Engineers Newsletter

volume 45–1

Condenser Water System Retrofit Opportunities

Although there are many publications dedicated to the topic of retrofitting chilled-water systems, much attention is given to the chilled-water side, often ignoring significant opportunities to retrofit the condenser water system. Through examples, this *Engineers Newsletter* focuses on energy-saving opportunities specific to condenser pump, cooling tower fan use and system sequence of operation and control.

Figure 1. Condenser water system schematic

Background

The search for energy savings can be never ending, especially in existing HVAC systems. One strategy to make the task more manageable is to segment the chiller plant into smaller sub-systems and consider opportunities within each.

For example, consider the retrofit opportunities within the condenser water system (chiller, condenser water pumps and cooling tower fans). Let's explore the opportunities by walking through the example system outlined in Table 1 and begin with a look at the cooling tower.

For simplicity, neither the chilled-water system nor chiller retrofits are addressed. For more information on these topics, please see the November 2009 *ASHRAE Journal* article, "Upgrading Chilled-Water Systems."

Table 1. Existing chiller plant characteristics
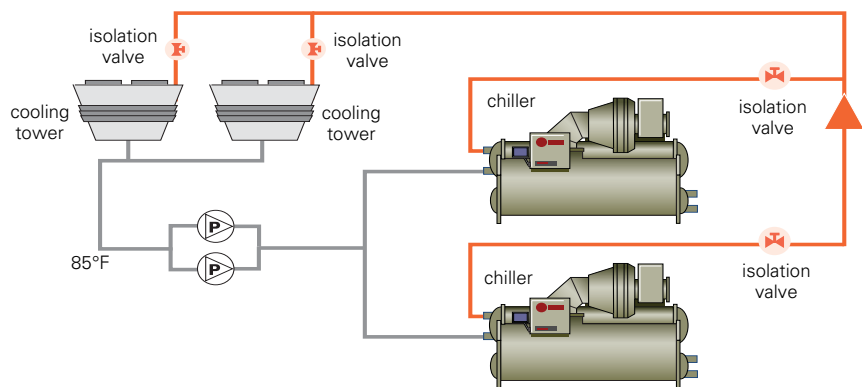
Component	Existing design
Chillers	
Number	2
Type	Centrifugal
Modulation	Variable-speed drive (VSD)
Full load kW/ton (AHRI Standard Conditions)	0.60
Design capacity (tons)	400
Condenser water flow rate (gpm)	1,200
Cooling Tower	
Number of cells	2
Humid climates (°F)	94.3 EWT/85 LWT/78 WBT*
Dry climates (°F)	89.3 EWT/80 LWT/70 WBT
Fan motor hp	30
Control method	Variable-speed drive (VSD)
Tower setpoint (°F)	65
Condenser water pumps	
Number	2
Flow rate (gpm)	1,200
Pump motor hp	40
Pump bhp	28.9
Configuration	Manifolded

*Entering-water temperature (EWT) /leaving-water temperature (LWT) /wet-bulb temperature (WBT)

Cooling tower opportunities

Add a variable-speed drive (VSD) to constant-speed cooling tower fans.

Since 1999, ASHRAE Standard 90.1 has required speed modulation control on cooling towers. At that time, the requirement was satisfied by the use of either two-speed motors or VSDs. Because of improved reliability and reduced cost, today's new installations feature the latter. A logical place to start is to add a VSD to the cooling tower fan motor.

When adding a VSD, it's very important to first ensure its compatibility with the motor (see inset below). Neglecting this step can negatively impact reliability.

Secondly, significant savings won't occur if tower fan control is ignored. When controlled properly, applying a VSD to a cooling tower fan results in significant system energy reduction.[2][3][4][5]

Crowther and Furlong[3] analyzed optimal cooling tower fan control for a 400-ton chilled-water plant. Table 2 shows optimal control savings compared to a 65°F tower setpoint. In all cases, the chillers used more energy, but *system* energy was reduced.

Drive and motor compatibility.

Lindhorst [1] begins his article on drive and motor compatibility, describing methods to assure compatibility:

"You bought VFDs to improve operations and processes while saving energy. Yet, you're seeing many costs going up and motor failures doubling. What's happening? It's almost certain you have a mismatch between your drives and motors. However, such a mismatch doesn't have to be.

'Our motors lasted for years when we had gear drive motors operating from line power. We put in a variable-speed drive, and now we have failures.' Despite coincidences, the drive is not the culprit. Drives don't make motors fail; not matching the drive and the motor does. Simply put, there is no reason for you to fear embracing modern drive technology."

Savings from 2.5 percent to 7.8 percent were realized by optimizing the cooling tower setpoint at each heat rejection load and outdoor air wet-bulb temperature.

These results reveal that the combination of adding a VSD to the cooling tower fans *and* having optimal tower setpoint control can create significant energy savings.

Operate additional cooling tower cells at the same condenser flow rate.

It may seem counterintuitive to suggest that *more* cooling tower cells can lead to *less* energy usage, but this is actually an excellent way to achieve significant savings.

Many chilled-water plants (including our example from Table 1) operate in a simple manner; when a chiller is turned on, a condenser water pump and an additional cooling tower cell are turned on. Using additional cooling tower cells allows more heat transfer surface area to be used, which allows less fan power to produce the same leaving-tower water temperature.

When executing this technique in an existing system, it's important to consider ASHRAE Standard 90.1-2013 requirements for tower flow turndown on new installations (see sidebar). Tower flow turndown reduces the flow rate per cooling tower cell, with the assumption that the cooling tower fill remains wetted. There is a minimum flow rate per cooling tower cell (available from your tower provider) that must be maintained. Because of this, in an existing application, retrofit of the cooling tower may be required to ensure proper tower performance and good heat transfer.

To illustrate how operating additional cooling towers at the same flow rate can impact energy savings, let's consider an example using the design conditions in

ASHRAE 90.1-2013 Tower Flow Turndown Requirements[6].

6.5.5.4 Tower Flow Turndown. Open-circuit cooling towers used on water-cooled chiller systems that are configured with multiple- or variable-speed condenser water pumps shall be designed so that all open-circuit cooling tower cells can be run in parallel with the larger of:

a. the flow that is produced by the smallest pump at its minimum expected flow rate or
b. 50% of the design flow for the cell.

Fulfilling tower flow turndown requirements. Marley[7] gives practical information for implementing reduced tower cell flow in crossflow and counterflow cooling towers. In crossflow towers, adding nozzle cups (Figure 2) to funnel water to the outboard areas of cooling tower, "…enables the ability to:

- Maintain uniform air-water contact for maximum efficiency
- Provide consistent off-design performance
- Minimize drift
- Minimize risk of icing in freezing weather."

Another crossflow method described uses dams to distribute the water across the tower fill, but the article points out that uneven water flow distribution may result in uneven airflow across various portions of the tower fill. It also states, "When operating a cooling tower in a free-cooling mode, the water at the ends of the cell may be at greater risk of icing."

Lastly, the article discusses two types of integral air inlet louvers that perform differently during periods, which could result in ice formation.

Figure 2. Marley VariFlow™ Nozzle Cap

Courtesy of SPX Cooling Technologies, Inc. ©2016

Table 2. Applying cooling tower fan controls to minimize "chiller plus tower" energy

City	Tower fan VFD (65°F tower setpoint)			Chiller-tower optimization			Savings vs. 65°F setpoint
	Tower (kWh/yr)	Chiller (kWh/yr)	Total (kWh/yr)	Tower (kWh/yr)	Chiller (kWh/yr)	Total (kWh/yr)	
Chicago	18,754	129,679	148,433	5,892	134,968	140,960	5.0%
Las Vegas	25,021	226,514	251,535	11,384	233,909	245,293	2.5%
Miami	74,972	440,145	515,117	14,815	460,094	474,909	7.8%

Figure 3. Tower performance with one tower cell operating
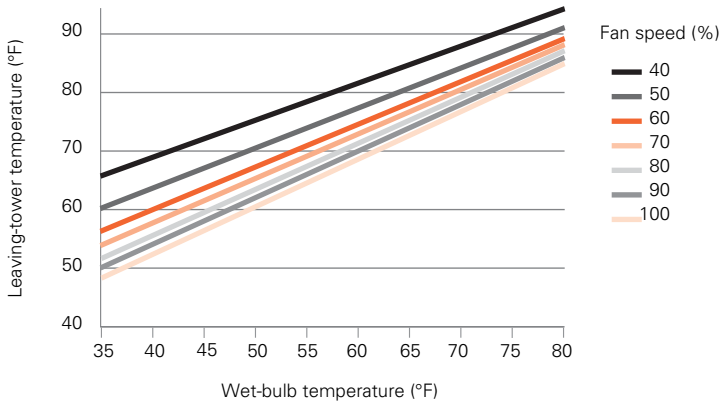
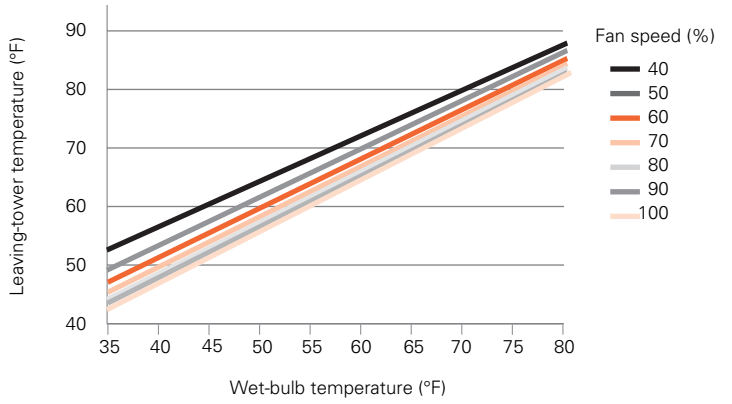**Figure 4. Tower performance with two tower cells operating**

Table 1. During "normal" use, when one chiller operates, one condenser water pump operates. Comparison is made between operating one or two cooling tower cells at the same total flow rate (1,200 gpm). This doubles the active tower heat exchange surface.

Figures 3 and 4 depict leaving-tower temperatures at various tower fan speeds and 60 percent chiller load. Note that with two cells operating at the same fan speed, the leaving-tower water temperature is considerably lower.

Using this data, Figure 5 compares cooling tower leaving-water temperature with one cell operating at 100 percent fan speed (30 hp) or two cells at 60 percent fan speed (total 14 hp). Roughly the same performance is delivered at 16 hp lower tower fan power. Since leaving-tower temperature is the same in either case, there is no effect on chiller energy. Therefore, system performance improves if two tower cells can be operated.

While near-optimal tower fan control is desirable, many systems are operated to

maintain a specific leaving-tower water temperature. Figure 6 compares fan power based on the number of operating tower cells at 60 percent chiller load, 60°F tower setpoint and various wet-bulb temperatures.

From this graph, two observations are evident:

- At wet bulbs below 54°F, operating two cells allows both fans to operate at partial speed, and therefore reduces tower fan power.

- At wet-bulb temperatures that are too high for the tower to attain its 60°F setpoint, operating two tower fans doubles the tower fan power. This may lead to increased system energy consumption.

In order to avoid this excess energy consumption, great care must be taken with the tower fans' control. The following equation ensures that fan energy is not increased when additional cells are operated. This is done by setting a

maximum fan speed. Table 3 provides examples.

$$N \times hp/fan = (N + A) \times hp/fan \times (MaxSpd)^3$$

Rearranged: $MaxSpd = [N / (N + A)]^{1/3}$

where,

N = the number of tower cells normally operating

A = the number of additional tower cells operating

$MaxSpd$ = the maximum speed at which the tower cells should operate so the fan power does not exceed "normal" operation

Table 3. Maximum tower fan speed when operating additional tower cells

Number of tower cells normally operating (N)	Number of additional tower cells operating (A)	Maximum fan speed
1	1	79%
1	2	69%
1	3	63%
2	1	87%

Figure 5. Comparison of one and two cooling tower cells operating at different fan speeds.
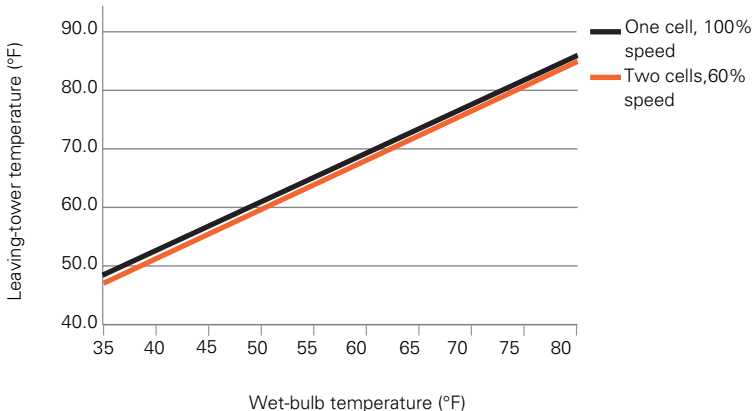
Figure 6. Tower fan power for one and two cells operating to maintain a 60°F setpoint.
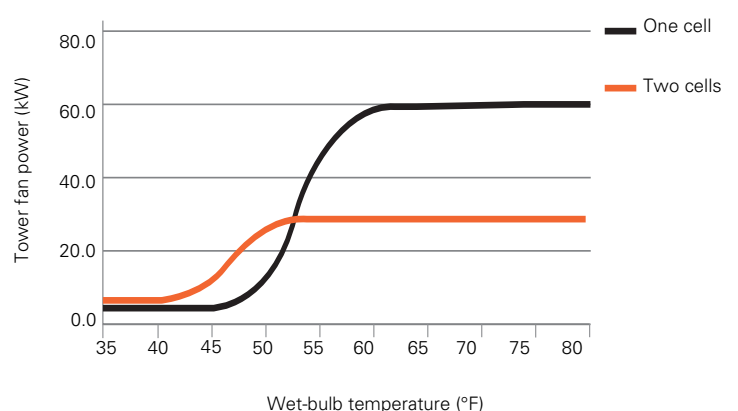
Repurposing cooling towers for load changes. It's widely believed that cooling towers are designed to reject a specific amount of heat. At selected conditions, this is true. When those conditions change—whether through an increase or decrease in load—the towers' entering- and leaving-water temperatures must change[8]. There are several strategies that can take advantage of these changing conditions.

Increase in design cooling load. It's not uncommon for building loads to increase, whether it's due to more occupants in the same area, an increase in internal load, or a change in the building's purpose. Table 4 compares the performance of the previously selected cooling tower at the original design conditions, as well as for loads increased by 50 percent and 100 percent.

As demonstrated in the table data, the increased heat rejection load can be served by the same condenser pump(s), pipes and cooling tower if the tower entering-water temperature (chiller leaving-condenser-water temperature) can be increased.

Application of this principle greatly reduces the first cost of a retrofit and, in some cases, brings a job back into budget, allowing the project to move forward.

Positive displacement compressor (screw or scroll) chillers typically have the capability to operate with higher leaving water temperatures and still meet the required capacity. Existing centrifugal chillers, however, may not have this capability. Instead they must be reselected to determine if they can operate at the elevated entering and leaving water temperatures.

While these elevated conditions enable the tower to provide more heat rejection with the same input power, they do require the chiller to do more work. More work means more power used than a chiller selected at original conditions, at least at full load.

Decrease in design cooling load. In a similar manner, when design load decreases (e.g. due to lighting retrofits or changes in the building envelope) the heat rejection load decreases. In turn, the approach temperature and the cooling tower range also decrease.

The tower can be used with its original design flow or with reduced flow to optimize the condenser water system energy use. In either case the entering tower (leaving-condenser) water temperature is significantly reduced, even at design outside air conditions (Table 5).

The energy used by the chiller at a given load is dependent on the chiller

condenser refrigerant pressure, which is dependent on its leaving-condenser-water temperature. At the design-condenser-water flow rate, cooling tower approach temperature and range reduction combine to reduce the chiller leaving-condenser water temperature by over 3°F, reducing the chiller power. Chiller power reduction is dependent on the specific chiller type, selection and unloading mechanism.

Condenser water pump opportunities

Let's move on to opportunities to reduce condenser pump energy.

The power a pump uses is proportional to the flow rate multiplied by the pressure drop:

$$kW \, \alpha \, gpm \times \Delta p$$

Because this is true, we can reduce the work the pump requires by reducing either flow rate or pressure drop. This can be done in a number of ways including:

- Reducing design flow rate
- Reducing pressure drop against which the pump is operating
- Dynamically varying the pump speed

Use pump VSD to reduce design condenser flow rate. Reducing condenser flow rate reduces the tower approach temperature, but increases the range, as shown in the two right most columns of Table 5.

The result is a tower entering water temperature lower than the original, but higher than at full flow. Based on the above equation, the pump energy at 70 percent flow is reduced by more than 50 percent, so the optimal combination of pump, chiller and tower fan-power energy at part load could be less than with the design flow rate.

Table 4. Tower performance when design load is increased

	Existing Design	50% load	100% load
Defined capacity (tons)	400	600	800
Ambient wet bulb (°F)	78	78	78
Flow rate (gpm)	1,200	1,200	1,200
Entering water temperature (°F)	94.3	101.0	107.6
Leaving water temperature (°F)	85	87	89
Range (°F)	9.3	14	18.6

Table 5. Tower performance when design load is decreased

	Existing Design	70% load	70% load 70% flow
Defined capacity (tons)	400	280	280
Ambient wet bulb (°F)	78	78	78
Flow rate (gpm)	1,200	1,200	840
Entering water temperature (°F)	94.3	89.5	91.3
Leaving water temperature (°F)	85	83	82
Range (°F)	9.3	6.5	8.7

Use pump VSD to balance condenser flow rate. There is potential energy savings by implementing both a reduced flow rate and a reduced pressure drop. Often to set the design condenser flow rate of a constant speed pump, a pressure drop is imposed. This is often referred to as *throttling*. The constant speed pump rides its curve and flow is reduced to the desired rate. Either a balancing valve or Triple Duty® Valve (TDV) can be installed to achieve this. As the name implies the TDV serves three functions; acts to balance the system flow, acts as a check valve (to keep water from flowing backwards through the pump), and acts as an isolation or shutoff valve.

Alternately, a VSD installed on a condenser water pump can be used to balance the system flow rate. This is done by opening the balancing valve, or the balancing portion of the TDV, and using the VSD to set the design flow rate. This reduces energy use more than throttling since the pressure drop associated with the balancing valve is no longer experienced.

Energy is reduced as a result of reduced pressure.

Condenser water pump power.

The condenser water pump must overcome the pressure drop through the condenser pipes, the valves and fittings, the chiller condenser, and also the static lift from the basin of the cooling tower to the top of the cooling tower. Pump power can be calculated:

Hp = gpm x (Condenser ΔP + Pipe ΔP + Static Lift) / (3960 x pump efficiency)

When condenser flow rate is reduced, the friction-based pressure drops decrease, but the static lift remains the same. For this reason, the condenser water pump power does not directly follow the affinity laws, which state the pump power varies with the cube of the flow rate. How close the pump power savings get to the affinity laws is dependent on the ratio of static lift to total design pressure drop.

Use pump VSD to dynamically vary condenser water flow rate.

It's commonly asked whether a VSD should be used to dynamically vary the condenser water pump speed and flow rate. This can provide energy savings but increases control complexity.

As the condenser flow rate is reduced, pump energy decreases.

This decreased flow rate raises the chiller leaving-condenser-water temperature which increases the condenser refrigerant pressure. To produce that refrigerant pressure, the compressor must do more work causing chiller energy use to increase.

However, as the entering cooling tower water temperature rises, the cooling tower becomes a more effective heat exchanger. The result is lower cooling tower fan energy use.

As you can see, there are energy trade-offs. Let's examine an all-variable-speed chilled-water plant. As mentioned earlier optimal system control is challenging. To optimally control such a system, the chiller energy, pump energy and cooling tower fan energy must *all* be considered at *all* permutations of system load and outdoor air wet-bulb temperatures.

We should mention some possible drawbacks of applying the presently available all-variable-speed technologies. For example, plant operators may not understand the optimization method and the controls rely heavily on proprietary algorithms. Additionally there is a high cost of adding VSDs on all components, not-to-mention modeling all variable-speed chilled-water plants is difficult. These issues exist but they should not deter building owners from exploring dynamic condenser-water flow further.

The design team will need to determine whether an all variable-speed plant is appropriate.

Many articles present solutions and demonstrate that energy use of many plants can be reduced by dynamically reducing the condenser-water flow rate through sophisticated system-level controls.[9, 10, 11, 12 13]

A previous *Engineers Newsletter*[14] showed that when an existing system was designed using condenser water flow rate of 3 gpm/ton, savings were available by using dynamic condenser-water-pump speed control.

Since many existing plants were designed using the old "rule-of-thumb" 3 gpm/ton, energy savings can be accomplished by varying the condenser water flow rate.

However, at lower and more optimal design flow rates (1.8 gpm/ton to 2.3 gpm/ton), the available savings from variable flow are minimal.

Figure 7. University building comparison in four cities.
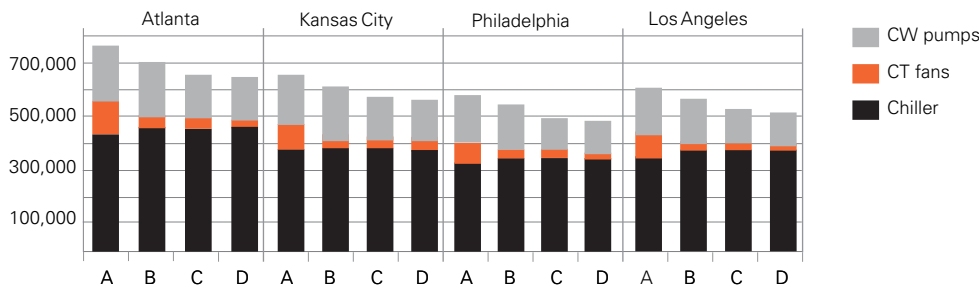
Figure 8. Office building comparison in four cities.
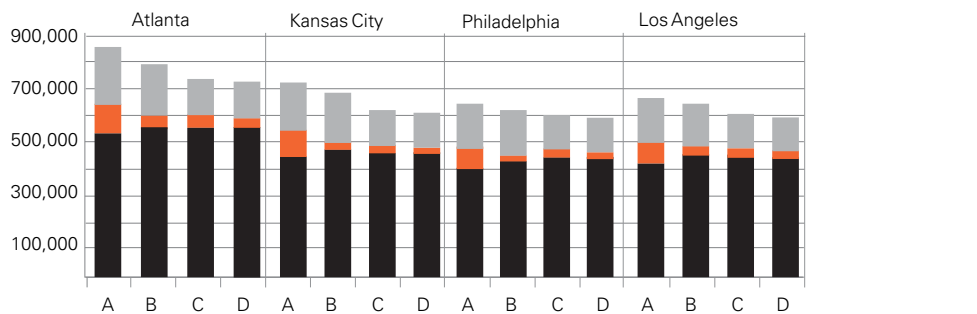
Table 6. Alternatives compared

	Alternative	Description
A	Base	see Table 1
B	Chiller -tower optimization	Near-optimal tower control
C	Chiller-tower optimization plus balanced pump (using a VSD)	Alt 2+ VSD to balance condenser water pump flow
D	Chiller-tower optimization plus balanced pump (using a VSD) plus operating an additional cooling tower cell	Alt 3 + retrofit of cooling tower to allow use of two tower cells when one chiller is operating.

Analysis

Using our previous base example in Table 1, models were developed for an 800-ton university building (Figure 7) and 800-ton office building (Figure 8) in Atlanta, Philadelphia, Kansas City and Los Angeles. Since the buildings were existing, the only location for which an airside economizer was assumed is Los Angeles. Alternatives are shown in Table 6.

It should be noted that because the analysis tool used cannot accurately model the effect of dynamic condenser flow rates on both chiller and cooling tower performance, estimated savings for dynamic flow rate control is not included in this newsletter.

Order of conservation. The order in which conservation is employed can impact energy savings. For example, if using additional cooling tower cells had been the first Energy Conservation Measure (ECM) employed, the percentage savings would have been higher. While the data is not shown here, if it had been the first ECM employed it would have saved about 5 percent, a little less than chiller-tower optimization.

Results of the modeling show that there is significant potential for energy savings when retrofitting is considered. In both building types and all locations, the following can be observed concerning the sum of chiller, cooling tower fan and condenser water pump annual energy use:

- Chiller-tower optimization saved 6 percent to 7 percent.
- Using a VSD to balance the condenser flow rate saved 6 percent to 7 percent.
- Activating an additional tower cell saved 1 percent to 1.5 percent additional energy. As previously discussed, when additional tower cells are operated, the fan speed is limited.

Summary

Cooling towers, condenser water pumps and system controls all provide retrofit opportunities with many benefits.

- By adding variable speed to cooling tower fans and controlling to near-optimal temperatures, we can save significant system energy.
- Significant energy savings also comes from using VSDs to balance condenser water flow. As long as tower fan speed is controlled, additional savings is also available by allowing more cooling tower cells to operate.
- Lastly, though presently available analysis tools make it difficult to accurately estimate the savings, project teams may want to consider "all-variable-speed" plant control for improvement of energy usage.

By Mick Schwedler with Jeanne Harshaw,Trane. You can find this and previous issues of the Engineers Newsletter at www.trane.com/engineersnewsletter. To comment, e-mail us at ENL@trane.com.

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DIY Chiller Plant Performance Modeling: Easy and Easier examines a number of quick analysis tools available that help system designers determine which chilled-water plant design options benefit the building owner and result in efficient system operation.

Acoustics in Outdoor Applications reviews the analysis steps required to avoid noise complaints caused by outdoor HVAC equipment. Topics include equipment and sound attenuation selection, equipment location, sound ordinances, barrier walls, reflective surfaces, sound power to sound pressure conversion calculations.

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