



Energy Impacts of Chilled-Water-Piping Configuration

Examining the energy-saving potential of three commonly used arrangements

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As the cost of energy continues to rise, it behooves chiller-plant owners and designers to consider the energy impacts of virtually everything under their control, including chilled-water piping.

This article will discuss the energy consumption of the three basic configurations of chilled-water piping currently in use: constant primary flow (CPF), constant primary flow/variable secondary flow (P/S), and variable primary flow (VPF). Also, it will discuss the attributes of equipment-room space, installed cost, and control complexity.

Constant Primary Flow

Operation. Figure 1 illustrates a CPF arrangement at 100-percent system load. The most basic of the three configurations, this is used in many smaller plants. As the name implies, the chilled-water (CHW) pumps are constant speed, and water flow varies only when a chiller and its pump are cycled off for capacity purposes.

Throughout this article, the following formula will be used to analyze how systems operate:

$$\text{Load} = \text{Flow} \times \text{Delta-T}$$

where:

Delta-T = chilled-water-temperature range

In a CPF configuration, load changes are reflected by changing delta-T. Typically, a three-way valve is placed on the discharge of each coil. The valve's job is to maintain the set-point temperature of the air leaving the coil. If the temperature of the air ventures above or below its set point, the valve modulates the amount of chilled water flowing through the coil, with excess water bypassing the coil. This modulates the temperature of the chilled water within the coil in accordance with the formula above; coil capacity is adjusted until leaving-air temperature once again is at its set point. Throughout this process, operating chillers experience (roughly) constant water flow.

Attributes. CPF designs have several advantages:

- Equipment-room space is minimized because there is only one set of chilled-water pumps.
- Installed cost is low because constant-speed pumps

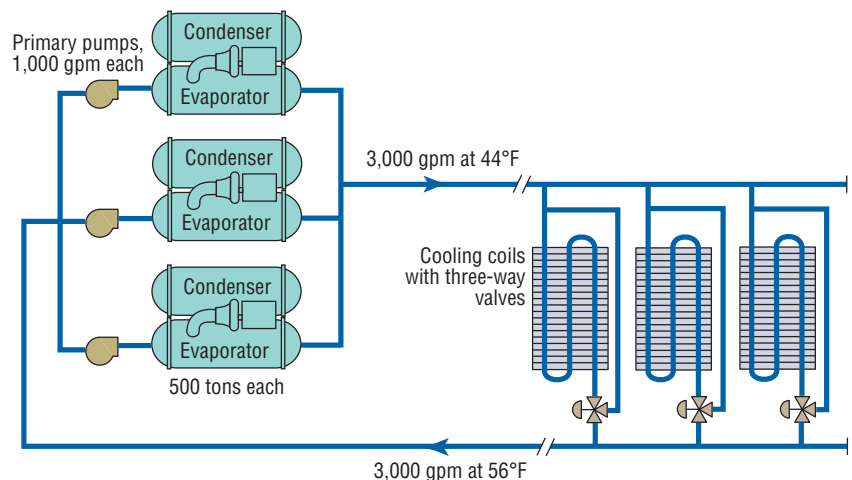


FIGURE 1. In a CPF configuration, chilled-water flow is constant, and load is controlled by varying delta-T with three-way valves.

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are used, avoiding the expense of variable-speed drives (VSDs). Also, low-pressure-differential-rated three-way valves, which are less expensive than high-pressure-differential-rated two-way valves, are used.

- Control and operation of the system is relatively simple and easy to understand.

The main disadvantage of CPF designs is high pump energy consumption. Any time a chiller plant is operating, active pumps are running at full flow, regardless of whether the load requires it.

Constant Primary Flow/Variable Secondary Flow

Operation. P/S configurations are divided into two loops:

- Primary, consisting of chillers, primary pumps, and interconnecting piping and using constant-flow pumping.
- Secondary, consisting of coils, secondary pumps, and interconnecting piping and using variable-flow pumping.

A decoupler pipe hydraulically separates the two loops, allowing temperature exchange, but independent pressures and flows.

Two-way valves control the temperature of air leaving the cooling coils by throttling water flow. Thus, load in a P/S configuration is controlled by varying flow, while delta-T remains relatively constant.

As the two-way valves throttle down chilled-water flow, pressure in the piping upstream increases. A differential-pressure sensor signals the VSDs on the secondary pumps to reduce their speed, which decreases secondary flow and lowers friction loss in the pipe. In the process, pump energy consumption is reduced.

Figure 2 illustrates a P/S plant at 100-percent system load.

The rate of flow in the primary loop must always equal or exceed the rate of flow in the secondary loop. The decoupler allows excess primary water to flow back to the

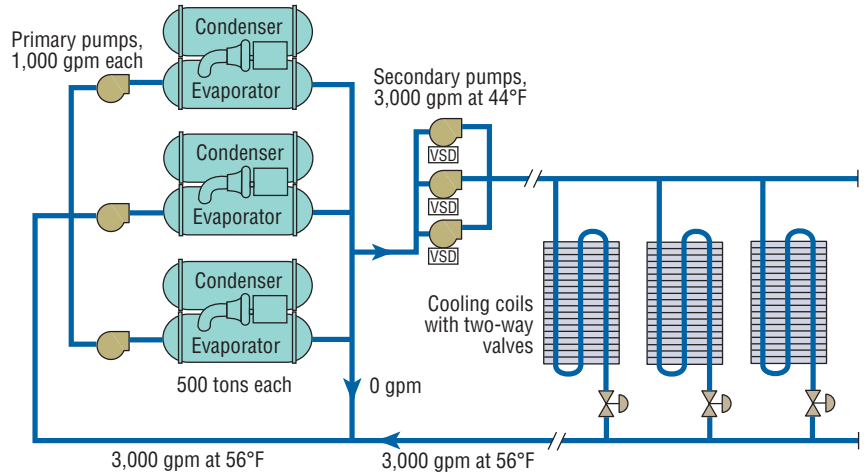


FIGURE 2. The flow of chilled water in the primary loop of a P/S system is constant, while two-way valves and variable-speed-driven pumps in the secondary loop control coil capacity by varying water flow. Ideally, delta-T in the coils remains constant.

return side of the chillers, ensuring constant flow.

If the rate of flow in the secondary loop exceeds the rate of flow in the primary loop, some of the water discharged from the coils is bypassing the chillers and flowing back to the secondary pumps, mixing with and increasing the temperature of water supplied to the coils. If that continues, the coils will lose their cooling capability, and system control will be lost.

Figure 3 illustrates a P/S configuration at 75-percent system load.

As cooling load falls, chillers and

their respective primary pumps can be cycled off, reducing energy consumption in the primary loop. Water flows rebalance so that the rate of flow in the primary loop equals or exceeds the rate of flow in the secondary loop.

Figure 4 illustrates a P/S configuration at 67-percent system load.

Delta-T in the secondary loop will be constant as long as the system is working properly. However, in all chilled-water systems using two-way valves, there are conditions that cause delta-T to be reduced independent of load. This is known

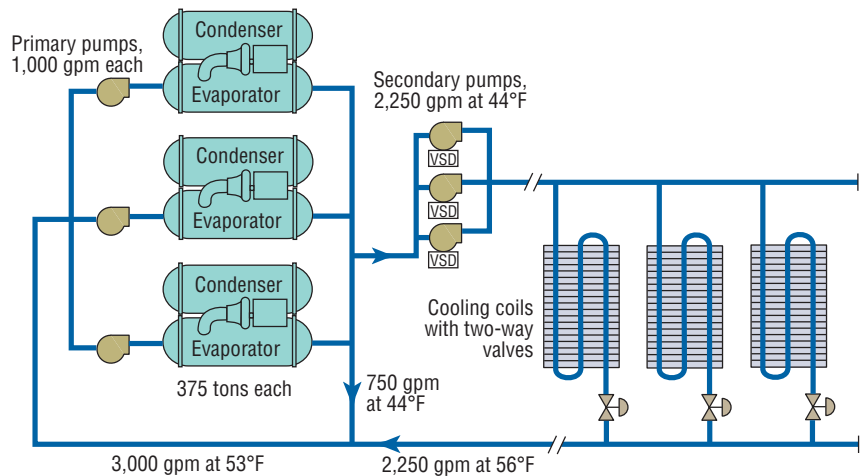


FIGURE 3. At 75-percent load, the flow of chilled water in the primary loop of a P/S system is constant at 3,000 gpm, while two-way valves and variable-speed-driven pumps throttle water flow through the coils to 2,250 gpm, approximately 75 percent of design value. The 750 gpm of excess water from the primary loop flows through the decoupler pipe.

as low-delta-T syndrome and will be discussed later.

Attributes. A P/S arrangement takes up more equipment-room space than a CPF arrangement because of the second set of pumps. Also, it has a higher installed cost because of the second set of pumps, the VSDs, and additional piping, rigging, wiring, and controls.

The use of VSDs on secondary pumps significantly reduces pump energy consumption in the secondary loop. Because horsepower reduction varies with distribution-flow reduction, the savings could be as much as 50 to 60 percent—compared with a CPF arrangement—overall.

Variable Primary Flow

Operation. Like its P/S counterpart, the VPF configuration utilizes two-way valves and VSDs. However,

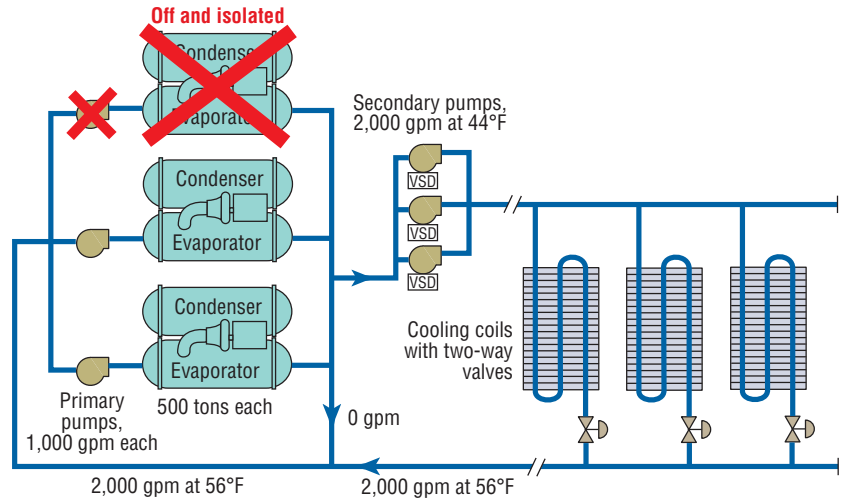


FIGURE 4. Below 67-percent load in a P/S system, one of the chillers and its chilled-water pump can be cycled off. Water flows adjust to rebalance the system.

the VSDs are on the main chilled-water pumps, as shown in Figure 5, and water flow is varied throughout the chilled-water circuit, including the chillers. This increases the systemwide pump energy that can

be saved.

Note that the pumps in Figure 5 are piped in a headered arrangement. This allows any combination of pumps to work with any combination of chillers. The benefit of this will be

explained later, during the discussion of low-delta-T syndrome.

Although it lacks a separate secondary piping loop, a VPF configuration does employ a bypass pipe (much smaller than the one used in a P/S system) because of the chillers' minimum-flow requirement. Typically, chillers are chosen with evaporator water velocities of 4 to 6 fps, depending on efficiency and pass-arrangement requirements. Flow through the evaporator can be reduced to as low as 1.5 fps, depending on supply-water temperature. Below that, the water may freeze and rupture the tubes. The bypass pipe allows minimum flow through the chillers to be maintained, even though flow through the coils may continue to decrease. The bypass valve is controlled by the flow meter.

In the following analysis of two off-design conditions, the chill-

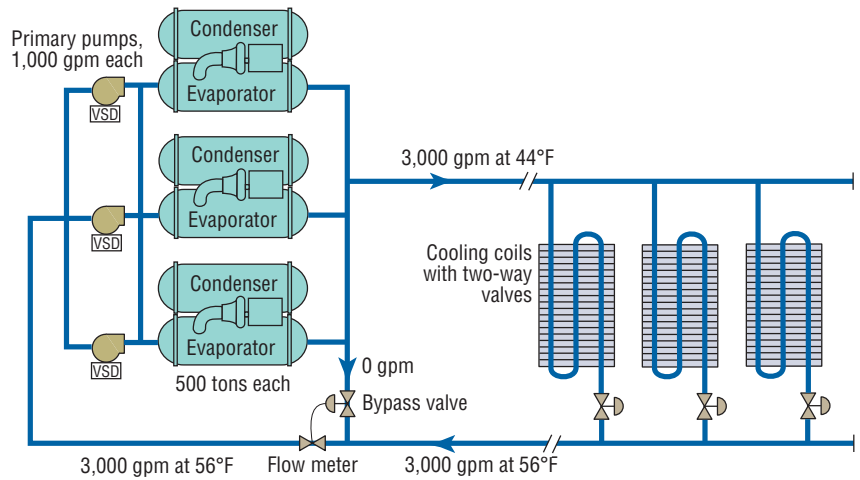


FIGURE 5. Like a P/S configuration, a VPF configuration uses two-way valves and variable-speed-driven pumps to vary water flow and control coil capacity, while delta-T remains relatively constant. However, there is only one water loop, and water flow is varied throughout the chilled-water circuit.

ers are assumed to have been chosen with 6-fps water velocity in the evaporator at design flow. Minimum flow through the evaporator of

each chiller, then, is:

$$1,000 \text{ gpm} \times (1.5 \text{ fps} \div 6.0 \text{ fps}) = 250 \text{ gpm}$$

Figure 6 illustrates a system operating at 50-percent load. When the load fell below 67 percent, one pump and one chiller were turned off, and the chiller was isolated with an automatic isolation valve (not shown). Water velocity in the two active evaporators is 4.5 fps (0.75×6 fps), well above the 1.5-fps lower limit, so there is no need to use the bypass pipe just yet.

Figure 7 shows the bypass operating at 6.7-percent system load.

Attributes. Because only one set of chilled-water pumps is used, the VPF configuration takes up less equipment-room space than the P/S configuration and the same as the CPF configuration. The installed cost is midway between that of the P/S and CPF configurations; there are no secondary pumps, valves, installation labor, or wiring, but bypass piping and a bypass valve, as well as more complex controls, are required. Additionally, the design is newer than the CPF and P/S configurations and, thus, not as well understood by designers and operators.

Pump energy consumption is less than with the CPF and P/S arrangements. The variable-speed pumps save as much as 60 to 70 percent annually, compared with a CPF design. Compared with a P/S arrangement, design energy is reduced. This is because:

- Eliminating secondary pumps eliminates the piping, strainer, and valve head losses associated with them.

- The primary pumps often operate at efficiencies higher than those in the CPF and P/S arrangements. Although the design heads are higher, the duty often can be performed with the same pump casings equipped with larger-diameter impellers, which moves the design operating point into a more efficient region of the pump. These two improvements can further reduce pump energy consumption, regardless of operating point.

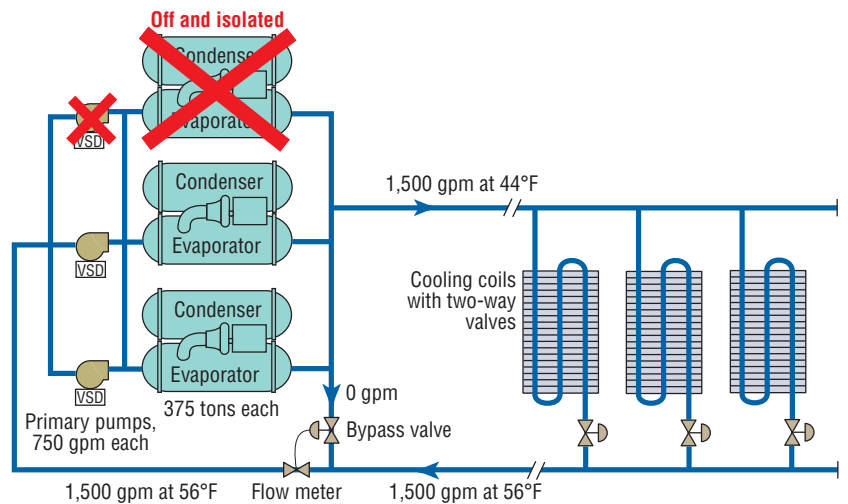


FIGURE 6. At 50-percent load, one pump and one chiller in this VPF arrangement have cycled off, and the chiller has been isolated from any water flow. The water-flow rate is well above the minimum of 250 gpm, so the bypass pipe is not used.

Low-Delta-T Syndrome

All chilled-water systems with two-way valves experience low-delta-T syndrome. Low-delta-T syndrome is a reduction in chilled-water-temperature range independent of load change. It increases the energy consumption of variable-speed pumps and chiller plants. It has many causes, including dirty coils, controls out of calibration, leaky two-way valves, coils piped backward, the mixing of three- and

two-way valves, and the use of air-side economizers.¹

Chillers in a system suffering from low-delta-T syndrome cannot be loaded above the ratio of actual delta-T to design delta-T (i.e., if actual delta-T is 8 and design delta-T is 12, 8/12, or 67 percent, of chiller capacity is all that is available, unless some mitigating action is taken). As a result, chiller-plant energy consumption increases, as chillers, along with their associated pumps and towers,

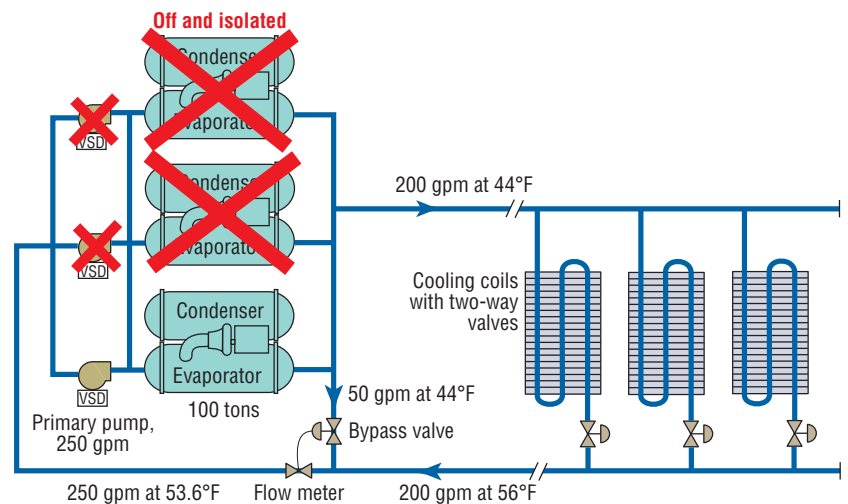


FIGURE 7. At 33-percent load, a second chiller and chilled-water pump cycle off. When the flow meter senses that flow in the main circuit has fallen to the 250-gpm minimum, it begins to open the bypass valve. At 6.7-percent system load, flow through the coils, bypass pipe, and evaporator is 200 gpm, 50 gpm, and 250 gpm, respectively.

must be activated sooner.

One method of increasing coil capacity and mitigating low-delta-T syndrome is resetting chilled-water supply temperature downward. With chilled water 3°F colder, coils are able to drench out an additional 2°F of delta-T. This increases the energy consumption of constant-speed chillers 1.0 to 1.5 percent per degree of reset (2 to 3 percent per degree for variable-speed chillers). However, chilled-water reset uses less energy than running the extra chiller, pumps, and towers. Figure 8 shows the use of chilled-water reset to improve delta-T from 8°F to 10°F in a P/S system at 50-percent load.

Another method of overcoming low-delta-T syndrome is increasing chilled-water flow (overpumping). With a P/S configuration, because of the constant-speed primary pumps, the only way to supply more water is to activate an additional full-flow pump, which results in excessive flow. With a VPF configuration, if the variable-speed primary pumps are headered, an additional pump can be activated, and the speed of all pumps can be increased to generate more water flow without the need to turn on an additional chiller and its associated auxiliaries (Figure 9).

Conclusion

Of the three basic piping configurations, VPF has the greatest potential for energy savings because of the inherent efficiencies of variable-speed pumping. Also, VPF makes the most efficient use of overpumping to mitigate low-delta-T syndrome. Operating a VPF system is not simple, though. Knowing why and how to add or shut down pumps or chillers requires training. Utilizing a VPF piping configuration, however, brings the rewards of using less energy than P/S and CPF designs. Attributes of the three systems are summarized in Table 1.

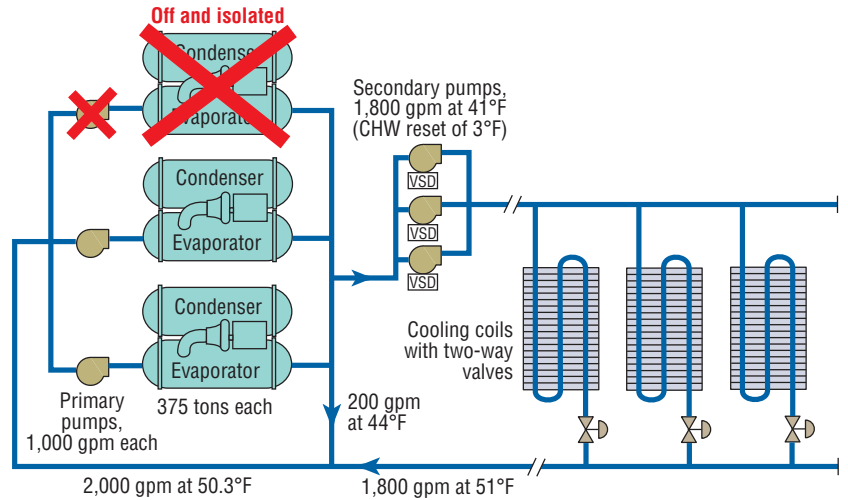


FIGURE 8. This P/S system, operating at 50-percent load and 8°F delta-T, requires 2,250-gpm coil flow and operation of three chillers. Resetting the supply temperature by 3°F to 41°F results in 10°F delta-T, coil flow of 1,800 gpm, and the need to operate only two chillers.

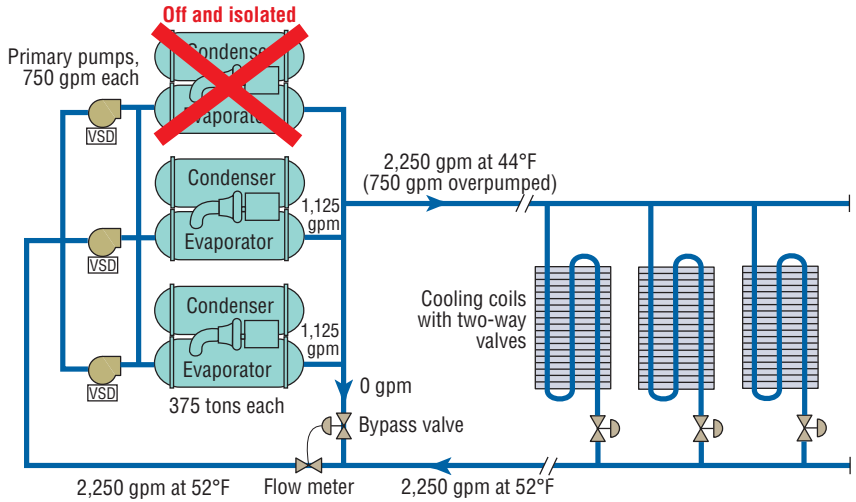


FIGURE 9. In this 50-percent-loaded VPF system with low delta-T of 8°F, two chiller systems cannot cool the 2,250 gpm needed to meet the load. If the third headered pump is activated and the two active chillers are overpumped, however, the load can be met.

	CPF	P/S	VPF
Pump energy	(Base case)	50 to 60 percent less	60 to 75 percent less
Delta-T mitigation	Does not apply	Higher energy	Less energy
Valve type	Three-way	Two-way	Two-way
Installed cost	(Base case)	10 percent higher	5 percent higher
Control complexity	Simple	Simple	Can be complex
Plant space	(Base case)	Larger	Same as base case

TABLE 1. Piping-system attributes.

Reference

1) Taylor, S.T. (2002). Degrading chilled water plant delta-t: Causes and mitigation. *ASHRAE Transactions*, 108 (1). Available at http://bit.ly/Taylor_delta-T

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