Trane Engineering News

Chiller Plant Case Study: Variable-Primary Flow Series Chillers with Free Cooling

The challenges of producing chilled water are not the same as those a decade ago. Today, protecting the environment and preserving resources play an important role in the design, construction and operation of a chiller plant.

The advancement in technology for HVAC controls applied to chilled-water production now make it possible to reduce the environmental impact and operating costs.

This white paper compares the advantages of designing a series configuration using variable-primary flow (VPF), free cooling and efficient sequence of operation through a comparison with a high-efficiency decoupled system.

Four basic design principles

When designing an efficient chiller plant there are four basic design principles to consider to achieve and sustain the highest efficiency possible.

Choose efficient equipment and components. The chillers are the biggest consumers in the chiller plant but other equipment such as pumps, cooling towers, dry coolers, fans and motors should also be considered. All components should be selected for stand-alone as well as *system* efficiency. Select chillers that are efficient at both full and partial loads and pumps and motors that have high efficiency at all operating conditions.

Employ efficient system design practices. Using an appropriate plant design is essential for achieving energy savings.

Combining plant configurations such as variable primary flow (VPF) and/or series water flow with specific technologies such as free-cooling or heat recovery can result in significant energy savings when applied and controlled properly.

State-of-the-art design of the chiller plant control system. Chiller plant designs that employ sophisticated energy-saving strategies can be inefficient if not controlled and operated properly. To ensure sustainable system efficiency in these cases, it's crucial to have a well-designed chiller plant control system that includes proper system instrumentation and reporting capability to realize the potential savings.

Proper system commissioning and operation. A formal commissioning process which tests the equipment and the plant under the different modes of operation is required to verify and maintain the performance of the chiller plant. In addition, periodic maintenance of system components helps maintain high system efficiency.

With these basic design considerations in mind let's move into our comparison systems to demonstrate a high-efficiency design that leverages control technology advancements to achieve a high-performing chiller plant.

Base hydraulic system: Decoupled system with high-seasonal efficiency (HSE) chillers

Our base "decoupled" system (Figure 1) uses common traditional design concepts—constant water flow through each chiller evaporator and variable water flow to the distribution side.

As implemented this design includes:

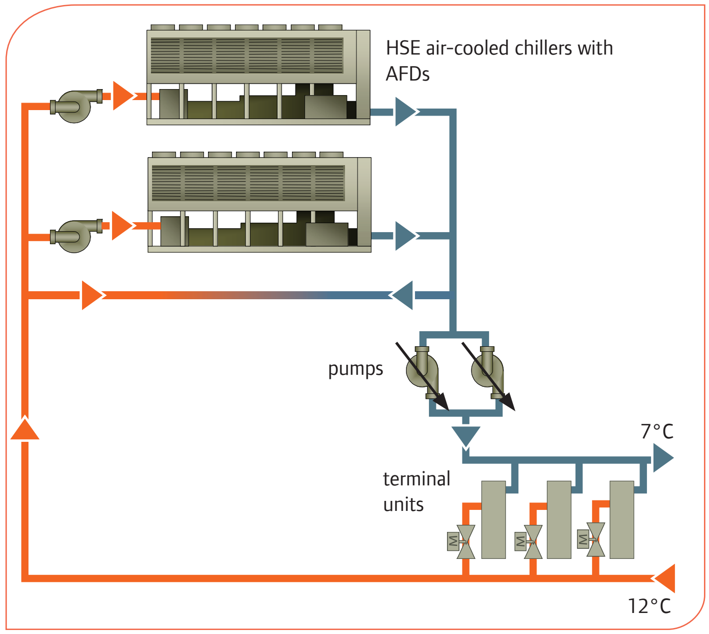
- A constant-speed (essentially constant-volume) pump and check valve for each chiller
- A variable-flow distribution pump system to serve the terminal units (speed and pressure modulation is usually accomplished by providing the pump with a variable-frequency drive)
- Two-way control valves to regulate the amount of chilled water that flows through the cooling coils of the terminal units and therefore the whole distribution system (e.g. fan coil unit, air-handling unit, etc.)
- A bypass to hydraulically decouple the primary (production) and secondary (distribution) sides of the system—water can flow in either direction, as needed to balance the system
- Commonly used chiller-water temperatures of 12 to 7°C are assumed for this system

As the two-way valves adjust the chilled-water flow through the coils to satisfy the existing load, the distribution pump speed responds to maintain required dynamic water pressure.

State-of-the art system: VPF series HSE chillers with free cooling on the upstream chiller

We'll compare this base decoupled system with a high-efficiency system that incorporates the following design strategies. These strategies are complementary when presented in the same plant.

Figure 1. Base chilled-water system



Integrated free-cooling, air-cooled chiller. A method of "free" cooling is to transfer heat between the chilled water and the outside air through the use of additional water coils within the air-cooled chiller.

When the outside air temperature is colder than the desired chilled-water temperature, the compressors are turned off and an automatic isolation valve inside the unit is opened. This allows the chilled water to flow through the water coils and be cooled by the outdoor air. If the outdoor air temperature drops below freezing conditions anti-freeze may be required.

Low Flow Systems. The ASHRAE GreenGuide recommends reducing system design flow rates and increasing system delta T compared to past design practices. Efficiency is improved by reducing the pump energy used to transport cooling (and heating) throughout a building. It has become more common to find cooling systems with optimized design flow rates and delta Ts for chilled water. (e.g. 15-5°C versus the traditional 12-7°C).

Series Chillers. The concept of series chillers is not new. Early Trane *Engineer's Newsletters* and application manuals discuss parallel versus series chillers. [1] [2]

A significant advantage of this configuration is that when chillers are piped in series, the upstream chiller's leaving-water temperature is higher, reducing the lift and work the upstream chiller requires resulting in less kW input per kW cooling output.

A higher return temperature is also beneficial to the free-cooling operation because the system will operate for a longer period in this mode and thus improve the total system efficiency. The series configuration also greatly simplifies sequencing in a VPF system, since there is no flow rate change when transitioning from one chiller to two chillers.

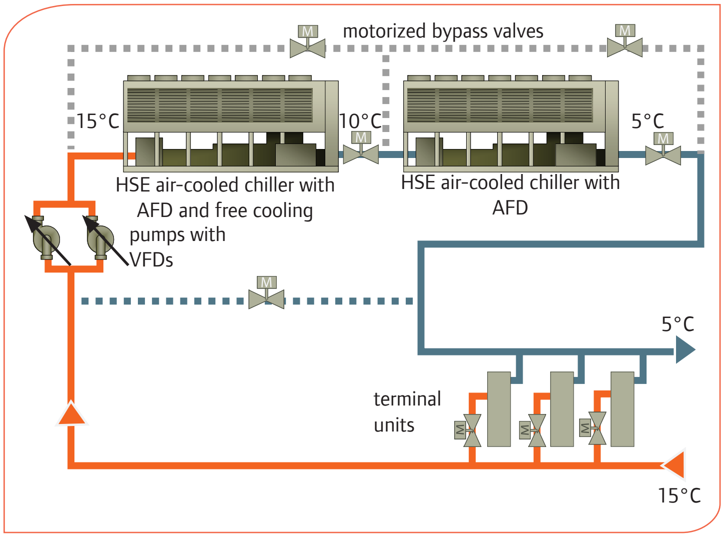
Variable Primary Flow (VPF). VPF designs use fewer pumps and piping connections than the traditional primary-secondary systems.

Again, this is not a new concept, but is enhanced by new advanced chiller controls and driven by the promise of pump energy savings at a lower installation cost. With a reduced footprint for the chiller plant and fewer components and electrical connections, VPF chilled-water systems are currently experiencing growing interest for new installations and renovation projects.

Combining concepts

Our state-of-the-art VPF system (Figure 2) incorporates these four concepts. The water flow varies throughout the entire system—that is, through the evaporator of each operating chiller as well as through the cooling coils.

Figure 2. State-of-the-art, VPF system with high seasonal efficiency (HSE) chillers and free-cooling upstream of chiller



Two-way control valves, isolation valves (for optional bypass), and a minimum chiller flow bypass are required to implement a VPF system. However:

- Variable-flow capable chillers eliminate the need for separate chiller pumps. This reduces the system installed cost and space required.
- The bypass can be positioned either upstream or downstream of the cooling coils.
- The control valve in the bypass is modulated to ensure that the amount of flow that returns to the operating chiller(s) never falls below the manufacturer-recommended minimum limit.
- An optional set of chiller bypass pipes and shutoff valves have been added to the plant to reduce the pump power when only one chiller is enabled. They are not required as the chiller's pressure drop falls to the square power of the VPF flow reduction. They also allow one chiller to operate while the other chiller is serviced and provides the same level of redundancy compared to the parallel configuration.

State-of-the art design considerations.[3]

The following discussion summarizes a few key considerations when desiging a VPF system.

Chiller selection. Chillers must be able to provide acceptable temperature control with a change of flow of at least 30 percent per minute, and remain operating, uninterrupted, with a change of 50 percent per minute is even better.

Chillers need to be selected with adequate flow turndown—that is the ratio of design to minimum flow rates. Ideally, the turndown ratio should be at least 2:1. It's important that the minimum and maximum flows must never be violated.

Plant configuration and accessories. Correctly size the bypass line and the modulating bypass valve. Oversizing will result in unstable operation. Select flow-sensing devices that provide precise, repeatable measurements at the minimum flow control point.

Impacts on terminal units and AHUs. Cooling coil selections require careful attention to ensure they are selected with the same delta Ts and flow as the chillers. Select slow-acting valves to control the chilled-water coils and ensure the valves are selected to give proper flow at all conditions. To minimize flow variations use more than one air handler and stagger their start/stop times.

Control of series/VPF with free-cooling chiller plants. In a *parallel* VPF system, varying the water-flow rate through the chiller evaporator poses two control challenges:

1. Maintain the chiller flow rate between the minimum and maximum limits of the evaporator.
2. Manage transient flows without compromising stable operation.

Since there is no flow rate transition when the second chiller is enabled, in a VPF series configuration, system control is much easier.

Integrated free-cooling requires the implementation of additional intelligent controls to reduce the plant energy consumption.

Implementing specific control sequences are essential to improve the efficiency of the plant. Examples sequences include:

- optimizing the chilled-water setpoint of the upstream chiller when both units are operating,
- applying chilled-water reset, particularly during free cooling,
- operating the most efficient chiller according to the building demand and outside conditions, and
- bypassing the evaporator of a chiller not called for in the sequence.

These specific sequences improve chiller performance, extend the free-cooling operation mode, decrease pumping energy and improve the overall efficiency of the plant.

It's also important that the control system **measure** and **trend log** the energy use of the chiller plant components and **calculate** the overall system efficiency.

Ultimately, this data can be analyzed and used to draw conclusions on how to improve chiller plant operation.

Quantifying the Benefits

One benefit of configuring chiller evaporators in series with a large delta T, is lower overall plant energy use.

Series chillers. The upstream chiller operates more efficiently since it need only cool the water from 15°C to 10°C, resulting in less total chiller power. This is partially offset by the downstream chiller operating at a colder leaving-water temperature.

Variable primary flow (VPF). When both chillers are enabled, the system water flow is pumped through both chiller evaporators; the incremental pump power is higher compared to systems with the chillers in parallel at full load and full flow. But the total power for both chillers plus pumping power is still lower with the chillers configured in series versus the chillers in parallel. Also at lower load conditions the flow rate is lower, evaporator pressure drop is reduced by the square of the flow rate reduction. The resulting system pump energy nears that of a traditional decoupled system.

In addition, because bypass pipes and shutoff valves can be added to the plant to reduce pump power when only one chiller is enabled, the series pump pressure may only exceed that of the parallel configuration when both chillers are operating. This strategy adds complexity because there is now a flow transition when the second chiller is enabled. An additional benefit of the bypass is that it allows one chiller to operate while the other chiller is isolated for service.

Free cooling and higher return temperature. Piping the free-cooling chiller in the upstream position allows the integrated free-cooling chiller to be preferentially loaded during the free-cooling period, since it receives the warmest return water temperature.

In addition, the higher return temperature (compared to a parallel arrangement) along with supply chilled-water temperature reset results in more hours of free-cooling economizing.

A plant load simulation, using Trane Chiller Plant Analyzer (TCPA), was created for a typical office building equipped with the following (Figure 3):

- two chillers, 500 kW each,
- 500 terminal units and
- two AHUs for managing fresh air
- base load: 200 kW (24-hour operation)
- peak load: 1.000 kW at 35°C outside air temperature during the weekly hours of operation (from 06:00 to 21:00).

Figure 3. Load profile versus outside air temperature

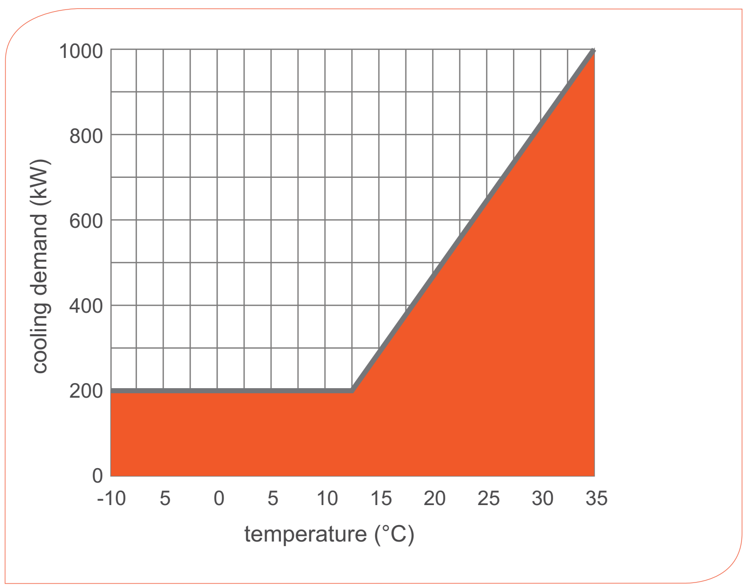
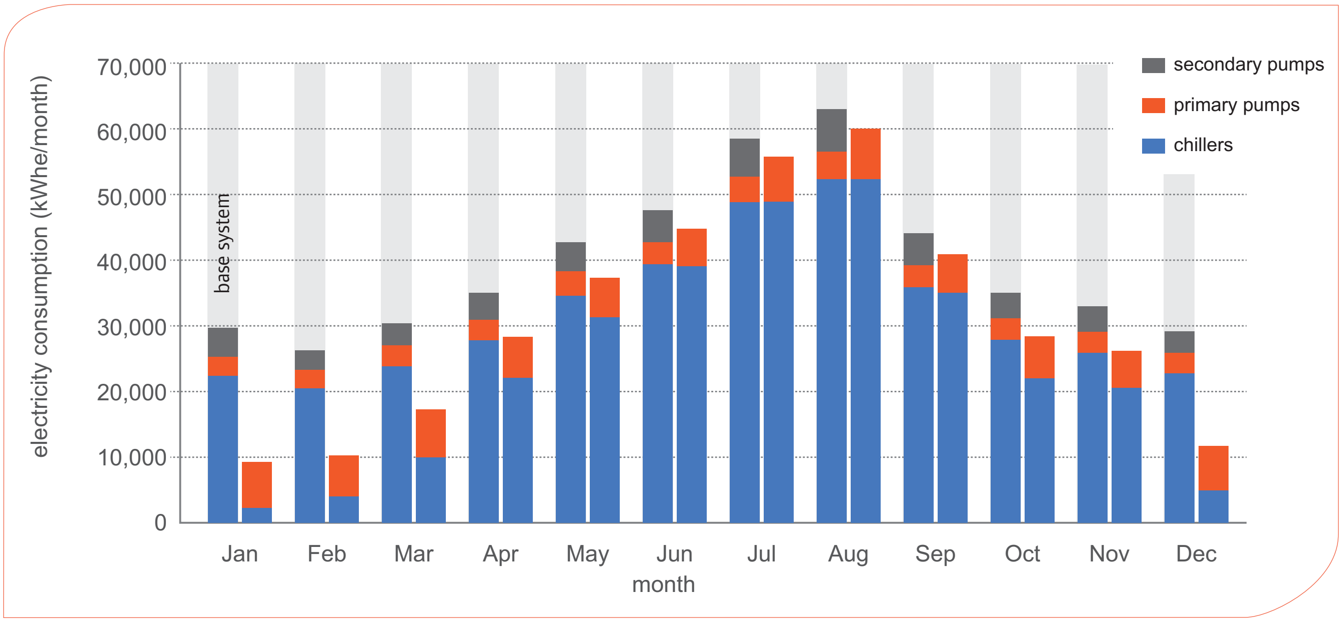


Figure 4. Electrical consumption profile comparison of base decoupled system versus VPF series with free cooling (Paris, France)



Figures 4 illustrates annual electrical consumption profiles for our comparison systems using the weather profile for Paris, France.

Various locations throughout Europe were analyzed (Table 1). Cost savings for the VPF series with free cooling were estimated to result in savings between approximately 5.200 - 9.500 €/year based on an electricity price of 0.10 €/kWh.

Installed Cost. The cost of the equipment (chillers, free-cooling option, terminal units and AHUs) was based on a quote from a manufacturer's representative.

The installation, piping, insulation and valves costs would be specific to each individual installation.

The cost is based on the assumptions that piping for the plant and throughout the building would be designed for a low flow system for a building located in France.

The first cost of the VPF series with free-cooling system was estimated to 4.000 € (over the cost of a parallel, decoupled system) based on material and installation cost estimates shown in the Table 2. Costs will vary depending on local labor and component costs.

Table 1. Expected annual electrical consumption comparison for both systems in various European locations

	FR-Paris	GB-Manchester	CZ-Prague	DE-Frankfurt	ES-Madrid	IT-Milano	PL-Warsaw
Decoupled							
Chillers (kWh/year)	385.210	351.629	380.626	390.288	493.465	438.816	373.327
Primary pumps (kWh/year)	39.579	41.437	40.957	39.703	40.177	41.728	40.758
Secondary pumps (kWh/year)	53.896	50.970	53.719	54.278	61.949	58.928	52.846
Total (kWh/year)	**478.685**	**444.036**	**475.302**	**484.270**	**595.591**	**539.472**	**466.931**
Series VPF with free-cooling							
Chillers (kWh/year)	321.320	279.207	288.758	309.395	459.741	373.536	267.546
Primary pumps (kWh/year)	90.444	99.821	100.184	96.097	83.555	92.806	103.406
Total (kWh/year)	**411.764**	**379.028**	**388.942**	**405.492**	**543.295**	**466.342**	**370.953**
Savings (KWh/year)	**66.921**	**65.008**	**86.360**	**78.778**	**52.296**	**73.130**	**95.978**

Table 2. First cost investment for VPF series with free cooling			
Cost increases	unit cost (€)	quantity	total cost (€)
Impact on the design of the terminal units (cooling coils)	40	500	20.000
Impact on the design of the AHUs (cooling coils)	500	2	1.000
Chiller free-cooling option	17.000	1	17.000
Total investment			**38.000**
Cost reductions			
Impact on chiller plant room piping and accessories (pumps, valves, wiring, concrete, etc.)	19.000	1	19.000
Impact of building piping (pipes, valves, insulation, support, etc.)	15.000	1	15.000
Total savings			**34.000**
Final investment (Total investement-total saving)			**4.000**

Estimated Payback. Based on the annual energy savings (between 5.500 and 9.500 €/year) and the 4.000 € incremental installed cost of the VPF series with FC system, the simple payback for the system is less than 1 year in all locations.

Use of the concept in other systems. It is expected that it would also be energy efficient in other types of applications such as buildings with AHUs and chilled beams—due to the presence of high-return chilled-water temperatures from the beams.

It's also expected to be cost-effective in industrial applications with high temperature processes, where relatively warm central chilled-water cooling is used.

Other free-cooling strategies may be more efficient and may result in greater savings in similar applications. This case study should not be interpreted as recommending one free-cooling configuration over another but rather a strategy that may be considered in specific cases.

Conclusion

The analysis presented showed that the VPF series with free-cooling chilled-water system configuration provides a cost-effective way to save energy in office applications with low base load (10-20 percent of the maximum demand).

In addition, this system configuration is simpler to operate since there are no flow rate transitions during chiller sequencing, and it has the versatility to respond to many different load profiles.

One important question remains.

Would this solution be as interesting for an application without a base load?

There is no single answer and only a more detailed study can validate the relevance of this solution. But in the vast majority of cases, a VPF series configuration brings significant savings and advantages over a conventional parallel piped system.

References

[1] S. Hanson and M. Schwedler, 2011. "Multiple-Chiller-System Design and Control", Trane application manual SYS-APM001-EN

[2] L. Cline, 2009. "Series Chillers and VPF Chiller Plants." Engineers Newsletter, volume 38-3.

[3] M. Schwedler and B. Bradley, 2002. "The Saga Continues: Variable-Primary-Flow Systems Revisited," Engineers Newsletter, volume 31-4.

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