EPRI

technical brief

Variable Flow Pumping

The Key to Energy Efficiency in Water Loop and Geothermal Heat Pump System Applications

Science & Technology Division
Commercial Heat Pump/Air Conditioner Technology Target

Two buildings conditioned by water-source heat pumps: A six-story office building in Middleton, Wisconsin with 146 tons of water-loop heat pumps, and a six-story hotel in Geneva, New York with 284 tons of geothermal heat pumps.

Introduction

Many commercial buildings use a distributed HVAC system known as a water loop heat pump system, where several smaller heat pumps/air conditioners are connected to a single water loop for conditioning individual zones in a building. The heat pumps reject heat to the common water loop when cooling the space, or extract heat from the loop when heating the space. A cooling tower rejects excess heat from the loop in summer when the building is cooling dominated, and a boiler adds heat to the loop in the winter when the loop temperature falls below a predetermined set point, such as 60˚ F as heat pumps extract loop heat for space heating. This approach allows for efficient heat recovery: heat rejected to the loop by interior heat pumps in cooling mode can be recovered for use by perimeter heat pumps that are extracting energy from the loop for space heating. The EPRI Brochure *"Water-Loop Heat Pump Systems: Cost Effective. Flexible and Efficient,"* BR-101133 provides more information on this technology and its applications.

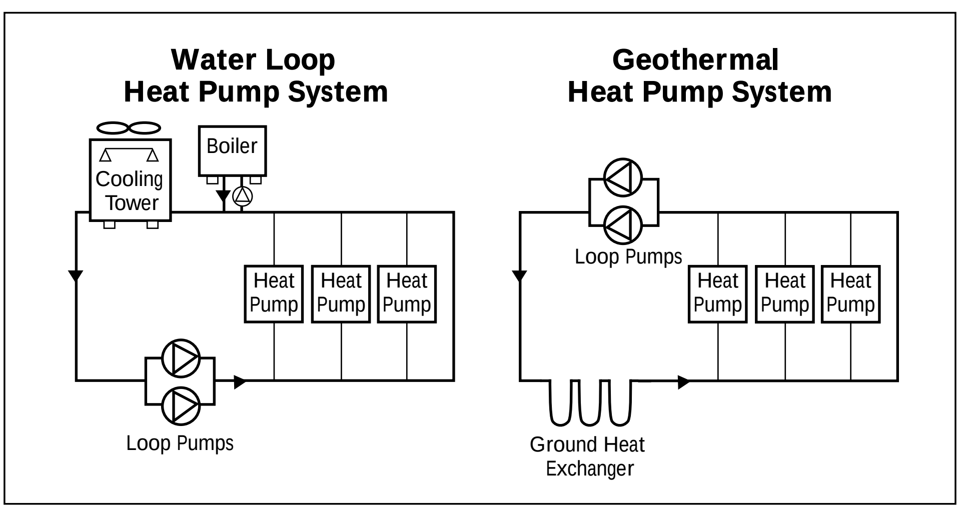


Figure 1 Two types of water source HP systems: 1) a water loop heat pump system that includes a boiler and a cooling tower, and 2) a geothermal heat pump system with a ground heat exchanger.

A variation on the water loop concept involves replacing the cooling tower and boiler with a ground loop heat exchanger to take care of heat rejection and extraction. This configuration is known as a geothermal or geoexchange heat pump system and provides some advantages over a typical water loop heat pump system—there are no outdoor components, which could be vandalized, and maintenance needs are reduced. The heat pumps in geothermal systems are designed to operate over a wider range of loop temperatures. Glycol or another anti-freeze solution may be used in the loop to prevent freezing, although loop temperatures in many commercial systems remain warm enough to prevent freezing.

Water Source Heat Pump Systems

Water source heat pump systems usually include the following major components: the heat pump units, loop pumps, the heat source/sink, and the loop piping itself. In a traditional water loop heat pump system, the heat source is a boiler and the heat sink is a closed-circuit cooling tower. Geothermal systems replace the boiler and cooling tower with a ground heat exchanger. The ground loop is usually made of polyethylene piping arranged in either vertical bores or buried in horizontal trenches. A vertical bore field requires 75 to 300 feet of vertical bore per installed ton of cooling capacity. Horizontal trenches are rarely used in commercial applications due to the large area required. Figure 1 illustrates the difference between the two types of heat pump systems.

Why Water Source Heat Pumps?

Building owners install water loop and geothermal heat pumps because of their efficiency, flexibility, and simple controls. High efficiency heat pumps provide space conditioning at a low cost, especially when integrated with a ground heat exchanger. Changeover between heating and cooling is also seamless and more efficient than in other options such as VAV. Water loop applications also provide flexibility to "build out" commercial space in stages and add heat pumps to the water loop as required. Tenants can also be billed easily for their own HVAC utility costs. Controls are also very simple. Each heat pump serves a single zone and can have a simple thermostat. Centralized and expensive DDC controls are not required.

Water loop and geothermal heat pumps also have lower electrical demand than conventional air-source equipment during peak summer and winter periods. The more moderate condensing temperatures of the water-cooled systems reduce the performance penalty compared to air source rooftop units at extreme ambient temperatures. The load diversity when operating with numerous heat pumps also provides a more stable load profile. In addition, the heat pumps provide efficient electric heating without the excessive demand and cost of resistance strip heat. Water-source heat pump systems handle building load diversity and the simultaneous need for heating and cooling operation better than other systems. The *EPRI Journal* article "New Market for Heat Pumps" provides more information on heat pumps, both water and air source.

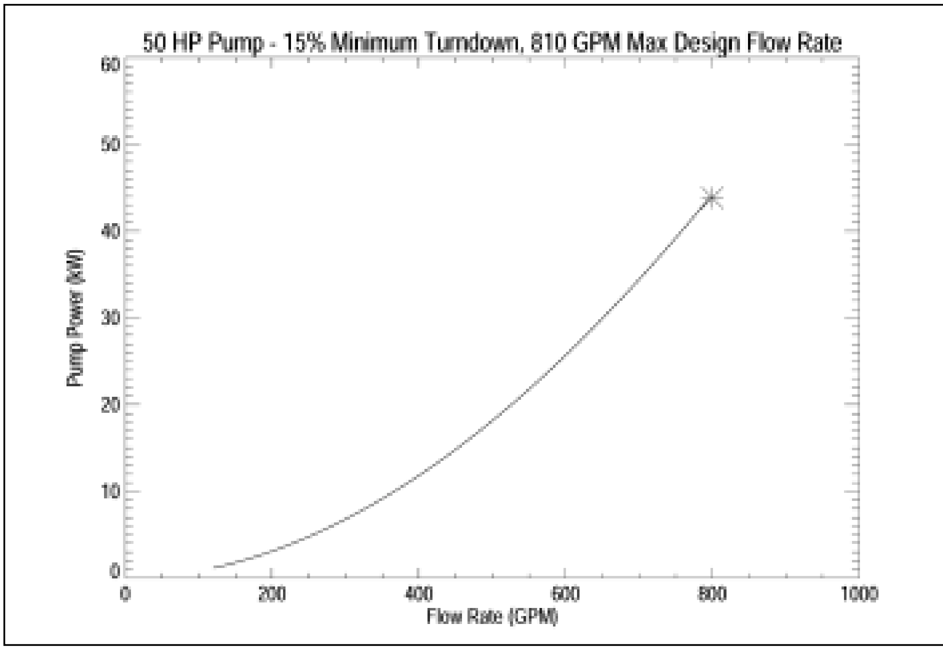


Figure 2 Typical pump power turndown for a variable speed pumping system. At the minimum flow of 15%, pumping power is a very small fraction of the design value.

Making Water Source Heat Pumps Efficient: Improved Loop Pump Control

The loop pumps are a very important element of a water loop or geothermal heat pump system. In some applications the energy use of the loop pumps—which usually must run 24 hours per day, seven days a week—can be greater than the energy use of the heat pumps themselves (Henderson and Walburger 1999; Carlson and Walburger 1999). For example, at a hotel in Geneva, NY with 284 tons of installed geothermal heat pumps, the annual heat pump energy use is 242 MWh. Had the hotel operated the 50 HP pump at full speed continuously, the annual loop pump energy use would be 350 MWh, or 145% of the heat pump energy use.

Heat pumps in commercial buildings rarely all operate at the same time. In fact, measured data from several buildings show that many applications never require the simultaneous operation of more than 50% to 60% of the units, even at design conditions (Henderson 1999). If the loop pumps operate at a constant speed, there are many hours per year when excess loop flow is being supplied. This unnecessary flow results in unneeded energy use.

Variable flow pumping can be used to minimize pumping energy use during periods of low loads. By adding shutoff or two-way valves to each heat pump, water flow through a heat pump's water coil is allowed only when that heat pump's compressor is operating. This reduces the flow through the loop during periods of light loads and allows a staged or variable speed pumping system to modulate down in response to the load. Because pump energy decreases substantially with loop flow, the annual energy savings can be large. The measured pump energy use with variable flow pumping has been found to be as low as one tenth of that required by constant speed pumping. This represents a major savings.

Variable flow pumping can be accomplished by either staging multiple pumps, using two-speed pumps, or with variable frequency drives (VFDs). Staging or speed variation is controlled to maintain an acceptable pressure difference across the heat pumps to ensure proper flow and operation.

Using two-speed or variable speed pumping has the advantage of providing a larger reduction in pumping power at low flow rates. At one-half the maximum flow (or pump speed), the pump uses 20-30% of the full load power. While the pump laws predict that the power decreases as the "flow cubed"—resulting in 12.5% of full power at 505 flow—the pump power is actually a bit higher (more like the "flow squared") in a system controlled to maintain a constant differential pressure set point.

VFD-controlled pumps have the added ability of dropping the flow to extremely low levels—as low as 10-15% of the full load flow. Figure 2 illustrates this point. In applications that spend many hours with virtually no heat pumps operating, (such as a school or office) the extra benefit of operating at very low flow rates becomes important.

Variable Flow System Design and Control Details

A variable flow pumping system requires more than a variable-speed or two-speed pump. Valves are required to restrict or shut off the flow through non-operating heat pumps. Controls and pressure sensors are necessary to modulate the flow in response to changes in loop pressure. All these components combine to make a system capable of effectively varying the flow (and energy use) in response to changes in heat pump loads.

Two-way or shutoff valves are generally installed in the loop piping in series with each heat pump. The valves are controlled to open when the compressor operates (sometimes a time delay circuit opens the valve slightly before the compressor turns on). When a heat pump has two compressors or water coils, individual valves are often placed on each refrigeration circuit. On some more complex loop components, such as large cooling units or refrigeration racks, a modulating valve is used to proportionally restrict the flow rate instead of shutting it off. Modulating three-way valves can also be used, but they defeat the purpose of variable flow pumping since there is no net reduction in the total loop flow rate.

Generally designers either intentionally omit valves for the heat pumps at the far end of the system, or add a "fixed" bypass to always allow some flow in the main loop. Typically a total bypass of 10-15% of the maximum flow is incorporated into the design to ensure that sufficient flow can be maintained through the loop pumps, even when all the heat pumps are off.

The typical design flow rate for water source heat pumps is 3 gpm per nominal ton. This flow results in a temperature difference near 10˚ F across the unit heat exchanger when the unit is in cooling mode. However, the ASHRAE ground source heat pump design guide (Kavanaugh and Rafferty 1997) shows that the efficiency of the heat pumps is nearly the same and pumping power is drastically reduced at flow rates of 2.0 to 2.5 gpm per ton.

Sometimes "flow limiting" valves are added to each heat pump to prevent the flow rate from exceeding the design value through individual units. While these devices can prevent excessive flow, they also create an additional pressure drop (about 2 to 5 psi). Often the penalty of extra flow through a few heat pumps is less than the added pressure drop these devices add to the system. Since these devices increase system pressure requirements throughout the loop system for the entire year, they should be applied with care.

The usual control scheme for a variable flow pumping system is to maintain a constant differential pressure across the heat pump supply and return headers. The differential pressure is usually sensed at a point near the end of the loop to ensure that all heat pumps see an acceptable pressure differential. The variable frequency drive modulates the pump speed to maintain this differential pressure using proportional-integral or "PI" control. The capability for PI control is typically built into most variable speed drives. In other cases, the buildings's direct digital controller handles this function.

Staged or two-speed pumping requires a controller to sequence pump operation. The ASHRAE design guide for ground source heat pumps (Kavanaugh and Rafferty 1997) recommends that heat pumps and valves be selected so that a differential pressure set point of 7-8 psig is required. In actual installations pressure set points ranging from 8 psig to 18 psig have been observed. Figure 3 shows a typical water-source heat pump system.

Load Diversity—The Reason for Energy Savings

Generally a building HVAC system operates at design conditions for a few hours annually. Furthermore, this overall design load for a building is only a fraction of the total installed capacity. This difference between the design load and the installed capacity is known as diversity. Diversity in the loads occurs because the equipment in each zone is sized to meet the loads of that space but the peak loads in each zone never occur simultaneously.

Large buildings with distributed water source heat pump systems have been shown to never have more than 50-60% of the installed heat pumps operating simultaneously (Henderson 1999). With these high levels of building load diversity at design conditions and the large number of hours at part load conditions, there is a considerable number of hours when variable flow pumping can provide high levels of energy savings.

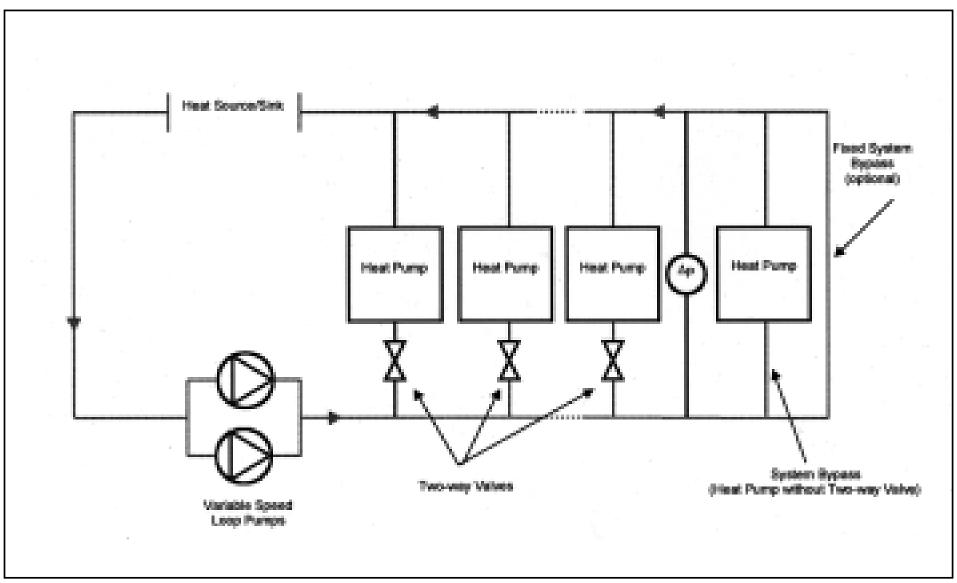


Figure 3 A water source heat pump system including variable speed pumping, two-way valves and pressure controls.

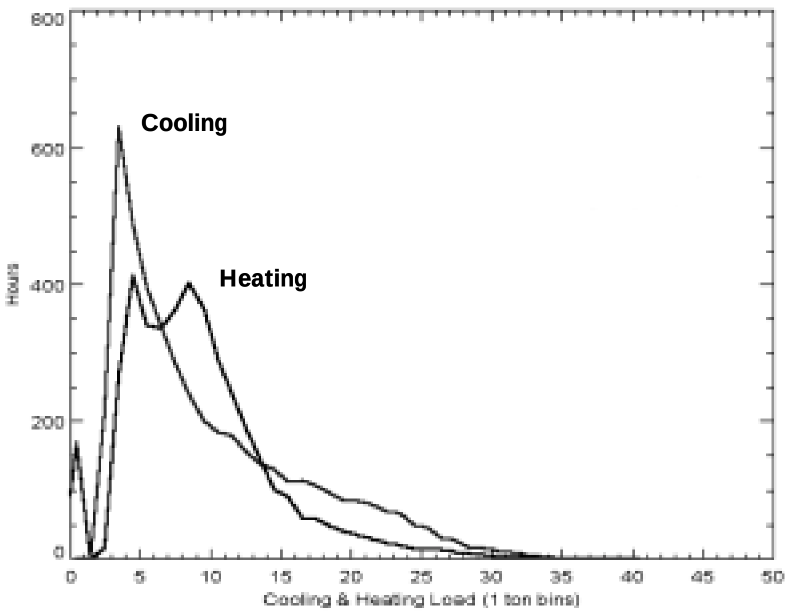


Figure 4 The annual distribution of heating and cooling loads in a 27,000 square foot office building in Sun Prairie, WI. The building has a 69 ton water loop heat pump system, but the peak loads have never exceeded 40 tons.

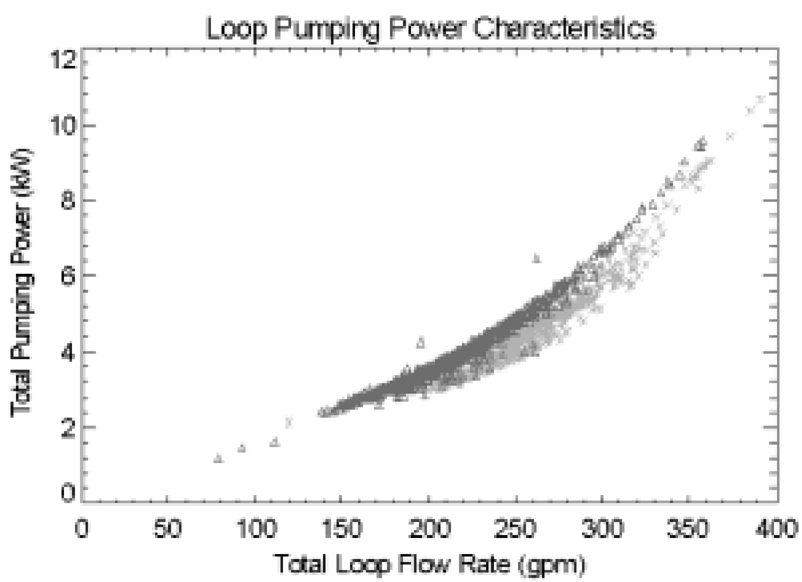


Figure 5 Because of load diversity, the pumping power on this 50 HP VFD pumping system at a Hotel in Geneva, NY never exceeded 50% of the 810 gpm design flow rate or 25% of the design pump power.

If a VFD is used to vary pump speed on a water source heat pump system with high load diversity, the pumping power can be turned down radically and often never reaches the design value. At the hotel in Geneva, NY, the VFD-controlled loop flow rate never exceeded 50% of the design value and the average flow rate was about one third of the nominal value. As Figure 5 shows, pumping power was less than 25% of the 44 kW that would have been expected for the 50 HP motor at constant full speed.

Annual Energy Savings from Three Applications

Just how much energy can a variable speed pumping system save? And how much energy do the loop pumps use compared to the heat pumps? The energy savings vary with each application and depend on the amount of load diversity as well as the relative pump size. But in a number of water loop heat pump systems with VFDs and two-way valves installed, annual savings of 70% to 90% compared to constant speed pumping have typically been observed. The annual energy savings measured in three different applications are discussed below.

McDonalds Geothermal System

At a McDonald's restaurant in Detroit, a 33 ton geothermal heat pump system was installed with a VFD pumping system. Two-way valves were placed on 5 of the 6 water source heat pump compressors installed at the facility. While the variable speed pumping system cut annual pumping energy use in half, even greater savings were possible. A high-differential pressure set point (18 psig) in the system limited the savings by requiring the pump to run at a higher speed at low flow rates in order to generate the specified pressure. If the set point had been more moderate, for example 8-12 psi, the variable flow pumping system would have used only 21% of the constant speed pumping energy requirement. Annual energy use for the system components are shown in Figure 6.

Wal-Mart Supercenter

The Wal-Mart Supercenter in Moore, Oklahoma has a water loop heat pump system containing 508 tons of space conditioning heat pumps, including six 55 ton dual path units that precondition outdoor air for the main store and 28 smaller heat pumps dedicated to various other areas (Khattar, 1998). 110 tons of water-cooled refrigeration is also connected to the water loop system. Each of the large dual path units had a two-way solenoid valve. However, the three refrigeration racks had three-way valves that modulated loop flow through the unit to maintain refrigerant pressure. These valves do not modulate the net water flow rate through the racks. In addition, these three-way valves require a differential pressure of at least 10 psig for proper operation, causing an arbitrarily high-pressure set point across the system. Even with this limitation, the VFD pumping system at the store saved 192 MWh/year, or 36% compared to constant speed pumping. An analysis of the system with the three-way valves replaced by modulating two-way valves and operating at a lower set point showed that VFD savings could be nearly doubled to 372 MWh/year, or 70%. These are shown in Figure 7.

Ramada Hotel

This hotel and conference center in Geneva, New York has a geothermal heat pump system installed with 284 tons of space conditioning and 40 tons of water heating. Most of the heat pumps in this facility had two-way valves. In spite of the relatively large loop pump, the system saved significant amounts of energy. The large load diversity of the building, combined with good VFD performance, resulted in pump savings of 309 MWh/year, or 88% compared to constant speed operation (Figure 8).

All three sites noted here showed significant savings from variable flow pumping. The largest savings occurred at the hotel, where there was a high degree of load diversity. At the retail store, the small number of heat pumps and the nature of the loads resulted in no diversity at peak load conditions, therefore the savings with variable speed pumping were much less. Typically, applications such as office buildings and schools, equipped with many small, single zone heat pumps, have shown the most diversity and therefore the highest potential for variable flow savings (Henderson 1999).

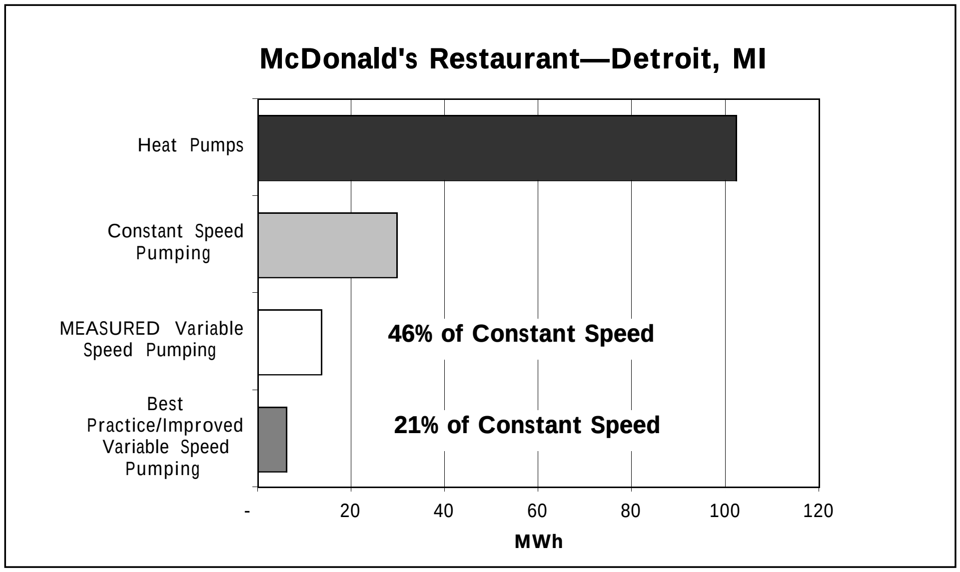


Figure 6 McDonald's

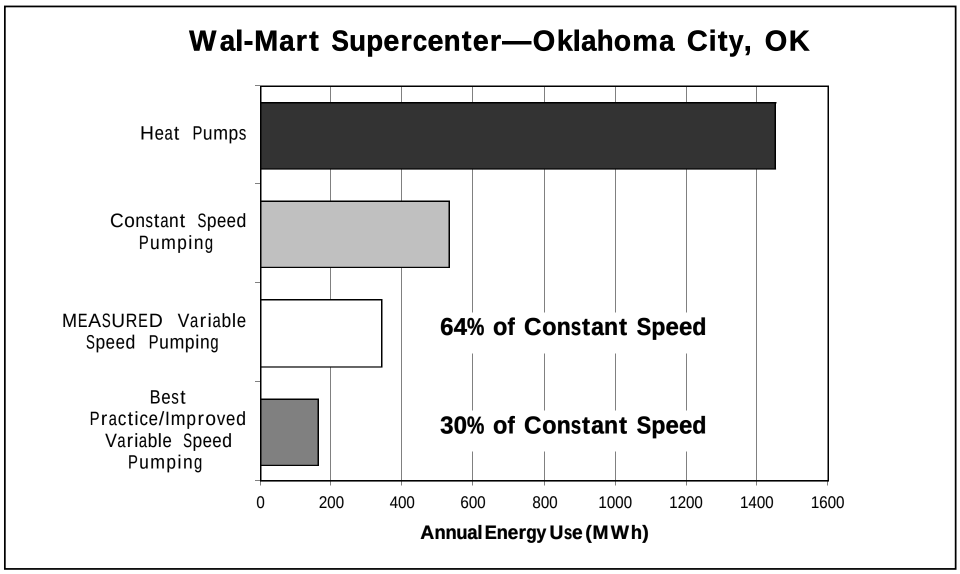


Figure 7 WalMart SuperCenter

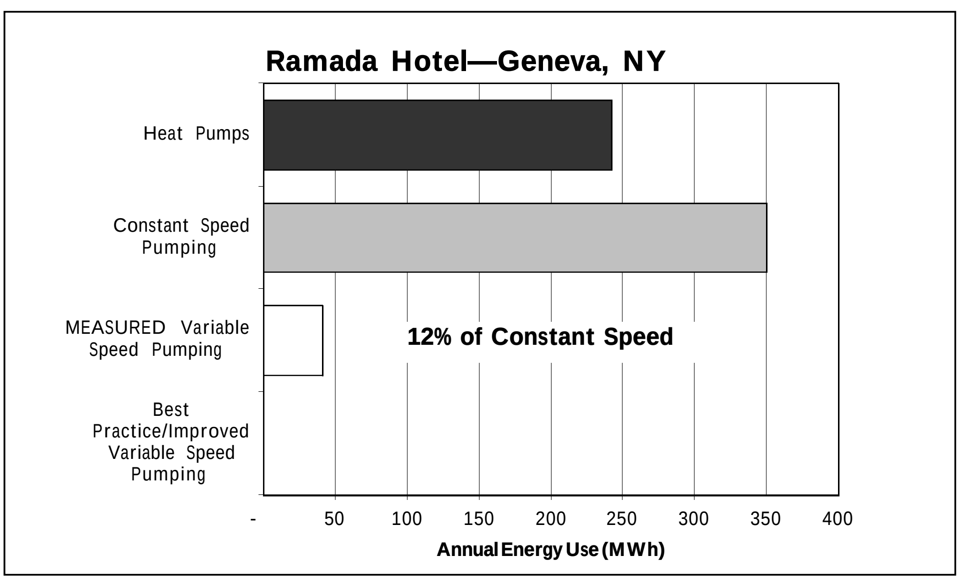


Figure 8 Ramada Hotel

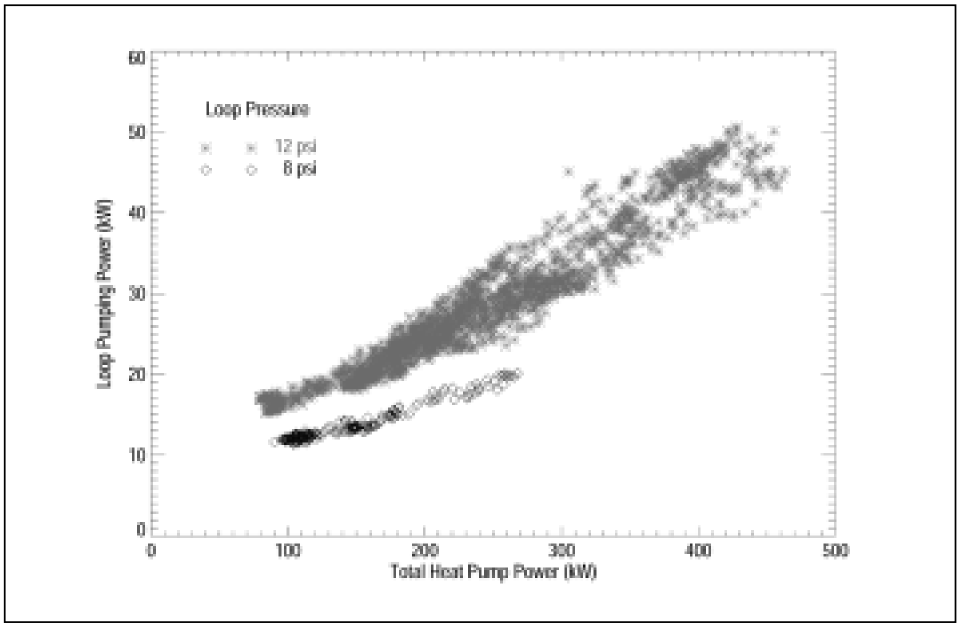


Figure 9 At Wal-Mart, a temporary reduction in the differential pressure set point, from 12 to 8 psi when the refrigeration racks were out of the system, demonstrated that pump energy use was directly proportional to the pressure difference for this water loop heat pump system.

Getting It Right—The Devil Is In the Details

As the buildings described previously demonstrate, several design and control issues must be addressed to ensure that variable speed pumping systems realize their full potential. Some important details are outlined below.

Valve Installation and Operation

Poor pumping system performance can often be linked to inoperable control valves. When valves are not operating, flow modulation is not possible and pumps essentially operate at a constant speed. Often these valves are installed in the field and wiring errors and other control details can hinder performance. If normally closed valves are specified, valve problems are generally found and addressed during the installation by the contractor since heat pump operation is directly affected. If the valves are specified as normally open devices, the heat pumps operate properly but pump energy may be high due to a lack of flow modulation. Often the dynamic nature of the system causes this type of fault to go undetected (Henderson and Walburger 1999).

Perhaps the best way to ensure proper valve operation is to purchase heat pumps with the valves already installed. This allows factory engineering and quality control procedures to be applied, and places the responsibility for proper installation and time delay details with the manufacturer. In field installations, common problems of quality control and blurred lines of responsibility among the various contractors (mechanical, electrical, controls) makes it difficult to ensure proper installation.

Loop Pressure Setpoints

Variable speed pumping systems vary the flow to maintain the required pressure set point. This set point is selected—often by the test and balance contractor—to provide the necessary flow to each heat pump. As shown in Figure 9 from the Wal-Mart example, this pressure set point is directly related to the energy use of the system and should be selected carefully.

Often non-critical valves and other components in the water loop impose a large pressure drop or require a high pressure to operate properly. Sometimes a single relatively low-cost device or valve at a key location in the loop can set the pressure requirement for the entire system, costing thousands of dollars in annual pump energy use.

In other cases, the set point may simply be set arbitrarily high by the system operators in an effort to “play it safe” or to meet some other perceived requirement. However, sometimes the system operators find that they must legitimately increase the pressure set point of the loop pumps to prevent one or two heat pumps in the system from locking out due to low flow. This flow restriction or other problem at a single heat pump can drastically affect the energy use of the entire system if the pressure set point is increased. In many instances, this type of problem is better addressed by adding a booster pump to counteract the flow restriction at the offending heat pump. This approach has been implemented successfully at a high school in Tennessee (Henderson and Walburger 1999) where a few heat pumps scattered around the 160,000 square foot facility were locking out on low flow. By adding a small cartridge pump to each heat pump (in place of the two-way valve), it was possible to reduce the pressure set point in the loop system and save significant amounts of pump energy.

Retrofitting Existing Systems: Is There an Option?

Many existing geothermal and water loop heat pump systems use constant speed loop pumps. These systems were installed before the reliability of VFDs was proven and the first cost of the drives became more competitive. In general, retrofitting a VFD onto the existing loop pump can be manageable and cost effective. However, the cost of retrofitting valves onto each heat pump in the building can be prohibitive. The heat pumps are typically in locations that make it difficult to break into the loop piping to add the valve. In addition, the extra wiring required for the valve can be time-consuming to install.

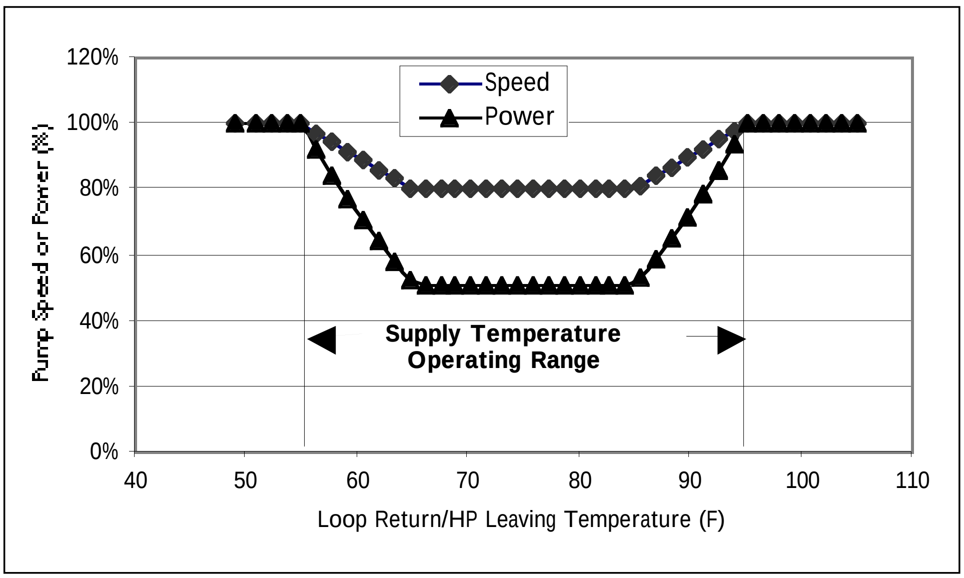
As outlined above, both the valves and the VFD must be installed to make a successful fully-modulating, variable flow pumping system. However, there is another option. A loop pump control algorithm, conceived as part of EPRI’s SmartLoop field test project, uses the loop temperatures to partially modulate the pump speed. This approach realizes part of the benefits of full pressure-based pump control without requiring two-way valves on each heat pump. The algorithm takes the conservative approach of operating the loop pump at 80% to 90% of full speed whenever full flow is not required. Operating at 80% to 90% of full flow reduces the pump power by 25% to 50%.

The need for full flow would be determined based on the following principles:

- If the loop temperature leaving the HP is above the heat pump's upper limit or cooling design point for entering temperatures, increase the pump speed to ensure that all units have full flow.
- If the loop temperature leaving the HP is below the heat pump's lower limit or heating design point for entering temperatures, increase the pump speed to ensure that all units have full flow.

To eliminate any control stability problems, a linear "reset" function would be used to gradually modulate the flow over a range of temperatures near the changeover point (the following graph shows a 10˚ F throttling range).

The algorithm takes advantage of the fact that less flow can provide the same amount of heat rejection/extraction when the available temperature difference across the refrigerant-to-water heat exchanger is greater. The available temperature difference is greater at modest loop temperatures. While most systems are designed to provide a flow rate of 3 gpm per ton, manufacturers typically design their heat pump units for flows as low as 2 gpm per ton. The efficiency curve for most heat pumps is flat in the 2.5 to 3.0 gpm/ton range. When operating at 80% of full flow when loop temperatures are modest, the pump power drops to nearly 50% of the full load value.



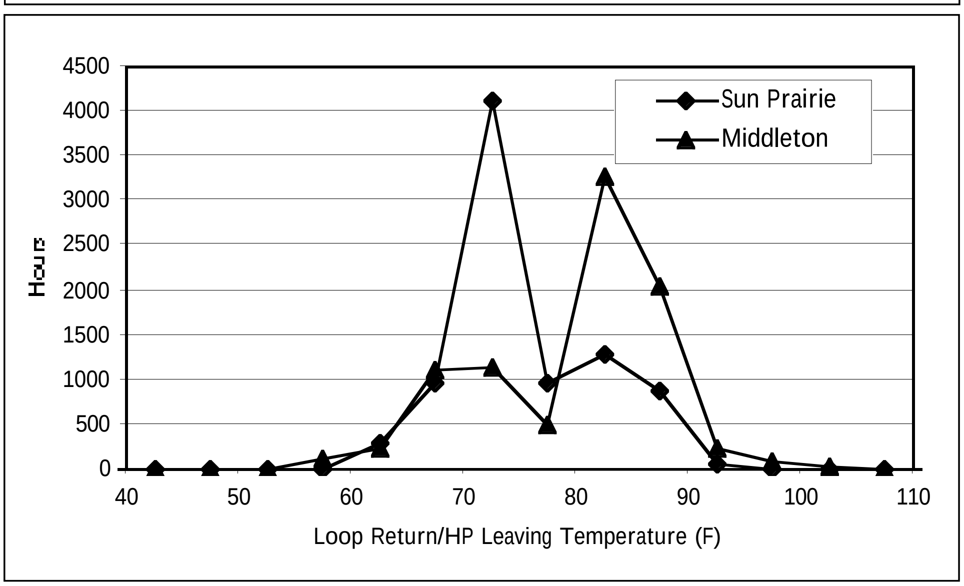


Figure 10 By varying pump speed based on the HP leaving temperature, the heat pumps have full flow near design conditions and can take advantage of lower flow rates when loop temperatures are modest. The measured data for the Sun Prairie and Middleton office buildings show that both systems spend the vast majority of their operating hours at modest temperatures, so significant savings are possible.

Figure 10 shows that leaving/return temperatures from two WLHP office buildings were frequently in the range at which the pumps would be throttled back to 80% of full flow. On an annual basis, the pump at Sun Prairie would modulate up from high speed less than 4% of the time and the pump power would be reduced by 47% annually compared to constant speed operation. At Middleton, where hotter loop temperatures were frequently observed, the algorithm would still save 43% annually compared to continuous full speed loop pump operation.

Summary

Loop pumping represents a significant portion of the energy use in water loop and geothermal heat pump systems. In some buildings, especially where the supply fans cycle with the compressor, pump energy use can exceed heat pump energy use on an annual basis. Variable flow pumping offers the potential to reduce pump energy use by about 70% to 90%. Savings are greatest in large facilities that have significant amounts of diversity in their heating and cooling loads.

While variable speed pumping has the potential to reduce operating costs drastically, several installation and control details must be addressed to ensure that those savings are realized. Savings are not possible without proper two-way valve operation. Having valves factory installed in the heat pumps reduces the risk of wiring errors during field installation. Flow-limiting valves and other loop components must be carefully selected (and, where possible, eliminated) to minimize the differential pressure set point that the pumping system must maintain. Good design practice should result in pressure drops of under 10 psi across the heat pumps. The added pressure drop of a single component can drastically affect total system energy use.

Often it is not cost effective to retrofit an existing system for variable speed pumping. A large portion of the effort is in adding the necessary valves to each heat pump for pressure-controlled variable speed pumping. EPRI is developing an alternative temperature-based control algorithm that is appropriate in retrofit applications and can realize more than half of the savings possible with traditional variable speed pump control. This algorithm provides the means for existing water source heat pump buildings to realize the benefits of variable speed pump technology.

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