Large-Capacity, Water-to-Water Heat Pumps For Centralized Plants

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A large-capacity (≥1,500 MBH [440 kW]) water-to-water heat pump (WTWHP) is a water-cooled chiller that has been adapted to produce hot water at a specified temperature. Heat is extracted from one low-temperature water flow, and its temperature is raised to a level that is useful, before being transferred to a second water flow.[1] It consists of evaporator and condenser shells, a compressor, and an expansion device. Unlike residential and light-commercial heat pumps, it does not contain a reversing valve.

The WTWHP has recently become more popular due to its economic and environmental benefits, including: higher efficiency than hot-water boilers; attractive payback periods; reduced quantity of makeup water for cooling towers and boilers; and reduced greenhouse gas emissions.

This article provides guidelines for building owners and designers interested in applying large-capacity WTWHPs in their facilities. This article does not contain an economic analysis of WTWHPs. That topic can be found in a previous *ASHRAE Journal* article by Hubbard.[2]

Selections and Economics

As a starting point, it is important to consider factors that can impact the selection of large water-to-water heat pumps.

Hot-water temperature. The maximum leaving hot-water temperature (LHWT) of a given heat pump is typically limited by the design working pressure of the unit for a given refrigerant. Sufficient cooling for the compressor motor can also be a limiting factor. The manufacturer should ensure that the unit will operate reliably at the selected conditions.

While higher LHWTs reduce the size of the airside heat-exchange equipment (coils), the operating cost, and possibly the capital cost, of the heat pump will increase. For each application, the best balance between airside and waterside capital costs will differ. For the highest efficiency, use the lowest possible LHWT.

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The difference between the LHWT and the leaving chilled-water temperature (LCHWT) is an indication of the pressure difference, or lift, against which the compressor must work. For centrifugal heat pumps, each stage of compression can provide about 70°F (40°C) of lift. A single-stage centrifugal heat pump is sometimes called a "low-lift" unit, while a centrifugal heat pump with two or more stages is referred to as a "high-lift" unit. Scroll and screw heat pumps can provide about 85°F to 150°F (47°C to 83°C) of lift.

Fouling. Water chillers are normally designed for waterside fouling factors of 0.00010 and 0.00025 ft^2·hr·°F/Btu in the evaporator and condenser, respectively, assuming the condenser operates in an open cooling-tower loop. In a heat pump, however, the condenser loop is normally closed, while the evaporator loop may be closed or open. Therefore, 0.00010 fouling should be used for the heating loop, and the evaporator should be assigned an appropriate factor, based on the water quality.

Turndown. Because heat pumps operate at essentially constant lift (the entering chilled-water temperature and LHWT remain relatively constant), the turndown (available load reduction) can be significantly less than the turndown for water chillers. This is especially true for centrifugal compressors, where minimum capacity may be only 40% to 50% of the design heating load, before the refrigerant flow may become unstable; this is known as "surge." Surge is not an issue for positive-displacement compressors; therefore, single-compressor screw heat pumps are able to unload to a minimum capacity of 25% to 35% of the design heating load. Scroll and screw heat pumps that use multiple compressors offer greater turndown capabilities.

Sizing. It is vitally important to remember that a heat pump condenser must always be able to fully reject the heat absorbed in the evaporator, plus the compressor work. *For this reason, a heat pump should never be oversized for the load.* If the facility's heating requirement is insufficient to accept the minimum heat output of a given heat pump, the temperature in the hot-water loop will rise uncontrollably until the heat pump shuts down.

In heating-only applications, the sizing of the heat pump is relatively simple: if the heat source is not a limiting factor, the heat pump can be sized for the maximum heating requirement.

In simultaneous heating-and-cooling applications, the sizing of the heat pump requires greater analysis. Consider a facility with year-round heating and cooling requirements. The heating load may include reheat, domestic hot water and other heating requirements. *Figure 1* shows the load profiles, plus the curve for the heat rejection from the cooling load (which is the sum of the cooling load and the compressor work).

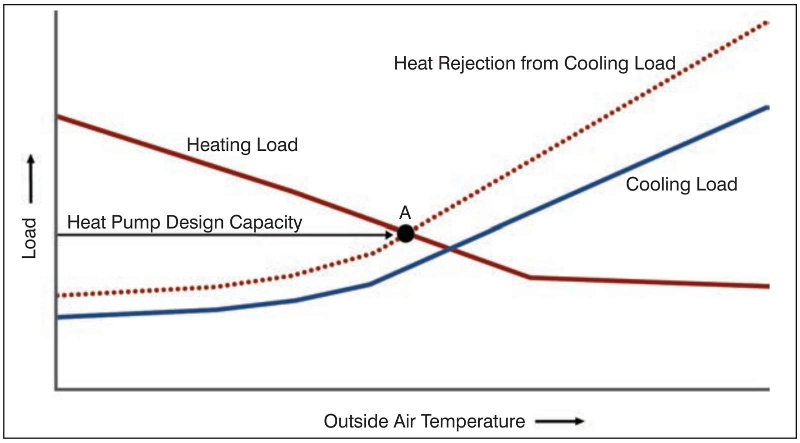

Figure 1: Selection point for simultaneous heating-and-cooling heat pump.

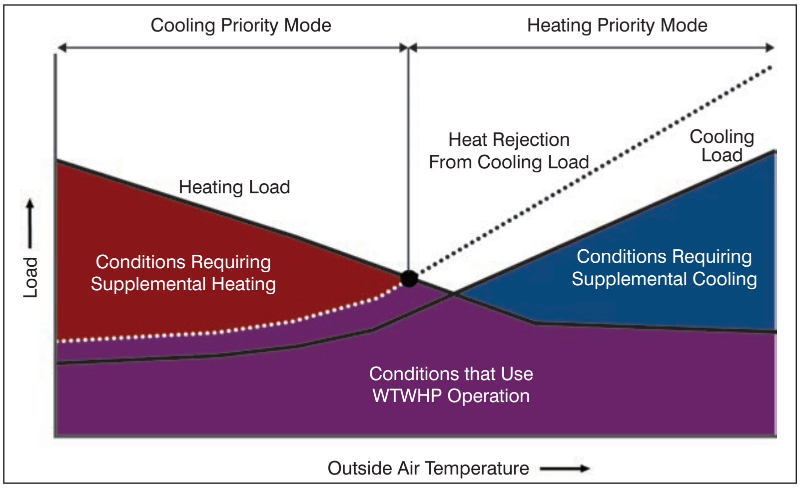

Figure 2: Operating areas for simultaneous heating-and-cooling heat pump.

Pumps and energy-delivery mechanisms. The energy performance of the system pumps and energy-delivery mechanisms (i.e., air-handling units) will impact the system COP. However, because there are an infinite variety of pumping and energy-delivery mechanisms, their impact is not covered in this article. Nor does the article attempt to analyze the impact of the central plant design on the efficiency of the overall system.

Remember, when sizing heat pumps for simultaneous heating and cooling, the heating output is never independent of the cooling requirement. In this example, one cannot select a heat pump to cover the entire heat requirement because the coincident cooling requirement (the heat source) is not sufficient to support it. Following this logic, the proper size of the heat pump is at the cross-over point of the curves for the heating load and the heat rejection from the cooling load (Point A in *Figure 1*).

A heat pump sized at this point will result in a unit, which will provide a portion of the total heating and cooling requirements of the building. It cannot completely replace the cooling or heating equipment in the building, but it can replace a portion of it in a highly efficient manner, as shown in *Figure 2*.[3]

At this point, the designer should decide how many heat pumps to use. There is no single correct answer. Some of the factors requiring analysis include: size of peak load vs. size of heat pumps available, number of hours that will be spent at low loads, energy costs, and installed costs for the heat pumps.

Since a heat pump can control either the LHWT or the LCHWT—but not both simultaneously—the machine will, by necessity, operate in either heating priority mode or cooling priority mode.

• In heating priority mode, the heat pump is controlled in response to the heating load, and the LHWT is the controlled parameter. If evaporator water flow is constant, the LCHWT will vary, based on the amount of heat removed from the evaporator.

• In cooling priority mode, the heat pump is controlled in response to the cooling load, and the LCHWT is the controlled parameter. If condenser water flow is constant, the LHWT will vary, based on the amount of heat rejected to the condenser. This is also known as heat reclaim mode.

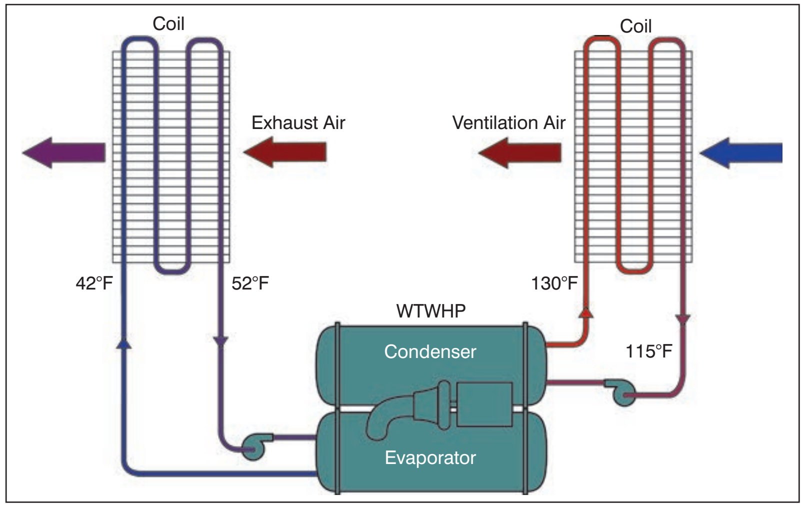

Figure 3: Heat pump system for exhaust air heat recovery.

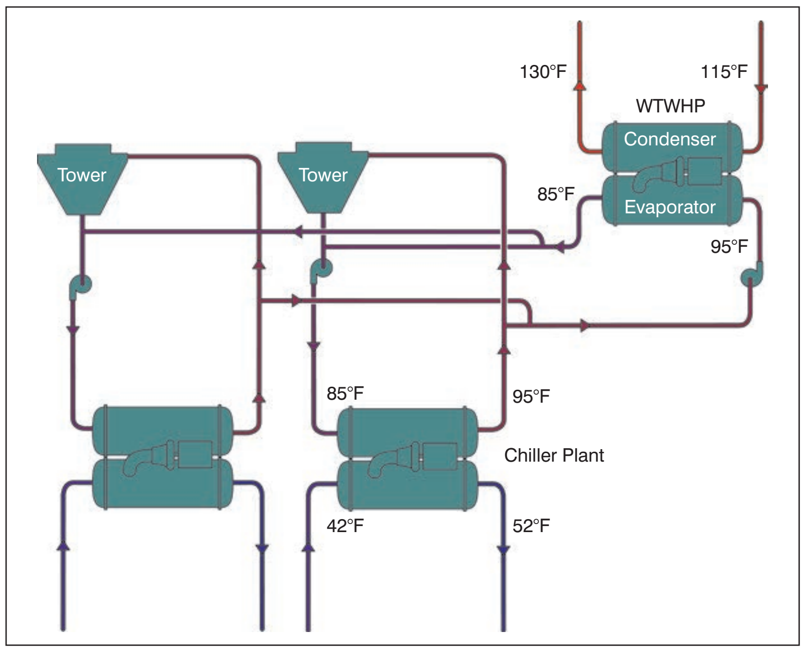

Figure 4: Tower water as heat source.

Heating-Only Mode

To aid in the understanding of heat pump system configurations, it is helpful to start with simpler heating-only systems before discussing the more complicated simultaneous heating-and-cooling systems.

Exhaust air heat recovery. Heat pumps have been used to replace or enhance "runaround" loops by extracting heat from building exhaust air and using it to warm incoming makeup air. If space exists, this system is relatively easy to add to an existing installation. *Figure 3* illustrates a typical installation.[4]

Tower water as a heat source. A heat pump can use cooling-tower water from chillers or other equipment as its heat source, as shown in *Figure 4*. If space exists, this arrangement can be a useful add-on to an existing installation.[5] Because the temperature of the heat-source water is relatively high, a low-lift heat pump is usually sufficient for this application.

Here are some application considerations for this system:

• Because the heat pump evaporator is connected to the open cooling-tower circuit, its fouling factor will need to be raised to an appropriate value.

• To maintain a consistent LHWT, the tower-water temperature must be artificially held at an elevated temperature, which penalizes the chillers' efficiency whenever the potential for lower tower water temperature exists. An option to avoid penalizing the chillers' performance is to design the heat pump for the lowest tower-water temperature that the chiller plant can use (say, 55°F [13°C]).

• Another option to avoid penalizing the chillers' performance is to consider connecting the heat pump to only one of the tower circuits.

• Another configuration for this system, which can reduce piping costs and increase efficiency, is to replace the low-lift heat pump and one of the water chillers with a high-lift heat pump that can provide both the cooling and the heating. This arrangement offers several advantages.

a. Two heat exchangers (the chiller condenser and the heat pump evaporator) and associated piping are eliminated, as are the pumping costs for both circuits.

b. The losses introduced by temperature approaches and fouling in these two heat exchangers are eliminated, which reduces lift and improves efficiency.

c. If the high-lift heat pump incorporates an interstage economizer, the overall cycle efficiency will be further increased.

d. The high-lift heat pump can reduce the required cooling tower capacity, and likely has a smaller footprint than the two units it replaces.

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Simultaneous Heating and Cooling

Simultaneous heating and cooling systems are more complicated, but offer higher COPs, which makes them worth considering.

Geothermal heating and cooling. Because the Earth's mass can be used as both a heat source and a heat sink, a geothermal system can provide simultaneous heating-and-cooling. *Figure 5* illustrates the system design.

When the facility requires heating, valves V1 and V2 connect the heat pump to the well field, while valves V3 and V4 connect the heat pump to the hot-water system. The evaporator water picks up heat from the well field and uses it to heat the hot water in the condenser, as illustrated in *Figure 5*. If the well field is of sufficient size, the heat pump can be sized to handle the entire heating requirement; it is not dependent on a simultaneous cooling load.

When the facility requires cooling (not illustrated), valves V1 and V2 connect the heat pump to the chilled water system, while valves V3 and V4 connect the heat pump to the well field. The evaporator water picks up heat from the facility and rejects it to the well field via the condenser water. Rejecting large quantities of heat to the well field can cause operational difficulties. Instead, there may be uses within the facility for the low-temperature hot water.

There will be times when both heating and cooling are needed. The heat pump can handle both functions simultaneously, and the well field can provide any additional heat supply that is not available from the cooling load, or heat rejection that the heating load cannot handle.

In this system, the cost of the well field increases the capital investment in the system. However, the conventional chillers and boilers can be eliminated, and the high COP of the heat pump generally leads to a reasonable payback.[6]

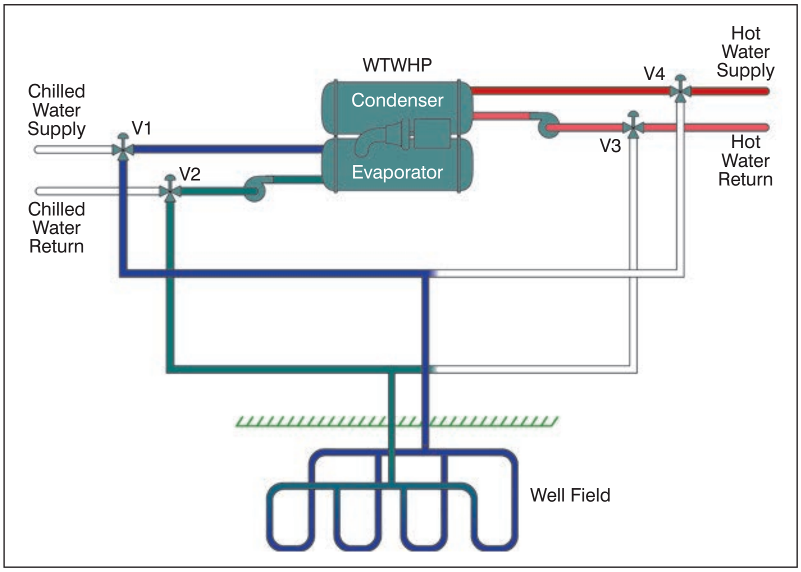

Figure 5: Geothermal system for simultaneous heating and cooling, operating in heating-only mode.

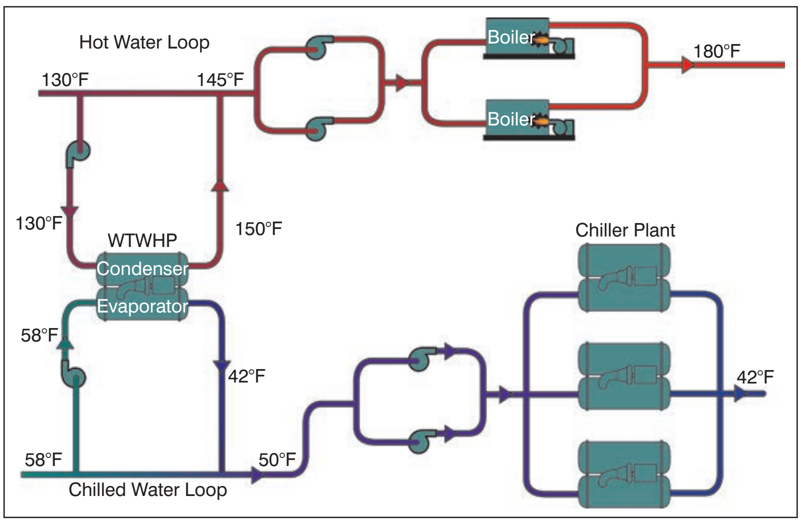

Figure 6: Side-stream arrangement.

Heat pump side-stream to chiller plant. *Figure 6* illustrates the most common piping arrangement for a simultaneous heating-and-cooling system. In this system, standard water chillers are used to supply chilled water to the building or process.

A portion of the return chilled water flows through the evaporator of the high-lift heat pump, where heat is extracted, and the chilled water leaves at a lower temperature. The heat absorbed from the chilled water, along with the compressor work, is transferred to the condenser, where the combined heat is rejected to the heating loop.

If necessary, the hot-water temperature can be boosted by the boilers. The heat pump reduces the loads on both the chillers and boilers. Although the boilers are still providing some of the water heating, producing some of the heat with the high-COP heat pump is much more efficient than producing all the heat using the boilers.

This system offers several advantages when compared to a system that uses cooling-tower water as the heat source. The heat pump can increase plant chilled water capacity, satisfy redundancy requirements, and reduce the required cooling tower capacity.

Heat pump parallel to chiller plant. This type of installation (not illustrated) is less common, but can be very useful if the cooling load is small enough that the heat pump is capable of handling all or most of it. The small cooling load is insufficient to sustain the total heating requirement, and a boiler must be used to supplement heating. All heat obtained from the chilled-water loop is transferred to the hot water, and beneficially used. However, the LHWT cannot be controlled by the machine while operating in the cooling priority mode, because the cooling load will vary, causing the heat production to vary.

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LHWT and/or LCHWT can be maintained if variable primary water flow is used on the water loop(s). For instance, when the heat pump maintains a constant LHWT, the chilled water flow can be varied to maintain a desired LCHWT.

Hybrid side-stream/parallel system. The most versatile system for simultaneous heating-and-cooling is one in which the heat pump can be used in either heating priority or cooling priority mode, depending on the specific requirements. It is generally applied in comfort applications, where seasonal changes dictate a swing in loads. This system, although more complicated hydronically, makes greatest use of the heat pump for both heating and cooling (*Figure 7*).

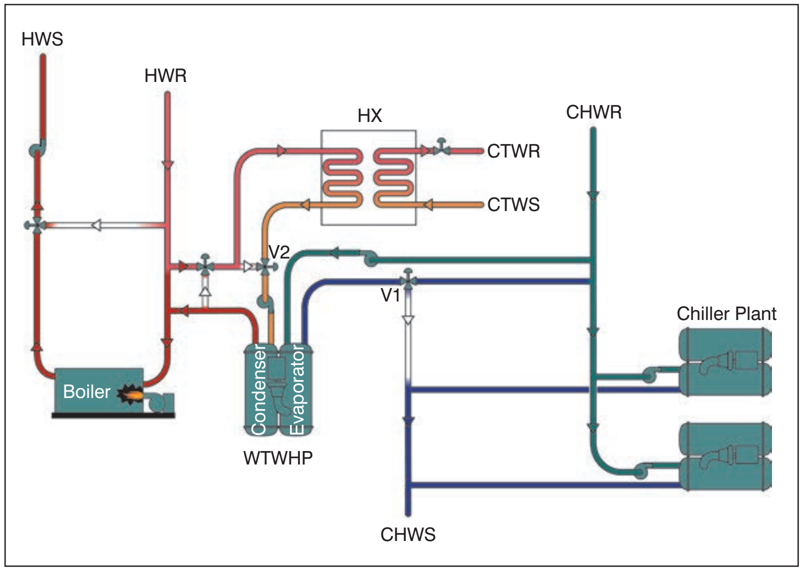

Figure 7: Hybrid side-stream/parallel system, operating in side-stream arrangement.

In warmer months, when the cooling load dominates, the side-stream arrangement is used (valve V1 allows the chilled water from the heat pump to flow into the CHWR pipe) and the heat pump runs in heating priority, since it is able to meet the entire heating requirement. In doing so, it also provides some cooling, reducing the load on the water chillers downstream.

In cooler months, when the heating load dominates, the parallel arrangement is used (valve V1 allows the chilled water from the heat pump to flow into the CHWS pipe) and the

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heat pump must run in cooling priority, since it cannot extract enough heat to satisfy the heating load.

Note that an optional "dump" heat exchanger (HX) can be installed, to serve two functions. First, it allows use of the heat pump as a standard water chiller, which may satisfy a redundancy requirement. Valve V2 can be positioned to direct the condenser water to the HX, and the heat exchanger can reject all condenser heat to a cooling tower if there is no requirement for heat in the building.

Second, in a case where the minimum building load is less than the heat pump's minimum operating point, it permits the surplus heat to be sent to the cooling tower, by diverting some of the condenser water flow. This provides a means to keep the heat pump on-line during periods of light load and, although some heat is wasted, it is still far more efficient than operating a boiler.

This second reason is why all heat pump applications should be examined carefully for the coincidence of loads. Even at low cooling loads, the compressor will produce heat, which must be rejected somewhere. If the heating requirement is insufficient, the LHWT will rise uncontrollably until the heat pump shuts down. In this situation, the heat pump system may require a dump heat exchanger.

Control System Guidelines

Heating-only applications. When a heat pump is used to produce only heat, with no beneficial cooling, the control system is rather simple. The minimum temperature of the heat source (ground water, sea water, process fluid, etc.) is treated as a constant supply entering the evaporator, and the hot-water requirement determines the amount of heat extracted.

Simultaneous heating and cooling applications. Control of simultaneous heating-and-cooling installations is more complex than conventional HVAC systems. The equipment controls for heat pump must be capable of switching between heating priority and cooling priority modes, while controlling the load(s) in response to the system requirements.

Regardless of the system arrangement, there will always be design setpoints for the LHWT and LCHWT, even if the chilled water is not produced for beneficial use. The control system must honor both of these setpoint limits, so as to confine the operation within the operating envelope of the heat pump.

When the cooling load dominates, the heat pump runs in heating priority mode, since there is always enough evaporator heat available to satisfy the LHWT setpoint. The heat pump cannot be able to handle the entire cooling load, so additional cooling equipment is required. If the cooling load decreases to the point where heating load dominates, the heat pump switches to cooling priority mode and the LCHWT becomes the controlled parameter. The heat pump cannot handle the entire heating load, so additional heating equipment is required. The reverse scenario takes place if the cooling load increases and again becomes dominate.

Because this switchover could occur multiple times during a day, it is advantageous if the heat pump can handle the operating mode switch automatically.

In addition to the controls onboard the heat pump, the building system controls may also be more sophisticated, to communicate with the heat pump and other equipment (pumps, valves, etc.).

Summary

Large-capacity, water-to-water heat pumps offer a number of desirable economic and environmental benefits. Building owners and designers interested in applying heat pumps in their facilities have a variety of system configurations to choose from to meet their specific needs. However, care must be exercised with the selection of the equipment and how it is controlled.

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