Variable-Primary-Flow SYSTEMS

An idea for chilled-water plants the time of which has come

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Chilled-water systems that vary flow through chiller evaporators have caught the attention of engineers, contractors, building owners, and operators. Chiller manufacturers are becoming increasingly receptive to this interest, thanks to ongoing advancements in control technology. Ten years ago, many of these manufacturers would have said, "No, you can't do that," if asked about variable evaporator flow. Five years ago, they would have said, "You probably shouldn't do that." Today, they will point to existing installations that successfully use variable evaporator flow.

This article will discuss several aspects of variable-primary-flow (VPF) systems, including benefits and complexities, and tips for successful implementation.

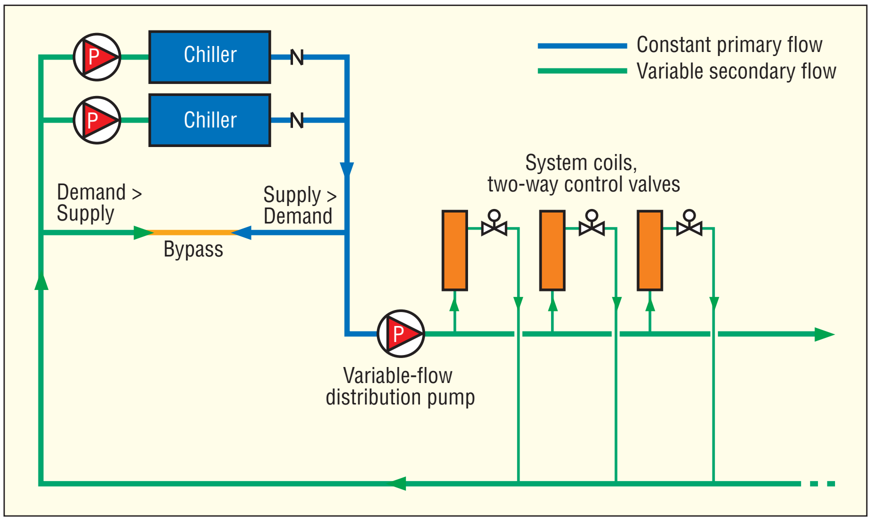

FIGURE 1. "Decoupled" (constant primary-variable secondary flow) system.

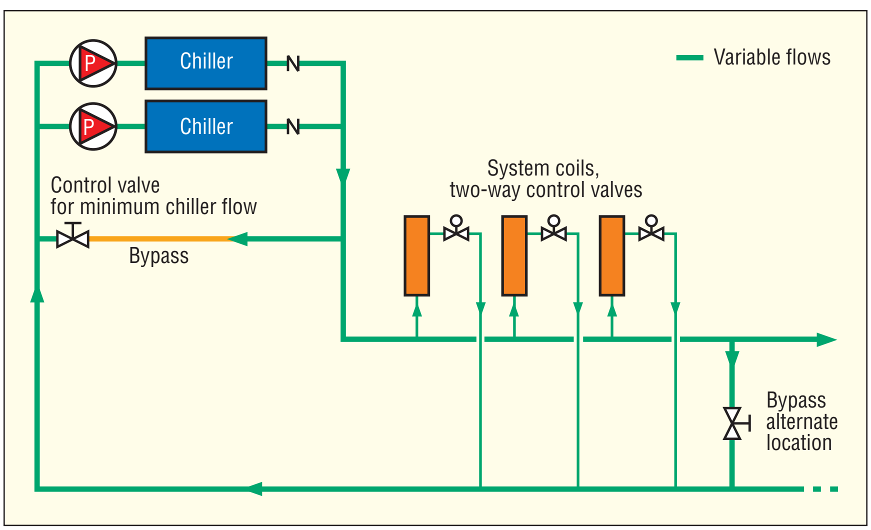

FIGURE 2. Variable primary-variable secondary flow system.

WHAT IS A VPF SYSTEM?

Conceptually, a VPF system resembles the familiar constant primary-variable secondary design more commonly known as the "decoupled" system. Figures 1 and 2 show the similarities between "decoupled" and VPF systems. For example, both require a bypass. Also, each chiller in the arrangements shown has a dedicated pump the operation of which coincides with the chiller. Differences between the two systems become apparent upon closer examination.

The "decoupled" system shown in Figure 1 uses constant water flow through each chiller evaporator and variable water flow through each cooling coil to satisfy space loads. Implementing this design requires:

• A constant-speed and, essentially, constant-volume pump (and check valve) for each chiller.
• Two-way control valves to regulate the amount of chilled water that flows through the cooling coils.
• A variable-flow distribution pump to serve the coils. (Flow modulation usually is accomplished by providing the pump with a variable-frequency drive.)
• A bypass to hydraulically decouple the primary (production) and secondary (distribution) sides of the system.

As each two-way valve adjusts the flow of chilled water through the coil to satisfy the existing load, the distribution pump responds by regulating the amount of chilled water delivered. Water flows through the bypass in either direction as needed to balance the system. Contrast this with the VPF system in Figure 2, which varies water flow throughout the entire system—that is, through the evaporator of each operating chiller, as well as through the cooling coils.

Two-way control valves, check (or isolation) valves, and a bypass 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 that returns to the operating chiller(s) never falls below the minimum limit.

Paradigm shift

For many years, chiller manufacturers encouraged cooling-plant designers and operators to maintain a constant flow of water through the chiller evaporator. The overriding concern was one of protection, because reducing water flow too quickly (that is, faster than the chiller safeties can respond) can result in nuisance shutdowns and perhaps even freezing temperatures, ruptured evaporator tubes, and costly equipment downtime.

What "suddenly" made variable primary flow feasible were advances in control technology that improved chiller operating stability. Indeed, the strategically placed sensors and real-time response of today's control systems let chillers perform their primary function—producing cold water—even when evaporator flow rates vary.

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 also is true that the LMTD can be increased by changing the production (primary) side of the chilled-water loop from constant to variable flow. However, there are other facts to consider.

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

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.

The net effect is that the power consumption of a chiller is virtually the same whether the system's primary flow is variable or constant.

WEIGHING THE PROS AND CONS

VPF systems present several cost-saving benefits, the most obvious of which results from eliminating the secondary distribution pump, which, in turn, eliminates the expenses of associated piping connections, electrical service, and a variable-frequency drive.

Building owners often say that pump-related energy saving is what prompted them to install a VPF system. Software such as System Analyzer™, TRACE®, and DOE-2 can help one determine whether anticipated energy saving justifies the use of VPF in a particular application.

It may be easier to apply VPF in an existing chilled-water plant. Unlike with a decoupled design, the bypass can be positioned at various points in the chilled-water loop, with an additional pump unnecessary.

Caveats

While modern chiller controls have improved operating stability dramatically, the laws of physics still apply. To be successful, a VPF system must comply with the following design rules:

• Each chiller has a design operating range that is defined, in part, by minimum and maximum flow rates. The fact that there is a minimum flow rate necessitates a bypass in the chilled-water loop in the event that the required system flow falls below the minimum flow required by the chiller.

• A bypass is required whether primary flow is constant or variable. The position of the smaller bypass required for a VPF system can be the same as the position of the bypass in a decoupled system. However, some designers prefer to use three-way valves at the system coils instead. While this approach ensures minimum chiller flow, it also reduces pump operating-cost savings by increasing the system flow.

• Measurement of evaporator flow is critical to VPF control. One common practice relies on direct measurement using a flow meter. Another relies on measurement of water-side pressure drop and estimation of evaporator flow based on manufacturer data.

• Knowing when to turn off a chiller requires a thorough understanding of system dynamics, because flow rates through every operating chiller vary. The already-complex strategy to avoid cycling (restarting a chiller too soon) becomes even more complicated as the number of chillers or chiller capacities increases.

• Fluctuating flow rates can be critical. For applications that require strict chilled-water temperature control, fluctuations should be limited to less

A comparison of pump operating costs

Energy-and-economic-analysis software can help engineers quickly and accurately assess the appropriateness of alternative designs. In the following case, such software was used to compare the energy and related operating costs of three pumping strategies. As the results show, a decoupled (constant primary-variable secondary) or VPF system can yield substantial savings when compared with a constant-flow design.

Design criteria:

- Medical office building in Atlanta.
- Design load is 470 tons of cooling (1560 KW refrigeration).
- Two air-cooled helical-rotary chillers piped in parallel.
- One pump per chiller.
- Alternative pumping strategies: constant flows, constant primary–variable secondary flows, and variable flows.

ANNUAL ANALYSIS RESULTS

System-flow alternatives	Pumping energy consumed	Operating costs, U.S. currency
Constant primary, constant secondary	52,588 KW-hr	$4,522
Constant primary, variable secondary (“decoupled”)	32,819 KW-hr	$2,822
Variable primary, variable secondary (VPF)	26,614 KW-hr	$2,289

than 10 percent of design flow per minute. Relaxing this limit to 30 percent of design flow per minute is permissible in most comfort-cooling applications. If the chiller is properly controlled, the leaving-evaporator-water temperature will not deviate from the set point for more than a few minutes, if it does at all.

• Operators must understand how VPF systems work. Training is mandatory.

WHAT ABOUT THE REAL WORLD?

So far, our discussion has provided an abstract look at the design and operation of VPF systems. For answers to questions of a more practical nature, such as, “Do they really work and, if so, how well?,” we spoke with several engineers who have applied systems with VPF. Two of them share their experiences below.

“We installed a variable-primary-flow system in a mall,” one said. “During operation, we were surprised to find that the pumps never operated below 60-percent flow. We discovered that the anchor tenant had disconnected their valve controllers, were running the coils wide open, and were varying air flow to maintain a constant leaving-air temperature and humidity.

“Though we weren’t allowed to change this setup, the good news is that we had already saved almost 80 percent of our pumping energy, since the pumps were operating at about 60 percent of their design flow and at about 20 percent ($0.6^3 = 0.216$) of their design power.” (*It should be noted that the designer used the common approximation of power changing with the cube of the flow. The actual relation is nearer to raising the flow ratio to the 2.85 power. In this case:* $0.6^{2.85} = .233$, *which still is close to the 80-percent savings the designer estimated.*)

The second engineer told a similar story: “We recently applied a VPF system in a hospital. We replaced the major air handlers and used two-way modulating valves, but the patient rooms are still served by fan coils with three-way valves. The good news is that the fan coils act as the bypass and keep us above the minimum chiller flow rates. The not-so-good news is that we’ve saved a lot of pumping energy, but not as much as we could.”

IMPLEMENTING A VPF SYSTEM

The financial benefits of VPF depend on the appropriateness of the application and the care with which the system is designed, installed, and operated.

As Steven T. Taylor, principal, Taylor Engineering, said, “Because of their lower first costs and lower energy costs, variable-primary-flow systems are clearly the right choice for many applications, but not all. They require complex staging-control sequences and minimum-flow (bypass) controls; so the designer and operator of the system have to be more sophisticated if the system is to be a success. On some projects, the ‘fail-safe’ nature of primary–secondary systems may offset their energy and first-cost disadvantages.”

With that in mind, we offer the following advice.

Do not use VPF if:

• System chilled-water temperature is critical, such as in a “clean-room” or process (computer-chip-making) application.

• Only three-way valves are used, meaning that the system flow rate does not vary. A design with *some* three-way valves is permissible. In fact, if 60 percent of design flow is reached, nearly 80 percent of the pumping power will have been saved.

• It is unlikely that the owner/operator will run the plant as designed.

• Existing chiller controls are old and inaccurate, as would be the case with, say, a 30-year-old chiller with pneumatic controls.

Consider VPF if:

• System flow can be reduced by at least 30 percent of design.

• It provides greater cost savings than does a decoupled design.

• Operators will understand how the system works and will run it properly.

• The system can tolerate a modest variation in supply-water temperature.

• A single chiller is being replaced *and* the primary flow can be varied. (Previously considered “too small,” such applications may be ideal for VPF designs.)

During design and installation:

• Use energy-analysis software to determine the payback period or return on investment. Be sure to account for reduced piping and electrical-connection costs.

• Remember to design a bypass into the system to provide minimum chiller flow.

• Size each chiller pump to accommodate the pressure drop of the system and the evaporator.

• If flow meters are used, specify high-quality models—they require less calibration and are more accurate. Also, pipe the flow meters in accordance with the manufacturer's instructions.
• Invest the extra time needed to determine the control points at which chillers should be turned off. This design task is critical to successfully reduce operating costs. Also, its complexity will increase with the number (and differing sizes) of chillers.
• Teach the operating staff about the system. Help the building owner design a program for ongoing training.
• Work with businesses that can supply and integrate the entire hydraulic system (chillers, pumps, and controls) during construction and operation. The financial benefits of a VPF design can be obtained only if the components operate as a system.

During plant operation:

• Maintain evaporator flow between the minimum and maximum limits. The cataloged range for many chillers is 3 to 11 fps (0.9 to 3.4 m/s). Ask the chiller manufacturer about the values for your machine.
• Keep changes in flow rate through the evaporator within manufacturer-set limits. In most applications with sophisticated chiller controls, a 30-percent-per-minute change in the rate of flow should work well.
• Continue to work with the operating staff and provide additional training as needed.
• If flow meters are used, calibrate them when required.
• Use the automation system to monitor system (chiller plus pump) performance. Document the operating costs.

A PARTING THOUGHT

Variable flow through chiller evaporators is not heresy now that chiller controls can adapt to changing operating conditions quickly. Use an analysis tool to determine the economic viability of VPF. When appropriate, offer it to building owners and operators as a value-added option in your system designs. HPAC