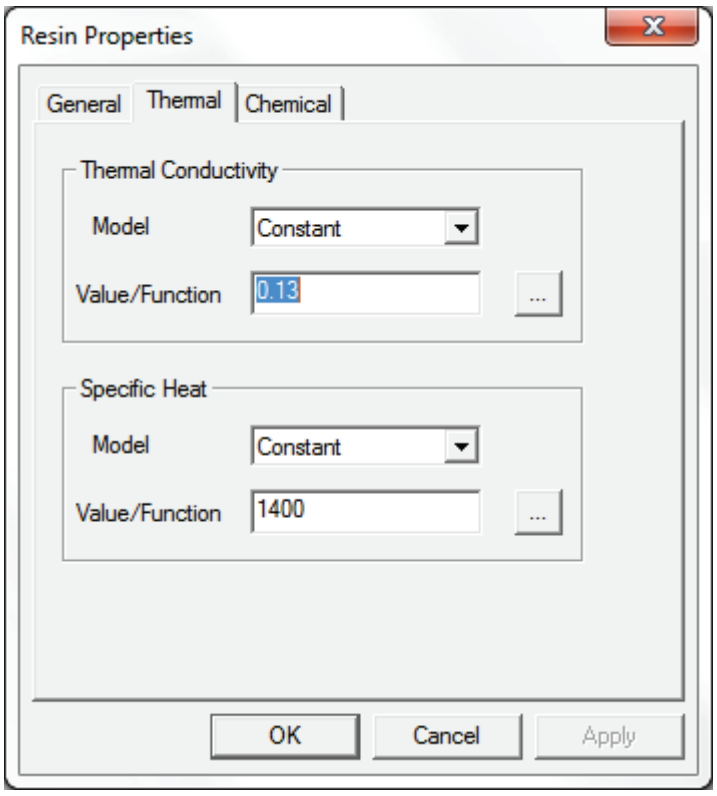
- Select the Viscosity_01 model where A = 5.7E-22, B = 1.45E+4 and C = 15.



Viscosity function edition

In the Thermal sub section:

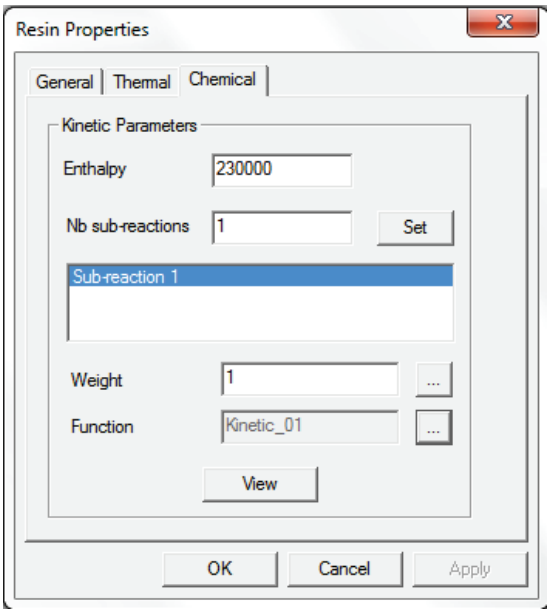
- thermal conductivity: 0.13 W/m.K
- Specific heat: 1400 J/Kg.K



Resin thermal sub section dialog box

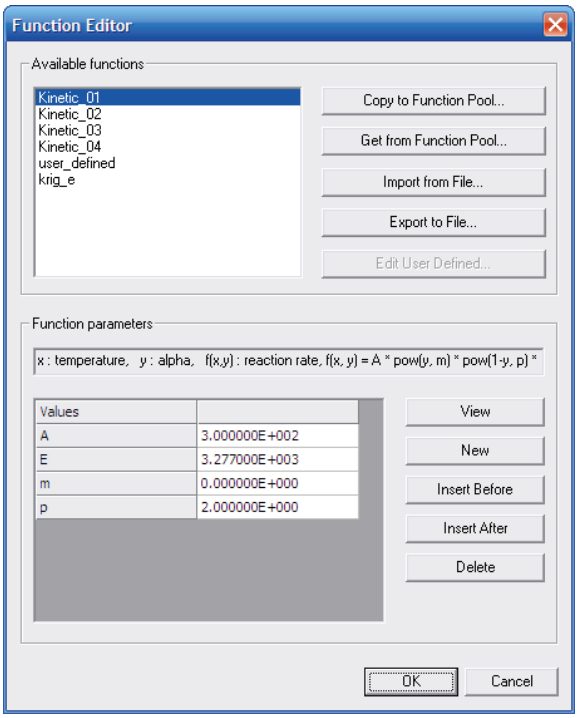
In the Chemical sub section,

- Enthalpy: 230000 J/kg



Resin chemical sub section dialog box

- kinetics model: Kinetic_01 where A=300, B=3277, m=0, p=2, as shown below



Kinetic function edition

The fibers parameters

The reinforcement characteristics are set as below:

- Name: Preform
- Density: 2540 kg/m^3
- Permeability K1: 6E-11 m^2
- Permeability K2=K3: 1E-11 m^2
- Thermal Conductivity K1=K2=K3: 0.1 W/m.K
- Effective Conductivity K1=K2=K3: 0.3 W/m.K
- Specific heat: 840 J/Kg.K

The mold parameters

The mold characteristics are set as below:

- Name: Metal
- Density: 2700 kg/m^3
- Thermal Conductivity: 10 W/m.K
- Specific heat: 950 J/Kg.K

Material Assignment

For each of the set-up step, the material assignment will be the same. It will have to be done for each step.

Visualize the zones of the parts and make material assignment as follows,

- zone ID 1 (Insert): Metal
- zone ID 2 (Mold): Metal
- zone IDs 3 to 7 (Reinforcement): Preform.

Keep parameters of all the zones as default:

- Porosity: 0.5
- Thickness: 0.0005m

Note:

- *A solid material such as the metal just defined is a non porous material; the porosity here is therefore set to zero. But this is not mandatory, as PAM-RTM will force porosity to zero for solid materials*

Simulation Stage1: Preheating

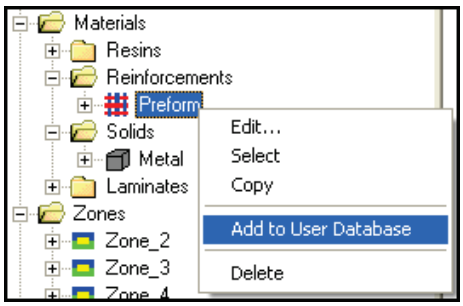
Create a Preheating analysis and import ***insert_3D.unv***, then define fiber orientations, material properties and material assignment to zones as in previous description.

The objective of this stage is to simulate 1 hour of part heating before injection starts.

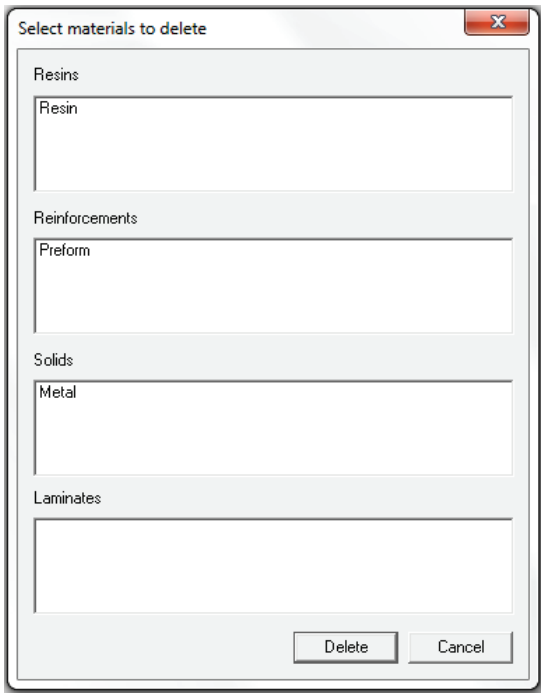
Material Database

To reuse the defined materials conveniently in the following analysis (heated RTM and curing), it is recommended to add them into the Material Database.

For example, **right click** on **Preform** in the Model Explorer and select **Add to User Database**, as shown below.



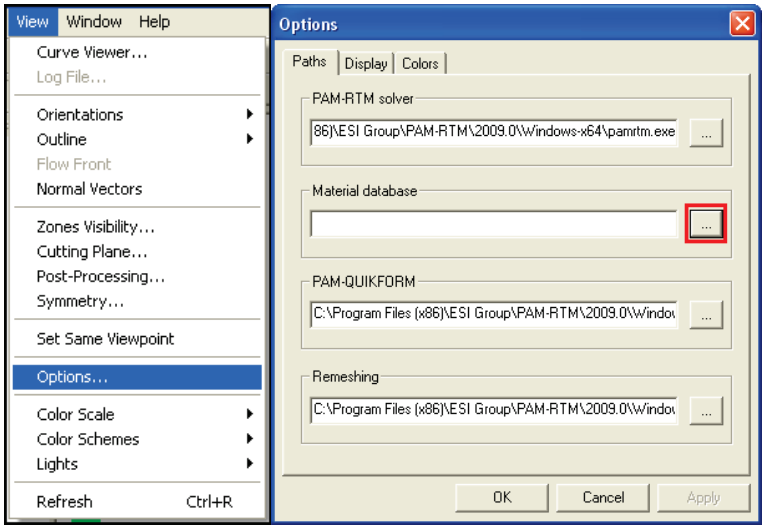
After adding the three materials, the user can check the modified material database by selecting the **Simulation -> Manage User Database** menu, as shown below



Material database content

Note:

- *The user needs to check if database path is set properly.*
- *In the Menu, select View → Options..., then in the Options interface, click on open button (as shown below) to select the file used for material database*



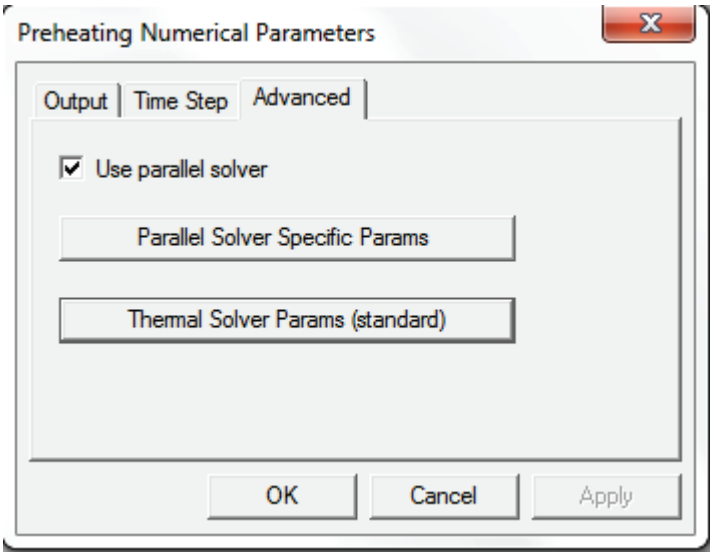
Material database path setting

- *If the material database is used for the first time in PAM-RTM, the user should create an empty .dtf file such as my_material_data.dtf in advance with a text editor, then select it in the Options>Paths tab*
  After this operation, the path of this dtf file is stored in the application settings, so it only needs to be entered once.

Numerical Settings and DMP solver activation

Set the following parameters in Preheating Numerical Parameters interface:

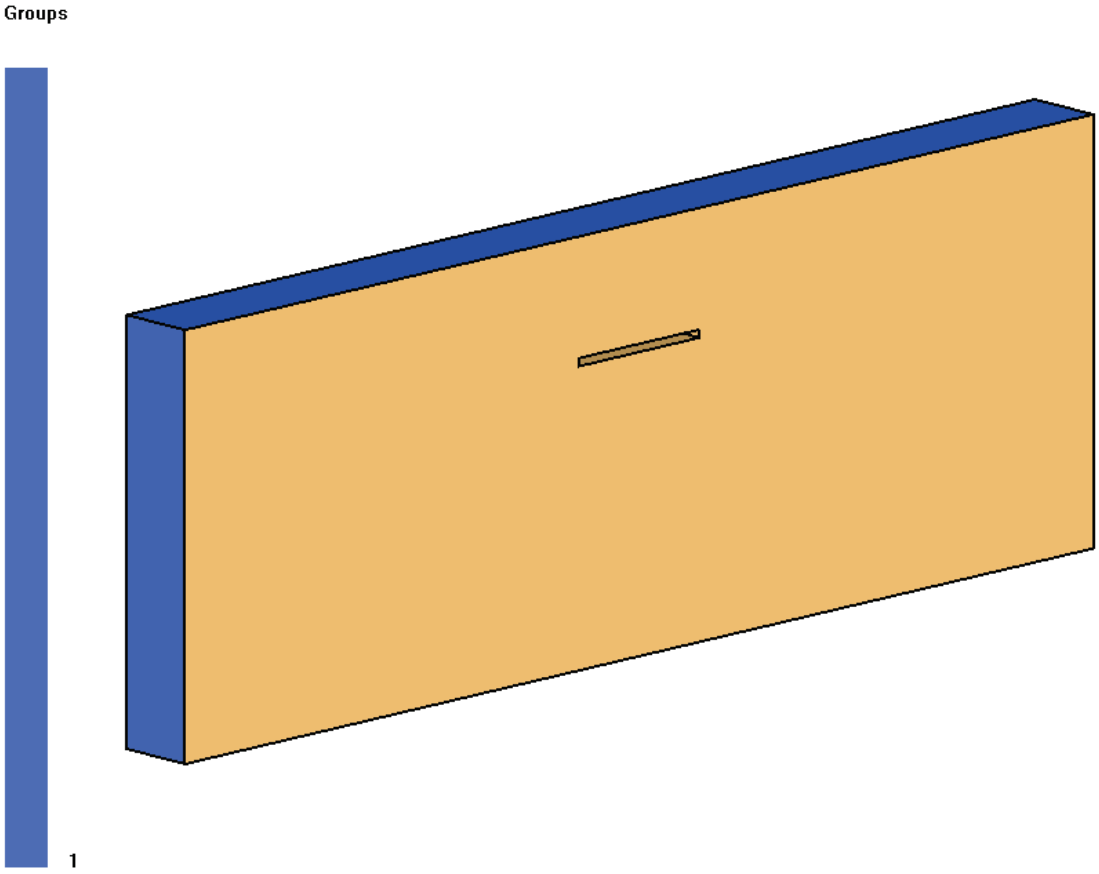
- Save temperature: checked
- Results sampling period: 50
- Max experiment time: 3600 s
- Max number of steps: 250
- Check use parallel solver, as shown below.



Boundary Conditions and Initial Values

- In the Process interface, keep initial temperatures as default,
  - initial fibers temperature: 300 K
  - Initial mold temperature: 300 K

  Create a group which corresponds to a **convection** boundary condition by selecting faces all around the mold, as shown below.

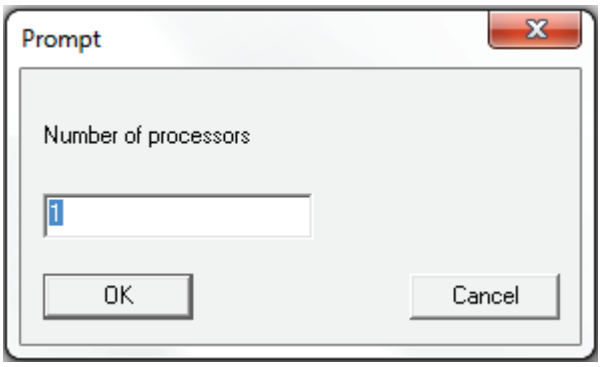


Group for preheating stage

- About the parameters of convection
  - Reference temperature: 323 K
  - Convection Coefficient: 300 W/m^2.K

Job Launching

When a job using the parallel solver is launched, a Prompt interface appears automatically to let the user enter the number of processors that will be used, as shown below.



Parallel job launching

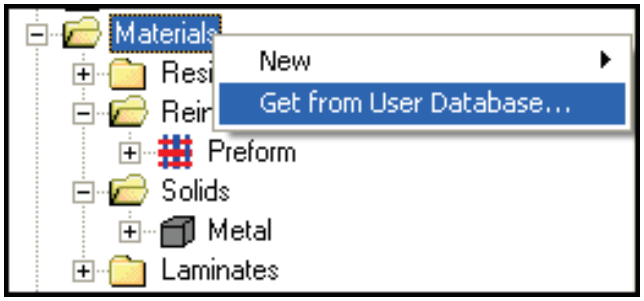
Simulation Stage2: Heated RTM

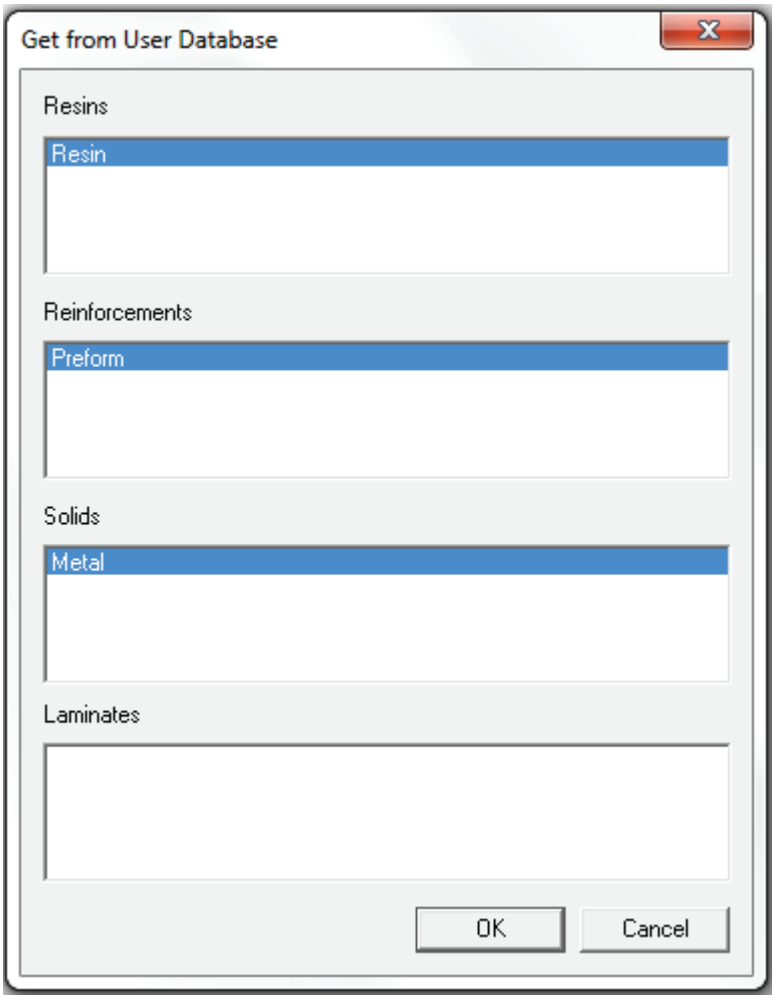
Create a Heated RTM analysis and import ***Insert_3D_Preheating.unv*** which is the mesh file generated by Preheating analysis and not the initial one ***Insert_3D.unv***.

As ***Insert_3D_Preheating.unv*** has included the fiber orientation definition in the previous Preheating analysis, there is no need to do it again in this analysis.
Check the parallel solver option in the numerical interface

Getting defined materials

In the Explorer, right click on the **Materials** folder and select **Get from User Database…**, then **select** all the 3 materials and click on **OK** button to load them into the current model, as shown below,





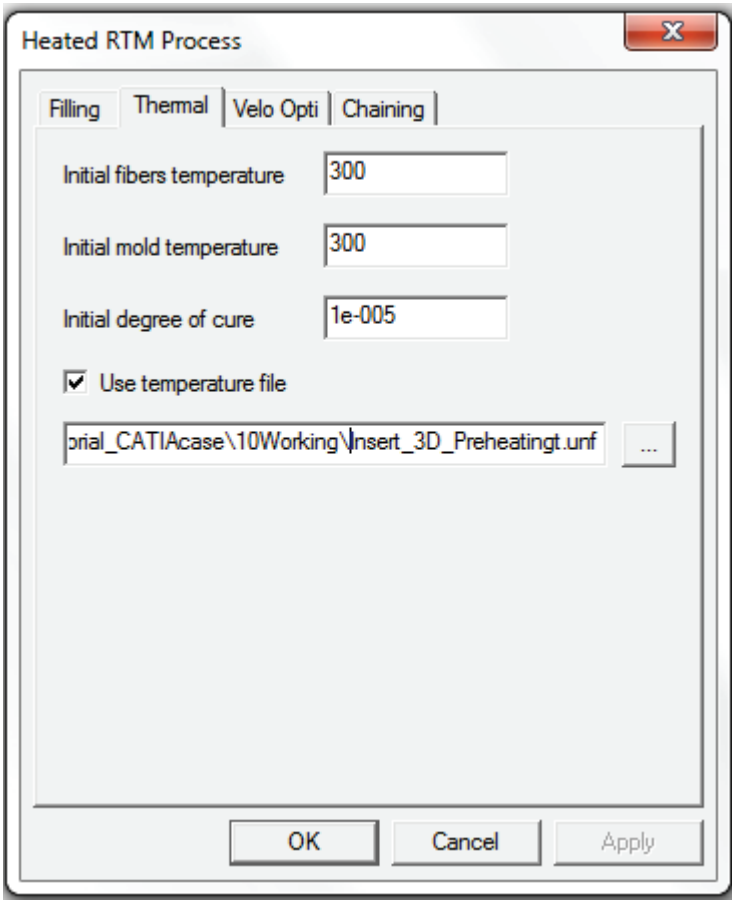
Material assignment

Visualize the zones of the parts and make material assignment as follows,

- zone ID 1 (Insert): Metal
- zone ID 2 (Mold): Metal
- zone IDs 3 to 7 (Reinforcement): Preform

Linking Preheating temperature

- Double click on **Process** in the Explorer, and then select the **Thermal** tab.
- Check the **Use temperature file** box.
- Click on the button **Open** to select the temperature results file.
- In this case, the temperature results of previous preheating analysis, **Insert_3D_Preheatingt.unf** is selected, as shown below,



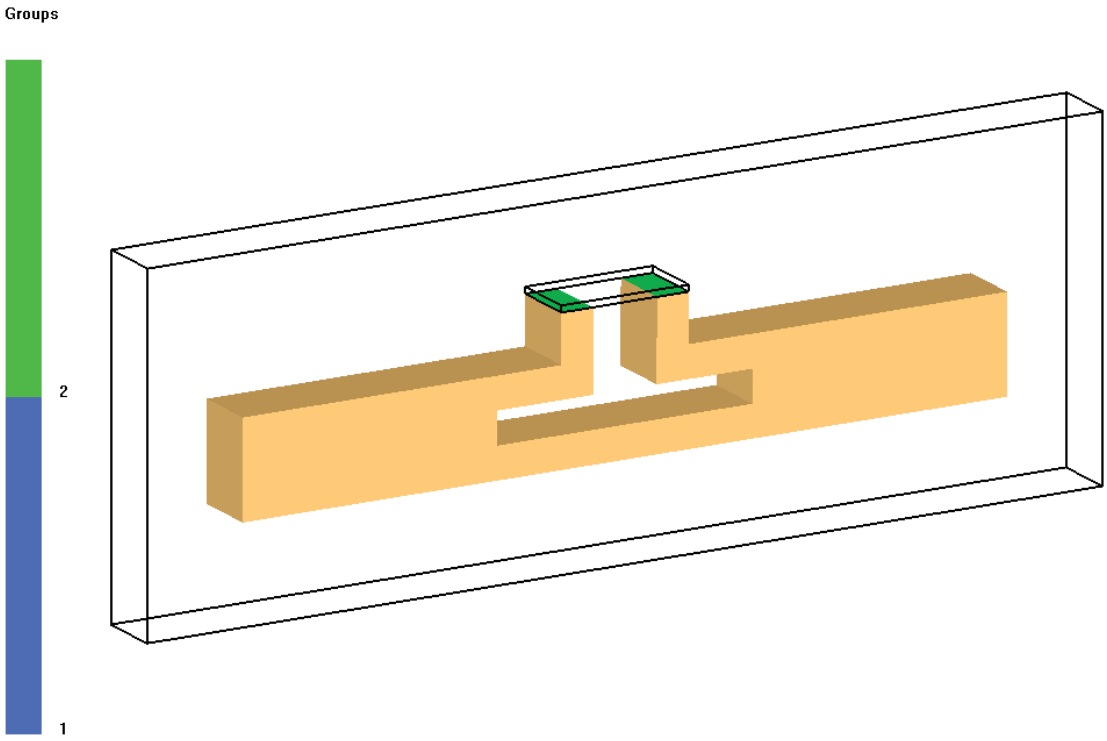
End of preheating temperature file path definition

Note:

- *This linking is to import previous Preheating results as initial temperature of the current Heated RTM analysis*
- *The file to select depends on the solver used for computation:*
  *- for parallel solver (this case), the file is *t.unf*
  *- for old solver, the file is *_p.dof.*

Boundary Conditions

- **convection** boundary (same as Preheating case, i.e. defined on group 1)
- **flow rate** (group 2, see image below) :
  - flow_rate = 1E-6 m^3/s
  - resin temperature = 300 K



Groups for filling stage

Simulation Stage 3: Curing

Create a Curing analysis and import ***Insert_3D_Preheating.unv***.
Get the 3 materials from the Material Database and make material assignment to zones.

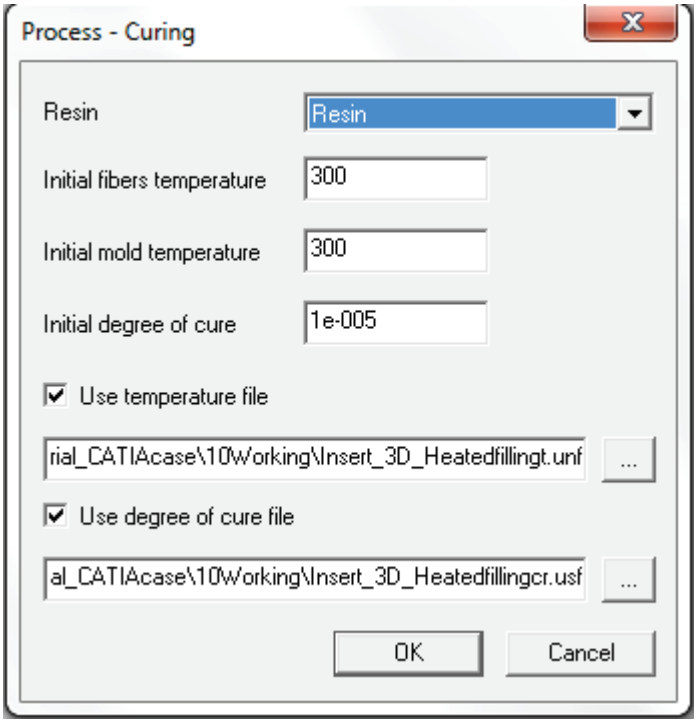
Numerical Settings and DMP solver activation

Set the following parameters in Curing Numerical Parameters interface:

- Save temperature: checked
- Results sampling period: 50
- Max experiment time: 3600 s
- Max number of steps: 250
- Check *use parallel solver*

Linking Heated filling temperature and Cure

- Double click on **Process** in the Explorer; make sure **Resin** material is selected
- check the boxes of **Use temperature file** and select **Insert_3D_Heatedfillingt.unf**
- check the boxes of **Use degree of cure file** and select **Insert_3D_Heatedfillingcr.usf**



End of filling temperature and cure files path definition

Note:

· *Linking files with respect to solver used for curing analysis*

	Temperature file	Cure degree file
Parallel(DMP)	***t.unf**	***cr.usf**
old solver	***_Thermal_f.dof**	***_Curing_f.dof**

Boundary Conditions

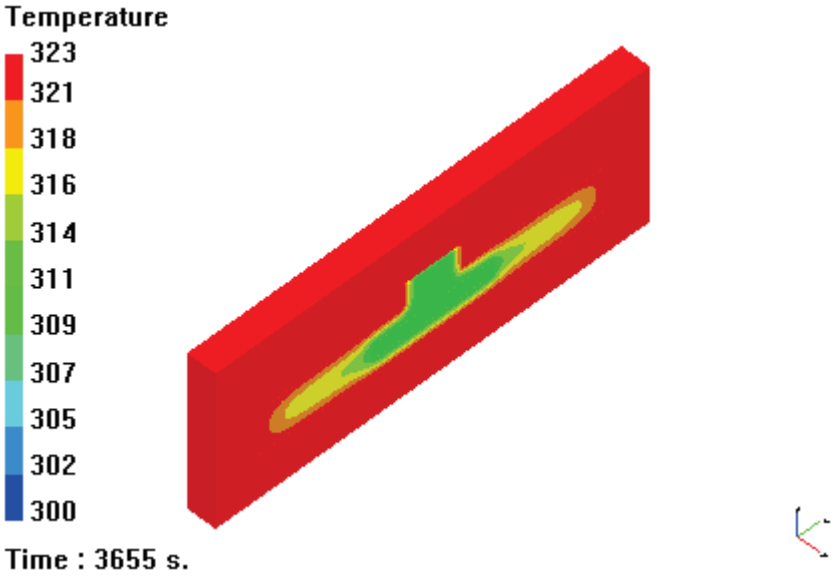
Convection boundary condition (same as Preheating case)

Analysis of the Results

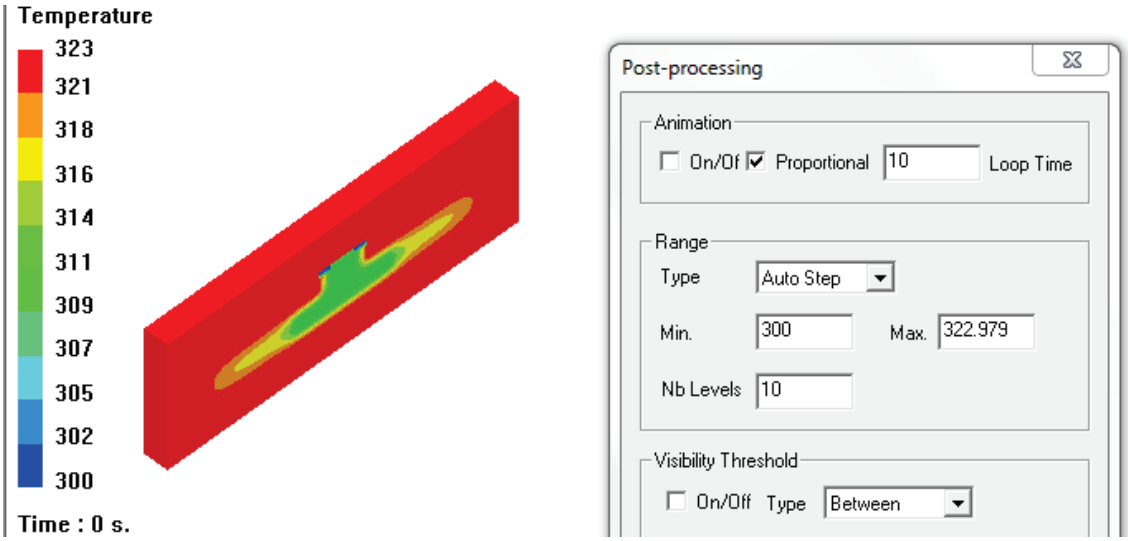
Preheating stage

The last time state of preheating is 3655s (stop time was set to 3600s but with the parallel solver the actual last state depends on the sampling period).

Because of temperature file linking, the temperature contour of last state is consistent with that of initial state of Heated RTM stage, as shown below.



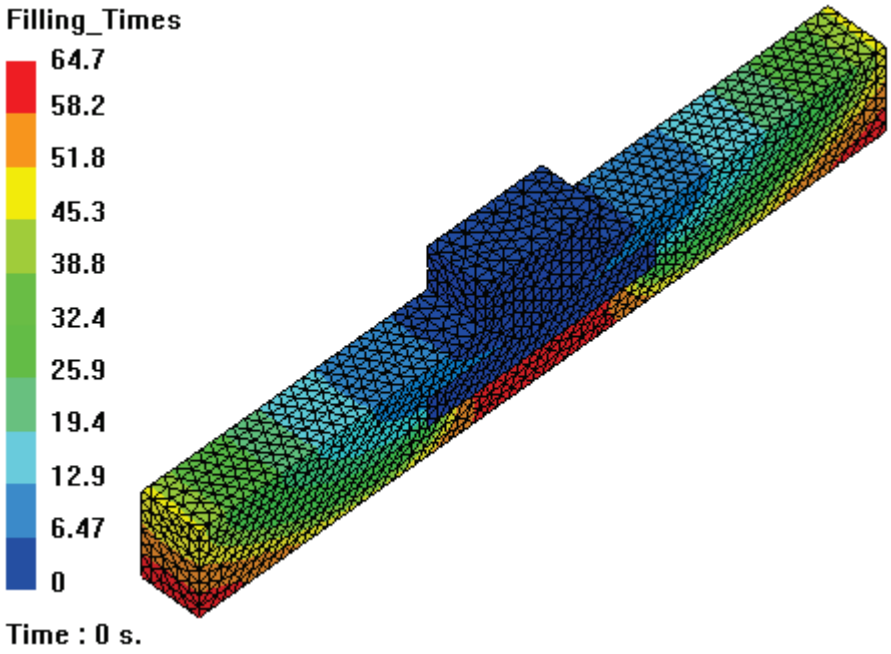
Last state of preheating stage

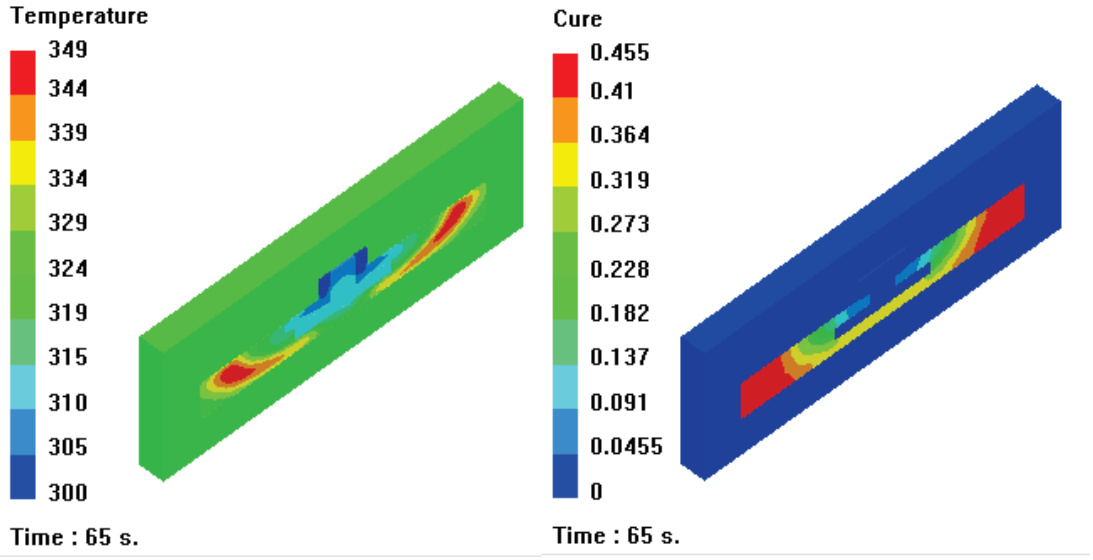


Initial state of heated RTM stage
(Range Type set as "Auto Step" for an easier comparison)

Heated RTM Stage

It shows that the filling time is 64.7s and at the end of filling there is a temperature and cure gradient, as shown below,

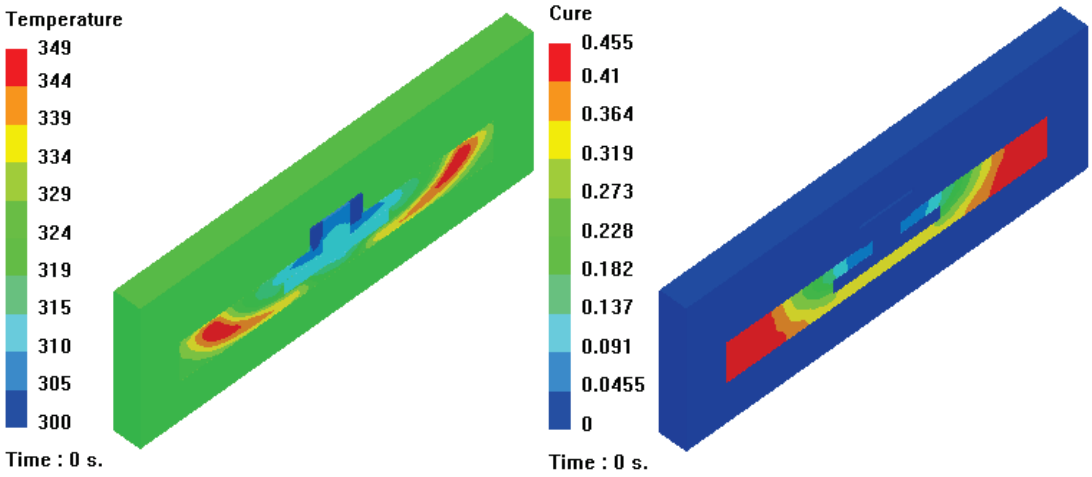




Temperature and cure distribution
(end of Heated RTM)

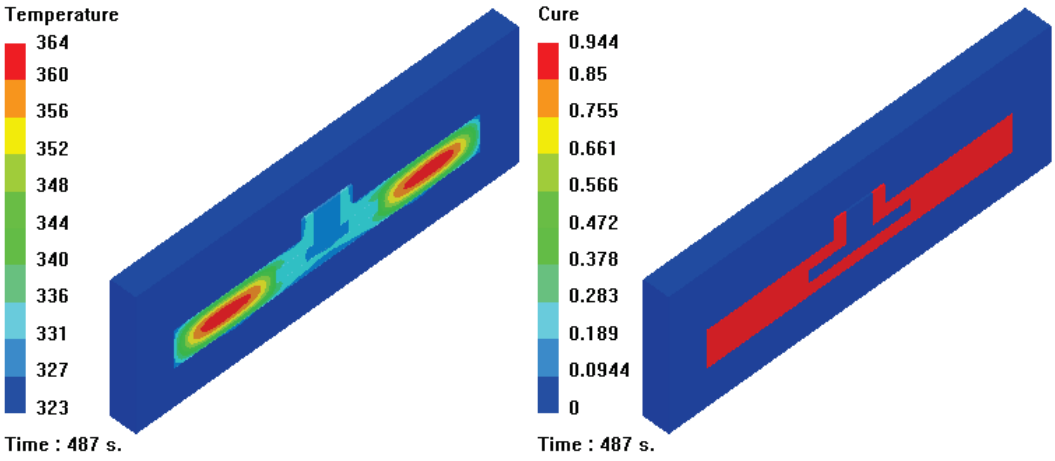
Curing Stage

Because of temperature and cure files linking, the temperature and cure distribution at curing start (as shown below) are consistent with end of Heated RTM.



Temperature and cure distribution(Curing start)

After 487 seconds, 100% of the part has reached a resin cure of 90%. The temperature distribution for this time step shows a peak of temperature at the center of the preform.



Temperature and cure distribution (end of Curing)

Conclusion

This tutorial has shown how to perform chained preheating, heated RTM and curing simulations.

USER DEFINED FUNCTIONS

The following files are used in this example.

- ***func_resinviscosity.c*** (source code template for resin viscosity)
- ***func_resinkinetics.c*** (source code template for resin kinetics)
- ***func_resinspecheat.c*** (source code template for resin specific heat)
- ***func_effthermalcond.c*** (source code template for effective conductivity of a wet reinforcement)

Objectives

Explain the procedure to compile user defined functions for resin viscosity, kinetics, specific heat, and effective conductivity of a wet reinforcement. This procedure only applies to the parallel solver.

Windows Procedure

Two batch files and four C-language files (.c) are provided in the installation directory of the PAM-RTM parallel solver, which is in general *C:\Program Files (x86)\ESI Group\PAM-RTM\version\Windows-x64\DMP*:

- compile_rtm_udf_vs.bat (compile script for Visual Studio)
- compile_rtm_udf_sdk.bat (compile script for Windows SDK)
- func_resinviscosity.c (source code template for resin viscosity)
- func_resinkinetics.c (source code template for resin kinetics)
- func_resinspecheat.c (source code template for resin specific heat)
- func_effthermalcond.c (source code template for effective conductivity of a wet reinforcement)

The first batch file is to be used with Visual Studio (free of professional edition), the second one is to be used with the Windows SDK (software development kit). In general it is better to work with Visual Studio, except for the case where the user doesn't have a professional edition and needs to compile for Windows 64-bit. The free editions of Visual Studio don't support 64-bit compilation. The free editions of Visual Studio and the Windows SDK can be downloaded from Microsoft's web site.

Here we will focus on user functions for resin viscosity and kinetics. User functions for resin specific heat and effective conductivity are most of the time used to define them as functions of temperature and degree of cure, so it is an advanced application. These will be discussed in the last section of this tutorial.

The first step is to copy the four provided .c files and the appropriate batch file (*VS* or *SDK*) in some user directory. It is necessary to copy all the .c files even if only two of them will be edited here (*func_resinviscosity.c* and *func_resinkinetics.c*), otherwise the build procedure will fail.

Open the batch file in a text editor and check that the PAMRTM_INSTALL_DIR variable corresponds to your actual installation directory, otherwise correct it. Then open the .c files in Visual Studio or any text editor.

Note that you don't have to create a project in Visual Studio. The procedure only relies on command-line tools.

In this example we want to define viscosity and kinetics for two resins: my_resin_1 and my_resin_2.

The first resin has a viscosity function of material age (i.e. function of time since a resin particle entered the mold):

$$f(t) = 0.01 + \frac{t^2}{7.2 \times 10^5} \text{ Pa.s}$$

The second resin has a viscosity function of temperature and degree of cure:

$$f(T, \alpha) = 2.38 \times 10^{-21} \cdot e^{\frac{14500}{T} + 3.8 \cdot \alpha} \text{ Pa.s}$$

Starting from the provided template for the viscosity function, the code to be written by the user is highlighted below. The first resin is using only parameter *local_time*, which corresponds to the time since a resin particle entered the mold, while the second resin uses parameters *temperature* and *alpha*.

```
/*
 *    Return resin viscosity as a function of the current temperature, current
degree of cure, or current time.
 */


real func_resinviscosity(
   char  prefix[],     /* case name  */
   char  resin_name[],     /* case name  */
   real  temperature,  /* current temperature in Kelvin */
   real  alpha,        /* current degree of cure (value between 0 and 1) */
   real  local_time,   /* current local time (time since particle entry in the
mold) */
   real  global_time)  /* current global time (time since beginning of
injection) */
{
```

```
/* ------------- Do not change anything above this line ------------- *
 * ------------- Program your function below this line  ------------- */

   if ( strcmp( resin_name, "my_resin_1" ) == 0 ) {

      return 0.01 + ( local_time * local_time ) / 7.2E5;

   }
   else if ( strcmp( resin_name, "my_resin_2" ) == 0 ) {

      return 2.38E-21 * exp( 14500. / temperature + 3.8 * alpha);

   }
   else {

      printf("unknown resin in user defined viscosity\n");
      exit(1);

   }

}
```

Note that this architecture doesn't currently support units. The solver assumes the returned value is in *Pa.s* for viscosity, s^{-1} for kinetics.

The code to be written for kinetics in file *func_resinkinetics.c* would have the same structure and is left as an exercise. Note that it is not mandatory to edit both viscosity and kinetics functions. Depending on the user's needs, only one of viscosity or kinetics could be defined. Even though both functions will be compiled (one of the definitions being the default implementation that just prints an error message and exits), there shouldn't be issues as long as the user doesn't choose function type *user_dll* in the PAM-RTM GUI for a function that is not defined.

We recommend that you print some messages in your functions to make sure the code is correctly called. This should only be done for the first run, as it will slow down execution a lot. For instance you could add these lines in *func_resinviscosity.c*:

```
real visc = …
printf("visc = %12.5E, T = %12.5E, alpha = %12.5E\n", visc, temperature,
alpha);
```

Now that the code is written, it is time to compile it. The procedure is a bit different for Visual Studio and Windows SDK.

Visual Studio 32-bit target

Open a command window with **Start>Programs>Microsoft Visual Studio 2005>Visual Studio Tools>Visual Studio 2005 Command Prompt**. This is the path for Visual Studio 2005, but it should be almost the same for other versions. This will open a console window in which the environment variables needed to compile with the command line tools are already set (PATH for instance). Then simply type the command:

```
compile_rtm_udf_vs.bat x86
```

Note the **x86** at the end of the command line.

This command compiles *func_resinviscosity.c*, *func_resinkinetics.c, func_resinspecheat.c, func_effthermalcond.c*, which generates the corresponding four .obj files. If compilation is successful, the command then copies a set of .obj files from the PAM-RTM installation directory to the current directory and links all these .obj files together to generate a dynamic link library called *libprocast_DMP.dll*. Once the command is done, the user should check the date of *libprocast_DMP.dll* to make sure it was just generated. If everything looks good, the new *libprocast_DMP.dll* must then be copied to the installation directory of PAM-RTM and overwrite the file with same name (make a copy of the file before overwriting it). That directory is in general C:\Program Files (x86)\ESI Group\PAM-RTM\CurrentVersion\Windows-x86\DMP.

Visual Studio 64-bit target

There are only 2 differences for a 64-bit target, compared to the procedure for a 32-bit target.

First the console window is opened with a shortcut that contains *x64* in its name. For instance with Visual Studio 2005, the shortcut is **Start>Programs>Microsoft Visual Studio 2005>Visual Studio Tools>Visual Studio 2005 x64 Win64 Command Prompt.**

Then the *x86* flag at the end of the command must be replaced by *x64*:

```
compile_rtm_udf_vs.bat x64
```

The newly generated *libprocast_DMP.dll* must then be copied to the installation directory of PAM-RTM and overwrite the file with same name. That directory is in general C:\Program Files (x86)\ESI Group\PAM-RTM\CurrentVersion\Windows-x64\DMP. Be careful not to copy a 64-bit DLL in a 32-bit directory, or vice-versa.

Windows SDK 64-bit target

Referring again to the procedure for Visual Studio 32-bit, the main difference here is that we use the following shortcut to open the console window, or a similar shortcut for a different version of the SDK:

Start>Programs>Microsoft Windows SDK v7.1>Windows SDK 7.1 Command Prompt

You should see a message similar to *Targeting Windows 7 x64* printed in the console.

Then the command to compile is:

```
compile_rtm_udf_sdk.bat x64
```

Once again be careful with the *x64* flag at the end of the command line. The batch file won't run correctly if you forget to specify it.

Linux Procedure

First locate the directory containing the binaries of the current PAM-RTM version. The command "*which pamrtmdmp*" should allow you to identify that directory. Let's call that directory *rtm_dir*, we will need it again below. There is a subdirectory *user_MP* in that directory. Copy all the files in *rtm_dir/user_MP* to the user directory where you will compile. This will copy some object files (.o) as well as the makefile *compile_rtm_udf.mk* and all the .c source code templates.

Edit the appropriate .c files to define viscosity and/or kinetics and/or specific heat and/or effective conductivity, as explained above.

Before launching compilation there is a critical step required to set up the appropriate compiler, which is the *mpicc* of the *Platform-MPI* version used by PAM-RTM. Be careful that there could be other versions of *mpicc* installed on your system, and using another version could lead to problems. The *mpicc* of the *Platform-MPI* used by PAM-RTM is located in *rtm_dir/pcmpi/bin*. Modify the PATH environment so that this directory is searched first, with a command such as:

```
export PATH=rtm_dir/pcmpi/bin:$PATH
```

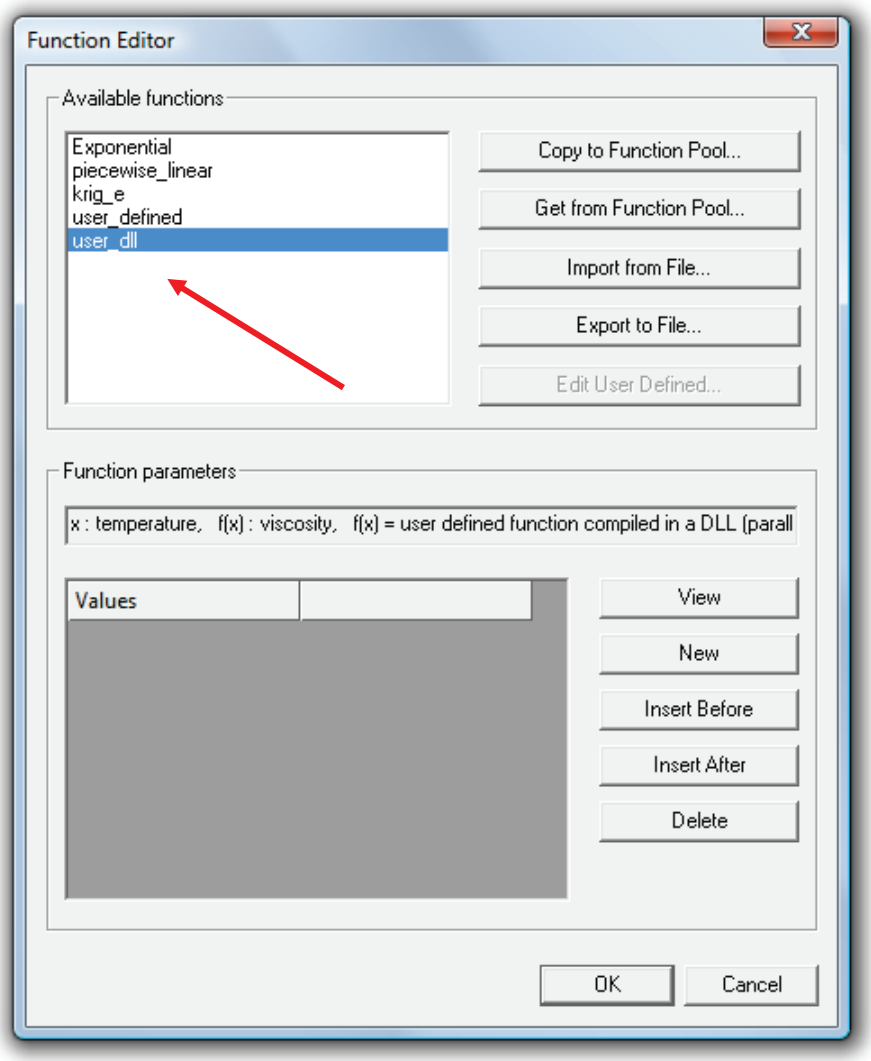
Once the PATH is correctly set, launch compilation with:

```
make -f compile_rtm_udf.mk
```

This will generate *libprocast_DMP.so*. Copy the new .so to overwrite the file with same name in the PAM-RTM installation directory.

Setting the parameters in the PAM-RTM GUI

In order to have the user defined viscosity and kinetics functions called for a given model, function type *user_dll* must be selected in the PAM-RTM GUI.



It is important to understand that libprocast_DMP.dll has no other use than to evaluate viscosity and/or kinetics and/or specific heat and/or effective conductivity for the only cases where *user_dll* is selected in the PAM-RTM GUI. If any type other than *user_dll* is selected, the DLL won't be called. This means there will not be any side effects if the user compiled DLL is kept in the PAM-RTM installation directory to run cases not using user functions.

User functions for resin specific heat and effective conductivity

These functions are used most of the time to define resin specific heat and effective conductivity of a wet reinforcement as a function of temperature and degree of cure ($f(T,\alpha)$).

Suppose we want to define the specific heat as the following function:

$c_p(T,\alpha) = 2 \cdot (T - 273) + 1800$ for $\alpha \leq 0.5$

$c_p(T,\alpha) = 3 \cdot (T - 273) + 1500$ for $\alpha > 0.5$

This specific heat model is just for the sake of the example, it doesn't correspond to a real resin.

For a resin with name *my_resin_1*, the corresponding user code would be:

```
/*
 *    Return specific heat of pure resin (i.e. not mixed with fibers).
 */


real func_resinspecheat(
   char  prefix[],     /* case name  */
   char  resin_name[],     /* resin name  */
   real  temperature,  /* current temperature in Kelvin */
   real  alpha,        /* current degree of cure (value between 0 and 1) */
   int*  vars)    /* return 1 for a function of temperature or 2 for a
function of temperature and cure */
{
/* ------------- Do not change anything above this line ------------- *
 * ------------- Program your function below this line  ------------- */

   /* Return value must be in J/kg/K */

   if ( strcmp( resin_name, "my_resin_1" ) == 0 ) {

      if ( alpha <= 0.5 ) {
         return 2. * ( temperature - 273. ) + 1800.;
      }
      else {
         return 3. * ( temperature - 273. ) + 1500.;
      }
```

```
      *vars = 1;  /* function of temperature only */

   }
   else {

      printf("unknown resin in user defined specific heat\n");
      exit(1);

   }

}
```

To have the user function for c_p called, the user must select first **f(temperature)** or **f(temperature, alpha)** for the c_p of the resin in the PÂM-RTM GUI, then **user_dll**. Note that it is the user's responsibility in his code to return "*vars = 1" for a function of temperature, or "*vars = 2" for a function of temperature and alpha, since the same user function is used for both situations. When "*vars = 2" is returned, the solver adds an extra term in the energy equation to take into account the time dependency of c_p through alpha:

$$\frac{\partial(\rho c_p T)}{\partial t} = \rho c_p \frac{\partial T}{\partial t} + \rho \frac{\partial c_p}{\partial t} T$$

For the effective conductivity of a wet reinforcement, since it involves the combination of a resin and a reinforcement, we recommend the following code structure. Here we have resins *my_resin_1* and *my_resin_2*, and reinforcements *my_rf_1* and *my_rf_2*.

```
/*
 *    Return effective thermal conductivity principal values (k1, k2, k3) of
the mix of resin and fibers, i.e. the
 *    conductivity to be used in the wet area.
 */

void func_effthermalcond(
   char  prefix[],     /* case name  */
   char  resin_name[],     /* resin name  */
   char  reinforcement_name[],     /* reinforcement name  */
   real  vf,           /* fiber volume fraction (value between 0 and 1) */
```

```
   real  temperature,  /* current temperature in Kelvin */
   real  alpha,        /* current degree of cure (value between 0 and 1) */
   real  *k1,   /* returned effective conductivity in the first principal
direction */
   real  *k2,   /* returned effective conductivity in the second principal
direction */
   real  *k3)   /* returned effective conductivity in the third principal
direction */
{
/* ------------- Do not change anything above this line ------------- *
 * ------------- Program your function below this line  ------------- */

   /* Returned values must be in W/m/K */

   *k1 = 0.;
   *k2 = 0.;
   *k3 = 0.;

   if ( strcmp( resin_name, "my_resin_1" ) == 0) {
      if (strcmp( reinforcement_name, "my_rf_1" ) == 0) {
         *k1 = ...
         *k2 = ...
         *k3 = ...
      }
      else if ( strcmp( reinforcement_name, "my_rf_2" ) == 0) {
         *k1 = ...
         *k2 = ...
         *k3 = ...
      }
      else {
         printf("unknown combination of resin and fibers\n");
         exit(1);
      }
   }
   else if ( strcmp( resin_name, "my_resin_2" ) == 0) {
      if ( strcmp( reinforcement_name, "my_rf_1" ) == 0) {
         *k1 = ...
         *k2 = ...
         *k3 = ...
      }
      else if ( strcmp( reinforcement_name, "my_rf_2" ) == 0) {
```

```
            *k1 = ...
            *k2 = ...
            *k3 = ...
         }
         else {
            printf("unknown combination of resin and fibers\n");
            exit(1);
         }
      }
      else {
         printf("unknown resin in user defined effective conductivity\n");
         exit(1);
      }

}
```

To have the user function for effective conductivity called, the user must select first **f(temperature)** or **f(temperature, alpha)** in the PAM-RTM GUI, then **user_dll**. Note that the fiber volume fraction of the zone (or local fiber fraction if draping is used) is also passed as parameter to the effective conductivity function. The user could implement a rule of mixture in his function so that the effective conductivity is valid for any fiber fraction.

ONE SHOT FILLING SIMULATION

The following files are used in this example.

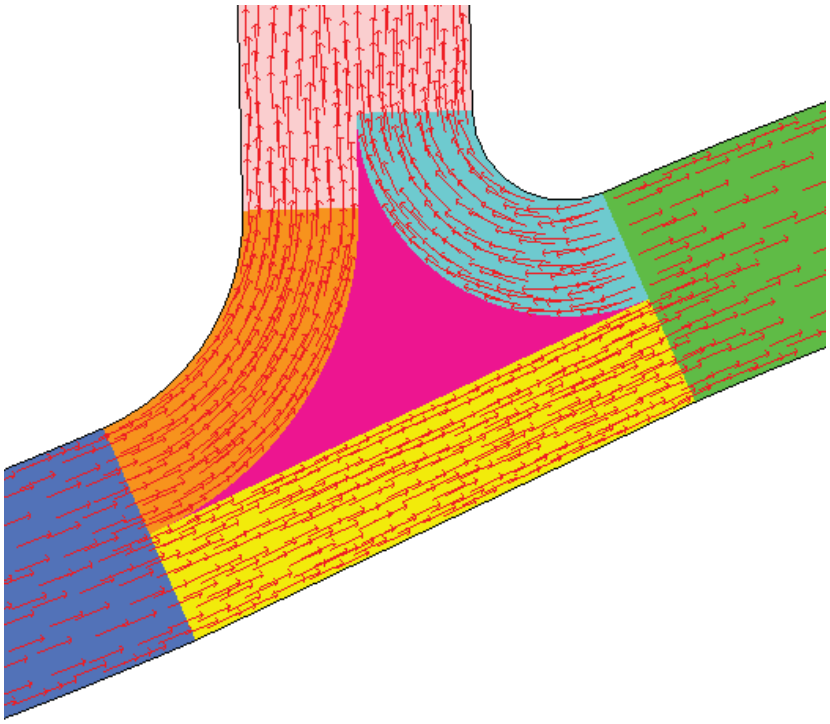
- ***one_shot_start.unv*** (starting mesh)
- ***one_shot.dtf + one_shot.unv*** (solution)

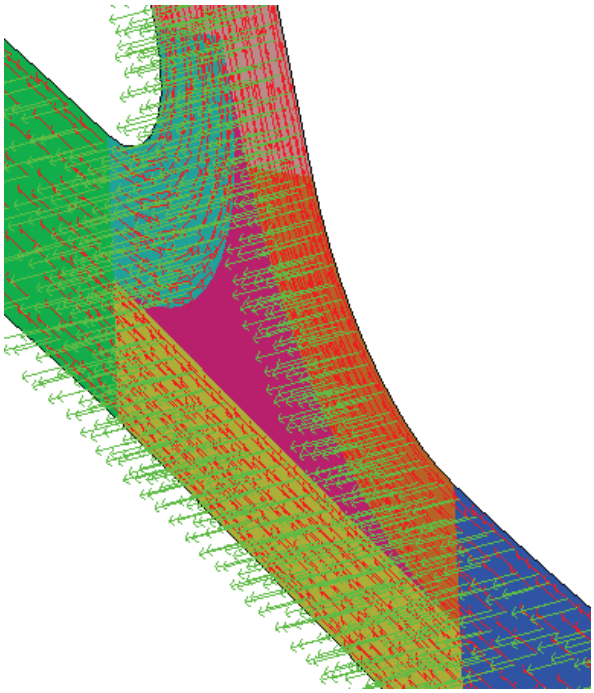
Objectives

The goal of this tutorial is to show how to use the *one shot* filling simulation, i.e. a very quick estimation of the filling time and location of the last points filled. This simulation doesn't solve the intermediate states of the flow. Only a few resolutions of Darcy's equation are needed, compared to thousands for a standard filling simulation, meaning just a few seconds of CPU time, even on a huge mesh.

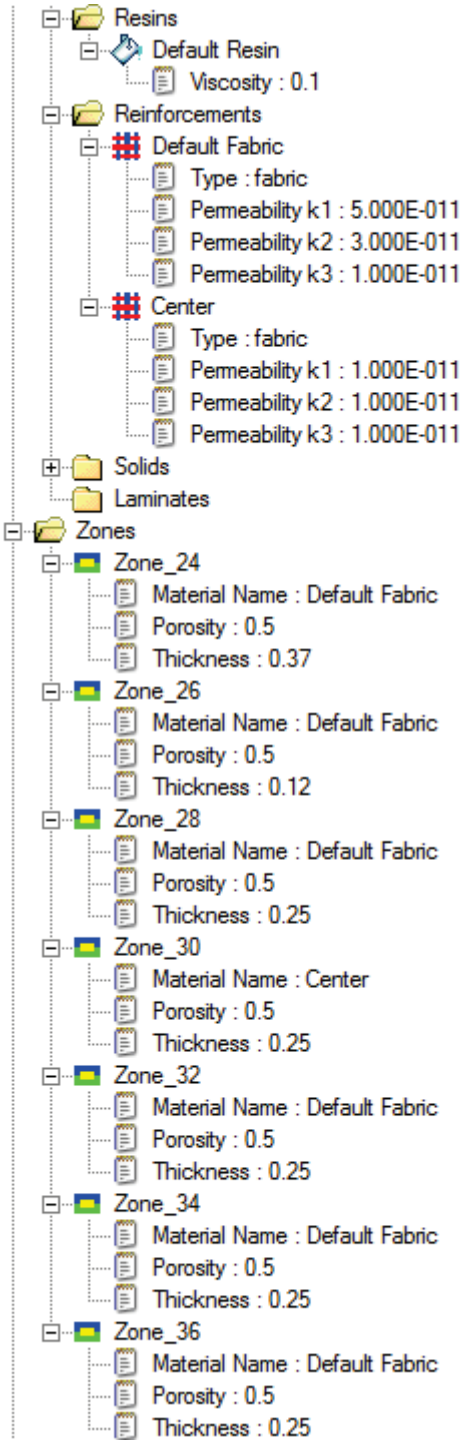
Material Properties

The 2D mesh can be seen as a cross section in a solid part with a T junction (see tutorial "Comparison 2D – 2.5D – 3D"). For this case, material orientations were defined because a reinforcement with non-isotropic permeability is used. The K1 principal permeability directions follow the shape of the part. They were set by projection of the elements on a "curve" (command **Mesh>Orientations>Set K from Selected Nodes**, see tutorial "Fiber Orientations"). The direction orthogonal to K1 and in the plane of the elements is here the transverse direction K3. Since we cannot set directly K3 in **PAM-RTM™**, the way to do it is to set K2 out of plane with **Mesh>Orientations>Set Vectors** and vector (0., 0., 1.). K3 is always calculated by **PAM-RTM™** orthogonal to K1 and K2, meaning we will have finally K3 orthogonal to K1 and in the plane of the elements. The K1 and K2 directions are shown below. The central zone has isotropic permeability, so orientations are not specified.



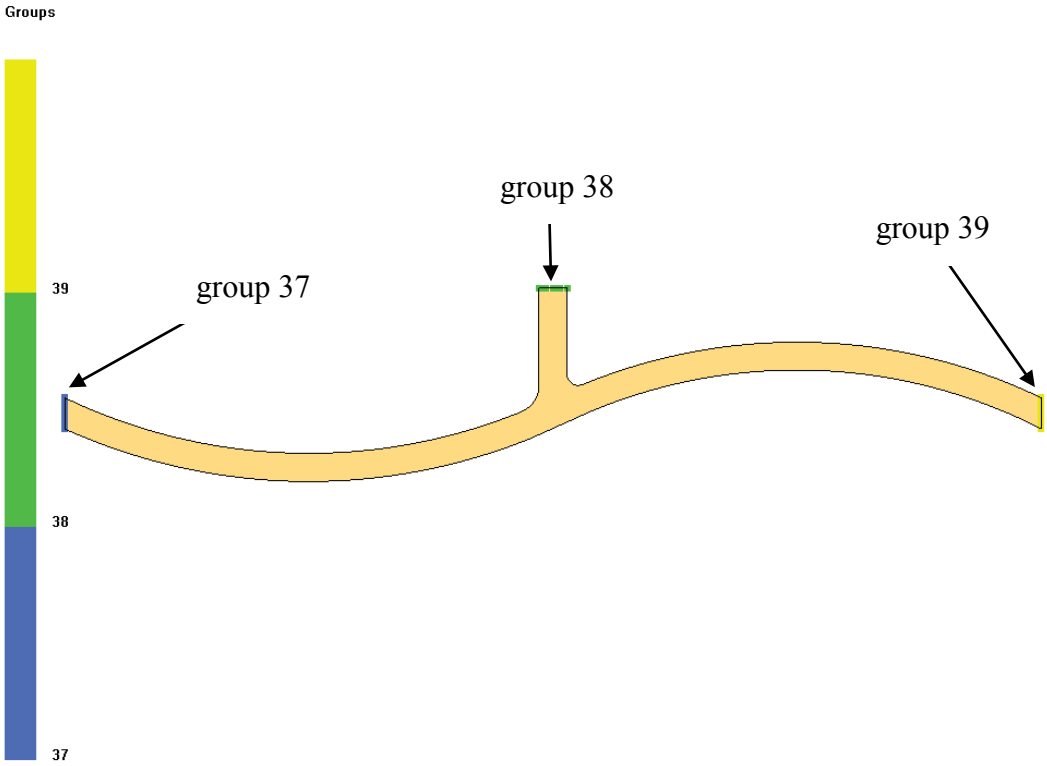


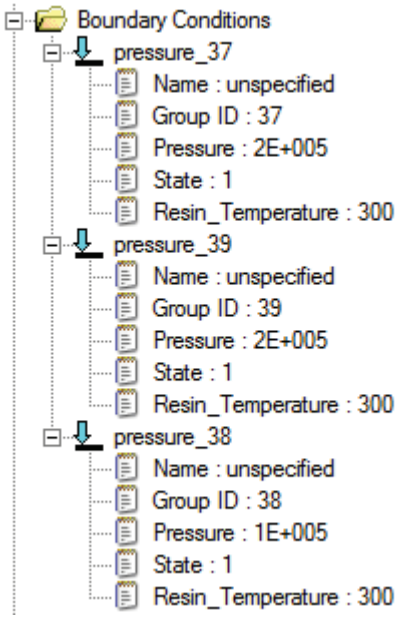
The material properties are summarized below.



Boundary Conditions

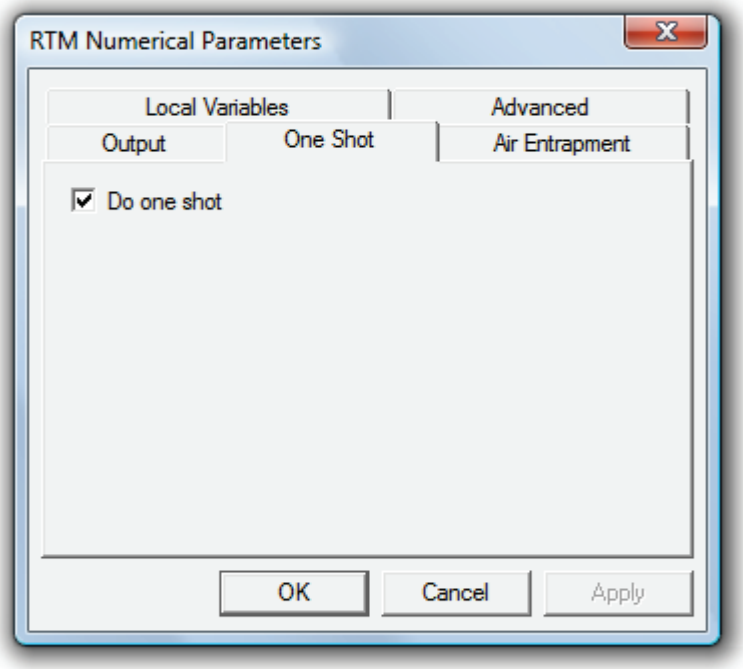
Three groups of nodes are created on the extremities of the part, that will be used as injection lines. All the lines are active at the same time, and all use imposed pressure. However the center injection line has a lower pressure (1 bar) while the left and right lines have 2 bars pressure. No vent is specified, as the goal of the one shot simulation is to help locate vents. The groups are shown below, with the corresponding boundary conditions in the document's tree.





One Shot Parameters

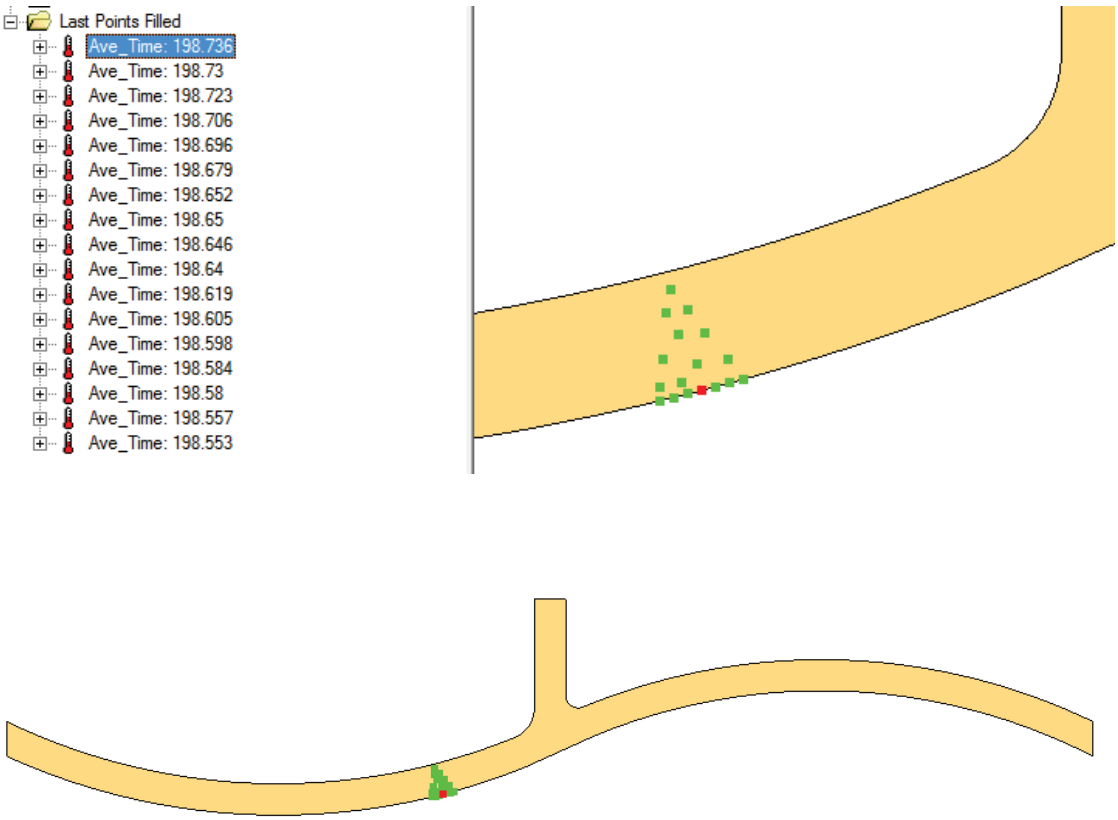
Only one parameter needs to be changed in order to run a one shot simulation, when compared to a standard filling simulation. It is the **do one shot** parameter, found in the **OneShot** tab of the **Numerical Parameters**. This parameter must be checked to run a one shot simulation.

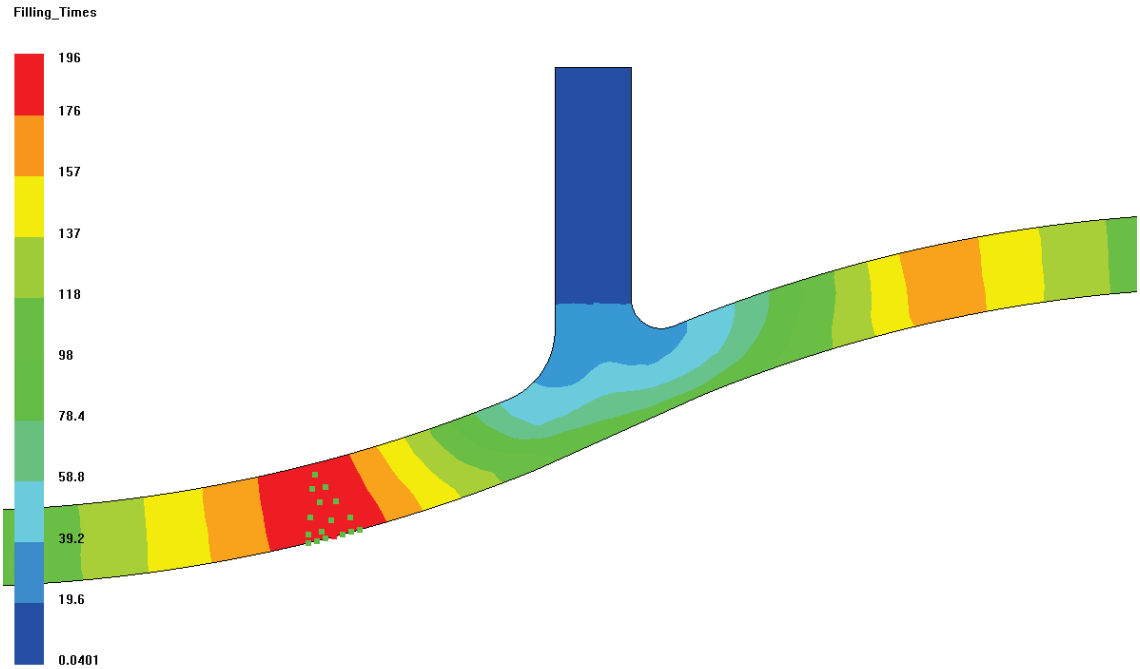


Launching the Simulation and Post-processing

Save the document and launch the simulation. When it is done, push the **Reload Results** button in the **Results** toolbar. A folder **Last Points Filled** is added to the document's tree. It contains the list of the last points filled, with the fill time for each point. Clicking one of these points in the document's tree highlights the corresponding point in the 3D view.

Most of the time, the output of a one shot simulation won't be a single point, but a set of points, which is some kind of fuzzy region for the actual last point filled. All these points should be considered candidates for potential last point filled. They are all within a 0.1 % tolerance on the total fill time. This is an internal tolerance that cannot be modified by the user in the current version.





Running first a one shot simulation, then unchecking the **do one shot** parameter to run a standard filling simulation, it is possible to superimpose the last points filled with the filling times contour, to check if they match. Here the match is very clear.

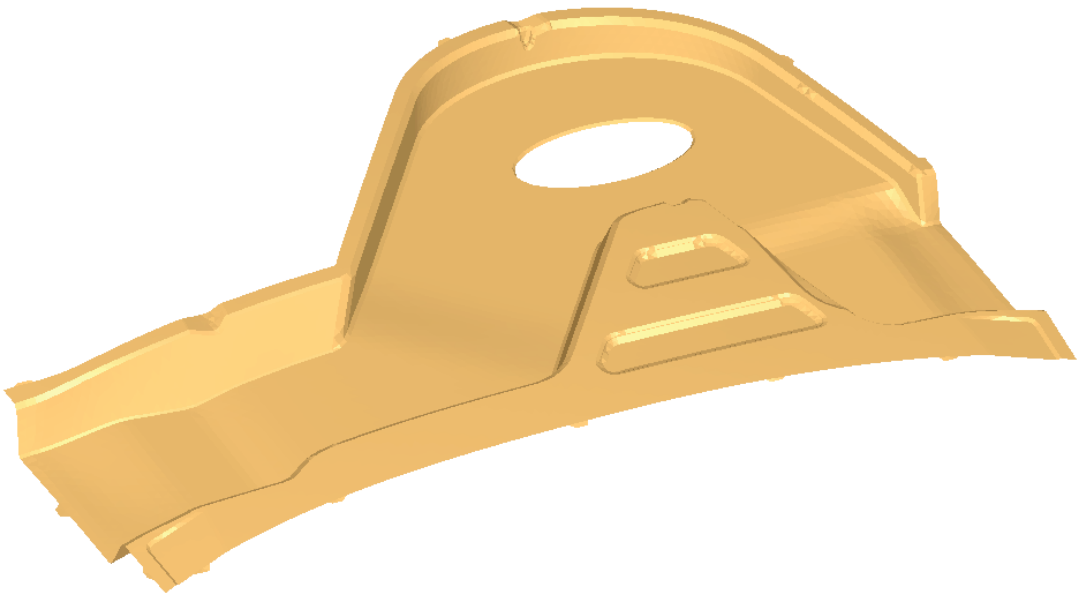
GENPORTS

The following files are used in this example.

- ***genports_start.unv*** (starting mesh)
- ***genports.dtf + genports.unv*** (solution).

Objectives

The goal of this tutorial is to show how to use the **GenPorts** module. **GenPorts** uses a genetic algorithm to find the optimal configuration of injection ports that minimize fill time. In this tutorial, we want to find the best configuration for 3 inlets on a complex part (shown below).



Material Properties and Boundary Conditions

Most of the material properties and boundary conditions usually set up in a standard RTM simulation are ignored by GenPorts. Actually the only material properties that are taken into account are permeability (principal directions and orientations) and porosity. High permeability areas used to define runners or race tracking are thus supported by GenPorts.

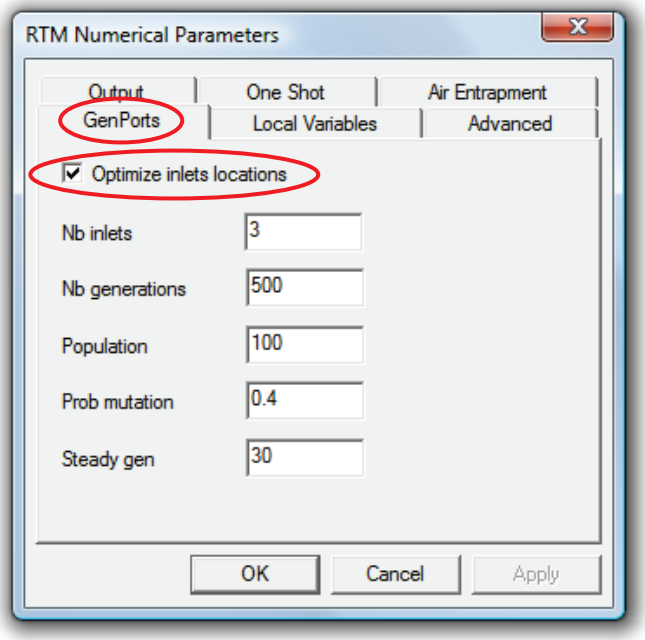
For the boundary conditions, the simulation will run without any boundary condition defined, as GenPorts will create internally the needed injection points and ignore any

boundary condition defined by the user. The optimization is independent of the actual pressure value used. It is assumed that all the points use the same pressure.

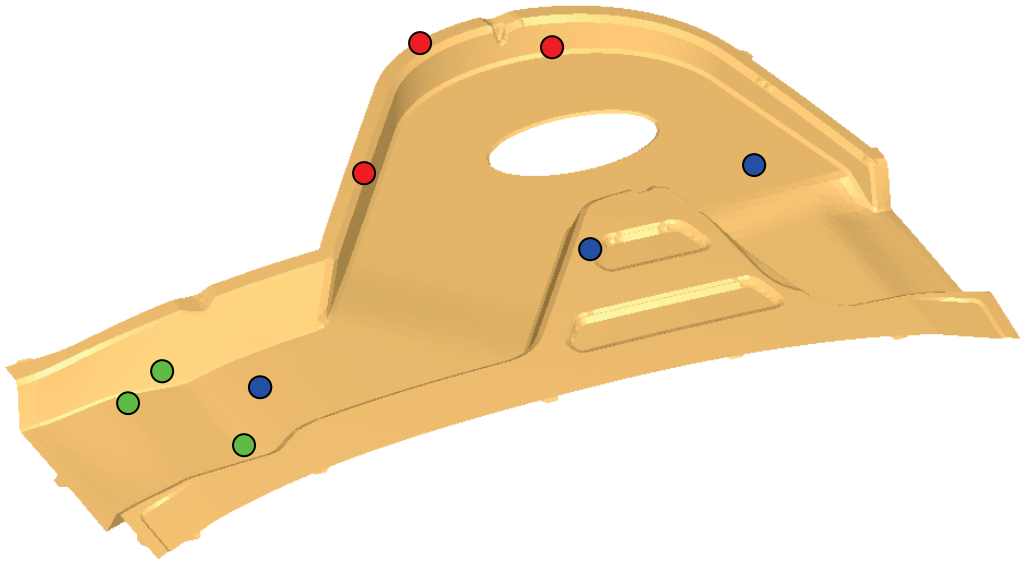
For this example, isotropic permeability is used (k1 = k2 = k3 = 2e-10 m2) with a porosity of 60%.

GenPorts Parameters

The GenPorts parameters are located in the GenPorts tab of the RTM Numerical Parameters. Assuming the user has already set up a model for a standard RTM simulation, there are basically 2 parameters that need to be changed to run a GenPorts simulation: the **optimize inlets locations** parameter must be checked, and the number of inlets to be used (**nb inlets**) has to be set. The other parameters, which are related to the genetic algorithm engine, could keep their default values. However here to reduce the CPU time, we use a smaller population of 100 and reduce the total number of generations to 500. The parameters are shown below.



It is very important to understand the meaning of **population**. A population is made of individuals. Here an individual is actually an injection configuration, i.e. in this example a set of 3 points (**nb inlets**). In the figure below we show 3 individuals (red set, green set and blue set). In this example a population of 100 individuals is used. We consider that value enough to insure a good "covering" of the part, taking into account the fact that the initial population is generated completely randomly, meaning that some individuals will be very "weak" (i.e. lead to a longer fill time, such as the green one below). For a larger part, the population should be increased.



The idea behind optimization using genetic algorithms is that the individuals within the population will combine to give birth to children. Some of the characteristics of both parents will be kept in the generation of a child, and some characteristics will be completely random. For instance, a point could be randomly generated on the line connecting 2 points from both parents. In that case, the characteristic is not completely random, it still is related to the characteristics of both parents even though some randomness is introduced. That is called a *crossover*. Also sometimes a *mutation* can occur. This is a more dramatic change in the characteristics of a child. For instance, a completely random node could be chosen on the mesh instead of being generated from the parents. The probability of a mutation can be entered with the **prob mutation** parameter. The user doesn't have control on the crossover parameters in the current version.

The number of individuals in a population is specified by the **population** parameter. That is an approximate number; the population will vary slightly from generation to generation as some individuals will die in the process. The maximum number of generations that will be calculated is specified in **nb generations**. It is possible that the calculation will stop earlier, if the calculation engine doesn't detect any significant improvement in the results for **steady gen** generations, meaning that a steady state has been reached.

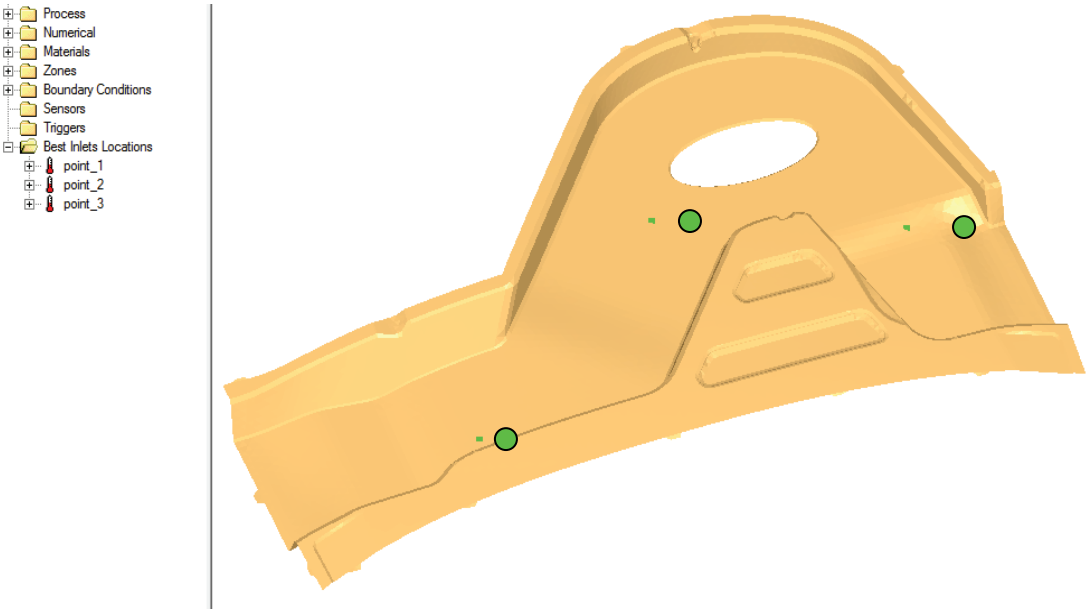
Launching the Simulation and Post-processing

The calculation is launched the usual way, by pushing the green arrow button , after saving the document.

A typical log file is shown below. The first column is the current generation, the second column shows the cumulative number of evaluations done, the third column shows the cumulative CPU time, and the last 3 columns show the best, average, and standard deviation results for the evaluation of the formulation on the population. Note that these high values come from the evaluation of a "mold coefficient" formulation, in which only material properties are taken into account, not boundary conditions. These values are related in some way to the fill time, but they are not of course actual time values.

```
************************************************************
GenPorts
Version 2010.0 (Aug 27 2010)
Copyright(c) ESI Group 2010
************************************************************

Calculation started Mon Aug 30 15:13:18 2010

Gen.     Eval.    Time     Best     Average & Stdev
1        91       28.392   1.07381e+009    1.55069e+009 3.82048e+008
2        130      40.497   9.57202e+008    1.35626e+009 2.7686e+008
3        171      53.055   9.60075e+008    1.38273e+009 3.32767e+008
4        212      65.52    9.60075e+008    1.35647e+009 2.93189e+008
5        259      79.95    9.89621e+008    1.27726e+009 1.65567e+008
```

Once the calculation is done, the user pushes the usual reload results button . This will add a **Best inlets locations** folder to the model explorer, in which the coordinates of the points are listed. The points are also displayed in the 3D view, as shown below.



SEQUENTIAL INJECTION (TRIGGER MANAGER)

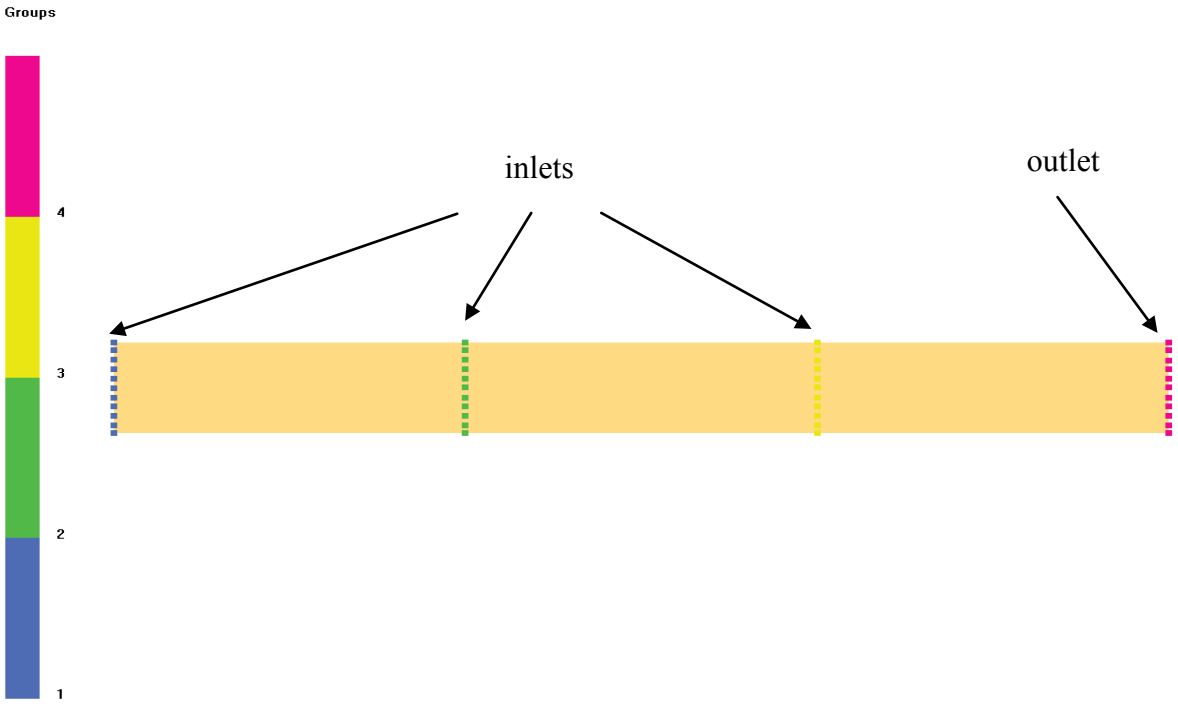
The following files are used in this example.

- ***sequential_start.unv*** (starting mesh)
- ***sequential.dtf + sequential.unv*** (solution)

Objectives

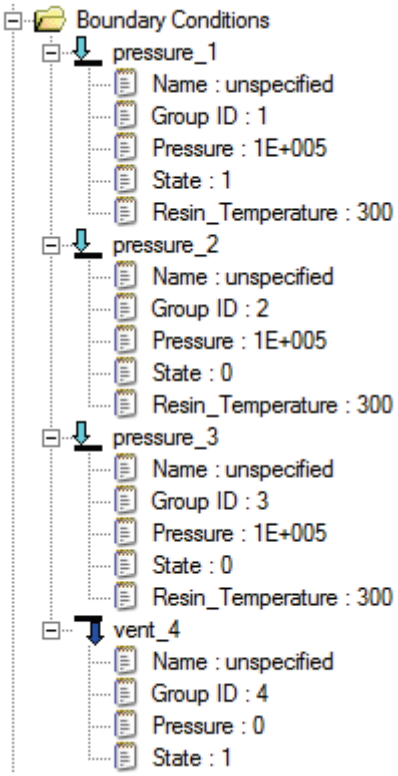
The goal of this tutorial is to show how to use the *trigger manager* to define a sequential injection. A long part is injected with many injection lines, which will be opened and closed sequentially in time. Even though it was possible with earlier versions to simulate sequential injection by using state curves and running many partial simulations, the trigger manager, introduced in **PAM-RTM™ 2009**, makes this kind of data setup much easier. Since **PAM-RTM™ 2013** the trigger manager is supported by the parallel solver; the tutorial uses the parallel solver.

Boundary Conditions

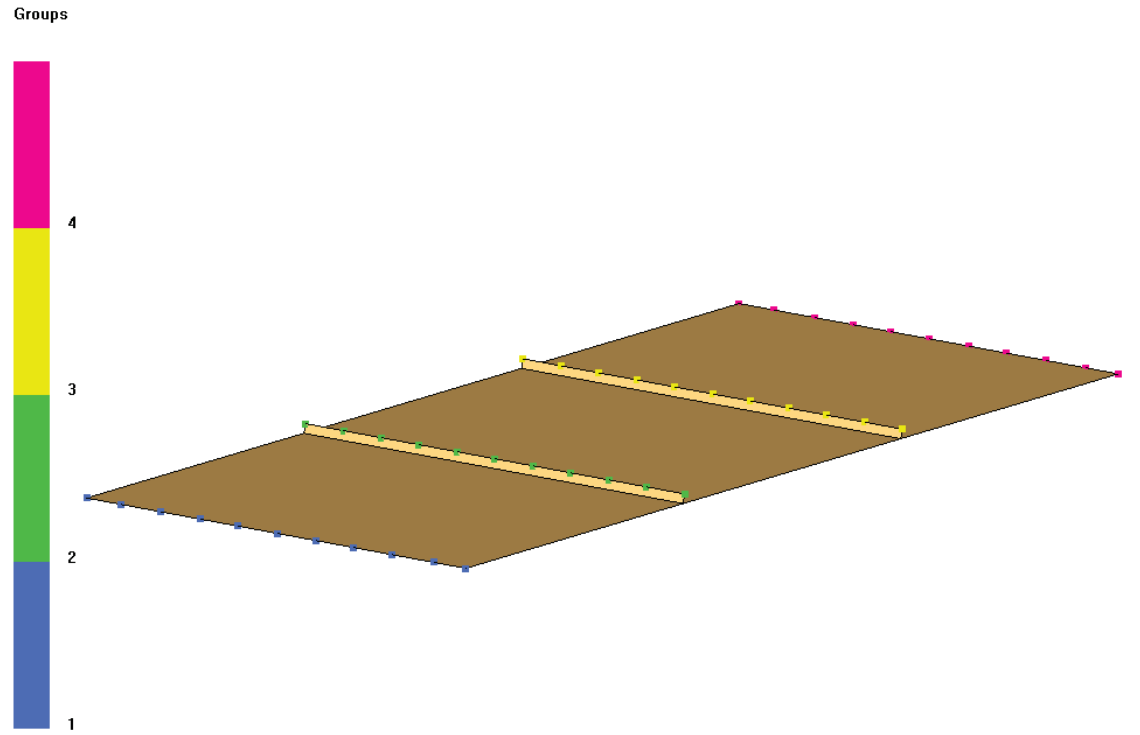


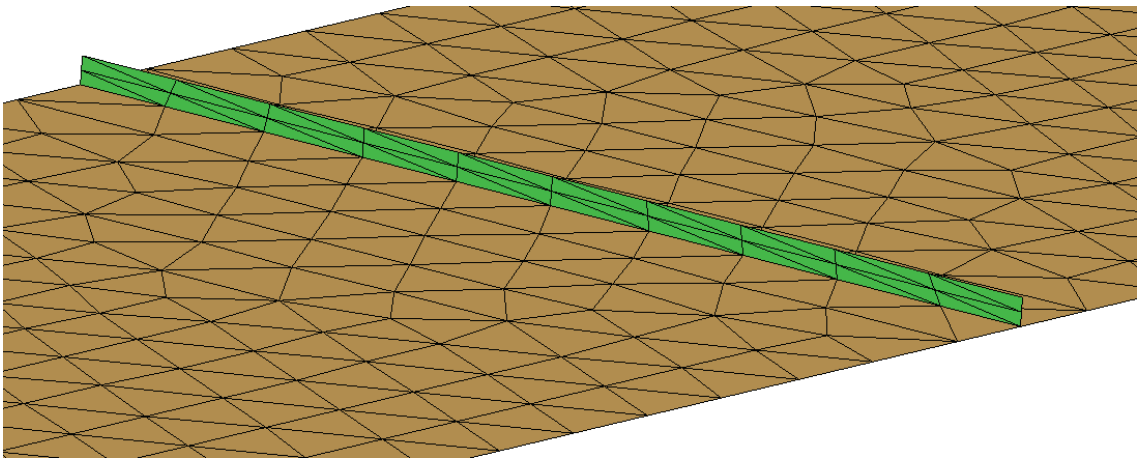
Four groups are created, equally spaced along the length of the part. The rightmost group is used for an outlet (vent) boundary condition, while the three other groups are inlets. Initially only the leftmost inlet is active (its *state* parameter has a value of one,

while the two other inlets have *state=0*). The outlet is kept open for the whole simulation. The corresponding entities in the document's tree are shown below.



The parallel solver doesn't support internal injection lines, i.e. defined with nodes that are not on free edges of the part. Therefore it is necessary to add some small surfaces orthogonal to the part, on which injection lines will be defined (see images below). Here the height of these surfaces is 5 millimeters, and 2 rows of elements were used. Note that PAM-RTM doesn't have a tool to create and mesh these small surfaces, so the user has to create them in his CAD software or mesh generator.



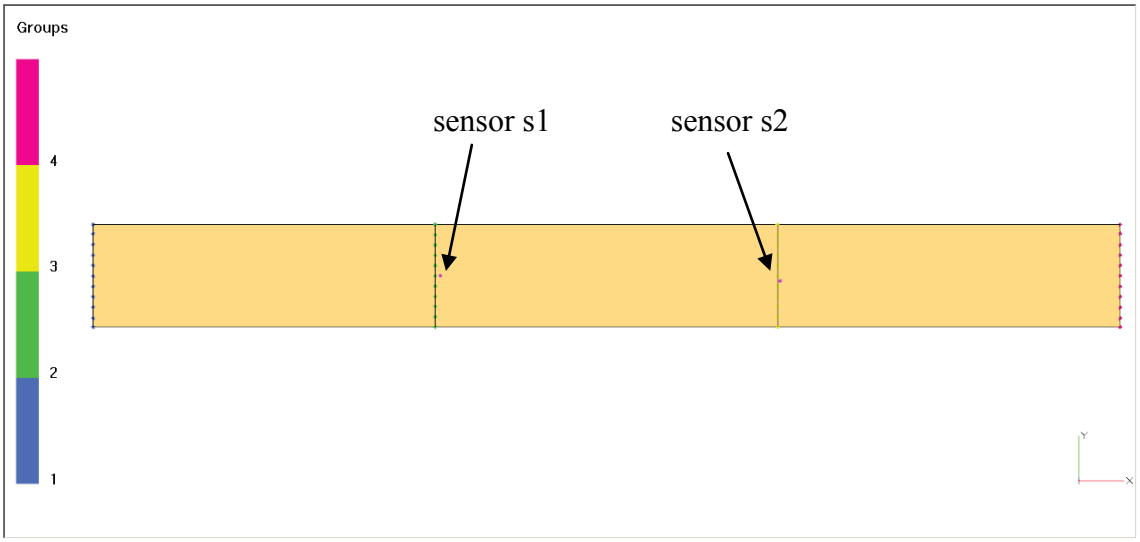


Material definition

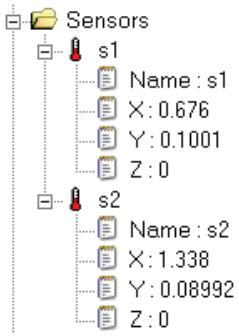
Because injection will be done in these small surfaces or "channels", permeability, thickness and porosity of these channels must match the values used for the part.

In this example, default fabric permeability of $10^{-9}m^2$, thickness of 5mm and porosity of 50% are used.

Sensors



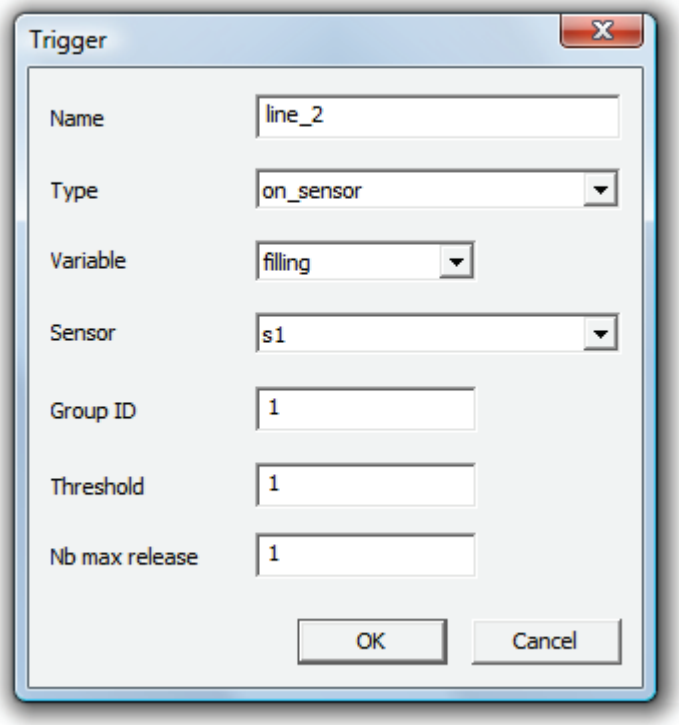
Two sensors are created just after the second and third injection lines. These sensors will be used as inputs by the trigger manager. For instance, when the resin will touch the first sensor, the first injection line will be closed, and the second one opened. The position of the sensors can be seen on the picture below.



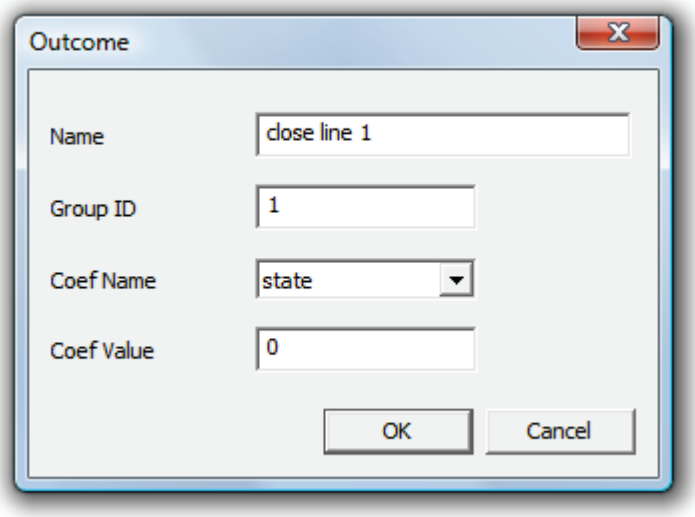
Trigger Manager

The goal of the *trigger manager* is to manage input conditions and fire outcomes when these conditions are reached. For instance an input condition could be the resin pressure on a sensor: when a given pressure is reached (parameter *threshold* of a trigger), a list of events is fired, such as closing a vent or opening an inlet. Other types of inputs are the injected or lost resin volume on a specific inlet or outlet, or the global injected or lost volume on all inlets and outlets. In this tutorial, we will use an input condition based on the filling factor, to determine if the flow has reached a given sensor: we use a threshold with a value of one. Note that another way to detect that the flow has reached a given sensor would be to use a trigger based on pressure, with a very small pressure value.

The first trigger will manage closing of the first inlet and opening of the second inlet. To create the trigger, right-click on the **Triggers** folder of the document's tree, and choose **New**. This opens the trigger dialog box shown below. Enter the parameters as shown. This means that when the flow will reach the first sensor (s1), condition detected by the fact that the filling factor (variable **filling**) has reached a value of one (**threshold**) on that sensor, outcomes will be fired.

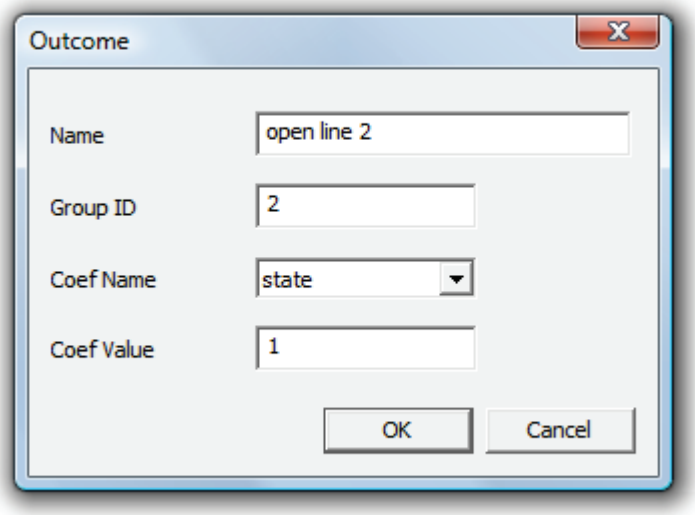


Once a trigger has been defined, outcomes can be created on that trigger by right-clicking the trigger in the document's tree, and choosing **New Outcome**. This opens the following dialog box.



First give a meaningful name to the outcome, such as "close line 1". Then enter the Group ID on which the specified coefficient will be set when the trigger is fired. Here we set the state coefficient of the inlet to zero, meaning the inlet is closed.

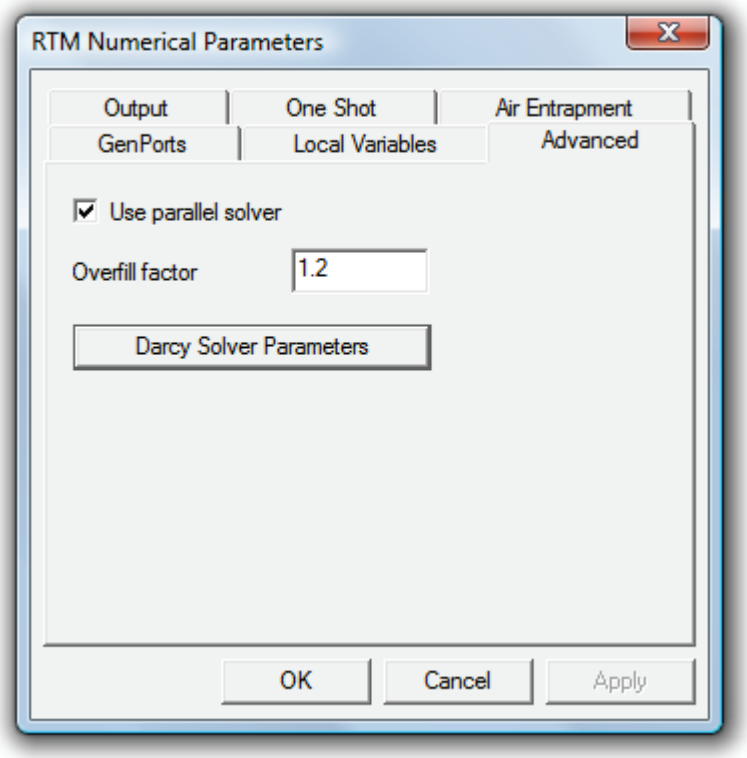
Define another outcome for the activation of the second inlet, as shown below.



Repeat this procedure for the second sensor, so that the second inlet is closed and the third inlet is opened when resin reaches the second sensor.

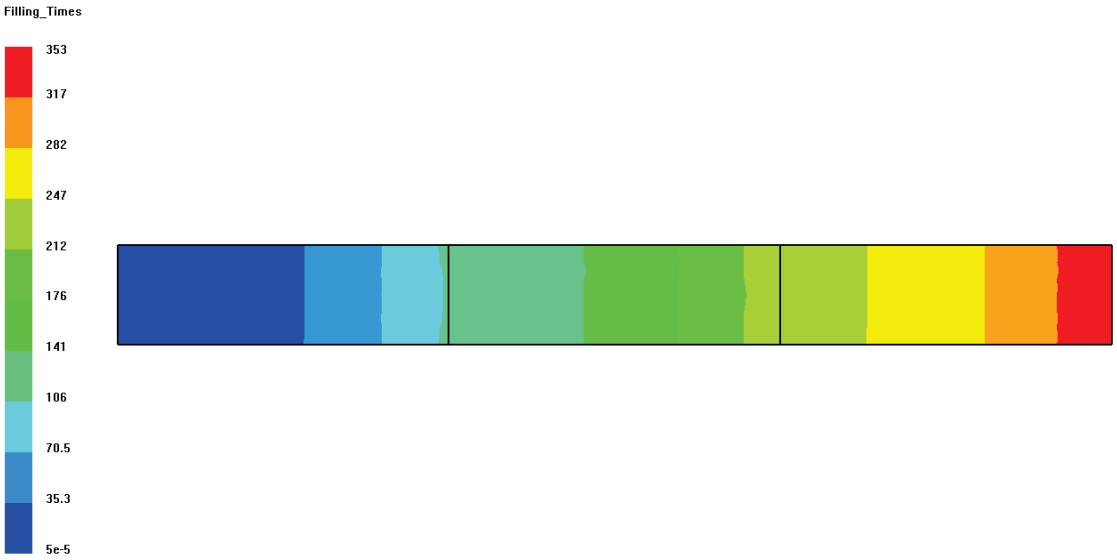
Launching the Simulation and Post-processing

The parallel solver is selected in the *Advanced numerical parameters*.

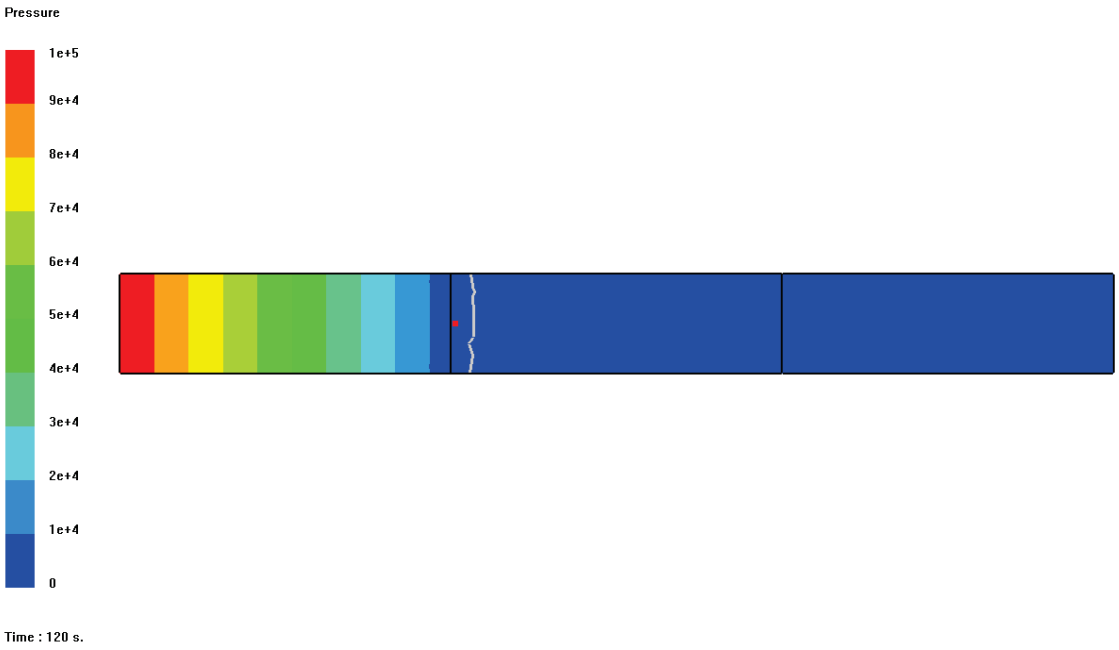


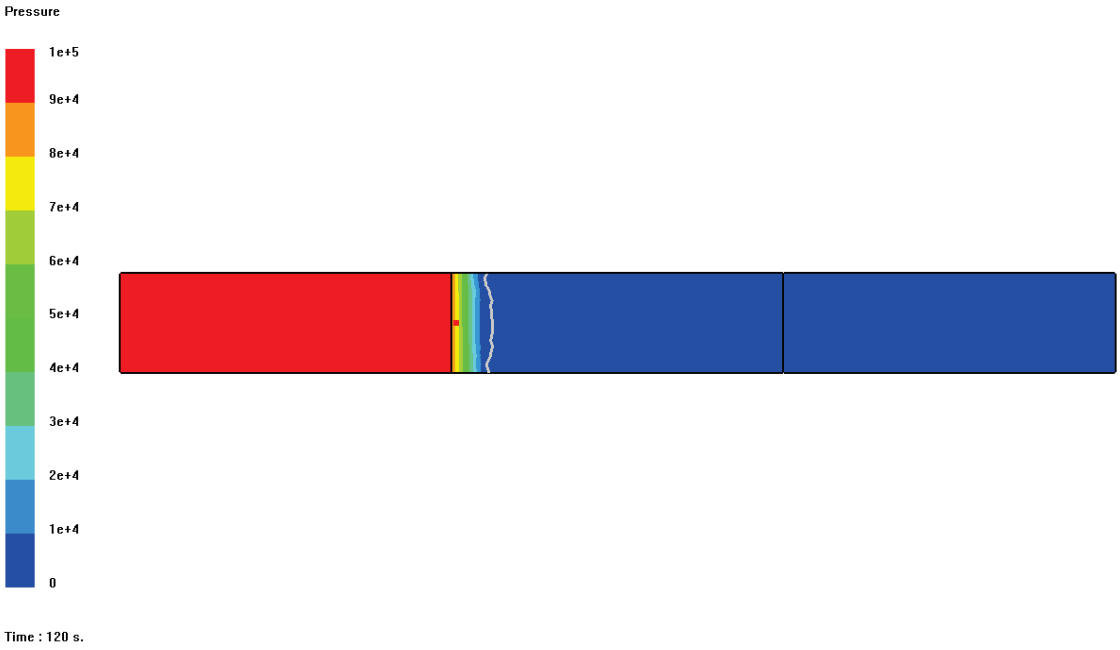
Save the document and launch the simulation. When it is done, push the **Reload Results** button in the **Results** toolbar.

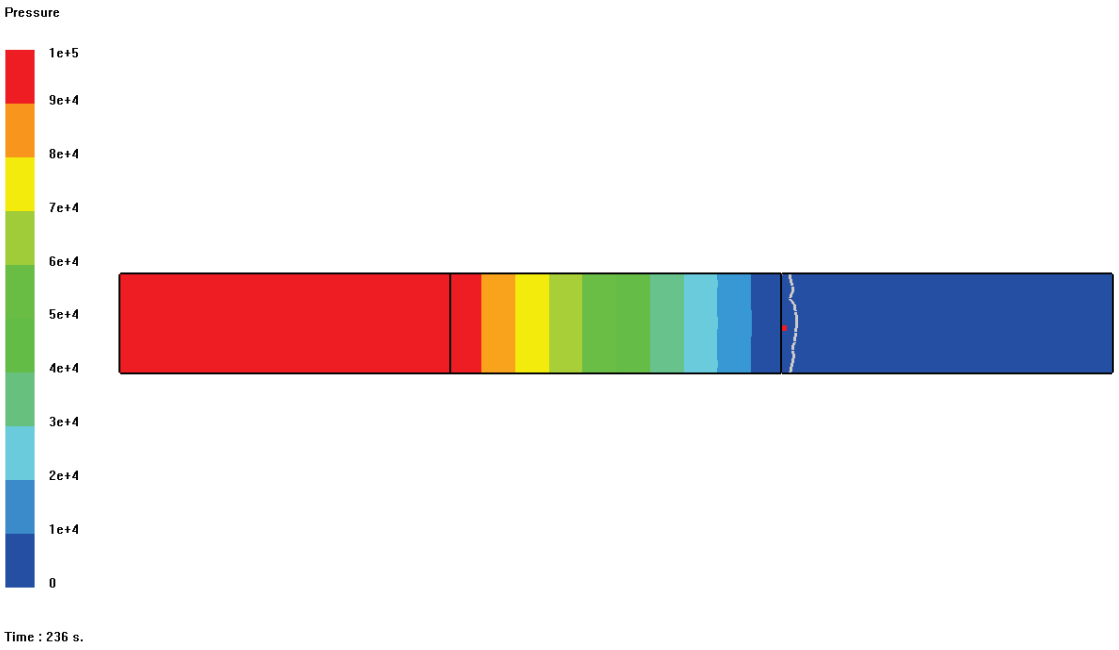
Have a look at the filling steps. The total filling time is 353 seconds.

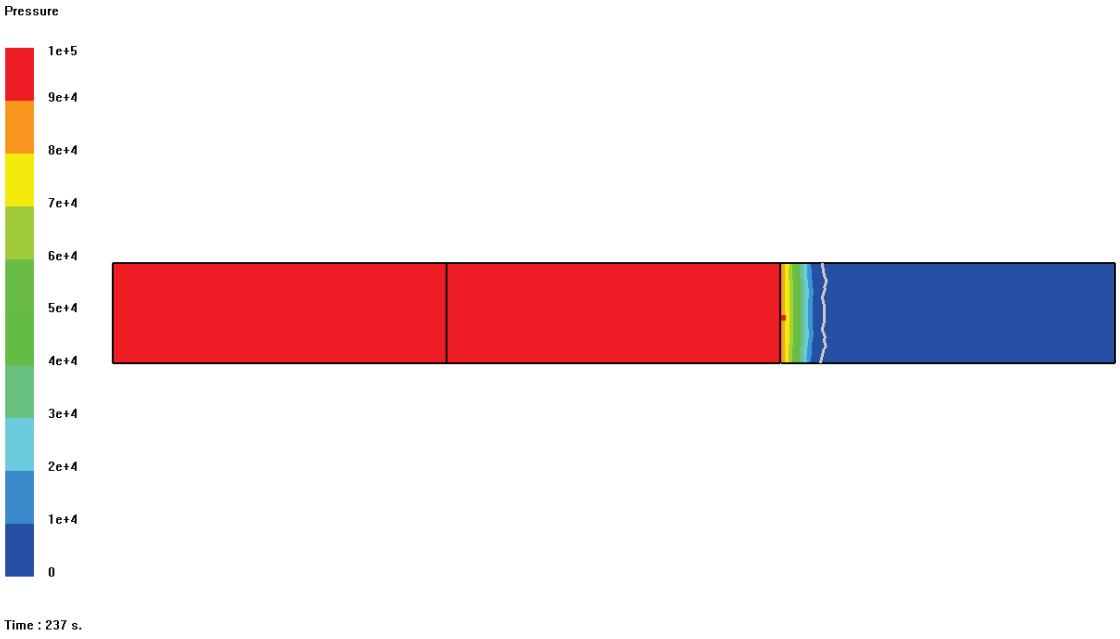


Images below show the pressure field just before and just after the triggers are fired, i.e. when the fill factor reaches a value of one on the sensors. The first trigger is fired around 120 seconds, and the second trigger around 236 seconds. When the first trigger is fired, the pressure to the left of the second injection line becomes uniform, which is normal since the first injection line is closed; meaning that end of the part becomes an impermeable wall. Similar images are also given for the second trigger.




Pressure
1e+5
9e+4
8e+4
7e+4
6e+4
5e+4
4e+4
3e+4
2e+4
1e+4
0
Time : 120 s.


Pressure
1e+5
9e+4
8e+4
7e+4
6e+4
5e+4
4e+4
3e+4
2e+4
1e+4
0
Time : 236 s.



VELOCITY OPTIMIZATION

The following files are used in this example.

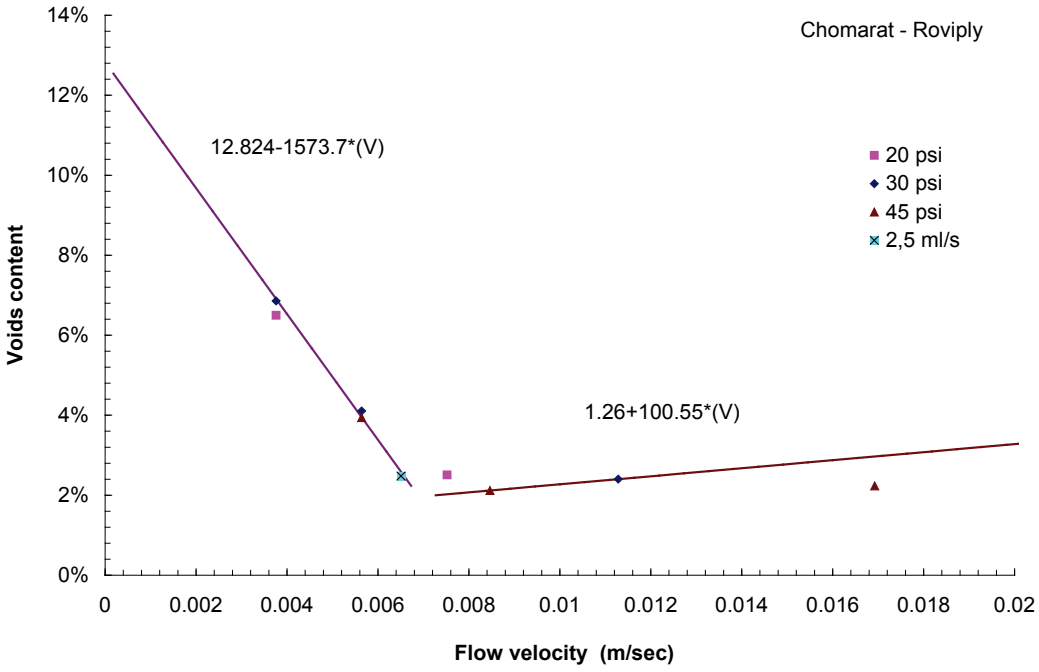
- ***velo_opti_start.unv*** (starting mesh)
- ***velo_opti.dtf + velo_opti.unv*** (solution)

Objectives

The goal of this tutorial is to show how to use the velocity optimization option, in order to minimize the final void content in a part.

Process and Numerical Parameters

The following assumes the user already has from experimental measurements, relations for the micro and macro void content as a function of the flow velocity. The relations used in this example are shown below. The curve with the negative slope is the macro void function, the other one is the micro void function. Looking at these curves, we can see that the optimal void content is around 2%.



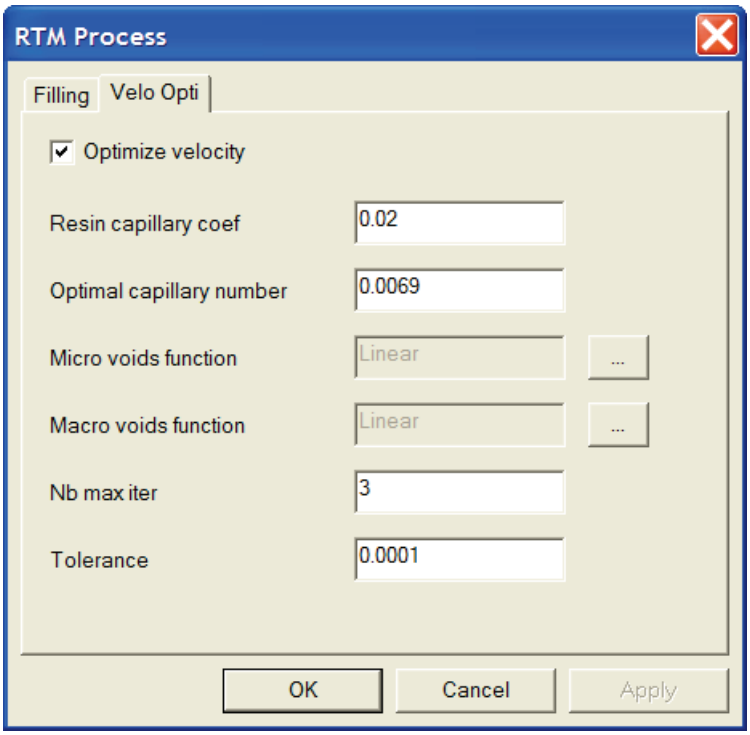
Note that normally we would work with curves that are functions of the capillary number. However in this case since the resin viscosity (0.02 Pa.s) is the same as the capillary coefficient, the capillary number actually reduces to the resin velocity.

Begin by creating a new **RTM** simulation. The most important parameters for velocity optimization are located in the **Velo Opti** tab of the **Process** dialog box. Double-click on the **Process** item in the document's tree to open the process dialog box.

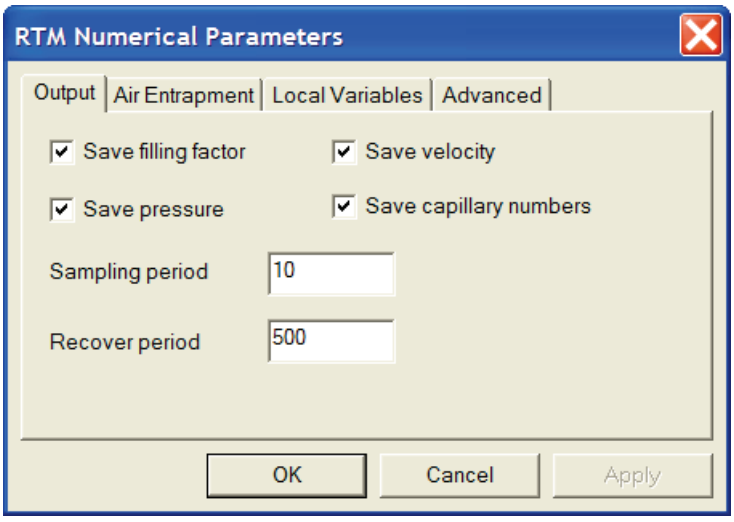
Enter the following values in the **Velo Opti** tab:

- Optimize velocity checked
- Resin capillary coefficient: 0.02
- Optimal capillary number: 0.0069
- Micro voids function: linear with A = 100.5, B = 1.27
- Macro voids function: linear with A = -1574, B = 12.82
- Nb max iter: 3
- Tolerance: 1e-4

This is shown below.



The next step is to tell PAM-RTM to save the results files related to velocity optimization: capillary numbers, micro voids, macro voids, and a file containing the sum of micro and macro void values. The saving of these 4 files is controlled by a single option: **save capillary numbers** in the **Output** tab of the **Numerical parameters** dialog box.



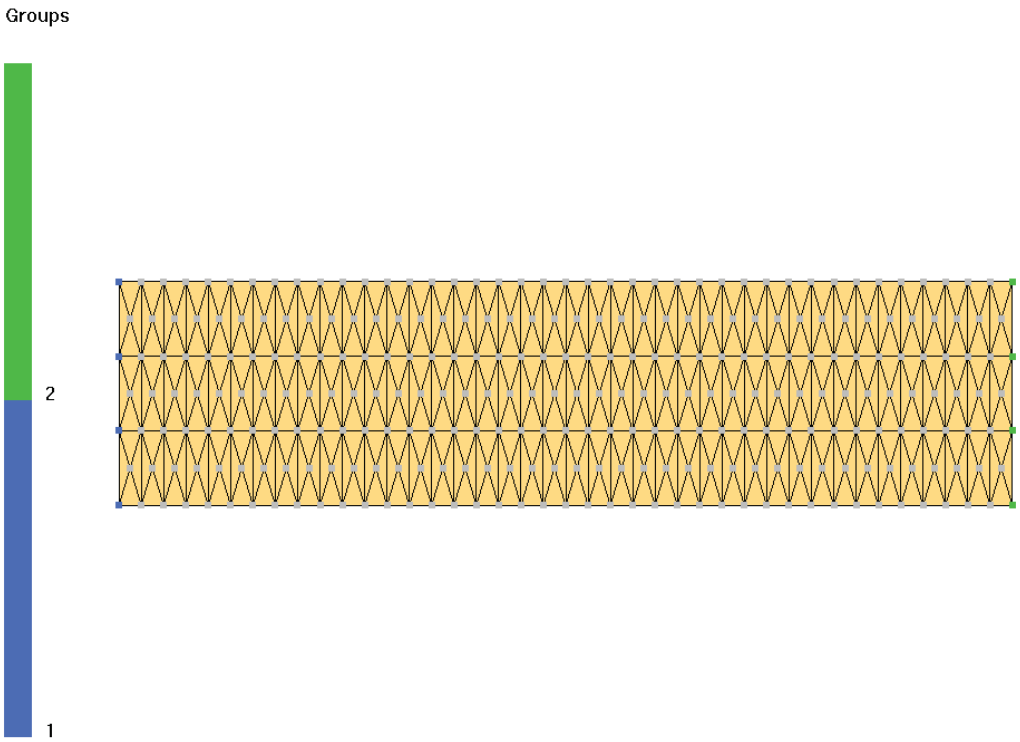
Material Properties

Enter the following material and zone properties:

- viscosity: 0.02 Pa.s
- Permeability: k1 = k2 = k3 = 1e-9 m^2
- Porosity: 0.5
- Thickness: 0.005 m

Boundary Conditions

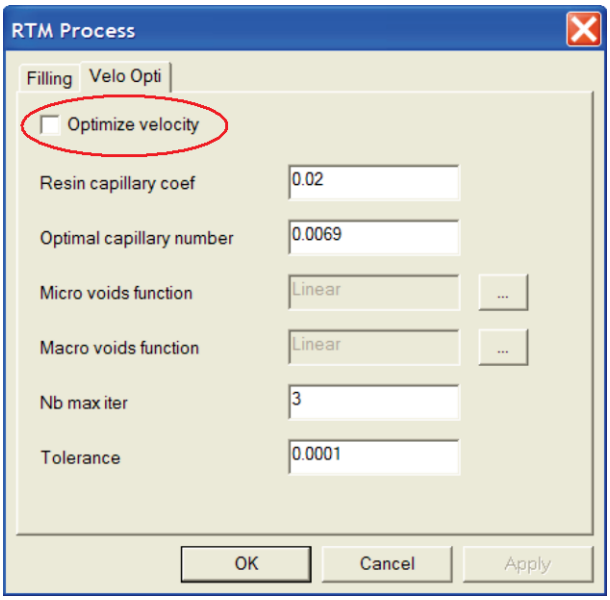
The provided mesh already contains 2 groups, as shown below. Group 1 is used as the inlet, and group 2 as the outlet. Define a pressure boundary condition of 0.1 bar (10 000 Pa) on group 1. Define a vent boundary condition with zero pressure on group 2.



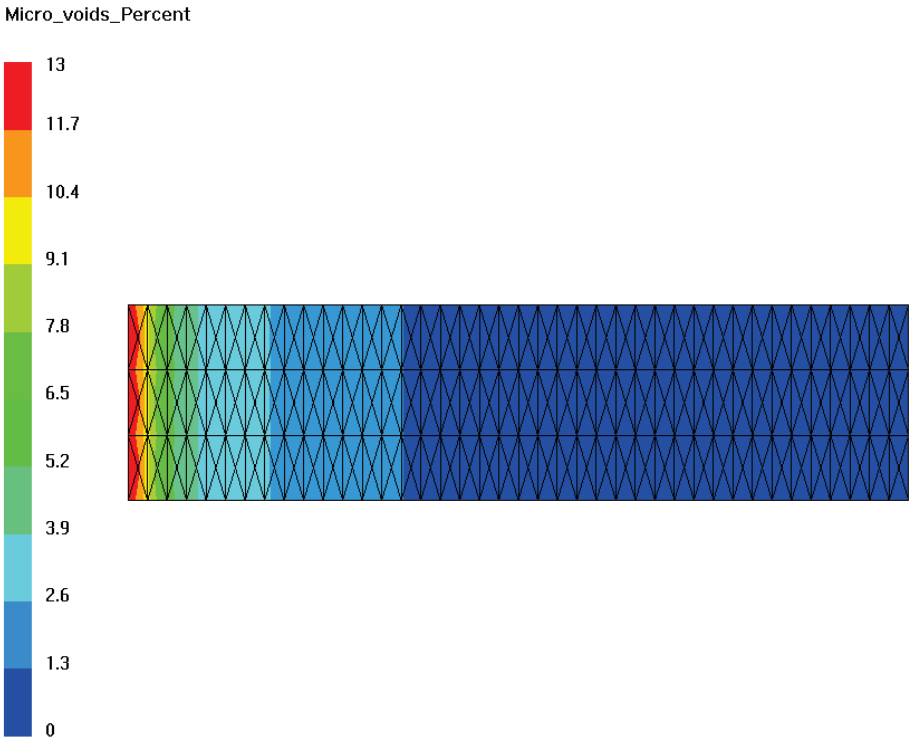
Launching the Simulation and Post-processing

We will run 2 simulations in this tutorial: the first one *without* the optimize velocity option, the second one *with* the option, to better understand its effect. For the first case, simply uncheck **optimize velocity** in the **Velo Opti** tab of the **Process** parameters, leaving all the other parameters the same. It is important to understand that it makes sense to run a simulation with all the parameters in the **Velo Opti** tab defined, but without the **optimize velocity** option active. This is useful to visualize the void content at the end of the injection that you would have if you didn't optimize velocity.

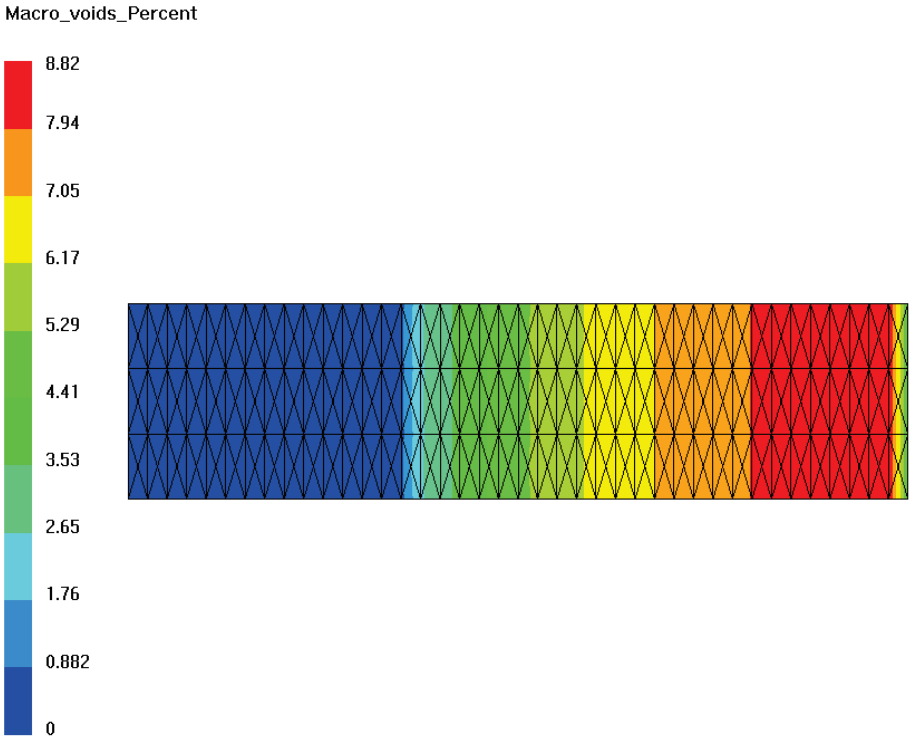
Save the document with **File->Save**, giving it a name so you can remember that the case was run without the optimization, then launch the simulation. When the simulation is done, load all the results files in a single click by pushing the **Reload results** button in the main toolbar. You should have the following.



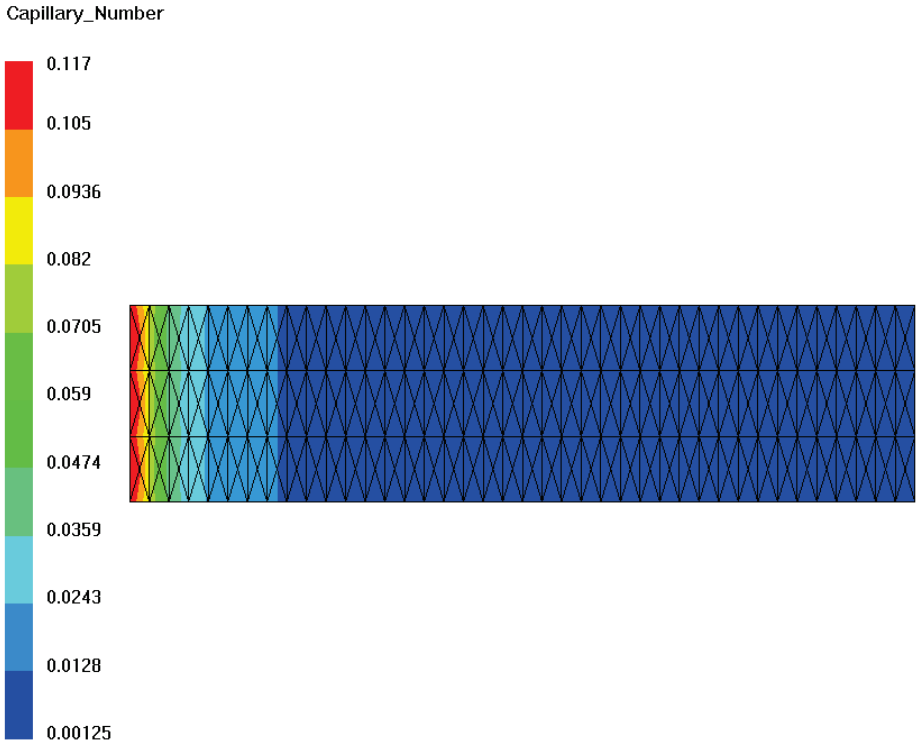
For the first case, uncheck "optimize velocity"



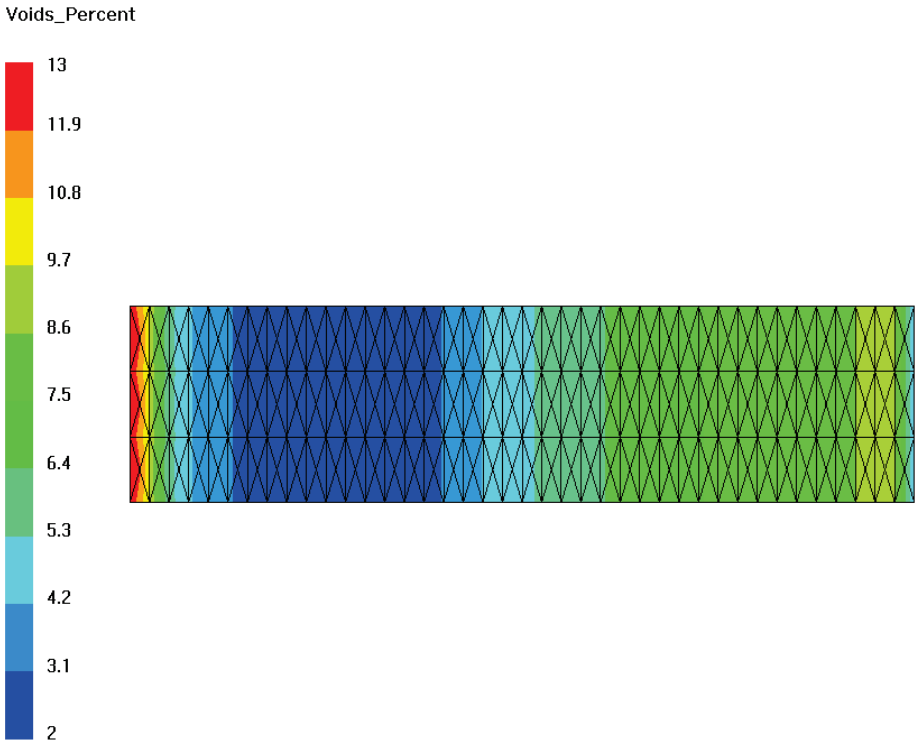
Micro voids percent at the end of filling for the first case (no optimization).



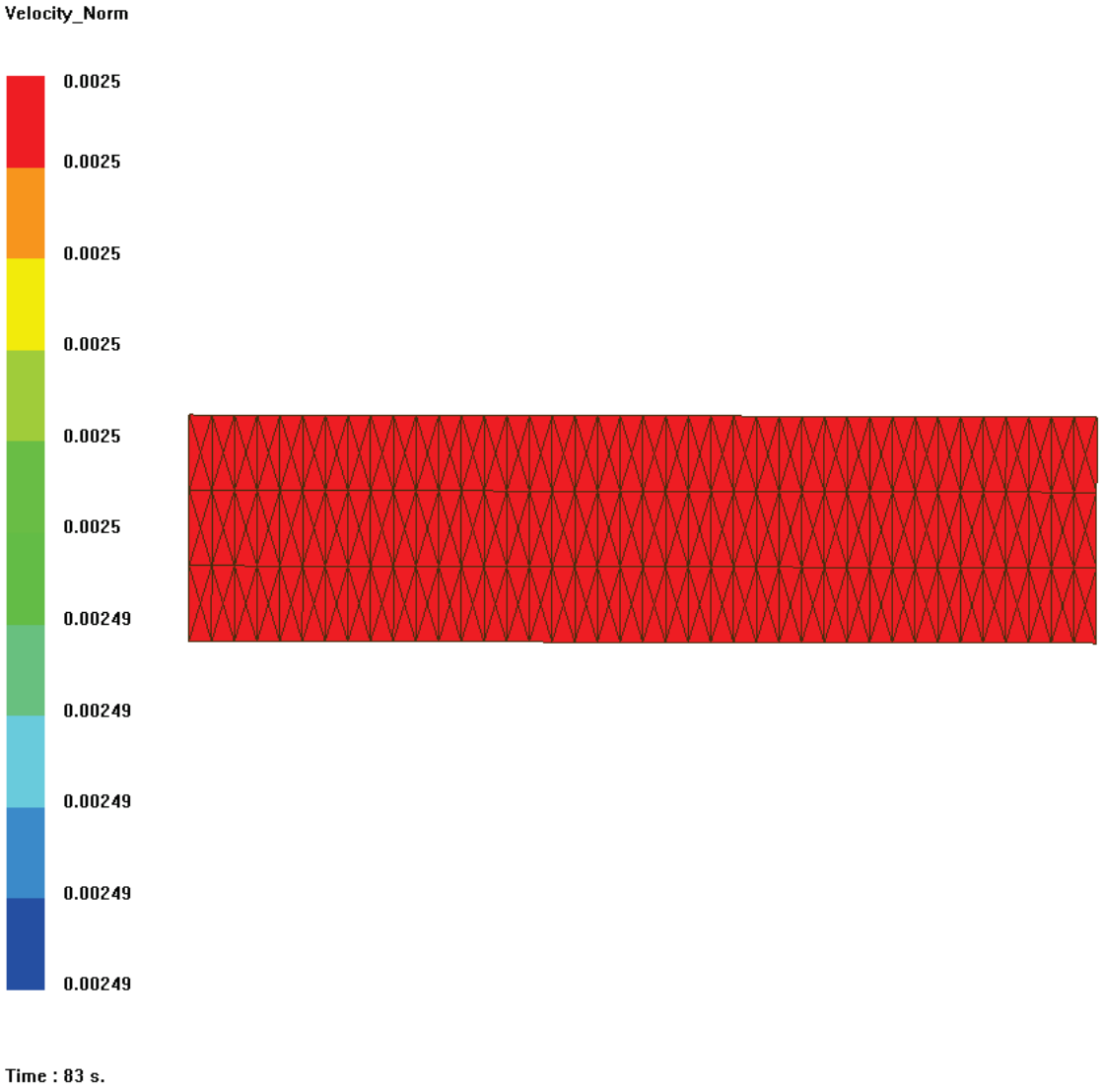
Macro voids percent at the end of filling without optimization.



Capillary number



Total voids percent (micro + macro voids)



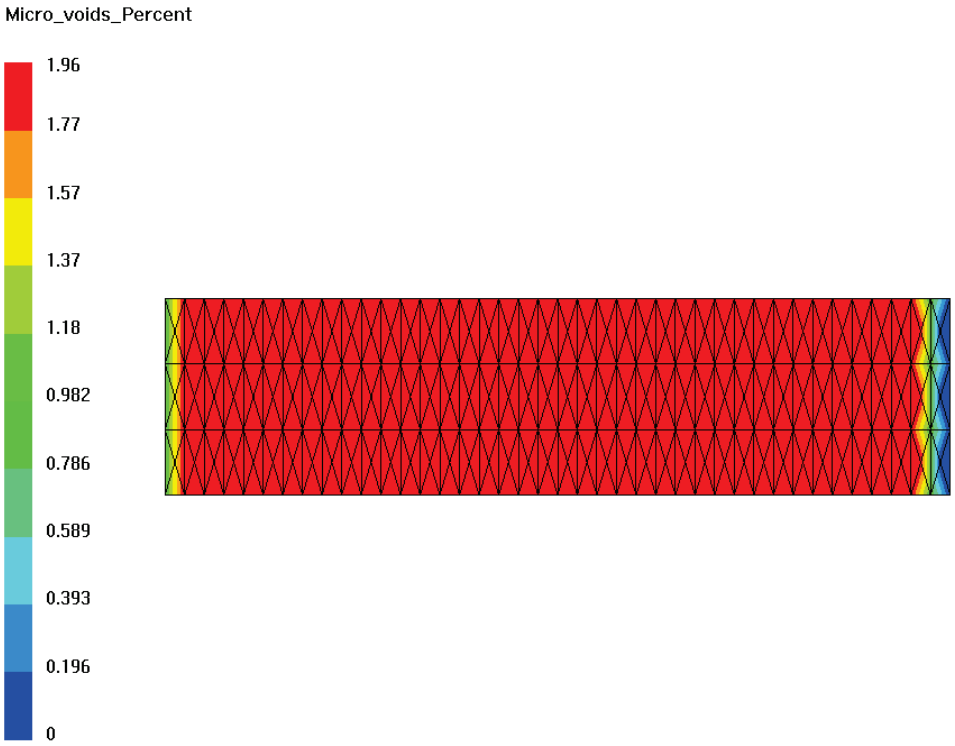
Velocity field at the end of filling (v = 2.5e-3 m/s)

It is important to understand that the micro voids, macro voids and capillary number results are non-transient (single step) fields. This is because the model relates the void content to the velocity at the exact time when the resin front touches an element, and it is assumed that void content doesn't change for the rest of the simulation once it is set on an element.

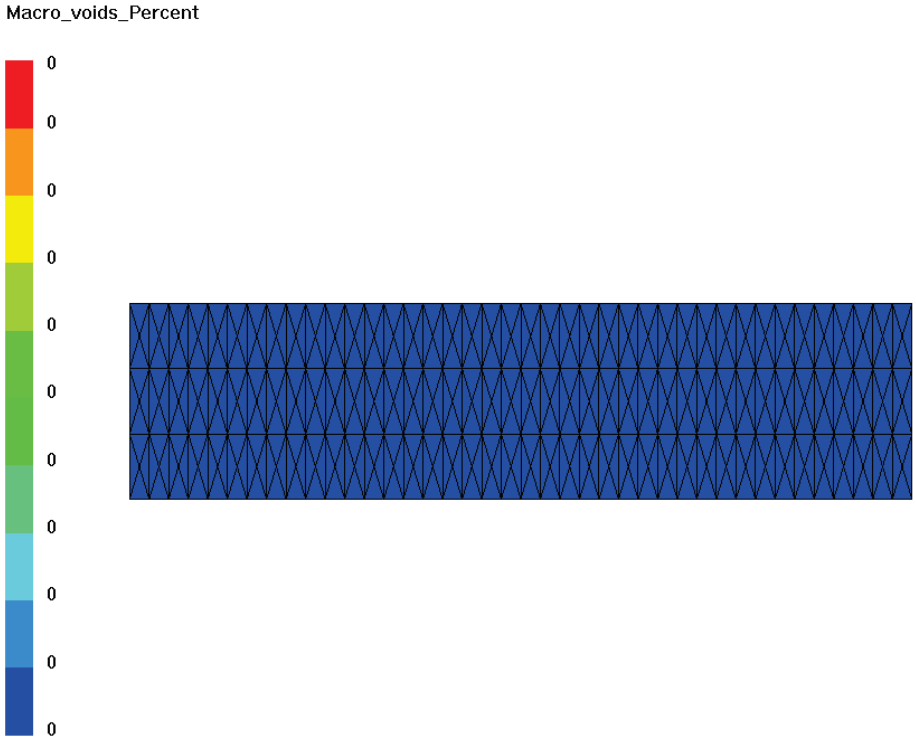
For the second case, reactivate the **optimize velocity** option. Save the file with **Save As**, with a new name so you can remember that the case was run with the optimize option. When the simulation is done, push the **Reload results** button. You should have the following. Notice that the micro voids result of 1.96% matches the value expected from the curves shown at the beginning of this tutorial.

For this simple case, the macro voids results remain always zero. This is because with this void model, for a given velocity, it is not possible to have micro and macro voids at the same time. This implies that if an element has a non-zero micro void value, its

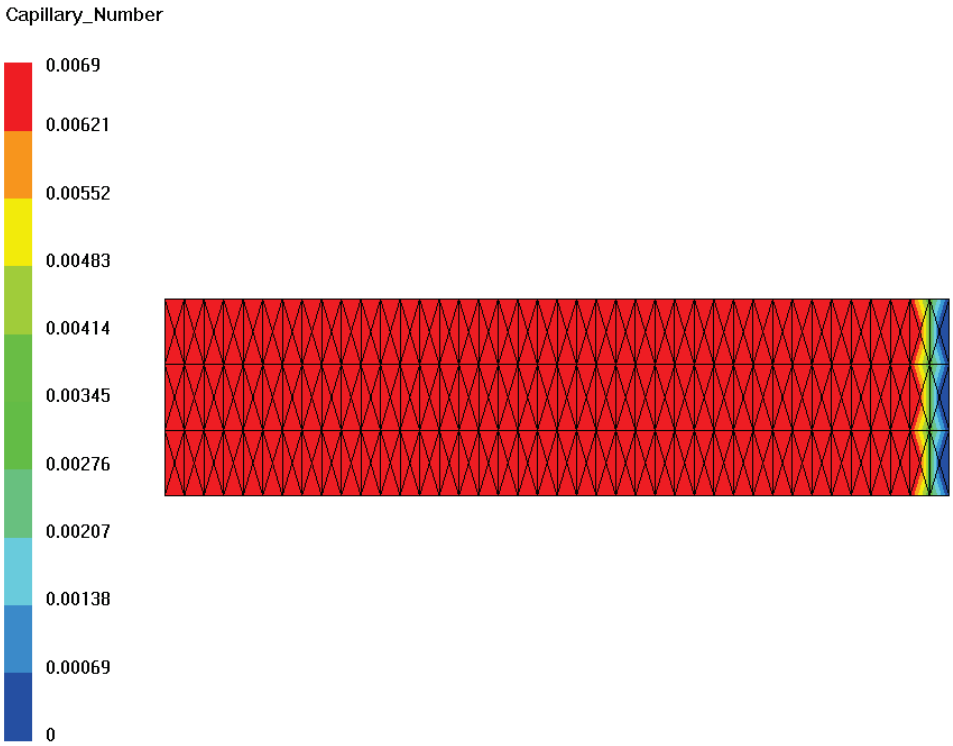
macro void value will be zero, and vice versa. On this case, the velocity optimization algorithm always converges to a velocity value slightly in the micro voids area, leading to a macro void value of zero. On more complex cases, the optimal void values would be scattered between the micro and macro void results. Finally notice that the velocity at the end of injection (6.9e-3 m/s) is much higher than the previous case (2.5e-3 m/s). This is because PAM-RTM had to convert the pressure imposed inlet to a flow rate imposed inlet, to be able to reach the optimal velocity.



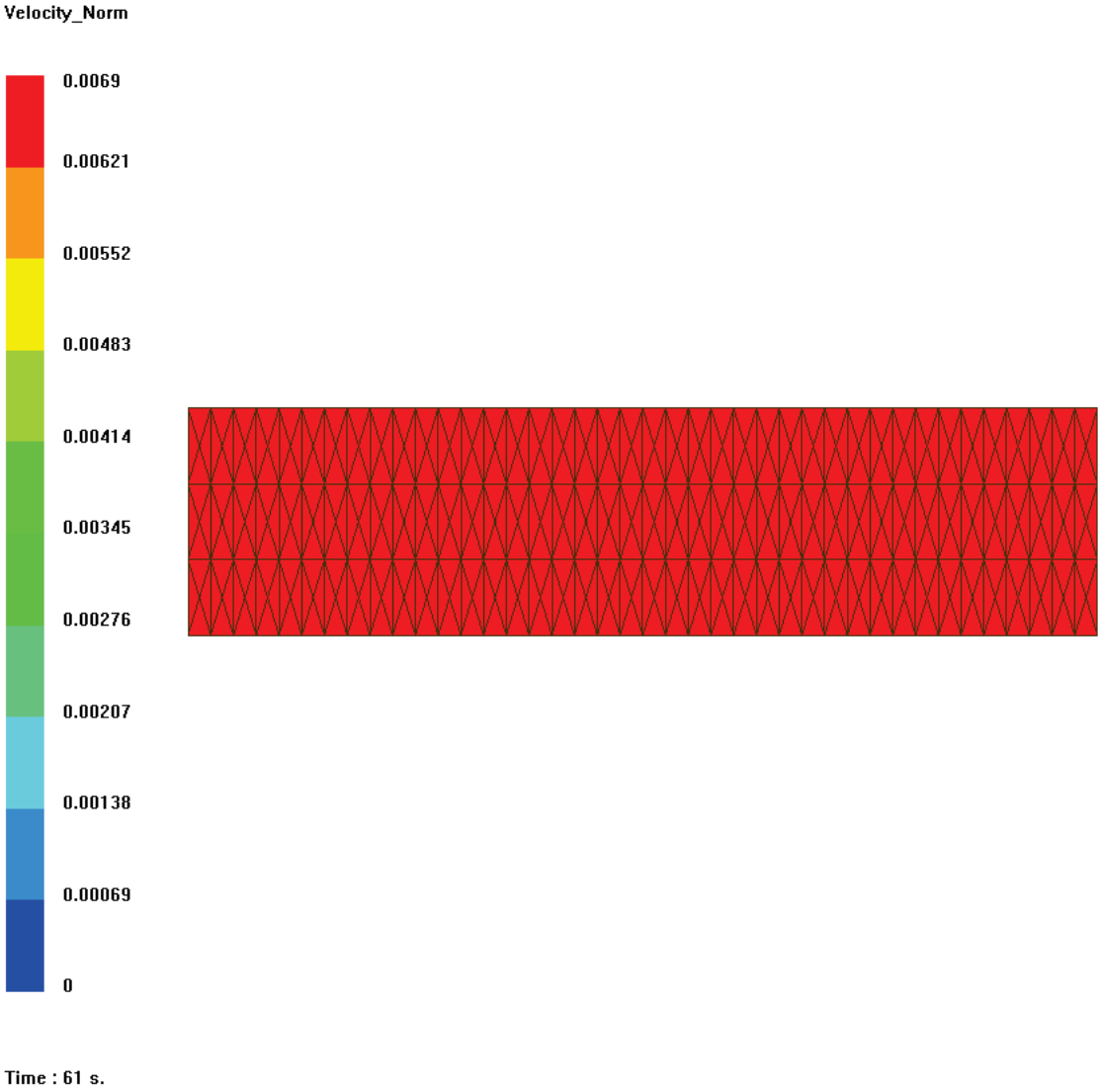
Micro voids result with optimization



Macro voids result with optimization



Capillary number with optimization



Velocity at the end of filling (v = 6.9e-3 m/s)

COMPRESSION RTM

The following files are used in this example:

- *crtm_start.unv* (starting mesh);
- *crtm_rtm.dtf* + *crm_rtm.unv* + *crtm.dtf* + *crtm.unv* (solution).

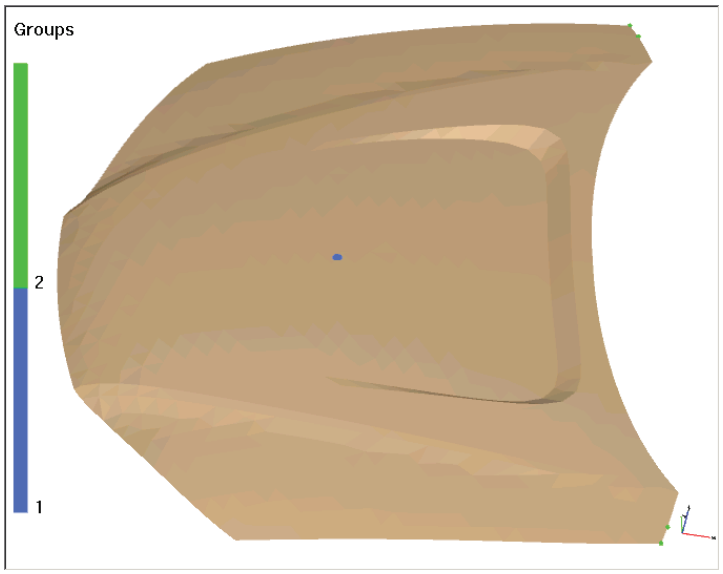
Objective

The objective of this tutorial is to show how to define a compression RTM data set-up. Compression RTM module is made to simulate the kind of process in which a compression of the reinforcement is used to push the resin inside the cavity.

This tutorial is limited to a case where only one tool is in movement, but Compression RTM module can treat more complex kinematics.

Geometry and Boundary Conditions

The part is a hood made of a unique zone (*zone 2*), which is injected from a single point in the center of the part (*group 1*), with two vents (*group 2*) at the corners of the part.



Groups

Two simulations will be carried out to obtain this result:

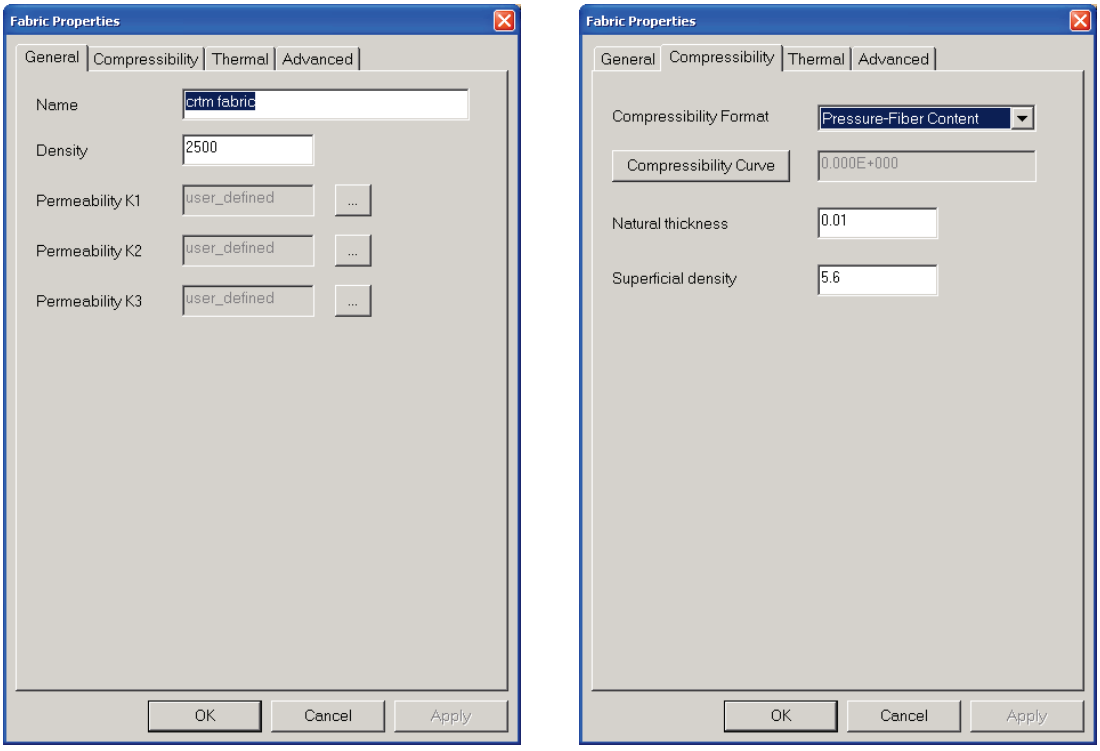
- standard RTM injection simulation with a set thickness , which is the final part thickness objective calculated so that fiber content of the part is 50%, to determine the volume of resin to inject;
- compression RTM simulation using this resin volume.

Material Characteristics

Resin viscosity will be set constant equal to default resin viscosity: 0.1Pa.s

The reinforcement is created with the following characteristics required for Compression RTM set-up and is saved in the database.

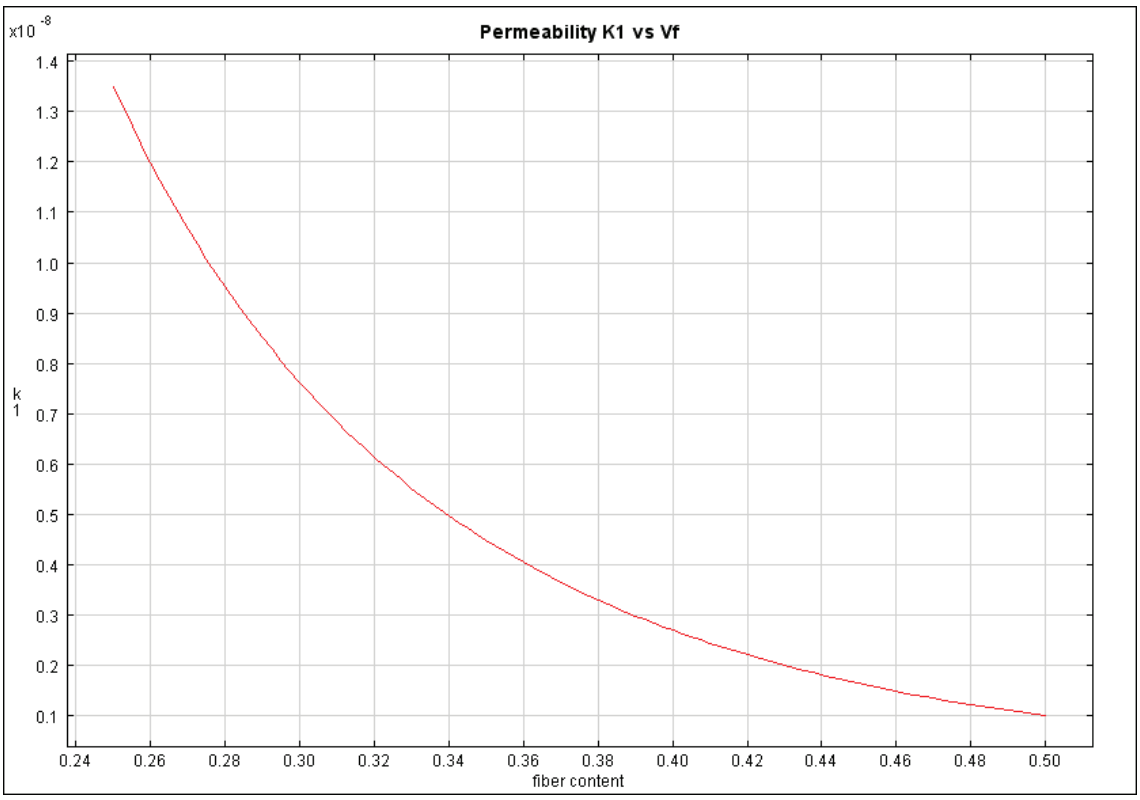
In the case of Compression RTM, permeability is a function of fiber content like in the VARI case. But unlike VARI, compressibility curve and natural thickness are not used, as thickness of the cavity is set by the gap between the two tools. Fiber content of each zone will be computed from this thickness, density and superficial density.



Reinforcement characteristics

Permeability function of fiber content is set isotropic and is defined with the following formula.

x : fiber content, f(x) : k1, 2e-9*((1-x)^3)/x^2



Permeability curve

This material is added to the material database so that it can be imported in next case.

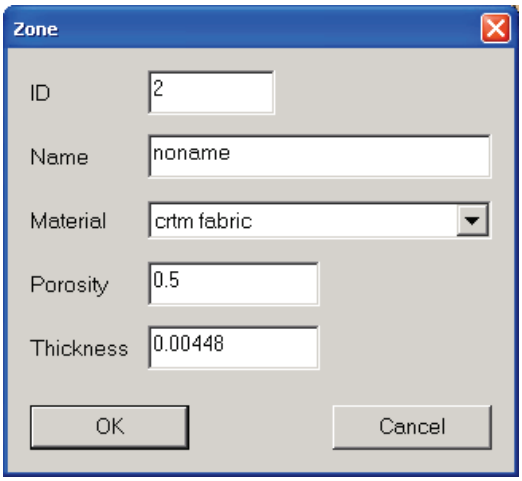
RTM Injection

Data Set-up

An RTM injection case is created; the mesh *crtm_start.unv* is imported.

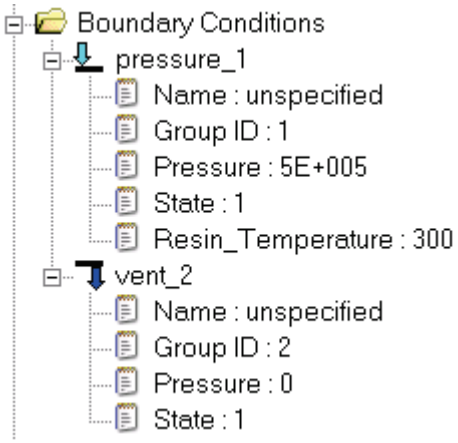
The reinforcement characteristics are defined as seen before.

The objective for final fiber content is 50%. The thickness is computed from this thickness; it is equal to 4.48mm (=5.6/(2500*0.5)).



Zone definition

Injection pressure is set to 5 bars on group 1, and the vent pressure is set to zero on group 2. The vents are opened during the complete process.



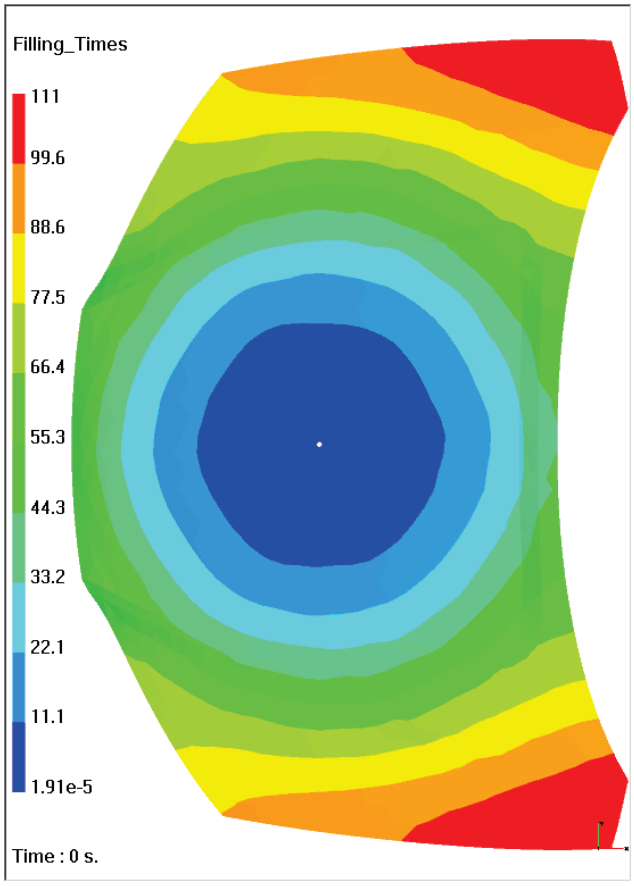
Boundary condition definition

Post-treatment

The filling time is 111s, and the injected volume is equal to 3.13 liters. This volume will be used in the compression RTM set-up.

```
Filling time : 1.10808E+002 s

Injected resin volume : 3.13289E-003 m3
Lost resin volume : 2.72344E-006 m3
```

Log file - Injected volume

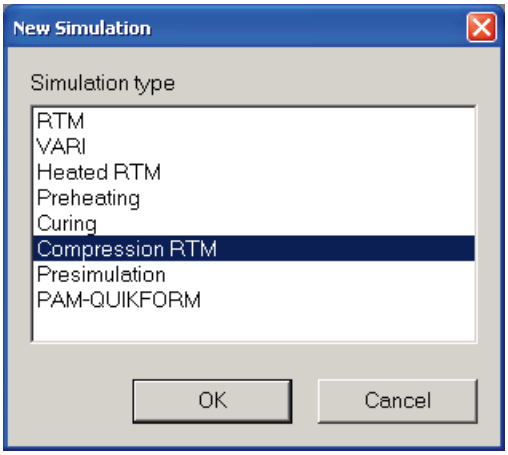


Filling time

Compression RTM Injection

Data Set-up

A new data set-up of type Compression RTM is created.



Compression RTM set-up creation

The following assumptions are made for CRTM simulation in Pam-Rtm:

- 2D mesh is used, and thickness is a variable of each element;
- reinforcement always fills complete the mold cavity, and there is no surface channel on top of the reinforcement;
- distance between the fixed tool and the moving tool is the thickness of each element.

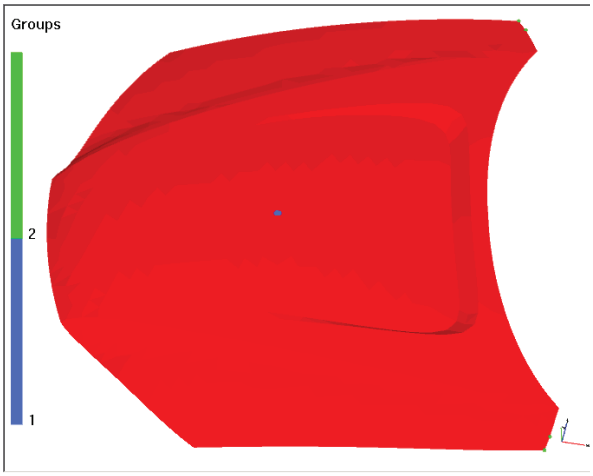
The mesh needs to be imported from the previous case.

The reinforcement material is imported from the material database.

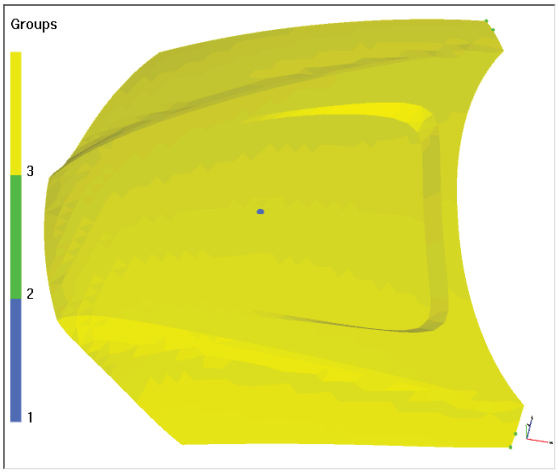
The pressure and vent boundary conditions need to be redefined.

Compression Boundary Condition

In both case, it is necessary to create a group on which compression will be defined. This group is a group of faces, which will contain all the faces of the model since compression is defined on the whole surface. This group will represent the tool that will move during compression.



Face selection



Group created

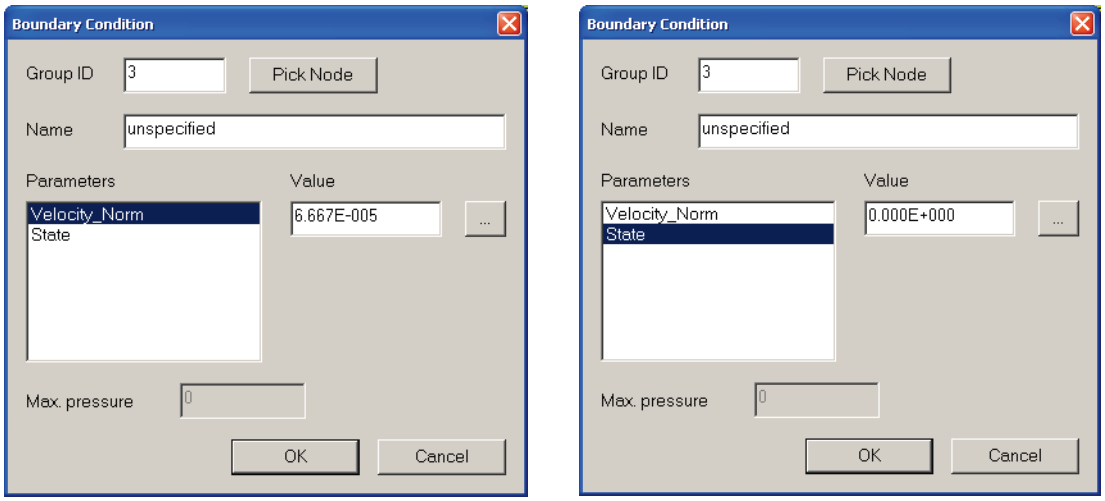
Compression boundary condition and compression process parameters

The compression process set-up will involve two modifications in the set-up:

- in the process parameters will be defined; the compression direction and the mold opening, which is the gap ;
- in the boundary condition will be defined; the closing velocity of the tool and the timing of the closing (start/stop state).

The group that closes as well as the closing velocity are defined in the *Compression* boundary condition. The closing of the mold is controlled with a trigger.

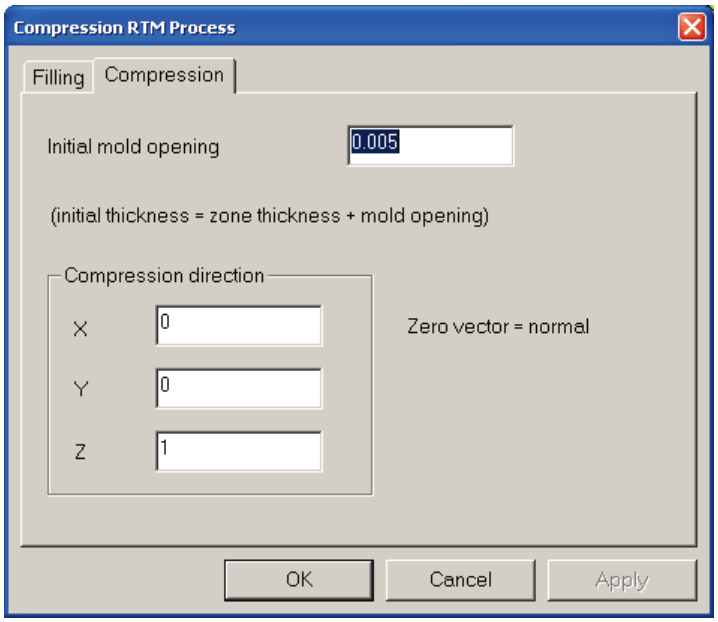
- compression velocity is equal to 0.4mm/min=$6.67.10^{-6}$m/s;
- *state* is set to 0 initially, since this boundary condition will be activated using a *trigger*. Closing of the mold will start when enough resin has been injected.



Compression boundary condition

Other compression process parameters are defined in the *Process* dialog box in the *Compression RTM* tab

- mold opening is set to 5mm;
- compression direction is set to +Z vector



Compression process parameters

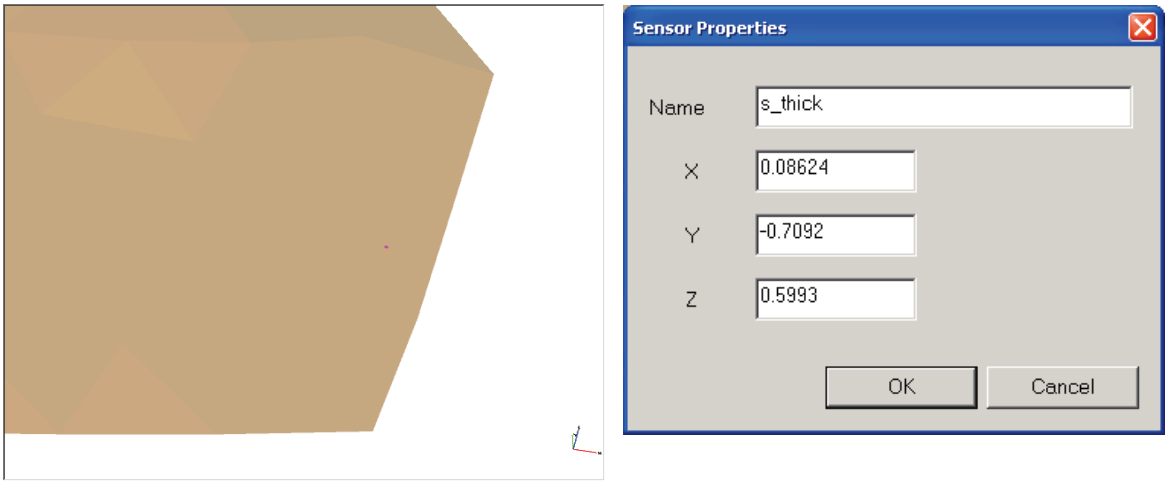
Trigger Definition

The compression boundary condition is controlled by one trigger:

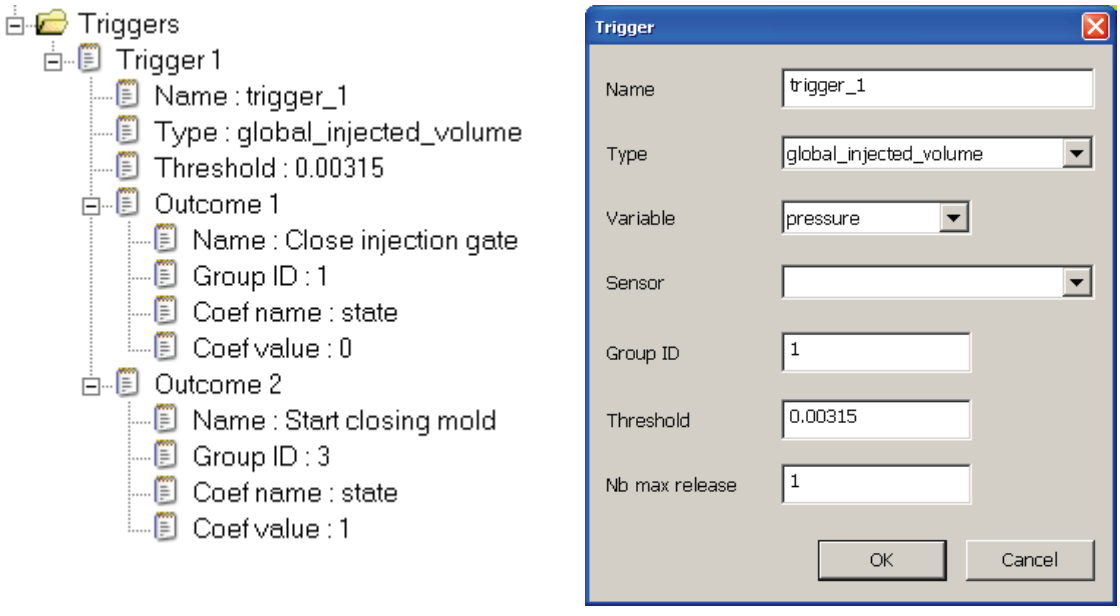
- volume trigger that will stop injection and start compression when the needed resin volume has been injected ; the volume is set to 3.16l to ensure enough resin is injected,

The trigger is a volume trigger that does not require the use of a sensor.

A sensor is created that can be used for post-treatment.



Sensor creation



Triggers definition

Zone Definition

Zone parameters set are thickness and porosity. In the case of CRTM, thickness is the final thickness of the part, that is when the mold is closed. Porosity parameter is not used and is computed from thickness value during the process in the same way as it is computed for VARI process:

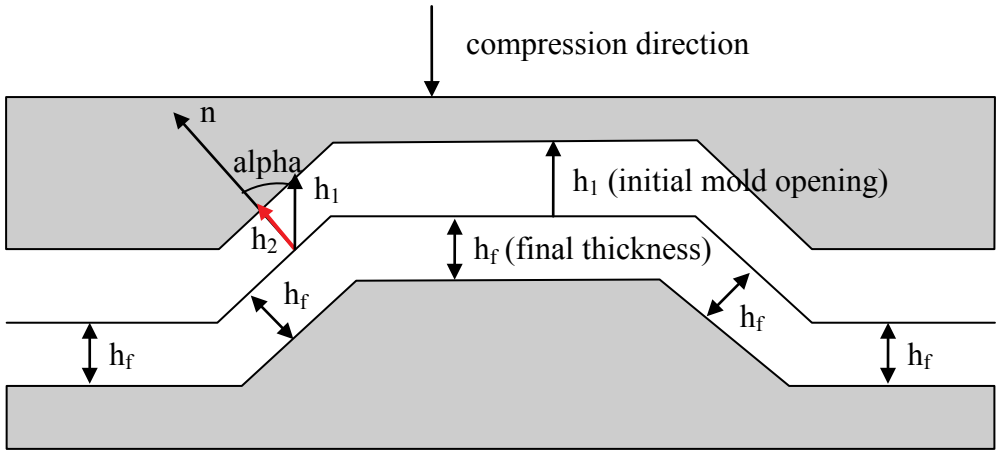
fiber content = 1 – porosity = superficial density / (density * thickness)

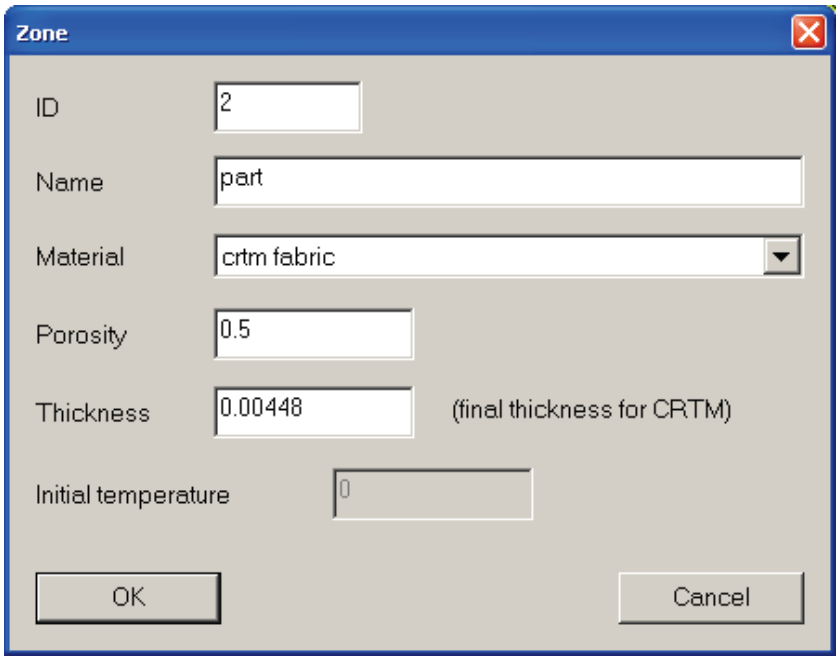
Initial thickness for each element is computed as

initial thickness = final thickness + mold opening * cos(alpha)

where alpha is the angle between compression direction and element normal as shown on picture below.

This formula is also used to compute thickness of the reinforcement at any time during compression.





Zone definition

Post-Treatment

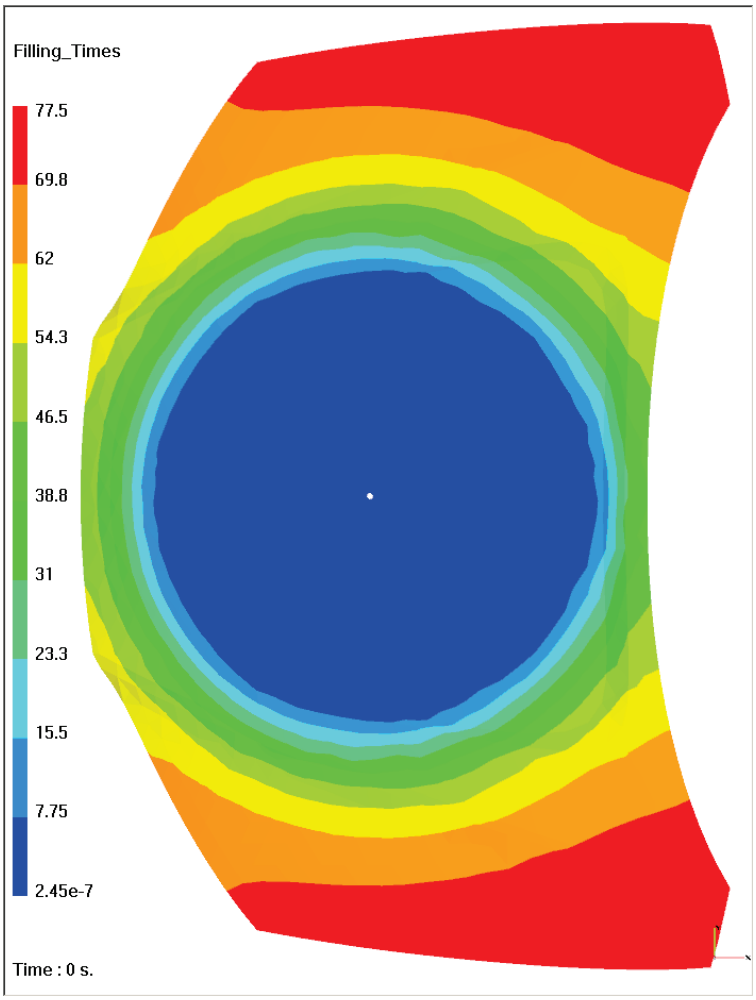
It can be verified in the log file that compression starts after 2.7s,

```
=> 849   time=2.74039E+000  filled=911  +1   36 %
Fired trigger 'trigger_1'
=> 850   time=2.74576E+000  filled=912  +1   36 %
```

and that injected volume is 3.16l.

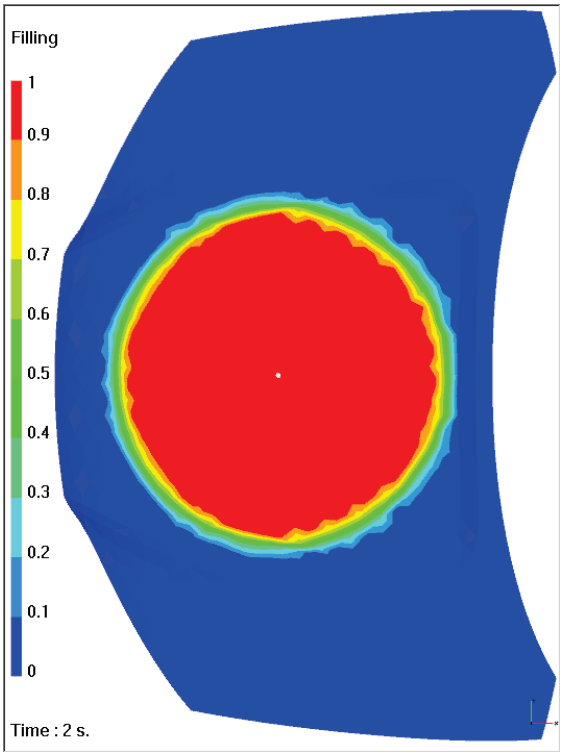
```
=> 2388  time=7.75400E+001  filled=2511 +1   100 %

Injected resin volume : 3.16158E-003 m3
Lost resin volume : 4.18250E-007 m3
```

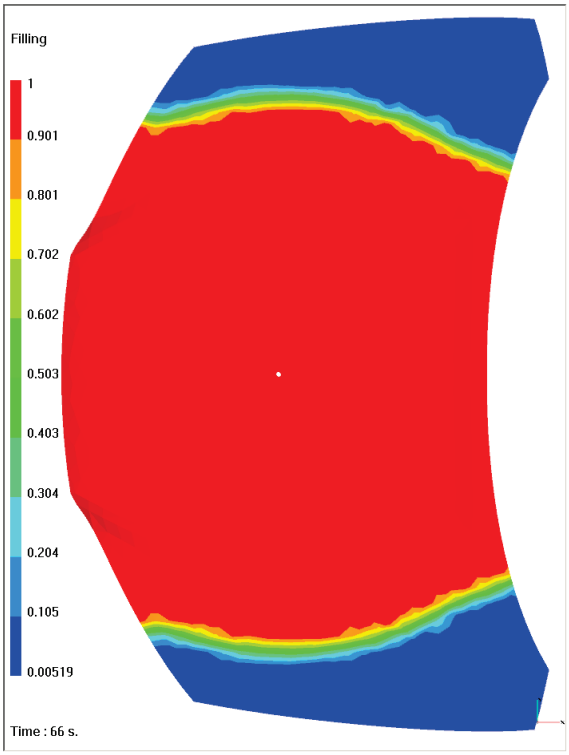
Filling time is 77.5s.



Filling time

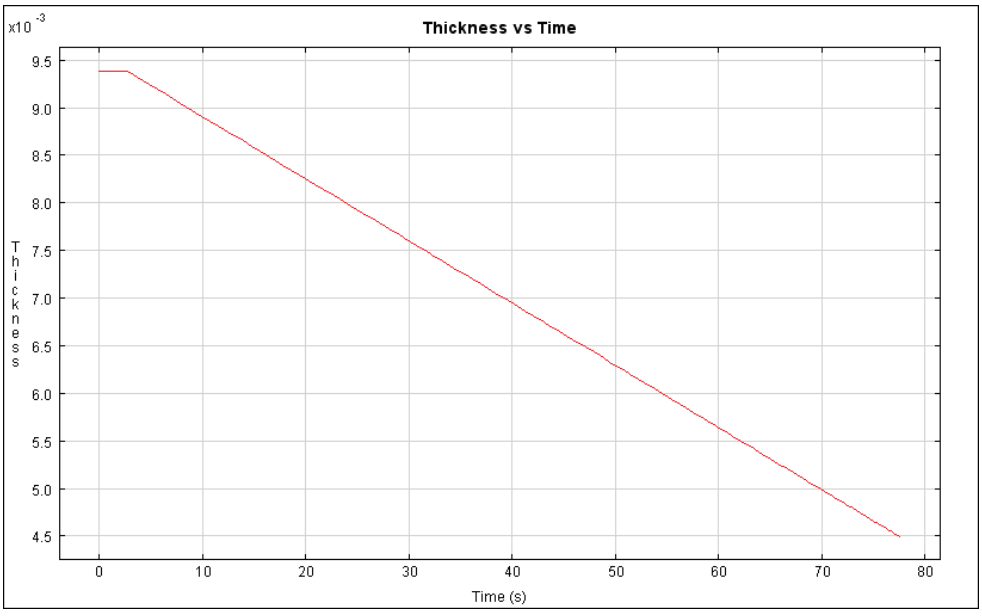
Flow front position is visualized at the end of injection at 2.75s, and during compression.





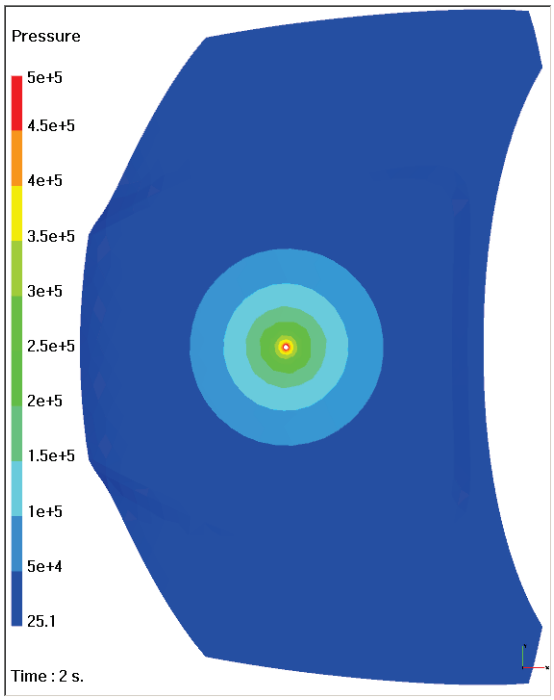
End of injection ***During compression***

Thickness variation at the sensor position is plotted.

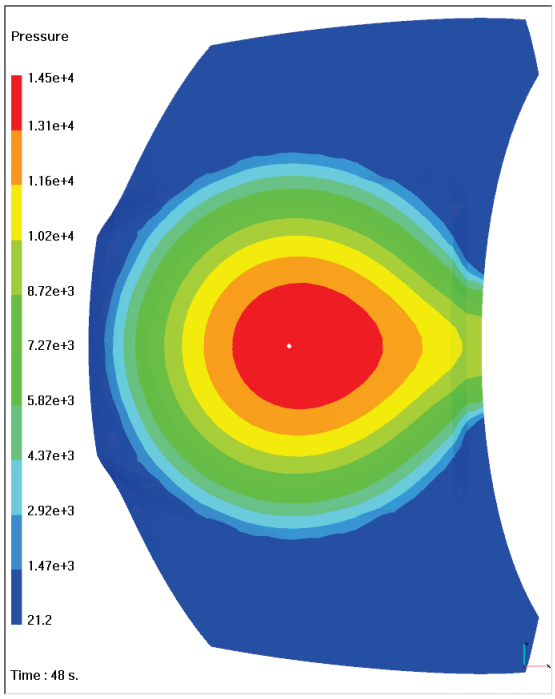


Sensor thickness

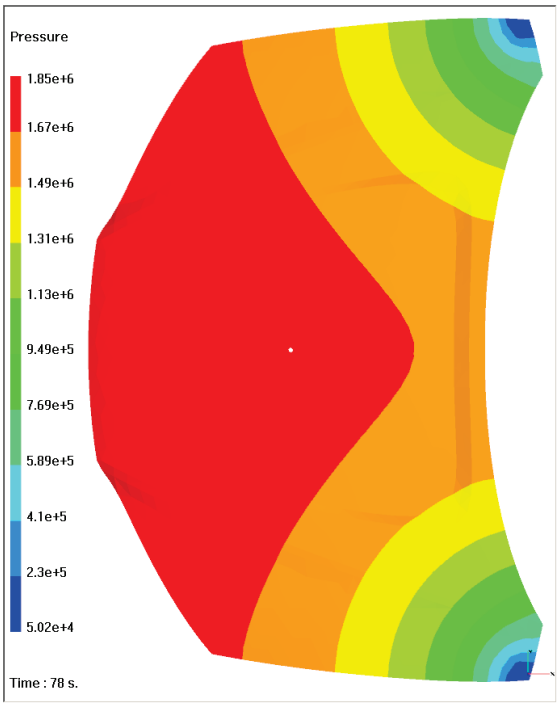
Pressure position is visualized at the end of injection, during compression, and at the end of compression. Pressure at the end of compression is higher than the injection pressure



End of injection



During compression



End of injection

Conclusion

This tutorial has shown how to model CRTM process in which impregnation of the part is divided in two phases:

- injection phase where reinforcement thickness is larger than final part thickness so that permeability is increased;
- resin is pushed inside the part by compression.

LOCAL PERMEABILITY FROM DRAPING RESULTS

The following files are used in this example.

- ***drape.dsy*** (**PAM-FORM™** result file, 1 ply)
- ***drape_start.unv*** (injection mesh file)

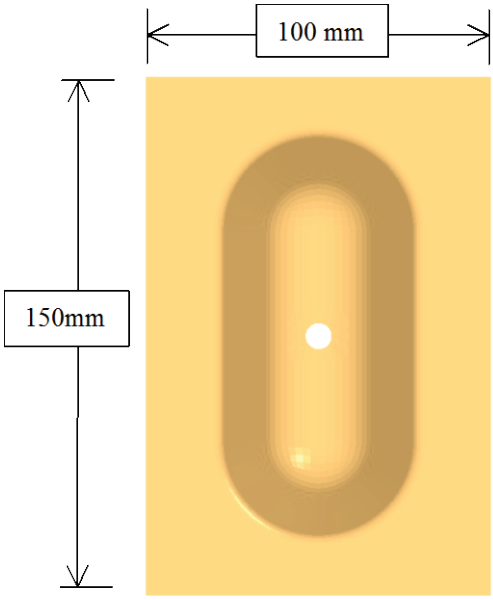
Introduction

The filling simulation in **PAM-RTM™** is macroscopic based on Darcy's law, where the permeability values of the fiber preform play a very important role. During the preforming process, such as draping, the local permeability of the preform may change due to the local fiber shearing, slipping, nesting, etc. This tutorial demonstrates the complete procedure for using draping results in a **PAM-RTM™** filling simulation. In summary, it is carried out in the following steps:

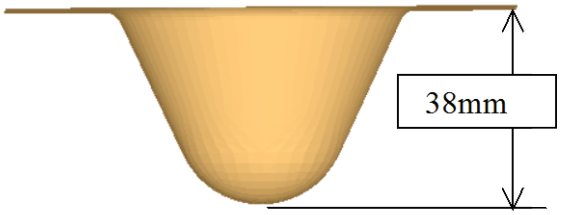
- ***Import draping results in PAM-RTM™***: imports the draped plies generated by the draping software in the current document.
- ***Map draping results***: projects draped plies on the injection mesh. The goal of this step is to calculate the geometrical correspondence between an element of the injection mesh and elements of the draped plies meshes.
- ***Local permeability calculation***: generate the local permeability and porosity distribution on the injection mesh taking into account the fiber directions of the draped plies.

PAM-RTM™ has direct interface with four draping simulation tools : **PAM-FORM™** and **PAM-QUIKFORM™** (ESI Group), **PATRAN Laminate Modeler** (MSC), **FiberSIM** (Vistagy). Without losing generality, a bathtub-like geometry is chosen in this tutorial with the draping results obtained from **PAM-FORM™**, as shown below.

It is important to understand that, even if we work with **PAM-FORM™** results here, the procedure is the same for the FiberSIM, PATRAN Laminate Modeler and **PAM-QUIKFORM™** interfaces.



Top View

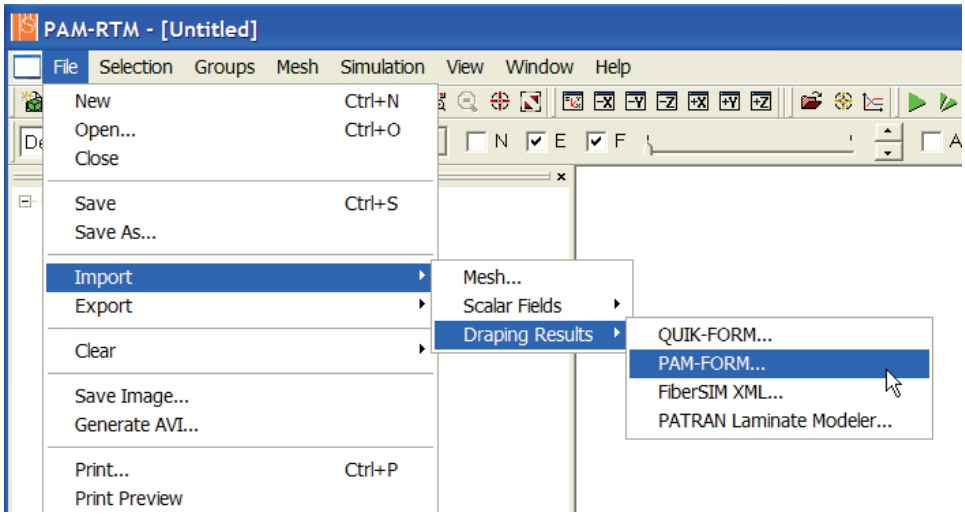


Side View

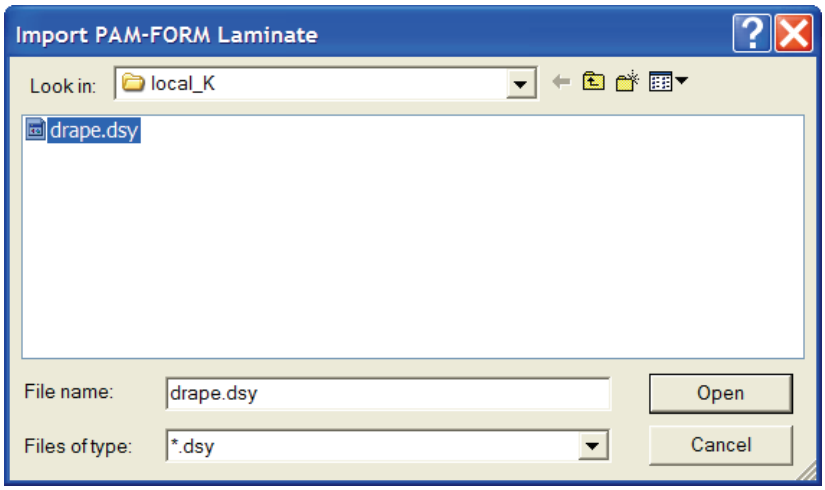
Map Draping Results

Create a new *RTM* simulation with **File->New**. Import the mesh file for the injection simulation `drape_start.unv`.

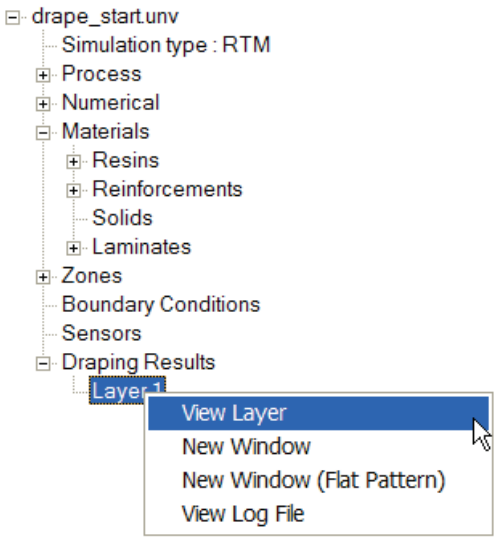
To import the draping results, select **File->Import->Draping Results->PAM-FORM**.

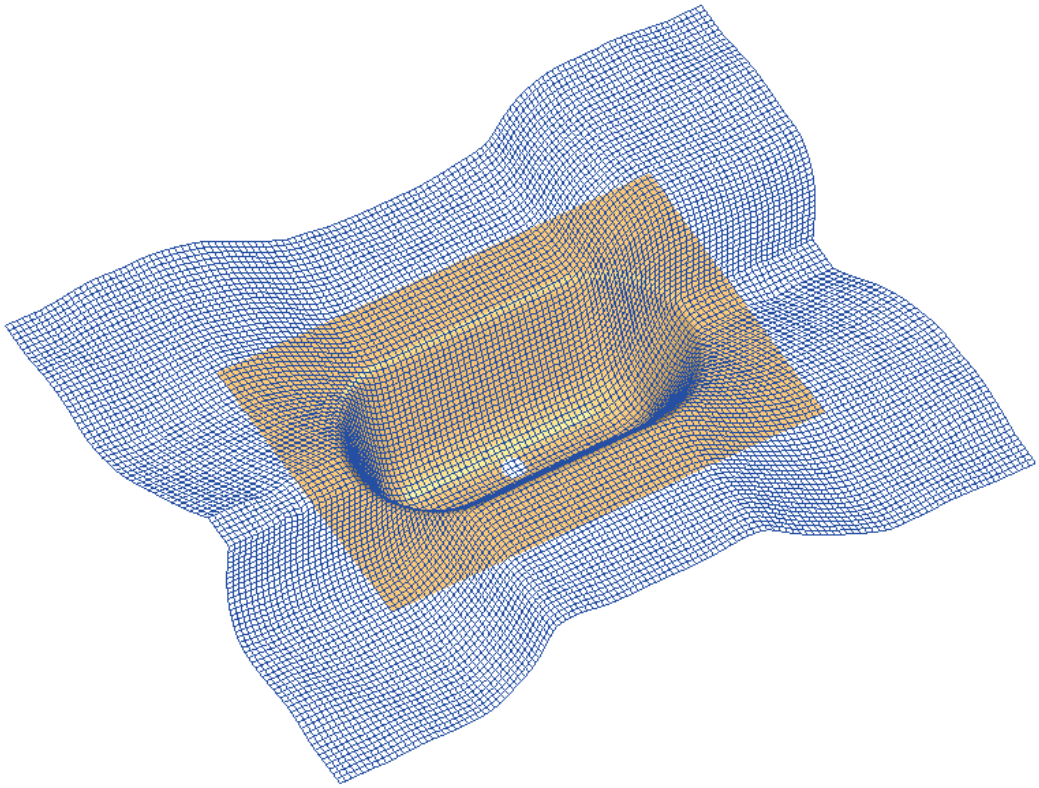


The **Import PAM-FORM Laminate** dialog box pops up. Select the **PAM-FORM™** file `drape.dsy`, and click **Open**.

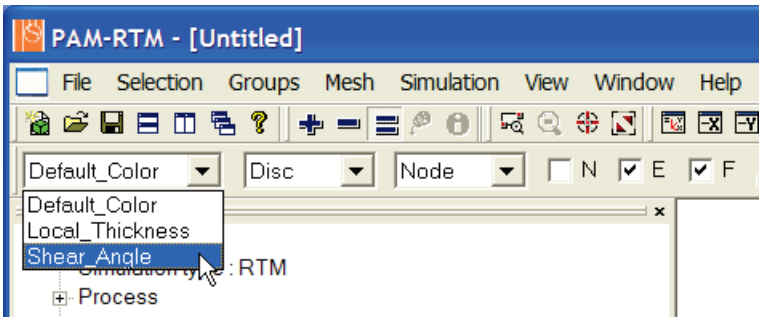


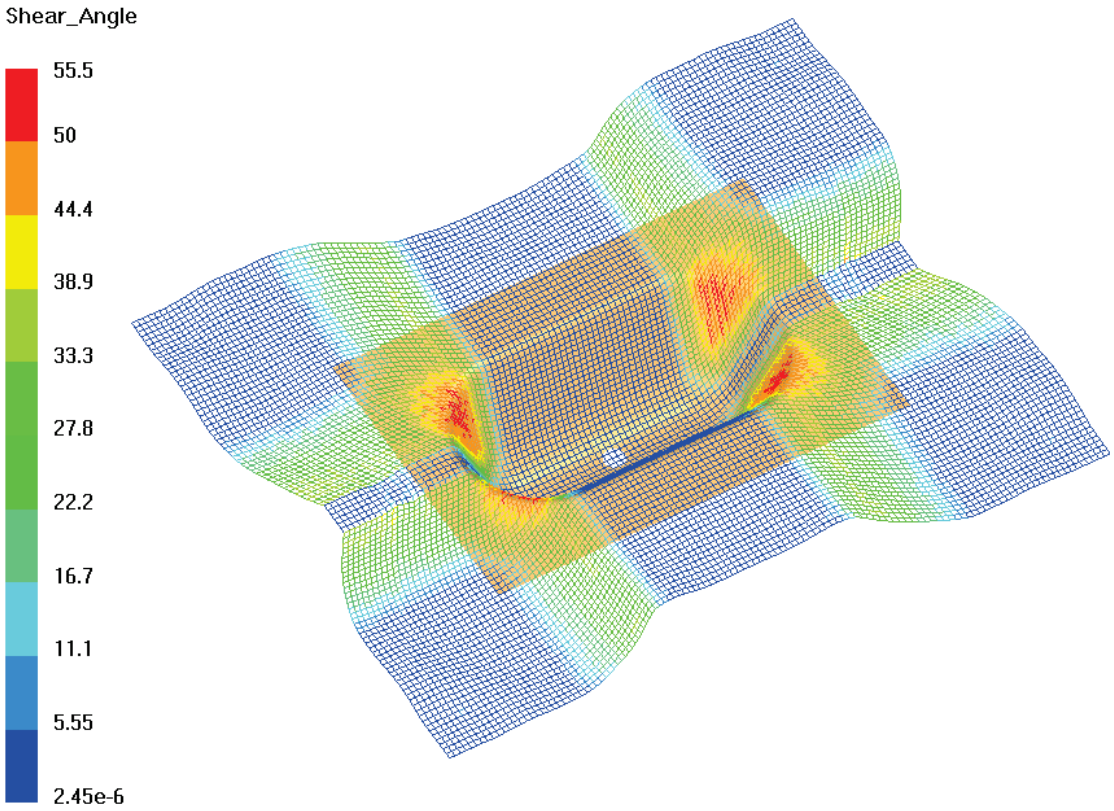
The imported plies are listed in the *Draping Results* folder of the explorer. It can be useful to visualize one of the imported plies on top of the injection mesh. Right-click on the layer to visualize and choose **View Layer**.



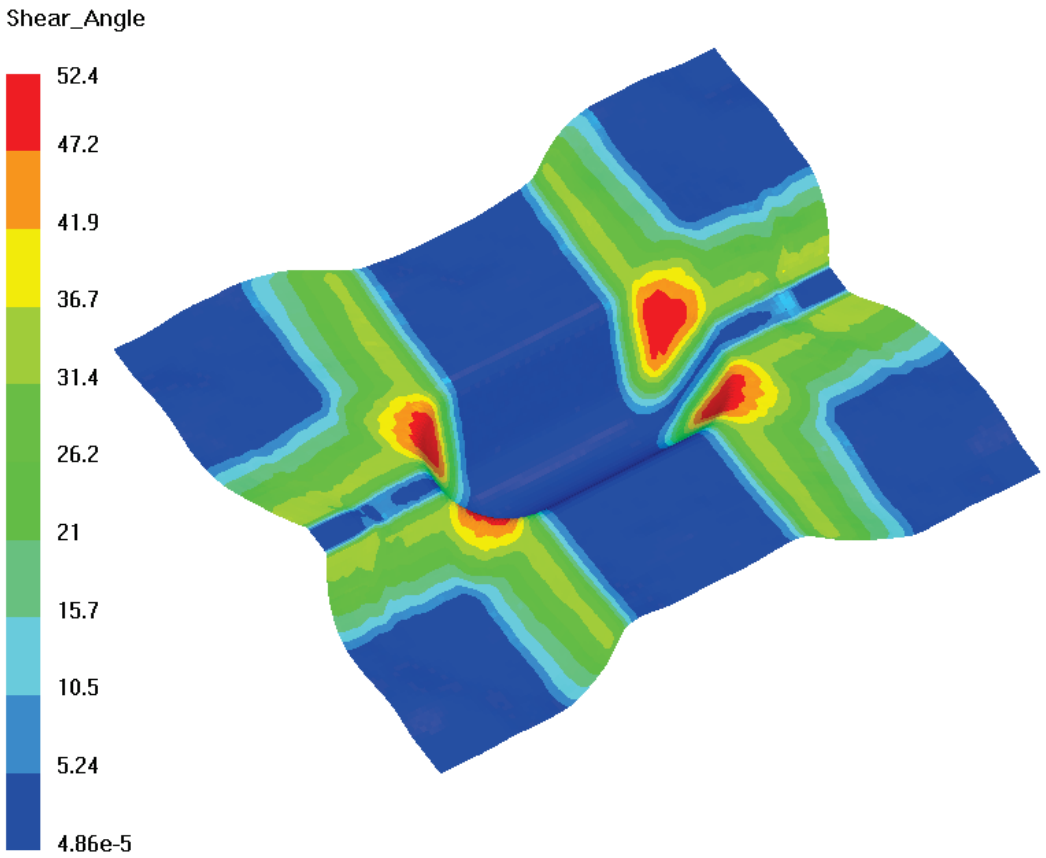


It is also possible to have the ply edges colored based on shear angle. Choose *Shear_Angle* in the scalar fields combo box.

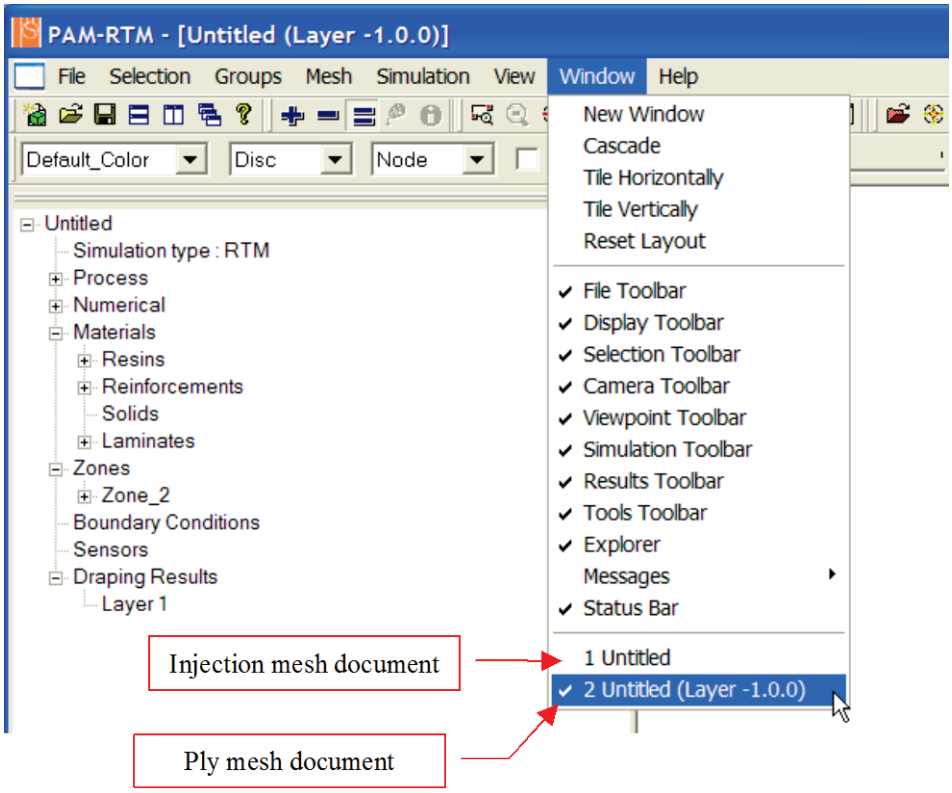




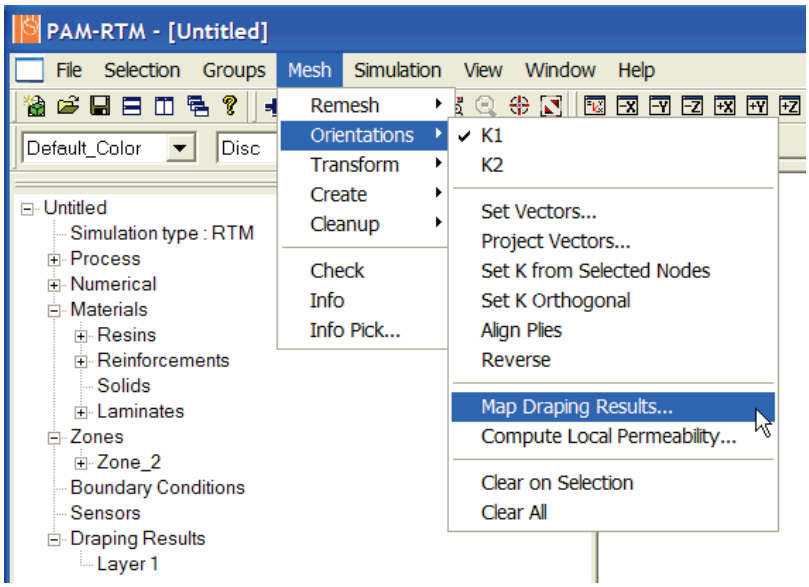
It is also possible to visualize a ply in its own 3D window, with the command **New Window** in the explorer. This gives more post-processing options. For example, with the first approach, only the edges are colored. With the **New Window** approach, the faces are colored so it is possible to obtain a contour.



The **Window** menu lists all open documents. Notice that a ply visualization activated with the **New Window** command is actually considered a document. It has the same name as the injection document, with the layer index appearing between parenthesis. Select the appropriate document to go back to the injection mesh.



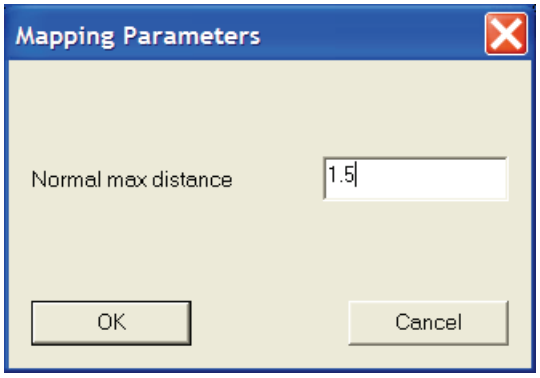
Activate the injection mesh display window. Use the command **Mesh->Orientations->Map Draping Results** to perform the mapping calculation from the draped plies to the injection mesh.



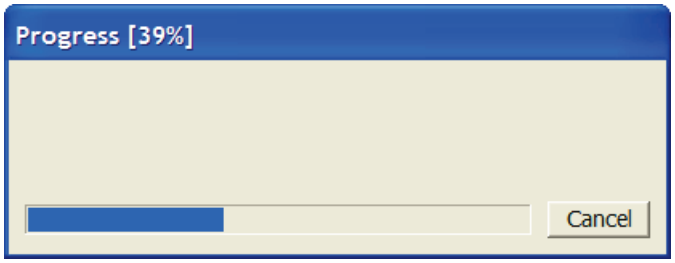
The mapping calculation can be carried out on the full injection mesh or on the currently selected elements only. This is useful for example to avoid plies to be mapped into zones used for runners in the injection mesh. If some elements are selected when

you launch *Map Draping Results*, **PAM-RTM™** asks for a confirmation that the mapping is to be done only on the selected elements.

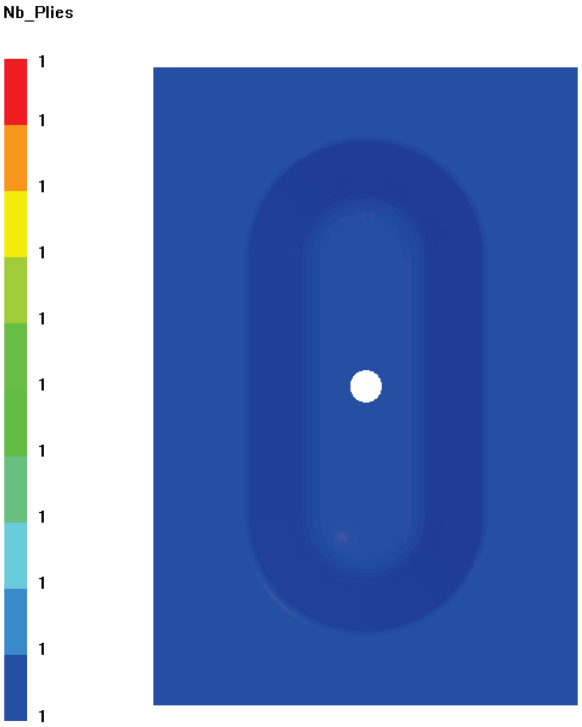
Then a dialog box pops up for the **normal max distance**. The units are the same as the length units of the model. Since we are currently working on a mesh in millimeters, enter a of **normal max distance** of 1.5 mm. This parameter is useful for instance on ribbed parts, to avoid elements on one rib to be mapped on another front facing rib. See the chapter describing the commands of the **Mesh** menu in the **PAM-RTM™** user's guide for more information.



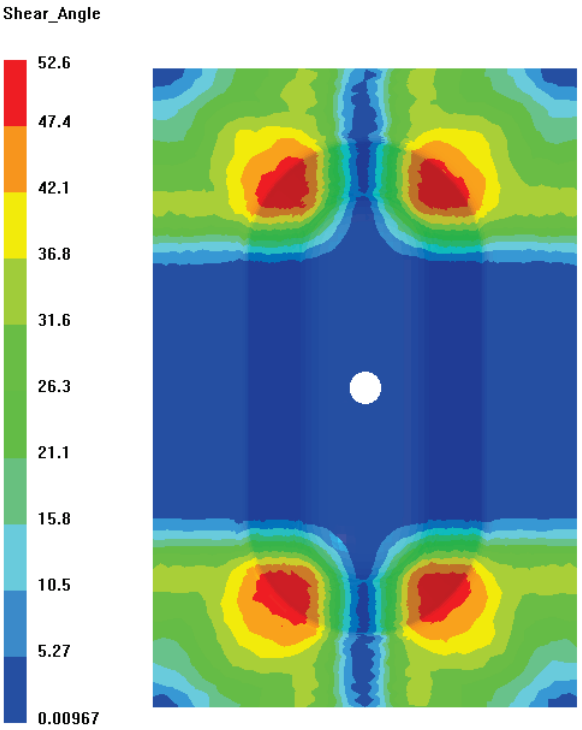
Click **OK**, and the mapping calculation starts. A progress dialog box appears. Since mapping calculations are typically very long, it is possible to stop the calculation with the **Cancel** button.



After the mapping calculation finishes, select *Nb_Plies* in the scalar field roll-down list, the number of laminate plies mapped to each element of the injection mesh is displayed. This is useful to verify the results of the mapping calculation. Since in this example, only one ply that covers completely the injection mesh was mapped, *Nb_Plies* must be equal to 1 everywhere. Otherwise you would have to adjust the tolerances.

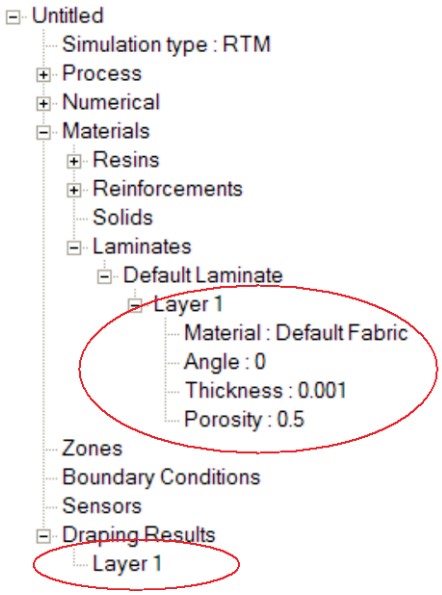


Select *Shear_Angle* in the scalar field roll-down list and *Iso* in the plot type roll-down list, and turn off the *Edge* display. The mapped shearing angle distribution from the first laminate ply on the injection mesh is shown in the current display window.



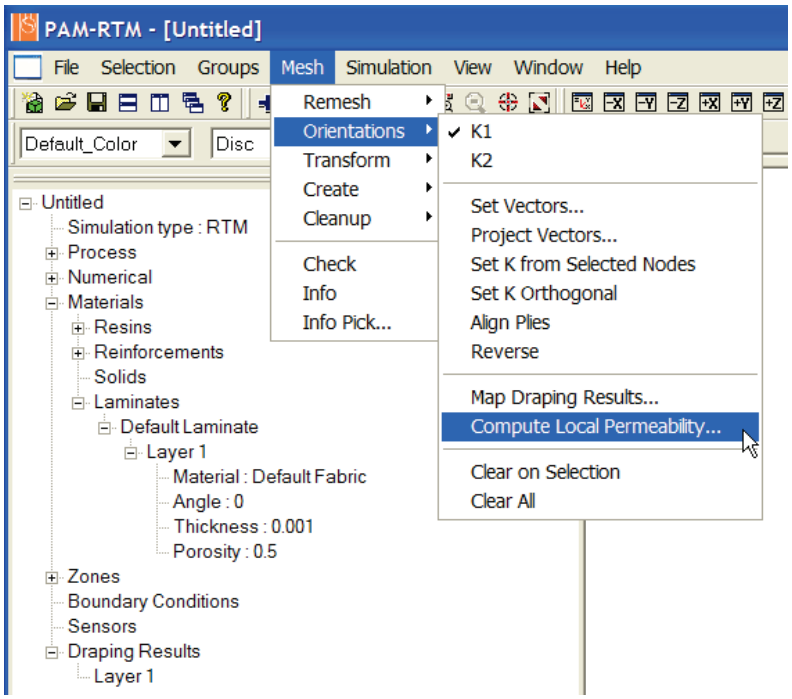
Local Permeability Calculation

The command **Mesh->Orientations->Compute Local Permeability** computes the average permeability and porosity on each element of the injection mesh, using the results of the *Map Draping Results* calculation. To calculate local permeability, **PAM-RTM™** needs to know the type of reinforcement and permeability model associated to each ply, as well as the initial fiber content of each ply. This is done using laminates. Before launching *Compute Local Permeability*, the user has to create a laminate material matching the imported plies, i.e. with the same number of plies.

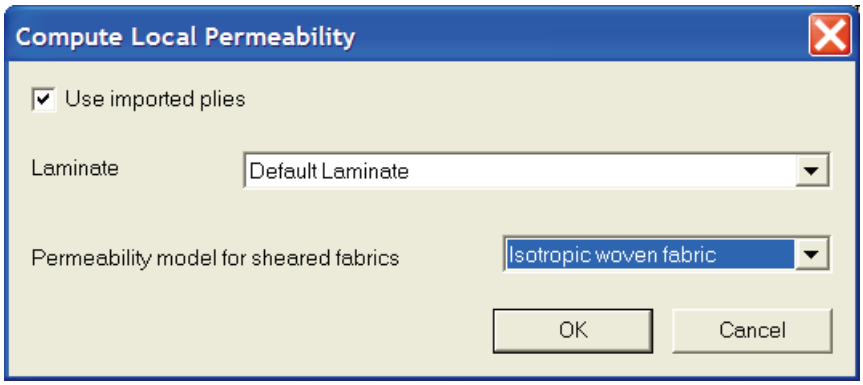


For this example, make sure that the initial porosity of layer 1 of the laminate is 0.5. This is the porosity before shearing. Set the permeability of the fabric linked to layer 1 (*default fabric)* to 1.10^{-11} m².

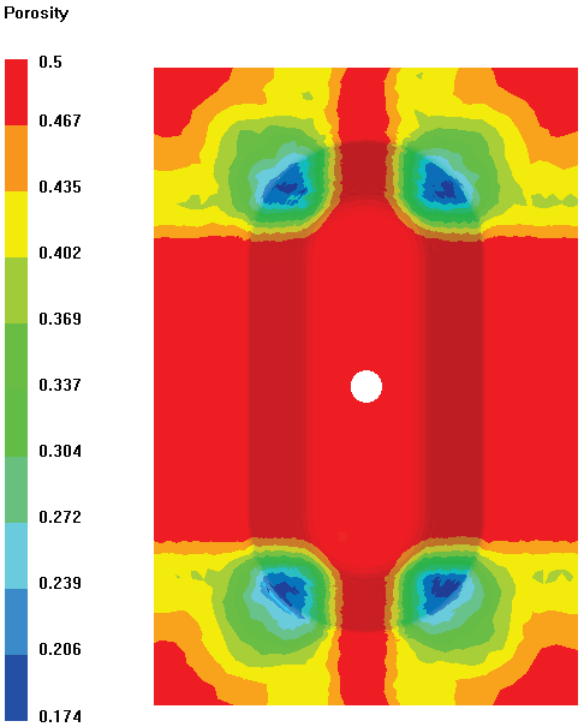
Now you can launch **Mesh->Orientations->Compute Local Permeability**.



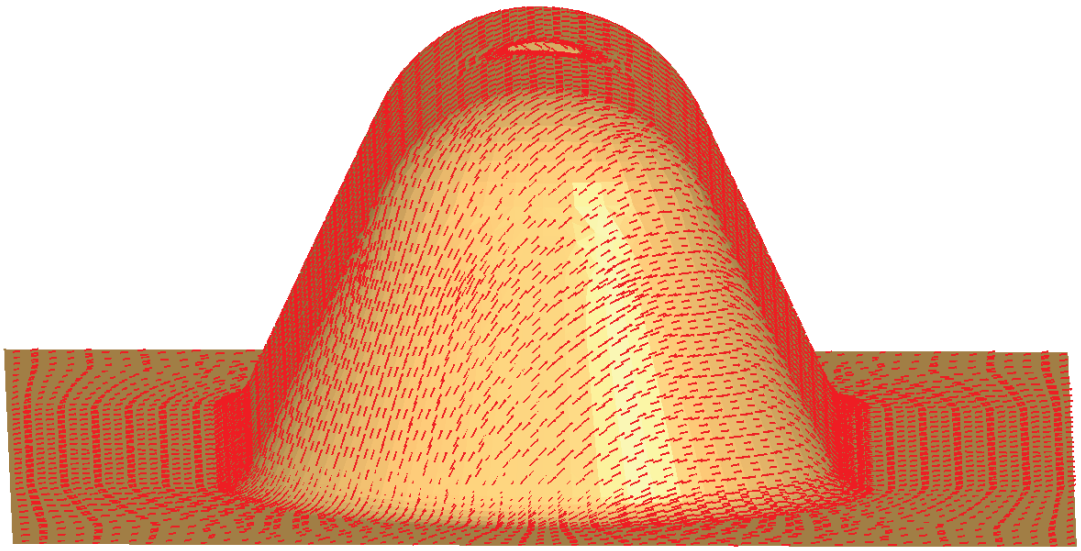
The **Permeability Model** dialog box pops up. In this example, we want the permeability calculation to be based on the imported **PAM-FORM™** ply, so check **use imported plies**. We assume in this example that the permeability of the undeformed fabric is isotropic. Choose the **Isotropic Woven Fabric** model in the **permeability model for sheared fabrics** roll-down list, then click **OK** to start the local permeability calculation.



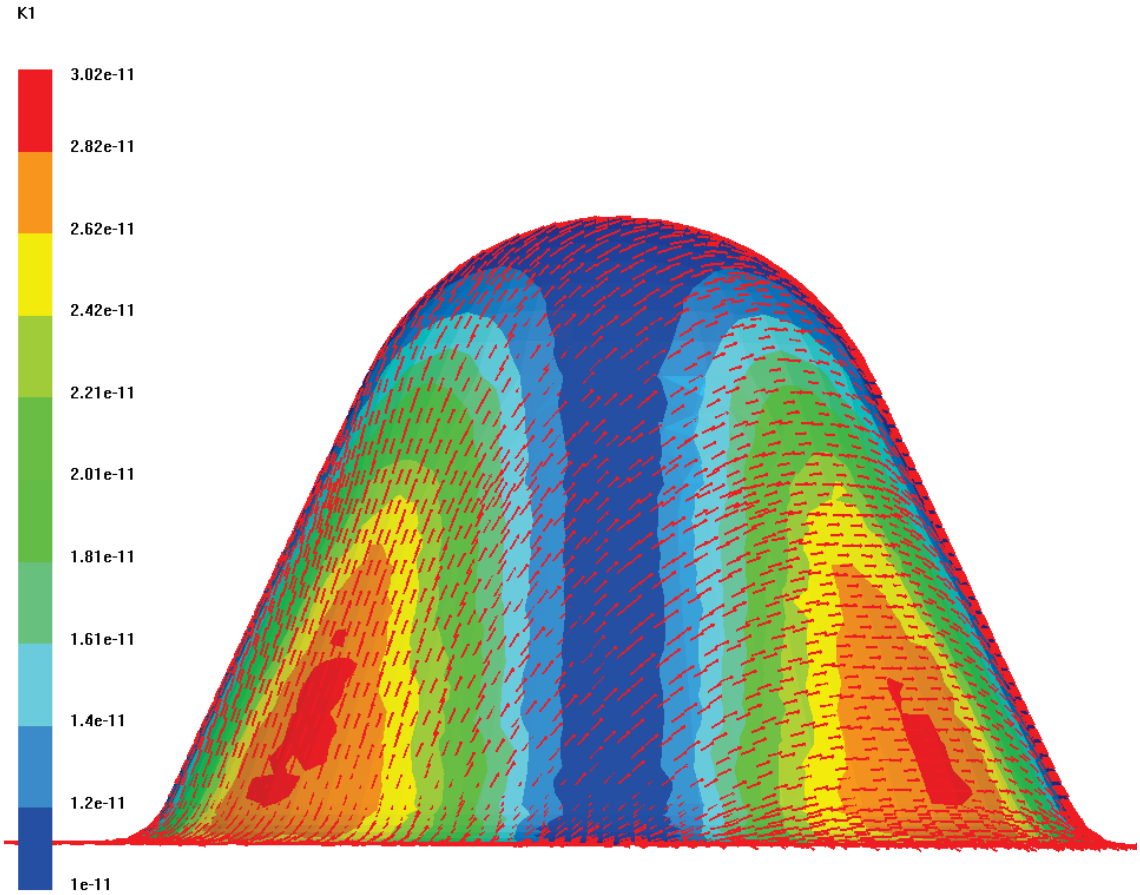
To view the local permeability calculation results, select *porosity* in the main toolbar's roll-down list. Then the local porosity field on the injection mesh is displayed.

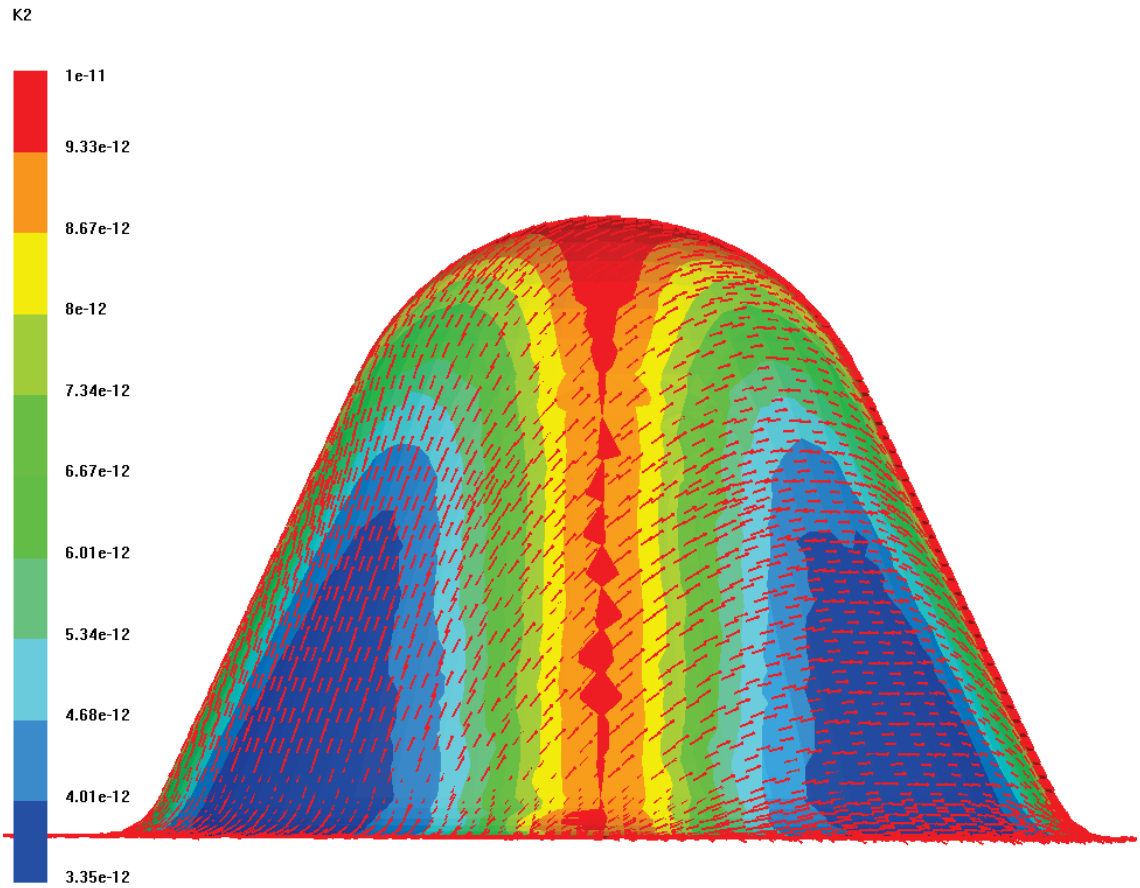


The K1 principal direction can be displayed by selecting **View->Orientations->K1**. Switch off the scalar field display by selecting *Default_Color* in the scalar field roll-down list. The K1 direction is displayed in the following image with red arrows.



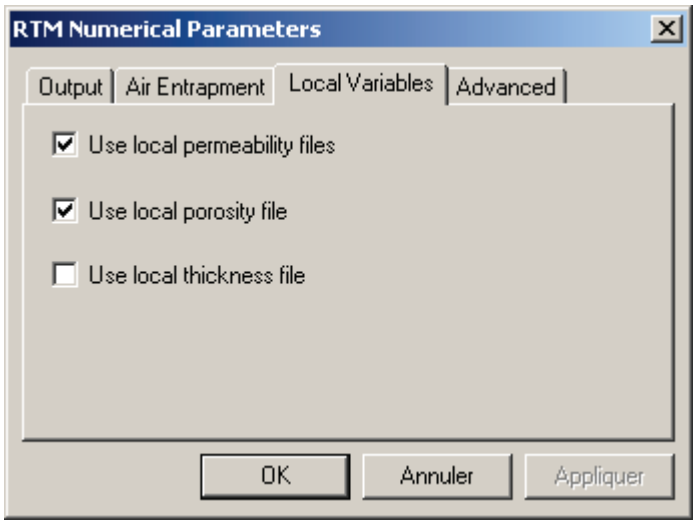
Contours for K1 and K2 in the high shearing areas are shown below.


K1
3.02e-11
2.82e-11
2.62e-11
2.42e-11
2.21e-11
2.01e-11
1.81e-11
1.61e-11
1.4e-11
1.2e-11
1e-11



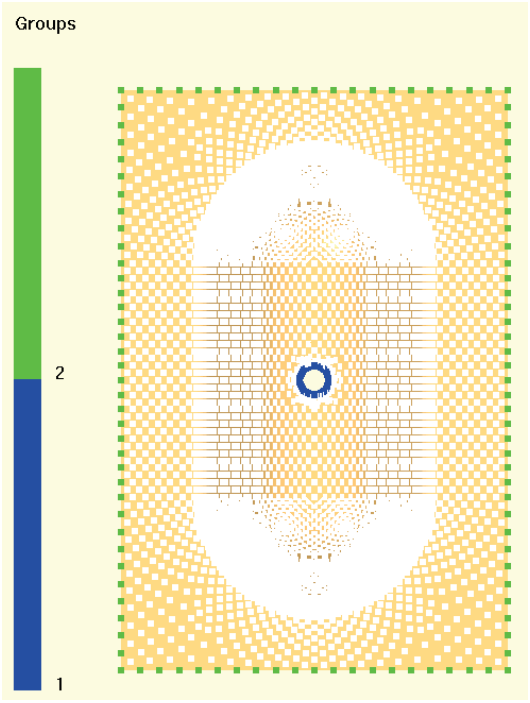
Filling Simulation

In the **RTM Numerical Parameters** dialog box, select **Use local permeability files** and **Use local porosity file**. We do not use the local thickness file in this example. We just assume a constant thickness cavity, specified in zone 2 of the injection mesh.



Normally, since local permeability files are used, there is no need to specify the permeability values using the fabric editor. However it is recommended to specify reasonable values for K1, K2 and K3, because if for some reason the value for an element is not found in the local permeability file, the value specified in the fabric editor will be used.

The following groups have to be created.

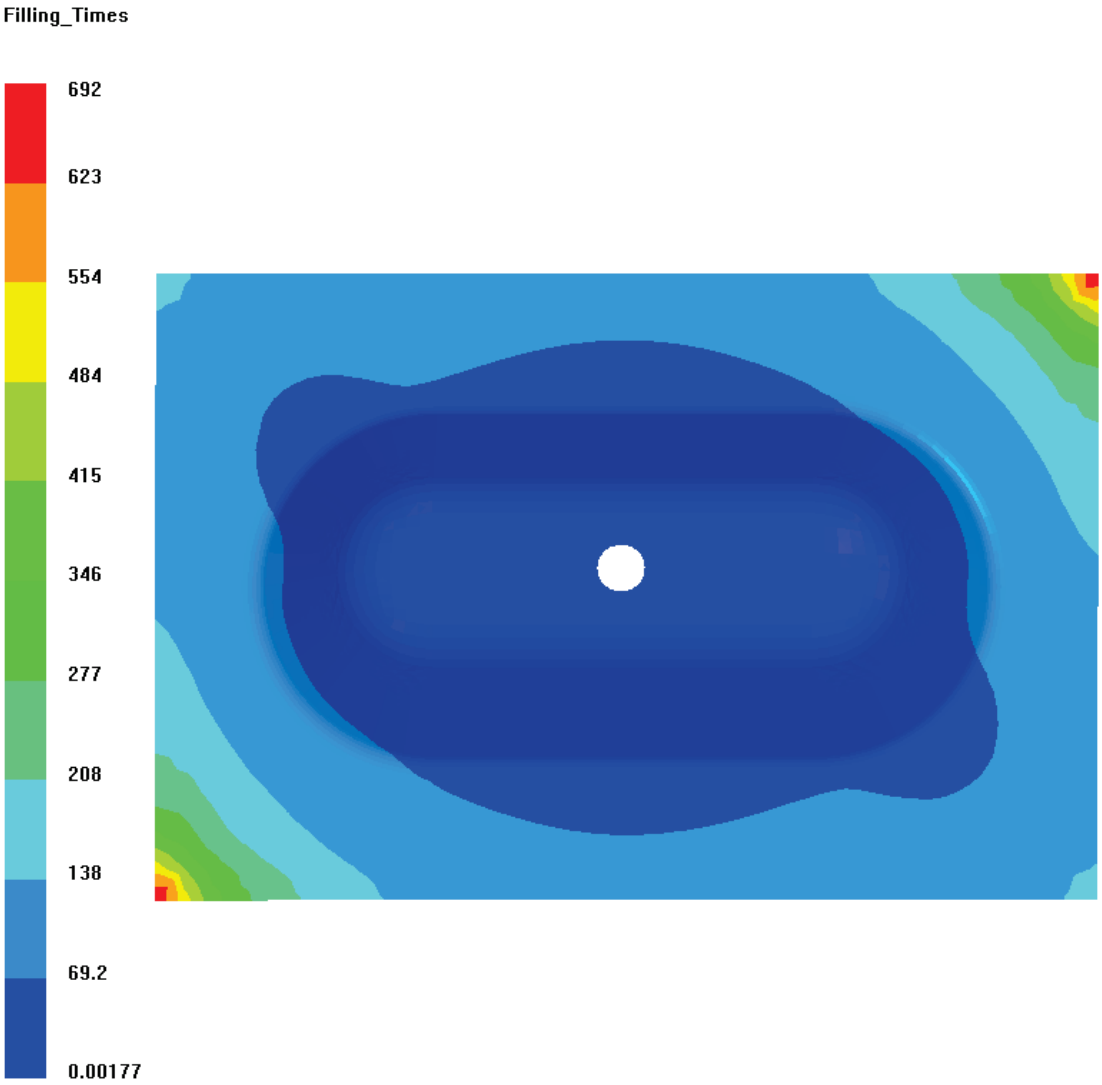


To summarize, here are the parameters that need to be set for the filling simulation:

- resin:
  - viscosity: 0.1 Pa.s
- fabric:
  - name: Default Fabric
  - K1: 1.10^{-11} m2
  - K2: 1.10^{-11} m2
  - K3: 1.10^{-11} m2
- zone:
  - ID : 2
  - material: Default Fabric
  - porosity: 0.5
  - thickness: 0.005 m
- boundary condition :
  - ID: 1
  - type: pressure
  - pressure value: 3.10^{5} Pa
- boundary condition:
  - ID: 2
  - type: vent
  - pressure value: 0 Pa
  - state:

Finally, save the PAM-RTM document before starting the simulation. Since a *compute local permeability* was done, some files will be automatically generated in the same directory as the `x.dtf` file: `x_k1.sf`, `x_k2.sf`, `x_porosity.sf`. These are the files read by the **PAM-RTM™** solver to initialize local permeability and porosity. When saving the files, **PAM-RTM™** detects that the span of the injection mesh is very large, which could mean that it is defined in millimeters, so it asks whether you want to automatically convert it to meters. Select **Yes**.

Launch the simulation. When it is done, load the results files. You should have the following segmented filling patterns. Filling time is about 692 seconds.


Filling_Times
692
623
554
484
415
346
277
208
138
69.2
0.00177

LOCAL PERMEABILITY FROM DRAPING RESULTS (ADVANCED)

The following files are used in this example.

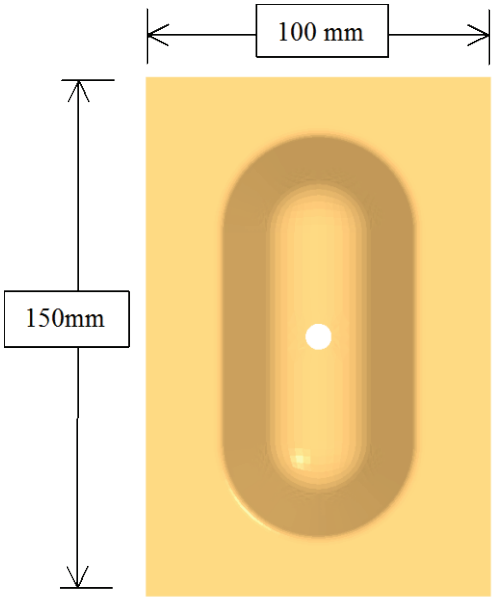
- ***drape2.dsy*** (4 plies laminate file)
- ***drape2_start.unv*** (injection mesh file)
- ***drape2_K1.srf*** (sheared permeability K1 kriged function data file)
- ***drape2_K2.srf*** (sheared permeability K2 kriged function data file)
- ***drape2_beta.srf*** (sheared rotation angle kriged function data file)

Objectives

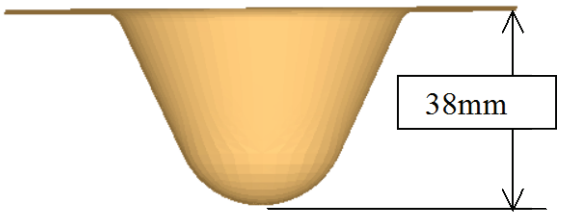
This document presents an advanced tutorial on local permeability calculation from draping results, complementary to the previous tutorial – **Local permeability from draping results**. The advanced features include

- how to assign materials to a more complex laminate made of many plies,
- how to use kriged functions to describe the fabric sheared permeability as a function of shear angle and fiber content.

The same bathtub-like geometry used in the previous tutorial is investigated again in this tutorial with the draping results of a 4 plies laminate obtained with **PAM-FORM™**, and the geometry is shown below.



Top View

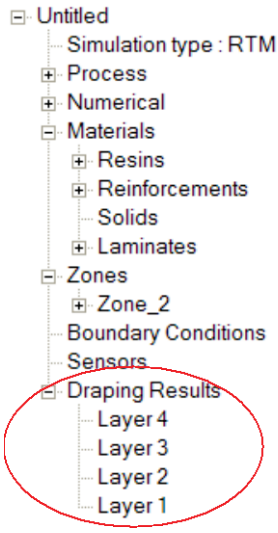


Side View

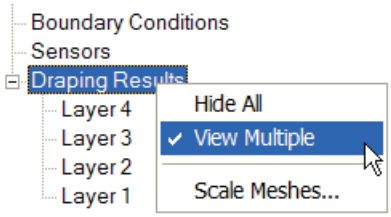
Map Draping Results

Create a new *RTM* simulation with **File->New**. Import the mesh file `drape2_start.unv`. Then select **File->Import->Draping Results->PAM-FORM** to import the draping results file `drape2.dsy`.

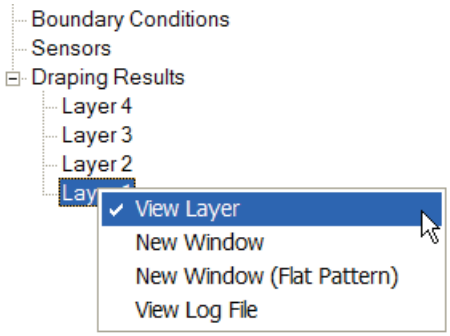
There are four plies in the draping file. They are listed in *Draping Results* folder of the explorer after importation.



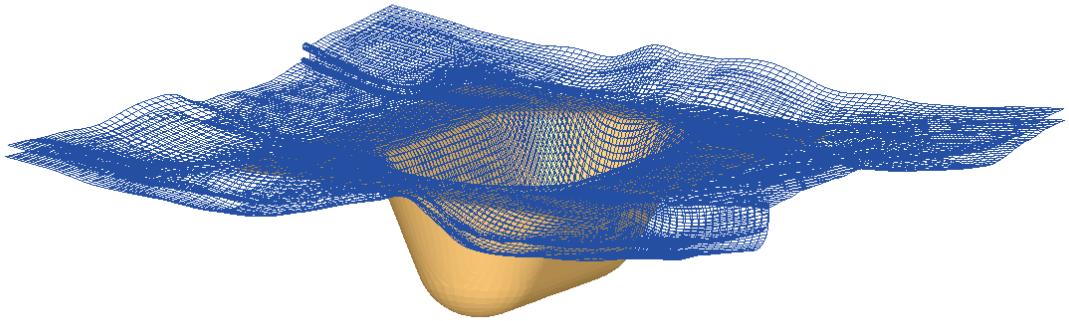
Right-click on the *Draping Results* item and choose *View Multiple* to allow visualization of many layers in the same window.



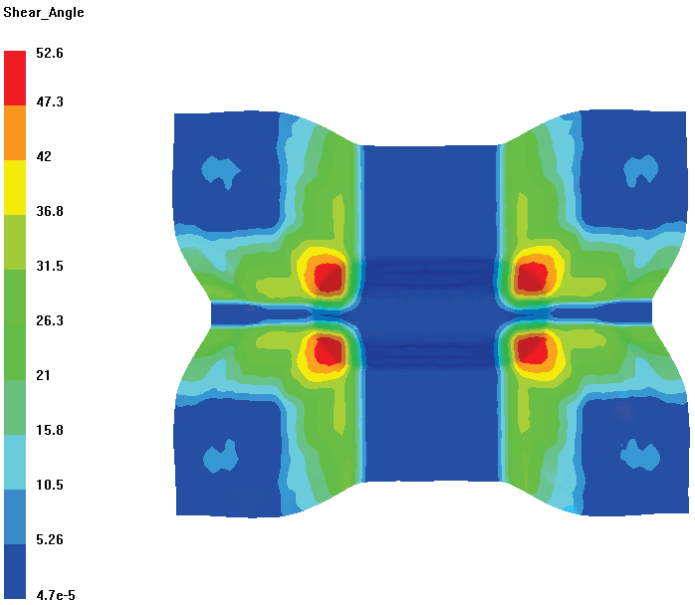
Then right-click on the first layer and choose *View Layer*.



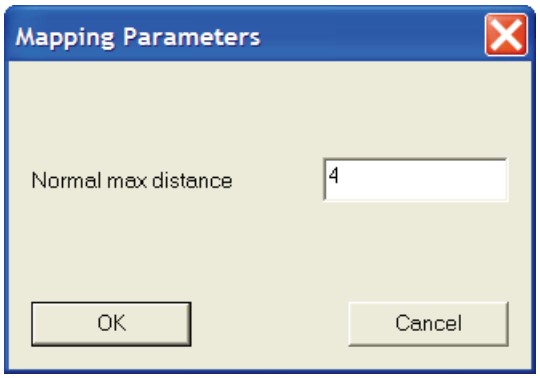
Do the same for the fourth layer. This leads to the following picture, where we can see clearly that there is an offset between the first and fourth ply. This will be important for the transverse tolerance when mapping draping results.



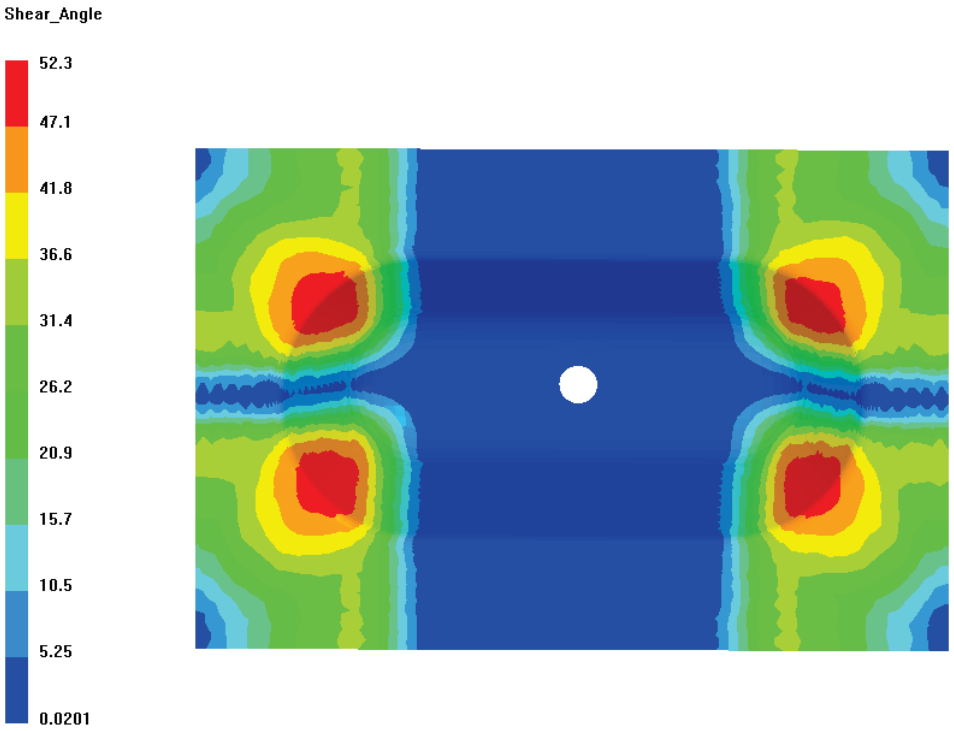
All the four plies in this **PAM-FORM™** file have a zero degree orientation, so all the plies have similar local deformations, but not exactly the same because of the thickness of the part. The figure below shows the shear angle distribution for ply 2.



Go back to the injection mesh window. Select **Mesh->Orientations->Map Draping Results** to perform the mapping calculation from the imported draped plies to the injection mesh. In the **Mapping Parameters** dialog box, enter *4.0* (mm) as **normal max distance**.



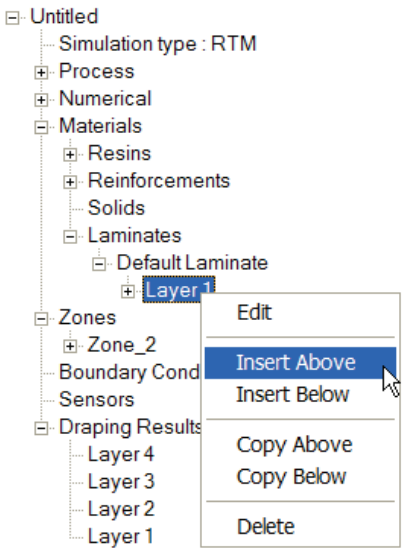
When the mapping calculation is done, the mapped shearing angle distribution from the first laminate ply on the injection mesh is shown as below.



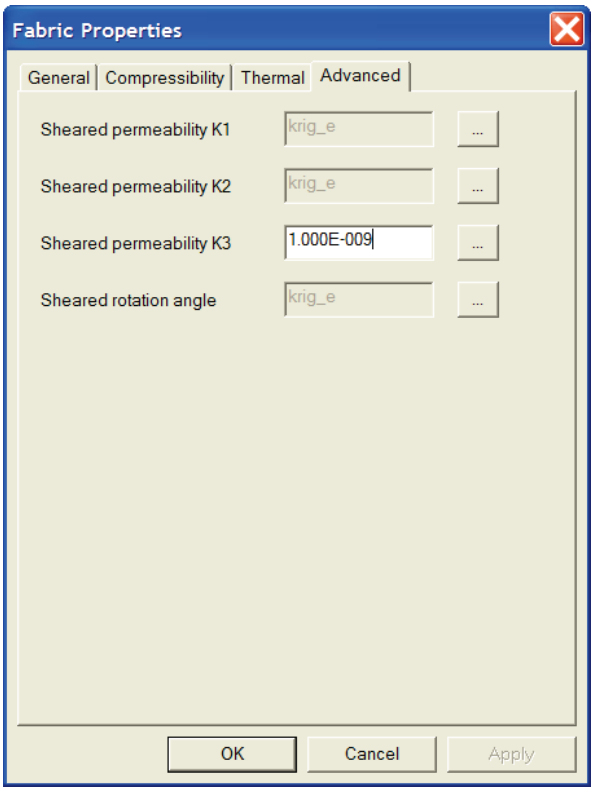
Select *Nb_Plies* in the scalar field roll-down list to view the number of laminate plies mapped to each element of the injection mesh. Since in this example, four plies that cover completely the injection mesh were mapped, *Nb_Plies* must be equal to four everywhere.

Local Permeability Calculation

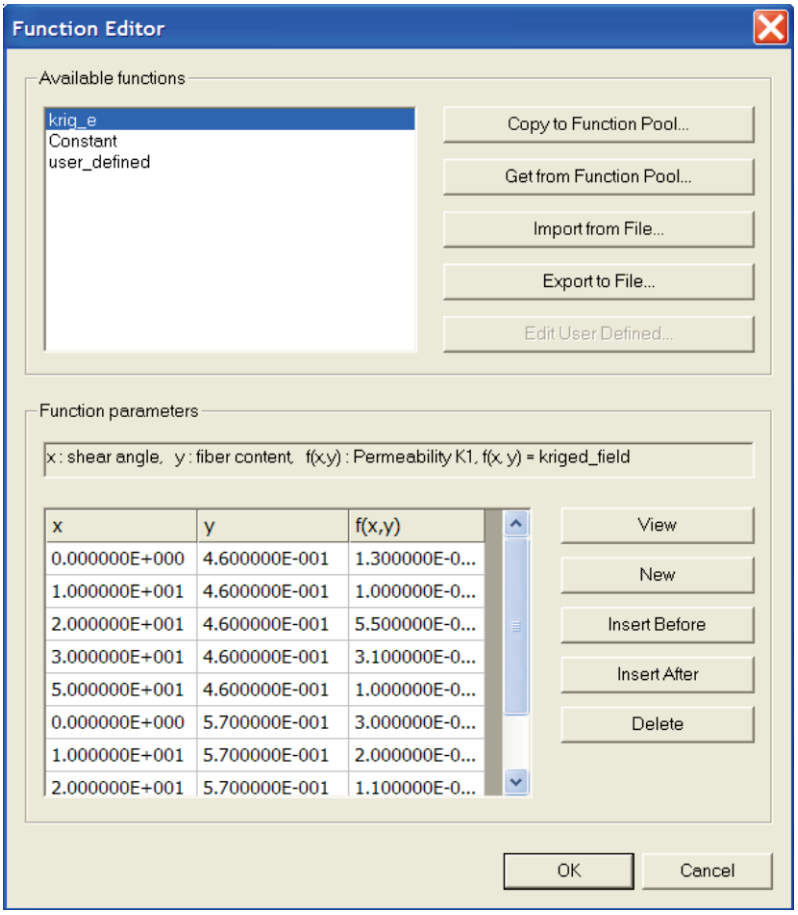
Before we can launch the local permeability calculation, we have to specify material properties for each of the imported draped plies. To do so, we first create a laminate material made of four layers, to match the four imported draped plies. Right-click the first layer of the *Default Laminate*, then choose *Insert Above* to add a layer above the selected one. Repeat this procedure until you have four layers.



All four layers reference the *Default Fabric*. Double-click *Default Fabric* to open the fabric editor. In the **Advanced** tab, we will specify a sheared permeability model with the fields *Sheared Permeability K1*, *Sheared Permeability K2*, *Sheared Permeability K3*, and *Sheared Rotation Angle*, where sheared permeability K1, K2, and K3 are 1st, 2nd, and 3rd principal direction of the permeability tensor, respectively.

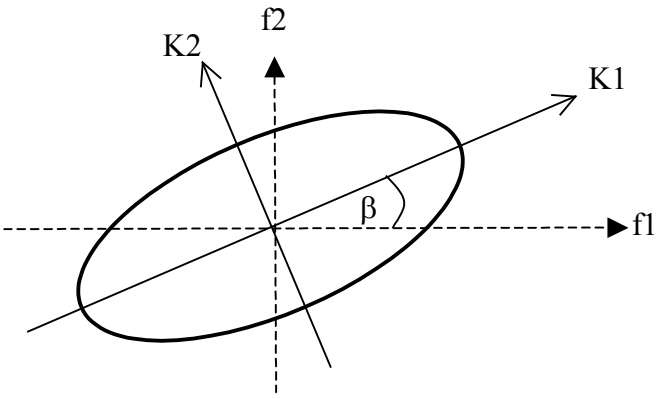


Click on the **…** button to the right of the **Sheared Permeability K1** field to open the **Function Editor** dialog box. Select **Import from file** and in the **Import** dialog box, choose in the **Type** roll-down list *PAM-RTM (*.srf)* and browse to `drape2_k1.srf`. By the same way, set the fields **Sheared permeability K2** and **Sheared rotation angle**. Before closing the **Function Editor** dialog box, don't forget to select the imported function.



The user could also enter the data points manually. The *x* column is the shear angle (in degree), *y* is the fiber content (a decimal value between *0* to *1*), and *z* is the sheared permeability (unit: m^2).

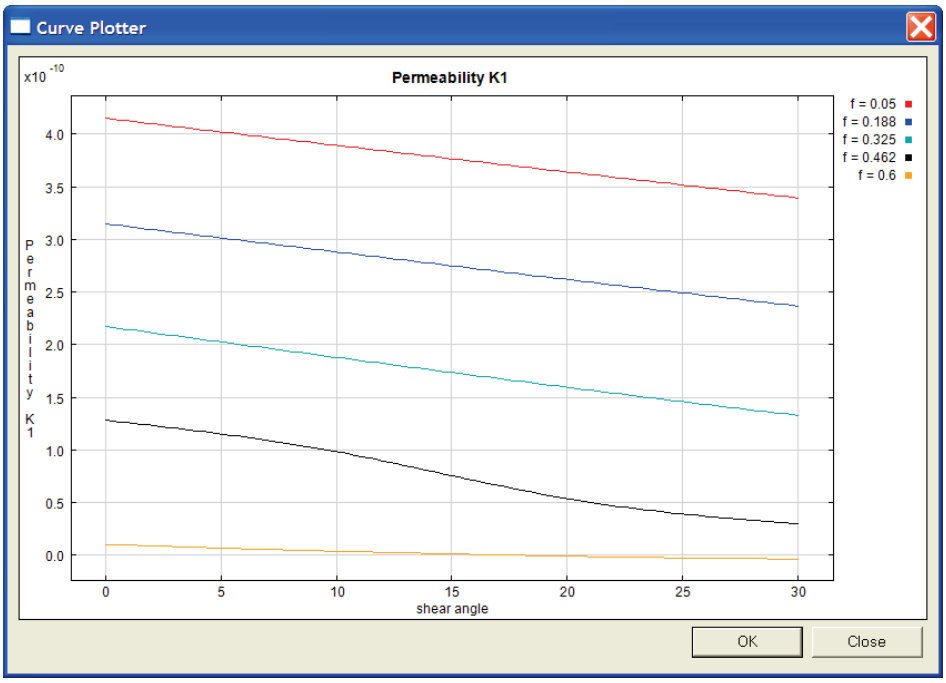
The sheared rotation angle designates the angular position of 1st principal direction of the permeability tensor (***K1***) with respect to the warp direction of the laminate fabric (***f1***), as shown in the following figure.

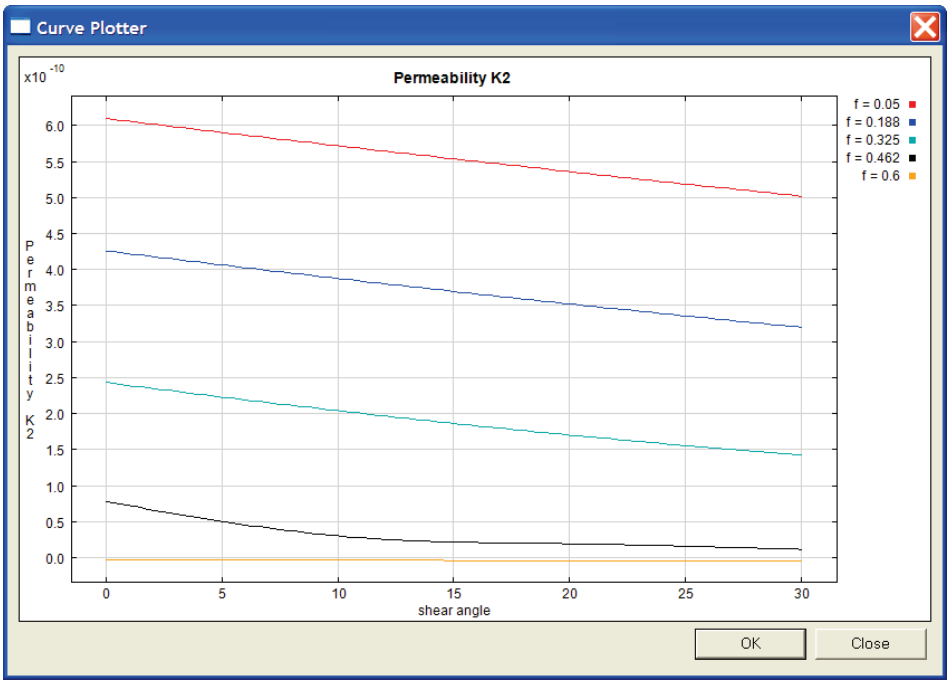


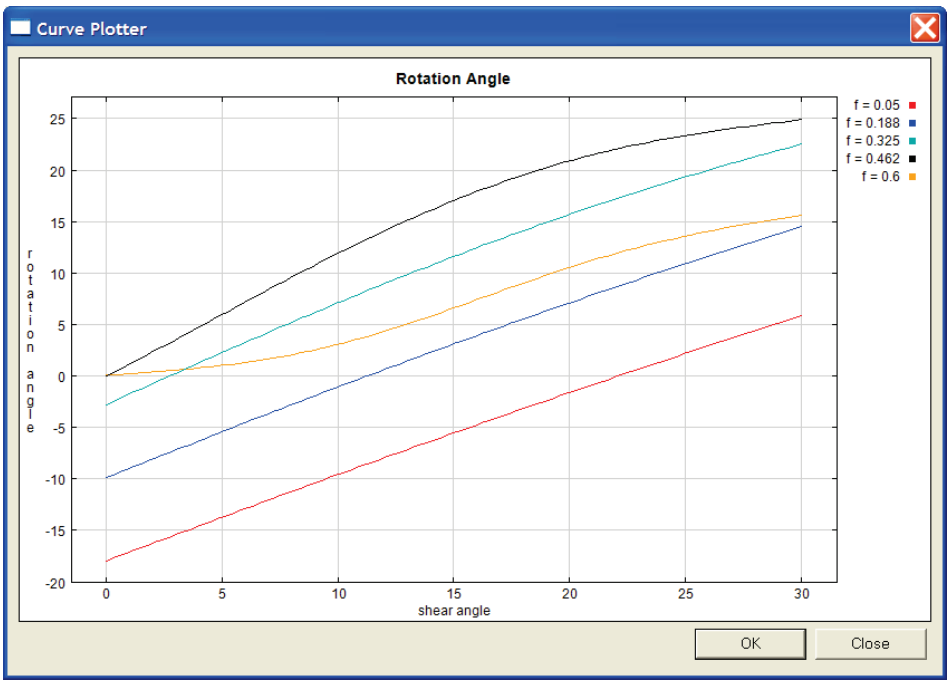
Note

- *If you select* ***View->Orientations->K1 Only*** *(or K2 Only) when the active window is a draped ply, the K1 direction represents the warp direction of a fabric, and K2 represents the weft direction. However if you visualize K1 on the injection mesh after Compute Local Permeability, the K1 direction is the 1st principal direction of the permeability tensor. So the same command* ***View->Orientations->K1*** *is used to visualize fiber directions or principal permeability directions, depending on the context.*

The sheared permeability K1, sheared permeability K2 and sheared rotation angle functions used in this example are displayed below.



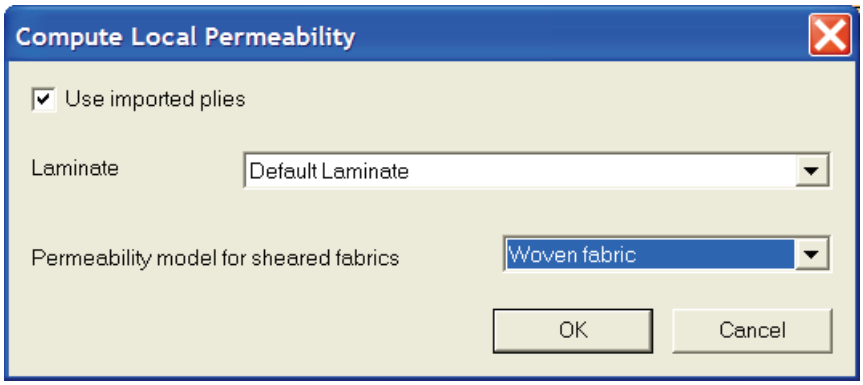




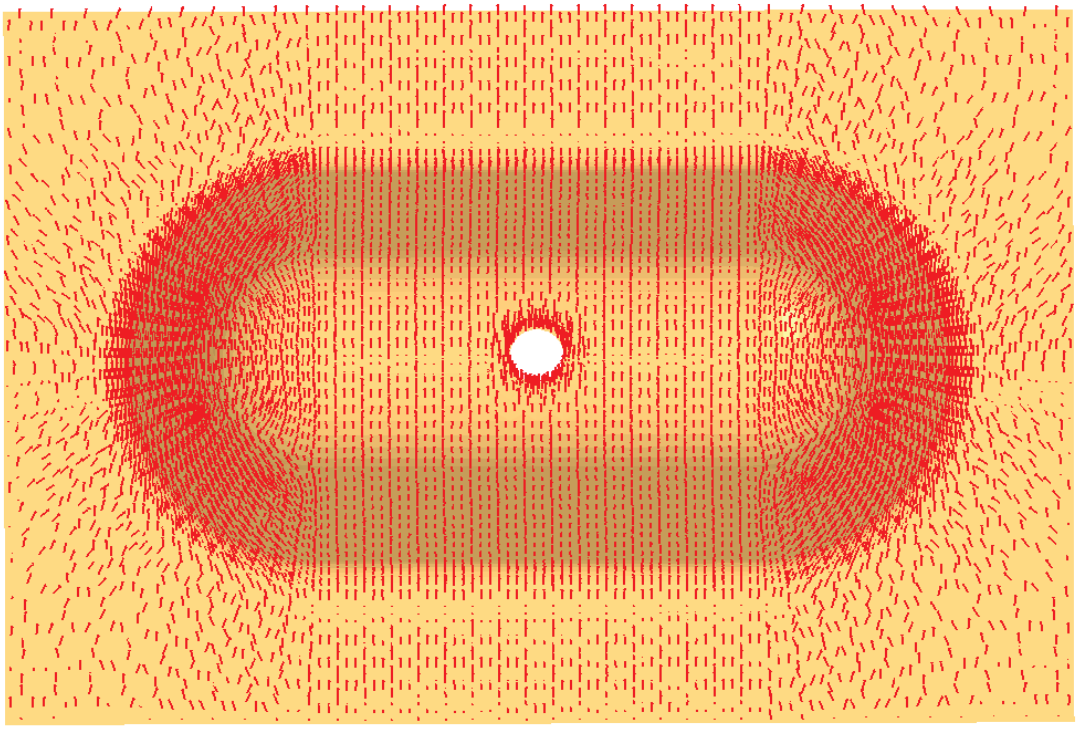
For 3D simulations, the *Sheared Permeability K3* could also be defined as a function of the fiber content and shear angle, if such experimental data is available. In this example, we set *Sheared Permeability K3* to a constant value.

To perform the local permeability calculation, select **Mesh->Orientations->Compute Local Permeability**.

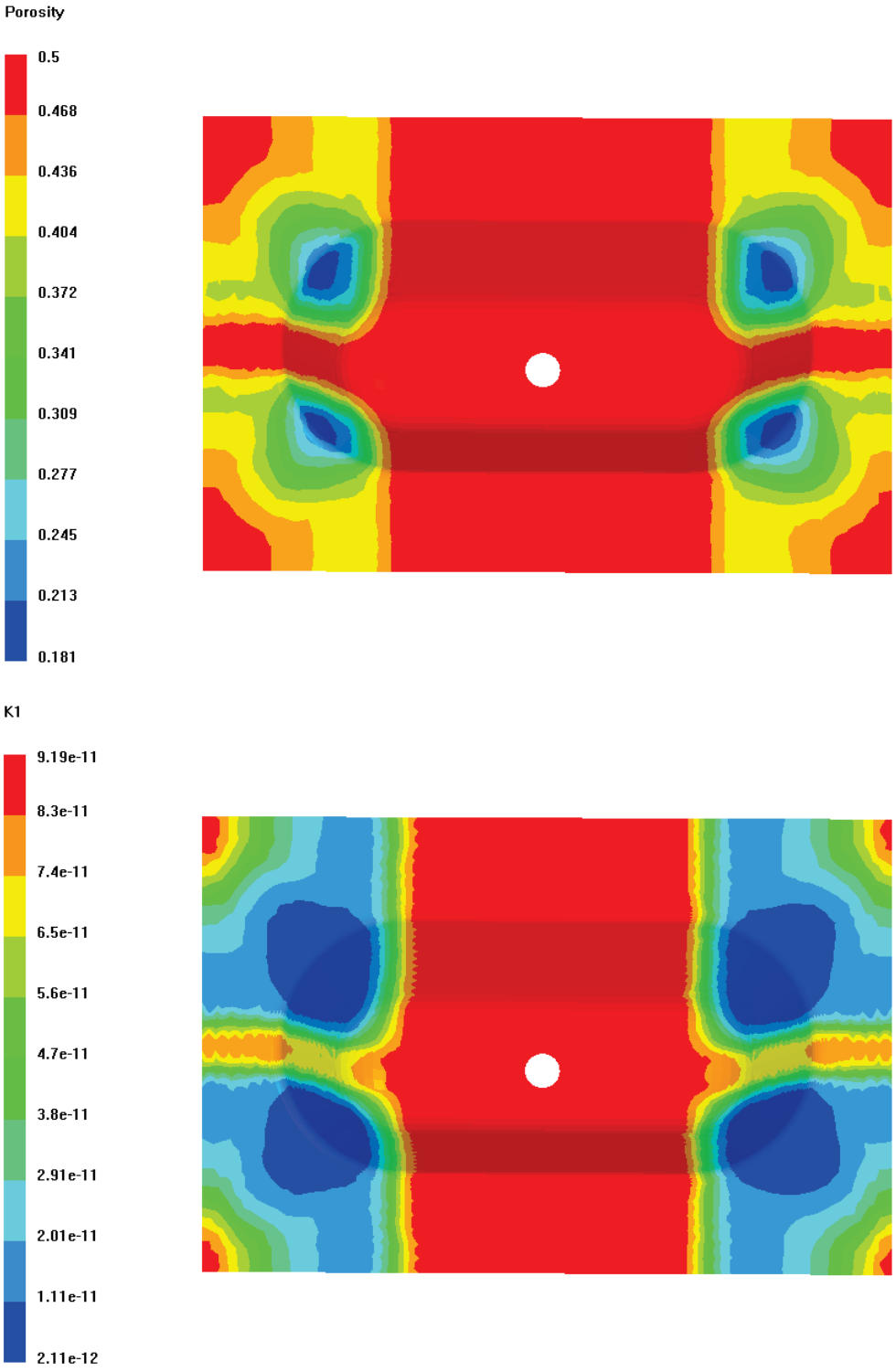
The **Compute Local Permeability** dialog box pops up. Check **use imported plies** and select **Woven Fabric** in the **permeability model** roll-down list, which means that the sheared permeability functions we've just defined will be used.



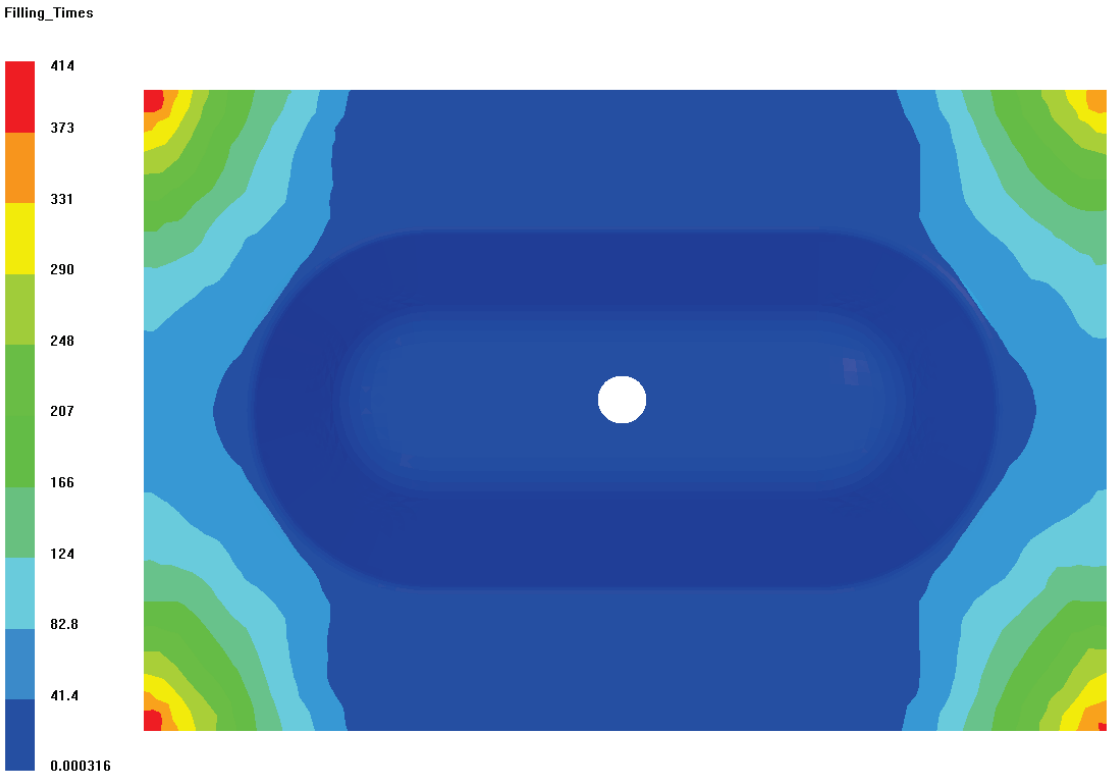
The figure below shows the 1st principal direction of the permeability tensor after local permeability calculation.



The following figures show the local porosity and local K1 value after mapping calculation.



The rest of the procedure is the same as described in the tutorial **Local permeability from draping results**. The following figure shows the filling pattern at a constant pressure injection, whose injection and vent conditions are the same as in the previous tutorial.


Filling_Times
414
373
331
290
248
207
166
124
82.8
41.4
0.000316

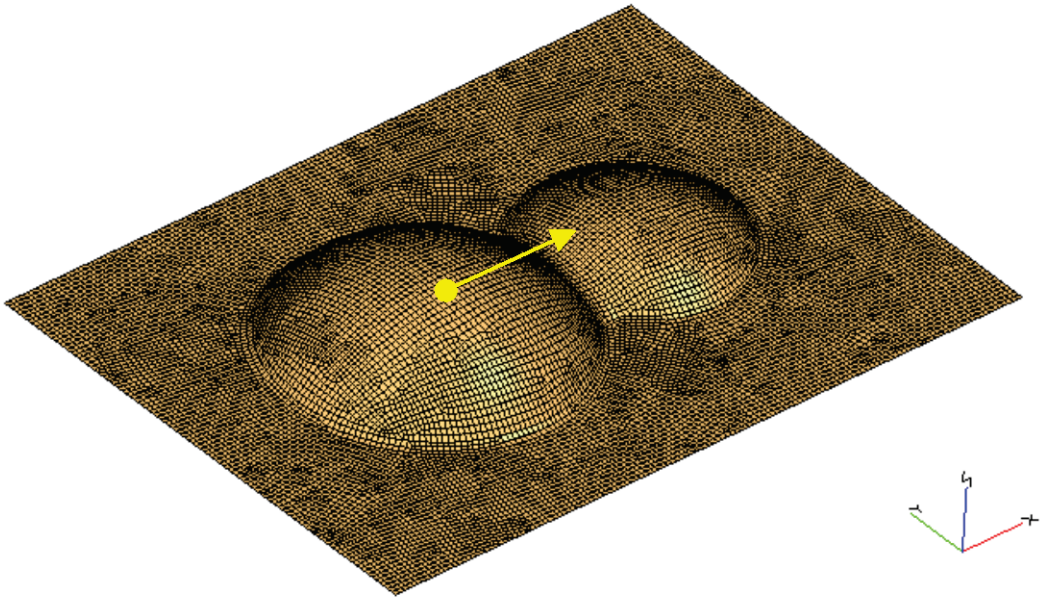
PAM-QUIKFORM

The following files are used in this example.

- ***quikform_start.ps (starting mesh)***
- ***quikform.dtf + quikform.ps (solution)***

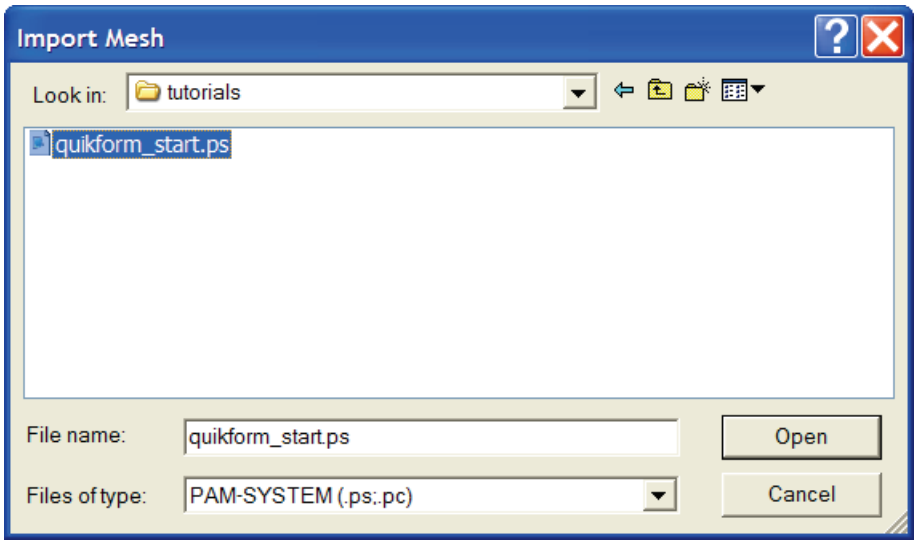
Objectives

The goal of this tutorial is to show how to perform a draping simulation using the **PAM-QUIKFORM™** user interface available in **PAM-RTM™**. The geometry used is a double hemisphere. We will drape a laminate made of two plies of fabric and two plies of unidirectional. The contact point is the top of the big hemisphere and the laminate reference axis (zero degree) is the global X axis.

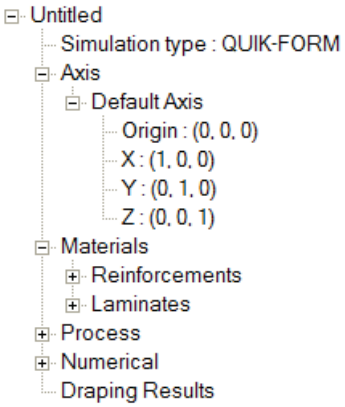


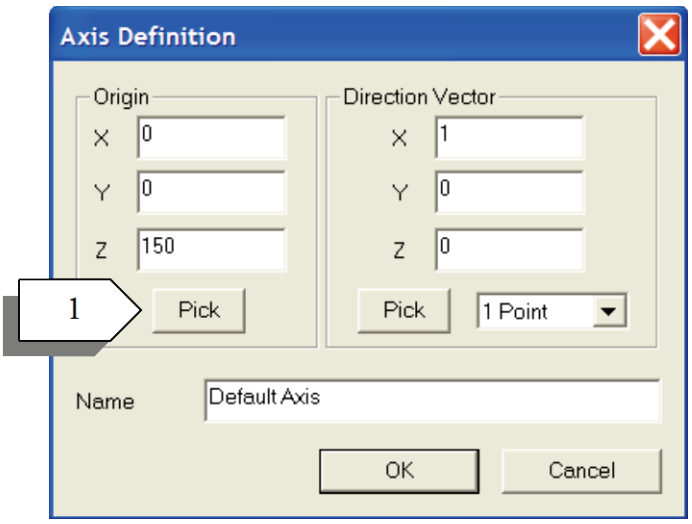
Process and Numerical Parameters

Create a new *PAM-QUIKFORM* simulation with **File->New->PAM-QUIKFORM**. Import the mesh file `quikform_start.ps` with **File->Import->Mesh**. Make sure to set the file filter to PAM-SYSTEM, as shown below.

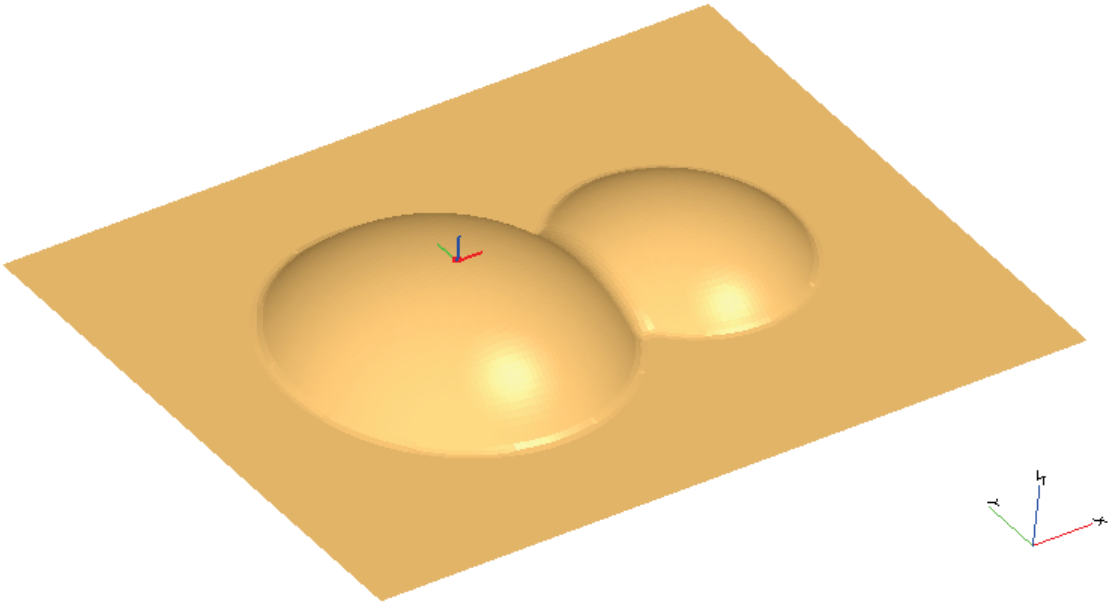


First we create a draping referential (also called *axis* in **PAM-RTM™**) on top of the big hemisphere. The default PAM-QUIKFORM document contains an axis located at the origin. It is unlikely that this axis is what you want, so double-click the default axis to open the **Axis Definition** dialog box.



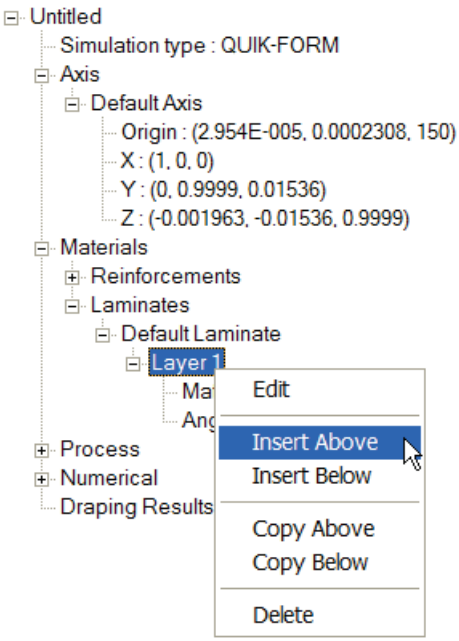


Push the *Pick* button **[1]** and pick a point near the top of the big hemisphere, or enter the coordinates of the origin manually (0, 0, 150). The *direction vector* is the local X axis of the draping referential, i.e. the axis on which zero degree plies will be aligned. The local Y and Z axis are set automatically by **PAM-RTM™**. The local Z axis is the normal vector on the picked point and the local Y axis is calculated to have a right-hand coordinate system. If you want the opposite local Z direction, use the command **Reverse Z**, available in the explorer when right-clicking an axis. In this tutorial, we keep the default *direction vector* (1, 0, 0), then we reverse the local Z axis to have it in the global Z+ direction, as shown below.

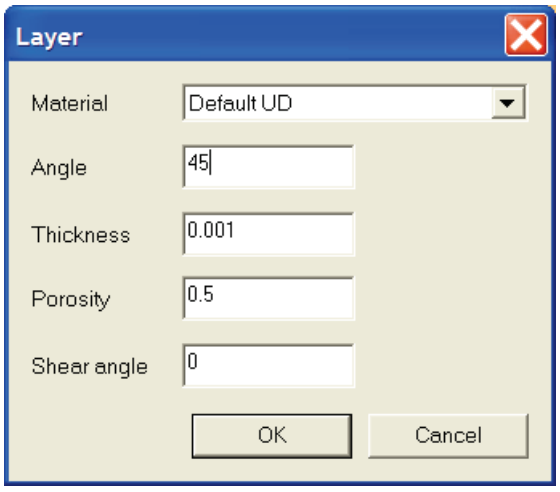


Now we have to define the following laminate:

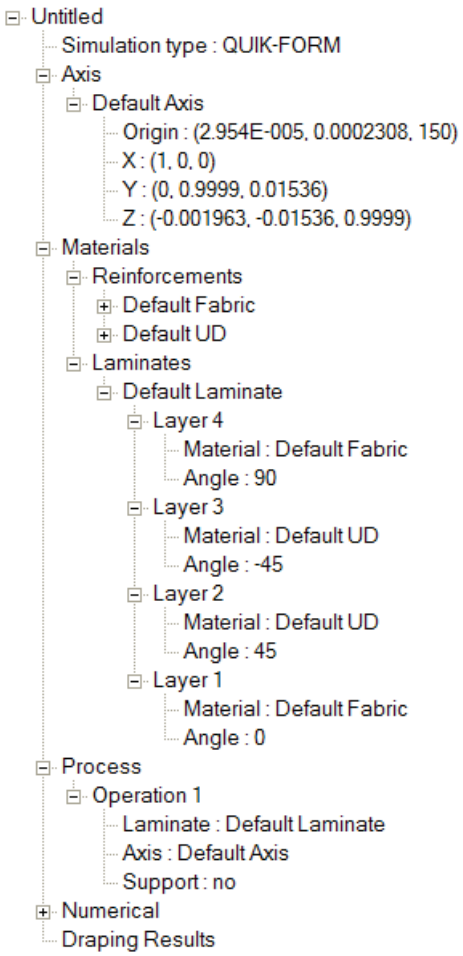
- layer 4: 90 degrees fabric
- layer 3: -45 degrees unidirectional
- layer 2: +45 degrees unidirectional
- layer 1: zero degree fabric



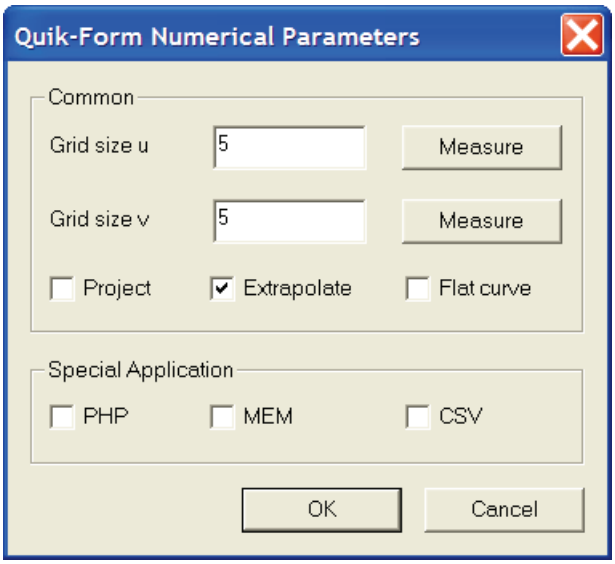
Right-click *Layer 1* in the *Default Laminate* and insert three layers above. Edit each layer by double-clicking it, then set the material and angle as specified above.



Finally you should have the following laminate in the explorer.



After having specified a draping referential and laminate, we would normally have to specify operations in the *Process* folder. Operations are used in the PAM-QUIKFORM interface of **PAM-RTM™** to associate a laminate to a draping referential, and also optionally to select a group of elements on which draping is to be done. In this tutorial, we just use the *Default Operation*, which refers to *Default Axis* and *Default Laminate*.

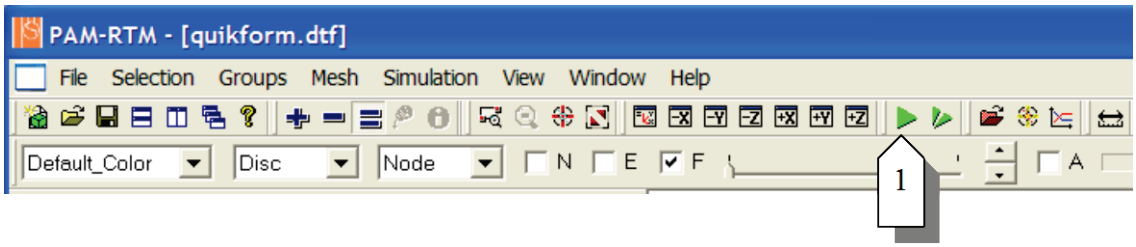


Finally, before launching the PAM-QUIKFORM simulation, we have to set some numerical parameters, the most important ones being *grid size u* and *grid size v*. These are the size of the elements of the draped plies meshes. The default size is zero, which means that it is unspecified and that PAM-QUIKFORM will calculate a size to get a reasonable mesh. In this example, we force the element size to 5 mm in the u and v directions.

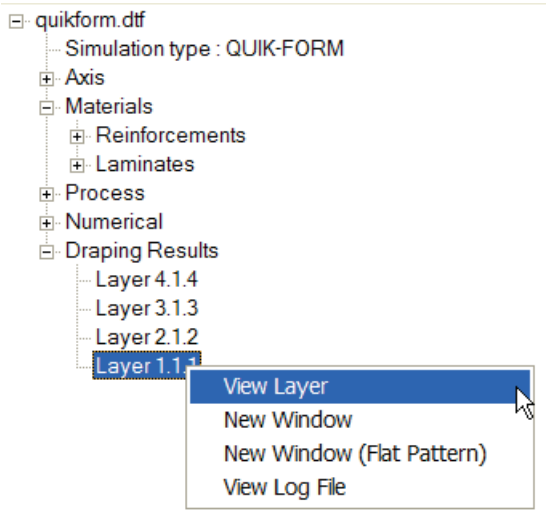
Launching the Simulation and Post-Processing

Before the simulation can be launched, the PAM-QUIKFORM document must be saved with **File->Save**.

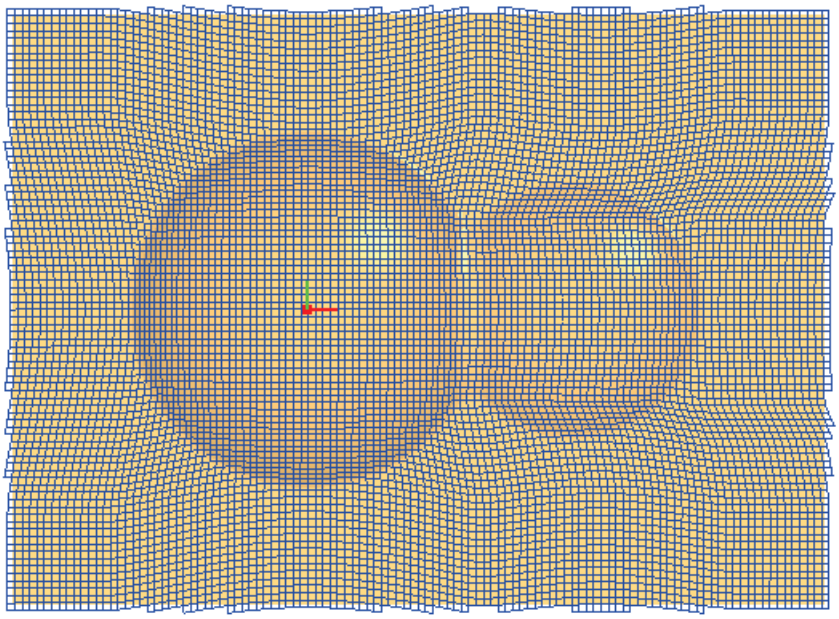
To launch the simulation, use the green arrow button in the toolbar **[1]**.



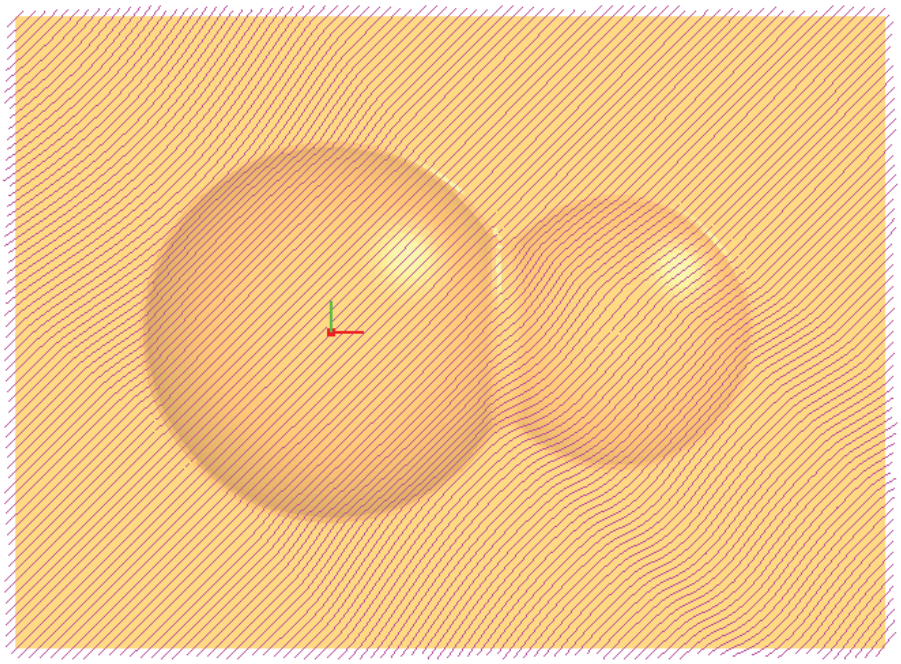
When the simulation is done, **PAM-RTM™** loads automatically all the draped plies meshes and lists them in the *Draping Results* folder of the explorer. Right-click one of the layers and choose **View Layer** to visualize the mesh of the layer on top of the tool mesh. It is possible to visualize many layers in the same window with the command **View Multiple** of the *Draping Results* popup menu.



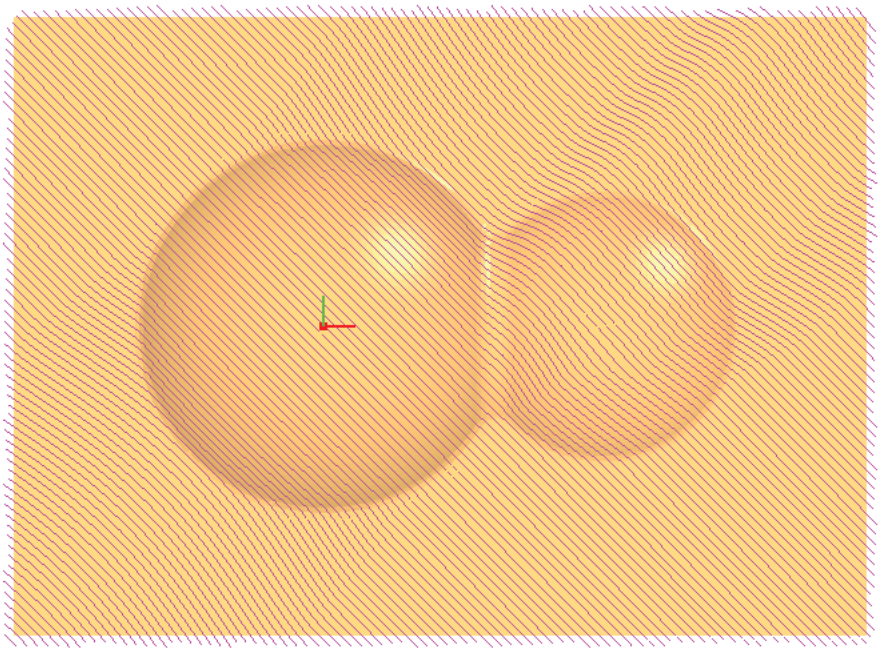
Using this approach for visualization of layers, here is what you should have for layers 1 to 3 (since layer 4 is a 90 degrees fabric, and since it is not possible to display warp and weft with different colors, there is no difference with layer 1).



Layer 1 (zero degree fabric)

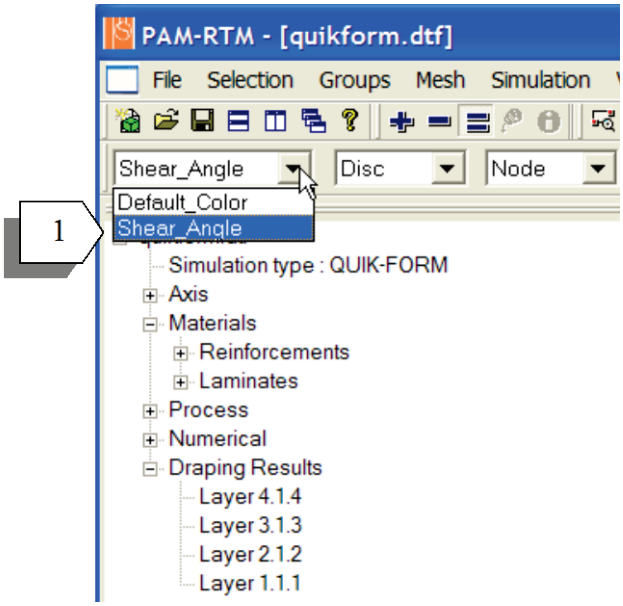


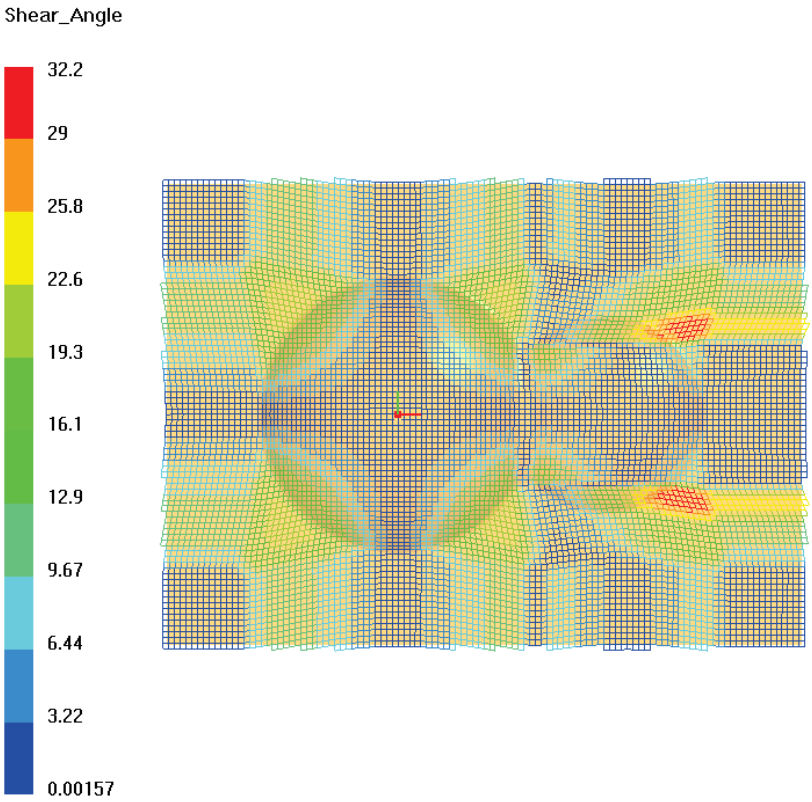
Layer 2 (+45 degrees UD)



Layer 3 (-45 degrees UD)

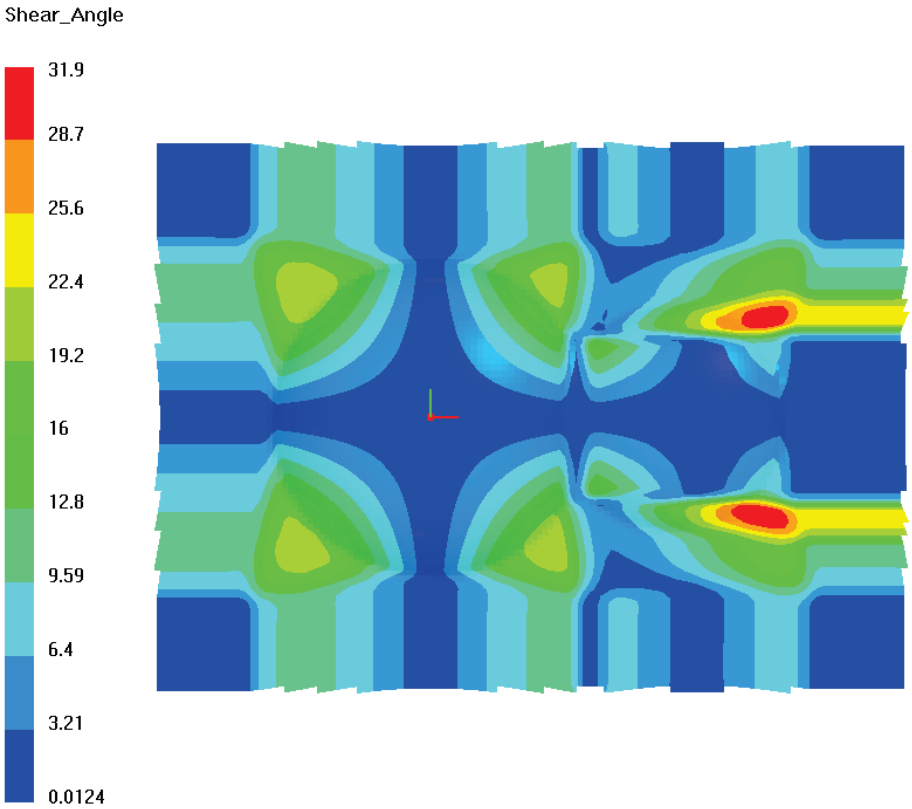
When a layer is visualized with **View Layer**, the tool mesh is forced to default color and the variables available in the scalar field combo box control coloring of the layer mesh edges. Choosing *Shear_Angle* **[1]** leads to the figure below.





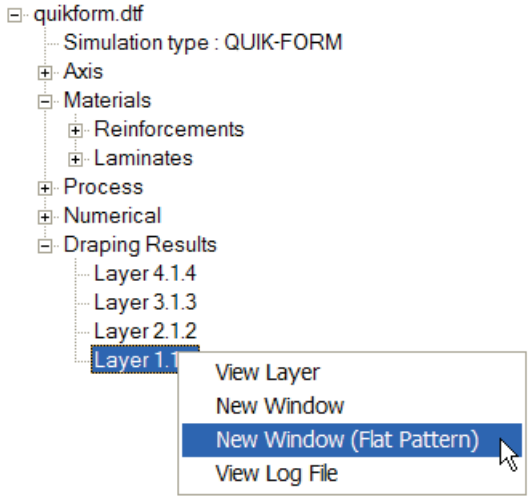
Edges colored with shear angle

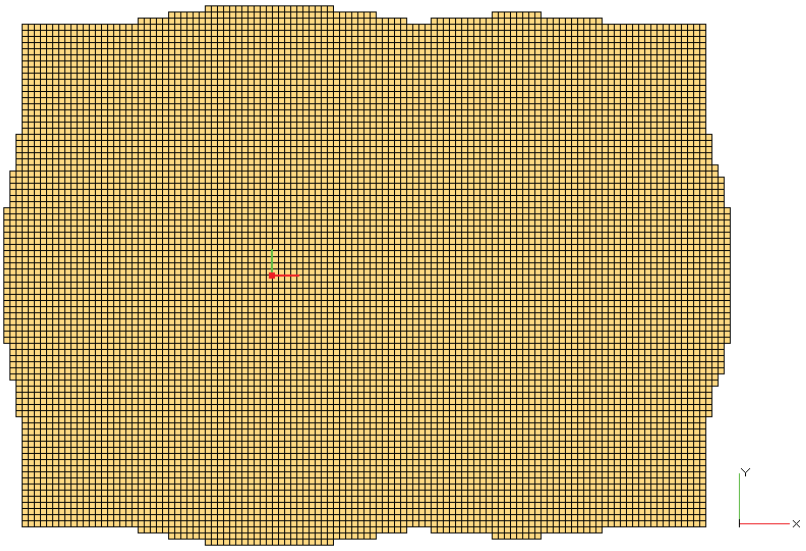
The **New Window** command, available when right-clicking a layer in the *Draping Results* folder, is used to visualize the mesh of a layer in its own 3D window. This gives access to more post-processing options. For example, it is possible to generate contours of the shear angle, as shown below, which is not possible when the layer is visualized in the tool window.



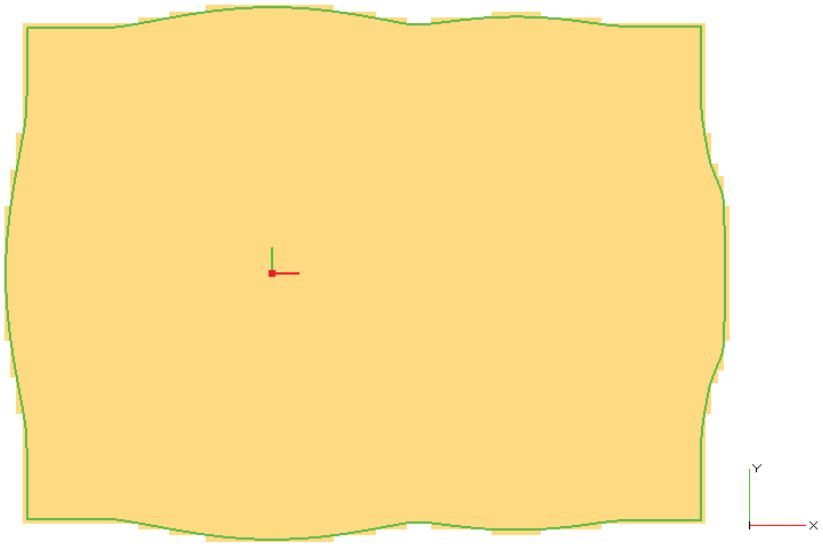
Shear angle contours

Finally, it is possible to visualize the mesh of the 2D flat pattern of a layer by choosing the command **New Window (Flat Pattern)**. To get a more accurate representation of the boundary of the flat pattern, you can activate the *Flat curve* option in the numerical parameters. This option calculates the green curve shown below.





2D flat pattern of layer 1



2D flat pattern of layer 1 with flat curve option

Credits

Twente University, Netherlands, for the tool geometry.

Cranfield University, UK, for the mesh.

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ABOUT ESI GROUP

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