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Engineers Newsletter

volume 41–3

Condenser Water System Savings

Optimizing flow rates and control

Optimized flow rates in the condenser water system provide installed and operating cost savings in chilled-water systems. This EN provides guidance with respect to flow rate selection and offers project teams options to consider for implementation in specific circumstances.

Rather than relegating condenser water system design to standards developed 50 years ago, consider taking a second look. Recent developments such as increased chiller efficiency, the escalating cost of materials, and the increased use of variable-speed drives on pumps and cooling tower fans provide significant opportunities to the owner and designer of condenser water systems.

Taking advantage of these opportunities requires determining the optimum condenser water flow rate. Present industry guidance has shifted from the "standard" 3 gpm/ton flow rate (and oft-assumed 10°F ∆T) to lower flow rates and larger ∆Ts as evidenced below.

- From the *ASHRAE GreenGuide*:[1] "The *CoolTools Chilled Water Plant Design and Performance Specification Guide* recommends a design method that starts with a condenser water temperature difference of 12°F to 18°F (7°C to 10°C)."
- Kelly and Chan[2] state, "In most cases, larger ∆Ts and the associated lower flow rates will not only save installation cost but will usually save energy over the course of the year."
- Taylor[3] states, "Calculate the condenser water flow rate for all pipe sections assuming a range of 15°F (8°C)."

From a design parameters perspective, reducing condenser water flow rates by increasing the design temperature difference is advantageous since it reduces both installed and operating costs. In addition, using variable-speed drives on cooling tower fan motors is beneficial during times when the heat rejection load is lower.

To understand this industry guidance, this newsletter covers the effect of condenser water flow rates and temperature on system design and operation.

System Design

Why do ASHRAE, Kelly and Chan, and Taylor recommend flow rates that are lower than the AHRI standard rating conditions?

To answer that question, let's examine the relationship between the condenser water flow rate and other system variables (see the sidebar on p. 7 for a brief overview). We note that as the condenser water flow rate decreases:

- The chiller leaving condenser water temperature and chiller power rise.
- The condenser water pump power drops.
- If the same cooling tower is used, its approach temperature decreases.
- If the pipe size is reduced and some of the pipe cost savings is used to oversize the cooling tower, the tower fan power can also be reduced.

Table 1. Summary of selection results for example condenser water systems for 700-ton building load

	AHRI Standard 550/590 9.3ºF ∆T*	ASHRAE GreenGuide 14ºF ∆T, same tower, smaller pipes	ASHRAE GreenGuide 14ºF ∆T, oversized tower, smaller pipes
CW flow rate	2100	1400	1400
CW pipe size	10	8	8
CW system PD	30	30	30
condenser PD	24	11	15.6
tower static lift	12.3	12.3	19.2
chiller power	398.9	410.7	411.9
CW pump power	37.6	20.2	24.5
tower fan power	32.1	32.1	16.0
total (kW)	468.6	456.7	452.4

*At the AHRI Standard flow rate of 3 gpm/ton, using today's efficient chillers, the ∆T is 9.3°F rather than the 10°F often assumed.

Let's illustrate these effects by looking at an example 700-ton chilled-water system using different condenser design parameters (Table 1).

Due to the reduction in pump and tower fan energy, system power is reduced at design conditions. Sometimes if the condenser system pressure drop is very low (< 20 feet of head) the design "GreenGuide" system power may be similar to a system designed at the AHRI standard rating conditions. How do the energy and life cycle costs compare? Taylor's analysis concentrates on life cycle costs and shows that reducing the condenser water flow rate (increasing the ΔT) reduces life cycle costs. In his summary he states:

> … life-cycle costs were minimized at the largest of the three ΔTs analyzed, about 15°F (8.3°C). This was true for both office buildings and data centers and for both single-stage centrifugal chillers and two-stage centrifugal chillers. It was also true for low, medium, and high approach cooling towers.

Summary. The information from the ASHRAE GreenGuide, Kelly and Chan, and Taylor all show that project teams should design condenser water systems nearer a 15ºF ΔT (1.9 gpm/ton). Reducing condenser water flow rates allows efficient system design, can reduce system first cost due to reduced condenser water pipe, pump, and cooling tower size, and reduces life cycle costs.

System Operation

Now that we've covered the design of condenser water systems, we can examine the control of the condenser water system—specifically, cooling tower fan and condenser water pump speed operation.

For a better understanding of the options, let's examine two control modes:

- **Mode 1** varies cooling tower fan speed only
- **Mode 2** varies both cooling tower fan and condenser water pump speeds

Mode 1: Cooling tower fan speed control. Many projects today use a fixed setpoint to control the cooling tower leaving water temperature. As the heat rejection load and/or wet bulb temperature drop, the tower fan speed is reduced to maintain the setpoint. The result is a reduction in cooling tower fan power. A number of parties* have found that "near-optimal" control can reduce the sum of chiller-plus-tower energy consumption.

The premise of finding a control point that minimizes the sum of chiller-plus-tower energy consumption can most simply be demonstrated by examining a point in time. Figure 1 shows chiller and cooling tower fan performance at a point in time during the year when the chiller load is 40 percent and the outdoor air wet bulb temperature is 65ºF.

Cooling tower cells

A cooling tower cell consists of the structure, media, and fan. It should be noted that it is more efficient to operate multiple tower cells at part speed than one tower cell at full speed. For example, one cell operating at full speed (40 hp) and the other off gives about 58% of the tower's capacity. Two cells with fans each operating at 60%—a total of 20 hp—gives 60% of the tower's capacity.

If the tower fan operates at full speed, it can produce 69.5ºF leaving water temperature. The chiller power is lowest, but the tower power is high.

The optimal system setpoint occurs at a tower leaving temperature of 75ºF and 60 percent fan speed. The chiller power rises. At these operating conditions, the chiller-plus-tower fan power is reduced by 8.7 percent.

Some assert that a system with a variable-speed chiller may benefit from operating the tower fan at full speed all the time. While the optimal tower fan speed is higher than for the constant speed chiller, running the cooling tower fan at full speed is not optimal. Figure 2 shows that for a system with a variable-speed-drive chiller, the same conditions (40 percent load and 65°F) result in optimal control at ~71°F and a tower fan speed of 70 percent, saving 7.5 percent of chiller-plus-tower power. Note this speed is higher than for the constant-speed chiller but still not at full speed.

Figure 1. Tower control for constant-speed chiller (CSPD), (40% load, 65ºF WB)

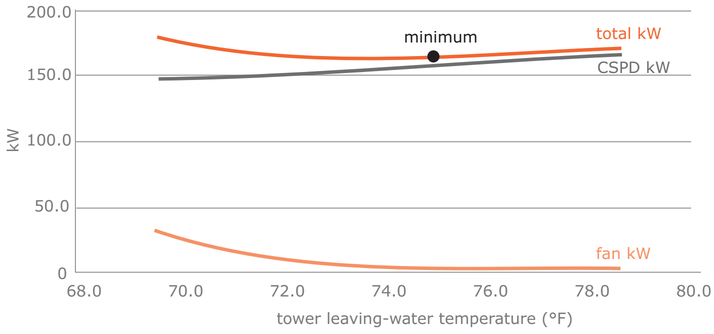
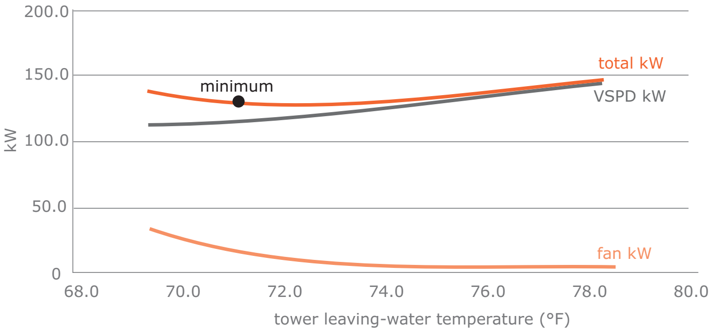


Figure 2. Tower control for variable-speed chiller (VSPD), (40% load, 65ºF WB)



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* They include Braun and Diderrich[4]; Cascia[5]; Crowther and Furlong[6]; Hydeman, Gillespie and Kammerud[7]; Kelly and Chan[8]; and Schwedler.[9] Represented in this list are three chiller manufacturers, three chilled-water system control providers, a utility, and a cooling tower manufacturer.

This is one point in time. How much can be saved over the course of a year? In their *ASHRAE Journal* article, Crowther and Furlong[10] found that for the system analyzed, optimal tower fan speed control saved 6.2 percent in Chicago, 4.7 percent in Las Vegas, and 8.5 percent in Miami.

In a study performed for this newsletter (Figure 3), a 720,000 ft^2 hotel was analyzed in a number of global locations using the following possible control setpoints:

- Fixed tower setpoint at design tower leaving temperature (85ºF in humid climates, 80ºF in dry climates)
- Near optimal setpoint
- Fixed tower setpoint at 55ºF

When compared to making the tower water as cold as possible, near optimal control savings ranged from just under 2 percent in Paris to 14 percent in Toronto. Although in a relatively dry climate with a short cooling season (e.g., Paris) the savings are small, it's clear that chiller–tower near optimal control saves energy and operating cost in all locations. This control is available from at least three control providers; therefore highly consider specifying it on new projects and implementing it on retrofit applications.

Mode 2: Variable-speed condenser water pump *and* cooling tower fans. Now that we understand near-optimal cooling tower fan speed control, let's add the variable of additionally changing condenser water pump speed.

Recently, a few parties have examined variable-speed drives on both cooling tower fans and condenser water pumps:

- Taylor provides a methodology that can be customized for each specific chilled-water system. It requires extensive modeling for each system.
- Hartman[11] reveals only concepts with few details that allow project teams to implement such control themselves.
- Baker, Roe and Schwedler[12] provide a simple method for controlling condenser water pump speed and cooling tower fan speed, but the method may not be optimal for all chilled-water plants or at all conditions.

None of the methods presently available are simple, understandable, all-inclusive, and straightforward at this time. So what are the issues with varying both condenser water pump and cooling tower fan speed?

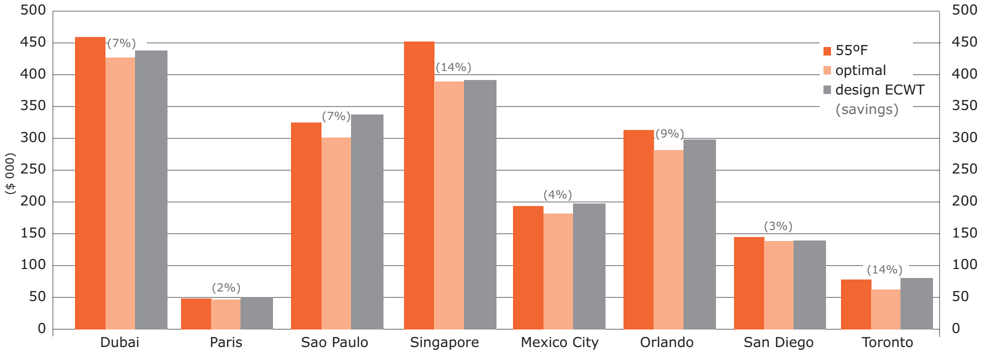
- There are limitations to minimum condenser water flow rate.
- Changing condenser water flow rate affects performance of the cooling tower, condenser water pump, and chiller.
- The control method is not easily understandable.

Let's examine each of these issues.

Flow rate. First, there are limitations to how far condenser water flow can be reduced. The minimum condenser water flow for a specific application is the highest of:

- The minimum flow rate allowed by the tower provider to maintain proper distribution over the fill. Proper distribution keeps tower surfaces wetted, heat transfer at good rates and avoids scaling.
- The minimum condenser flow rate allowed by the chiller provider to keep heat transfer in an acceptable range.
- The minimum pump speed required to produce the tower static lift.

Figure 3. Chiller–plus–tower operating costs



Component performance. Much changes when the condenser water flow is reduced. As previously mentioned:

- Pump power goes down.
- Chiller power rises (as flow rate goes down, leaving condenser water temperature rises).
- Initially, cooling tower heat exchange effectiveness gets better, since the cooling tower receives warmer water. However, as flow is reduced further, heat exchange effectiveness is reduced. This may occur even above the minimum flow rate allowed by the cooling tower manufacturer.

Control method. Finally, the optimal interaction of the cooling tower, condenser water pump, and chiller is not simple to determine since optimal control changes at all system loads, operating combinations, and outdoor air wet bulb temperatures. In addition, slowing condenser water pump and cooling tower fan speeds too much when the chiller is heavily loaded and the wet bulb temperature is high will cause a centrifugal chiller to surge.

An example. To provide a high-level understanding of the trends, system performance is shown for a 700-ton system designed at:

- The AHRI standard rating conditions of 3 gpm/ton design condenser water flow rate. *(column 1, Table 1)*
- The ASHRAE GreenGuide recommended conditions; for this example, 2 gpm/ton condenser water flow rate was chosen. In addition, this system was designed using an oversized cooling tower to reduce design cooling tower fan power by 50 percent. *(column 3, Table 1)*

Figures 4 through 15 (pp. 4-5) depict various chiller loads and outdoor wet bulb temperatures. The black dot indicates the minimum chiller + condenser water pump + cooling tower fan power for each figure.

Trends are noted in Table 2 (p. 6); general observations of these operating choices are shared on p. 6.

Figure 4. AHRI Standard conditions: 90% load, 75ºF wet bulb

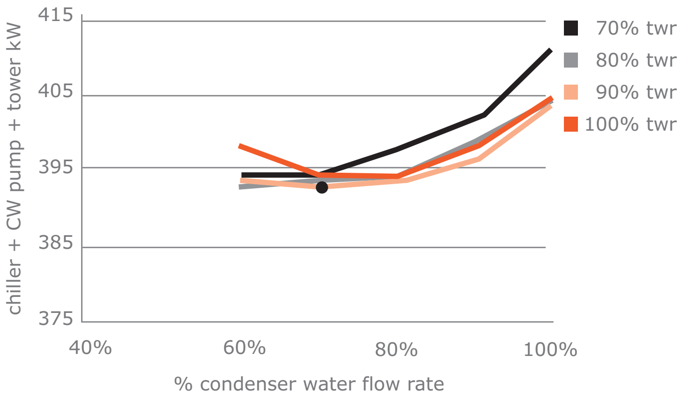


Figure 5. GreenGuide conditions: 90% load, 75ºF wet bulb

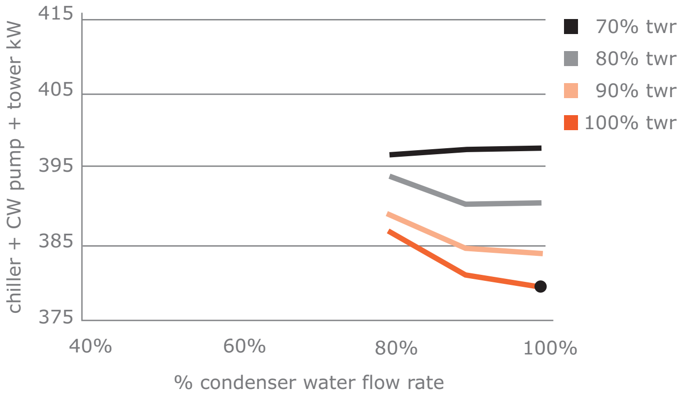


Figure 6. AHRI Standard conditions: 70% load, 65ºF wet bulb

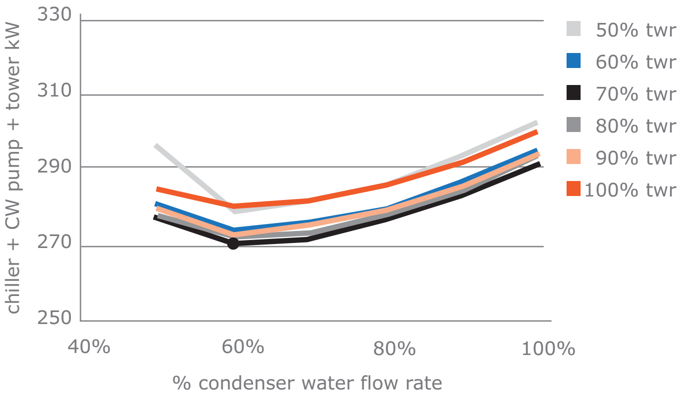


Figure 7. GreenGuide conditions: 70% load, 65ºF wet bulb

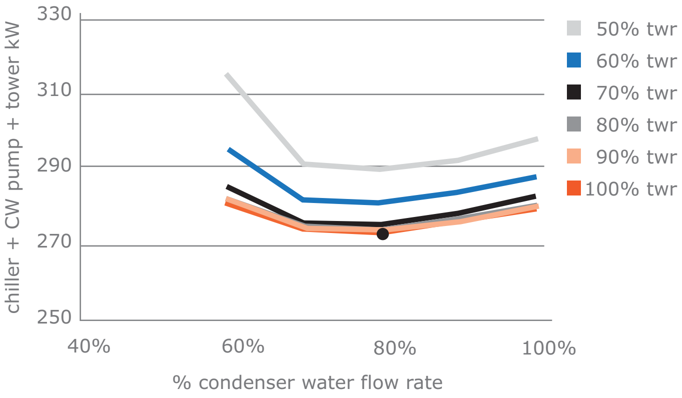


Figure 8. AHRI Standard conditions: 70% load, 55ºF wet bulb

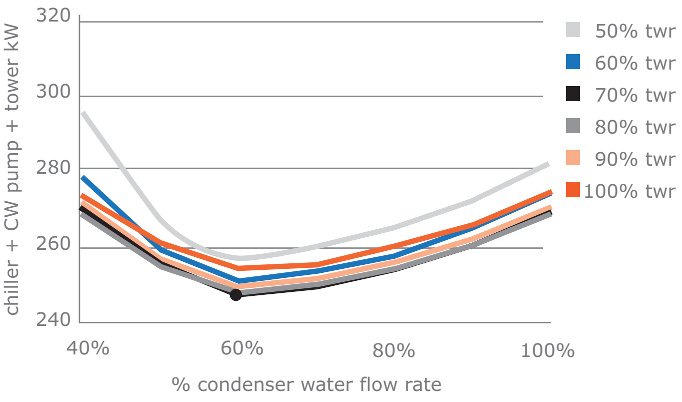


Figure 9. GreenGuide conditions: 70% load, 55ºF wet bulb

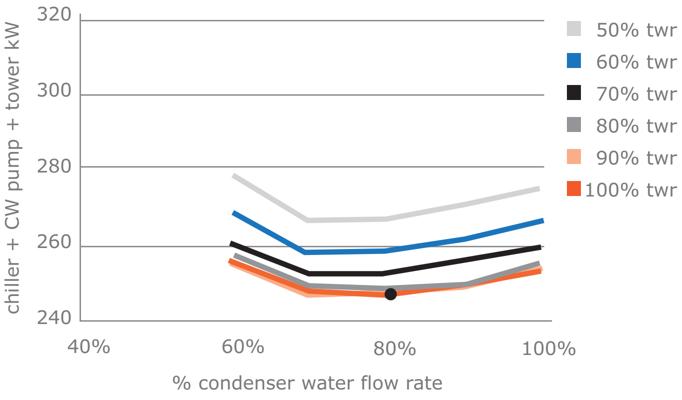


Figure 10. AHRI Standard conditions: 50% load, 65ºF wet bulb

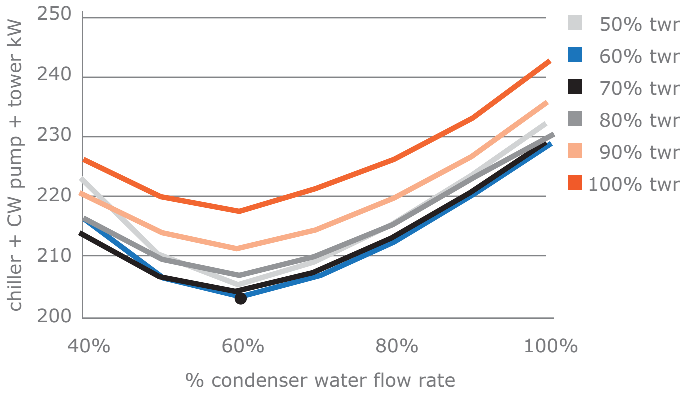


Figure 11. GreenGuide conditions: 50% load, 65ºF wet bulb

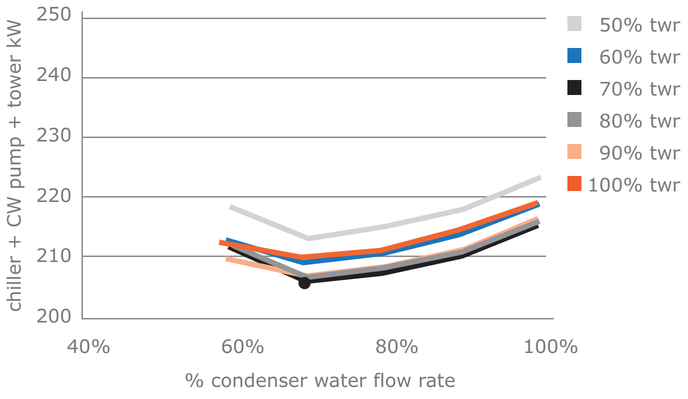


Figure 12. AHRI Standard conditions: 50% load, 55ºF wet bulb

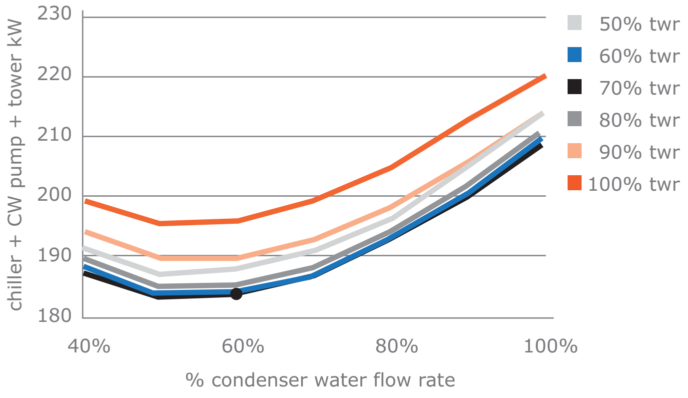


Figure 13. GreenGuide conditions: 50% load, 55ºF wet bulb

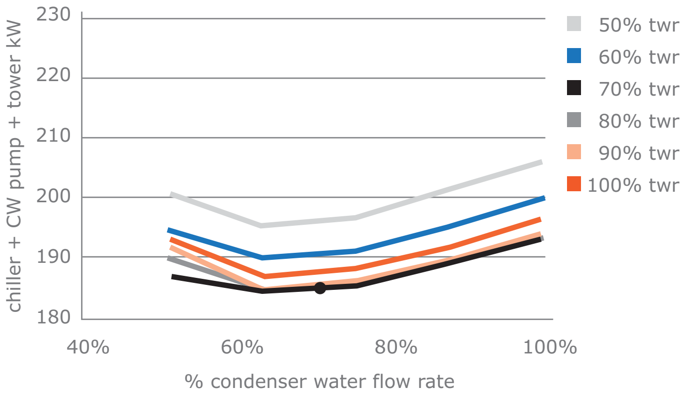


Figure 14. AHRI Standard conditions: 30% load, 55ºF wet bulb

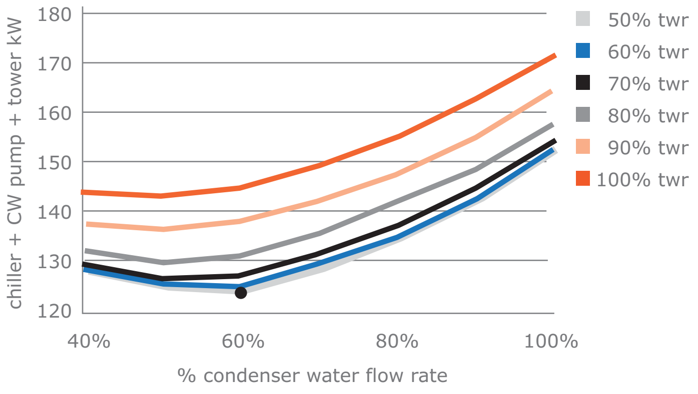


Figure 15. GreenGuide conditions: 30% load, 55ºF wet bulb

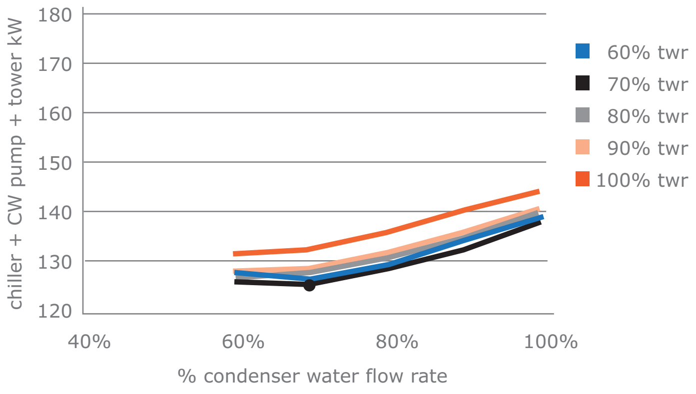


Table 2. Study trends

	Operating Mode	AHRI Standard Conditions 3 gpm/ton design condenser water flow rate				GreenGuide Conditions 2 gpm/ton condenser water flow rate; oversized cooling tower			
		System kW range	**Potential % savings**	**Water flow control**	**Tower speed control**	**System kW range**	**Potential % savings**	**Water flow control**	**Tower speed control**
Figures 4-5	**90% load** **75°F WB**	393-412	4.6	Some savings by reducing flow to 70%	Little savings by reducing speed	380-399	4.8	Reducing flow increases energy usage	Reducing speed increases energy usage
Figures 6-7	**70% load** **65°F WB**	271-303	10.6	Reasonable savings by reducing flow to 60%	Some savings by reducing speed to 70%	271-314	13.6	Some savings by reducing flow to 80%	No savings by reducing fan speed. Fan speeds below 70% increase energy usage significantly
Figures 8-9	**70% load** **55°F WB**	246-282	12.8	Reasonable savings by reducing flow to 60%	Some savings by reducing speed to 70%	245-278	11.8	Some savings by reducing flow to 80%	No savings by reducing fan speed. Fan speeds below 70% increase energy usage significantly
Figures 10-11	**50% load** **65°F WB**	205-243	15.6	Significant savings by reducing flow to 60%	Significant savings by reducing speed to 60%	207-224	7.6	Some savings by reducing flow to 70%	Minimal savings by reducing fan speed. Fan speeds below 70% increase energy usage.
Figures 12-13	**50% load** **55°F WB**	185-221	16.3	Reasonable savings by reducing flow to 60%	Reasonable savings by reducing speed to 70%	185-206	10.2	Some savings by reducing flow to 70%	Minimal savings by reducing fan speed. Fan speeds below 70% increase energy usage.
Figures 14-15	**30% load** **55°F WB**	125-172	27.3	Reducing flow saves significant energy	Reducing speed saves significant energy	126-144	12.5	Some savings by reducing flow to 70%	Some savings by reducing speed to 70%

Discussion: AHRI Standard conditions (3 gpm/ton).

- Not surprisingly, when design condenser water pump power and cooling tower fan power are high, there are significant system energy savings (4 to 27 percent) available at all part load and reduced wet bulb conditions.
- Reducing condenser water flow rate is beneficial at all the conditions examined.
- Reducing cooling tower fan speed is beneficial at 70 percent chiller load and lower—and necessary to reduce system energy use at chiller loads of 50 percent or lower.
- At most operating conditions, optimal system control can reach that of a system designed at a lower condenser water flow rate.
- With that said, below 50 percent chiller load, the spread between the minimum and maximum system power (% max savings) is large. Proper control at these loads is *imperative* when the system design condenser water flow rate is high (3 gpm/ton). Therefore energy-saving *retrofit* control opportunities are available on condenser water systems with design flow rates of 3 gpm/ton.

Discussion: GreenGuide conditions (2 gpm/ton was used).

- Since pump and tower fan power are lower at design conditions, there is less advantage to optimizing the off-design control.
- Reducing condenser water pump speed is *detrimental* at high wet bulb conditions.
- Reducing condenser water pump speed is beneficial at reduced ambient wet bulb conditions.
- Reducing tower fan speed has little or no benefit until chiller load is less than 50 percent.

Overall conclusions.

- On existing systems designed at AHRI conditions, reducing condenser water pump speed and cooling tower fan speed offers significant savings.
- Designing new systems at the AHRI standard flow rate significantly increases the risk of control decisions resulting in inefficient system operation—at all load and wet bulb conditions.

continued on p. 8

Condenser Water System Components

This section provides an overview of how condenser water system components react to changing conditions; these facts are used throughout the newsletter.

Cooling towers. Cooling towers reject energy (building load and heat of compression) from water-cooled chilled-water systems.To reject heat, water is passed through the cooling tower where a portion of it evaporates. How close the leaving tower water temperature is to the outdoor air wet-bulb temperature is called the *approach*.

The approach changes as outdoor condition, heat rejection, and cooling tower airflow vary. The lower the approach temperature, the colder the water temperature will be leaving the cooling tower. The approach is important because the tower leaving water temperature is the same as the chiller entering condenser water temperature.

During operation, approach changes as follows:[13]

- At a decreased heat rejection load, approach decreases.
- At a constant heat rejection load, as wet bulb decreases, approach increases.
- As water flow decreases, approach decreases.*
- As tower fan speed is reduced, approach increases.

Let's turn our attention to cooling tower performance as fan speed is reduced. It is important to understand how tower fan speed and airflow reduction affect cooling tower fan energy.

At off-design conditions, cooling tower fan speed may be modulated. Figure 16 shows that the tower fan power varies with the cube of the speed—so reducing fan speed by just 30 percent (i.e., to 70 percent) results in a power reduction of almost 66 percent.

Note that even when the tower fan is off, due to convection there is still heat rejection available—often a bit above 15 percent of the tower capacity.

Condenser water pumps. Condenser water pumps supply the required condenser water flow rate and overcome the pressure drop through the chiller's condenser, the condenser water pipes, elbows and valves, and lift the water from the basin to the top of the cooling tower (the static lift). As flow varies, the pressure drop through the system and the condenser vary approximately with the square, but static lift remains constant.

The equation for pump power is shown below. As flow rate and pressure drop decrease, the pump power decreases. The effect of condenser pump power reduction on optimal system operation is considered on p. 3 of this newsletter.

Condenser water pump kW =

$$\frac{\text{gpm} \times \Delta P \times 0.746}{3960 \times \text{PE} \times \text{PME} \times \text{PDE}^{\dagger}}$$

Chillers. A chiller's compressor must produce the pressure difference (lift) between the evaporator refrigerant pressure and the condenser refrigerant pressure. The evaporator pressure is determined primarily by the chilled water *leaving* temperature. Often people think of the entering condenser water temperature as setting the pressure the chiller's compressor must produce. That is incorrect. The condenser refrigerant temperature and pressure are determined primarily by the *leaving* condenser water temperature—which in turn is determined by the entering condenser water temperature, chiller heat rejection, and flow rate.

As shown in the first two columns of Table 3, for a given cooling tower, as flow rate is reduced, the entering tower water temperature rises. Note, the range difference is 4.7°F, but since the tower approach temperature improves, the entering tower water temperature only increases by 2.8°F. Entering tower water temperature is the same as the chiller leaving condenser water temperature. So, as flow rate is reduced, the chiller leaving condenser water temperature rises, as does the chiller power.

Figure 16. Cooling tower fan performance

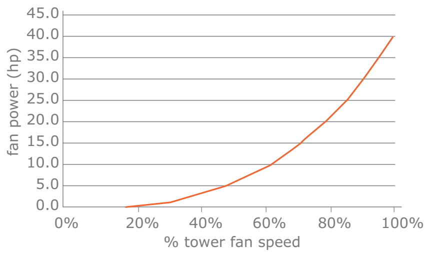


Table 3. Cooling tower operation/selection with decreased flow

Condition	Load (%)	WB (ºF)	Range (ºF)	Flow (gpm)	Approach (ºF)	LWT (ºF)	EWT (ºF)	Fan speed (%)	Tower power (hp)
AHRI flow rate	100	78ºF	9.3ºF	2100	7	85ºF	94.3	100	40
Same tower, GreenGuide recommended flow rate	100	78ºF	14ºF	1400	5.1	83.1ºF	97.1	100	40
Oversized cooling tower (37% more cost)‡	100	78ºF	14ºF	1400	5.5	83.5°F	97.5	100	20

* At some reduced flow rate the approach increases, even if the flow rate is above the minimum for the tower. This is due to reduced heat transfer effectiveness.

† PE = Pump Efficiency; PME = Pump Motor Efficiency; PDE = Pump Drive Efficiency

‡The larger cooling tower can be paid for by the reduction in the condenser pipe and pump installed cost. In this case, the tower fan power was reduced by oversizing the tower.

What about the operator?

All of the previous analysis is predicated on optimal control working properly, and being allowed to continue to work without "manual override." Often the chilled-water system operator wants to understand system operation, so he or she can change that operation when necessary. For example, they may ask, "What is the cooling tower setpoint?" When condenser water pump and cooling tower fan speeds are varied, there is no cooling tower setpoint—since the leaving cooling tower temperature is a result of the system operation decisions. This can be unsettling to some system operators.

So it is imperative that the system operator be "on board" with the control methods, understand them, and have the ability to both monitor and change them if necessary.

- Control is project, load, and ambient condition dependent.
- On new projects, designing to the ASHRAE GreenGuide conditions (12–18°F temperature differences resulting in 2.3 to 1.6 gpm/ton) and oversizing the cooling tower to reduce fan power offers savings at all conditions and savings are less dependent on coordinating system control—especially at lower load conditions.

Simply put, designing condenser water systems at flow rates of 1.6 to 2.3 gpm/ton results in reduced installed costs as well as a much higher probability that the system will operate efficiently—no matter how the condenser water pump and cooling tower fan are controlled.

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Summary

1. Use the ASHRAE GreenGuide guidance of 12-18ºF ΔT for condenser water systems (2.3 - 1.6 gpm/ton) to reduce plant installed and life cycle costs.
2. Consider varying cooling tower fan speeds on all installations.
3. Consider varying condenser water pump and cooling tower fan speeds on systems not designed using the ASHRAE GreenGuide guidance, and where the plant operators are on board, trained, and retrained when the operators change. When used, keep the control method understandable, transparent, and as simple as possible (but not any simpler).

By Mick Schwedler, manager, applications engineering, and Beth Bakkum, information designer, Trane. You can find this and previous issues of the Engineers Newsletter at www.trane.com/engineersnewsletter. To comment, e-mail us at comfort@trane.com

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October 2012

Air-to-Air Energy Recovery

Join Trane for a discussion of the various technologies used for air-to-air energy recovery and the importance of properly controlling these devices in different system types.

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