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S Y S T E M   S O L U T I O N S

When it comes to optimizing chiller plants, the best option is to consider variable flow. ASHRAE Standard 90.1 requires variable flow in systems over 10 hp, and most of these plants are designed using primary/secondary systems. However, this proven design is not without its challenges – particularly with low delta T issues.

Variable primary flow is quickly becoming an alternative to primary/secondary systems. This article discusses a specific application of variable primary flow with series chillers. Series chillers can help resolve some of the design and operational issues associated with variable primary flow. Series chillers are also a great idea when large chilled water temperature ranges make sense.

J.C. Kuttruff, our Global Account Manager, provided technical expertise in variable primary flow design for this newsletter. For more information on variable primary flow systems, contact your local McQuay Representative or visit www.mcquay.com.

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Series Variable Primary Flow Design

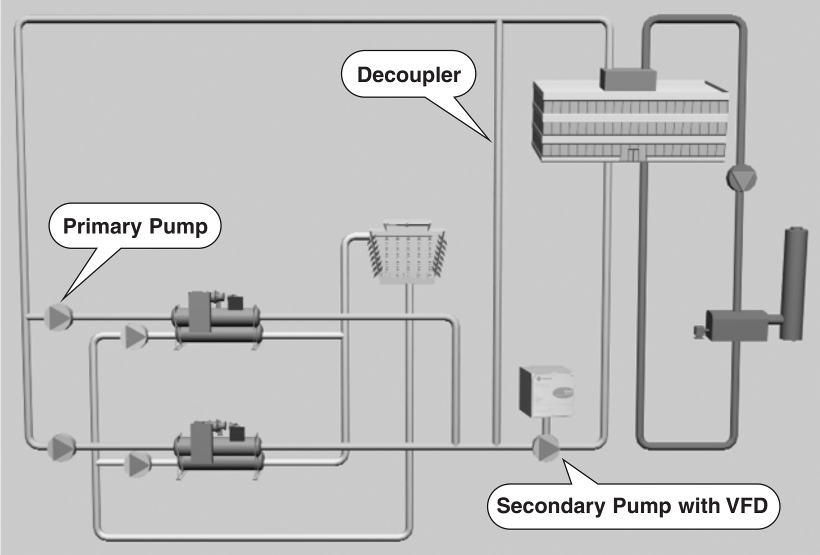
While they have traditionally been used for special projects and difficult retrofit applications, variable primary flow systems are increasingly entering the mainstream as a system for schools, office buildings and process applications. The system offers designers several benefits and a few challenges.

Background

Figure 1 shows a conventional primary/secondary chiller design. The flow through each chiller is constant and set by the constant flow of a primary pump. The flow in the building, or the secondary loop, is variable and is typically controlled by the loop pressure differential which adjusts the secondary pump variable frequency drives (VFD). Any extra primary flow not required by the building passes through the decoupler and is returned to the chiller. This flow through the decoupler represents "wasted" flow because it delivers no value to the building occupants.

What the decoupler flow does provide is constant flow through the chiller evaporators. Until recently, this constant flow was considered essential for reliable chiller operation. However, research has shown that varying flow through the chiller is possible as long as the minimum flow is maintained.[1]

Figure 1 – Conventional Primary/Secondary System



[1]Redden, George. *Effect of Variable Flow on Chiller Performance.* ASHRAE Transaction SA- 96-12-3. 1996, ASHRAE, Atlanta, Ga.

Figure 2 – Variable Primary Flow System With Parallel Chillers

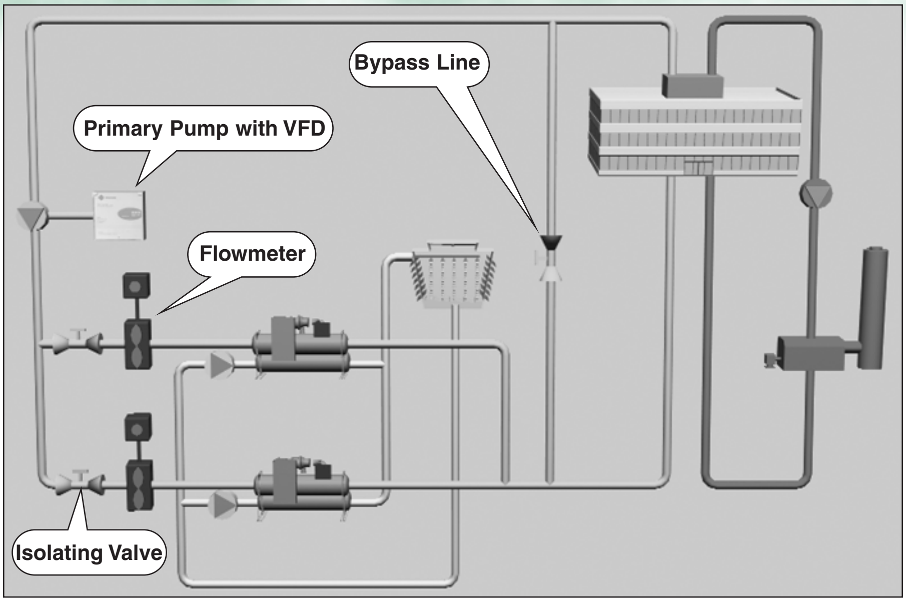


Figure 2 shows a typical variable primary flow system with the chillers in parallel. In this system, the primary pumps are variable flow and there are no secondary pumps. The decoupler is replaced by a bypass line with a modulating flow valve. As long as the flow is above the minimum required by the chiller, the bypass line remains closed and the flow through the chiller(s) varies with the building requirement. When the minimum chiller flow is reached, the bypass valve is modulated so that minimum flow is maintained.

Variable Primary Flow Benefits

Variable primary flow systems are gaining popularity for the following reasons:

- They require smaller mechanical rooms because only one set of pumps is used.
- They generally cost less to install. Once the construction team is familiar with the requirements, they are easier to design and build because there are fewer pumps and pipe fittings. More time should be allowed for commissioning because the controls can be more complicated, but the overall cost of a variable primary flow system can be less than a primary/secondary system.
- There is no wasted pump work as is the case with the decoupler in a primary/secondary system. Unless the flow drops below the minimum required by the chiller, any flow that is pumped in a variable primary flow system is sent to the building and used.
- In many applications there are fewer pipe fittings associated with pumps (e.g. for check valves, isolating valves, elbows, etc.) because there is only one set of pumps. As a result, the overall design pressure drop for a variable primary flow system will be about 10% less than a primary/secondary system in the same application.
- Variable primary flow creates the opportunity to operate chillers in their "efficiency sweet spot" without paying for extra, unused pump energy. In other words, variable primary flow allows two chillers to be used when it is still possible to meet the load with only one chiller. Plants with dual compressor chillers or chillers with VFDs can benefit. Lower pressure drops created by splitting the flows across multiple chillers and the benefit of operating in an efficiency "sweet spot" can provide enough savings to offset the liability of additional condenser pump and tower fan work. This strategy will save energy (operating costs) over the life of the facility.

Variable Primary Flow Challenges

Every new application creates new challenges, and variable primary flow is not without challenges. New design elements need to be addressed for a reliable, problem-free installation. Two issues are of critical importance. The first is transient flows encountered when additional chillers are enabled or turned off. The second is maintaining minimum required chiller flows at very low loads. Simple solutions are available.

Minimum Flows

Chillers have maximum and minimum flow limits. The maximum limit avoids tube erosion. The minimum limit provides stable heat transfer in the evaporator, which results in stable chiller operation. Since flow is proportional to load in a variable primary flow system, maintaining minimum flow across the evaporator becomes an issue when the cooling requirement in the facility falls below the minimum flow of one chiller.

Normally, a bypass valve is installed to maintain minimum flow to the chiller. When the cooling load and coincident chilled water flow is less than a chiller's minimum flow limit, the bypass valve modulates to divert flow back to the chiller. This is done via a flow sensor or by monitoring for a minimum ΔP across the evaporator barrel.

Sizing the bypass and bypass valve for the chiller's minimum flow is an important design consideration with a variable primary flow system. Smaller valves are less expensive and control minimum flows much more accurately.

A common error is to size the bypass valve the same as the chilled water line. This almost universally oversizes the bypass and creates problems. Using an oversized valve to modulate a fraction of the flow is equivalent to opening a barn door to let a mouse out. The mouse gets out, but so do the rest of the farm animals. In much the same way, instead of modulating a trickle of water, a torrent rushes through. In many cases, the chilled water supply is completely diverted and the chiller sees a return water temperature equal to the supply. When this happens, the chiller believes the load is satisfied and it shuts down.

Transient Flows
As the cooling load increases, a second chiller will be required. When the isolating valve to the second chiller opens, the flow is split, resulting in an immediate 50% reduction in load for the first chiller. If the first chiller cannot respond quickly enough, then it will trip a safety (such as low refrigerant pressure or a freezestat) and be taken off line.

The most reliable remedy for this reduction in flow is to reduce the output (demand limit) of the first chiller prior to opening the isolating valve for the second chiller. For example, if the operating chiller is demand limited to 50% capacity prior to opening the isolating valve for the second chiller, the operating chiller will not see the dramatic drop in load. Demand limiting can be accomplished with an analog signal to most chiller controllers. McQuay MicroTech II™ controls allow the signal to be provided digitally and communicated via open, standard protocols using our Protocol Selectability™ feature.

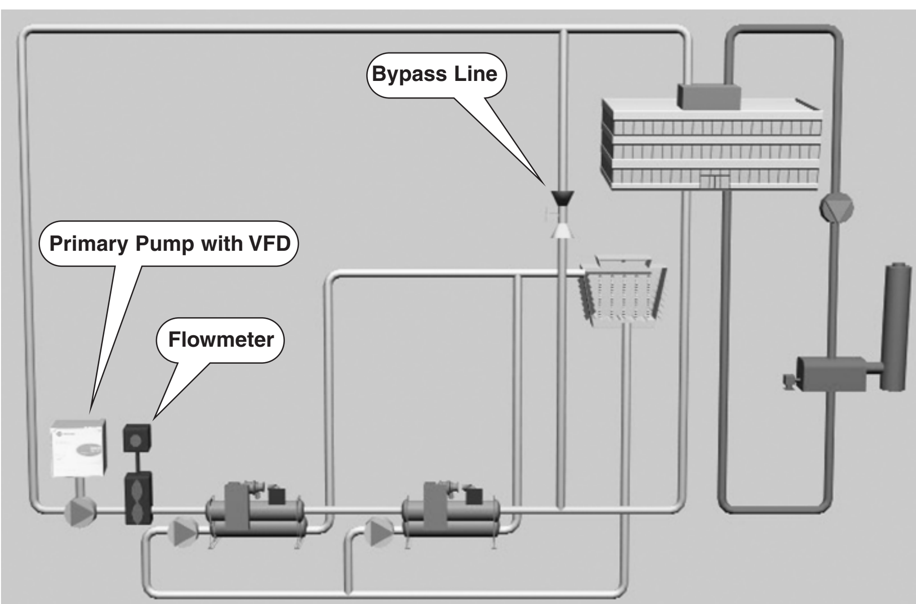
A second consideration would be opening the isolation valve slowly over a 2 to 3 minute period. By minimizing the effect of an instantaneous 50% reduction of flow and load on the operating unit, you minimize the possibility of tripping a chiller.

When reducing the number of chillers, transient flows are usually not a problem. When a chiller is taken off line and its isolation valve closes, its flow is diverted through the remaining operating chillers. As the flow increases, the remaining chiller(s) see an elevated supply water temperature and compensate by increasing capacity.

Why Not Consider Series Chillers?
Figure 3 shows a variable primary flow system with the chillers in series. In this arrangement, the flow passes through both chillers so there is no problem with starting the second chiller. Staging the chillers is very easy for McQuay because our centrifugal chillers come with a lead/lag load balance feature that will use the chiller with the least operating hours when only one chiller is required. When a second chiller is required, the two chiller control panels communicate via a twisted, shielded pair of wires and the second chiller is started. The load is evenly distributed between the two chillers which results in about a 2% improvement in efficiency over base loading the first chiller.

One flowmeter can be used to control the bypass valve when the flow drops below the minimum. Overall, series chillers are easier to design and operate.

Figure 3 – Variable Primary Flow System With The Chillers In Series



What About The Pressure Drop?
When series chillers are suggested, a primary consideration must be the pressure drop incurred when the two chiller pressure drops are added together. The common solution is to change the chiller shell from a two pass to a single pass arrangement. While this greatly reduces the pressure drop, it also increases the minimum flow rate (or reduces the turndown). A two pass chiller at typical conditions can have the flow reduced to about 50%. A single pass chiller can only have the flow reduced to about 70%.

It is important to remember that flow varies through a chiller proportionally with the load in a variable flow system. As a result, the chiller sees a reduction in flow and pressure drop most of the time. At 70% flow, the pressure drop across the chillers is reduced to 49%. This results in a small annual energy penalty when using a higher design water pressure drop.

If we accept the higher pressure drop at design conditions and use two pass chillers in the same system, we gain better turndown at part load conditions. Raising this minimum turndown point reduces the flow through the bypass line and improves pump savings to offset part of the penalty incurred at design conditions. Performing an annual energy analysis using McQuay's Energy Analyzer™ software can be an invaluable design tool in helping to determine which pass arrangement will be most beneficial for a specific application.

Performance Comparison – Parallel and Series One Pass and Two Pass Variable Primary Flow Systems
Let's compare chillers in parallel to series chillers with one pass and series chillers with two pass arrangements. We will use a model office building in

Table 1 – Design Performance For Parallel and Series One Pass and Two Pass Variable Primary Flow Chiller Plants.

Design	SWT	Range	Design FLOW	Perfor-mance	CH-1 PD	CH-2 PD	Min Flow	Min Turndown	Min Flow PD	Chiller Price Ratio
	(°F)	(°F)	(GPM)	(kW/ton)	(ft)	(ft)	(GPM)	(%)	(ft)	
Parallel 2 pass	44	10	1920	0.560	17	17	375	20	3.1	1.00
Series 1 pass	44	10	1920	0.547	8.6	8.4	725	38	2.8	0.95
Series 2 pass	44	10	1920	0.547	19.1	18.7	575	30	5.4	0.95

Los Angeles. It is a VAV system with two 400-ton chillers. We will start with conventional ARI conditions, 44°F/54°F chilled water and 85°F/95°F condenser water.

Table 1 shows the design performance of the three systems. All were selected to provide about 0.55 kW/ton full load performance. The performance of the series chillers is based on the total of the two chillers (total kW/ total tons). The same chiller model was used in both the lead and lag position. This allows either chiller to be the lead chiller when only one chiller is required. It is possible to further enhance the chiller performance by selecting chillers specifically for the operating conditions (See Engineering Solutions #10, *Series Chillers - What's Old Is New Again,* January 2002 on www.mcquay.com). However, it is unlikely that the upstream chiller will operate at the higher lift conditions required by the downstream chiller.

Notice that the pressure drop for the parallel chillers and the one pass chillers is the same (17 ft.). The two pass series chiller pressure drop is nearly twice as high. The parallel chillers offer the best overall minimum flow at 375 gpm (or 20% of design flow).

The chiller price ratio shows the relative price change for the series chillers when compared to the parallel chillers. Notice the two series offerings cost about 5% less because the series arrangement is a very efficient use of chillers. The designer has the option to use this cost difference to get better performance from the series chillers or it can be taken as a cost savings.

Table 2 shows the annual operating cost for the three systems. Overall, there is very little difference between the three. The higher design pressure drop of the two pass series arrangement results in only a minor cost penalty. The same is true for the higher minimum turndown for the one pass series arrangement.

What this analysis demonstrates is that there is little or no operating penalty when using series chillers in variable primary flow systems. We have already established that variable primary flow systems are easier to design and operate (as long as issues with starting the second chiller are resolved). Using series chillers in a variable primary flow system resolves the issues surrounding starting the second chiller, making the system even easier to design and operate.

However, the real opportunity comes when we consider larger chilled water temperature ranges than the conventional 10°F. While the larger range provides only nominal operating savings (See Engineering Solutions #14, *Why Change The Chilled Water Temperature Range,* December 2002 on www.mcquay.com), it can offer significant capital savings on the entire HVAC system as it affects the chillers, pumps, piping, cooling coils, supply air fans, etc. Generally, as the range is increased, the chilled water supply temperature will have to be lowered to strike a balance between the fan penalty (due to coils with more rows) and chiller penalty (due to increased lift).

Series chillers are a very good arrangement for providing larger ranges and lower chilled water temperatures. As the supply water temperature is lowered, the chillers in series will require less power than a single chiller trying to provide the same chilled water temperature.

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Table 2 – Annual Operating Performance For Parallel and Series One Pass and Two Pass Variable Primary Flow Chiller Plants.

Run	Design Flow	Min Flow	Chiller PD	Chiller	Pumps	Tower Fan	S.A. Fan	Total
	(GPM)	(GPM)	(ft)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
Parallel 2 pass	1920	375	17	$ 82,482	$ 21,850	$ 7,890	$ 72,959	$ 185,181
Series 1 pass	10	725	17	$ 82,552	$ 23,629	$ 6,904	$ 73,023	$ 186,108
Series pass	10	575	37.8	$ 82,584	$ 24,198	$ 6,907	$ 73,051	$ 186,740

Table 3 - Design Performance Of A Two Pass Series Variable Primary Flow Plant At Different Chilled Water Temperature Ranges.

Design	SWT	Range	Design Flow	Perfor-mance	CH-1 PD	CH-2 PD	Min Flow	Min Turndown	Min Flow PD	Chiller Price Ratio
	(°F)	(°F)	(GPM)	(kW/ton)	(ft)	(ft)	(GPM)	(%)	(ft)	
Series	44	10	1920	0.547	19.1	18.7	575	30	5.4	1.00
Series	44	12	1600	0.549	18.4	18.1	550	34	5.4	0.97
Series	42	14	1371	0.588	18.8	18.4	475	35	5.4	0.96
Series	42	16	1200	0.581	19.7	19.2	400	33	5.4	0.91
Series	42	18	1067	0.576	15.9	15.5	400	37	5.4	0.88
Series	40	20	920	0.641	22	21.3	300	33	5.2	0.84

Table 3 shows the design performance from a 10°F to 20°F range for a two pass series variable primary flow plant. For each design, the water pressure drop was held approximately constant. As the chilled water temperature was lowered, the chiller performance decreased. However, the decrease in flow requires smaller chilled water pumps and piping.

Reviewing the chiller pricing ratio, we see a large pricing improvement for the same performance and water pressure drop. This occurs because the lower flow for the same pressure drop results in less copper tubing – the most expensive component in a chiller. This can be added to the other capital savings (listed previously) that result from increasing the chilled water temperature range.

Table 4 shows the annual operating cost as the range is increased from 10°F to 20°F. In this example, the best operating performance occurs at a 12°F range and 44°F supply water temperature. However, the 18°F range and 42°F supply water temperature allows the supply piping to be 8 inch (versus 10 inch), which results in significant savings with less than a 2% increase in operating cost. In addition, the chillers are 12% less expensive while still offering excellent performance. Series chillers are one of the best ways to optimize chiller selections.

Other Considerations

Series Counterflow

Switching to series counterflow may add even more savings. Series counterflow improves annual chiller performance by about 5%. However, the condenser water must be pumped at design flow even if only one chiller is operating. The increased condenser pump work may offset the chiller savings. For short condenser loops, series counterflow may make sense.

Chiller bypass line

In most cases, a chiller bypass line is a good idea because it will allow chiller servicing without shutting down the entire plant. If service is the only goal, then the valves can be manual. If the valves are automated and only one chiller is operating, then the other chiller can be automatically bypassed for additional pressure reduction and pump savings. It needs to be determined whether the pump savings will pay for the automatic valves.

Add a VFD chiller

Adding a VFD chiller to a series arrangement offers additional savings. First, it can be the lead chiller when only one chiller is required. During these lighter loads, there is likely to be condenser water relief that the VFD chiller can benefit from. When both chillers are required, the VFD chiller can be the upstream chiller. Assuming the chillers are identical and selected to do the more difficult lead chiller duty, the VFD can slow the upstream chiller down to the appropriate tip speed for the lower lift duty. This will optimize the chiller for the upstream duty.

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Table 4 – Annual Operating Performance For Two Pass Series Variable Primary Flow Chiller Plants At Different Chilled Water Temperature Ranges.

Run	SWT	Range	Min Flow	Chiller PD	Chiller	Pumps	Tower Fan	S.A. Fan	Total
	(°F)	(°F)	(GPM)	(ft)	($/yr)	($/yr)	($/yr)	($/yr)	($/yr)
Series 2 pass	44	10	575	37.8	$ 82,584	$ 24,198	$ 6,907	$ 73,051	$ 186,740
Series 2 pass	44	12	550	36.5	$ 82,104	$ 23,007	$ 6,904	$ 73,025	$ 185,040
Series 2 pass	42	14	475	37.2	$ 88,322	$ 22,296	$ 6,909	$ 73,078	$ 190,605
Series 2 pass	42	16	400	38.9	$ 87,247	$ 21,790	$ 6,907	$ 73,058	$ 189,002
Series 2 pass	42	18	400	31.4	$ 86,470	$ 21,016	$ 6,905	$ 73,036	$ 187,427
Series 2 pass	40	20	300	43.3	$ 96,360	$ 20,799	$ 6,915	$ 73,136	$ 197,210

Conclusion

Variable primary flow systems are coming of age. They cost less to build and operate than traditional primary/secondary systems. In addition, they are less susceptible to low delta T syndrome.

Series chillers in a variable primary flow system resolve the issue of transient flow when a second chiller starts, making the system even easier to design. Switching to series chillers sets the stage for larger chilled water temperature ranges while minimizing the impact on chiller performance. This can actually lower the cost of the chillers, in addition to all the other capital savings that come from lowering the design flow rate.

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