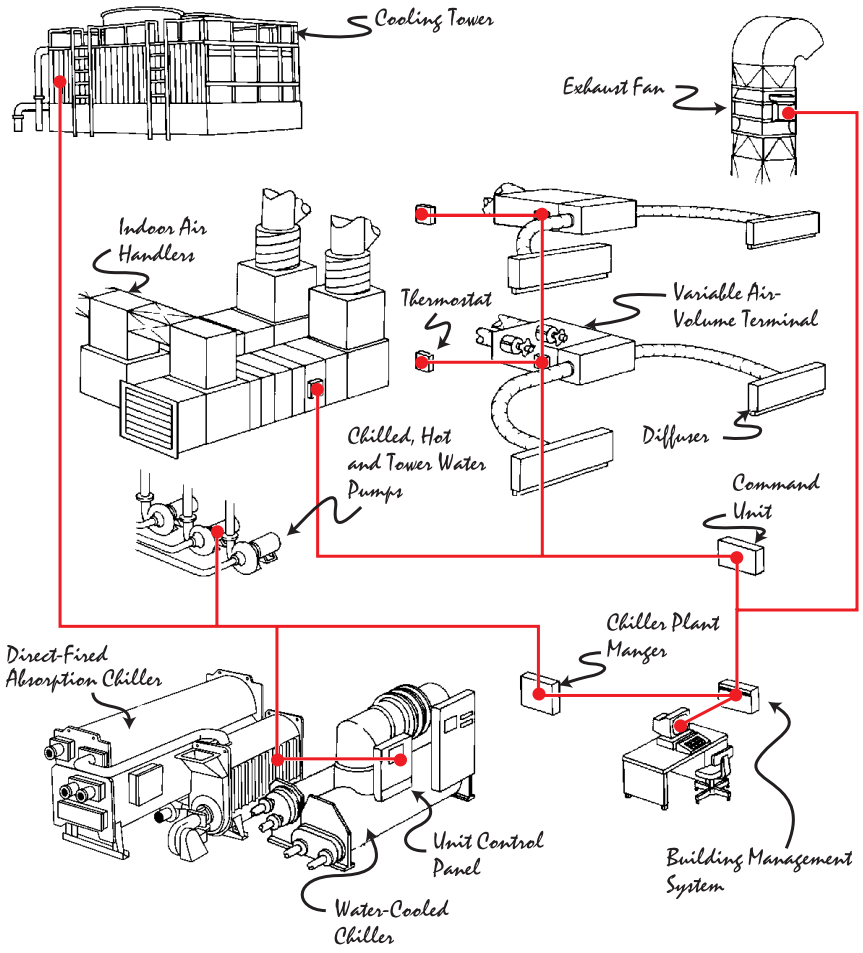
TRANE®

Applications Engineering Manual

Multiple-Chiller-System Design and Control



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TRANE®

Multiple-Chiller-System Design and Control

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Preface

This manual examines chilled-water-system components, configurations, options, and control strategies. The goal is to provide system designers with options they can use to satisfy the building owners' desires, but this manual is not intended to be a complete chiller-system design manual.

System designers may get the most use from this manual by familiarizing themselves with chilled-water-system basics and understanding the benefits of various options. Thereafter, when a specific job will benefit from these advantages, consult appropriate sections of the manual in detail.

The *Engineers Newsletters* that are referenced in this manual are available at: www.trane.com/commercial/library/newsletters.asp

The Trane Company, in proposing these system design and application concepts, assumes no responsibility for the performance or desirability of any resulting system design. System design is the prerogative and responsibility of the system designer.

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Introduction

Many building owners continually search for solutions that allow their businesses to offer higher quality, and to be more competitive and profitable. HVAC systems designers often use chilled-water systems to provide high-quality, cost-effective air conditioning for building owners. With the advent of more flexible chillers, system-level controls, and software analysis tools, the number of chilled-water-systems options has exploded.

Chilled-Water-Plant Basics

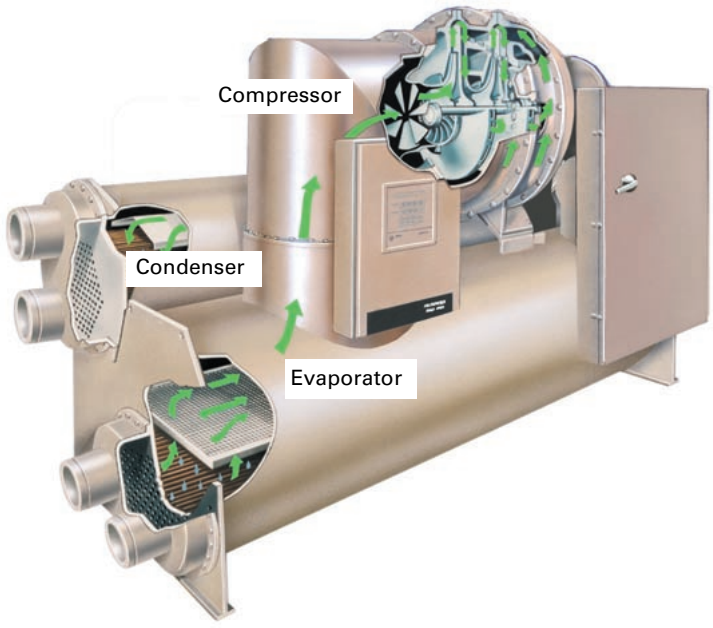
Chilled-water plants consist of these functional parts:

- Chillers that produce chilled water
- Loads, often satisfied by coils, that transfer heat from air to water
- Chilled-water distribution pumps and pipes that send chilled water to the previously mentioned loads
- Condenser-water pumps, pipes, and cooling towers that reject heat (for water-cooled chillers)
- Controls that coordinate the operation of the mechanical components together as a system

Chiller

There are a variety of water chiller types. Most commonly, they are absorption, centrifugal, helical rotary, and scroll. Some reciprocating chillers are also available. Chillers can be either air- or water-cooled. Major vapor-compression chiller components include an evaporator, a compressor(s), a condenser, and an expansion device(s). This manual discusses the chiller's evaporator and condenser and their relationship to the chilled-water plant.

Figure 1 Typical vapor-compression chiller



Chilled-Water-Plant Basics

Evaporator

The evaporator section of a water chiller is a shell-and-tube, refrigerant-to-water heat exchanger. Depending on the chiller's design, either the refrigerant or the water is contained within the tubes.

- In a flooded shell-and-tube evaporator, cool, liquid refrigerant at low-pressure enters the distribution system inside the shell and moves uniformly over the tubes, absorbing heat from warmer water that flows through the tubes.
- In a direct-expansion (DX) shell-and-tube evaporator, warmer water fills the shell while the cool, lower-pressure liquid refrigerant flows through the tubes.

In either design, there is an approach temperature, which is the temperature difference between the refrigerant and exit water stream. The approach temperature is a measure of the heat transfer efficiency of the evaporator.

Effect of chilled-water temperature

For a given chiller, as the leaving chilled-water temperature drops, the refrigerant temperature and pressure must also drop. Conversely, as the leaving chilled-water temperature rises, so do the refrigerant temperature and pressure. When the leaving chilled-water temperature changes, the work a compressor must do also changes. The effect of leaving chilled-water temperature change on power consumption can be 1.0 percent to 2.2 percent per degree fahrenheit [1.8 percent to 4.0 percent per degree celsius]. Always consider the energy consumption of the entire system — not only the chiller. It is important to remember that although reducing leaving chilled-water temperature penalizes the chiller, it may benefit the pumps because less water is pumped through the system. System interactions are covered in more detail in the next section C*hilled-Water-System Options*.

Effect of chilled-water flow rate

Since the evaporator is a heat exchanger, it is sensitive to water flow rate. Excessive flow may result in high water velocity, erosion, vibration, or noise. Insufficient flow reduces heat-transfer efficiency and causes poor chiller performance. Some designers have concerns over low flow rates causing fouling. Generally, as Webb and Li[3] noted, these concerns are unwarranted since the chilled-water loop is a closed system, thus reducing the chances of materials entering the system and causing fouling. Chilled-water flow through the chiller must be kept within specific minimum and maximum limits. Contact the manufacturer for these limits.

Chilled-Water-Plant Basics

Some chiller controls can accommodate very little flow variation during machine operation.[2] Other, more sophisticated, chiller controls allow some flow variation. Some chillers can tolerate flow-rate variations of as much as 30 percent per minute or greater, while others can only tolerate up to 2 percent per minute. It is important that chiller capabilities are matched to system requirements. Contact the chiller manufacturer to determine allowable rate of flow variation before varying the flow through the evaporator in a chiller. Flow variation is discussed in detail in the section *Variable-Primary-Flow Systems*, page 40.

Water-cooled condenser

To cool a building or process, the transferred heat must ultimately be rejected. The total amount of heat rejected includes the sum total of the evaporator load, the compressor work, and the motor inefficiency. In a hermetic chiller, where the motor and compressor are in the same housing, these loads are all rejected through the condenser. In an open chiller, where the motor is separate from the compressor and connected by a shaft, the motor heat is rejected directly to the surrounding air. The evaporator load and the compressor work are rejected through the condenser and the motor heat must be taken care of by the air-conditioning system.

Effect of condenser-water temperature

For a given chiller, as the leaving condenser-water temperature rises, refrigerant temperature and pressure also rise. Conversely, as leaving condenser-water temperature drops, so do refrigerant temperature and pressure. As the refrigerant pressure and temperature changes, the work a compressor must do also changes. The effect of leaving-condenser-water temperature change on power consumption can be 1.0 percent to 2.2 percent per degree fahrenheit [1.8 percent to 4.0 per degree celsius]. Always consider the energy consumption of the entire system — not just the chiller. It is important to remember that although raising the leaving condenser-water temperature penalizes the chiller, it may benefit the pumps and cooling tower through the use of reduced flow rates and higher thermal driving-forces on the tower. System interactions are covered in more detail in the section *Condenser-System Variations*, page 69.

Effect of condenser-water flow rate

Since the condenser is a heat exchanger, it is sensitive to water flow rate. For example, excessive flow may result in high water velocity, erosion, vibration, or noise, while insufficient flow reduces heat transfer efficiency and causes poor chiller performance. Therefore, condenser-water flow through the chiller should be kept within a specific range of limits, except during transient startup

conditions. Contact the manufacturer for these limits. Some chillers may allow extended operation below the selected flow rates.

If water velocity through the condenser tubes is too low for significant periods of time and the water is extremely hard, long-term fouling of the tubes may also occur. Webb and Li[3] tested a number of internally-enhanced condenser tubes at low velocity (3.51 ft/s [1.07 m/s]) and high water hardness. While they found that some of the internally-enhanced tubes fouled, in the long term they concluded:

> Because of the high hardness and low water velocity used in these tests, we do not believe that the fouling experienced is typical of that expected in commercial installations. With use of good maintenance practices and water quality control, all of the tubes tested are probably suitable for long-term-fouling applications.

It is important to remember that a chiller selected for low flow (as discussed in the next section *Chilled-Water-System Options*) does not necessarily have low velocity through its tubes. If tube fouling is a major concern, consider the use of smooth, rather than internally-enhanced, tubes in the condenser for ease of cleaning.

Air-cooled condenser

Obviously, air-cooled chillers do not use condenser-water, since they reject their heat by having ambient air passed across refrigerant-to-air heat exchangers. In packaged air-cooled chillers, the manufacturers attempt to provide optimal performance by staging fans in response to chiller load and ambient, dry-bulb temperature.

Loads

In comfort-cooling applications, loads are usually satisfied by air handlers equipped with coils to transfer heat from conditioned space air to circulating chilled-water. Air is thus cooled and dehumidified as it passes across the finned surface of the cooling coils. Since the psychrometric process of conditioning air takes place at the coils, selection of the optimum coil size and type from the wide variety available is important for proper system performance.

Chilled-Water-Plant Basics

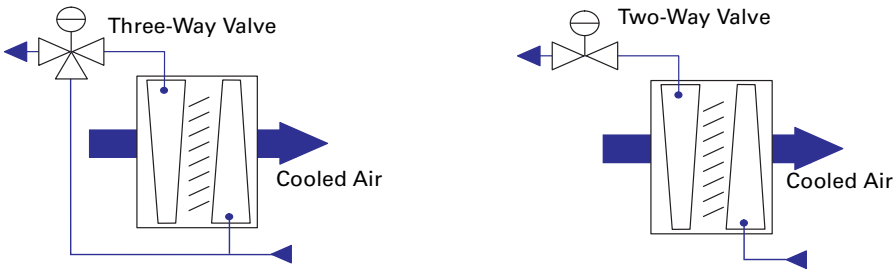
Some specialized process loads do not involve cooling air. Instead, they may involve heat transfer directly within a piece of process equipment, such as the cooling jacket of an injection-molding machine. Heat transferred from the loads can be controlled in a number of ways:

- Three-way valve
- Two-way valve
- Variable-speed pump
- Uncontrolled coils

Three-way valve load control

A three-way control valve regulates the amount of water passing through a coil in response to loads. The valve bypasses unused water around the coil and requires a constant flow of water in the system, regardless of load. A drawback of this bypass is that the temperature of the water leaving the three-way valve is reduced at part-load conditions. This can be a major cause of so-called "low ΔT syndrome" discussed on page 63 in the section *Chilled-Water-System Issues*. Three-way valves are used in many existing systems.

Figure 2 Valve-controlled loads



Two-way valve load control

A two-way, water modulating valve at the coil performs the same water throttling function as the three-way valve. The coil sees no difference between these two methods. The chilled-water system, however, sees a great difference. In the case of the two-way valve, *all* flow in the coil circuit is throttled. No water is bypassed. Consequently, a system using two-way valves is a variable-flow chilled-water system. The temperature of the water leaving the coil is not diluted by bypass water so at part-load conditions, the system return-water temperature is higher than with three-way valve control.

Chilled-Water-Plant Basics

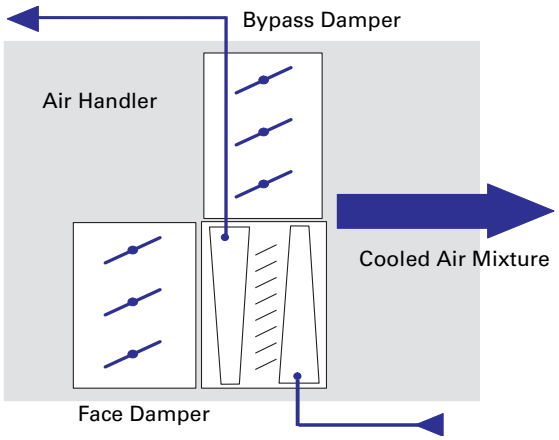
Variable-speed pumping load control

By using a pump for each coil, the flow may be controlled by varying the pump speed. In such systems, there may be no control valves at the coil. This can reduce both the valve and the valve installation costs.

Uncontrolled coils

Figure 3 shows a control variation using an uncontrolled or "wild"coil. In this system, control of the conditioned air supply is executed by face-and-bypass dampers that permit a portion of the air to bypass the coil surface. Advantages of the strategy are the elimination of control valves and improved part-load dehumidification. A disadvantage is that all the water is pumped all the time; however, in systems with very small water pressure drops, this system arrangement may work economically.

Figure 3 Uncontrolled coil



Chilled-water distribution system

Chilled water is circulated through fixed piping — most commonly steel, copper, or plastic — that connects the chiller with various load terminals. Piping is sized to meet a project's pressure loss, water velocity, and construction cost parameters. Pressure drop is overcome by the use of a chilled-water pump.

Chilled-Water-Plant Basics

Chilled-water pump

The purpose of the chilled-water pump is to circulate chilled water within the loop. Generally, the pump must overcome the frictional pressure losses caused by the piping, coils, and chiller and the pressure differential across open control valves in the system. The pump, while working at the system static pressure, does not need to overcome this static pressure. For example, in a forty-story building the pump need not overcome the static pressure due to those forty stories.

The pump is typically located upstream of the chiller, however it may be anywhere in the system, provided that the pump:

- meets the minimum pump net positive suction-head requirements. That is, the system pressure at the pump inlet must be both positive and high enough to allow the pump to operate properly;
- maintains the minimum dynamic pressure head at critical system components (usually the chiller). If the dynamic pressure head is not high enough at these components, proper flow will not be established through them;
- accommodates the total pressure (static head plus dynamic head) on system components such as the chiller's evaporator, valves, etc.

Note that the pump heat is added to the water and must be absorbed by the chiller. Generally, this represents a very small temperature increase.

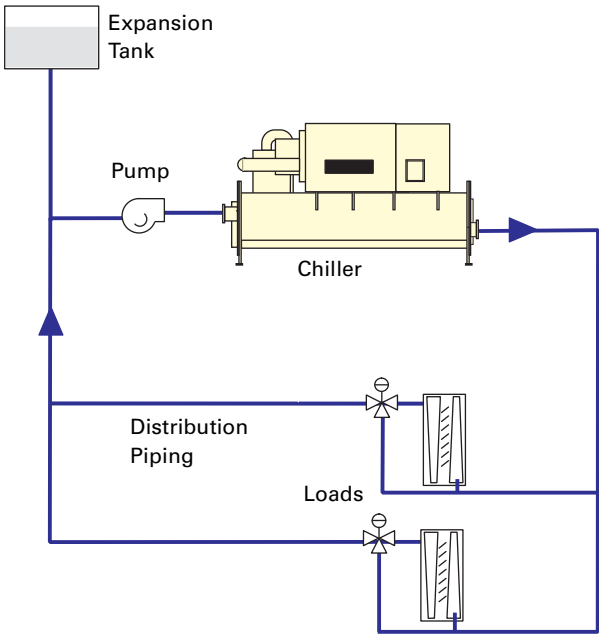
Multiple pumps are often used for redundancy. Depending on the terminal control devices and system configurations, the chilled-water pumps may be either constant or variable-flow.

Chilled-Water-Plant Basics

Distribution piping

By itself, the distribution system is easy to understand. Figure 4 shows a simplified distribution system consisting of multiple cooling coils, each controlled by a thermostat that regulates the flow in its respective coil. The valves may be either three-way or two-way. As previously discussed, three-way valves require constant water flow, while two-way valves allow the water flow in the system to vary. As flow varies, the pump may simply ride its curve or use a method of flow control such as a variable-speed drive. See the section *System Configurations*, on page 27, for a detailed discussion of distribution-system options.

Figure 4 Simplified distribution system



The distribution system may contain other components, such as an expansion tank, control valves, balancing valves, check valves, and an air separator, to name a few. The density, and therefore the volume, of the water in a "closed" chilled-water distribution system varies as it undergoes changes in temperature. The expansion tank allows for this expansion and contraction of water volume.

2000 ASHRAE HVAC Systems and Equipment Handbook, Chapter 12, Hydronic Heating and Cooling System Design[1] contains additional reference information on the components of a chilled water distribution system.

Chilled-Water-Plant Basics

Condenser-water system

As in chilled-water distribution systems, condenser-water system piping — most commonly steel, copper, or plastic — is sized to meet a project's operating pressure, pressure loss, water velocity, and construction cost parameters. Pressure drop through piping and the chiller's condenser, plus the cooling-tower static lift, is overcome by use of a condenser-water pump.

Cooling tower

To reject heat, water is passed through a cooling tower where a portion of it evaporates, thus cooling the remaining water. A particular cooling tower's effectiveness at transferring heat depends on water flow rate, water temperature, and ambient wet bulb. The temperature difference between the water entering and leaving the cooling tower is the range. The temperature difference between the leaving water temperature and the entering wet-bulb temperature is the approach.

Effect of load

As the building load — or heat rejection — decreases, range and approach also decrease. This means that when the building is at part load, the cooling tower can provide colder water at the same ambient wet-bulb temperature.

Effect of ambient conditions

As ambient wet-bulb temperature drops, the approach — at a constant load — increases. This must be considered when cooling-tower-control strategies are developed. Detailed descriptions of these conditions appear in the subsection, *Chiller-tower energy balance,* page 72. For additional information, refer to *2000 ASHRAE HVAC Systems and Equipment Handbook*, Chapter 36, "Cooling Towers."[1]

Chilled-Water-Plant Basics

Controls

The chilled-water supply temperature is usually controlled at the chiller. Most commonly, supply water temperature is used as the sensed variable to permit control of chiller capacity to meet system load demand. Supply-temperature control strategies may be used on either constant- or variable-flow systems. As previously discussed, flow control is executed at the load terminals using three-way or two-way valves, or separate pumps for each coil.

Control capabilities run the gamut from slow-acting pneumatic controls, to electromechanical controls, to sophisticated digital controls that use algorithms tuned to give superior performance.

Chiller control

Today's chiller controls are capable of doing more than simply turning the chiller on and off. At a minimum, these controls should monitor:

- Safety points such as bearing temperatures and electrical points that, when out of range, may cause motor failure.
- Data points that may cause operational problems if corrective action is not taken. An example is low chilled-water or refrigerant temperature, which may result in freezing in or around the evaporator tubes.
- General points that should be logged daily to ensure proper chiller performance.

Table 1 lists the ASHRAE-recommended monitoring points.

Table 1 Recommended chiller-monitoring points per ASHRAE Guideline 3-1996

Chilled Water	Flow	Condenser Water	Flow
	Inlet Pressure		Inlet Pressure
	Inlet Temperature		Inlet Temperature
	Outlet Pressure		Outlet Pressure
	Outlet Temperature		Outlet Temperature
Evaporator	Approach Temperature	Condenser	Approach Temperature
	Refrigerant Pressure		Refrigerant Pressure
	Refrigerant Temperature		Refrigerant Temperature
Oil	Level	Refrigerant	Level
	Pressure		Compressor Discharge Temperature
	Temperature		Additional Required
	Additional Required	Vibration Levels	

Chilled-Water-Plant Basics

In addition to monitoring data, it is vital that the chiller controls alert operators to possible problems. Diagnostic messages are necessary for the operator to respond to safety issues and data points that are outside normal operating ranges.

While communicating these diagnostic messages is a requirement, some chiller controls include factory-installed programming that responds to the diagnostic messages. For example, when the chilled-water temperature nears freezing, the chiller sends a diagnostic message and *adapts* its operation by reducing the compressor capacity, raising the chilled-water temperature to a safer condition.

Finally, the chiller controls should communicate with a system-level controller. There are many system aspects that are outside the chiller's direct control, such as condenser-water temperature and the amount of fluid flowing through the evaporator and condenser. To minimize the system energy costs, the system controls must coordinate chiller, pump, cooling-tower, and terminal-unit controls. This can only be done if adequate information is communicated from each system component to the system-level controls.

Pump control

In so-called constant flow systems, the pumps are either on or off, providing relatively constant flow when in the *on* position. In practice, some flow variation will occur as system pressure drop changes. In a variable-flow system, pump control is most often performed by maintaining a pressure differential at a selected point in the system. For example, a variable-speed drive will increase its speed if the sensed pressure differential is too low, or slow down if the pressure differential is too high. The control point is selected to minimize over-pressuring the system and to assure adequate flow at all critical loads. Optimal pumping control strategies are addressed in *Critical valve reset*, page 48.

Chapter references

1 2000 *ASHRAE HVAC Systems and Equipment Handbook,* Chapter 12, Hydronic Heating and Cooling System Design and Chapter 36, Cooling Towers, American Society of Heating, Refrigeration and Air-Conditioning Engineers.

2 Schwedler, M., PE and Bradley, B.; "An Idea for Chilled-Water Plants Whose Time Has Come...Variable-Primary-Flow Systems," *Engineers Newsletter*, Volume 28, No. 3, The Trane Company, 1999.

3 Webb, R.L. and Li, W.; "Fouling in Enhanced Tubes Using Cooling Tower Water, Part I: Long-Term Fouling Data," *International Journal of Heat and Mass Transfer*, 2000.

Chilled-Water-System Options

There are many chilled-water-system design options; however, in a basic sense, each option is a function of flow, temperature, system configuration, and control. This section discusses the effect of flow rate and temperature decisions.

It is important to remember that temperatures and flow rates are variables. By judicious selection of these variables, chilled-water plants can be designed to both satisfy chilled-water requirements and operate cost effectively.

Refer to ARI Standard 550/590–1998, *Standard for Water Chilling Packages Using the Vapor Compression Cycle* and the ARI Standard 560–1992, *Standard for Absorption Water Chiller and Water Heating Package*, for additional information. Both are published by the Air-Conditioning & Refrigeration Institute. (www.ari.org)

Chilled-water systems are often designed using flow rates and temperatures applied in testing standards developed by the Air-Conditioning and Refrigeration Institute (ARI), ARI 550/590–1998[1] for vapor compression chillers and ARI 560–1992[2] for absorption chillers. These benchmarks provide requirements for testing and rating chillers under multiple rating conditions. They are *not* intended to prescribe the proper or optimal flow rates or temperature differentials for any particular system. In fact, as component efficiency and customer requirements change, these standard rating conditions are seldom the optimal conditions for a real system. There is great latitude in selecting flow rates, temperatures, and temperature differences.

Chilled- and condenser-water temperatures

Leaving chilled-water and entering condenser-water temperature selection can be considered independently of their respective flow rates. However, temperatures and flow rates should be selected together to design an efficient and flexible chilled-water-system.

Standard rating temperatures

Currently, the standard-rating-condition temperatures in ARI 550/590[1] and ARI 560[2] are:

- Evaporator leaving water temperature: 44°F [6.7°C]
- Water-cooled-condenser, entering-water temperature: 85°F [29.4°C]
- Air-cooled-condenser, entering-air dry bulb: 95°F [35.0°C]

For years, these temperature definitions were the benchmarks in system designs. Today, designers apply a variety of different temperatures. ARI 550/590 reflects this trend by allowing the chilled-water and condenser-water temperatures to be selected at non-standard points and the chiller to be tested as specified by the standard.

Chilled-Water-System Options

Chilled-water temperatures

Chilled water (without antifreeze) at 34°F (1.1°C) is possible with some chillers that use sophisticated evaporator-design and chiller-control methods.

Currently, comfort cooling systems are designed with chilled-water-supply temperatures that range from 44°F [6.7°C] to 38°F [3.3°C], and, in some cases, as low as 34°F [1.1°C]. Reasons to decrease the chilled-water temperature include these:

- The system design more readily accommodates wider temperature *differences* (lower flow rates) than the standard rating conditions (see the subsection *Selecting flow rates*, page 16).
- Lower water temperature allows lower air temperatures (and flows) to be selected resulting in reduced airside installed and operating costs.
- Colder water in the same chilled-water coil may provide better dehumidification.
- Colder water can be used to increase the capacity of an existing chilled-water distribution system. In some instances, this can save significant capital expenditures to add capacity to large central plants that have reached their flow limits.

Some system designers hesitate to use lower chilled-water temperatures, concerned that:

- the chiller will become less efficient. As discussed earlier, lower chilled-water temperature makes the chiller work harder. However, while the lower water temperature increases chiller energy consumption, reducing the chilled-water flow rate reduces pump energy. This combination often lowers system energy consumption.
- lower chilled-water temperatures may require more insulation on piping to prevent condensation ("sweating"). Ensure that pipes are properly insulated at all water temperatures. Lower temperature water will not always require more insulation.

Condenser-water temperatures

Today's chillers can run at various entering condenser-water temperatures, varying from design temperature to the lowest-allowable temperature for that particular chiller design. However, many existing older chillers are limited in their allowable condenser-water temperatures. Contact the chiller manufacturer for these limits. Optimal condenser-water-temperature control is discussed in the section, *Condenser-System Variations*, page 69.

Chilled-Water-System Options

Chilled- and condenser-water flow rates

The selection of chilled-water and condenser-water flow rates is a powerful tool that designers have at their disposal. Kelly and Chan[5], and Schwedler and Nordeen[6], found that reducing flow rates can reduce the costs of chilled-water-system installation and/or operation.

Standard-rating flow rates

Presently, the standard-rating-condition flow rates in ARI 550/590 are:

- 2.4 gpm/ton [0.043 lps/kW] for evaporator
- 3.0 gpm/ton [0.054 lps/kW] for condenser

This evaporator flow rate corresponds to a 10°F [5.6°C] temperature difference. Depending on the compressor efficiency, the corresponding condenser temperature difference is 9.1°F to 10°F [5.1°C to 5.6°C].

Absorption chillers are rated using ARI Standard 560–1992, *Standard for Absorption Water Chiller and Water Heating Package*[2]. The evaporator flow rates are the same as those used in ARI 550/590; however, condenser (often called cooling water) flow rates differ depending on the absorption chiller design. Table 2 shows the standard rating conditions for various absorption chillers.

Table 2 Standard rating conditions for absorption chillers

Absorption Chiller Type		Condenser Flow Rate gpm/ton	Condenser Flow Rate lps/kW
Single Effect		3.60	0.065
Double Effect	Steam or hot water	4.00	0.072
	Direct fired	4.50	0.081

Chilled-Water-System Options

Selecting flow rates

Designers may use the standard *rating* conditions to compare manufacturers' performances at exactly the same conditions. However, these standards allow any flow rates to be used and certified comparisons to be made at those conditions. For a given load, as flow rate decreases, the temperature differential increases. Table 3 reflects a 450-ton [1,580-kW refrigeration] chilled-water system, both as a base case and with low flow.

Table 3 Standard rating conditions for chilled-water systems

Chilled Water System		Base Case	Low Flow
Evaporator flow rate, gpm [lps]		1,080 [68.1]	675 [42.6]
Chilled water temperature °F [°C]	Entering	54.0 [12.2]	57.0 [13.9]
	Leaving	44.0 [6.7]	41.0 [5.0]
Condenser flow rate, gpm [lps]		1,350 [85.2]	900 [56.8]
Condenser water temperature °F [°C]	Entering	85.0 [29.4]	85.0 [29.4]
	Leaving	94.3 [34.6]	99.1 [37.3]
Chiller power, kW		256.0	292.0

In this example, notice that the leaving-chilled-water temperature decreases and the leaving-condenser-water temperature increases. This means that the chiller's compressor must provide more lift and use more power. How does this impact system energy consumption? Using the following assumptions, we can calculate system energy usage:

- 80 feet of water [239 kPa] pressure drop through chilled-water piping
- 30 feet of water [89.7 kPa] pressure drop through condenser-water piping
- 78°F [25.6°C] design wet bulb
- 93 percent motor efficiency for pumps and tower
- 75 percent pump efficiency
- Identical pipe size in chilled- and condenser-water loops (either a design decision, or indicating changing flows in an existing system)

The pressure drop through the chiller will change. When using the same size pipe, the pressure drop changes with nearly the square of the flow rate. While this is true for straight piping, the pressure drop does not follow this exact relationship for control valves or branches serving loads of varying diversity.

Chilled-Water-System Options

Be sure to calculate the actual pressure drop throughout the system. Hazen–Williams and Darcy–Weisbach calculate the change is to the 1.85 and 1.90 power, respectively. The examples here use the more conservative 1.85 power:

$$DP2/DP1 = (Flow2)/(Flow1)^{1.85}$$

Table 4 Low-flow conditions for chilled-water pump

	Base Case	Low Flow
Flow rate, gpm [lps]	1,080 [68.1]	675 [42.6]
System pressure drop, ft water [kPa]	80.0 [239]	33.5 [100]
Evaporator-bundle pressure drop, ft water [kPa]	29.7 [88.8]	12.6 [37.7]
Pump power output, hp [kW]	39.9 [29.8]	10.5 [7.80]
Pump electrical power input, kW	32.0	8.4

Given different flow rates and entering water temperatures, a different cooling tower can be selected for the low-flow condition:

Table 5 Low-flow conditions for cooling tower

	Base Case	Low Flow
Flow rate, gpm [lps]	1,350 [85.2]	900 [56.8]
Static head, ft water [kPa]	19.1 [57.1]	12.6 [37.7]
Tower fan power output, hp [kW]	30.0 [22.4]	20.0 [14.9]
Tower fan electrical power input, kW	24.1	16.0

Table 6 Low-flow conditions for condenser-water pump

	Base Case	Low Flow
Flow rate, gpm [lps]	1,350 [85.2]	900 [56.8]
System pressure drop, ft water [kPa]	30 [89.7]	14.2 [42.5]
Condenser-bundle pressure drop, ft water [kPa]	19.9 [59.5]	9.6 [28.7]
Tower static lift, ft water [kPa]	19.1 [57.1]	12.6 [37.7]
Pump power output, hp [kW]	31.4 [23.4]	11.0 [8.2]
Pump electrical input, kW	25.2	8.8

Chilled-Water-System Options

The total system power is now as follows:

Table 7 Total system power

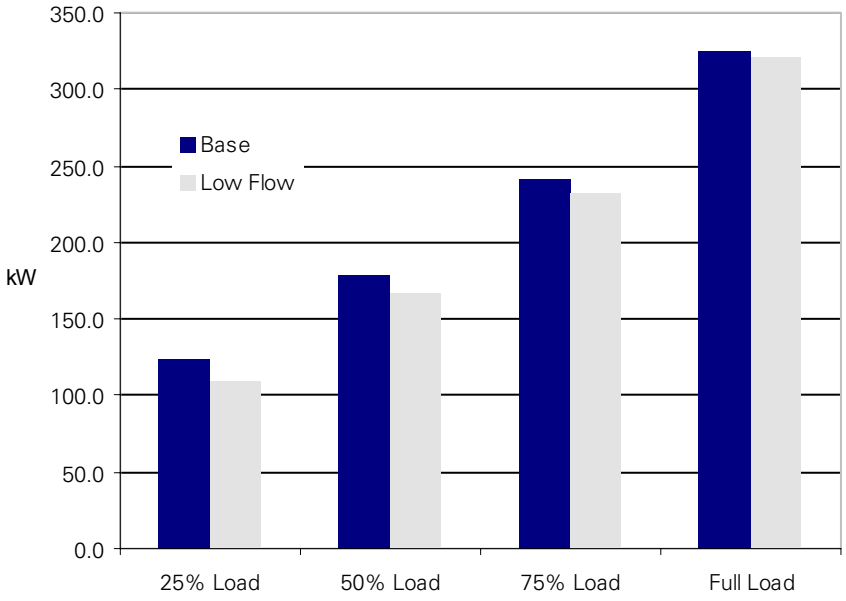
Component Power (kW)	Base Case	Low Flow
Chiller	256.0	292.0
Chilled-water pump	32.0	8.4
Condenser-water pump	25.2	8.8
Cooling tower	24.1	16.0
Total power for chilled-water system	337.3	325.2

It becomes clear that flow rates can affect full-load system power. Even though the chiller requires more power in the low-flow system, the power reductions experienced by the pumps and cooling tower result in an overall savings for the system. What happens at part-load conditions? Figure 5 shows the part-load performance based on the following assumptions:

- The chilled-water pump includes a variable-frequency drive
- The condenser-water pump remains at constant power
- The cooling tower is controlled to produce water temperatures lower than design

Chilled-Water-System Options

Figure 5 Chilled-water-system performance at part load



While the magnitude of the benefit of low-flow changes depends on the chiller type used (centrifugal, absorption, helical-rotary, scroll), all chilled-water systems can benefit from judicious use of reduced flow rates.

Coil response to decreased entering water temperature

A coil is a simple heat exchanger. If we want it to deliver the same sensible and latent capacity while we supply it with cooler water, the coil's controls respond by reducing the amount of water passing through it. Because the amount of water decreases while the amount of heat exchanged remains constant, the leaving water temperature increases. Thus, by producing cooler water, a low-flow system can be applied to an existing building. In a retrofit application it is wise to reselect the coil, using the manufacturer's selection program, at a new chilled-water temperature to ensure its performance will meet requirements.

When coil performance data is not available from the original manufacturer, some designers use this approximation. For each 1°F –1.5°F [0.6°C–1.1°C] the water temperature entering the coil decreases, the water returns 1°F [0.6°C] warmer and gives about the same sensible and total capacities.

For example, consider a coil operating at 44°F [6.7°C] entering temperature and 54°F [12.2°C] leaving temperature. By changing the entering-water temperature to 41°F [5.0°C] the coil-leaving temperature will be approximately 56°F –57°F [13.3°C–13.9°C]. Let's look at this example in a table.

Chilled-Water-System Options

Table 8 Effect of decreased water temperature

		Original Selection °F [°C]	Chilled-water reduction for each 1° return water increase °F [°C]			
Coil water temperature	Entering	44 [6.7]	1°	41 [5.0]	1.5°	41 [5.0]
	Leaving	54 [12.2]		57 [13.9]		56 [13.3]

One possible concern of low-supply water temperatures is the ability of the valve to control flow properly at low-load conditions. A properly-sized valve with good range can work well in low-flow systems. In existing systems, valves may need to be replaced if they cannot operate with the new range of flows, but the coils do not need to be replaced.

Cooling-tower options with low flow

Smaller tower

Like coils, cooling towers are heat exchangers—although often misunderstood heat exchangers. The tower exchanges heat between the entering (warmest) water temperature and the ambient wet-bulb temperature. Therefore, in a new system or when a cooling tower is replaced, a low-flow system design allows a smaller, more efficient cooling tower to be selected. How is this possible?

Since the amount of heat rejection is approximately the same in standard-rating-condition and low-flow systems, we can estimate the heat exchange area necessary to reject the heat:

$Q = U\ A_1\ \Delta T_1$, where A = area, U = coefficient of heat transfer, and
ΔT = temperature difference

$= U\ A_2\ \Delta T_2$ or $A_1\ \Delta T_1 = A_2\ \Delta T_2$

Using standard rating conditions, the temperature difference between tower entering temperature and ambient wet bulb for ΔT_1 is:

$\Delta T_1 = 94.2 - 78 = 16.2°F\ [34.6 - 25.6 = 9.0°C]$

while at typical low-flow conditions for ΔT_2 it is:

$\Delta T_2 = 99.1 - 78 = 21.1°F\ [37.3 - 25.6 = 11.7°C]$

Therefore:

$A_1 \times 16.2 = A_2 \times 21.1$ or $A_2 = 0.77\ A_1$

Chilled-Water-System Options

In a cooling tower, the heat exchange capacity can be changed by either surface area or airflow, or some combination of the two. A cooling-tower manufacturer's selection program can give the exact size and power requirements. In the example on pages 16–18, both the cooling-tower size and airflow (hence, required fan power) were reduced.

Same tower, smaller approach

Another option is to use the same cooling tower at a lower flow rate. In a new system, this is a design decision, but in an existing system, it is often a constraint. Given the same heat-rejection load, the low-flow system allows the cooling tower to return colder water; that is, the tower's approach to the ambient wet-bulb temperature decreases. In the previous example of 450 tons [1580 kW], the same cooling tower would have resulted in an entering condenser-water temperature of 83.5°F [28.6°C] instead of the 85°F [29.4°C] with the smaller cooling tower. It is important to realize that the entering temperature for the tower would be approximately 97.6°F [36.4°C]. Therefore, the effect of reduced flow rate on chiller energy consumption is partially offset by the lower entering- condenser water temperature.

Same tower, larger chiller

One retrofit option that benefits many building owners is installing a new, larger chiller and using the existing cooling tower, condenser-water pump, and condenser-water pipes. In many cases, this allows the building owner to increase the chilled-water-system capacity for an expansion, with a limited budget. Table 9 shows the conditions for an existing 450-ton [1,580-kW] chiller replaced by a 675-ton [2,370-kW] chiller. This is a capacity increase of 50 percent. A more extensive discussion of this example is contained in the next section, *System Configurations*. It is important to select the new chiller based on the new conditions.

Table 9 Retrofit capacity changes

		Present	Expansion retrofit
Capacity, tons [kW refrigeration]		450 [1,580]	675 [2,370]
Cooling tower	Flow rate, gpm [l/s]	1350 [85.2]	1,350 [85.2]
	Entering temperature, °F [°C]	94.3 [34.6]	103 [39.4]
	Leaving temperature, °F [°C]	85 [29.4]	88 [31.1]
Ambient wet-bulb temperature, °F [°C]		78 [25.6]	78 [25.6]

Chilled-Water-System Options

Cost implications

Several considerations should be kept in mind when determining sizes for new systems. As pipe size is decreased, so are valve and specialty sizes and costs. Remember that reducing pipe size increases pressure drop. Keep a balance between first cost and operating costs. This can significantly reduce the system retrofit costs since existing pipes may be used.

By reducing either chilled- or condenser-water flow rates alone, the following installed-cost reductions are possible:

- Reduced pump size, valves, strainers, fittings, electrical connections
- In new systems, reduced pipe sizes
- In existing systems, more capacity from existing chilled-water piping systems
- Reduced cooling-tower size, footprint, and fan power

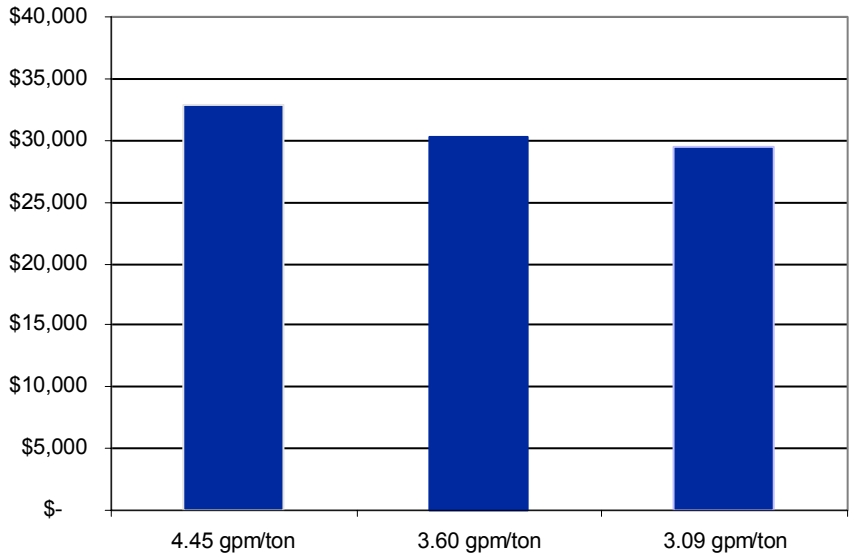
Alternatively, a physically-smaller cooling tower may be selected using low flow. A reduced footprint can benefit building owners in a number of ways:

- Reduced real estate requirements (often more important than realized)
- Reduced structural requirement, since the amount of tower water is reduced
- Reduced excavation and material costs in the case of a large, built-up tower with a concrete sump
- Improved aesthetics because of the reduced tower height

In addition to reducing installation costs, operating cost reductions for the whole system are also available. Due to a smaller pump and/or tower, the pump and tower operating costs can be reduced substantially with less adverse impact on the chiller operating cost. Analysis programs such as DOE 2.1, TRACE®, or System Analyzer™ software can be used to determine annual operating costs. Nordeen and Schwedler[6] showed that operating costs for chilled-water systems using absorption chillers can benefit greatly from reduced condenser-water flow. Figure 6 shows operating costs as generated with System Analyzer™ analysis software.

Chilled-Water-System Options

Figure 6 Annual system operating costs



Kelly and Chan[5] compare the operational costs of chilled-water-system designs in site locations. Their summary states:

> In conclusion, there are times you can "have your cake and eat it too." In most cases, larger ΔT's and the associated lower flow rates will not only save installation cost but will usually save energy over the course of the year. This is especially true if a portion of the first cost savings is reinvested in more efficient chillers. With the same cost chillers, at worst, the annual operating cost with the lower flows will be about equal to "standard" flows but still at a lower first cost.

Chilled-Water-System Options

Misconceptions about low-flow rates

Some common misconceptions about low-flow systems include:

1. Low flow is only good for long piping runs
2. Low flow only works well for specific manufacturers' chillers
3. Low flow can only be applied to new chilled-water systems

Let's discuss each of these three misconceptions.

Misconception 1 — Low flow is only good for long piping runs.

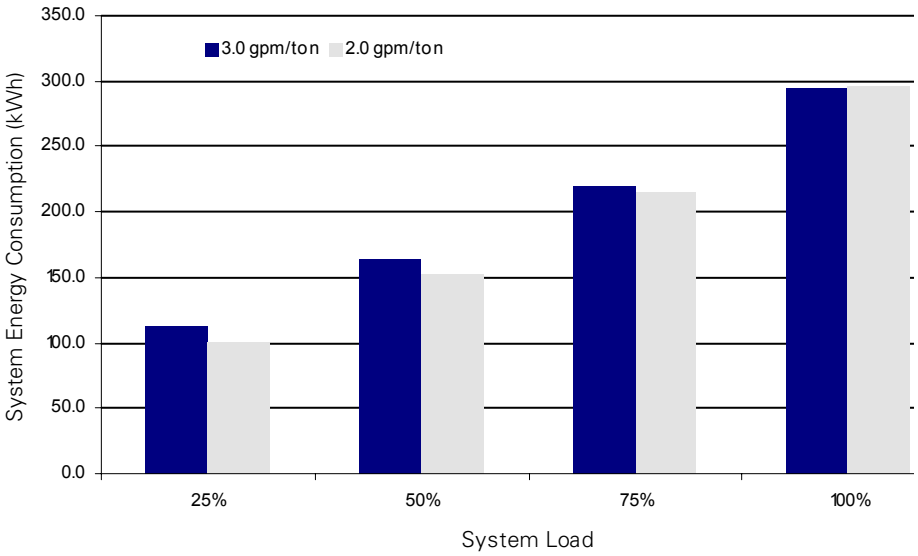
One way to examine this claim is to use our previous example, but to concentrate on the condenser-water side. We'll start with the example covered on pages 16–18. Using the same chiller, but a smaller cooling tower and a more conservative zero condenser-water-pipe pressure drop, we can examine the effect of reducing flow rates.

Table 10 Reduced flow-rate effect

Condenser Water Pump	Base Case	Low Flow
Flow rate, gpm [lps]	1350 [85.2]	900 [56.8]
System pressure drop, ft water [kPa]	0	0
Condenser bundle pressure drop, ft water [kPa]	19.9 [59.5]	9.6 [28.7]
Tower static lift, ft water [kPa]	19.1 [57.1]	12.6 [37.7]
Pump power output, hp [kW]	17.7 [13.2]	6.7 [5.0]
Pump fan electrical input, kW	14.2	5.4

Chilled-Water-System Options

Figure 7 System energy comparison (no pipe)



Energy consumption for the chiller, condenser-water pump, and cooling-tower fans is shown in Figure 7. Note that only at full load does the total power of the chilled-water *plant* increase. Recall that this is with absolutely **no** pressure drop through the condenser-water piping, valves, or fittings. It is interesting to note that the break-even point at full load is approximately 8 feet of head (water) [23.9 kPa]. Also note that at all part-load conditions, the total power of the low-flow system is less than that of the base system. It is easy to see that even for short piping runs, reducing flow rates can improve plant energy consumption.

Misconception 2—Low flow only works for specific manufacturers' chillers.

Demirchian, et al.[3], Eley[4], and Schwedler and Nordeen[6] independently showed that system energy consumption can be reduced by reducing flow rates. It is interesting to note that in the systems studied, three different chiller manufacturer's chillers were examined, yet the energy savings only varied from 2.0 to 6.5 percent. In all cases, regardless of which manufacturer's chillers were used, the system energy consumption was reduced. In addition, Demirchian, et al.[2], and Schwedler and Nordeen[6] also noted reduced first costs.

Chilled-Water-System Options

Misconception 3 — Low flow can only be applied to new chilled-water systems.

As previously discussed in the manual in the sub-sections *Coil response to decreased entering water temperature* and *Cooling tower options with low flow*, there are distinct opportunities to use existing infrastructure (pumps, pipes, coils, and cooling towers) to either expand available cooling capacity and/or reduce system energy costs by using lower-flow rates.

Upon examination, it is clear that low-flow systems allow savings even on short piping runs, work with all manufacturers' chillers, and can be used in retrofit applications. As a designer, remember to review the benefits to the building owner. Often, reducing flow rates can provide significant value.

Chapter references

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2. ARI Standard 560–1992, *Standard for Absorption Water Chiller and Water Heating Package*, Air-Conditioning & Refrigeration Institute.
3. Demirchian, G.H. PE and Maragareci, M.A. PE.: "The benefits of higher condenser-water ΔT at Logan International Airport central chilled-water plant." *IDEA 88th Annual Conference Proceedings,* 1997, pp. 291–300.
4. Eley, C.: "Energy analysis–replacement of chillers for buildings 43, 47, and 48."Eley Associates, CA, April 1997.
5. Kelly, D.W. and Chan, T.; "Optimizing chilled-water plants," *Heating/Piping/ Air Conditioning*, January 1999, pp. 145-7.
6. Schwedler, M., P.E. and Nordeen, A.; "Low flow works for absorbers too!" *Contracting Business*, November 1998, pp. 108-112.

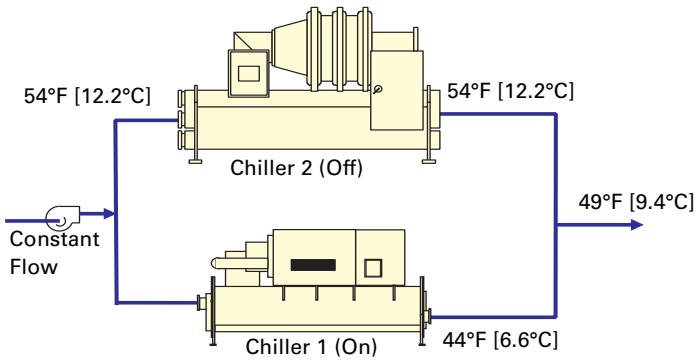
System Configurations

Multiple-chiller systems are more common than single-chiller systems for the same reason that most commercial airplanes have more than one engine—the balance of reliability and cost. The most typical system configuration, by far, has two chillers. Since system loads can vary throughout a wide spectrum, multiple-chiller systems can often operate with one chiller. During these periods, if the system is designed properly, the energy required to operate a second chiller and its auxiliaries can be conserved.

Parallel chillers

Figure 8 shows a system with two chillers piped in parallel, using a single chilled-water pump.

Figure 8 Parallel chillers with single, common chiller pump

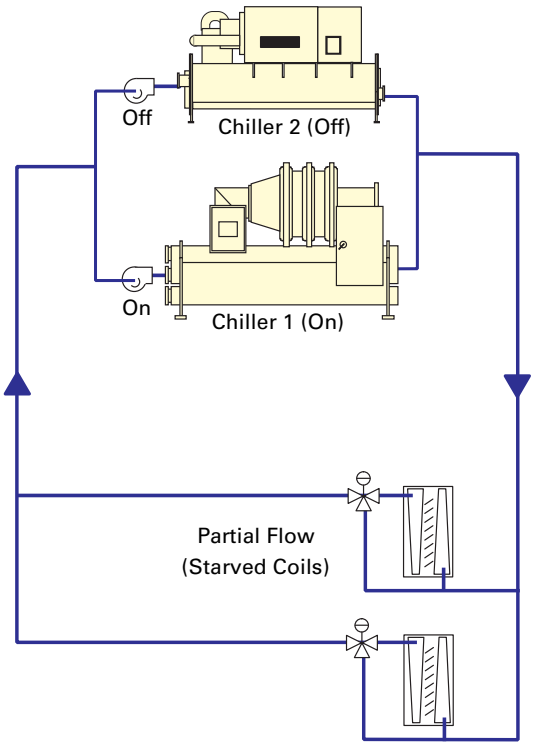


With constant flow loads, water flows in both chillers continually, whether the chiller is operating or not. Clearly, this can disrupt the supply chilled-water temperature when only one chiller is operating. The temperatures indicated in Figure 8 show how the supply water temperature rises when one chiller is cycled off in response to a part-load condition. This may result in inadequate dehumidification capabilities or the inability to satisfy specific loads.

Alternatively, the running chiller can be reset to produce a lower supply temperature at this condition. In this way, the mixed system-supply-water temperature may be maintained at a more acceptable temperature. This complicates the control system and presents the possibility of increasing chiller energy consumption due to the requirement for lower-temperature water. There will also be a low limit to this water temperature, dependent on the chiller's low pressure cut out control, low-evaporator-refrigerant-temperature limits, or low leaving-chilled-water limits.

System Configurations

Figure 9 Parallel chillers with separate, dedicated chiller pumps



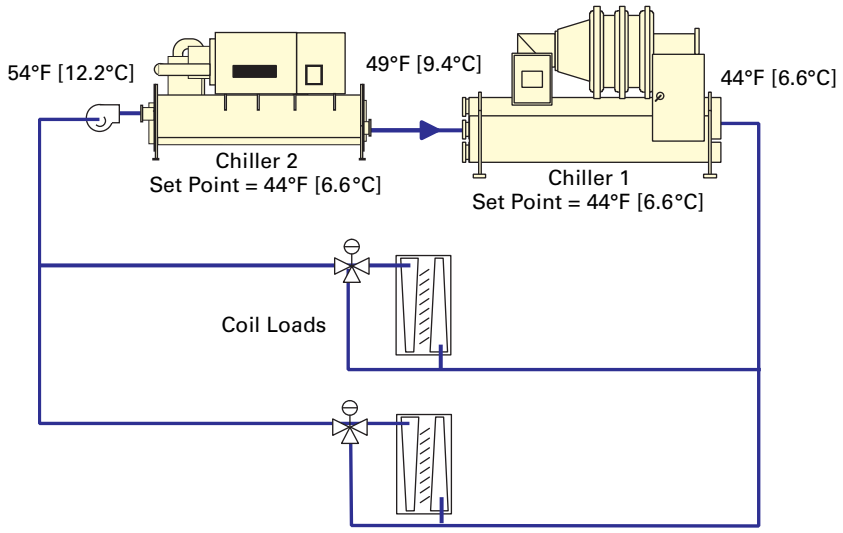
If separate, dedicated chiller pumps are used (Figure 9), a chiller–pump pair can be cycled together. This solves the flow mixing problem described above, but presents a new problem. With only one pump operating, total system water flow will decrease significantly, according to the pump–system curve relationship. All the load terminals in the system will receive less water, regardless of their need. Consequently, it is possible to starve some loads that are still high, perhaps those serving internal spaces with constant loads, or to starve the loads farthest from the pump.

System Configurations

Series chillers

If chillers are piped in series, as in Figure 10, the mixing problem disappears and the starving coils problem, when one of the pumps is not running, is resolved. Series flow presents a new set of temperature and flow control challenges.

Figure 10 Series chillers



The flow rate through each chiller is the entire system flow, that is, double the individual flow rate of the parallel chillers (two chillers). This means that the chiller evaporator must accommodate the doubled water quantity. All things being equal, this results in fewer water passes and decreased chiller efficiency. However, this efficiency loss is more than offset by increased chiller efficiency because the upstream chiller operates at warmer temperatures. Also, pressure losses are additive when the chillers are piped in series. This may increase total system pressure loss significantly. On the other hand, series chillers may work very well in low-flow systems, where the system temperature difference is greater than 16°F [9°C], resulting in less pressure loss. Low-flow systems are discussed in detail beginning on page 16.

System Configurations

Temperature control can be executed in several ways. Figure 10 shows a strategy where the controller on each chiller is set at the system design set point. Either chiller can be used to meet the system demand for up to 50 percent of the system load. At system loads greater than 50 percent, the upstream chiller is preferentially loaded because it will attempt to produce the design leaving chilled-water temperature. Any portion of the load that remains is directed to the downstream chiller.

If chiller set points are staggered (upstream at 49°F [9.4°C] and downstream at 44°F [6.7°C]), the downstream chiller is loaded first. The upstream machine then meets any portion of the system load that the downstream chiller cannot meet. This control strategy offers several benefits. The first is that the upstream chiller is always operating at an elevated temperature. This allows it to operate at a higher efficiency. Also, placing an absorption chiller in the upstream position increases its capacity. As an example, an absorption chiller that can produce 500 tons [1,760-kW] at a leaving chilled-water temperature of 44°F [6.7°C] may produce 600 tons [2,110-kW] at 50°F [10°C]. Centrifugal, helical-rotary, reciprocating, and scroll chillers experience capacity and efficiency changes to a lesser degree. By judicious use of the series configuration, these benefits can provide reduced installed cost and fuel flexibility to the building owner.

Equal loading of the two chillers may be accomplished by using a chiller plant management system to reset the upstream chiller's set point in response to changes in system load.

System Configurations

Primary–secondary (decoupled) systems

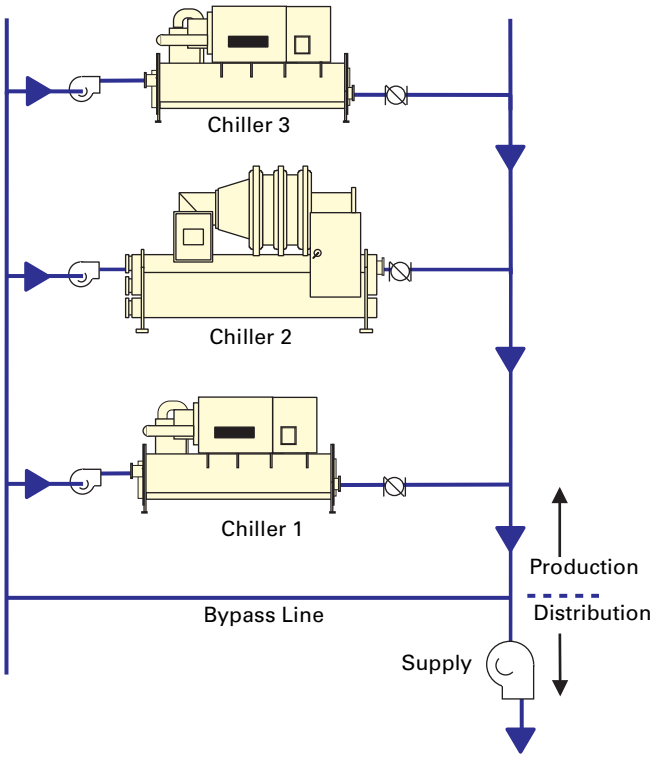
The root cause of essentially all of the difficulties with parallel chiller control is the fixed relationship between chiller and system flow rates. If, instead, we can hydraulically decouple the production (chiller) piping from the distribution (load) piping, it is possible to control them separately. The fixed relationships are then broken apart.

System basics

Hydraulic decoupling

Figure 11 shows the basic decoupled system. This strategy is also referred to as a primary–secondary pumping arrangement. Separate pumps are dedicated to production and distribution. While the same water is pumped twice (by different pumps), there is no duplication of pumping energy. This is because the production pumps overcome only the chiller and production-side pressure drop while the distribution pumps overcome only the distribution system pressure drops.

Figure 11 Decoupled arrangement



System Configurations

The unrestricted bypass line hydraulically decouples the production and distribution pumps so that they cannot operate in a series coupled pumping arrangement.

Although the two pumping systems are independent, they have three things in common:

- bypass piping,
- no-flow static head (from the building water column), and
- water.

Changes in flows or pressures, due to variations in dynamic head or the number of chillers operating, cannot cross the bypass line.

The extent of decoupling depends solely on the restriction (or lack of restriction) in the bypass pipe. Total decoupling is accomplished only if the bypass piping has zero pressure loss at any flow. Since this is not possible, some insignificant pump coupling will exist. The important issue is to keep the bypass piping free of unnecessary restrictions such as check valves. See *Check valve in the bypass line*, page 63, for further discussion.

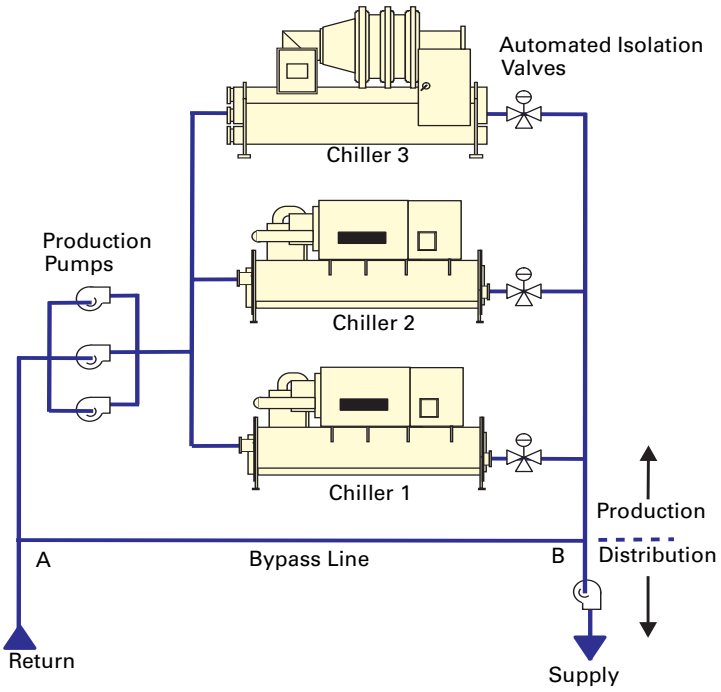
Production

An individual production (chiller) pump need only pump water from the return bypass tee (point A in Figure 12), through its chiller, and into the tee at the supply-end of the bypass line (point B in Figure 12). This represents a relatively small pressure differential and a low pumping-power requirement. In addition, each individual pump operates only when its corresponding chiller runs.

Production loops are independent, one from another, as well as from the distribution loop. They may consist of pump–chiller pairs that act as independent chillers. Or, manifolded and stepped pumps can be teamed with automatic, two-position chiller valves to operate in the same way as pump–chiller pairs. Figure 12 shows the latter arrangement. Temperature control is also independent. The conventional, chilled-water temperature controller furnished with the chiller, serves this function.

System Configurations

Figure 12 Production loop



Chillers may be of any type, age, size, or manufacturer. System operation is simplest, however, if all of the chillers are designed to operate with the same leaving chilled-water temperature and through the same system temperature rise (temperature difference) across the chiller.

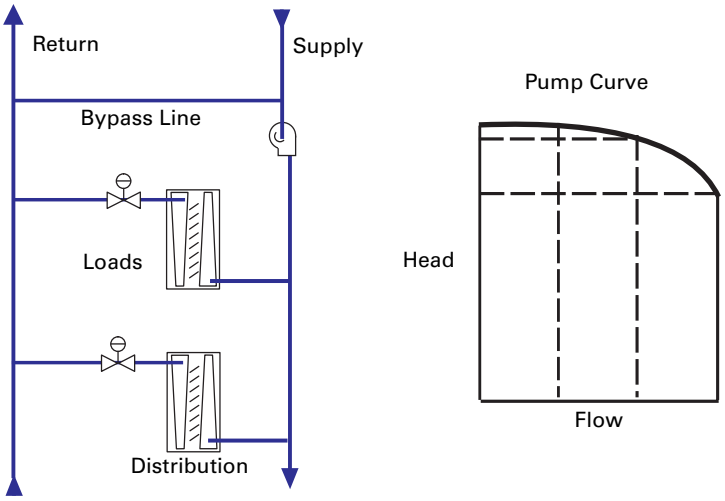
It is interesting to note that if the chillers in a decoupled system make the same chilled-water temperature, then all the operating chillers are loaded to equal *percentages*. There may be times when preferentially loading a chiller is desired. This is discussed in the section *Chilled-Water-System Variations*, page 54.

System Configurations

Distribution

Distribution pumps take water from the supply water tee (point B in Figure 12), push it through all the distribution piping and load terminals, and then on to the return water tee (point A in Figure 12). This pump can (and should) allow variable flow.

Figure 13 Distribution loop



By itself, the distribution system is easy to understand. Figure 13 shows a simplified distribution system consisting of multiple cooling coils, each controlled by a valve that regulates the flow in its respective coil. In this case, the flow control valves should not be three-way because a constant flow is not desired. Instead, two-way modulating valves are used. As the aggregate loads change system flow, a constant speed pump would "ride" its flow-rate-versus-head-pressure. This means that in response to the change of flow required, the pump will find a new equilibrium point along its operating curve. An example pump curve is shown in Figure 13.

Alternatively, multiple pumps or variable-speed pumps can be used to limit the dynamic pumping head, similar to VAV fan control. Properly designed, part-load pumping power can approach the theoretical cubic relationship to flow, thus reducing energy consumption significantly. Today, most decoupled systems use a variable-speed drive on the distribution pump.

Distribution basics The distribution system benefits from the ability to accommodate load diversity, the fact that system flow is variable, and (in a properly operating system) the fact that return water is maintained at temperatures near design. The last assumption is further discussed in the subsection *Low ΔT syndrome*, page 63.

System Configurations

Load diversity Not all chilled-water loads peak simultaneously. Therefore, the quantity of water that flows at any one time is reduced from the "sum of the peaks" load that would be required in a constant-flow-distribution loop. This presents the possibility of reducing chiller, pump, and pipe sizes significantly.

Variable flow Only the water that the loads actually use is pumped. Most of the time, this means a significantly reduced flow rate, accompanied by an even more significant reduction in pumping energy.

Elevated return-water temperatures Because unused chilled water does not bypass the cooling coils, all water that is returned accomplishes some cooling. Theoretically, the return-water temperature will always be at least as high as it is at full load. From a practical standpoint, this is not always possible, but it is closely approached in a properly operating system. In fact, at most part-load conditions, water returns from properly functioning air-conditioning coils at higher-than-design temperatures. In systems that use counterflow cooling coils, this occurs because the water leaving the coil tries to approach the temperature of the entering air stream.

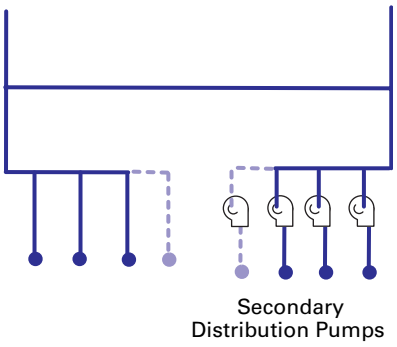
Warm return water provides advantages in system design. It permits "preferential" loading of chillers, for example. Warmer return water is useful with all systems, but particularly so with heat recovery and free cooling applications. The section *Chilled-Water System Variations*, page 54 has further information.

Pumping Arrangements

Common

A variety of distribution system arrangements is possible. A single, large pumping station, as shown in Figure 12, can be used. The station may consist of single or multiplexed pumps sequenced on or off.

Figure 14 Campus pumping arrangement



Campus

Alternatively, each of several secondary distribution systems can be piped in parallel. For example, Figure 14 shows separate distribution systems for each of three loads. Clearly, this arrangement lends itself to the possibility of plant expansion by simply adding secondary distribution pumps to the existing plant.

Tertiary or distributed

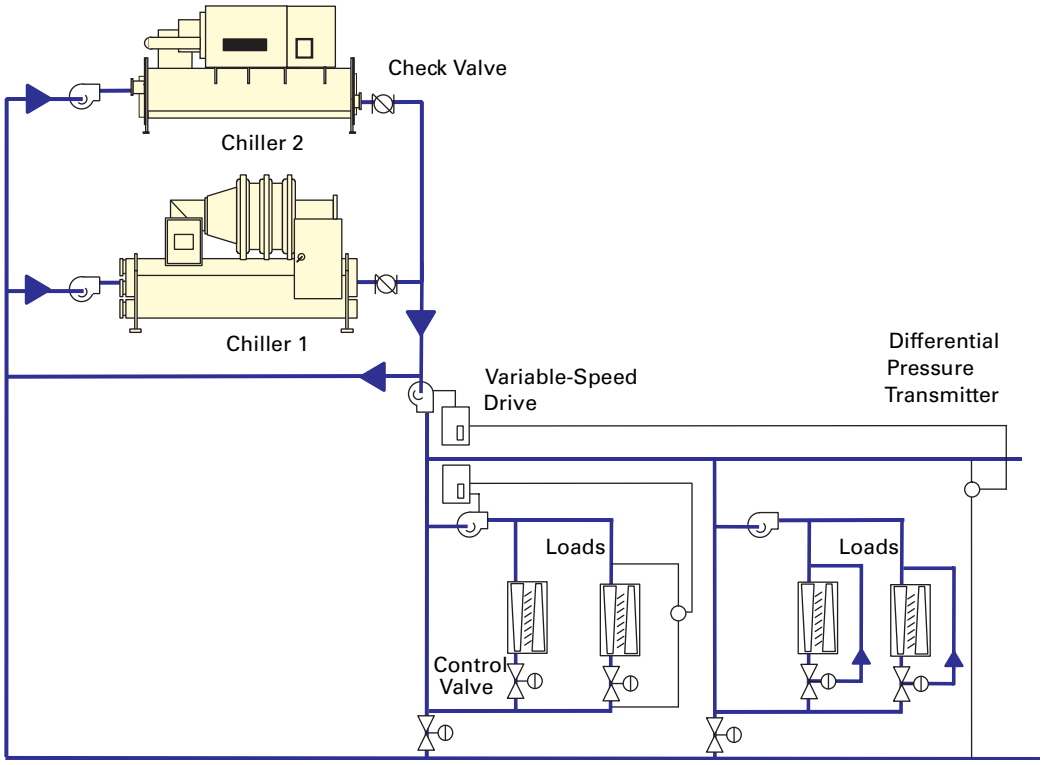
Tertiary pumping is an extension of primary–secondary pumping when the distribution or secondary pump must overcome diverse and severe pumping requirements.

System loads can also be decoupled from the secondary distribution system. This is frequently done with very large systems. Figure 15 shows one method of providing “tertiary pumping” at the loads. A “load” may be something as large as an entire building, or as small as an individual cooling coil. When one or more loads have extreme head requirements, the degree of rangability of the distribution pump is severely curtailed. Tertiary pumping allows the excess pumping requirements to be placed on a third pumping system thus shielding the distribution pump from divergent pressure requirements.

Most importantly, the loads must be controlled so that only the water needed to perform cooling is taken from the distribution loop. Water must not be allowed to flow into the return piping until it has sustained a specific temperature rise. Tertiary pumps can be either constant flow or variable flow, to best meet the terminal load requirements.

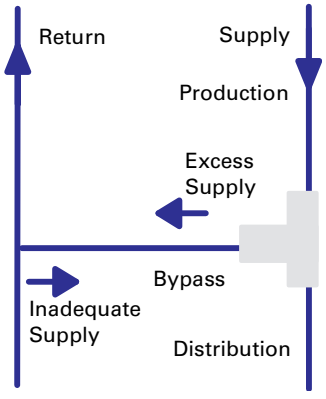
Pumping Arrangements

Figure 15 Tertiary pumping arrangement



Decoupled system–principle of operation

Figure 16 Decoupled system supply tee



At the tee connecting the supply and bypass lines, a supply–demand relationship exists, as shown in Figure 16. Think of the total flow rate from all operating pump–chiller pairs as supply. Demand is the distribution system flow required to meet loads. Whenever supply and demand flows are unequal, water will flow into, or out of, the bypass line. Flow can be sensed directly or inferred from the bypass-water temperature.

An inadequate supply to meet demand causes return water to flow out of the bypass leg of the tee, into the distribution system. The mixture of chiller-supply and warm system-return water, then, flows into the distribution loop. Supply-water temperature control is compromised when this happens. If the bypass-line flow into the supply tee (Figure 16) can be sensed, its presence can be used to energize another pump–chiller pair. The increase in supply water flow from the additional pump changes the supply–demand relationship at the tee, eliminating return-water mixing. As long as return-water mixing does not occur at the supply tee, no additional chiller capacity is required. When mixing does occur, an additional chiller may be needed, depending on the amount of mixing that can be tolerated.

Pumping Arrangements

Much of the time, supply exceeds demand and the surplus flows to the return tee. If a chiller pump is stopped prematurely, the bypass-line flow will again show a deficit and the pump will be cycled on again. The amount of surplus flow necessary depends on the size of the chiller to be shut off. The surplus flow must exceed a certain quantity before shutting off a chiller–pump pair. This is discussed in *Chiller sequencing*, page 39. If all chillers are equal in size, the surplus-flow signal can be constant.

Control of the number of chillers is accomplished by simply noting the direction of flow in the bypass line. Thus, the system operates as a flow-based demand system, not a temperature-based demand system.

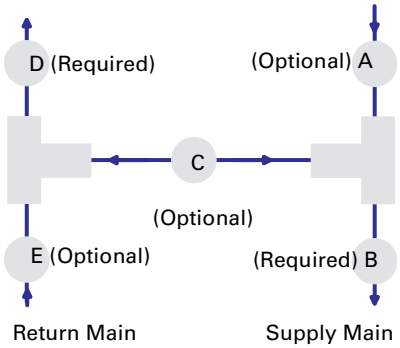
Flow-based control

To properly operate a primary–secondary system, an indication of direction of flow and the flow rate through the bypass line is necessary. This may be done either directly or indirectly. When bypass flow is from supply to return, it is called *surplus*. Bypass flow moving from return to supply is termed *deficit*.

Flow-sensing

Direct flow-sensing in the bypass line can be accomplished in several ways. A number of flow-metering technologies have been used successfully. These include Pitot tube, Venturi, orifice plate, differential pressure, turbine, impeller, vortex, magnetic, and ultrasonic transit-time. The accuracy, ease of installation, maintainability, and cost of meter technologies vary widely. To give accurate results, a flow meter must be calibrated periodically, with some flow meters requiring more-frequent calibration than others. When using flow-sensing devices, it is important to understand the range of flows a device can properly measure and its calibration requirements. The readings will only be as good as the instrumentation. Also note that many flow-measurement devices require several diameters of straight pipe for accurate readings.

Figure 17 Temperature-sensing



Temperature-sensing

Mixed water streams at the outlets of the supply- and return-water tees, Figure 17, can be used to indirectly determine the supply–demand relationship. Standard temperature-mixing equations can be used to determine the exact amount of surplus or deficit flow in the bypass line.

The five temperatures sensed — at points A, B, C, D, and E — are received by a programmable controller. (Some control systems use only two sensors, at points B and D, in conjunction with "pre-programmed" algebraic mixing equations.) Processing software applies the classic mixing equations and determines the resulting action to properly control the chilled-water system.

Pumping Arrangements

Note that sensor D needs to be very accurate, especially if there are many chillers, since small temperature changes may warrant chiller sequencing. Either temperature-sensing strategy has a cost and flexibility advantage if a building or chiller-plant management system already exists, or is planned.

Chiller sequencing

Given the amount and direction of flow in the bypass line, chillers can be added or subtracted.

Adding a chiller

When there is deficit flow in the bypass line, the system is receiving water at a temperature above the system design temperature. (Also see the *Low ΔT syndrome* discussion, page 63.) At this point in time, a chiller and pump may be added. Many operators sense deficit flow for a particular amount of time (for example, 15 minutes) to ensure that the deficit flow is not a result of system transients. This reduces the chances of cycling a chiller; that is, turning on a chiller and then turning it off after a short time.

Subtracting a chiller

A chiller may be turned off when enough surplus water is flowing through the bypass line. How much is enough? Enough so that the chiller does not cycle on again in a short time period. Many system operators compare the amount of surplus flow with the flow rate of the chiller they are considering turning off. If this ratio is 110 to 115 percent, they turn the chiller off. Let's look at an example:

Chiller 1 can make 960 gpm [60.6 lps] of 40°F [4.4°C] chilled-water, while Chiller 2 can make 1,440 gpm [90.8 lps]. At present, there is 1,100 gpm [69.4 lps] of surplus flow in the bypass line.

- The surplus bypass flow is presently 115 percent of Chiller 1's flow. If we turn Chiller 1 off, we will have 140 gpm [8.8 lps] of surplus flow left.
- Note that the surplus bypass flow is presently only 76 percent of Chiller 2's flow. If we turn Chiller 2 off, we will have 340 gpm [21.5 lps] of *deficit* flow. It is clear that we would have to cycle that chiller back on soon.

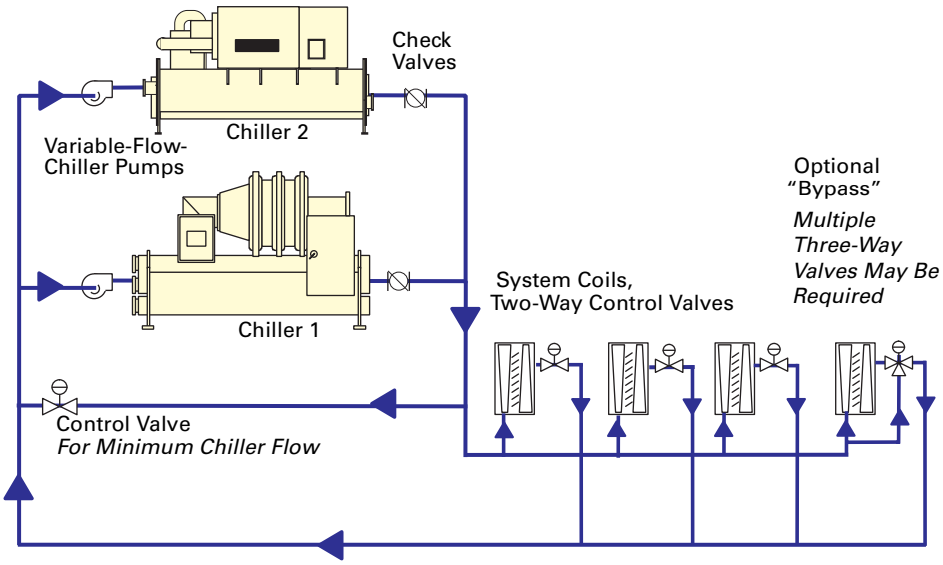
In this case, we could turn Chiller 1 off, but leave Chiller 2 on for the most efficient use of the chillers.

Variable-Primary-Flow Systems

Another method for balancing the production and distribution flows is to make them equal. Variable-flow systems require chillers that can operate properly when evaporator flow varies.

Conceptually, the variable-primary-flow (VPF) system resembles the familiar constant primary–variable secondary design more commonly known as the decoupled" system.[1] For example, both require a bypass. The bypass line for a VPF system is required to ensure that minimum flow through chillers can be maintained. Each chiller in the arrangement shown has a dedicated pump whose operation coincides with the chiller it serves.

Figure 18 Variable-primary-flow system



In a VPF system, **water flow varies throughout the entire system**—through the evaporator of each operating chiller as well as through the cooling coils.

Two-way control valves on coils, check (or isolation) valves on chillers, and a bypass pipe with a control valve are required to implement a VPF system. However:

- variable-flow chiller pumps eliminate the need for a separate distribution pump.
- the bypass can be positioned either upstream or downstream of the cooling coils.
- a control valve in the bypass ensures that the amount of flow through the operating chiller(s) never falls below the minimum limit.

Variable-Primary-Flow Systems

Dispelling A Common Misconception
True or false: "Chillers operate more efficiently in a system with variable rather than constant primary flow because of the greater log mean temperature difference (LMTD)."

It is true that the return water temperature in a properly operating VPF system remains constant as the amount of flow changes. It is also true that the LMTD can be increased by changing the production (primary) side of the chilled-water loop from constant to variable flow. But there are other facts to consider.

In a system with constant primary flow:
- Entering-evaporator temperature and LMTD fall as the cooling load diminishes.
- The convective heat transfer coefficient, like the primary flow, remains constant despite reductions in load.

In a system with variable primary flow:
- The convective heat transfer coefficient in the chiller evaporator decreases with a reduction in flow.
- Reduced flow decreases the overall heat-transfer effectiveness of the chiller evaporator.

The net effect is that the power consumption for a given chiller is virtually the same whether the chiller's evaporator flow is variable or constant.

VPF advantages

VPF systems present building owners with several cost-saving benefits that are directly related to the pumps. The most obvious cost savings result from eliminating the secondary distribution pump, which, in turn, avoids the material and labor expenses incurred with the associated piping connections, electrical service, and variable-frequency drive. Although the number of pumps is reduced, the sizes of both the pumps and the variable-frequency drives increase since the pumps must be sized to overcome the entire system's pressure drop. This offsets some of the installed cost savings due to fewer pumps.

Building owners often cite pump-related energy savings as the reason that prompted them to install a VPF system. With the help of a software analysis tool such as System Analyzer™, TRACE® 600, or DOE 2.1, you can determine whether the anticipated energy savings justify the use of variable-primary flow in a particular application.

It may be easier to apply a variable-primary-flow system rather than a primary–secondary system to an existing chilled-water plant. Unlike the primary–secondary design, the bypass can be positioned almost anywhere in the chilled-water loop and an additional pump is unnecessary.

VPF caveats

Sequencing chillers requires a thorough understanding of system dynamics since flow rates will vary through every operating chiller. The control strategy needed to avoid cycling, or restarting the chiller too soon, becomes complicated as the number of chillers or the capacities of the different chillers increases. The system designer must thoroughly define the control sequence early in the design process and clearly communicate it to the controls provider. Better yet, on such a system, a partnership among owner, operator, designer, and chiller plant provider (including controls) can be formed.

Controlling the flow rate fluctuation is critical. Confirm the allowable flow fluctuations with the chiller manufacturer and design the system so that the rate of flow change is never exceeded. Operators must understand how VPF systems work, therefore training is mandatory. The success of a system design is directly related to the operator's ability to carry out the design intent.

An important consideration when investigating variable-primary-flow systems is the fact that VPF systems take more time and planning than other systems to design and commission properly. If this time and planning can't, or won't, be invested, you will probably have better results with the use of systems other than VPF.

Variable-Primary-Flow Systems

Limits

Evaporator flow rates change as system demand changes. However, there are limits to absolute flow rate and allowable rate of change. Exceeding those limits may cause chiller-control instability or catastrophic failure.

Absolute flow limits

Maintain the evaporator flow between the minimum and maximum limits. Today, the cataloged water velocity range for many chillers is 3–11 fps [0.9–3.4 m/s], although some manufacturers now allow selections in the 1.5–2.0 fps [0.46–0.61 m/s] range. Ask the chiller manufacturer for the actual flow-rate-limit values (gpm [lps]) for your machine. The upper limit is generally set to avoid tube erosion problems, while the lower limit maintains control stability.

Rate of change

If a chiller's control system can not respond properly, the chiller might actually respond to rapid flow-rate changes by turning off or locking out on a safety trip. To ensure that chillers stay on line, keep changes in evaporator flow rate within manufacturer-set limits. This may require the use of slow-acting, modulating control valves at each chiller to reduce flow variation as chillers are sequenced, especially if pumps are manifolded.

Application note
While flow through a chiller's evaporator is now allowed to change, chillers with advanced controls may react by temporarily unloading. This results in an elevated leaving chilled-water temperature—generally only for a short time. For applications that require strict chilled-water temperature control, check with the chiller manufacturer for recommendations concerning the use of variable-evaporator flow.

As of this manual's writing, the most advanced chiller controls can provide close temperature control if flow fluctuations are limited to less than 10 percent of design chiller flow per minute. For some advanced controls, relaxing this limit to 30 percent of design flow per minute is permissible in most comfort-cooling applications since the leaving-evaporator water temperature will not deviate from set point for more than a few minutes, if at all. Again, check with the chiller manufacturer for base limits

Bypass flow control

Just as in a primary–secondary system, VPF systems respond to load changes by modulating flow. As the system demand nears the minimum flow rate for a single chiller, water must be bypassed to keep the flow rate through the chiller evaporator above that minimum.

Methods

- **Bypass line with valve** As previously discussed, bypass may either be controlled at a central location or be ensured through the use of three-way valves. When a bypass line and valve are used, the valve must be slow acting and modulate open when the flow rate nears the minimum of any chiller on-line. When the flow rate rises above the chiller's minimum by a preset limit, the valve may close.
- **Three-way valve** An alternative is to provide three-way valves in distant portions of the system. The pump must be controlled so these valves always keep the total of their flow above the chiller's minimum. One method to ensure this flow rate is to control the pump to maintain a pressure differential at this valve, thus ensuring nearly constant flow at this point in the system.

Variable-Primary-Flow Systems

Evaporator flow measurement

Measurements of evaporator flow are critical to VPF control. One common practice relies on direct measurement using flow meters. (Be aware that some flow meters require, but seldom receive, frequent calibration.) Another measures water pressure drop through the evaporator bundle and estimates evaporator flow based on manufacturer data.

Bypass locations

A bypass is required whether the primary flow is constant or variable. In a primary–secondary system the decoupler allows excess primary water to be bypassed. In the VPF system the bypass allows system control to maintain the flows to chillers' minimum flow requirements.

There are three common locations for the VPF bypass line:

- Place the smaller bypass required for a VPF system in the same position as the bypass in a "decoupled" system. A variable-speed drive on the pump located near the chillers reduces flow and allows substantial energy and operating cost savings. One drawback is that the valve must work against higher pressures — possibly causing wear and lack of controllability.
- Use three-way valves at some of the system coils. While this approach ensures minimum chiller flow, it reduces the pump operating cost-savings, due to the increased system flow and decreased return-water temperature.
- Locate a bypass line and valve near the end of the piping run. The bypass control valve sees a lower operating pressure and stable control. Some operating cost savings may be sacrificed to maintain the pump-operating pressure at a higher level with the bypass located away from the chillers. The line sizes must be large enough to allow the minimum flow rate.

Chiller sequencing

Variable-primary-flow systems have more complex chiller sequencing requirements than primary–secondary systems. In fact, it is the time and thought put into chiller sequencing that will ultimately allow a VPF system to work well — or cause it to fail. System designers must think through the process, communicate the sequence of operation to those providing system-level programming and make sure the system operator understands the system function for it to have any chance to work.

Variable-Primary-Flow Systems

Adding a chiller in a VPF system

When the chiller(s) already on-line can no longer increase their flow rate — due either to the pump capacity or the maximum allowable evaporator-flow rate — or when chillers cannot meet the system-chilled-water set point, a chiller may be added. In a properly operating system the supply-water temperature is monitored. When the temperature exceeds the design setpoint by a certain amount (for example, 1.5°F [0.8^{3}C]) for a set time (for example, 15 minutes) an additional chiller starts.

As chillers are brought on-line, flow rates may fluctuate substantially. This is especially true in a system with two chillers. An example will help explain the challenges.

Table 11 Flow-rate-fluctuation examples

	Design flow rate gpm [lps]	Minimum flow rate gpm [lps]	Maximum flow rate gpm [lps]
Chiller 1	960 [60.6]	576 [36.3]	2,110 [133.1]
Chiller 2	1,440 [90.8]	675 [42.6]	2,474 [156.1]

At a point in time, Chiller 1 is active and has 1,100 gpm [69.4 lps] flowing through its evaporator. It can no longer satisfy the required system supply temperature. What happens if Chiller 2's valve is opened with no other action taken? If we assume that pressure drops are equal, 550 gpm [34.7 lps] will flow through each chiller. This means Chiller 1's flow rate drops by 50 percent instantaneously (probably beyond what its controls can respond to) and we are below each chiller's minimum flow rate. Be aware that this could become an issue since chiller controls may protect the chiller by shutting it off. The result is that some combination of pump speed, bypass valve control, and slow-acting valves at the chillers must do two things:

- Keep change in flow rate within the equipment limitations
- Keep each chiller's flow rate above its minimum

The bottom line is that control of VPF systems MUST be considered during system design.

Variable-Primary-Flow Systems

Subtracting a chiller in a VPF system

Subtracting a chiller in a VPF system is not simple, either. As an example, suppose that both chillers are running near their minimum flow. Chiller 1 is at 650 gpm [41.0 lps] and Chiller 2 is at 760 gpm [47.9 lps], so the system total is 1,410 gpm [88.9 lps].

Choice 1

Turn off Chiller 1: It is obvious that we should be able to turn Chiller 1 off and satisfy system load as long as the flow rate doesn't increase too rapidly. However, the system flow rate is close to the Chiller 2's design flow rate, and if the system flow increases, we may need restart Chiller 1.

Choice 2

Turn off Chiller 2: If Chiller 1 has a condenser water temperature lower than design, its capacity has increased. Could we turn off Chiller 2? Chiller 1's flow is certainly within the allowable limits, but it may or may not be able to supply the required capacity. In this case, the dilemma is to ensure that there is enough chilled water capacity after a chiller is turned off.

Obviously, control is an extremely important aspect of a VPF system. In many chilled-water systems with between two and five chillers, system designers elect to use a primary–secondary system design to minimize control complexity.

"Overpumping" a chiller in a VPF system

Some VPF practitioners use manifolded pumps, allowing them to "overpump" a chiller. As used here, overpump means to pump more water through a chiller than was specified in the original design. In the previous example, Chiller 1 would be "overpumped" any time its evaporator water flow exceeds 960 gpm [60.6 lps]; however, the flow rate must still be less than the maximum allowable. Recall that pressure drop through the evaporator will increase roughly with the square of the flow. There are two reasons one might want to overpump a chiller.

As the condenser water temperature is allowed to fall, the chiller could produce more cooling—if allowed. The only way to actually get that increased capacity is to increase either the flow rate or the temperature difference. The return water temperature is set, so now the only choices are to decrease the leaving water temperature or increase the flow. Changing water temperature complicates the system operation, but increasing water flow may be fairly simple in a VPF system. By increasing the evaporator flow rate, the chiller can provide more cooling.

Variable-Primary-Flow Systems

Some system operators overpump a chiller as a "band-aid" for systems experiencing low ΔT syndrome (see page 61). An example of low ΔT syndrome is receiving a depressed (for example, 49°F [9.4°C]) return-water temperature rather than the design (for example, 56°F [13.3°C]) return-water temperature. Again, the only methods to load the chiller are to decrease the chilled-water temperature or to increase the flow. If the pumping power and speed allows, the operator may be able to increase the chiller's flow rate and capacity. Do not exceed the pump's operating envelope.

Critical VPF system requirements

While they do have benefits, variable-primary-flow systems[1] should not be used on all systems. Understanding and accounting for the following prerequisites are critical for a successful VPF system.

- Chiller controls must adequately regulate temperature as flows vary
- System level controls must adequately regulate both temperature and flow as system demand varies
- Adequate time must be budgeted to design and program the system control sequence
- The system operator must understand the intended operation
- The system must include a means of assuring all chiller minimum-flow requirements, normally one of the bypass methods previously discussed.

VPF complicates all aspects of system design and operation. Consequently, there are many steps that must be taken to allow a VPF system to work well.

Chapter references

1 Schwedler, M., PE and Bradley, B.; "An Idea for Chilled-Water Plants Whose Time Has Come...Variable-Primary-Flow Systems," *Engineers Newsletter*, Volume 28, No. 3, The Trane Company, 1999.

Chilled-Water-Control Options

Chilled water reset — raising and lowering

Many chilled-water plants use chilled water reset, that is, changing the chiller's control setpoint, in an effort to reduce chiller energy consumption. As discussed in the first section *Chilled-Water Plant Basics*, page 3, raising chilled-water temperature reduces *chiller* energy consumption. In a constant-volume pumping system, this may reduce system energy consumption as long as humidity control is not lost. Humidity control may be lost if, as chilled-water temperature is increased, the air temperature leaving the coil increases to a point where it no longer performs adequate dehumidification.

In a variable-volume pumping system, however, raising the chilled-water temperature increases pump energy, often substantially, and typically increases total system energy. Before considering increased chilled-water temperature, the system operator should calculate the increased pumping energy and compare it with the chiller energy savings. It should be noted that ASHRAE/IESNA Standard 90.1–1999[1] requires chilled-water reset for constant-volume systems — with exceptions — but exempts variable-volume systems from this requirement for the reasons discussed.

An often overlooked method of decreasing *system* energy consumption is to *reduce* the chilled-water temperature, thereby decreasing pumping energy but increasing chiller energy. This strategy is possible with adequate chiller capacity and lift capability. Reducing chilled-water temperature may also improve dehumidification in the building. Another result of reducing the chilled-water temperature is increased chiller capacity during times when the condenser water temperature is cooler than design. This allows more time before another chiller and its ancillary equipment are started. This option is more fully discussed in *Low ΔT syndrome*, page 63.

Be aware that *any* change in chilled-water set point requires changes to be made to the system chiller-sequencing algorithms to ensure that system capacity is met. This added complication may not be warranted.

Chilled-Water-Control Options

Critical valve reset

Often, pumps are controlled to maintain a constant-pressure differential at a remote coil. Unless this coil serves the zone requiring the most cooling (the critical zone), the pump provides more pressure than necessary and consumes more power than necessary. Systems that have integrated air-side and chiller plant control systems and contain valves with direct digital controls present an opportunity for further pump operating-cost reduction. If a system is monitored to determine the critical valve at each point in time, the pump's operating pressure can be reset so that the critical zone's control valve is nearly open. Integrated control allows a system-level controller to determine the critical zone and reset the pump's set point dynamically, therefore reducing pump operating costs.

The controllers know the position of their individual valves, which modulate to maintain the required water flow through the coil. The building automation system continually monitors the valve controllers, looking for the most open valve. The controller resets the pump set point so that at least one valve, the one requiring the highest inlet pressure, is nearly wide open. The result is that the pump generates only enough pressure to get the required water flow through this "critical" valve, thus saving pumping energy.

Chapter references

1 *BSR/ASHRAE/IESNA 90.1–1999*, "Energy standard for buildings except low-rise residential buildings," Illuminating Engineering Society of North America and American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1999.

Design Considerations

Chilled-water-pump configuration

Pumps may be either on the inlet or the outlet of the chiller, as long as the inlet of the pump experiences an adequate, positive suction pressure. In applications where there is a significant liquid column head (for example, a high-rise building), the pump is often located at the chiller's *outlet* so that the evaporator bundle is subject to the static head rather than the static-plus-dynamic (added by the pump) head. The need for high-pressure water boxes on the chiller can be eliminated.

An additional advantage of locating the pump upstream of the chiller is that if the pump motor rejects its heat to the water, the heat can be removed directly by the chiller. The chiller does not need to compensate for the pump heat by making colder water.

Pump per chiller

In either a primary–secondary or variable-primary-flow system, using one pump per chiller simplifies system hydraulics. The pump can be selected to produce the flow and pressure drop necessary for the specific chiller. Bringing additional pumps on changes system hydraulics, but only minimally. One drawback of such a system is a lack of redundancy, since the pump and chiller are dedicated to one another. This may be overcome by using a spare pump, pipes, and valves so that the spare pump could work with any chiller during emergency conditions.

Manifolded pumps

In an effort to resolve the redundancy consideration, some designers prefer to manifold pumps and provide *n*+1 pumps, where *n* is the number of chillers. Such an arrangement allows any pump to be used with any chiller. However, system hydraulics become more complicated. Unless all piping runs and evaporator pressure drops are equal, the amount of water flowing to each chiller will differ. As discussed with the variable-primary-flow system, manifolded pumps present a control challenge when chillers are sequenced.

Either pump configuration can be successful; one pump per chiller simplifies the hydraulics, while manifolded pumps allow redundancy.

Design Considerations

Bypass-line sizing

Bypass lines are required in both primary–secondary and variable-primary-flow systems. In a decoupled system, the bypass line should be sized for 110 to 115 percent of the largest chiller's design flow rate. In a VPF system, the bypass line should be sized for the largest chiller’s minimum flow rate.

While minimal pressure loss is desirable, substantial water velocity can be accommodated without significant pressure loss in the relatively short length of bypass piping. The bypass line must be of sufficient length to prevent random mixing of the supply and return water streams; a minimum length of five to ten pipe diameters is recommended.

Amount of fluid in the loop

Two questions must be answered when determining how much fluid is necessary to maintain proper chilled-water-system control.

- How fast can the specific chiller respond to changing conditions?
- How fast can the system respond to changing conditions?

The amount of fluid the loop requires to operate properly is related to the larger of these two answers. Note that both answers describe an amount of time.

Required Volume = Flow Rate x Loop Time

Where:

- Required Volume = the amount of fluid in the coil, pipes, evaporator barrel, storage tank, etc., in gallons [liters]
- Flow Rate = the system flow rate, in gpm [lps]
- Loop Time = the time it takes for fluid to leave the chiller, move through the system and return to the chiller, *and allow for stable system operation*, in minutes [seconds]

Design Considerations

Chiller response to changing conditions

Follow the manufacturer's advice for the specific chiller being considered. This determines the absolute minimum amount of water the loop requires. However, this is the chiller minimum, not the system minimum, as discussed in the next section. Many of today's chillers have controls that respond quickly to changing conditions. Some chillers can react to a change in return water temperature in one minute; other chillers may require five or more minutes to react. The response varies, depending on chiller type and design.

System response to changing conditions

It is important to understand that even if a chiller can respond to rapidly changing conditions, the interaction between the chiller, system pumps, and control valves may define the minimum loop time. These components may "hunt" if the system conditions change too rapidly. Review these interactions to ensure that system control will be stable.

Example:
A specific chiller requires at least two minutes of water in the loop to operate properly. However, after considering the system interaction, it's decided that a five-minute loop time will work best. The system flow rate is 960 gpm [60.6 lps].

Required Volume (R.V.) = 960 gpm × 5 minutes = 4,800 gallons
[R.V. = 60 lps × 5 minutes × (60 seconds/1 minute) = 18,180 liters]

If the volume of fluid in the evaporator bundle, piping, and coils is less than the required volume, a tank should be added to increase loop volume. For optimal stability, the tank should be placed in the return water position and be designed to *mix* the returning-water stream with the water currently in the tank.

Plant expansion

Plant expansion can be performed easily in either a primary–secondary or variable-primary-flow system by adding another chiller and pump to the system. The two major considerations will be whether the chilled-water distribution pipes will be able to handle the flow and how to install the new chiller while other chillers are still providing cooling. When the new system flow rate complies with good piping practice and the pumps can deliver the water, the process works well. To maintain chilled-water flow during installation of a new chiller, some plants are constructed with piping stubs in place for the new chiller. In this way, the new chiller can be installed while the system is still operating, then the valves in the stubs can be opened.

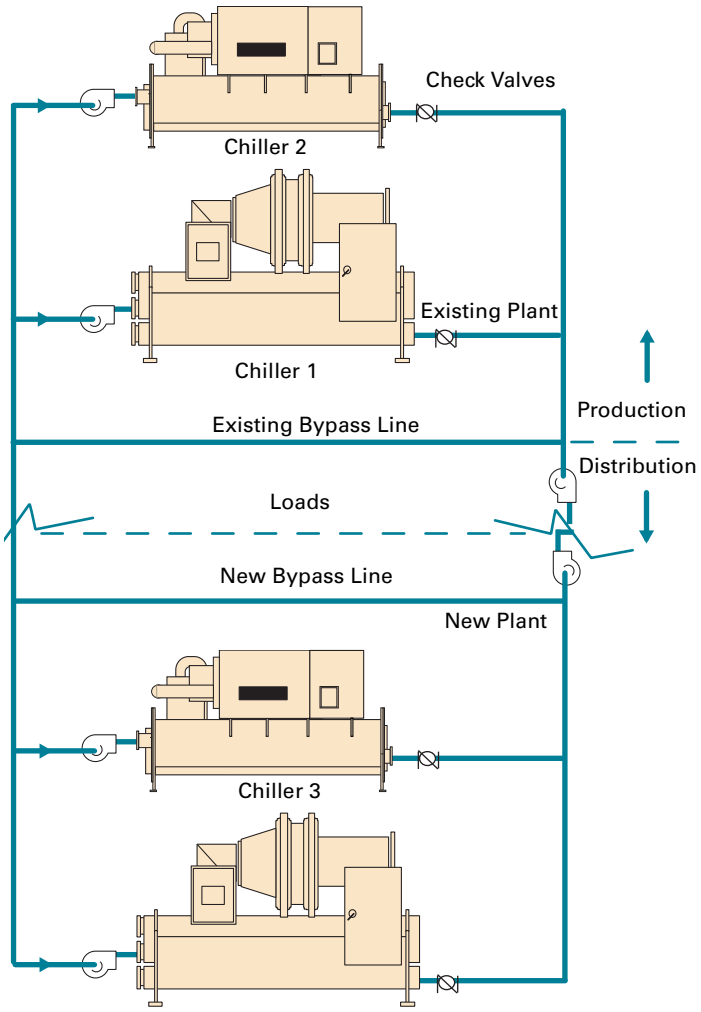
Design Considerations

When decoupled systems are used on large campus-type systems, added loads are often located some distance away from the original loads. Yet, planners like the idea of somehow hooking the new loads to the existing system. The double-ended system shown in Figure 19 is one way of handling this requirement. A second production facility is placed at a convenient location in the new part of the campus. Its distribution plant is laid out as a mirror image of the original piping, and connects to it at the ends of each system.

This way, either production loop can feed into the now common distribution loop. The point of no-flow simply floats as the two production plants are loaded. If, at very low seasonal loads, the operators want to secure one entire production loop, it is not a problem if the on-line plant has adequate production and distribution capacity. With full-time plants, this tactic can be used to reduce operating expenses significantly for many weeks of the year. Further, it permits preferential loading of the newer, more efficient machinery.

Design Considerations

Figure 19 Double-ended decoupled system



Chilled-Water System Variations

A number of chilled-water system variations can and should be used when appropriate. Each configuration offers specific advantages to solve problems and add value to the system.

Heat recovery

ASHRAE/IESNA Standard 90.1–1999[1] now requires heat recovery in specific applications. Indoor air quality concerns have spurred the use of systems that subcool supply air to dehumidify, then temper, the air to satisfy space conditions. ASHRAE/IESNA Standard 90.1–1999 also limits the amount of new reheat energy used in these applications. With these drivers, and energy costs, there has been a resurgence of heat recovery chillers. The example on page 57 describes a cost-effective recovered-heat scheme. This scheme is commonly used for service-water heating in resort hotels and for certain process loads.

Preferential loading

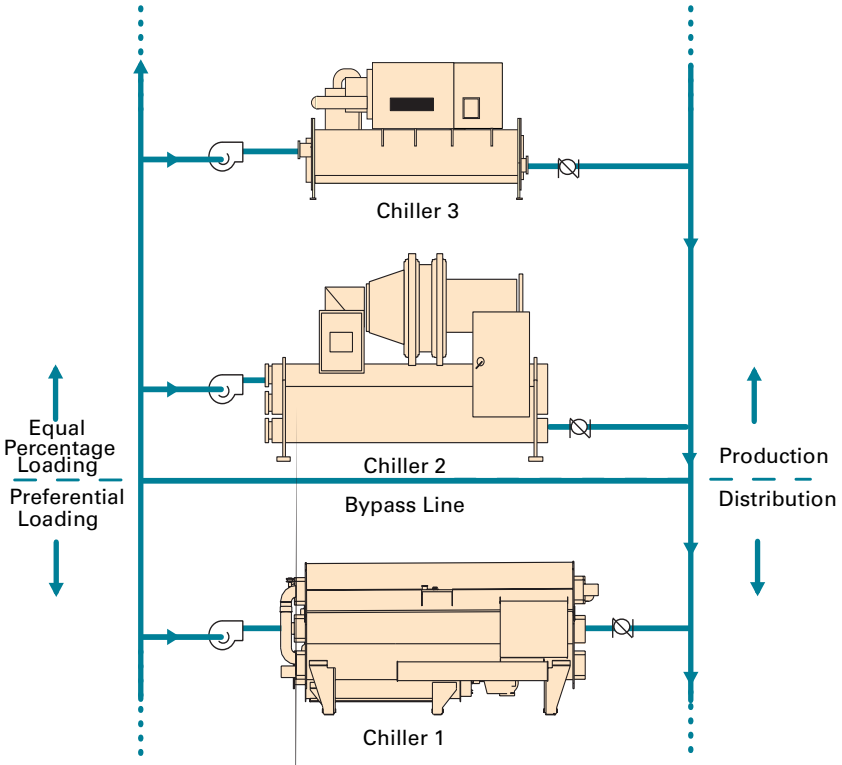
Preferential loading is desirable for systems that use heat recovery since the heat recovery chiller may remain more fully loaded, thus producing more heat that can be recovered for the desired process. Preferential loading may also be beneficial for use with either a high-efficiency chiller that should be fully loaded whenever possible, or a chiller using a fuel other than electricity, such as an absorption chiller using waste steam from a cogeneration plant or a chiller coupled with an engine that generates electricity. When used with the latter, the system is able to preferentially load the alternate fuel chiller when the cost of electricity is high.

Chilled-Water System Variations

Parallel arrangement

If a chiller, in a decoupled system, is moved to the distribution side of the bypass line, system hydraulics, and temperatures, the chiller is preferentially loaded when it is turned on. As shown in Figure 20, Chiller 1 always sees the warmest system water and is preferentially loaded. As previously discussed, chillers on the production side of the bypass line (Chillers 2 and 3) will be loaded to equal percentages.

Figure 20 Parallel preferential loading arrangement



One caveat when applying this arrangement is that chillers on the production side of the bypass line will run more often at low part-load conditions. Older chillers or newer chillers that have a high cycle point may not have this capability.

Chilled-Water System Variations

Sidestream arrangement

Figure 21 Sidestream preferential loading arrangement

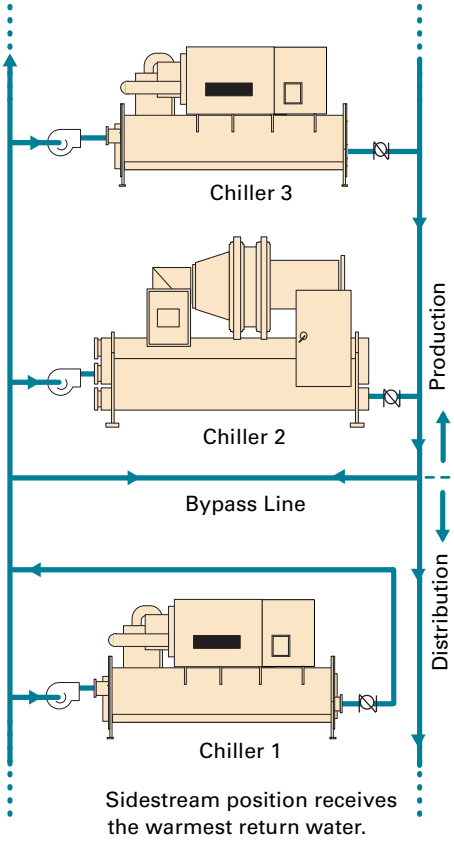


Figure 21 shows a simple modification to the traditional decoupled arrangement. The sidestream arrangement assures that the chiller piped in the sidestream position receives the warmest entering-water temperature and can fully load it whenever the chiller plant operates.

This arrangement is unique because it not only allows preferential loading, but it also permits the cooling device (chiller, heat exchanger, etc.) in the sidestream position to operate at any temperature change. This configuration precools the system-return water for the chillers downstream, reduces their loads and energy consumption, and decreases the overall operating cost of the chilled-water plant.

When cooling devices are located in the return piping of the distribution loop, they do not contribute to system demands for flow. They simply reduce the temperature of return water to the production loop. While this is counter-productive to the principle of striving for the highest possible return water temperature, it is often the best way to obtain free cooling, specialized heat recovery, or reduce the capital cost of ice storage equipment.

Sidestream, decoupled applications are usually most economical when the sidestream chiller is smaller than those on the production side of the bypass line. Since pumping requirements and energy consumption change with modifications to the system arrangement, it is best to use a computerized analysis tool to model the economic effects.

Following are three different system configurations that can benefit from the sidestream application.

Chilled-Water System Variations

Figure 22 Plate-and-frame heat exchanger

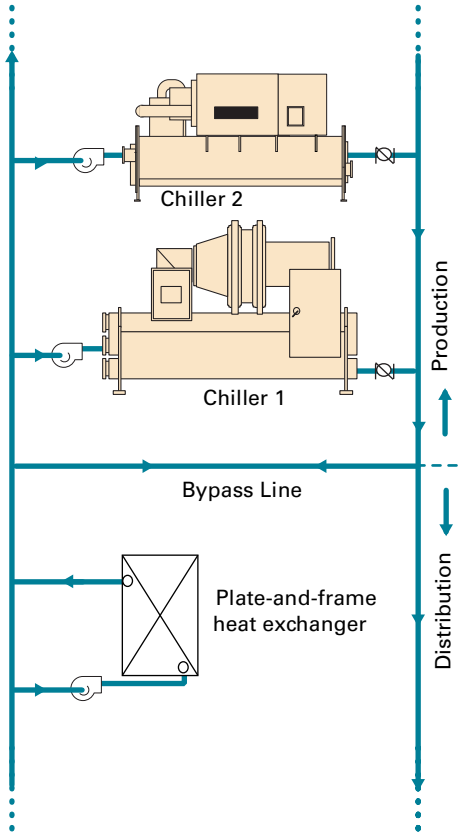


Plate-and-frame heat exchanger

A free-cooling heat exchanger[8] may be capable of chilling water to only 48°F [8.9°C] during some periods. Rather than overlook this portion of cooling capacity assistance, the heat exchanger does whatever it can to its portion of the total return stream. Chillers operating downstream can reduce chiller-water temperature further, allowing simultaneous free cooling and mechanical cooling. This configuration increases the hours that the heat exchanger may be used. Since this capacity is brought to bear on the warmest water in the system, it has the greatest impact.

Heat recovery

A similar situation occurs if a heat-recovery chiller is placed in this sidestream position[5] (see Figure 22). This chiller may be equipped with a heat recovery condenser or it could be a standard, single-condenser chiller operating as a heat pump. The chiller may not be capable of cooling water to the system supply temperature. That is unimportant with this configuration. Think of the machine as a heater instead of a chiller. Its primary function is heating, and cooling is a beneficial by-product. The passing return-chilled-water stream appears as an infinite heat source to the heat recovery chiller. The chiller only cools its evaporator water enough to satisfy the heating demand. This avoids the control predicament of deciding how to reject surplus condenser heat when the cooling and heating loads of a chiller do not strike a perfect heat balance.

Optional fuels

An absorption chiller may be applied in a sidestream location. This allows the chiller to be loaded whenever utility rates make it beneficial. It also ensures the absorption water chiller the warmest entering-water temperature, allowing it to operate more efficiently and produce more cooling.

System control

The flexibility of sidestream applications is increased by the fact that the devices are used to precool return water, not to produce the system chilled-water temperature. This means that they may be loaded by a different signal. In the case of a plate-and-frame heat exchanger, as long as return water is being cooled, there is an advantage to using it. A heat-recovery chiller can be loaded to produce just the amount of hot water necessary using the condenser-water leaving temperature as a signal. If preferential loading is used with an absorption chiller, it may be loaded simply by decreasing its leaving-water temperature.

Chilled-Water System Variations

Unequal chiller sizing

Many designers seem to default to using the same capacity chillers within a chilled-water plant.[2,3] There are benefits to sizing chillers to meet the system loads. One is that when a chiller is brought on line, so is its ancillary equipment, thus increasing *system* energy consumption. In general, the smaller the chiller, the smaller the ancillary equipment. Another is being able to ensure that chillers are efficiently loaded. Many times this can be accomplished by using chillers that do not have the same capacity. Examine the use of 60/40 splits (one chiller at 60 percentage system capacity, the other at 40 percent) or 1/3–2/3 splits (one chiller at 1/3 of system capacity the other at 2/3). The benefit is that the system load can be more closely matched with the total chiller capacity, increasing total system efficiency.

Series–counterflow application

The series–counterflow configuration can work with all types of chillers. Duplex chillers are shown in Figure 23. A single large chiller may be built as a duplex machine. The evaporator and condenser water circuits are common to both *halves* of the duplex. Increased efficiency comes from the separation of the compressors and refrigerant circuits. Thus, each *half* is redundant for increased system reliability.

Another system configuration that can be very energy efficient incorporates the previously described series application, but does so for both the chilled water *and* condenser water. Figure 23 shows such a configuration.

Note that the downstream machine, in this case, produces 40°F [4.4°C] chilled water, while the upstream machine produces 50°F [10°C] chilled water. The downstream machine receives 85°F [29.4°C] condenser water, while the upstream machine receives 95°F [35°C] condenser water. Therefore, the pumping requirements are only 1.2 gpm/ton on the chilled water side and 1.5 gpm/ton on the condenser water side — greatly reducing pumping costs.

The configuration has the effect of equalizing each chiller's required lift, as shown in Figure 23a. The chilled- and condenser-water flow directions are opposite, or counter, to one another. Thus the name, series-counterflow.

Chilled-Water System Variations

Figure 23 Series–counterflow arrangement

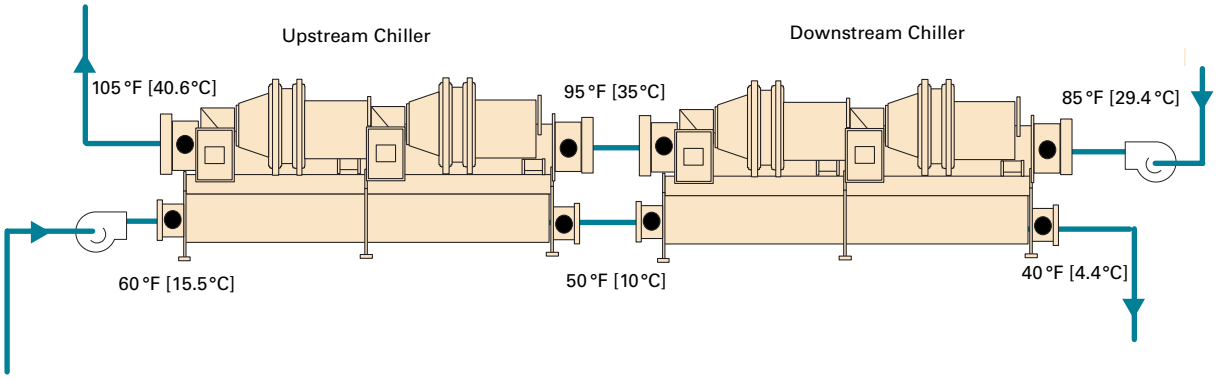
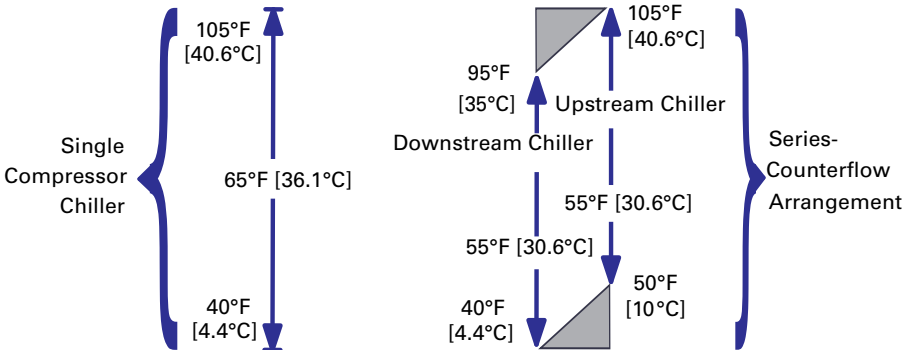


Figure 23a Equal lift concept



Chilled-Water System Variations

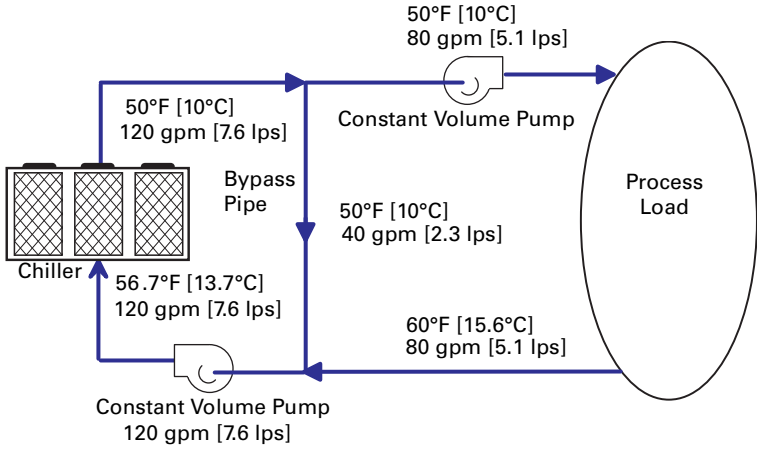
Applications outside the chiller's range

Designers may wish to use chillers to provide cooling for which the flow rate or temperature requirements are not within the ranges of a particular chiller, even though the chiller has adequate capacity. This often occurs with manufacturing processes. Let's look at two examples showing *system* designs that can satisfy the desired conditions.

Flow rate out of range

A plastic injection molding process requires 80 gpm [5.1 lps] of 50°F [10°C] water and returns that water at 60°F [15.6°C]. The selected chiller can operate at these temperatures, but has a minimum flow rate of 120 gpm [7.6 lps]. The following system in Figure 24 can satisfy the process. Decoupling the chiller from the process load allows the water flow to be different, ensuring that the flow through the chiller is within acceptable limits. With a single chiller system, one pump and a three-way valve gives the same results.

Figure 24 Flow rate out of range for equipment



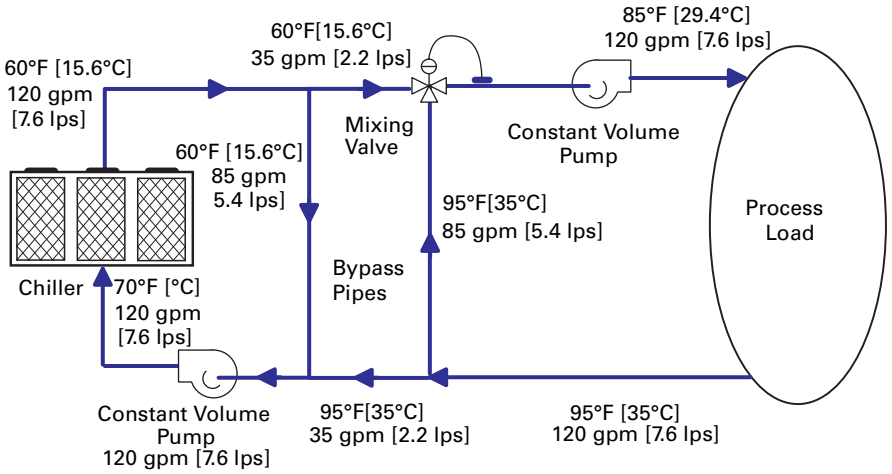
Chilled-Water System Variations

Temperatures out of range

A laboratory load requires 120 gpm [7.6 lps] of water entering the process at 85°F [29.4°C] and returning at 95°F [35°C]. The accuracy required is more precise than the cooling tower can provide. The selected chiller has adequate capacity, but a maximum leaving-chilled-water temperature of 60°F [15.6°C].

Using a pair of bypass pipes allows the mixing valve to supply the proper temperature to the process load and maintains acceptable water flow rates and temperatures through the chiller. In the example shown in Figure 25, the chiller and process flow rates are equal, although this is not a requirement. For example, if the chiller had a higher flow rate, more water would bypass and mix with the warm return water.

Figure 25 Temperatures out of range for equipment



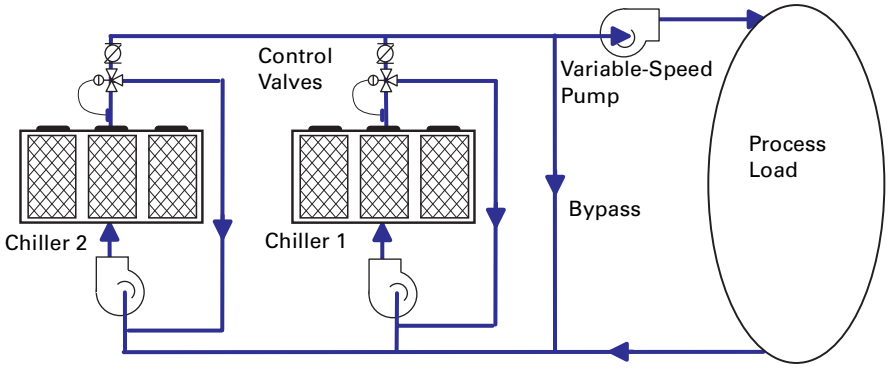
An example of a process application layout where the required temperature control tolerance is more precise than the chiller controls allow is shown in the Figure 26.

For example, when Chiller 2 is turned on, it takes a certain amount of time to reach its supply-temperature setpoint. The dedicated control valve remains closed and water is bypassed until Chiller 2 reaches its setpoint, which keeps the water temperature supplied to the process within tolerance. When Chiller 2 reaches its setpoint, the control valve opens.

This design requires a different chiller-sequencing strategy than the standard decoupled system. Water must not be allowed to bypass from the return side to the supply side, since this will cause the temperature of the water supplied to the process to vary outside the tolerance. Set the system controls to turn on Chiller 2 before deficit flow occurs.

Chilled-Water System Variations

Figure 26 Precise temperature control, multiple chillers



Chapter references

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Chilled-Water System Issues

Low ΔT syndrome

During the past several years the "low ΔT syndrome" debate has raged.[1,3] The symptom of the problem is that, in large systems, return-water temperature is too low, thus not allowing the chillers to fully load. Many system operators simply turn on more chillers to satisfy flow requirements. Some system designers advocate putting a check valve in the bypass line—thus putting chilled-water primary and secondary pumps in series and varying the flow through chiller evaporators. Other designers install primary pumps that are larger than necessary and "overpump" chillers at part-load conditions. These solutions are all "band-aids" and do not treat the source of the problem.

Coad[2] points to the fact that a properly operating hydraulic system will work as designed and explains the fallacies in the check valve and overpumping approaches. Taylor[5] recommends that a number of mitigating procedures be implemented to eliminate the problem. They include:

- Eliminate three-way valves
- Ensure that airside control is not causing the problem
- Properly maintain the system, including regular air filter changes, coil cleaning, control calibration, and proper setpoints

Before applying band-aid approaches to "fix" symptoms such as low ΔT syndrome, ensure that the system is operating properly using some or all of the procedures Taylor[5] discusses. In addition to these procedures, simply reducing the chilled-water supply temperature will have the effect of raising the system return-water temperature in systems using two-way valves.

Check valve in the bypass line

Some designers recommend the installation of a check valve in the bypass line of a primary–secondary system to eliminate the possibility of deficit flow in the bypass line. The premise is that if there is a system problem (low temperature differential), the check valve will put the primary and secondary pumps in series and pump more water through the chiller, thus balancing the primary and secondary flow requirements. This is not universally accepted. Coad[2] states,

> One constraint is that if the system is designed as variable flow and is experiencing operating problems related to low return water temperatures, the solution is *not* in the plant but rather in the load.
>
> **and**

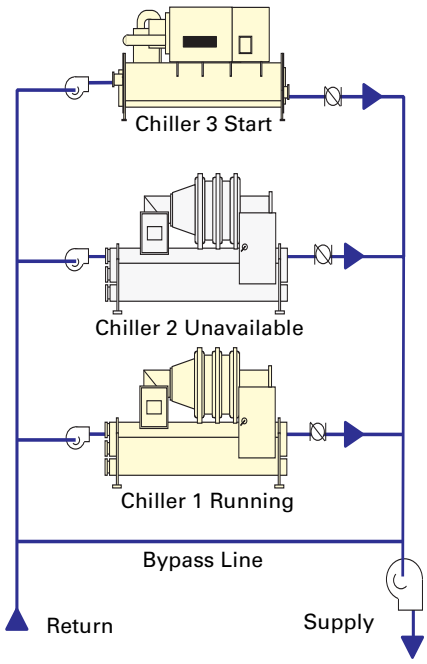
Chilled-Water System Issues

> One solution that has been suggested is to install a check valve in the plant common pipe or decoupling line circuit ... However, to be realistic, all that the check valve can do is assure that no water bypasses the chillers, which in turn has the effect of increasing flow in the chiller. Thus with the installation of the check valve must be an algorithm to either slow down system pump(s) when flow increases beyond the design maximum for the on chiller or turn on additional chillers. Thus the check valve solution offers its own problems and many designers feel very uncomfortable with forcing pumps into series operation without the benefit of understanding the full impact thereof.

This manual does *not* recommend the use of check valves in the bypass line.

Failure recovery

Figure 27 Failure recovery



With all the varied approaches available to potential customers, it sometimes seems that the main idea gets lost. People purchase chilled-water plants to reliably produce chilled water to satisfy another need, such as comfort or process cooling. Therefore when the plant operates there must be a process in place to recover from the failure of a chilled- or condenser-water pump, cooling tower, or chiller. Failure recovery should be integral to the chilled-water plant control system. Refer to Figure 27. If the control sequence tries to start Chiller 2 and its pump, but the pump has an electrical malfunction, the sequence should immediately lock out Chiller 2 and its pump. The control system should then attempt to start Chiller 3 and its pump. At the same time, the control system should send a pump malfunction alarm to the system operator.

Alternative energy sources

Energy source redundancy is receiving increased attention due to rate variations and reliability issues brought about by the deregulation of electrical utilities across the country. There are two basic approaches to meet these issues:

- Provide an alternate source of internally-generated electricity to serve a system in the event of general failure or an unacceptably high temporary cost of electricity (time-of-day rates).
- Provide an alternate source of chilled-water producing capability, possibly fueled by natural gas, another fossil fuel, or even using low cost electricity as an alternative energy source.

Chilled-Water System Issues

Electricity generation

The design, construction, and operation of full-capacity, electrical-generation systems is well understood. The electrical-generation capacity can be sized to allow an entire facility to operate or it can be sized for an emergency situation. Electrical generation can be outsourced to avoid internal capitalization.

A variation of electrical generation uses an engine indirectly- or directly-coupled to a chiller. Either variation produces chilled water using an alternative fuel such as natural gas or fuel oil. The indirect-coupling method allows the chiller to operate using an alternative fuel or electricity from the grid. An engine directly-coupled to a chiller can only run using the alternative fuel.

Alternative fuel

Some designers prefer to employ chillers that use fossil fuels. Examples are absorption chillers using natural gas, steam, or hot water. Plants with these chillers, discussed in detail elsewhere[4], allow the owner to take advantage of permanently expected fuel rate separations.

Thermal storage

Another successfully applied alternative-energy source is thermal storage. Chillers make either ice or chilled water during times of decreased electricity costs. The energy is stored in tanks and then discharged to satisfy cooling loads during times of high electrical costs. Other manuals describe the use of thermal storage in detail. [6,7,8,9]

Use any of these technologies to provide value to the building owner through judicious use of alternative fuels.

Chilled-Water System Issues

Contingency

In addition to failure recovery, it may be wise for plant designers to work with building owners to develop a contingency plan for chilled water in the case of emergency shutdown or an extended breakdown. Often this is critical for process cooling applications. Such a plan can include working with suppliers to establish a short lead-time on equipment leasing. When equipment leasing is combined with, for example, piping stubs built into the chilled-water system for quick connection, a contingency plan can be put into action quickly and the system can produce chilled water again in a short period of time.

Cooling contingency planning

Today, many organizations have contingency plans for critical areas of their business. Some deal with natural disasters and others with the loss of power in critical areas. However, few have actually taken the time to think about what a loss of cooling would mean to their facility. If the cooling system failed or was suddenly grossly undersized due to weather, etc., how would that affect business? What financial risk would be involved with a loss of cooling?

Cooling contingency planning is intended to minimize the losses a facility may incur as a result of a total or partial loss of cooling. It allows a building owner to act more quickly by having a plan in place and by proactively preparing his or her facility to accept temporary equipment. Although a number of facilities are prepared after the construction phase, the construction phase provides an easy and cost-effective opportunity to prepare a facility and is a logical time to provide water stubouts and electrical connections. This helps to keep costs down and reduces the need to shut down existing equipment to make necessary building preparations.

Cooling contingency planning is the process of preparing for a loss of cooling while in a nonemergency situation. This allows common sense, rather than panic, to prevail during a critical event. The following topics are general and broad in scope. They provide a sense of what is involved in the planning process. Contingency planning itself is very detailed and situation-specific.

Minimum capacity required It is important to first identify the minimum capacity required. With multiple chillers in a facility, it may be acceptable to have less tonnage in an emergency situation. For example, a facility's chiller plant may consist of 1,800 tons [6,330 kW], but the minimum tonnage required may only be 1,200 tons [4,220 kW]. Therefore, it is also important to identify the plan of action if Chiller 1 fails, if Chiller 2 fails, if Chillers 2 and 3 fail, and so on.

Chilled-Water System Issues

Type and size of chiller The type and size of contingency cooling required by a facility are determined by several factors. In turn, the choice of chiller determines how the facility is prepared. Examples of parameters that determine the chiller are:

- Electrical requirements
- Ease of installation (air-cooled chillers are easier to set up)
- Location or available space
- Comfort or process cooling

Location of equipment Location can be a major factor in contingency planning. When selecting the location of the temporary equipment it is important to consider:

- Water and electrical connections location
- Sound sensitive areas in the facility
- Location easily accessible to service staff
- Equipment separated from the public

Water and electrical connections

- Water connection size requirements
- External stubout locations
- Sufficient power to run the temporary unit
- Possible generator requirement

Ancillary equipment

- Pumping system requirements
- Temporary hose requirements
- Electrical cable requirements

This section briefly describes some of the items to consider when establishing a cooling contingency plan. Keep in mind that there may be other considerations, depending on the application.

Chilled-Water System Issues

Chapter references

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Condenser-System Variations

Water-cooled chillers require condenser-water-system variations to be considered. For a discussion of condenser-water temperatures and flow rates refer to the section, *Chilled-Water-Plant Basics,* page 3. Since air-cooled-chiller condenser controls are part of the chiller design, they are not discussed in this manual.

To ensure optimum heat transfer performance, the condenser-heat transfer surfaces must be kept free of scale and sludge. Even a thin deposit of scale can substantially reduce heat transfer capacity and chiller efficiency. Specifics of cooling-tower-water treatment are not discussed in this manual. Engage the services of a qualified water treatment specialist to determine the level of water treatment required to remove contaminants from the cooling tower water.

Condenser flow configurations

Most importantly, the inlet to the pump must be under sufficient net positive head. This often means locating the pump below the cooling-tower sump.

Single tower per chiller

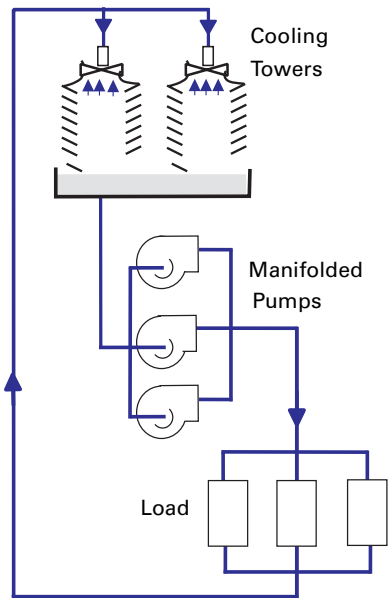
In some applications each chiller has a dedicated cooling tower. This is most likely to occur when chillers, and their accompanying towers are purchased at different times during the facility's life—such as when additions are made.

Manifolded pumps

A much-used pumping arrangement has a single cooling-tower sump with manifolded pumps, one condenser water line, and separate, smaller, pipes for each chiller as shown in Figure 28. This provides a number of advantages:

- Pumping redundancy
- If cooling towers cells can be isolated, any cooling-tower cell runs with any chiller
- Hydraulics are generally less problematic than on the chilled-water side
- Cooling towers can be located remotely from chillers, with only a single supply and return pipe to connect them

Figure 28 Manifolded condenser-water pumps



Condenser-System Variations

Condenser water control for transient conditions

Every chiller requires a pressure differential between the evaporator and condenser in order to operate. The chiller must develop its pressure differential within a manufacturer-specified time or its controls will shut it off. During some start-up conditions, this pressure differential may be hard to produce within the time limitation.

An example of such a condition is an office building that has been unoccupied during a cool, clear, fall weekend. The tower sump water is at 40 °F [4.4 °C]. Monday is sunny and warm, which requires a chiller to be turned on. Since the chiller is lightly loaded and the tower sump is large, the pressure differential can not be reached before the chiller turns off. If the condenser flow rate for a given chiller can be reduced, this scenario is less likely to occur. The lower flow rate increases the leaving condenser-water temperature, condenser-refrigerant temperature, and refrigerant pressure.

The flow reduction options include:

- Cooling tower bypass
- Chiller bypass
- One or two throttling valves in the condenser-water pipe with the pump riding its curve
- A variable-speed condenser water pump

After the minimum-pressure differential is reached, the flow may be increased as long as that minimum-pressure difference is maintained. Some designers and operators become concerned with possible fouling of condenser-water tubes during these start-up conditions. There is little to fear due to the short duration of reduced flow operation and the limited occurrences. The advantages and disadvantages of these options are discussed in a variety of publications.[1,5]

Condenser-System Variations

Cooling-tower-fan control methods

Cooling towers operate to produce the sump water temperature. As the heat-rejection load and ambient wet-bulb tempersture change, the cooling tower fans must move more or less air to produce the desired water temperature.

Cycling a single fan

Cycling a single fan on and off is one method to maintain rough water temperature control. Since airflow changes greatly between fan speeds, so does heat rejection. Temperature swings of 7 °F to 10 °F [3.9°C to 5.6°C] are not uncommon. Some chillers, especially older chillers with pneumatic controls, may operate poorly in response to these changing temperatures. Care must also be taken to ensure that the fan does not cycle too often and damage the motor, drive, or fan assembly.

Two-speed fans

The installation of two-speed cooling tower fans is an option used frequently to reduce temperature swings. Typically, the low fan speed is between 50 and 70 percent of full speed. Since the heat rejection changes roughly in proportion with the fan speed, the temperature swing will be only 50 to 75 percent of cycling a single fan. Again, care should be taken not to cycle too often between speeds—or the gear box may incur excessive wear and fail. A distinct advantage of two-speed fans is that at low speed, the fan power is greatly reduced. Since the fan power varies with the cube of the speed (approximately) the power at half speed is about 15 percent of full speed.

"Pony" motors

Another option offered by cooling-tower manufacturers is to have two separate motors available to drive the fan. The smaller motor is referred to as a "pony" motor. It operates at two-thirds of the full speed and uses about 30 percent of the full speed power. While controlling the tower, it is important to minimize cycling between speeds.

Variable-speed drives

Using variable-speed drives on cooling-tower fans offers two distinct benefits. First, the tower-water-temperature control is extremely good. Second, the fan power varies with the cube of the speed, so there is great potential for energy savings. Variable-speed drives also allow the fan speed to be changed without fear of gear box or motor wear. They may also offer acoustical advantages by significantly lowering sound power at reduced speeds.

Condenser-System Variations

Plate-and-frame heat exchanger

As previously discussed in the section *Chilled-Water-System Variations*, page 57, a plate-and-frame heat exchanger may be used in conjunction with a cooling tower to provide cooling during very low wet-bulb temperature conditions. When it is to be used for these purposes, designers often specify a cooling tower larger than necessary for design conditions so that it can be used for many hours with the plate-and- frame heat exchanger.

Well, river, or lake water

There are times when well, river, or lake water will be pumped through the condenser. In these cases, an examination should be undertaken to balance the cost of pumping the water with the benefit the chiller gets when more water passes through its condenser. The environmental limitations imposed by local codes are another consideration. Some locales will not allow well water to be dumped after being used. Other local authorities limit the maximum water temperature that may be returned to a body of water. Flow rates need to be carefully selected to balance the economic and environmental requirements.

Condenser-water temperature control

Chiller–tower energy balance

The subject of condenser-water temperature control has been studied by a number of people. In recent years, Braun and Didderich[2]; Hydeman, Gillespie, and Kammerud[3]; and Schwedler[4] have all independently noted that balancing chiller and cooling-tower energy is important. Hydeman, et al., showed that at various loads and ambient conditions, the optimal condenser-water temperature for a specific chilled-water plant depends on both chiller load and ambient conditions, see Figure 29. All the studies showed that during many points of operation, the optimal condition is *not* the lowest water temperature the cooling tower can produce. It is important for the system designer and operator to examine the use of system-level controls to set the tower-sump-temperature setpoint to reduce the sum of chiller-plus-tower energy. This optimal chiller-tower control can be automated by a chiller-plant management system.

Condenser-System Variations

Figure 29 Chiller–tower energy consumption

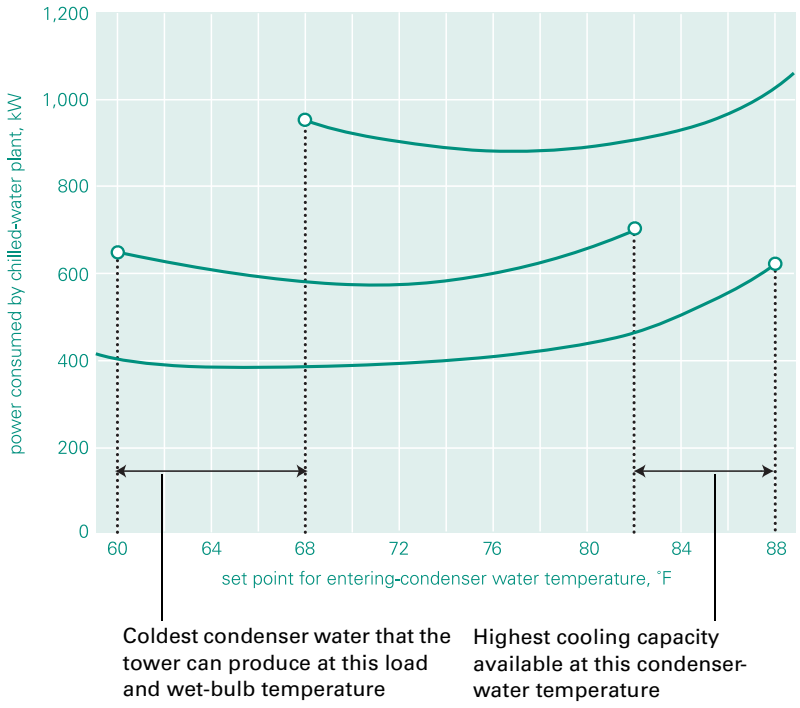


Figure 29 from Hydeman, et al., used with permission.

Condenser-water pump options

Chiller–pump balance

There are times when a system designer may choose to vary the condenser water flow in addition to, or instead of, the cooling-tower fan speed. This may be beneficial in systems with high pumping power. If a variable-speed drive is installed, the flow may be reduced and the pump power can be reduced substantially — approximately with the cube of the speed. Attempting to vary both the pump and the tower fan speeds is complex and requires adequate time for design and implementation.

Condenser-System Variations

Variable flow limitations

Care should be taken to keep the flow through the condenser above the minimum allowable flow rate for the chiller's condenser. The operator should regularly log the condenser approach temperature (the temperature difference between the condenser's refrigerant temperature and the condenser-water leaving temperature) to ensure that the tubes are not becoming fouled. The approach temperature may be monitored using a chiller plant management system.

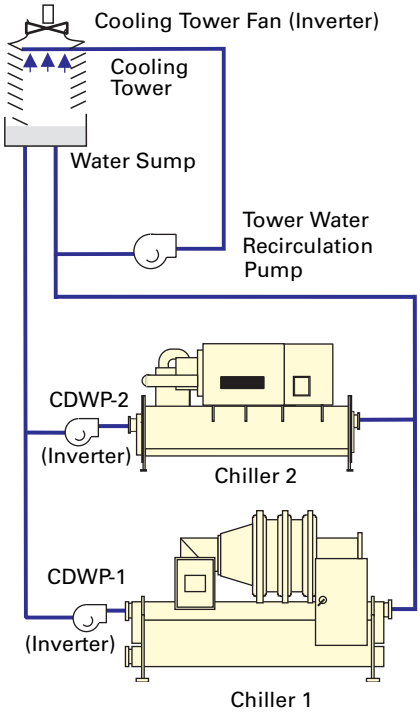
Tower and/or tower nozzle design can affect the allowable condenser-water flow. If the flow drops below the manufacturer's specified limit, the water is no longer evenly distributed over the tower fill. This results in a decrease in cooling-tower heat-transfer effectiveness. In extreme cases, it can also result in water freezing in the cooling tower. If variable tower flow is a consideration, contact the cooling-tower manufacturer to determine the flow limit and possibly choose nozzles or cooling-tower configurations that can handle variable-water flow.

Decoupled condenser-water system

To overcome possible problems with variable-water flow across a cooling tower, some designers decouple the condenser-water system as shown in Figure 30. This arrangement allows energy optimization through a reduction of pumping power without excessively complicating the system. Because cooling towers work best with full water flow over the transfer media, a separate wetting (recirculation) pump provides a constant flow of water through the tower. This is a low energy pump, as very little lift is required.

Dedicated, variable-flow condenser pumps (CDWP-1 and CDWP-2) permit a reduction in the pumping energy whenever the temperature of condenser water results in an unproductive reduction of condenser refrigerant pressure. While the number of dedicated pumps may seem complicated at first, remember the number of valves and controls that are eliminated.

Figure 30 Decoupled condenser-water system



Condenser-System Variations

Retrofit opportunities

A tremendous retrofit opportunity can be realized if the low-flow concepts discussed earlier in the section *Chilled-Water-System Options*, page 20, are utilized. Building owners may need to increase the capacity of an existing system, for example in response to a building addition. In many of these buildings, the condenser water system (piping, pump, and tower) is in good condition, but is considered to be too small. By changing from traditional design conditions, the existing infrastructure can often be used while still providing additional capacity.

Keep in mind that a cooling tower is not limited to a specific tonnage. A cooling tower is a heat exchanger that exchanges heat between the entering water temperature and the ambient wet bulb. By varying the flow or the temperature, the tower capacity can be changed—often increased. An example can easily show this.

Example A hospital presently has a 450-ton [1,580-kW] refrigeration] chiller that needs to be replaced. The condenser water flow is 1,350 gpm [85.2 lps]. The cooling-tower selection conditions are

- entering water temperature: 95°F[35°C]
- leaving water temperature: 85°F[29.4°C]
- ambient wet bulb: 78°F [25.6°C]

Recently, the cooling-tower fill was replaced. The tower, condenser water piping, and pump are in good condition. The hospital is planning an addition with 50 percent more load for a total of 675-tons [2,370-kW]. Must the hospital replace the condenser water system? The answer is "no", as long as the chiller is selected properly.

How is this possible? As long as the new chiller's condenser-water pressure drop is at or below that of the present chiller, the same amount of water can still be pumped. With the same flow rate, a 675-ton [2,370-kW] chiller may be selected with a condenser-water-temperature rise of approximately15°F [8.3°C]. Using the cooling- tower manufacturer's selection software, the same cooling tower can be selected at the elevated temperature difference. As shown in Figure 31, the new selection point will be:

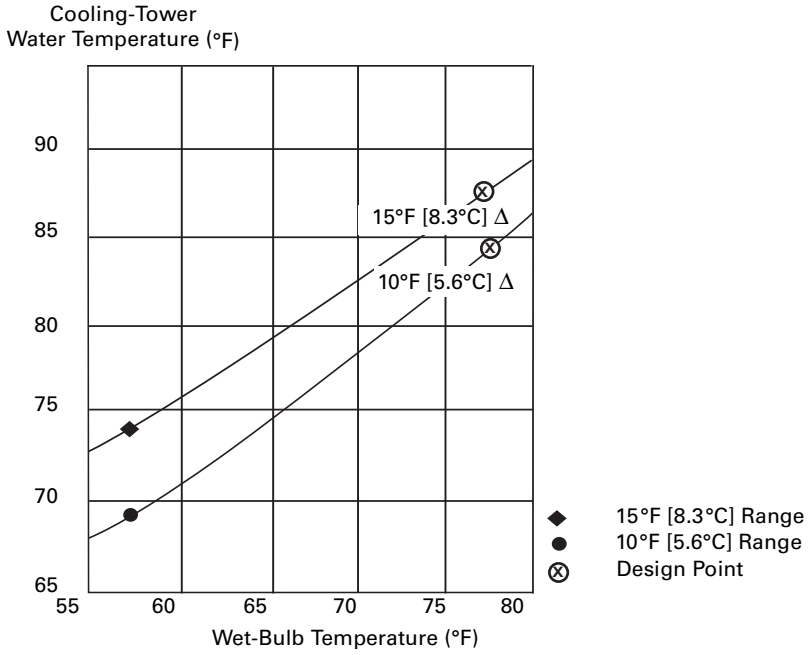
- entering water temperature: 103°F [39.4°C]
- leaving water temperature: 88°F [31.1°C]
- ambient wet bulb: 78°F [25.6°C]

Condenser-System Variations

It quickly becomes evident that the same cooling tower and flow rate are adequate to reject more heat, in this case, approximately 50 percent more heat.

The design engineer can often help reduce total project costs using the existing infrastructure and selecting a chiller with a higher temperature differential.

Figure 31 Chiller–tower selection with different chiller capacities



Condenser-System Variations

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Conclusion

Since most chilled water systems incorporate more than one chiller, it is vital to have a clear understanding of multiple-chiller concepts and their application. There is nothing particularly complex about the principles involved. Instead, system design is simply a matter of exercising a few key rules of applied physics.

A myriad of choices are available for the design and operation of chilled water systems. These choices include flow rates, temperatures, system configurations, and control options. After determining the needs and wants of the building owner and chiller plant operator, judicious use of these choices allows designers to provide solutions that add real value.

When applying the principles in this manual, it is important to remember the following rules:

- **Rule 1** Strive for simplicity. Simple does not always mean using the fewest components. Simplicity is usually elegant in its ability to be universally understood.
- **Rule 2** If the system designer can explain how a design works, there is a good chance that the system will function well. If the designer can't explain how the design works, there is *no* chance that the system will operate efficiently.
- **Rule 3** If the system operator understands the designer's explanation of how the system works, there is a good chance that the system will work. If the system operator doesn't understand the explanation, there is *no* chance that the system will operate efficiently.

Glossary

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers.

building automation system A combination of controllers and other software products which communicate and control various mechanical systems to enable building management. These include the heating, ventilation, and air conditioning (HVAC) systems as well as lighting systems, access control, and miscellaneous other devices within a building. Also called a building management system (BMS).

chilled water Also know as leaving-chilled-water or leaving-evaporator-water; the cold water produced by the chiller (flowing through the tube bundle in the evaporator) and pumped to the air handler coils throughout the building. Within the evaporator, refrigerant surrounds the tube bundle and accepts heat from the return chilled water.

chiller An air-conditioning system that circulates chilled water to various cooling coils in an installation.

coil An evaporator or condenser made up of tubing either with or without extended surfaces (fins).

condenser The region of the chiller where refrigerant vapor is converted to liquid so that the temperature and pressure can be decreased as the refrigerant goes into the evaporator.

condenser water, leaving *See* cooling water.

cooling tower water *See* cooling water.

cooling water Also known as tower water, leaving-cooling water, leaving-condenser water, entering-absorber water, condenser-absorber water, entering-cooling water, or cooling tower water; obtained from the source (tower, river, pond, etc.) to which heat is rejected, flows through the tubes that run through the absorber and the condenser, and is returned to the source.

In electrically driven chillers, the cooling water picks up heat only from the condenser. In an absorption chiller, the cooling water also has to pick up heat from the absorber. The water typically flows from the source at 85°F [29.4°C], first to the absorber and then to the condenser (series flow). Associated water temperatures are referred to as entering-absorber-water temperature (or leaving-tower-water temperature) and leaving-condenser-water temperature (or entering-tower-water temperature).

COP Coefficient of Performance; cooling effect divided by heat input (dimensionless); the reciprocal of efficiency.

direct digital control Programming used by building control systems to control variable outputs, such as valves or actuators. In the HVAC industry, DDC means direct digital control by a microprocessor controller with no intermediate device.

Glossary

evaporator The region in the chiller where the system chilled water is continuously cooled down by flashing the refrigerant to vapor in a deep vacuum as it picks up heat from the returning system water.

fouling Deposits of foreign material in the water side of tubing in refrigeration condensers or chillers which affect the transfer of heat.

heat exchanger A device used to transfer heat between two physically separated fluids.

heat transfer The movement of heat from one body or substance to another. The three methods of heat transfer are conduction, convection and radiation.

load Any one of several output devices that are to be controlled by a building management panel.

mechanical-compression refrigeration cycle The electrically driven chiller makes use of an electric motor, driving a compressor to produce chilled water for cooling. It does this via a mechanical process that uses a refrigerant for a working fluid. Inside the vessel are pressure and temperature differentials, where heat is absorbed at a low temperature and then rejected at a higher temperature.

psychrometric chart A chart that shows the relationship between the temperature, pressure, and moisture content of the air.

psychrometric measurement The measurement of temperature, pressure, and humidity of air using a psychrometric chart.

pumps (system)

> **chilled water** Circulates the chilled water through the evaporator section of the chiller and then through the building coils.
>
> **cooling water** Circulates the cooling water from the source through the chiller, condenser, and back to the source.

shell-and-tube A designation for a type of heat exchangers consisting of a tube bundle within a shell or casing. Often used in chiller condensers and evaporators.

shell-and-tube flooded evaporators Evaporators that use water flow through tubes built into a cylindrical evaporator with refrigerant on the outside of the tubes.

temperature, ambient The temperature of the air surrounding the object under consideration

temperature, wet-bulb A measure of the degree of moisture in the air. It is the temperature of evaporation for an air sample, measured with a thermometer that has its bulb covered by a moistened wick.

tower water *See* cooling water.

Glossary

three-way valve A flow-control valve with three fluid-flow openings. It controls constant flow through or around the load.

two-way valve A flow-control valve with two fluid-flow openings.

valve, throttling A small valve used primarily in gauge lines to shut off the line between readings, and to throttle the line to prevent fluctuations during readings.

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