Primary-Only vs. Primary-Secondary Variable Flow Systems

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Several articles over the last several years have extolled the virtues of primary-only variable flow chilled water pumping systems compared to the conventional primary-secondary pumping system. One article[1] even predicts the "demise" of primary-secondary systems. While there is no question that the primary-only system has many advantages, the primary-secondary system may still be preferable for some applications.

System Description

This article addresses two pumping configurations applied to variable flow, variable speed chilled water systems: primary-only (p-only) pumping, shown in *Figure 1*, and conventional primary-secondary (p-s) pumping, shown in *Figure 2*. There are other pumping schemes, in particular variations on the p-s system using distributed secondary pumps[2] that may be preferable to these two schemes in some applications, but they are beyond the scope of this article.

For both options, the distribution system is variable flow using two-way valves at cooling coils. The distribution pumps (primary pumps for the p-only system and secondary pumps for the p-s system) are fitted with variable speed drives (VSDs). VSDs are optional — the pumps could simply "ride their curves" as flow varies — but VSDs significantly reduce pump energy and are cost effective in most variable flow chilled water applications. For both systems, the VSDs are controlled to maintain differential pressure at a remote location in the system at a setpoint determined to be sufficient to deliver the required chilled flow through any coil. The setpoint may be constant or reset downward at part-load conditions.

Two elements of the p-only system in *Figure 1* deserve more detailed discussion:

- The chillers are piped in parallel with automatic isolation valves at each chiller to shut off flow when the chiller is off. The pumps could also be piped individually to each chiller as shown with the p-s system in *Figure 2* (see discussion later regarding the advantages and disadvantages of this approach for p-s systems). But with p-only systems, the headered pump design has two key advantages that make it preferable to dedicated pumping:

1. Flow through a chiller that is just starting up can be slowly increased from zero to the minimum rate by controlling the speed at which the isolation valve opens. This slows the rate of change of chilled water flow through other operating chillers, which is a concern with p-only variable flow systems. Staging issues are discussed later.

2. The number of operating pumps need not match the number of operating chillers. In systems that are able to maintain high temperature differences (ΔT) between chilled water supply and return at part load, this pumping arrangement can allow two pumps to serve three chillers, for instance. For systems with degrading ΔT, a common problem at low loads, two pumps can serve one chiller, allowing the chillers to fully load before having to stage on the next chiller. With fixed speed chillers, this can improve chiller plant efficiency.[3,4]

- A bypass control valve and flow meter are provided to maintain minimum flow through the chillers. When there is a low demand for chilled water by coils, the system flow rate may be below the minimum flow rate required by the chill-

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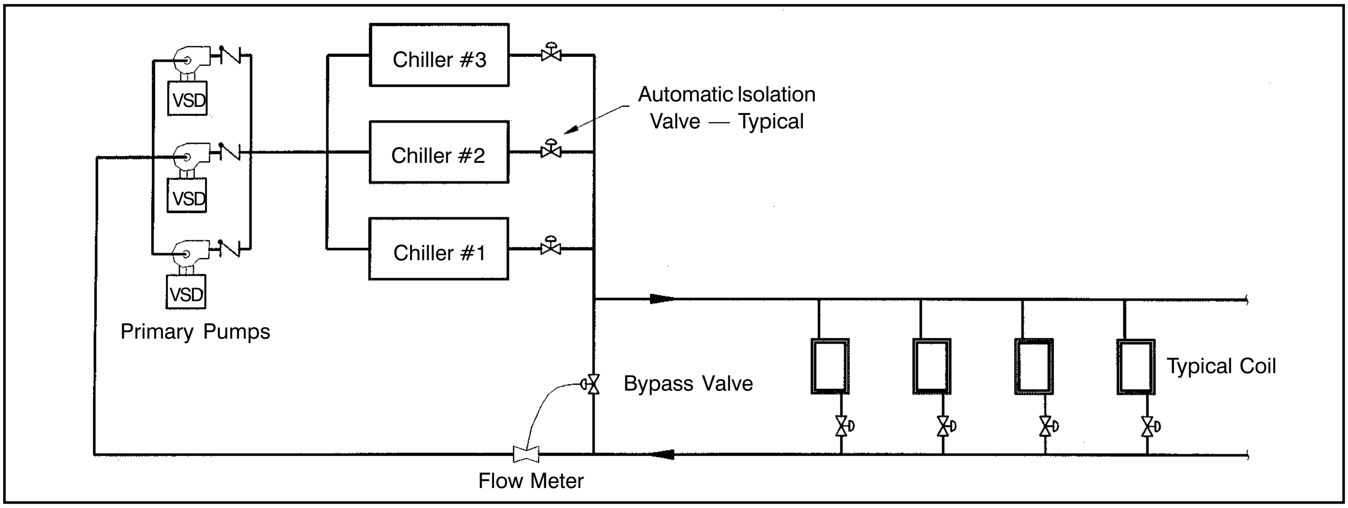

Figure 1: Primary-only system.

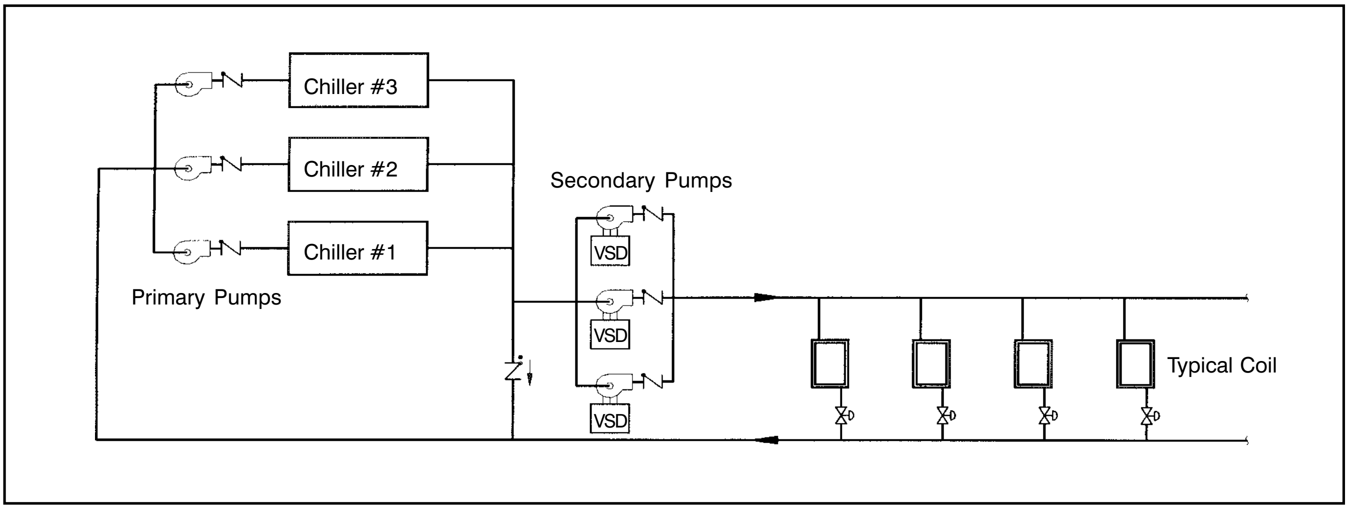

Figure 2: Conventional primary-secondary system.

ers. This is sensed by the flow meter. The control system then opens the bypass valve as required to maintain minimum chiller flow. In lieu of a flow meter, differential pressure across the chillers can be measured and correlated to flow based on chiller flow vs. pressure drop data from the chiller manufacturer.

The bypass valve should be located near the pumps (as opposed to near the end of the distribution system) to minimize flow and pressure drop through the distribution system, minimizing pump energy. This location also reduces control system costs because the flow meter and valve (control point and controlled device) must be connected to the same direct digital control (DDC) panel, as opposed to separate panels connected by a DDC network, to ensure stable control unaffected by network traffic. Hence, a remote valve location would require additional control wiring.

The p-s system shown in *Figure 2* also has some elements that should be discussed in more detail:

- The primary pumps are piped dedicated to each chiller. They could also be piped in a headered arrangement as shown in *Figure 1*. Unlike the p-only system where the headered arrangement is definitely preferred, with p-s systems, there are valid arguments for selecting either approach. The headered arrangement offers additional redundancy since any pump may supply any chiller. With the dedicated arrangement, should any chiller or pump fail, its associated pump or chiller is also out of service unless some complex piping and valving arrangement is provided. It is also easier with the headered arrangement to add a standby pump that can serve any chiller. On the other hand, the dedicated pumping arrangement has the advantage of control simplicity: the pump may be controlled directly from the chiller control panel, which ensures it operates whenever the chiller wants it to. It also can result in reduced primary pump energy for plants with differing chiller pressure drops, such as hybrid absorption/electric chiller plants and plants with unequally sized chillers, since each dedicated pump may have a different head and flow rate as required by the chiller it serves.
- A check valve is shown in the common leg. With con-

stant speed chillers in plants with degrading ΔT at low load, the check valve in the common leg can allow chillers to be more fully loaded before staging on the next chiller, reducing plant energy usage.[3,4,5] The only disadvantage to having the check valve is when the primary pumps and chillers are piped in the headered arrangement in *Figure 1*. If the primary pumps are off and chiller isolation valves are closed while the secondary pumps are on, the secondary pumps will be deadheaded. This can be avoided simply by shutting off the secondary pumps whenever primary flow is off.

For variable speed chillers, the part-load efficiency of the chillers is such that the plant can use less energy if chillers are staged on before they are fully loaded,[4,6] so there is little value to having the check valve. In general, the check valve is recommended for fixed speed chiller plants, and not recommended for variable speed chiller plants.[7]

• The primary pumps are constant speed. VSDs could be added to these pumps to vary flow through the primary system from minimum chiller flow up to design chiller flow to reduce primary pump energy, but the added cost and control complexity are generally not justifiable. Moreover, the main benefit of the p-s system is its simplicity and fail-safe nature (discussed further later). Adding VSDs to the primary pumps compromises this advantage.

Advantages of Primary-Only Systems

The advantages of p-only variable-flow distribution systems compared to conventional p-s systems include:

• Lower first costs. This is due to the elimination of the secondary pumps and associated fittings, vibration isolation, starters, power wiring, controls, etc. These savings are partly offset by higher costs of variable speed drives for the p-only system and the cost of the bypass valve and associated controls.

• Less space required, again due to the eliminated secondary pumps. This can result in substantial cost reductions, depending on the plant layout and space constraints.

• Reduced pump design motor power requirement and size. There are two reasons for this reduction. First, the additional fittings and devices (shut-off valves, strainers, suction diffusers, check valves, headers, etc.) required for the secondary pumps are eliminated. Second, in most cases, average pump efficiency is also higher with the p-only system because primary pumps in the p-s system are usually high flow, low head pumps that are inherently less efficient unless pumps are oversized with low speed (e.g., 1,200 rpm) motors.

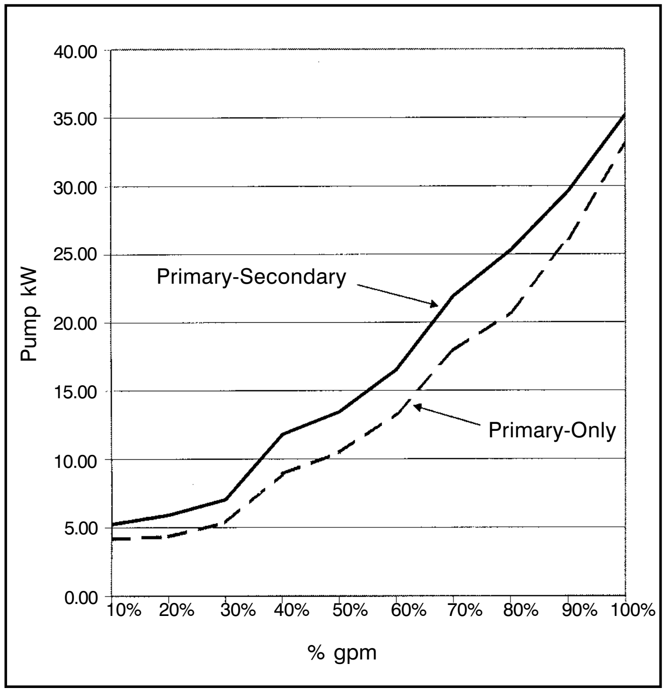

***Figure 3:** Pump energy for primary-only and primary-secondary systems in three chiller plants.*†

• Lower pump energy costs. Contrary to conventional wisdom, p-only systems *always* use less pump energy than conventional p-s systems. This is in part due to the reduced pump full-load power requirement discussed earlier, but mostly because the variable speed drives provide near "cube-law" savings for both flow through the primary circuit as well as flow through the secondary circuit.* With p-s systems, pump energy in the primary circuit is constant for each chiller stage and primary pumps must be staged on as chillers are staged on. *Figure 3* demonstrates this performance advantage for the three-chiller, three-pump plants shown in *Figures 1* and *2*.

Disadvantages of Primary-Only Systems

Along with the considerable advantages of the p-only system, it does have two significant disadvantages: the complexity and possible failure of the bypass control, and the complexity and possible failures associated with chiller staging.

Bypass Control Problems

The bypass valve (*Figure 1*) is required to ensure that minimum flow rates are maintained through operating chillers. The

*The cubic relationship between pump energy and flow assumes that pressure drop varies as the square of fluid velocity, an assumption valid only for fully developed turbulent flow in systems with fixed geometry. In real systems, pressure drop in most system elements varies less than this since flow is not fully turbulent; velocities are more typically in the transitional region between turbulent and laminar flow at design load conditions, and in the laminar flow regime at low loads. Control valves open and close, changing system geometry and, hence, its flow characteristics. Most variable speed pumping systems maintain a minimum differential pressure setpoint, further changing the pressure drop/flow relationship as well as pump efficiency. Finally, motor efficiency and variable speed drive efficiency drop off at lower loads. All of these factors combine to make part-load pump energy savings less than what may be expected from the ideal cube-law relationship.

valve must be automatically controlled by flow — the pressure-activated bypass valves commonly used in the past with constant-speed pumping systems will not work with variable-speed pumping because the differential pressure across the valve will always be less at part load, so the valve will never open. Bypass control can be somewhat complex and, as with all controls, subject to failure:

- Some means to measure flow through the chillers is required, such as a flow meter in the primary circuit or a differential pressure sensor across chillers that can be correlated to flow. These devices must be maintained in calibration to provide proper control. Because of the importance of this meter in p-only systems, a magnetic flow meter should be considered. While much more expensive than other common meter types, such as turbine meters, they are extremely accurate, less susceptible to error when installed close to elbows and valves, and are nearly maintenance-free (no calibration other than the signal transmitter).
- Selecting the bypass control valve and tuning the control loop is sometimes difficult because of the widely ranging differential pressure across the valve caused by its location near the pumps. The valve must be large enough to bypass the minimum chiller flow through it with a pressure drop as low as the differential pressure (DP) setpoint used to control chilled water pump VSDs. If only a few valves are open in the system, the pressure at the DP sensor location will be what is available at the plant as well since there is little pressure drop between the two points due to the low flow. If the chillers are all identical and selected so that the minimum flow rate of each chiller is less than half of the design flow rate, then the valve will only be active when the system is operating at low load and low differential pressure with one chiller on. The valve can be relatively easily sized and the control loop should be relatively easily tuned and stable. However, for plants with a range of chiller sizes or with relatively high minimum flow rates, the bypass valve may also have to be active when flow, and therefore differential pressure, is high. In this case, choosing the valve and tuning the control loop is more difficult. For these plants, use of a pressure-independent control valve should be considered. This relatively new product includes a device that maintains a constant differential pressure across the modulating valve, improving control over a range of system flow and differential pressures.
- The "robustness" of the controls may be insufficient to handle sudden changes in flow. For example, when a many air-handling units (AHUs) shut off at the same time, each shutting their two-way valve at the same time, flow will suddenly drop through the system. The change can be too sudden for the bypass valve to respond quickly enough, causing chillers to trip on low temperature or flow. This can be mitigated by causing valves on AHUs to be slow-closing (inherent in most modern electric valves) and staggering the time that AHUs are programmed to shut off.
- Complex control systems are prone to failure. At some point in the life of the plant, one can expect the bypass control to fail. A failure of the bypass system can cause nuisance chiller trips, which generally require a manual reset. If an operator is not present to reset the chiller, the plant can be out of service for some time.

Advantages of Primary-Only	Disadvantages of Primary-Only
Lower First Costs	Complexity of Bypass Control
Less Plant Space Required	Complexity of Staging Chillers
Reduced Pump Peak Power	
Lower Pump Annual Energy Usage	

***Table 1:** Advantages and disadvantages of primary-only systems versus primary-secondary systems.*

Chiller Staging Problems

When one or more chillers are operating and another chiller is started abruptly by opening its isolation valve (or starting its pump for dedicated pumps), flow through the operating chillers will abruptly drop. The reason for this is simple: flow is determined by the demand of the chilled water coils as controlled by their control valves. Starting another chiller will not create an increase in required flow, so flow will be split among the active machines. If this occurs suddenly, the drop in flow will cause a nuisance trip in the operating chillers.

To stage the chillers without a trip, active chillers must first be temporarily unloaded (demand-limited or setpoint raised), then flow must be slowly increased through the new chiller by slowly opening its isolation valve. Then all chillers can be allowed to ramp up to the required load together. (The need for slowly allowing flow to pass through the chiller that is just starting is one reason why it is advantageous to pipe the chillers and pumps using a headered arrangement rather than the dedicated pump arrangement. With dedicated pumping, flow through operating chillers will always change abruptly even though the pump has a variable speed drive. This is because no flow will go through the starting pump or chiller until the pressure at the pump discharge exceeds the backpressure on its check valve caused by the pumps serving the operating chillers. At that point, the check valve will suddenly open and flow will abruptly change through the starting pump and chiller, causing an abrupt change in flow through the operating chiller.) During the staging sequence, chilled water temperatures will rise somewhat. This is seldom a problem in comfort applications, but may be an issue for some industrial applications.

Summary & Recommendations

Primary-only pumping systems cost less and use less energy than the conventional primary-secondary pumping system. Given this, deciding among the two would seem to be a "no-brainer." However, the complexity of the bypass and staging controls requires more sophisticated engineering (both on the part of the designer and operator) and reduces the reliability of the system since complex controls can be expected to fail at some point in the life of the system. Primary-secondary systems, on the other hand, do not require complex staging controls and have no need for bypass controls — they are virtually fail-safe. These advantages and disadvantages are summarized in *Table 1*.

Given these considerations, primary-only systems are most appropriate for:

- Plants with many chillers (more than three) and with relatively high base loads, as might be expected in an industrial application. For these plants, the need for bypass is minimal or nil due to the high base loads, and flow fluctuations during staging are small due to the large number of chillers.
- Plants where design engineers and future on-site operators understand the complexity of the controls and the need to maintain them.

The primary-secondary system may be a better choice for buildings where fail-safe operation is essential or on-site operating staff is unsophisticated or nonexistent.

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Notes

† Data developed from a detailed computer model validated by a pump package manufacturer's software. Based on the following:

P-only pumps: 480 gpm (30 L/s), 85 feet head (254 kPa), 81% pump eff., 91% motor eff., 98% VSD eff.

P-s primary pumps: 480 gpm (30 L/s), 25 feet head (75 kPa), 78% pump eff., 87.5% motor eff.

P-s secondary pumps: 480 gpm (30 L/s), 65 feet head (194 kPa), 81% pump eff., 91% motor eff., 98% VSD eff.