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peanut butter and jelly

Series Chillers and VPF Chiller Plants

Dramatically rising energy costs, water shortages, and emerging carbon footprint concerns all equate to the need for more efficient building operation. Many owners are looking for innovations in HVAC system designs to help meet that need. This newsletter discusses three design concepts and explores how their merger can make the system both more efficient and more reliable.

The Three Concepts

Series Chillers. An early *Engineers Newsletter,* "Control Systems That Save Energy," contained a discussion of parallel versus series chillers. It included an evaluation stating:

> *Instead of piping chillers in parallel so that each must produce the coldest water in the system, they are piped in series. The upstream chiller requires less kW input per ton output, thus improving system efficiency.*

Low Flow Systems. There is growing realization that system parasitic losses can be reduced and efficiency improved by reducing the energy used to *transport* cooling and heating throughout a building. It is unusual to find a cooling system whose *optimal* design flow rates are the ARI standard rating conditions of 2.4 gpm/ton and 3.0 gpm/ton for chilled-water and condenser-water systems, respectively. [1]

Variable Primary Flow (VPF). Enabled by the advances in today's intelligent chiller controls and driven by the promise of significant pump energy savings at a lower first cost, VPF chilled-water systems are currently experiencing explosive growth. [2]

Quantifying the Benefits

Series Chillers and Low Flow. Table 1 provides a comparison of the efficiency advantage of series versus parallel configurations for a two-chiller system.

The chiller selections represent efficiencies for chillers selected for 1.5 gpm/ton chilled-water flow with a 40°F supply temperature. Several points become apparent after studying the data:

- Both the capacity and the efficiency of the chiller pair increase in the series chiller configuration.
- Even at 1.5 gpm/ton, a series chiller system appears to suffer from a prohibitively high chiller pressure drop.

It is this last point that bears further examination. Could it be that the apparent pressure drop penalty is not prohibitive but actually beneficial in a VPF system?

Table 1. Two-chiller system comparison data (1.5 gpm/ton flow @ 40ºF supply water)

Chiller model	System capacity (tons)	Combined chiller efficiency (EER)	Chiller design flow (gpm)	Design PD (ft)	Min flow (gpm)	Flow turn down ratio (design/min.)
Parallel RTAC 200 Hi Eff 2-pass	380	9.8	284	5.1	241	1.2
Parallel RTAC 200 Hi Eff 3-pass	388	9.9	290	17.6	161	1.8
Series RTAC 200 Hi Eff 2-pass	404	10.1	580	37.1	241	2.4
Series RTAC 185 Hi Eff 2-pass	372	10.2	555	40.8	117	4.7

The *ASHRAE GreenGuide* recommends designing with:
12-20°F chilled water ΔT and
12-18°F condenser water ΔT

This equates flow rates of:
1.2 - 2.0 gpm/ton chilled water and
1.6 - 2.3 gpm/ton condenser water

VPF: Flow Considerations. VPF systems save considerable system energy primarily because the flow varies proportionally to the system load. If something were to corrupt this relationship it would adversely impact the expected energy savings. What are some corrupting influences?

Two come to mind. One would be the dreaded "Low Delta T" syndrome. One of the commonly touted advantages of VPF is that chillers can be "overpumped" in VPF systems to prevent the premature operation of additional chillers just to satisfy system flow. This compensates for low delta T from the chiller-sequencing point-of-view. However, the system pumps still expend extra energy moving additional water through the system. VPF cannot compensate for the pumping energy penalty of low delta T.

A second "corrupter" of the system load/flow relationship can be the selected chiller's required minimum flow.

In a VPF system, the pumps must provide enough flow to meet *the greater of* system flow *or* the chiller's minimum flow requirements.

Figure 1 shows the idealized pump flow for a two-chiller VPF system—ignoring the chiller's minimum flow. The pump flow is proportional to the system load under all conditions.

Figure 2 shows the same system's *actual* pump flow (including the chiller's minimum flow) based on chillers with a 2.5:1 flow turndown (TD) ratio.

Figure 3 shows the same system's actual pump flow (including the chiller's minimum flow) but this time based on chillers with a 1.4:1 flow TD ratio.

With this in mind, if we look back at the Table 1 chiller selections, another conclusion becomes evident.

- The extremely low-flow TD ratio for the parallel chillers with 2-pass evaporators in the first row would not work well in a VPF system.

Figure 1. Ideal VPF flow relationship

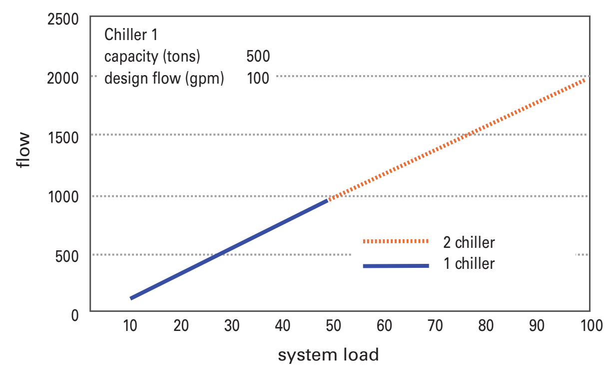


Figure 2. Actual VPF flow relationship: 2.5 TD ratio

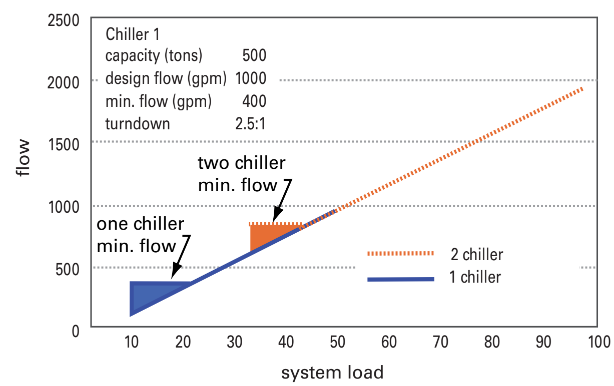
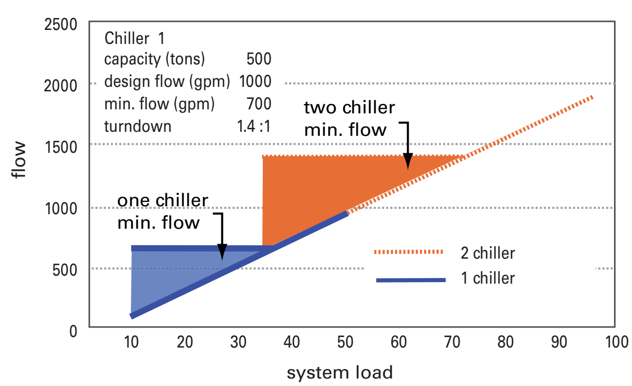


Figure 3. Actual VPF flow relationship: 1.4 TD ratio



However, this might be a perfect selection in a constant-flow system for reduced design pump power.

It's clear: a low turndown ratio significantly impacts VPF pump operation. But is lack of adequate chiller evaporator flow turndown a real concern? It depends on the chiller type, but the general answer is yes and it will only get worse due to the need for more efficient systems.

Manufacturers are being driven to produce more and more efficient chillers to meet code or customer requirements. A common way to improve chiller efficiency is to increase the heat exchanger's surface area—add more tubes to the evaporator and/or condenser. More tubes result in a greater flow area and a lower design fluid velocity. A higher minimum flow is required to maintain sufficient fluid velocity to prevent laminar flow conditions. Laminar operation can lead to unstable chilled-water temperature control that can be hazardous to the chiller.

Additionally, engineers are following industry "best practices" and designing more efficient systems through the use of lower system and chiller design flow rates. Systems at 2.0, 1.7 or even 1.5 gpm/ton are becoming the norm, rather than the exception. While lowering the design flow is good for system efficiency, it reduces the available TD ratio for a given chiller.

Applied centrifugal chillers typically have many heat exchanger options so that an adequate TD ratio can be selected. However, it's becoming common to see packaged chiller selections with very low TD ratios. This can make them difficult to apply in parallel chiller/VPF systems.

Impact

Impact of Low Turndown and Bypass Selection and Control. In addition to the pumping energy impact, a high bypass flow requirement such as shown in Figure 3 (due to a low TD ratio) forces the selection of a relatively large VPF bypass line and control valve.

The required range of control for both flow and pressure makes stable control more challenging. When a second chiller is added, the bypass valve must open quickly at a relatively low system differential pressure to allow sufficient flow to keep the operating chiller above its minimum flow. The same valve must also stably control flow at higher system pressures when only a small amount of bypass is required to keep multiple chillers operating above their minimum flow requirements.

VPF Chiller Requirements. How can a designer ensure that the chillers applied in a VPF have sufficient flow TD to work well in a VPF design? There are several steps that can be taken.

- Evaluate the bypass flow requirement with different chillers running, across the full system load spectrum.
- Include the requirement for a minimum TD ratio as part of the chiller specification.
- Include the requirement to submit chiller minimum and maximum rated flows as a line item in the bid package.
- Don't specify chillers with excessive capacity safety factor.
- Consider applying the chillers in a series configuration.
- Remember that series chiller system flow rate-of-change limitations are set by the chiller's limitations just as in parallel VPF systems.

VPF Flow with Series Chiller. Figure 4 plots the pump flow for the same chillers shown in Figure 3 but in a series configuration. In the series configuration, the chillers have an effective 2.8:1 TD ratio when both chillers are operating. We see that the operating curve looks quite different.

Some bypass flow is still required during periods of very low load when a single chiller is operating. However, all bypass flow is eliminated when two are operating.

System Power for VPF with Series Chillers. In systems with constant flow through the chillers' evaporators, designers often specify maximum acceptable pressure drops. The design flow pressure drop through a pair of chillers in series is likely to be much higher than what is considered acceptable in a parallel system.

Figure 4. Series chiller VPF flow relationship: 1.4 TD ratio

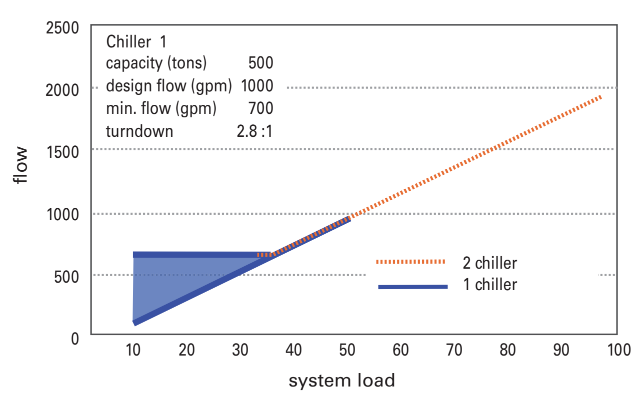


Table 2 compares the system energy use at different load points for the 3-pass chillers in parallel compared to the 2-pass chillers in a series configuration.

Note: These specific 2-pass chillers should not be used in parallel in a VPF system with a 1.5 gpm/ton design flow because of poor flow TD, and the resultant high bypass flow requirement.

This comparison demonstrates that the series chiller configuration has a better system COP at all load points. Even with a 20 ft higher system pressure drop at design load, it uses less energy!

This is a direct result of the chiller's greater combined efficiency as well as the decreased bypass flow at part-load conditions.

Control of Series/VPF Chiller Plants

Some owners and engineers shy away from series chiller plants because they are unsure of the system control requirements. In fact, the only additional series plant control requirement is the reset of the upstream chiller's leaving chilled-water setpoint to equalize chiller loading. The three rules for chiller setpoint are actually quite straightforward.

1. If one chiller is operating, it is given the system setpoint.
2. If both chillers are operating:
   (a) the downstream chiller is given the system setpoint.
   (b) the upstream chiller is given a setpoint that results in each chiller carrying one half the instantaneous load.

The equation for the upstream chiller's setpoint is based on chilled-water return temperature and desired chilled-water supply temperature and calculated simply:

$$CHSP_{up} = CHRT + \left(\frac{CHRT - CHSP_{sys}}{2} \right)$$

The setpoint is periodically recalculated and sent to the chiller. The chiller controls its own loading.

CHSP*up* Upstream chilled-water setpoint

CHRT Actual chilled-water system return temperature

CHSP*sys* Chilled-water system supply setpoint

3. If there is a failure of a chiller or controller, the operating chiller(s) defaults to the system setpoint.

Sequencing *lag chillers* on and off to match the building load can use the identical logic that a parallel VPF system uses. Deviation in system chilled-water supply temperature is a simple and robust way to decide when to add a chiller. Chiller load, as measured by chiller RLA or kW, is a reliable and repeatable indication of the point to subtract a chiller from operation.

When NOT to use series chillers.

Although a series chiller configuration saves energy and makes sense in many cases, there are times when it should not be applied.

1. Systems with design flow rates greater than 1.5 gpm/ton are probably not good candidates because of chiller pressure drop. It's best to start with a high-efficiency low-flow system design to optimize pumping power.
2. The control interaction between chillers with step-loading compressors (multiple scrolls) can result in undesirable compressor cycling. Standard step-loading chillers should not be applied in series.
3. Constant-flow systems are not typically good candidates for series chillers.

Table 2. System energy use comparison

Load	Parallel RTAC 200 3-pass chiller						Series RTAC 200 2-pass chiller						
	Tons	Pumping PD	Pump kW	Chiller kW	Total kW	Sys COP	Tons	Pumping PD	Pump kW	Chiller kW	Total kW	Sys COP	COP Increase %
100	388	70	10	472	482	2.83	404	90	14	482	496	2.87	1.3
90	349	60	8	396	404	3.04	364	76	10	400	411	3.11	2.6
80	310	51	6	326	332	3.29	323	63	8	323	331	3.44	4.4
70	272	43	4	260	264	3.62	283	52	6	265	271	3.67	1.6
60	233	36	3	208	211	3.88	242	43	4	207	211	4.04	4.0
50	194	31	3	160	163	4.19	202	35	3	164	167	4.26	1.9
40	155	27	2	123	124	4.39	162	29	2	121	123	4.62	5.3
30	116	24	1	99	100	4.09	121	25	1	98	99	4.31	5.3
20	78	21	1	85	86	3.18	81	22	1	84	85	3.36	5.7
10	39	20	1	71	72	1.90	40	20	1	70	71	2.01	5.7

See the *Engineers Newsletter* on VPF systems for more details on chiller sequencing. [2]

More Than Two Chillers? Odd numbers of chillers are difficult to deal with in a series configuration. Except for some very low flow process applications, the system pressure drop for three chillers in series becomes untenable. The solution is to resize the chillers so that an even number can be applied.

If a system requires four, six or more chillers, one possible system configuration is series "chiller pairs" situated in parallel as shown in Figure 5.

An alternate, and more versatile, approach of "series plants," shown in Figure 6, should be considered.

A "series-plant" configuration provides several benefits:

- One chiller out of service doesn't affect the operation of other chillers.
- The operation of upstream and downstream chillers can be mix-matched for better flexibility and reliability.

Chiller Bypass Piping. Discussions of series chillers often include the issue of including extra bypass piping around each chiller. An example of such piping is shown in Figure 7.

There are two potential reasons to include chiller bypass piping.

The first is to eliminate a non-operating chiller's pressure drop from a series pair of chillers. However, as shown previously in Table 2, the pumping energy penalty at such part load conditions is minimal. While bypassing a non-operating chiller will provide additional pump savings, the added piping and control complexity may not justify the savings.

Second, including chiller bypass piping with manual isolation valves to enable serviceability may be desired for the following reasons:

- The cooling system in question serves a critical load that cannot tolerate a short-term scheduled shutdown of both chillers in a series pair.
- One chiller must be available for comfort conditioning at all times.

Chiller service external to the refrigeration system may be performed with chilled water flowing through the evaporator heat exchanger. However, the refrigeration system must never be exposed to ambient atmosphere with active chilled-water flow. Moisture can enter the chiller's exposed refrigeration system and rapidly cause corrosion or contamination of hygroscopic oils used with many current refrigerants. Also,

Figure 5. Series chiller pairs

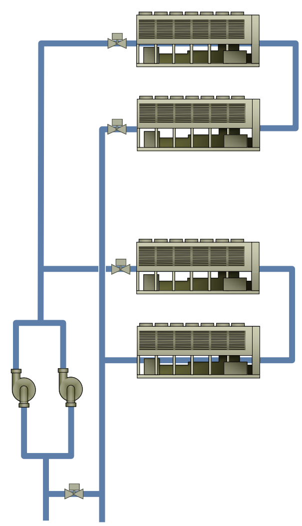


Figure 6. Series plants

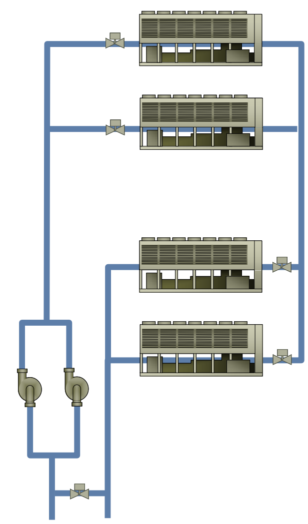
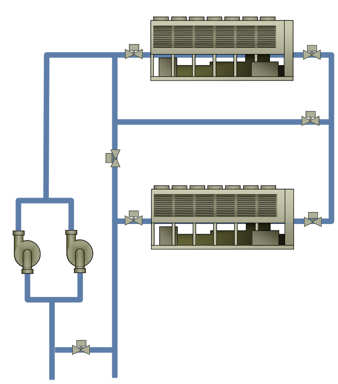


Figure 7. Series chiller pair with service bypass



proper evacuation of a refrigeration system is practically impossible with active chilled-water flow.

Series Unlocks Other System Efficiency Options

There are several energy-saving system options that can work very well in conjunction with a series/VPF system.

Series and "Free" Cooling. Use of cold condenser water, available during periods of low wet-bulb temperatures, to produce chilled water via plate-and-frame heat exchangers or refrigerant migration within a chiller are methods to significantly reduce system energy use.

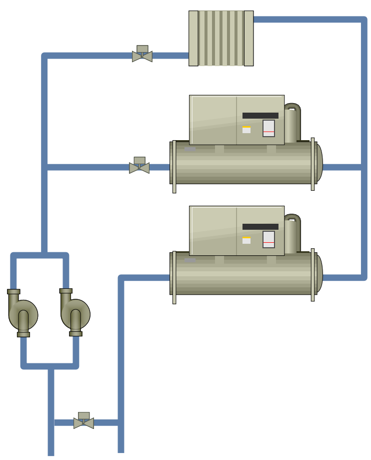
An excellent strategy for applying a refrigerant-migration, free-cooling chiller in a series system is to locate it in the upstream position. See reference [3] for more information.

A free-cooling chiller can provide 30 to 40 percent of its design tonnage, depending on the operating conditions.

When the refrigerant-migration chiller cannot meet the full building load, the downstream chiller can be started to augment the system cooling capacity. This coincident free and mechanical cooling greatly extends the free-cooling operating hours and energy savings. Since the free cooling is provided through an option on a chiller, there is no additional space required in the equipment room and minimal increase in maintenance.

Another free-cooling option is the application of a dedicated free-cooling heat exchanger in parallel with the up-stream chiller as shown in Figure 8. While this option requires additional equipment room space and maintenance, it can be designed for greater free-cooling capacity than a refrigerant-migration chiller can provide. It also may be the only water-side free-cooling option for systems with chiller types that do not offer a

Figure 8 - Free-cooling heat exchanger in upstream position.



free-cooling option. Because of its upstream position, the heat exchanger also provides for coincident free, mechanical cooling, increasing the free-cooling energy savings.

Series and Heat Recovery. A chiller with a dedicated heat-recovery condenser (sometimes called a *double-bundle* condenser) or an additional, properly sized, heat-recovery chiller works very well in a series/VPF plant in the upstream position (see Figure 9). The upstream positioning benefits from the warmest system return-water temperature for more efficient heat-recovery chiller operation.

There is a growing synergy between the application of chiller heat-recovery and high-efficiency heating systems. Condensing boilers require lower heating system water temperatures to achieve their efficiency potential. As a result, heating system design temperatures of 180°F are being replaced with 105°F to 130°F. Many chiller types can provide efficient heat recovery in conjunction with lower heating temperatures.

As with the free-cooling application, it is a simple matter to optimize the system operation by controlling the upstream heat-recovery chiller for optimum operation and allow the downstream chiller to carry any leftover cooling load. [4]

The key to answering the question of whether to apply a chiller with a heat-recovery condenser or a completely separate heat-recovery chiller is a building hourly energy analysis with a program such as Trane TRACE™. Such an energy analysis will reveal if the heating and cooling load magnitude and occurrence are favorable to the application of a double-bundle condenser chiller. Relatively similar loads work well with double-bundle heat-recovery chillers. However, if the

Figure 9. Heat-recovery chiller with double-bundle condensers

Series counterflow.

The natural progression for increasing the efficiency of water-cooled series/VPF systems is configuring the condensers in series as well as the evaporators. This is a concept known as "Series-Counter."

For a detailed analysis of the performance of a series-counterflow chiller plant, see the *ASHRAE Journal* June 2002 article: "Series-Series Counterflow for Central Chilled-Water Plants" by Groenke and Schwedler.

heating load magnitude and occurrence result in the available heating load to the chiller being a small fraction of its cooling capacity, then applying a properly sized, dedicated heat-recovery chiller may likely be a better option.

More to Come...

Peanut butter & jelly,
Bacon & eggs,
Table & chairs,
Series chillers & VPF..

There are many things that naturally complement each other. Many designers and contractors are finding this true of series chillers and variable primary flow when a high-efficiency, chilled-water system is the goal.

The benefits of efficiency and controllability, along with the natural performance enhancing fit of free cooling or heat recovery, is resulting in rapid growth and application of these system concepts.

Systems using series chillers in conjunction with variable primary flow have the following advantages:

- Great fit with "reduced flow" systems as recommended by the *ASHRAE GreenGuide*.
- Significant ability to accommodate reduced flow rates at part load conditions.
- Maximized pump savings due to minimal requirement for bypass flow.
- High efficiency due to the upstream chiller operating at an elevated temperature.
- Simple control and loading of either chiller.
- Ability to apply other energy-saving options such as "free cooling" or heat recovery.

By Lee Cline, application engineer, and Jeanne Harshaw, Trane. You can find this and previous issues of the Engineers Newsletter at www.trane.com/engineersnewsletter. To comment, e-mail us at comfort@trane.com

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Footnotes:

[1] M. Schwedler, 1997. "How Low-Flow Systems Can Help You Give Your Customers What They Want." Engineers Newsletter, volume 26-2.

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[4] M. Schwedler, 2007. "Waterside Heat Recovery." Engineers Newsletter, volume 36-1.

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application manuals are comprehensive reference guides that can increase your working knowledge of commercial HVAC systems. Topics range from component combinations and innovative design concepts to system control strategies, industry issues, and fundamentals. Visit www.trane.com/bookstore.

Chiller System Design and Control 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. (SYS-APM001-EN, May 2009)

Chilled-Water VAV Systems focuses on chilled-water, variable-air-volume (VAV) systems. These systems are used to provide comfort in a wide range of building types and climates. To encourage proper design and application of a chilled-water VAV system, this guide discusses the advantages and drawbacks of the system, reviews the various components that make up the system, proposes solutions to common design challenges, explores several system variations, and discusses system-level control.(SYS-APM008-EN, August 2009)

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