HVAC&R ENGINEERING
update

Chiller-plant energy performance

In large, air-conditioned buildings, the chiller-plant is one of the major energy consumers. Consequently, the energy performance of the chiller has been studied closely. This has usually meant evaluating the efficiency of a constant-speed chiller running at design conditions; that is, at full load and at maximum entering condenser water temperature (ECWT).

Recently, the perspective on chiller-plant energy performance has broadened to encompass the energy-cost impact of *off-design* conditions. These conditions exist whenever the building doesn't demand the chiller's full cooling capacity and/or whenever the ECWT is lower than its design value. This wider view also takes into account the energy consumption of auxiliary chiller-plant components: the cooling tower, the chilled-water pump, and the condenser-water pump.

When cost-effective variable-speed drives (VSD) are added to the picture, it pays to look at whether applying VSD to the chiller-plant components can offer reductions in energy cost. And what is the trade-off in first cost and maintenance cost?

Since this is a broad subject, we'll begin by examining the energy consumption of the chiller by itself. Then, we'll add in the tower, followed by the pumps. Where energy decisions also have maintenance implications, we will discuss those. Finally, we'll draw some conclusions about the operation of the chiller-plant as a whole.

Chiller performance

In order to understand energy consumption of the chiller, we must first appreciate the difference between design and *off-design* conditions. To do that, we start with weather data. We'll use the Baltimore/Washington area as an example, since this is where the most chillers have been purchased over a recent 25-year period[1].

The Baltimore/Washington weather shown in Figure 1 is based on 25-year averages[2]. It shows hours spent at outdoor dry-bulb temperatures above 50°F, and the ECWT typically available at those outdoor temperatures.

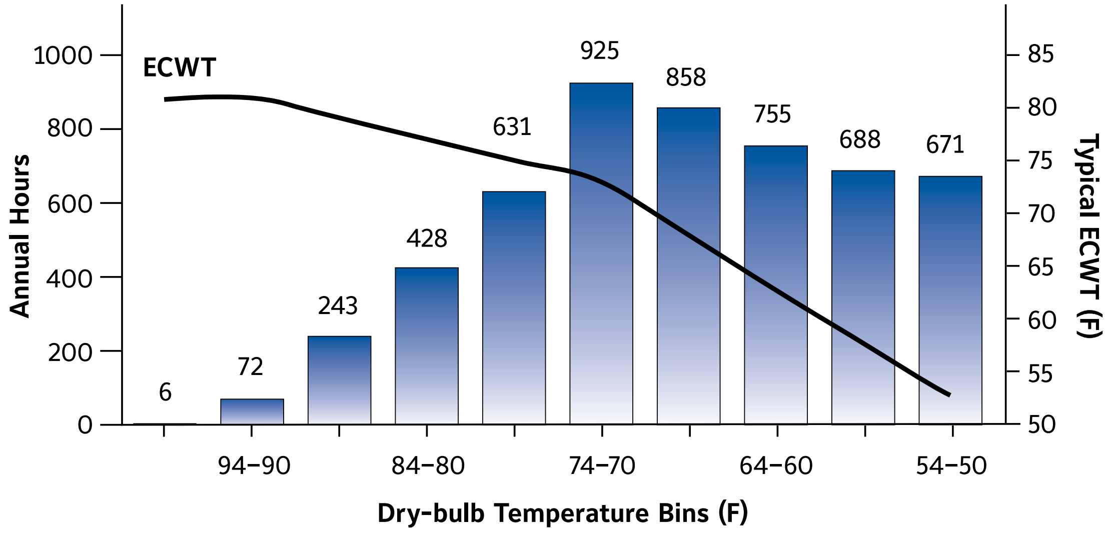

Figure 1: Baltimore/Washington weather above 50°F

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A chiller system in this locale could potentially run for a total of 5,277 hours—if we assume 24-hour operation whenever the outdoor temperature exceeds 50°F (if operation below 50°F is required because the facility has no airside economizer, there would be an additional 3,483 hours).

Over 99% of chiller operating hours are spent at *off-design* conditions.

Chiller design conditions typically occur when the outdoor temperature and ECWT are at their peak. Of all those hours, note how little time is spent at design conditions. Temperatures are in the 95–99°F bin (which can be considered "full-load" on the chiller) for only six hours per year. The other 5,271 hours are *off-design* hours. Consequently, the chiller only runs about one-tenth of one percent of potential operating hours at full-load and design ECWT.

Note also how quickly the ECWT declines, falling below 75°F for almost 4,400 hours (almost 7,900 hours if there is no economizer), and reaching as low as 55°F. This is a result of the outdoor air getting drier as it gets colder, which allows the cooling tower to cool the condenser water further.

The bottom line in this case (and most others) is that over 99% of chiller operating hours are spent at *off-design* conditions: either at part-load, or with colder ECWT, or both.

Importance of off-design performance

In the past, it has been generally assumed that by picking a chiller with good performance at design conditions, you'd also get good performance at off-design conditions. Unfortunately, that isn't always true.

To illustrate, let's use Baltimore/Washington weather data to compare a chiller with a design efficiency of .55 kW/TR and *excellent* off-design performance against a chiller with a design efficiency of .50 kW/TR and *poor* off-design efficiency. We'll assume a single, 500-TR, constant-speed, centrifugal chiller cooling water from 54 to 44°F using 3 GPM/TR of condenser water at 85°F ECWT. Further, we'll assume the chiller runs 24 hours per day, whenever the outdoor temperature is above 50°F, and that electricity demand and usage charges result in a blended rate of $.08/kWh.

Table 1 shows the energy consumption and energy cost for each chiller in each temperature bin. The interesting point is that both chillers use virtually the same amount of energy. While the .55 kW/TR unit uses more energy at higher loads, there are fewer operating hours spent there. Conversely, it uses less energy at lower loads, where the majority of operating hours are spent.

Just as interesting as the energy-cost comparison is the first-cost comparison. The .50 kW/TR chiller would cost as much as $25,000 more to purchase. That's a big premium for the same energy performance.

Off-design efficiency factors

But why do some chillers have better performance at off-design conditions? To understand that, we must look at the factors that affect off-design efficiency. While there are many, the two with the greatest impact are the chiller's ability to operate efficiently at lower ECWTs and lower loads.

The ability to efficiently handle lower ECWTs is a function of the chiller's basic design—some do it well, some don't. If a chiller can use colder ECWTs, the compressor workload can be reduced substantially, saving energy.

			.50 kW/TR, Poor Off-design				**.55 kW/TR, Excellent Off-design**			
Temp. Bin (°F)	**Opg. Time (hrs)**	**Chiller Load (TR)**	**Typ. ECWT (°F)**	**Power Use (kW)**	**Energy Use (kWh)**	**Energy Cost ($)**	**Typ. ECWT (°F)**	**Power Use (kW)**	**Energy Use (kWh)**	**Energy Cost ($)**
95–99	6	500	83	246	1,477	118	83	266	1,598	128
90–94	72	464	81	222	15,957	1,277	81	237	17,066	1,365
85–89	243	427	79	197	47,844	3,828	79	208	50,569	4,045
80–84	428	391	77	175	74,768	5,981	77	183	78,427	6,274
75–79	631	355	75	154	97,307	7,785	75	161	101,864	8,149
70–74	925	319	75	138	127,227	10,178	73	142	131,646	10,532
65–69	858	282	75	121	104,121	8,330	68	120	102,763	8,221
60–64	755	246	75	107	80,422	6,434	63	101	75,936	6,075
55–59	688	210	75	93	63,702	5,096	58	84	57,705	4,616
50–55	671	174	75	80	53,388	4,271	55	72	48,031	3,842
Total					**666,213**	**53,298**			**665,605**	**53,247**
Savings with .55 kW/TR & excellent off-design performance = $51										

Table 1: Chiller performance comparison

Temp. Bin (°F)	Opg. Time (hrs)	Chiller Load (TR)	Typ. ECWT (°F)	Power Use (kW)	Energy Use (kWh)	Energy Cost ($)
95–99	6	500	83	270	1,614	129
90–94	72	464	81	240	17,256	1,380
85–89	243	427	79	212	51,517	4,121
80–84	428	391	77	188	80,237	6,419
75–79	631	355	75	165	104,243	8,339
70–74	925	319	75	148	137,148	10,972
65–69	858	282	75	132	113,159	9,053
60–64	755	246	75	117	88,292	7,063
55–59	688	210	75	103	70,852	5,668
50–55	671	174	75	90	60,393	4,831
Total					**724,711**	**57,975**

Table 2: Energy use of chiller with 75°F ECWT minimum

A simple analogy will help to illustrate the point. Think of the compressor as a man trying to throw a rock to the top of a hill. The rock represents the cooling load, and the height of the hill represents the pressure difference which the compressor must overcome. Lowering the ECWT is like lowering the height of the hill—the man will need less energy to throw the rock to the top of the hill, regardless of the load.

In order to establish a basis for future comparison, let's determine the energy consumption of a different chiller in the Baltimore/Washington area. We'll assume this chiller has a design efficiency of .55 kW/TR, *average* off-design performance, and that its ECWT is artificially limited to 75°F minimum, as has often been done in the past. Otherwise, we'll use the same assumptions as in our previous example.

Table 2 shows that this chiller uses 724,711 kWh annually, at a cost of $57,975.

If we now take this example and substitute a chiller that can use ECWT down to 55°F, rather than requiring an artificial minimum of 75°F, the results are significant, as shown in Table 3. Our chiller now uses only 686,260 kWh at a cost of $54,900, a savings of almost $3,100.

What's especially attractive about this low-ECWT capability is that it doesn't require any additional first cost. An efficient chiller has this capability built-in. And there's no additional maintenance cost because there is no additional hardware.

What about our second factor—lower loads? While our examples show lower ECWTs and lower loads occurring together, that is not always the case (as we shall see later). In reality, a chiller must handle varying ECWTs and varying loads in order to perform efficiently. Constant-speed chillers handle lower loads by gradually closing a set of guide vanes on the compressor inlet, while keeping the motor turning at full speed. But closing the vanes creates friction losses in the refrigerant flow, producing a drag on efficiency. A simple analogy would be trying to control a car by stepping on the brake—while keeping the accelerator floored.

Good performance at design conditions doesn't guarantee good performance at *off-design* conditions.

A better method utilizes variable-speed technology. A VSD efficiently decreases its power draw in response to off-design loads and ECWTs, similar to controlling a car by easing off the accelerator. The energy savings can be as much as 30% annually when compared to a constant-speed chiller. In our example, we now substitute a VSD chiller that can

			75°F ECWT Minimum				55°F ECWT Minimum			
Temp. Bin (°F)	**Opg. Time (hrs)**	**Chiller Load (TR)**	**Typ. ECWT (°F)**	**Power Use (kW)**	**Energy Use (kWh)**	**Energy Cost ($)**	**Typ. ECWT (°F)**	**Power Use (kW)**	**Energy Use (kWh)**	**Energy Cost ($)**
95–99	6	500	83	270	1,614	129	83	270	1,614	129
90–94	72	464	81	240	17,256	1,380	81	240	17,256	1,380
85–89	243	427	79	212	51,517	4,121	79	212	51,517	4,121
80–84	428	391	77	188	80,237	6,419	77	188	80,237	6,419
75–79	631	355	75	165	104,243	8,339	75	165	104,243	8,339
70–74	925	319	75	148	137,148	10,972	73	146	134,783	10,783
65–69	858	282	75	132	113,159	9,053	68	124	106,459	8,517
60–64	755	246	75	117	88,292	7,063	63	105	79,050	6,324
55–59	688	210	75	103	70,852	5,668	58	88	60,292	4,823
50–55	671	174	75	90	60,393	4,831	55	76	50,809	4,065
Total					**724,711**	**57,975**			**686,260**	**54,900**
Savings with 55°F ECWT minimum = $3,075										

Table 3: Effect of lower ECWT on chiller energy use

			Constant-speed Drive 75°F ECWT Minimum				Variable-speed Drive 55°F ECWT Minimum			
Temp. Bin (°F)	**Opg. Time (hrs)**	**Chiller Load (TR)**	**Typ. ECWT (°F)**	**Power Use (kW)**	**Energy Use (kWh)**	**Energy Cost ($)**	**Typ. ECWT (°F)**	**Power Use (kW)**	**Energy Use (kWh)**	**Energy Cost ($)**
95–99	6	500	83	270	1,614	129	83	278	1,652	132
90–94	72	464	81	240	17,256	1,380	81	239	17,193	1,375
85–89	243	427	79	212	51,517	4,121	79	202	49,143	3,931
80–84	428	391	77	188	80,237	6,419	77	170	72,896	5,832
75–79	631	355	75	165	104,243	8,339	75	142	89,634	7,171
70–74	925	319	75	148	137,148	10,972	73	119	109,667	8,773
65–69	858	282	75	132	113,159	9,053	68	89	76,712	6,137
60–64	755	246	75	117	88,292	7,063	63	65	49,150	3,932
55–59	688	210	75	103	70,852	5,668	58	47	32,016	2,561
50–55	671	174	75	90	60,393	4,831	55	35	23,600	1,888
Total					**724,711**	**57,975**			**521,663**	**41,732**
Savings with VSD and 55°F ECWT minimum = $16,243										

Table 4: Effect of variable-speed drive and lower ECWT on chiller energy use

utilize ECWT down to 55°F. As seen in Table 4, our chiller energy consumption is now only 521,663 kWh at a cost of $41,732, a savings of $16,243. With energy savings of this magnitude, the added cost of the VSD for the chiller can be paid off very quickly—well within the timeframe required by most building owners.

Multiple chillers

Up to this point, the focus has been on a single centrifugal chiller. But most chiller plants have more than one chiller, which will affect chiller loading and energy performance. Do plants with multiple chillers negate the importance of off-design chiller performance? Absolutely not!

The impact of multiple chillers on loading can be seen in an example of a 1,000-TR building. Assume a two-chiller plant with one chiller designated as the lead unit and the other as the lag unit. The lead chiller is the first unit on and the last unit off. The lag chiller provides supplemental cooling capacity. Each chiller is constant-speed, with a design capacity of 500 TR, using 275 kW (.55 kW/TR) to chill water from 54 to 44°F. The condenser water-flow is 3 GPM/TR, ECWT is 85°F at design and is limited to 75°F minimum.

As seen in Table 5, when the building load is below 500 TR, the lag chiller cycles off and the lead chiller carries the building load alone. One result of this loading pattern is that

Building				Lead Chiller				Lag Chiller			
Temp. Bin (°F)	**Bldg. Load (TR)**	**Opg. Time (hrs)**	**Typ. ECWT (°F)**	**Chiller Load (TR)**	**Power Use (kW)**	**Energy Use (kWh)**	**Energy Cost ($)**	**Chiller Load (TR)**	**Power Use (kW)**	**Energy Use (kWh)**	**Energy Cost ($)**
95–99	1,000	6	83	500	270	1,614	129	500	270	1,614	129
90–94	928	72	81	464	240	17,256	1,380	464	240	17,256	1,380
85–89	854	243	79	427	212	51,517	4,121	427	212	51,517	4,121
80–84	782	428	77	391	188	80,237	6,419	391	188	80,237	6,419
75–79	710	631	75	355	165	104,243	8,339	355	165	104,243	8,339
70–74	638	925	75	319	148	137,148	10,972	319	148	137,148	10,972
65–69	564	858	75	282	132	113,159	9,053	282	132	113,159	9,053
60–64	492	755	75	492	239	180,168	14,413	0	0	0	0
55–59	420	688	75	420	198	136,409	10,913	0	0	0	0
50–55	348	671	75	348	161	108,269	8,662	0	0	0	0
Subtotal						**930,020**	**74,401**			**505,174**	**40,413**
Totals for both chillers										**1,435,194**	**114,814**

Table 5: Multiple chillers with constant-speed drive and 75°F ECWT minimum

the lead chiller sees many more hours near full-load than it would have seen if it were a single chiller cooling a 500-TR building. Specifically, in the 60–64°F temperature bin, the lead chiller is spending 755 hours near its design capacity of 500 TR.

But note that more hours at full-load don't mean more hours at design conditions. That's because at lower building loads, the *ECWT is also lower*—in this case 75°F, down from the design of 85°F. So, the lead chiller is seeing more hours at higher loads, but at lower ECWTs—which is another form of off-design conditions.

So even in multiple-chiller plants, almost all operating hours are at off-design conditions—with lower loads, lower ECWT, or both. Consequently, chillers that are optimized for off-design conditions are excellent choices for plants with multiple chillers, as well.

Suppose we take this same multiple chiller plant and substitute variable-speed chillers that can utilize ECWT as low as 55°F. As seen in Table 6, the results are dramatic. Equipped with chillers optimized for off-design conditions, this plant shows a savings of $25,596. Simple payback for the VSDs would be very attractive.

What about the maintenance-cost impact of utilizing these type of chillers? If there is any impact, it will be that maintenance costs will be lower. Being able to use 55°F ECWT is inherent to the chiller and will have no effect. Using VSDs may lower maintenance costs because they "soft-start" the chillers, saving wear-and-tear on the driveline and extending its life for years.

To summarize our chiller discussion, we've found that off-design performance is of critical importance in all types of chiller plants. We've also found that chillers designed to operate efficiently with varying loads and ECWTs can take advantage of off-design conditions to offer unsurpassed chiller efficiency, reasonable first cost, lower maintenance cost, and longer life.

Next, we'll connect the chiller to the cooling tower, and look at their combined performance.

Cooling tower performance

The energy consumption of a cooling tower is greatly influenced by the chiller to which it is connected. We stated previously that some chillers require the ECWT be held at 75°F, while others can save energy by utilizing ECWT as low as 55°F. Let's examine what that means to the tower.

Multiple-chiller plants also spend over 99% of their operating hours at *off-design* conditions.

There are five methods by which ECWT can be controlled:

1. Have some water bypass the tower and not be cooled (a.k.a. Cooling Tower Bypass)
2. Have some water bypass the chiller and not be heated (a.k.a. Condenser Bypass)
3. Cycle the tower fan on and off to limit the cooling effect (a.k.a. Fan Cycling)
4. Use a two-speed motor (or pony motor) on the fan to limit the cooling effect
5. Use a VSD on the fan motor to limit the cooling effect

Let's connect the tower to the chiller and look at the energy-cost and maintenance-cost impact of these five control methods.

Building				Lead Chiller				Lag Chiller			
Temp. Bin (°F)	Bldg. Load (TR)	Opg. Time (hrs)	Typ. ECWT (°F)	Chiller Load (TR)	Power Use (kW)	Energy Use (kWh)	Energy Cost ($)	Chiller Load (TR)	Power Use (kW)	Energy Use (kWh)	Energy Cost ($)
95–99	1,000	6	83	500	278	1,652	132	500	278	1,652	132
90–94	928	72	81	464	239	17,193	1,375	464	239	17,193	1,375
85–89	854	243	79	427	202	49,143	3,931	427	202	49,143	3,931
80–84	782	428	77	391	170	72,896	5,832	391	170	72,896	5,832
75–79	710	631	75	355	142	89,634	7,171	355	142	89,634	7,171
70–74	638	925	73	319	119	109,667	8,773	319	119	109,667	8,773
65–69	564	858	68	282	89	76,712	6,137	282	89	76,712	6,137
60–64	492	755	63	492	185	139,641	11,171	0	0	0	0
55–59	420	688	58	420	125	86,097	6,888	0	0	0	0
50–55	348	671	55	348	83	55,712	4,457	0	0	0	0
Subtotals						**698,347**	**55,867**			**416,897**	**33,351**
Totals for both chillers										**1,115,244**	**89,218**
Savings with variable-speed drive & 55°F ECWT minimum = $25,596											

Table 6: Multiple Chillers with variable-speed drive and 55°F ECWT minimum

Bypassing the water around the tower has nothing to offer in the way of energy-cost savings because the tower fan continues to run full-bore, even though only partial capacity is required. Even worse, this method increases maintenance costs because reducing water flow through the tower increases scaling on the internal surfaces, and increases the probability of freeze-up during winter operation. For these reasons, cooling-tower bypass is not a recommended control method.

Chiller control offers greater savings than tower control.

Bypassing the water around the chiller condenser has nothing to offer in the way of energy-cost savings, either. While the chiller is seeing lower ECWT, it is also seeing less water-flow. The result is that refrigerant pressure in the condenser remains high, and chiller energy is not reduced. In addition, the tower fan continues to run full-bore, even though only partial capacity is required. This method also increases maintenance costs because reducing water flow through the condenser decreases water velocity through the tubes, increasing fouling.

Cycling the tower fan does save energy. In Table 3, we compared the energy cost of chillers that kept the ECWT at 75°F to those that could use ECWT as low as 55°F. The 55°F chillers used $3,100 less in energy. But to do that, they require that the tower fan runs at all times. The 75°F chillers can cycle the fan, and in our example, that would generate tower-fan energy savings of about $2,700. So the 55°F chillers would still be the better energy-cost choice, but only by about $400.

However, fan cycling has a major maintenance-cost drawback. All the starting and stopping of the fan subjects its driveline to an incredible amount of wear-and-tear. The cost of maintenance on belts, pulleys, gearboxes, and motors quickly outweighs any energy-cost savings. This is the same reason the HVAC industry abandoned the technique of cycling air-handler fans to save on demand charges.

Putting a two-speed motor on the fan is a bit better than fan cycling. It cuts down on the number of on-off cycles the driveline must incur because often the fan can just cycle between high and low speed. However, it doesn't completely eliminate the cycling, so there are still higher maintenance costs. Energy costs will be somewhat lower than with fan cycling because running the motor at low speed will consume less energy than cycling the motor on and off.

If the chiller requires that ECWT must be held above 55°F, the best alternative is to equip the tower fan with a VSD. Maintenance cost will be minimized because cycling is eliminated, and even start-ups will be "soft," with a gradual ramp-up in speed. Energy cost for the tower will be lower, even when compared to the fan-cycling or two-speed motor options.

However, if the chiller can utilize ECWT as low as 55°F, then it is better to put a VSD on the chiller and keep the tower fan at constant speed. Using our earlier example, Table 7 shows the energy-cost comparison.

The combination of the variable-speed chiller and constant-speed tower yields $11,100 in energy-cost savings. The maintenance costs will be a wash because neither system will cycle the tower fan. The first cost of the tower VSD partially offsets the first cost of the chiller VSD, so the energy savings will pay for the balance of the chiller VSD very quickly.

In summary, the most economical choice is to use a variable-speed chiller that is optimized for off-design conditions, rather than putting additional money into a tower VSD and controls. There is, however, one other situation where a variable-speed tower does make sense. If the building has no economizer and the chiller is required to run year-round, some kind of temperature control will be required for the tower to maintain 55°F ECWT during the winter. In this case, VSDs on both the chiller and the tower is the best solution.

Chilled-water pump performance

The chilled-water pump connects the chiller and the airside equipment. If the airside is designed to handle variable water-flow, a VSD on this pump can be a real energy-saver. However, there are two cautions on the chiller-side. The flow rate-of-change must not be too rapid, or the chiller will begin to hunt. Care must also be taken with the minimum velocity of the water.

Most chillers require that the velocity of the chilled-water flowing through their tubes not fall below 3.0 to 3.3 fps. This limit can be a concern when a high-efficiency chiller is being utilized. High-efficiency chillers are often selected to operate at full-load with a water velocity at or below 4.0 fps, which would allow the variable-speed pump to reduce its speed only 10 to 20%—limiting the energy-saving potential.

One solution is to increase the number of passes the water makes through the chiller. This will increase the velocity,

	Constant-speed Chiller Variable-speed Tower 75°F ECWT Minimum	**Variable-speed Chiller Constant-speed Tower 55°F ECWT Minimum**
Chiller energy cost	$58,000	$41,700
Tower energy cost	$2,600	$7,800
Total of chiller & tower	$60,600	$49,500
Savings	**–**	**$11,100**

Table 7: Effect of variable-speed drive on tower versus chiller

allowing greater turndown of the pump speed. However, it will also increase the water pressure drop through the chiller. The added energy cost of pumping the water through the chiller will have to be weighed against the savings with VSD control. If this strategy is applied to our earlier 500-TR example, Table 8 shows that the savings are almost $6,000, making for a very attractive payback.

Condenser-water pump performance

What about putting a VSD on the condenser-water pump? Does this offer the same energy benefits as the chilled water pump? Potentially yes, but maintenance is a serious question.

When water velocity is slowed, any materials suspended in the water have a greater tendency to drop out. In the chilled-water circuit, this is less of a problem because the circuit is closed and the water stays relatively clean. However, the condenser-water circuit is open to the atmosphere in the cooling tower and has a much greater tendency to foul. If the water velocity is reduced, the chiller, piping, valves, and tower will see increased fouling. Either chiller and pump energy costs will increase because of the fouling, or the maintenance cost will increase to control the fouling.

Even if fouling is controlled, variable flow will have an adverse effect on the performance of the tower. If flow is reduced more than 15%, there will not be enough water pressure to feed water to all the nozzles, and performance will fluctuate wildly. For both these reasons, VSD on the condenser-water pump is not recommended.

Reduce condenser-water flow

As a different approach to reducing chiller-plant costs, it has been suggested that reducing the condenser-water flow from the standard 3 GPM/TR to 2 GPM/TR will save both energy cost and first cost. Although the lower flow will penalize the energy performance of the chiller, it is proposed that the energy savings on the tower and condenser-water pump will outweigh the chiller losses. It is also suggested that the tower, the pump, and the condenser-water piping can be smaller, reducing first cost.

There are several fallacies with this strategy. In the first place, it may not be possible to reduce pipe size. That’s because pipe doesn’t come in an infinite range of sizes. More often than not, the same diameter pipe used with a 3 GPM/TR system must be used for a 2 GPM/TR system. Take our 500-TR example. At 3 GPM/TR, the water-flow would be 1500 GPM. Pipe is sized according to the ASHRAE friction guideline of 1 to 4 feet of pressure drop per 100 feet of pipe. 1500 GPM would require 8" pipe. If the flow is reduced to 2 GPM/TR, or 1000 GPM, could 6” pipe (the next smallest size) be used? No, because the friction loss would exceed the upper limit of 4 feet with 6" pipe. So, there is no first-cost savings on the pipe.

There are several fallacies in the 2 GPM/TR strategy.

Even on the occasions when the pipe size can be reduced, there is a trade-off between first cost and energy cost. You can’t reduce the pipe size and still save the same amount of energy. Reducing the pipe size will increase the frictional loss. You can’t have it both ways.

Similarly, the size of the cooling tower cannot be reduced without affecting its efficiency. If energy savings are to be maximized, then the tower size must be the same. If the tower is downsized, the energy savings will be reduced.

You would think that the condenser-water pump could be reduced in size without penalty, but that’s not necessarily

			Constant-speed Pump Two-pass Chiller			Variable-speed Pump Three-pass Chiller		
Temp. Bin (°F)	**Opg. Time (hrs)**	**Chiller Load (TR)**	**Pump Power (kW)**	**Pump Energy (kWh)**	**Energy Cost ($)**	**Pump Power (kW)**	**Pump Energy (kWh)**	**Energy Cost ($)**
95-99	6	500	21.2	127	10	29.7	178	14
90-94	72	464	21.2	1,529	122	23.7	1,706	136
85-89	243	427	21.2	5,159	413	18.5	4,488	359
80-84	428	391	21.2	9,087	727	14.2	6,069	486
75-79	631	355	21.2	13,397	1,072	10.6	6,697	536
70-74	925	319	21.2	19,640	1,571	7.7	7,123	570
65-69	858	282	21.2	18,217	1,457	5.3	4,564	365
60-64	755	246	21.2	16,030	1,282	3.7	2,798	224
55-59	688	210	21.2	14,608	1,169	3.7	2,550	204
50-55	671	174	21.2	14,247	1,140	3.7	2,487	199
Total				**112,041**	**8,963**		**38,660**	**3,093**
Savings with VSD pump and three-pass chiller = $5,870								

Table 8: Effect of variable-speed drive on chilled-water pump energy use

true, either. Using our example, it turns out that in order to keep pump efficiency high, the best selection to handle 1000 GPM is the same pump which was selected to handle 1500 GPM, but running at 1150 RPM instead of 1750 RPM. This is not a coincidence, but is a function of pump laws. So, there is no first-cost savings on the pump, either.

> The reality of 2 GPM/TR systems doesn't measure up to the claims.

Let's use our 500-TR example again and compare a 3 GPM/TR system optimized for off-design conditions with a 2 GPM/TR system optimized for design conditions. We'll keep the same size components on the 2 GPM/TR system, so as to maximize energy savings. All the components will be constant speed, except that we'll make a third comparison with a VSD on the off-design-optimized chiller only. The results are summarized in Table 9.

In the 2 GPM/TR system, the energy savings available from the cooling tower and the condenser-water pump are not enough to overcome the energy penalty on the chiller. This conclusion may vary depending upon how the chiller-plant is operated, but generally a 3 GPM/TR system will outperform a 2 GPM/TR system.

However, the addition of a VSD on a chiller optimized for off-design conditions will always make good economic sense, because it takes maximum advantage of the savings potential available with lower loads and lower ECWTs, while extending chiller life-expectancy.

Bottom-line chiller-plant savings

Traditional efficiency comparisons for large-tonnage chillers have been based on energy ratings at design conditions. But *off-design* conditions prevail in the real world. Chillers that are optimized for off-design conditions can utilize VSDs to take advantage of lower loads and lower ECWTs, producing significant energy savings when compared to chillers designed primarily for design conditions.

A VSD on the cooling tower makes sense if the chiller plant will run year-round, otherwise a VSD on the chiller is a better investment. A VSD on the chilled-water pump can be an energy-saver, but care must be taken not to have the water velocity fall below the chiller's lower limit. A VSD on the condenser-water pump is not recommended because of the increased maintenance cost caused by fouling in the chiller and tower. Finally, the savings claims being made about 2 GPM/TR systems are contradictory, and the reality doesn't measure up to the theory.

System dynamics will always find a way to make us pay for our shortcuts. But by focusing on applying variable-speed drives to chillers, you will see that you can maximize your chiller plant's energy savings at an attractive first cost and with no hidden maintenance costs.

	2 GPM/TR Constant-speed Chiller 75°F ECWT Minimum	3 GPM/TR Constant-speed Chiller 55°F ECWT Minimum	3 GPM/TR Variable-speed Chiller 55°F ECWT Minimum
Chiller energy cost	$63,900	$54,900	$41,700
Tower energy cost	$4,400	$7,800	$7,800
CW pump energy cost	$4,500	$7,200	$7,200
Total	**$72,800**	**$69,900**	**$56,700**
Savings versus 2 GPM/TR		**$2,900**	**$16,100**

Table 9: Effect of 2 GPM/TR versus 3 GPM/TR condenser water-flow

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1. ARI data from 1967–1992.
2. Engineering Weather Data; Department of the Air Force, the Army, and the Navy; July 1, 1978.

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