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Advanced Controls for Ground-Source Heat Pump Systems

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June 2017

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Energy and Transportation Science Division

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ACRONYMS

ASHRAE	American Society of Heating Refrigeration and Air-conditioning Engineer
DGSHP	distributed ground source heat pump
DP	differential pressure
EE	electric element
GHP	geothermal heat pump
GSHP	ground source heat pump
GS-IHP	ground source integrated heat pump
SC	space cooling
SH	space heating
VFD	variable frequency drive
WH	water heating
WSHP	water source heat pump

ABSTRACT

Ground source heat pumps (GSHP), also known as geothermal heat pumps (GHP), are proven advanced HVAC systems that utilize clean and renewable geothermal energy, as well as the massive thermal storage capacity of the ground, to provide space conditioning and water heating for both residential and commercial buildings. GSHPs have higher energy efficiencies than conventional HVAC systems. It is estimated, if GSHPs achieve a 10% market share in the US, in each year, 0.6 Quad Btu primary energy consumption can be saved and 36 million tons carbon emissions can be avoided (Liu et al. 2017). However, the current market share of GSHPs is less than 1%. The foremost barrier preventing wider adoption of GSHPs is their high installation costs. To enable wider adoption of GSHPs, the cost-effectiveness of GSHP applications must be improved.

Under a collaborative research and development agreement (CRADA), researchers at Oak Ridge National Laboratory (ORNL) worked with ClimateMaster, a U.S. GSHP manufacturer, to improve the performance and efficiency of GSHPs by advancing controls in both component and system levels. Main results of this CRADA collaboration include:

- an innovative flow-demand-based control for variable speed pumping for distributed GSHP (or DGSHP) systems, which can dynamically adjust the pump speed at real time and deliver only the water flow needed to each individual heat pump in a DGSHP system. This newly invented pumping control (patent pending, Invention Disclosure #: 201403380, DOE S-138,004) has potential to reduce pumping energy by 60% in typical DGSHP systems,
- a new control for ground source integrated heat pumps (GS-IHP), which avoids the electric power surges resulting from the existing control during the simultaneous space cooling and water heating operation, and significantly reduces or even eliminates the operation of the electric backup water heating elements. Experimental test results indicated that this new control improved the combined COP of GS-IHPs for space cooling and water heating by 10% compared with the existing control when the ground source supply temperature is below 75ºF, and
- a first-of-its-kind research facility capable of supporting development and verification of various emerging technologies for DGSHP applications in a low-risk and realistic real-building environment.

1. STATEMENT OF OBJECTIVES

Ground source heat pumps (GSHP), also known as geothermal heat pumps (GHP), are proven advanced HVAC systems that utilize clean and renewable geothermal energy, as well as the massive thermal storage capacity of the ground, to provide space conditioning and water heating for both residential and commercial buildings. GSHPs have higher energy efficiencies than conventional HVAC systems. It is estimated, if GSHPs achieve a 10% market share in the US, in each year, 0.6 Quad Btu primary energy consumption can be saved and 36 million tons carbon emissions can be avoided (Liu et al. 2017). However, the current market share of GSHPs is less than 1%. The foremost barrier preventing wider adoption of GSHPs is their high installed costs. To enable wider adoption of GSHPs, the cost-effectiveness of GSHP applications must be improved.

The objective of this project is to improve the performance and efficiency of GSHPs by advancing controls in both component and system levels through close collaboration with ClimateMaster, a U.S. GSHP manufacturer. Particularly, this project focused on two areas: one is to improve the water heating efficiency of the newly developed ground source integrated heat pump (GS-IHP)—a single packaged unit providing both space conditioning and 100% water heating; and the other is to improve the pumping efficiency of distributed ground source heat pump (DGSHP) systems, which is predominantly used in GSHP applications for multi-family residential, commercial, and institutional buildings in the US.

As a result of a previous CRADA collaboration with Oak Ridge National Laboratory (ORNL), ClimateMaster launched the Trilogy™ 40 Q-Mode™ series GS-IHP in 2014, now known as the Trilogy 45® Q-Mode® (http://www.climatemaster.com/residential/trilogy/ and http://www.climatemaster.com/residential/trilogy/qe/). This project utilized the ClimateMaster® pat. pending Trilogy® Q-Mode® (QE) series GS-IHP (http://www.climatemaster.com/residential/trilogy/qe/). The Q-Mode® technology produces year-round domestic hot water on demand, even when space conditioning is not required. The patent-pending Q-Mode technology produces year-round domestic hot water on demand, even when space conditioning is not required. This project will characterize the water heating performance resulting from existing controls and further refine the controls by using additional inputs (e.g., historical usage patterns, temperatures at various levels within the tank, etc.) to improve the water heating performance and efficiency. Field studies indicate that excessive pumping energy consumption is a common issue in commercial building or multi-family building DGSHP systems, which results in lower than expected operational energy efficiency of DGSHP systems. A system-level pumping control that can optimize the operation of the circulation pump will be developed to provide additional energy savings.

2. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

The Building Technologies Office (BTO) within DOE’s Office of Energy Efficiency and Renewable Energy (EERE) is responsible for developing and deploying technologies that can substantially reduce energy consumption in residential and commercial buildings. While many high efficiency options are available, GSHPs are among the most efficient and was identified by BTO as a high-impact technology. As stated in DOE’s Research and Development Roadmap for Geothermal (Ground-Source) Heat Pumps (DOE 2012), reducing cost and improving performance is crucial to making GSHPs more economically competitive and thus widely adopted.

This project aimed to improve the operational efficiency of GSHP systems by developing smart controls at both the component and system levels. These smart controls would be essential components of the next-generation GSHP systems, which will be able to optimize their operation based on thermal loads in real time and capable of meeting all the space conditioning and water heating demands.

The results of this project will help improve the cost effectiveness of GSHP applications and enable wider adoption and sustainable growth in the US and other countries.

3. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

This CRADA project includes following tasks:

- Characterize the water heating performance of GS-IHPs with existing controls
- Refine the existing controls to improve performance of GS-IHPs
- Develop a smart control for the circulation pump of DGSHP systems
- Characterize the performance of the developed smart pumping control

To support the above tasks, a first-of-its-kind test facility for DGSHP systems was designed and built at a flexible research platform (FRP) in ORNL. ClimateMaster donated GSHP units and provided valuable inputs, technical support, and feedbacks during this study. In addition, ClimateMaster also conducted initial lab tests to evaluate various water heating controls. Technical discussions of the work performed by all parties are presented in following sub-sections.

3.1 A FIRST-OF-ITS-KIND FLEXIBLE RESEARCH PLATFORM FOR DGSHP SYSTEMS

3.1.1 Overview

The DGSHP system test facility at ORNL is a first-of-its-kind facility. It is in a 3,200 ft^2 two-story building at the main campus of ORNL (Figure 1). This building has 10 zones (five zones on each floor), and the plan of each floor is almost identical, except for two entrances on the first floor. The occupancy in each zone is simulated with an electric heater and a humidifier that are controlled based on a set of predefined schedules to represent the internal heat and moisture gains in a typical residential or commercial building.

The facility is comprised of (1) a ground source emulator, which can mimic the supply temperatures of various ground sources (e.g., groundwater, surface water, and ground loop); (2) a 12-ton DGSHP system with two two-stage 2-ton GSHP units and two 5-ton GS-IHP units, which can provide not only space heating and space cooling but also 100% domestic hot water; (3) a hydronic piping system with two alternative pumping configurations (i.e., a central pumping station and individual circulator in each GSHP unit), and (4) a data acquisition and visualization system to collect and visualize data from the more than 150 sensors and meters. Each GSHP unit conditions multiple zones in the two-story building through a damper-controlled duct system. A hot water usage simulator is installed to automate hot water draws following various programmable patterns. Figure 2 shows the schematic diagram the water side of the research facility.

3.1.2 Ground Source Emulator

A ground source emulator (GSE) is designed and built to provide source water at a user-specified temperature to represent various ground sources, including groundwater, surface water, and ground loop. As shown in figures 2 and 3, the GSE includes a 15-ton air-cooled chiller (including three 5 ton modules), an 85 gallon 35 kW (125 kBtu/h) electric water heater, a 1.5 horsepower constant speed circulation pump, a plate frame heat exchanger (PFHX), a 50-gallon buffer tank, and a controller.

Figure 1. The building hosting the flexible DGSHP system test facility.

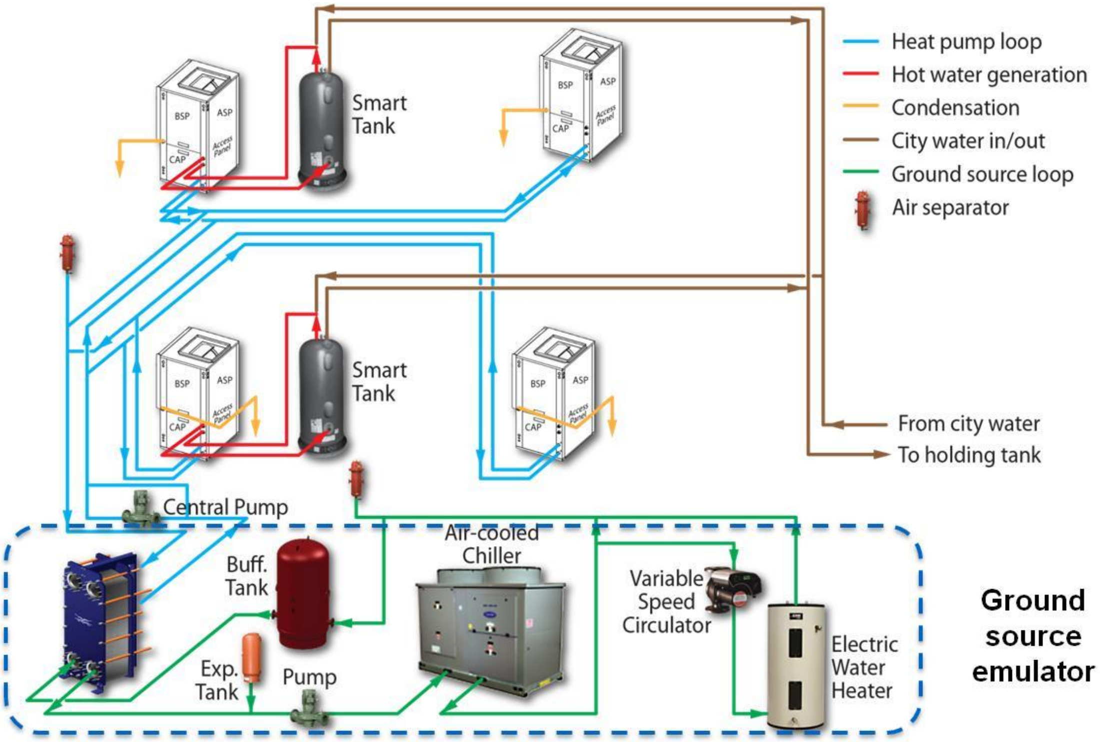

Figure 2. Diagram of the DGSHP test facility.

Figure 4 shows a control diagram of the GSE. The operation of the chillers and the water heater is controlled based on the temperature difference across the PFHX at the source water side. The controller turns on the chiller if the source water is receiving heat from the GSHP units, and it turns on the water heater when the source water is releasing heat to the GSHP units. The source side supply temperature to the PFHX is maintained at a user-specified set point by modulating the output of the chiller or the water heater. The allowable range of the source water supply temperature ("T_GSE_S" shown in Figure 4) is

50–75ºF, and the supply water temperature to the GSHP (“T_HP_S” at the other side of the PFHX) will vary between 45 and 80ºF, which represents the typical range of ground source temperature in the United States. The cooling output of the chiller is staged depending on the difference between the measured T_GSE_S and its set point. The heating output of the water heater is modulated through a two-step process: (1) staging the opening of a motorized valve to initially adjust the hot water flow rate and (2) varying the speed of a hot water circulator through a PID control to maintain T_GSE_S at the set point. The water temperature in the hot water tank is maintained at 120ºF by the built-in control of the water heater.


Mechanical Room of the Ground Source Emulator

Air-cooled Chillers

Figure 3. The ground source emulator.

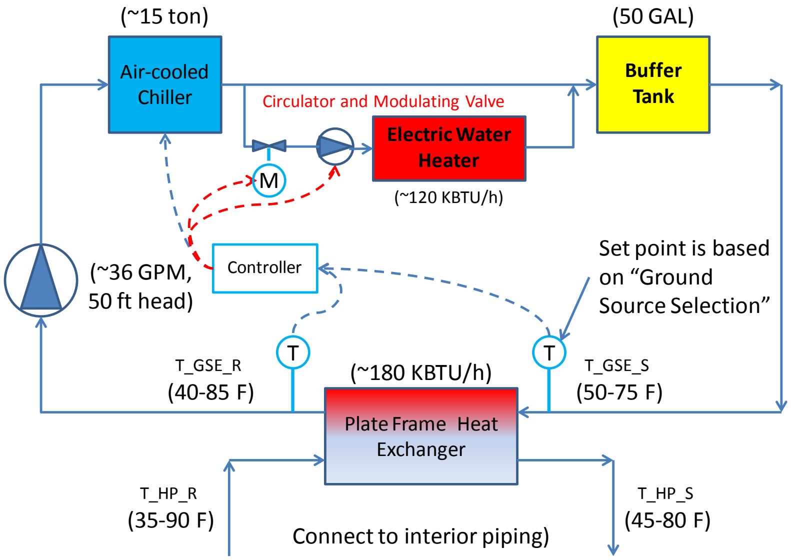

Figure 4. A control diagram of the ground source emulator.

A control panel for GSE is developed for setting control parameters and monitoring the performance of the GSE. Figure 5 is a screenshot of the control panel. The dynamic plot at the bottom of the control panel gives various temperature measurements at GSE. This figure shows that T_GSE_S was maintained within a 2°F deadband of different set points. The deadband can be reduced to 1°F if a more constant source water temperature is desired.


FLexible Research Platform #2
GROUND SOURCE EMULATOR

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CHILLER CONTROL

SETPOINTS

0.0 DT CHILLER 1 ON
3.5 DT CHILLER 2 ON
7.0 DT CHILLER 3 ON
1.0 HYSTERESIS
2.0 DEADBAND
55.0 T_SP
2.00 WH Valve Control (0-10VDC)
1.18 WH Pump Speed (0-10V)

DT sim 0.00

GSE LOOP TEMPERATURES

T_WHout	115.4 °F
T_BufferTank	50.7 °F
T_GSE_S	54.5 °F
T_GSE_R	54.5 °F
DT_GSE	0.00 °F
Tout_Chiller 1	54.0 °F
Tout_Chiller 2	54.1 °F
Tout_Chiller 3	54.4 °F
Tout_Chillers All	54.4 °F
DT_test	-3.65 °F

*NOTE: DT_Test = T_BufferTank - Tout_ChillersAll

ROTATION: 4 HRS, Enable; Order: 3-1-2

1.0 Kp
0.1 Ki
0.0 Kd

2.0 ValvePos_IN (0-5V)
5.2 PID Volts Out
5.2 MV (modified variable)
51.8 PV_DegF (process variable)
3.2 Error (SP - Actual Position)

Figure 5. A screenshot of the control panel of the ground source emulator.

3.1.3 Experimental DGSHP System

The experimental DGSHP system is comprised of four GSHPs: two of them are identical two-stage GSHP units, and the other two are identical GS-IHP units. Each GS-IHP unit also ties with a hot water tank to produce domestic hot water in addition to space conditioning. To simulate various hot water usage patterns, a hot water draw simulator is implemented at each hot water tank, which can automatically draw hot water from the tank based on a predefined schedule for the flow rate and duration of each water draw. Figure 6 shows photos of the GSHPs, the water tank of GS-IHP, and the hot water draw simulator used in the experimental DGSHP system.

These GSHPs are attached to a two-pipe common water loop to exchange heat with the GSE through the PFHX. Each of these GSHPs serves multiple zones in the building through a ductwork, each branch (to a zone) of which has a motorized damper for modulating airflow in response to the varying heating and cooling loads in the zone. The layout of the first and the second floors is identical, and each floor is served with a two-stage GSHP and a GS-IHP, as shown in Figure 7.

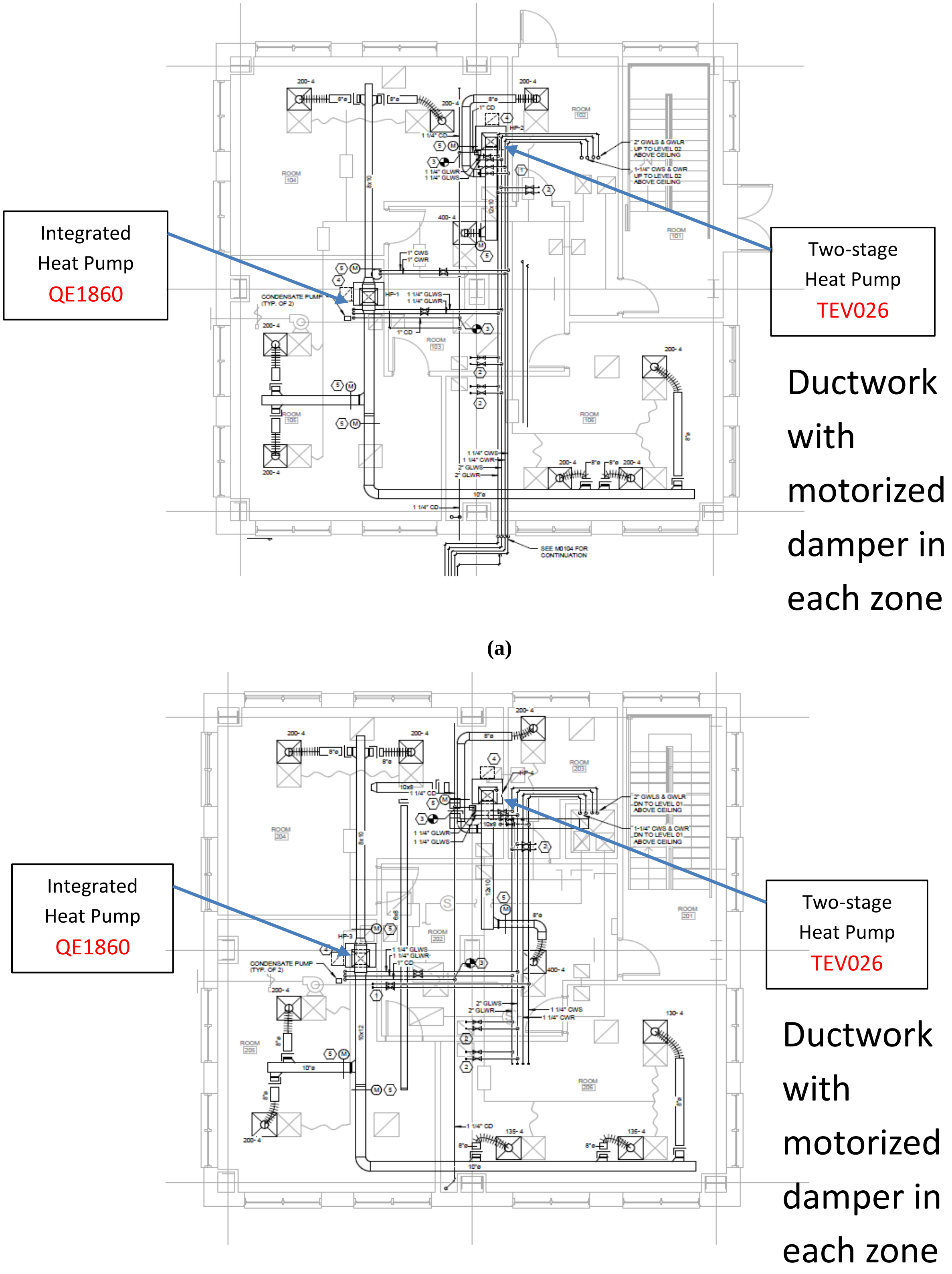
Each GSHP has its own built-in variable-speed circulator, which draws water from the water loop and returns it back after exchanging heat with the GSHP. The internal circulator is controlled by the GSHP to modulate the water flow rate so that a constant temperature difference across the water-refrigerant coil can be maintained. These internal circulators can be bypassed so that the water flow can be delivered to each GSHP with an external central pumping station, which is the most typical pumping configuration of DGSHP systems in commercial applications. Figure 8 shows the equipment of the central variable-speed pumping system, including a variable frequency drive (VFD), a circulation pump, two differential pressure transducers (one at the main supply and return and the other at the hydraulically furthest GSHP from the central loop pump), a motorized two-way valve in each of the two-stage GSHP units to shut off flow when the GSHP is not called on by its thermostat. The major equipment used in the GSE and the DGSHP system is listed in Table 1.

State-of-the-art 2-stage GSHP

Automated hot water draws with various programmable patterns

Integrated GSHP with hot water generation

Figure 6. Heat pumps, water tank, and hot water draw simulator.



(a)

(b)

Figure 7. Layout of heat pump, ductwork, and pipeline at (a) first floor and (b) second floor.

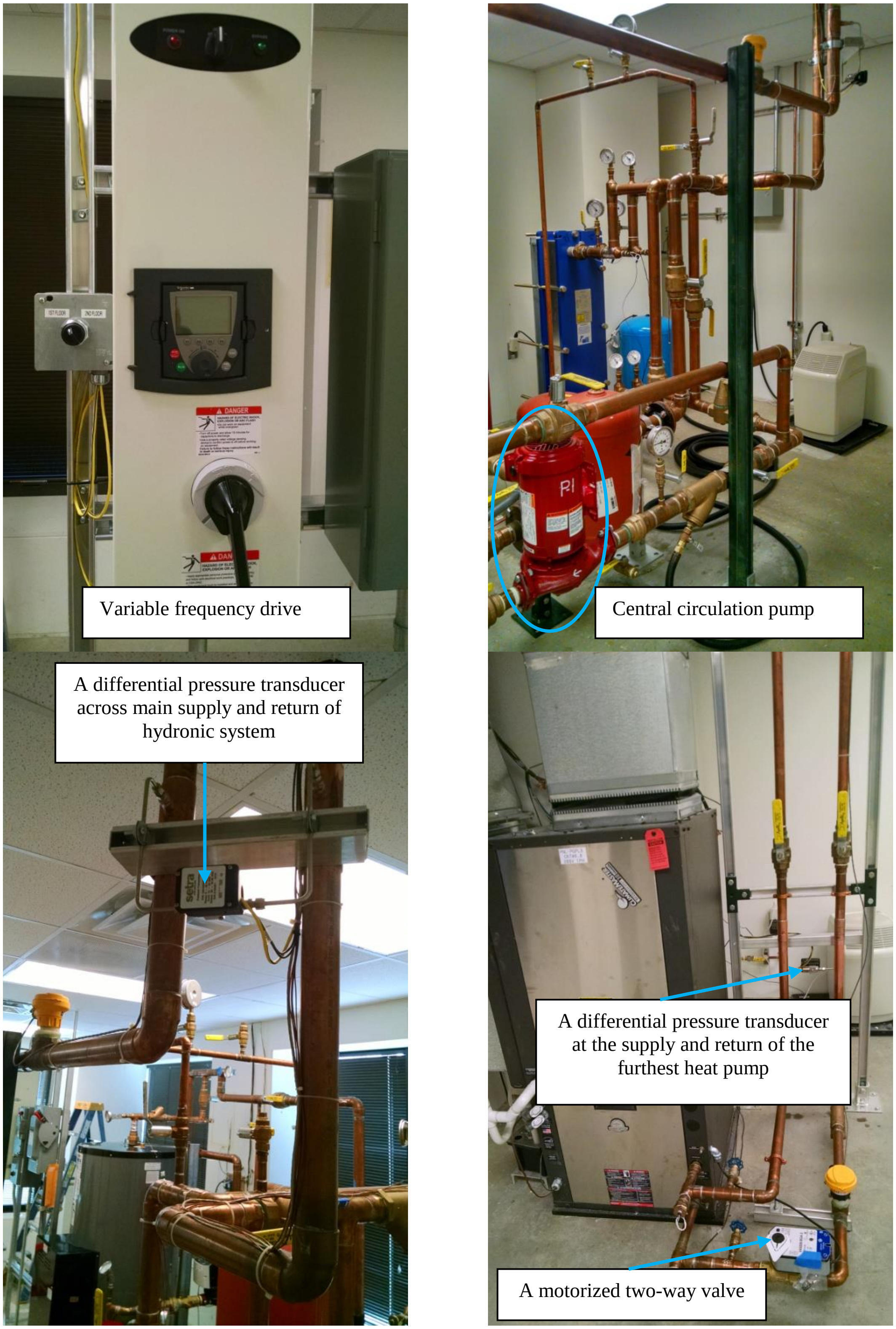


Figure 8. Equipment of a central variable-speed pumping system.

Table 1. Major equipment used in the DGSHP test facility

Name	Manufacturer	Model	Count
Heat Pump	ClimateMaster	TEV026BGD02ALTS, 2 ton	2
	ClimateMaster	QEV1860AGE02BLS, 4 ton integrated with water heating	2
Smart Tank	ClimateMaster	ATC32U02 (50 gallon)	2
Thermostat	ClimateMaster	AWS050AW1245S (for TEV026)	2
	ClimateMaster	AWC99B01R (for QEV1860)	2
Air-cooled Chiller	Unico	UCH0605-2C0	3
Electric Water Heater	Rheem-Ruud	85 gallon, 480V/3ph, 36 kW input	1
Circulation pump (ground source loop)	Bell & Gossett	1-1/2 hp, 208V/3ph, 57 gpm at 68 ft head (90 series)	1
Circulation pump (water heater)	Bell & Gossett	ECOCIRC XL 20-35	1
Circulation pump (heat pump loop)	Bell & Gossett	1-1/2 hp, 208V/3ph, 30 gpm at 85 ft head (90 series)	1
Variable frequency drive	Schneider Electric	S-Flex^{TM} 212	1

3.1.4 Data Acquisition System

There are 152 data points collected by two Campbell Scientific data loggers at four time intervals (30 seconds, 1 minute, 15 minute, or 1 hour), including the following.

- Indoor air temperature and humidity at each zone of the building
- Performance of each GSHP unit
  - Power draw, water flow rate, inlet and outlet water temperatures
  - Fan power, airflow rate, temperature and humidity of return air and supply air of each GSHP unit

- Performance of individual circulator integrated within each GSHP unit
  - Flow rate
  - Pump power

- Performance of central pumping system
  - Flow rate
  - Pump power
  - Differential pressures

- Performance of water heater tank
  - Water temperature at specified locations within the tank (via a thermocouple tree)
  - Tank supply and discharge water temperatures
  - GSHP supply and return water temperature to the tank, as well as the flow rate
  - Power draw of electric elements in the water tank

- Performance of outdoor air (OA) ventilation system
  - OA temperature and humidity
  - Total OA flow rate
  - OA fan power

All these sensors and meters, as well as the hot water draw simulator, have been calibrated either by their vendors or by ORNL staff onsite at the facility. An automated data visualization and analysis tool has been developed for this project.

3.1.5 Research Capability

The flexible DGSHP system test facility at ORNL is used to (1) test advanced control strategies for water heating of the GS-IHP and (2) evaluate various pumping configurations and controls. Besides, this facility can also be used to support other studies, such as:

- optimizing performance of a virtual-sensing-based low-cost monitoring and fault detection and diagnostics (FDD) system,
- validating results of energy simulation tools and the methods for estimating energy savings,
- evaluating various outdoor air (OA) ventilation designs and controls, as well as their impacts on the overall system efficiency, and
- improving multi-zone variable air supply control of advanced GSHP unit.

3.2 SMART WATER HEATING CONTROL FOR GS-IHP

3.2.1 Background and Introduction

GS-IHPs can provide for building water heating needs in one of the three operation modes: (1) dedicated heat pump water heating (DHPWH); (2) simultaneous water heating with space cooling (SSC&WH); and (3) alternative water heating and space heating (ASH-WH). In addition, when the GS-IHP is not available to provide water heating (e.g., being locked out due to a fault or its full capacity is used to meet the demand for space heating or space cooling), the two backup electric elements installed in the hot water tank can be activated to provide water heating, which is referred as electric element water heating (EEWH). The water heating operation of a GS-IHP unit is controlled with following built-in strategies:

- run in DHPWH mode if room temperature is satisfied (i.e., below the space cooling set point or above the space heating set point), and the water temperature at the lower portion of the water tank is below the hot water tank (HWT) set point minus a deadband (e.g., 15°F),
- run in SSC&WH mode if room temperature is less than 1°F (adjustable) above the cooling set point, the cooling output is less than a user-specified maximum, and the water temperature at the lower portion of the water tank is below the HWT set point minus a deadband,
- run in ASH-WH mode if both space heating and water heating demands coexist. Water heating normally takes priority over space heating. If space temperature drops more than 1°F (adjustable) below the space heating set point, space heating will be activated and water heating will be terminated, and
- run in EEWH mode when the GS-IHP is not available for water heating. If the temperature at the upper portion of the water tank is below the HWT set point minus a deadband, the upper electric element is turned on; or if the temperature at the lower portion of the water tank is below the DHW set point minus a deadband, the lower electric element is turned on. Only one electric element is turned on at a time, and the upper electric element takes higher priority.

In this study, the water heating performance of GS-IHPs resulting from the built-in control strategies was evaluated through a series of tests at the flexible DGSHP test facility. Based on the observed shortcomings of the existing controls, two new control strategies were developed and implemented. Performance of the new controls was tested and compared with the existing controls. The test apparatus and measured performance data are presented below along with conclusions and recommendations.

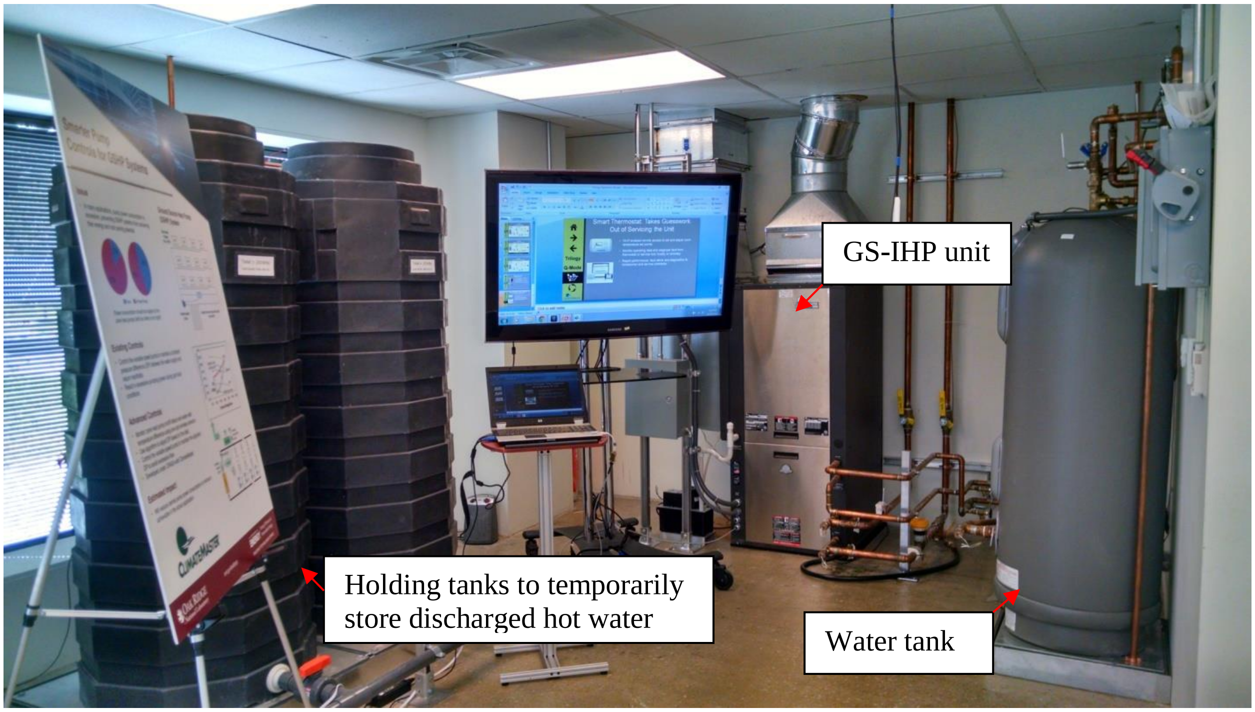
3.2.2 Apparatus for Water Heating Test

The two GS-IHP units have the same apparatus for evaluating their water heating performance. As shown in Figure 9, each apparatus is comprised of a GS-IHP unit, a water tank, and two holding tanks. The hot water draw is automated with a hot water draw simulator. The hot water draw schedules (i.e., the flow rate and duration of each hot water draw) were developed using the Domestic Hot Water Event Generator developed by National Renewable Energy Laboratory (Hendron et al. 2010). This tool can generate a series of year-long hot water event schedules consistent with realistic probability distributions of start time, duration and flow rate variability, clustering, and seasonality. Based on the generated hot water event schedules of a three-bedroom house in Knoxville, TN, three daily hot water use schedules representing low, medium, and high hot water usage are loaded in the hot water draw simulator. The main characteristics of the three daily schedules are presented in Table 2. The discharged hot water is stored temporarily in a holding tank before it is de-chlorinated and dumped into a storm drain outside the building.

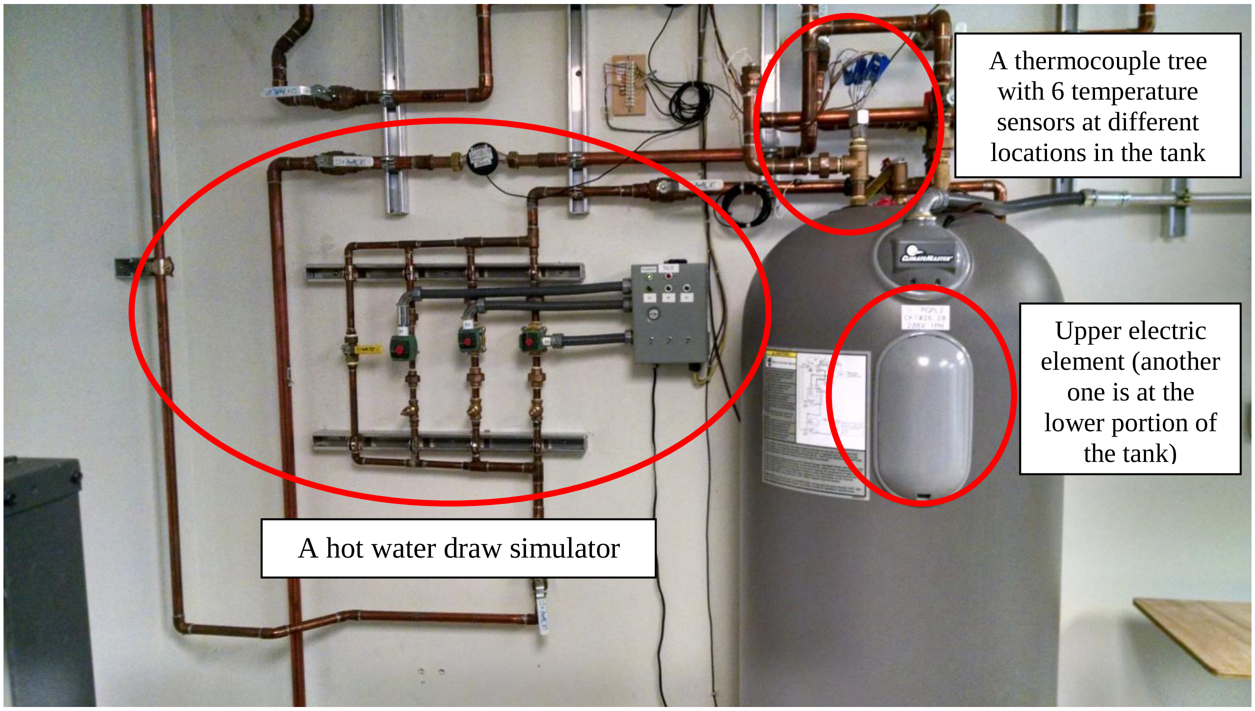
Table 2. Three daily hot water use schedules representing low, medium, and high hot water usage

Schedule	**Max flow rate** (GPM)	**Total hot water draw** (Gallons)	**Max hot water draw** (Gallons/Draw)	**Number of hot water draws** (-)
Low	2.1	29	13.7	14
Medium	2.2	40	8.3	18
High	3.5	107	17.2	24

Figure 10 shows the instrumentation at the hot water tank tied with a GS-IHP unit. A thermocouple tree is inserted into the tank to measure the water temperature at six different locations. Other measurements include the inlet temperature of the city water, outlet temperature of the tank, the delivered hot water temperature (after mixing the hot water from the tank with the city water to reach a given set point), the inlet and outlet water temperature and flow rate of the GS-IHP, and the power consumption of the electric elements.



(a) A GS-IHP unit tied with a hot water tank and a holding tank for discharge hot water



(b) Hot water tank and hot water draw simulator

Figure 9. Apparatus for evaluating water heating performance of GS-IHP.

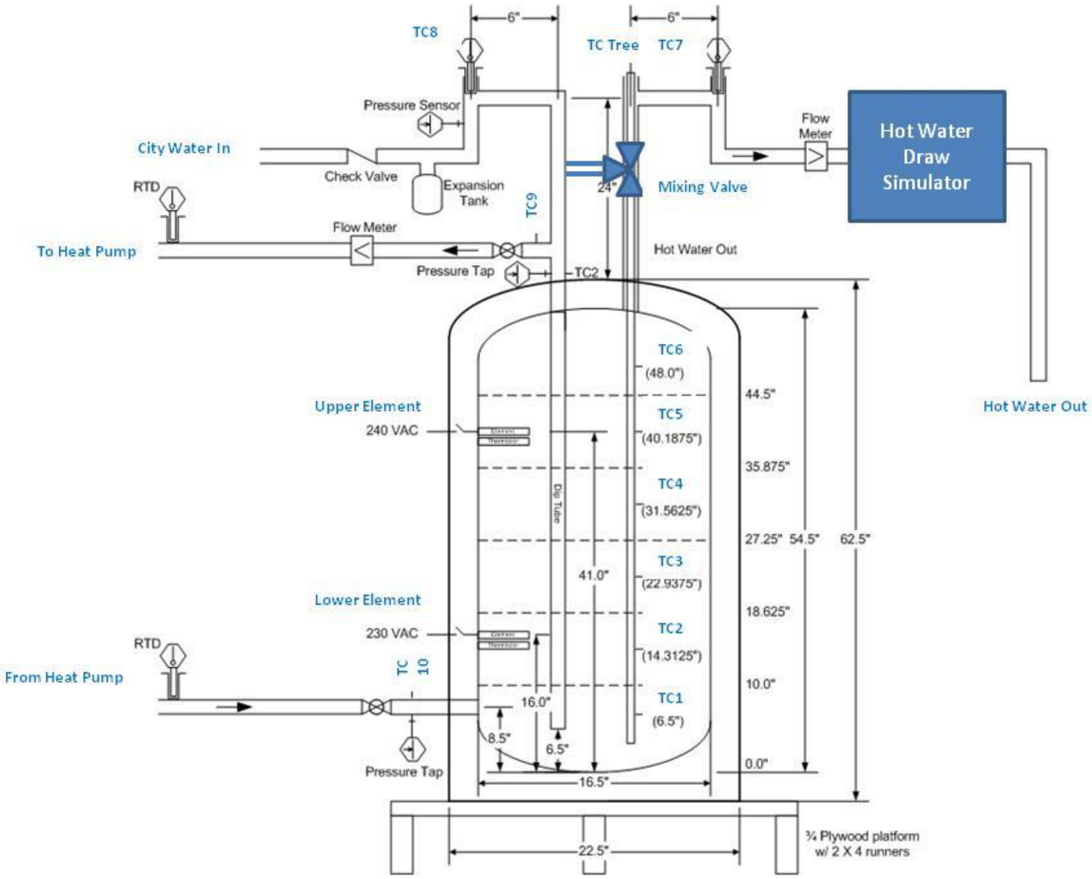
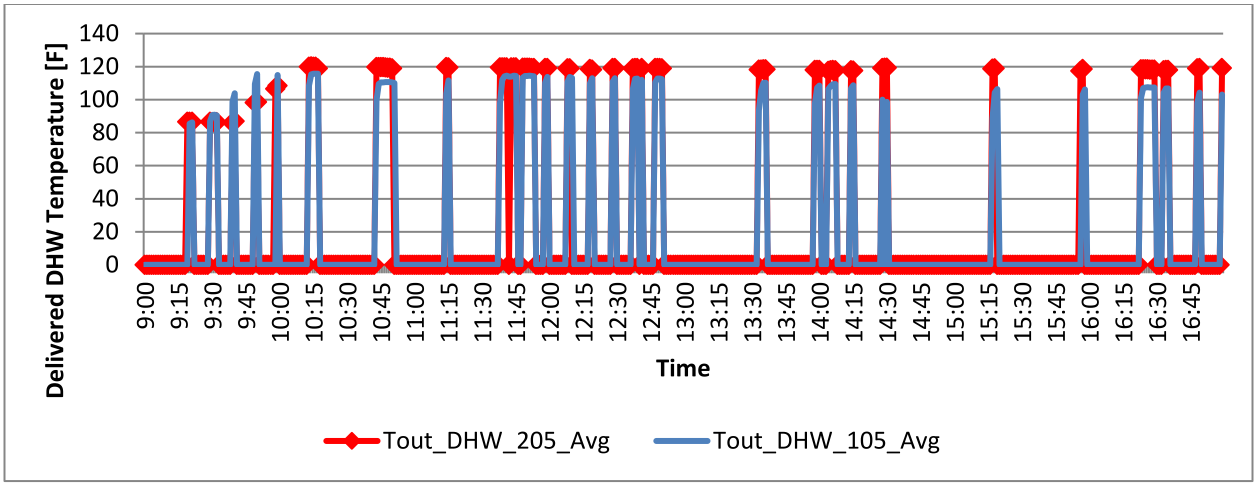


Figure 10. Piping connections and data collection points for the water tank.

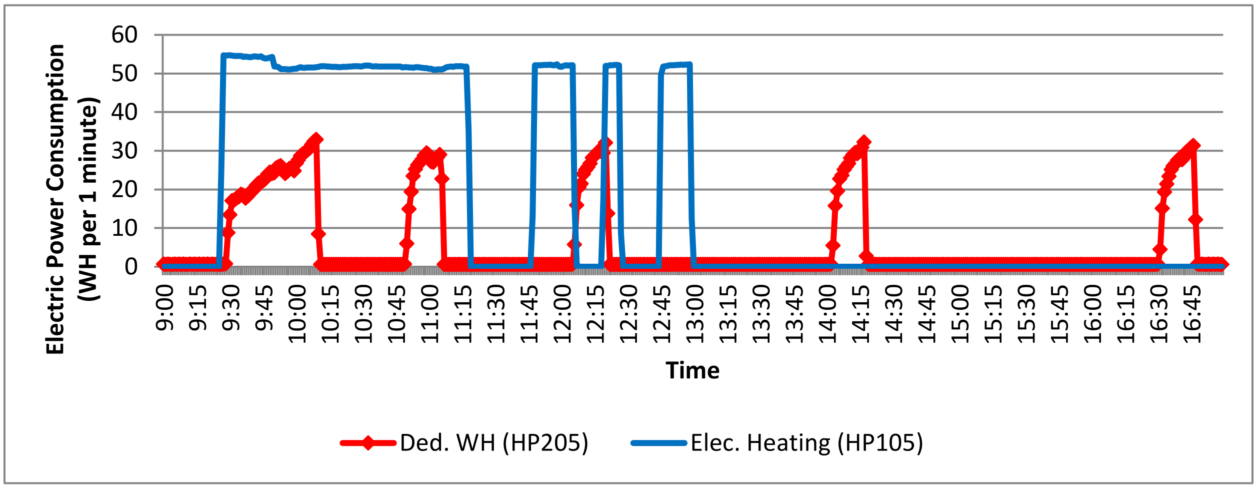
3.2.3 Water Heating Performance with Existing Control

3.2.3.1 Performance Evaluation: DHPWH vs EEWH

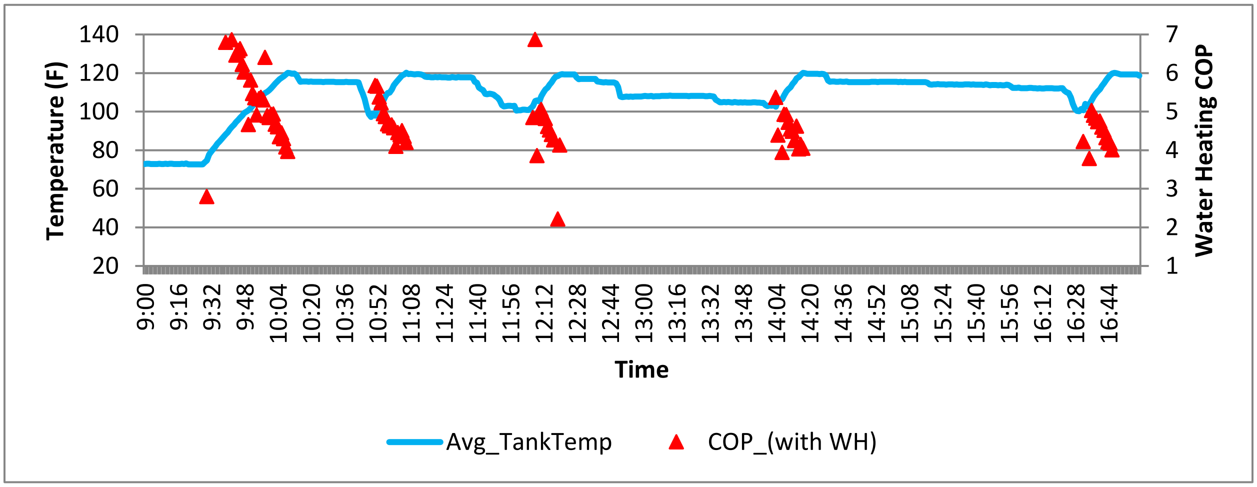
Water heating performance in the DHPWH and EEWH modes was tested with a high daily hot water load (i.e., 107 gallons in total and with a maximum 3.5 GPM hot water draw flow rate). In this test, the GS-IHP in room 105 (referred to as HP105) was turned off and only the two electric elements in the hot water tank were available for water heating in EEWH mode; the GS-IHP in room 205 (referred to as HP205) ran in DHPWH mode. Figure 11 compares the performance of the two water heating operation modes. As shown in Figure 11 (a), hot water delivered by HP205 was maintained at 120ºF for all the hot water draws, which is 10–15ºF higher than that delivered by HP105. In addition, HP205 ran for a shorter time and with about 40% lower power draw than HP105, as shown in Figure 11 (b). The source water supply temperature of HP205 was maintained at 75±1 ºF by the GSE when it ran in DHPWH mode. Figure 11 (c) shows that the water heating COP of DHPWH dropped from 6.8 to 3.8 when the average hot water temperature in the tank increased from 73 to 120ºF. The average water heating COP of the DHPWH operation is about five times higher than that of the EEWH operation.



(a) Domestic hot water supply temperatures



(b) Electricity consumptions



(c) Average hot water tank temperature and water heating COP of HP205

Figure 11. Comparison between the dedicated heat pump water heating with the GS-IHP (HP205) and the electric element water heating (HP105).

HP205 consumed 65% less electricity than HP105 during the day for these tests (Figure 12), which is less than the expected 80% electricity savings suggested by the DHPWH mode water heating COPs shown in Figure 11(c). This is because HP205 provided more heat to the tank than HP105. As shown in Figure 13, while the entire tank was warmed up to 120ºF by HP205 after each DHPWH operation, the water temperature at the lower portion of the water tank of HP105, which is measured by temperature sensors #1 and #2 as shown in Figure 13 (b), was around 70ºF during most time of the day because only the upper electric element was activated and the EEWH operation did not create convection to mix the water in the tank. Thus, the tank water temperature was stratified—cold water at the lower portion and hot water at the upper portion.

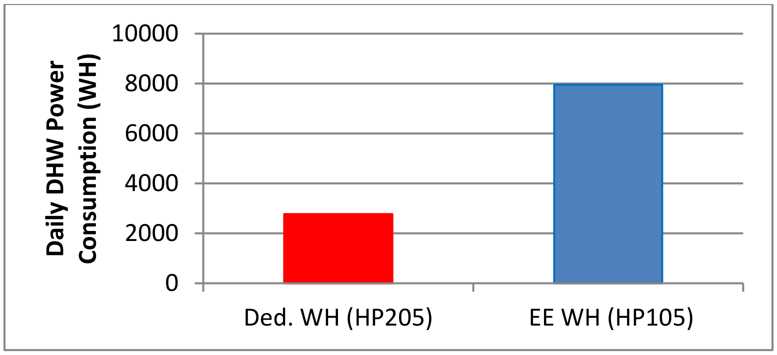
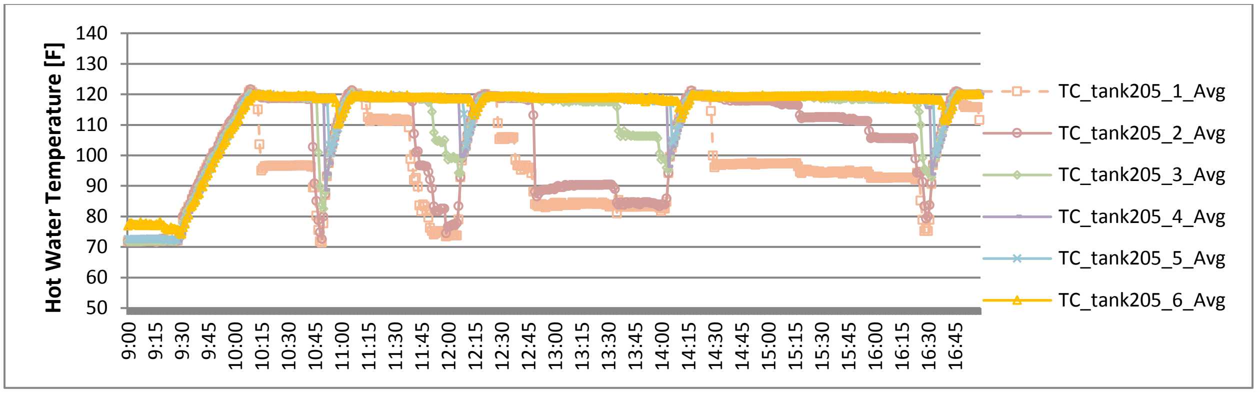
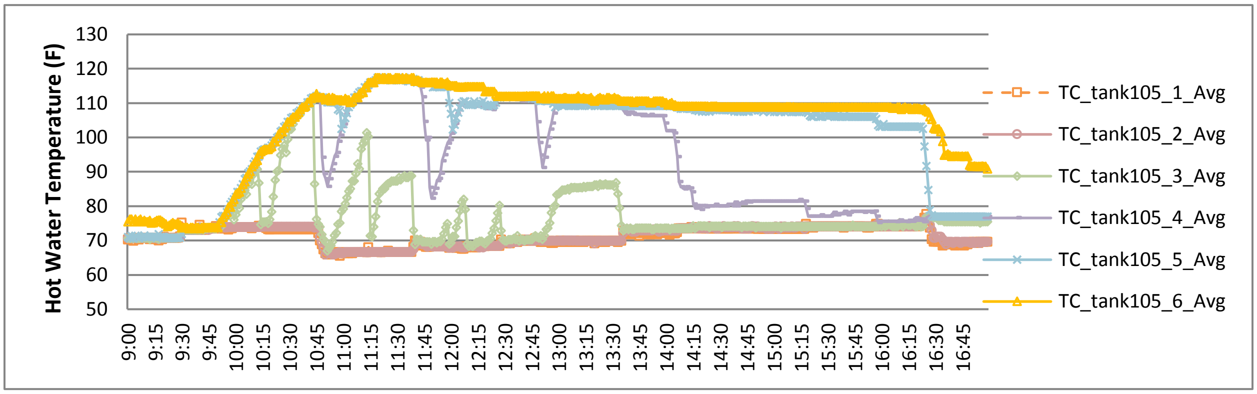


Figure 12. Comparison of daily accumulative electricity consumption between the dedicated heat pump water heating and electric element water heating.



(a) Water temperature at various levels of the water tank of HP205 (DHPWH mode)

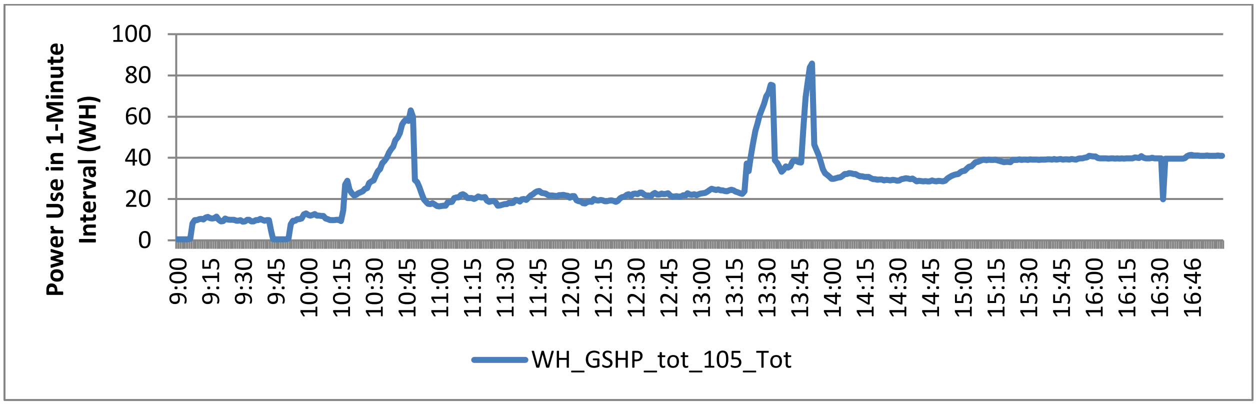


(b) Water temperature at various levels of the water tank of HP105 (EEWH mode)

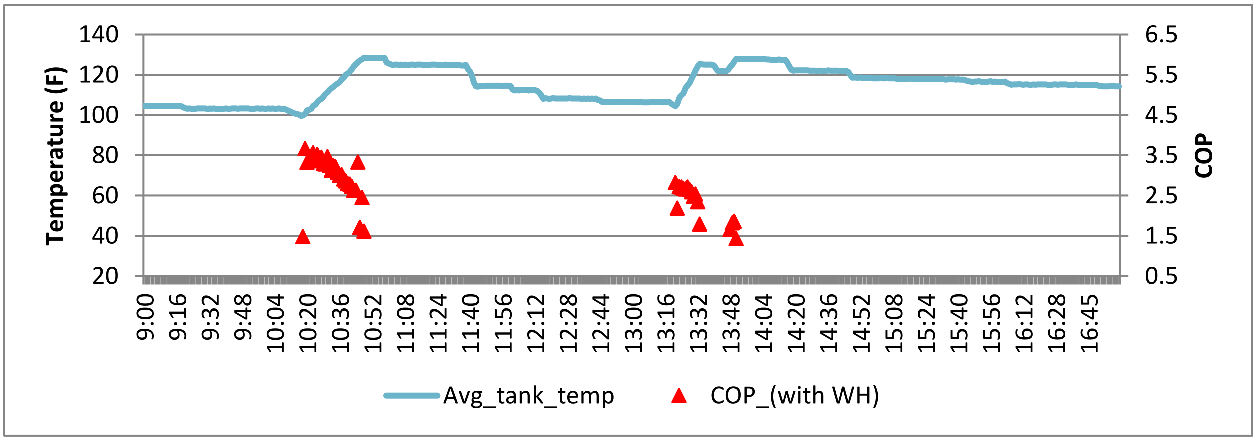
Figure 13. Comparison of water tank temperatures resulting from different water heating operations: (a) dedicated heat pump water heating and (b) electric element water heating.

3.2.3.2 Performance Evaluation: SSC&WH

Performance in the SSC&WH mode was tested with the three different daily hot water loads—light, medium, and high. During an 8-hour test shown in Figure 14, the GS-IHP (in room 105) was supplied with 65±1ºF source water and it ran in the dedicated space cooling (DSC) or SSC&WH mode. The room temperature was maintained at 75ºF by the GS-IHP. Figure 14 (a) shows the measured power consumption of the GS-IHP at each 1 minute time interval. As can be seen from this figure, the power consumption was flat and gradually increased with time (due to increased cooling load in the afternoon), except at three short time periods when the power consumption suddenly surged three to four times higher. These surges resulted from the SSC&WH operation, as indicated by the increase of the average tank temperature during the same time periods. The power surge during SSC&WH operation was due to the switch of source water—from the 65±1°F ground source to the hot water tank, which has a much higher temperature. Figure 14 (b) shows that the combined COP of the GS-IHP, which is the ratio of the total output in space cooling and water heating to the total power input of the GS-IHP, dropped from 3.7 to 1.4 when the average tank temperature increased from 100ºF to 130ºF.



(a)



(b)

Figure 14. An example of GS-IHP operation with existing controls: (a) power consumption and (b) average tank temperature and combined COP of simultaneous space cooling and water heating.

Since GS-IHP can modulate its cooling capacity to match the varying cooling load, it runs continuously when there is any cooling load in the building. If the cooling load is mild (so the room temperature is maintained less than 1°F above the cooling set point), the water heating operation will be in the SSC&WH mode, in which case the water heating output is dependent on the cooling load instead of the water heating load. On the other hand, when the cooling load is high (i.e., the room temperature is more than 1°F above the cooling set point), the existing control gives priority to space cooling and disables the water heating operation of the GS-IHP no matter how cold the water in the tank is. When the tank water temperature dropped below its set point minus a deadband due to water draws or tank heat loss, the electric element in the tank was activated to warm up the water. Since the heat output of the 3 kW electric element was only about 40% of the average water heating capacity of the GS-IHP, the hot water recovery was slow. Experimental test results indicated that the delivered hot water temperature could still be below 100°F even after running the electric element for 20 minutes. This poor hot water supply could be avoided if the GS-IHP is allowed to heat up the tank at an earlier time. It indicates that a more active control for the water heating is needed to eliminate the operation of the electric element.

3.2.4 New Controls

A new water heating control was developed that alternates the space cooling and water heating operation of the GS-IHP based on real time measurements of the room temperature and the water temperature at various depths in the tank. When significant thermal stratification in the water tank is detected (e.g., the lower portion of the water tank is 15°F cooler than the DHW set point), the GS-IHP will run in DHPWH mode until the room temperature is 2°F higher than its set point; then GS-IHP is switched to DSC mode to cool down the room temperature 2°F below the set point. If the tank temperature is still lower than its set point at the end of the DSC operation, GS-IHP will switch back to the DHPWH mode. This alternative space cooling and water heating operation (ASC-WH) continues until the entire tank is warmed up to its set point. This new control eliminates the power surge resulting from SSC&WH operation and reduces or avoids backup electric element operation since the tank is fully charged even when the cooling load is high. Since the DSC operation rejects heat to the ground source, while the DHPWH operation extracts heat from the ground, by alternating these two operations, the ground source can recover quickly from previous operations and thus provide a more favorable temperature for the DSC and DHPWH operations.

In addition, another new control strategy was tested for GS-IHP, which raises the set point (up to 130°F) of the water in the tank if more than 60 gallon daily hot water demand is expected in the coming day. The elevated tank water temperature increases the thermal energy stored in the tank and thus helps reduce or even eliminate the operation of the electric element. The measured performances of the above two new controls are discussed below.

3.2.4.1 Performance Evaluation: SSC&WH vs ASC-WH

Figure 15 shows the ground source supply and return temperature of the GS-IHP at room 105 on 29 July, 2015, when it was operated with the new control to alternate between DSC and DHPWH operations. The ground source supply temperature was maintained at 65±1°F during the day. When the GS-IHP ran in the DHPWH mode, the ground source return temperature was lower than the supply temperature since heat was extracted from the source water and vice versa in the DSC operation. Figure 16 shows the measured power consumptions of the GS-IHP (at each 1-minute time interval) resulting from the existing (SSC&WH) and the new (ASC-WH) controls, respectively. As can be seen from this figure, the new control reduced peak power use by 36% compared with the existing control.

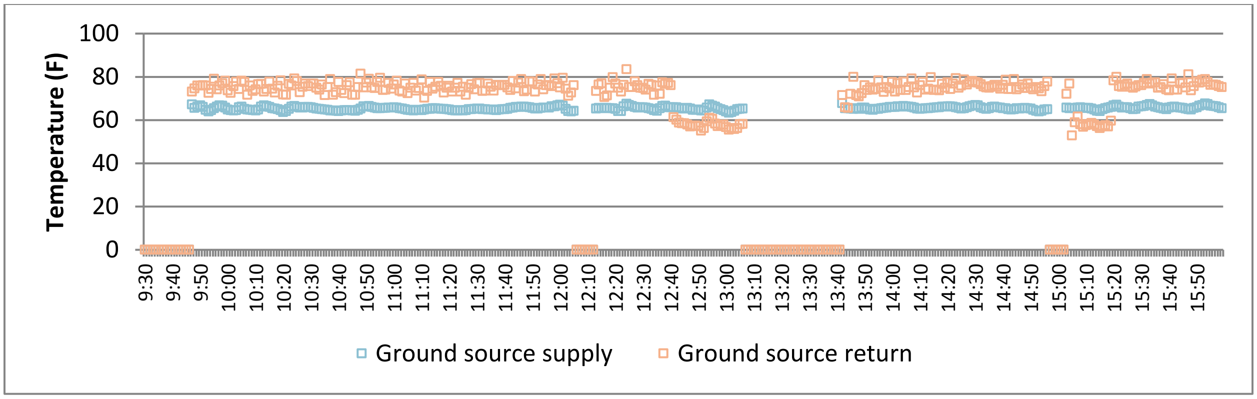


Figure 15. Ground source temperature when GS-IHP was operated with new control (tested on 7/29/2015).

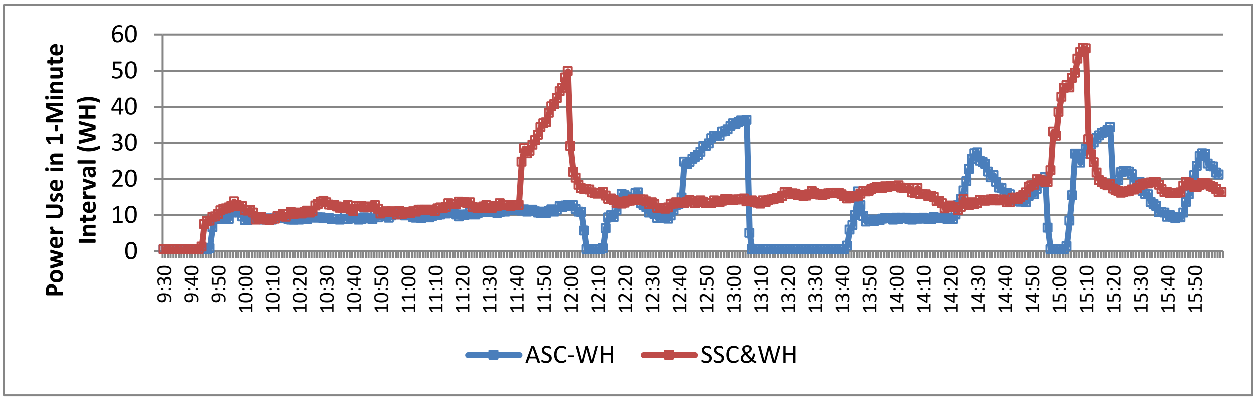


Figure 16. Power consumption of GS-IHP resulting from two different controls.

The daily combined COPs of the GS-IHP resulting from the existing and new controls were calculated with equations (1) and (2), respectively. The results indicated that the new control resulted in a 10% increase (from 4.0 to 4.4) in the combined COP compared with that resulting from the existing control.

$$COP_{Sim} = \frac{Q_{SC} + Q_{WH}}{3.413 \times WH_{SC+WH}}, \tag{1}$$

$$COP_{Alt} = \frac{Q_{SC} + Q_{WH}}{\dfrac{Q_{SC}}{COP_{DSC}} + \dfrac{Q_{WH}}{COP_{DHPWH}}}, \tag{2}$$

where

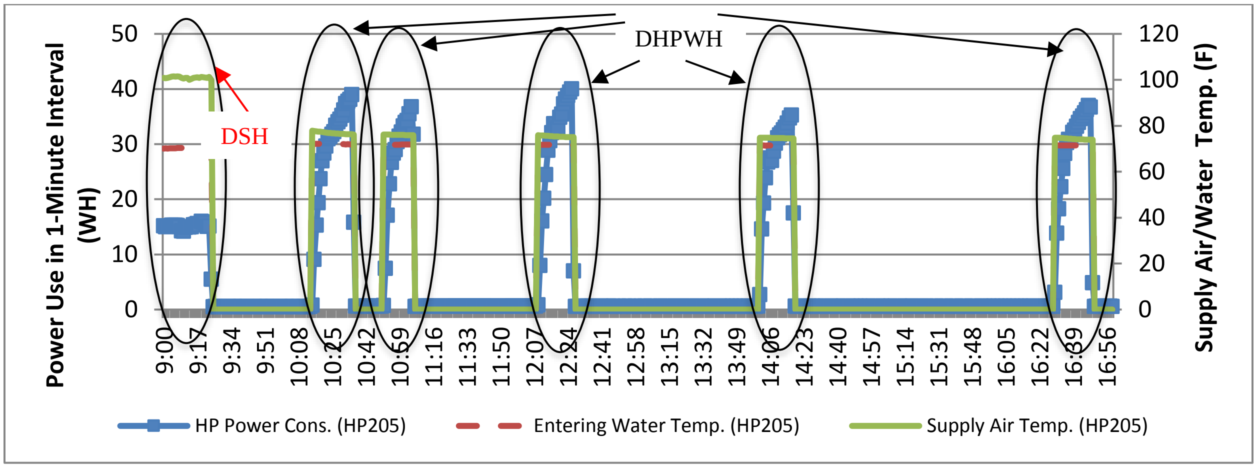
COP_{Sim} is the combined efficiency of SSC&WH mode, Q_{SC} is the space cooling output, Q_{WH} is the water heating output, WH_{SC+WH} is the total power consumption of the GS-IHP when it ran in SSC&WH mode, COP_{Alt} is the combined efficiency of ASC-WH mode, COP_{DSC} and COP_{DHPWH} are the efficiency of the GS-IHP when it ran in DSC and DHPWH modes, respectively.

Further analysis indicates that the combined COP of the SSC&WH is higher than that of ASC-WH when the ground source supply water temperature is higher than 75°F. So, if reducing power consumption is more desirable than reducing peak electricity demand, the SSC&WH operation would be recommended when the ground source supply water temperature is higher than 75°F.

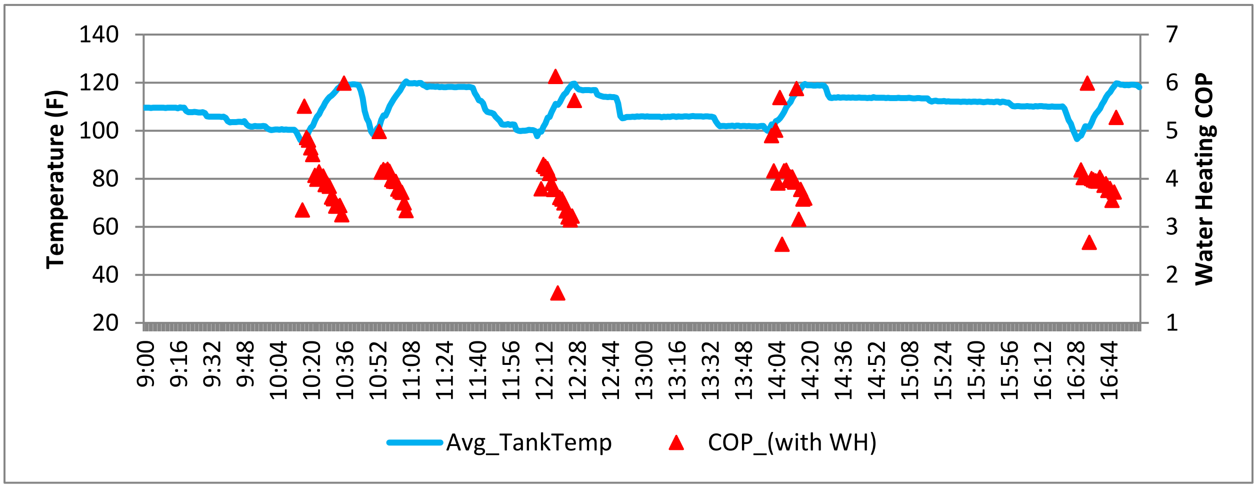
3.2.4.2 Adjust Tank Temperature Set Point Based on Predicted DHW Loads

The impact of the elevated tank water temperature set point on the water heating COP was evaluated by running the two identical GS-IHP units simultaneously but with different tank water temperature set points. The same high hot water draw schedule (Table 2) and ground source supply temperature (50–80°F) were applied to the two GS-IHP units.

Figure 17 shows the measured performance of the GS-IHP unit in room 205 (120°F tank water temperature set point). As shown in Figure 17 (a), the GS-IHP unit ran in two different modes during the day, including five DHPWH operations and a DSH operation. Figure 17 (b) shows that the water heating COP decreased with the increase of the average tank water temperature. The average water heating COP of the five water heating events is 5.1.



(a) Power consumption, water and air side supply temperatures

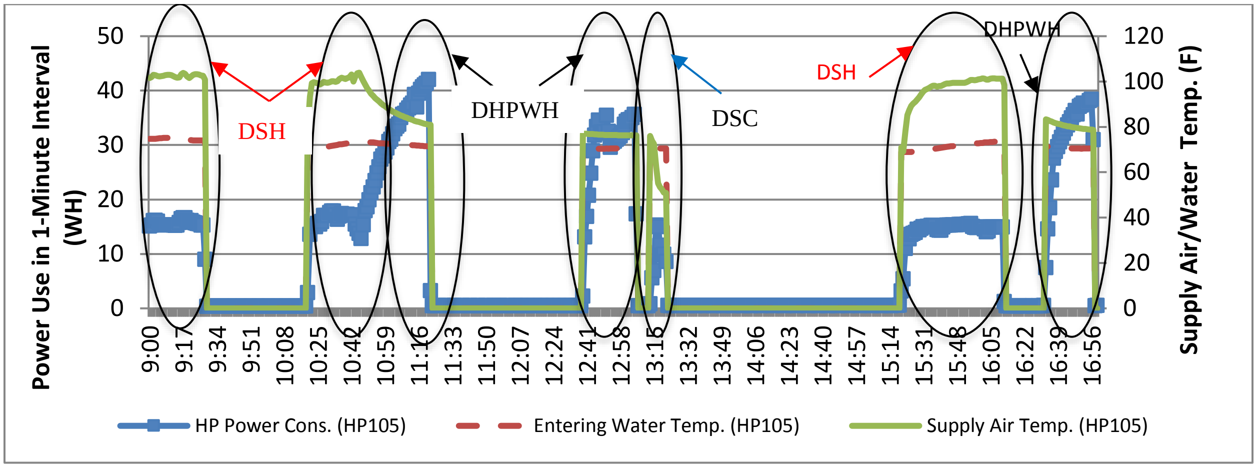


(b) Average tank temperature and water heating efficiency

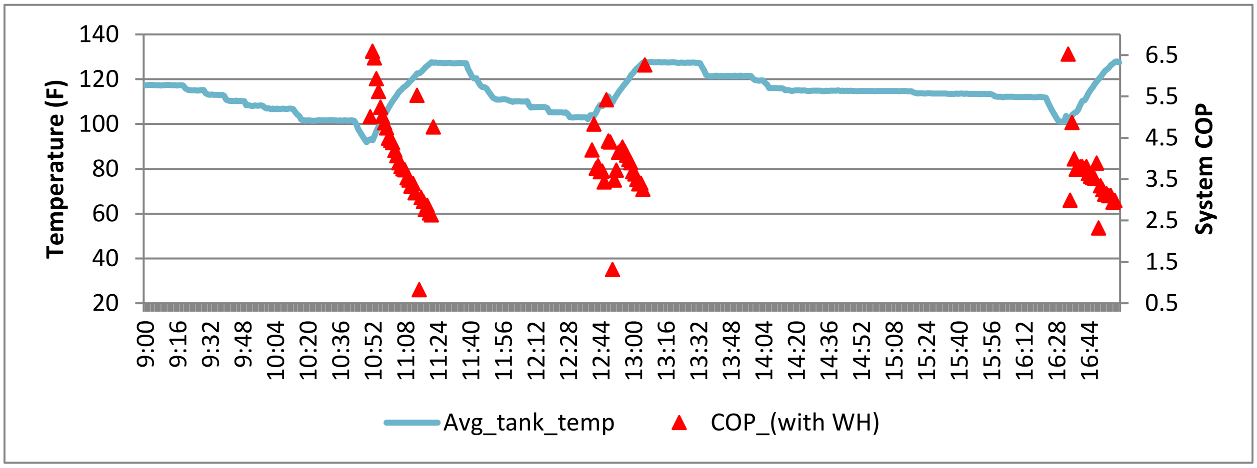
Figure 17. Performance of GS-IHP with 120°F tank temperature set point.

Figure 18 shows the measured performance data of the GS-IHP unit in room 105 (130°F water tank set point). As shown in Figure 18 (a), the GS-IHP unit ran in three different modes during the day, including

DSC, DHPWH, and dedicated space heating (DSH). There were three DHPWH operations during the day. Figure 18 (b) shows that the water heating COP decreased with the increase of the average tank water temperature. The average COP of the three water heating events was 4.6.



(a) Power consumption, water and air side supply temperatures



(b) Average tank water temperature and water heating efficiency

Figure 18. Performance of GS-IHP with 130°F tank temperature set point.

By comparing figures 17 and 18, it can be seen that elevating tank water temperature set point reduced the frequency of water heating cycles because of the increased hot water thermal capacity in the water tank. However, elevating tank water temperature set point reduced the heat pump water heating efficiency as shown in the above case. There was no any backup electric element operation observed at either of the two GS-IHPs during this test, which was conducted on December 18, 2015 when the weather was mild and the demand for space conditioning was low.

However, if space conditioning demand is higher, there could be competitions between the space conditioning and water heating operations. The increased hot water thermal capacity resulting from the elevated tank water temperature could help avoid or reduce backup electric element operation during periods with competing hot water and space conditioning demands. An earlier test performed on October 15, 2015 showed that the backup electric element in the water tank at room 205 was activated in the late afternoon to keep the hot water at 120°F when the space cooling load was high. In contrast, the electric element in the water tank at room 105 was off during the entire test and the tank temperature was maintained by the GS-IHP at about 130°F. As a result, the combined COP for space cooling and water heating of the GS-IHP in room 105 is 6% higher than that in room 205 (5.5 *vs.* 5.2).

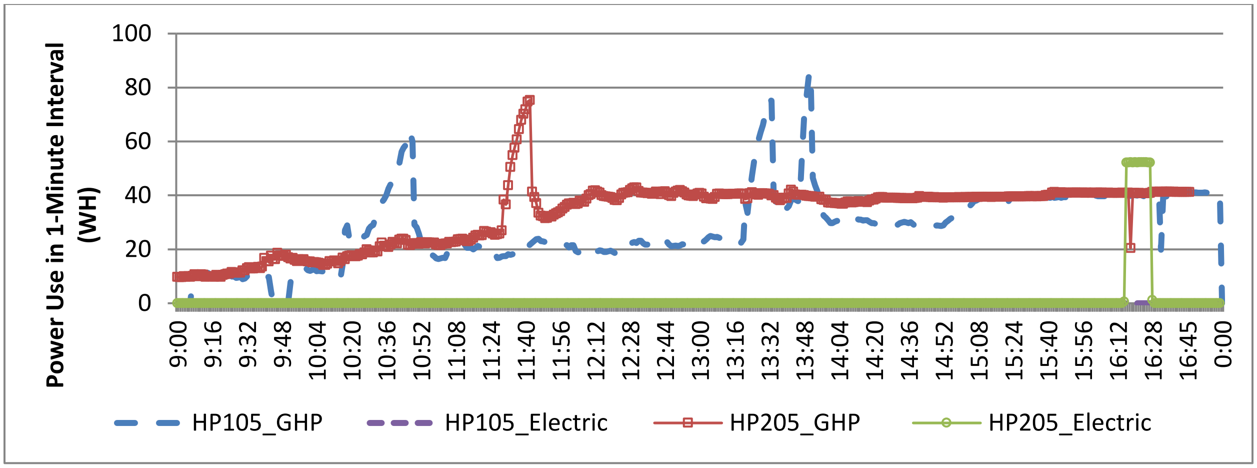


Figure 19. Performance of GS-IHP with 130°F tank temperature set point.

3.2.5 Conclusions and Recommendations

- The DHPWH operation of the GS-IHP is significantly more energy efficient than the EEWH operation. With a 75ºF source water supply temperature, the water heating COP of DHPWH is about five times higher than that of EEWH. In addition, the quality of hot water delivery is better and the recovery time is shorter in DHPWH operation.

- The existing controls of the tested GS-IHPs enabled SSC&WH operation even when the ground source temperature is much lower than the hot water tank temperature. This resulted in power surges, due to the increased pressure lift of the compressor for providing both space cooling and water heating at the same time.

- A new control for GS-IHP was developed that enables ASC-WH operation. This control avoids the power surges resulting from the SSC&WH operation while delivering hot water as needed and maintaining room temperature within a wider (but acceptable) range. Furthermore, this control significantly reduces or even eliminates the operation of the electric elements since the water tank is fully charged even when cooling load is high. Experimental test results indicated that this new control improved the combined COP of the GS-IHP for space cooling and water heating by 10% compared with the existing control when the ground source supply water temperature was 65ºF. However, the SSC&WH operation may have a higher combined COP than the ASC-WH operation when the ground source supply water temperature is higher than 75°F.

- Elevating the tank water temperature increased the stored hot water capacity and thus reduced the frequency of water heating operation. This could help avoid or reduce backup electric element operation during periods of high hot water demand. However, elevating tank water temperature set point will reduce the water heating efficiency when hot water demand is low.

3.3 SMART PUMPING CONTROL

3.3.1 Background and Introduction

Most commercial building and large multi-family residential building GSHP systems in the United States are in a distributed or DGSHP configuration. In a DGSHP system, each zone of the building is conditioned with an individual water source heat pump (WSHP) unit each connected in parallel through a common water loop. Each zone heat pump can be turned on and off independently to satisfy the varying heating or cooling load in the zone it serves. A two-way solenoid valve is usually installed at each heat pump, and this valve will be closed to block the water flow when the heat pump is not in operation and vice versa. Variable speed pumps are commonly used in DGSHP systems and controlled to maintain a fixed differential pressure (DP) either across supply-return mains or at the WSHP unit hydraulically furthest from the central pump, as shown in Figure 20.

Although variable speed pumps have potential to reduce pumping energy, field studies of installed DGSHP systems (Henderson et al. 2000; Kavanaugh and Kavanaugh 2012) indicated that most variable speed pumps did not operate at expected low speeds during part load conditions and excessive pumping energy use is a common issue. Recent case studies of six new commercial DGSHP systems indicate that pumping power contributed 16% to 45% to the total power consumption (Liu et al. 2015). The high pumping energy use resulting from the excessive pumping led to a lower-than-expected operational efficiency of the DGSHP systems, especially when building heating and cooling loads were not at peak. Reducing pumping energy use is crucial for improving the operational efficiency of DGSHP systems.

It was found that the excessive pumping during part load conditions was due, at least in part, to the conventional control strategy for the variable-speed pump, which modulates pump speed to maintain a fixed DP across the supply-return mains of the piping system. This DP set point is usually arbitrarily determined and often much higher than needed (Henderson et al. 2000; Moore and Fisher 2003; Su et al. 2013). At part load conditions when some individual WSHP units are shut off, the water flow to these units is usually blocked off, and thus the total water flow demand of the DGSHP system is reduced. With the reduced system water flow, the hydraulic resistance of the main pipelines of the piping system decreases. However, since a fixed DP is maintained between the supply-return mains, the reduced hydraulic resistance at the main pipelines must be offset by the increased resistance at each operating WSHP unit. When there is not any flow regulating valve at the WSHP unit (to automatically adjust its hydraulic resistance), more-than-needed water flow will be pumped through the operating WSHP unit(s). Lowering the DP set point can significantly reduce system flow rate and the associated pumping energy use, but a DP set point that is too low will result in significant underflow in operating WSHP units, especially at high loading conditions, resulting in low operational efficiency and potentially damage to those units. Dynamically resetting DP is recommended in 2015 *ASHRAE Handbook for HVAC Applications* (ASHRAE 2015), but no specific recommendations on how to do so are provided.

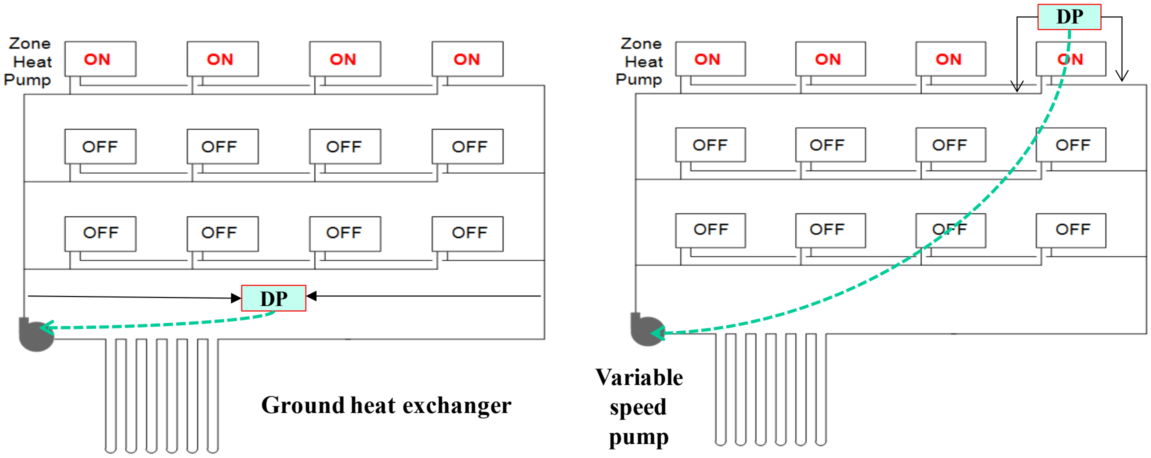


Figure 20. Configuration of a typical DGSHP system with a central pump controlled to maintain (a) a fixed differential pressure across supply-return mains and (b) a fixed differential pressure across the hydraulically furthest WSHP unit.

A new control for the variable speed pump was developed in this project (**patent pending**). It utilizes the available design parameters of the individual WSHP units and real time measurements from a few additional temperature sensors to determine the needed system water flow rate at any given time and automatically adjusts the DP set point based on the system water flow demand and the characteristics of the hydraulic resistance of the piping system. The DP set point is then further refined based on the measured temperature difference at each operating WSHP unit to ensure proper water flow is delivered to them.

A simulation-based study was performed to compare the performance of the conventional and the new pumping controls and assess the energy saving potential of improving pumping controls. A brief summary of this study is presented in the next section, and more detailed information can be found in a technical paper (Niu, Liu, and O'Neill 2016). Both the conventional and the new pumping controls were implemented and tested at ORNL's flexible research platform for DGSHP systems. The experimental tests and the main findings are introduced in section 3.3.3.

3.3.2 Simulation-based Study

A computer model for a simplified DGSHP hydronic piping system was developed using Modelica model (Modelica 2015) on the Dymola platform (Dassault 2015). The component models of the hydronic piping system were adapted from LBNL's Modelica Building Library V1.6 (Wetter et al. 2014). Three different pumping control strategies were simulated, including the two pressure-based conventional controls and the new flow-demand-based control.

The simulation results indicate that a significant overflow occurs at part load conditions when the pump is controlled to maintain a constant DP across the supply-return mains of the piping system. On the other hand, an underflow occurs at part load conditions when the pump is controlled to maintain a constant DP across the furthest WSHP unit. The flow-demand-based control can provide the needed flow rate to each WSHP unit at any given time and with less pumping energy use than the two conventional controls. A case study for applying the new pumping control to a typical DGSHP system serving a medium size office building indicates that the annual pumping energy consumption can be reduced by 64% if the new control is used to replace the conventional control, which is to maintain a constant DP across the supply-return mains (Niu, Liu, and O'Neill 2016).

3.3.3 Experimental Tests

Both the conventional and the new pumping controls were implemented at the DGSHP system flexible test facility. The hydronic piping system of the DGSHP system was balanced by adjusting the hydraulic resistance of each parallel loop to ensure the needed (design) water flow rate can be delivered to each of the four individual heat pump units when all of them are in operation (i.e., at full load condition). A series of tests were conducted to (1) validate the Modelica model and (2) verify the energy savings achieved by the new pumping control.

3.3.3.1 Validation of the Modelica Simulation Results

All the 15 possible combinations of the on/off status of the four WSHP units were set up successively at the experimental DGSHP system. The central pump was controlled with the two conventional control strategies to maintain a constant DP across (1) the supply-return mains (referred as DP1 henceforth) or (2) the hydraulically furthest WSHP unit (referred as DP2 henceforth). The set points for DP1 (14.8 ft of H_2O) and DP2 (6 ft of H_2O) are the measured values of DP1 and DP2 at the full load condition after the piping system is balanced. The measured pumping performance data include DP1 and DP2, the flow rate in each WSHP unit, pump power consumption, and the frequency of the electric power supplied from the VFD.

The hydronic piping system was modeled with the Modelica program. Figure 21 shows a graphical presentation of one of the computer models, in which the conventional control with fixed DP across the supply-return mains is modeled. The modeled piping system is comprised of several components, including the main pipes, which distribute water flow to multiple WSHP units, and branch pipes dedicated to particular heat pump units. Each WSHP unit was modeled as a hydraulic resistance, which varies with the unit water flow rate. The hydraulic resistance of each component of the modeled piping system at full load condition is estimated based on the measured values of DP1 and DP2 during the balancing process and listed in Table 3. The central pump was modeled based on its performance data provided by the pump manufacturer.

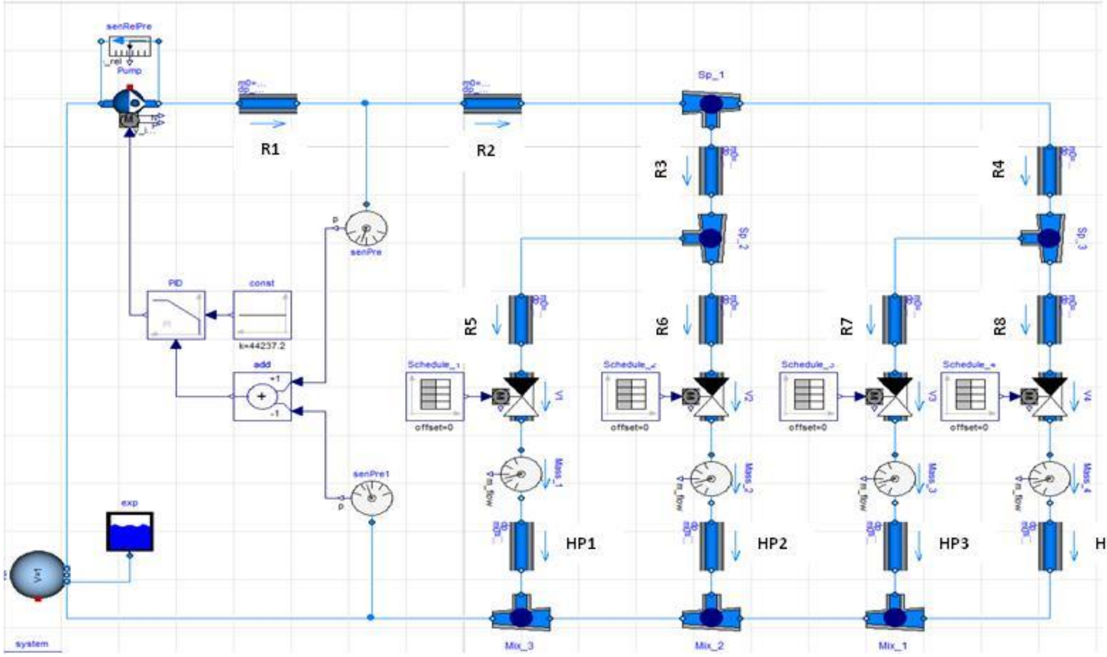


Figure 21. A representation of the experimental DGSHP system modeled with the Modelica program.

Table 3. Hydraulic resistance of each component of the modeled hydronic piping system at full load condition

Section name	R1	R2	R3	R4	R5	R6	R7	R8	HP1	HP2	HP3	HP4
Hydraulic resistance (ft H_2O)	7.1	1.4	1.4	1.4	6	6	6	6	6	6	6	6

The pumping energy saving potential (PESP) is determined by comparing the actually measured pumping power to what would have been if the design water flow were delivered to each operating individual WSHP unit, which is calculated according to the affinity law as expressed in following equation.

$$\mathrm{PESP} = 1 - \left(\frac{\mathrm{Fl\_Exp}}{\mathrm{Fl\_Mea}}\right)^3, \tag{3}$$

where

Fl_Exp and Fl_Mea are the expected and the measured flow rate in the piping system, respectively.

Figure 22 shows a comparison between the measured and the simulation-predicted pumping performance when the pump is controlled to maintain DP1 at a fixed set point. As can be seen in this figure, the Modelica simulation correctly predicted the overflow, and the discrepancy between the measured and simulation-predicted maximum overflow percentages was less than two percentage points (8.5% *vs.* 9.9%). Thus, the PESPs calculated with the measured and simulation-predicted overflow percentages are close to each other (21.7% *vs.* 24.6%).

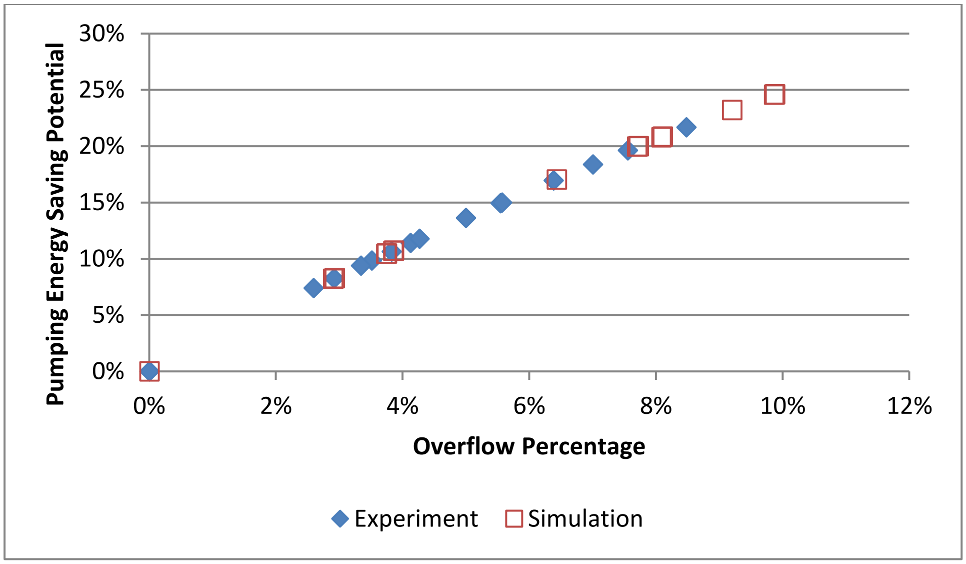


Figure 22. A comparison between the measured and simulation-predicted pumping performance when the pump is controlled to maintain a fixed differential pressure across the supply-return mains.

Both the measured data and simulation results indicate that the overflow increases with a decrease of the part load ratio (PLR), which is the ratio of the expected system water flow at a given time (depending on which individual WSHP units are running) to the system water flow when all the WSHP units are in operation. Furthermore, for a given PLR, the degree of overflow depends on the locations of the operating units—the further away from the central pump, the more significant overflow.

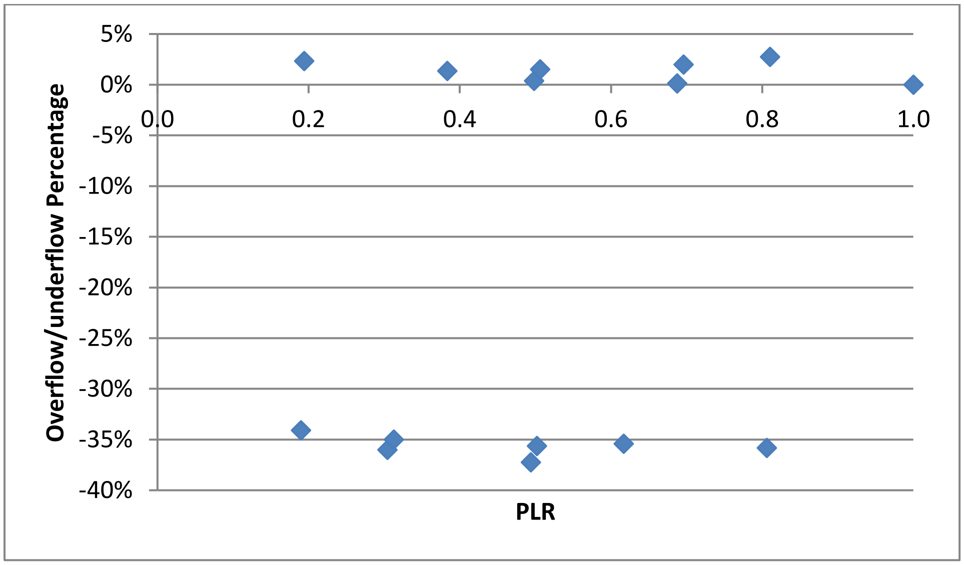


Figure 23. Measured overflow or underflow when the pump is controlled to maintain a fixed differential pressure across the furthest operating WSHP unit.

Figure 23 shows the experimental results of the overflow or underflow at various PLRs when the pump was controlled to maintain DP2 at a fixed set point. As shown in this figure, this pumping control resulted in slight (<5%) overflow or significant (>30%) underflow for a given PLR. The significant underflow occurred when the water flow to the hydraulically furthest WSHP unit, where the DP2 sensor is located, was blocked off. However, only a little overflow occurred at each operating WSHP unit if water flow was not blocked off. It indicates that, to prevent underflow, continuous water flow is needed at the hydraulically furthest WSHP unit in the DGSHP system no matter whether it is called on or not. Although the reduced overflow resulted in lower pumping power, the continuous water flow at the furthest heat pump unit offset some of the pumping energy savings.

The observed overflow and the corresponding PESP are moderate at the experimental DGSHP system (serving a 3,200 ft^2 building). This is due to the short main pipes for distributing water flow to the multiple individual heat pumps, of which the head loss is affected by PLR. These short main pipes have low hydraulic resistances (see R2, R3, and R4 in Table 3) and thus only account for a small fraction of the needed DP1. Therefore, the needed DP1 does not change much under part-load conditions, as does the system flow rate.

In order to assess the PESP for typical DGSHP systems, the piping system of a DGSHP system serving a medium-size office building (with 53,628 ft^2 floor space) was simulated with the Modelica model. The predicted pumping performance with this typical DGSHP system is shown in Figure 24 along with that for the experimental DGSHP system. As shown in this figure, both the overflow and the PESP are much more significant (about 80%) in the typical DGSHP system.

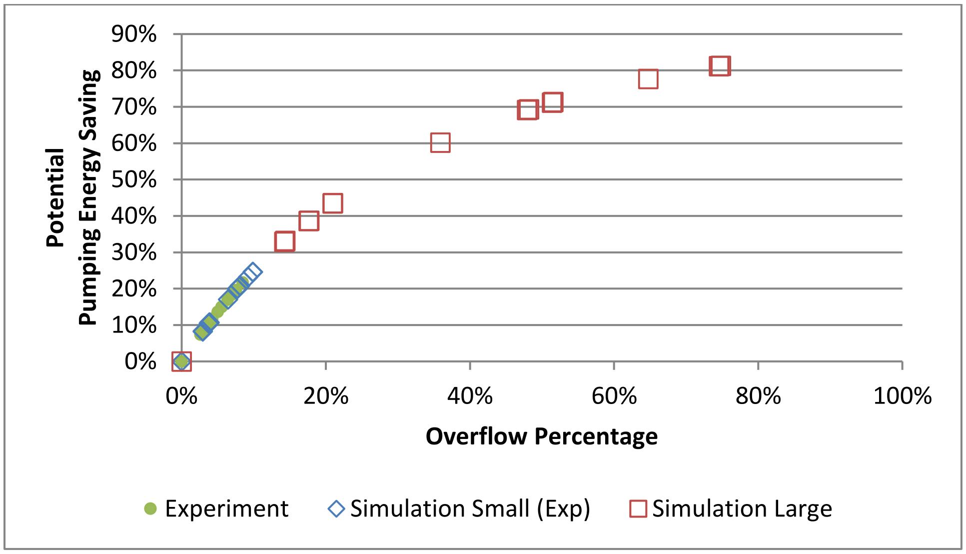


Figure 24. Simulation-predicted pumping performance of a typical DGSHP system when the pump is controlled to maintain a fixed differential pressure across the supply-return mains.

3.3.3.2 Implementation of the Smart Pumping Control

Below is a step-by-step procedure of the flow-demand-based pumping control.

1. Set the initial set point of DP1 (e.g., the measured value of DP1 when the piping system is balanced and all individual heat pump units are supplied with the needed water flow).

2. When the DGSHP system is running, determine the system flow demand at each time interval (e.g., every minute) based on the on/off status and the design flow rate of each individual WSHP unit.

3. If the system flow demand is different from it was at the previous time interval, change the DP1 set point based on the new system flow demand and the hydraulic characteristic of the piping system.

4. Refine the DP1 set point according to the measured water side temperature difference (WSTD) at each operating WSHP unit.

    - If the WSTD of any WSHP unit is greater than a predefined upper bound (e.g., 12°F), the DP1 set point will increase gradually at small intervals until the WSTDs of all the running WSHP units are below the upper bound.
    - If the WSTD of any WSHP unit is less than a predefined lower bound (e.g., 8°F), the DP1 set point will decrease gradually at small intervals until the WSTDs of all the operating WSHP units are above the lower bound.
    - When some WSTDs are above the upper bound but other WSTDs are below the lower band, the DP1 set point will increase until all the WSTDs are below the upper bound.

The hydraulic characteristic of the piping system is defined here as a correlation between the system flow demand and the required DP1 to deliver such a flow. This correlation can be roughly determined after balancing the piping system at full load condition. First, close the two-way valves of a few WSHP units to block off water flow through these units and then manually adjust the DP1 set point until the expected system flow is delivered, which can be verified by a fixed or portable flow meter. Repeat this process several times by blocking off different WSHP units (to mimic a range of part-load conditions) to determine the DP1 set points for delivering the expected system flows at various part-load conditions.

The on/off status of an individual WSHP unit can be obtained from the building's energy management system or by examining the air-side supply temperature at each unit. Additional temperature sensors are needed if the above information is not available. Wireless temperature sensors may be more convenient and cost-effective for implementing the flow-demand-based control for existing DGSHP systems. Figure 25 shows a diagram of the flow-demand-based pumping control that uses wireless sensors for measuring WSTD at each WSHP unit.

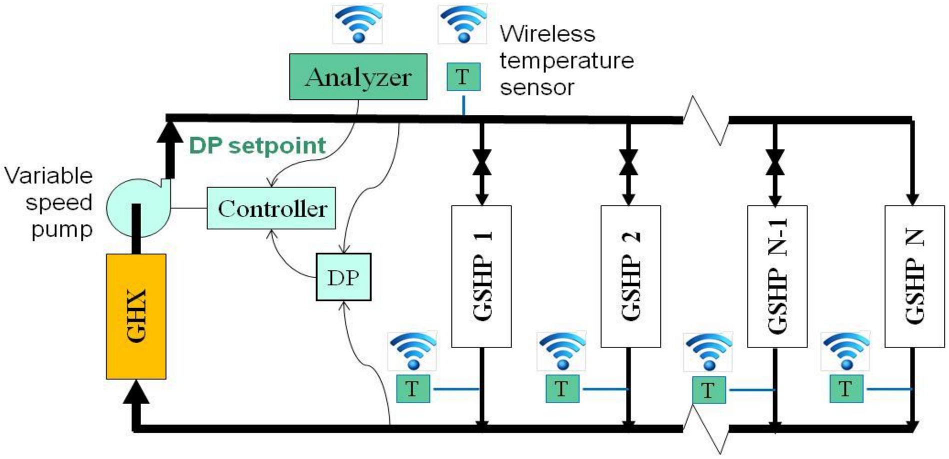
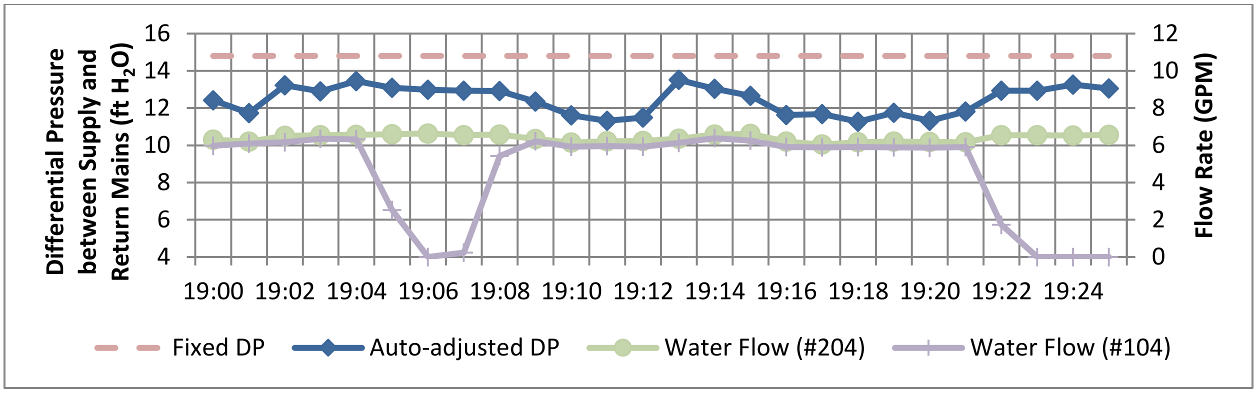


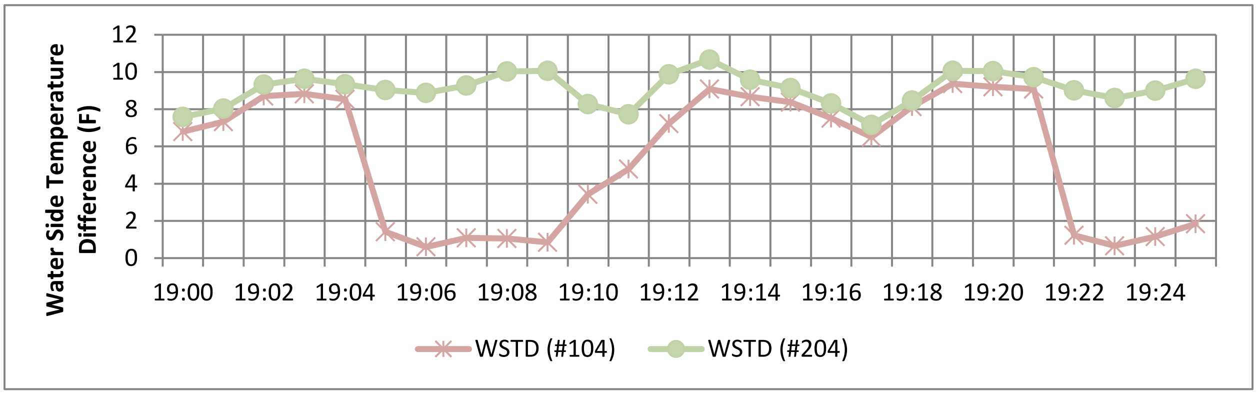
Figure 25. Flow-demand-based pumping control for DGSHP systems (patent pending).

3.3.3.3 Lab Test of the Smart Pumping Control

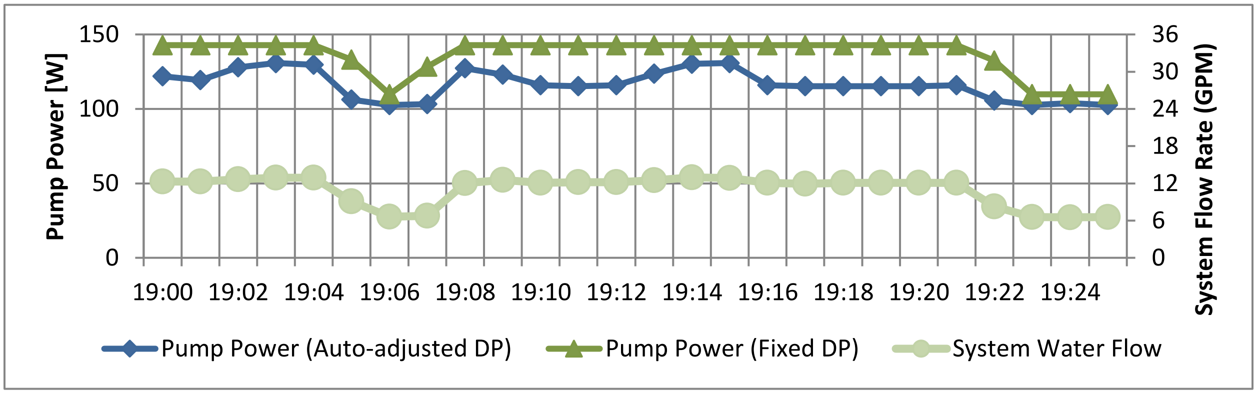
The smart pumping control has been tested at ORNL's experimental DGSHP system. Figure 25 presents the results of one of the tests. In this test, one 2-ton heat pump unit (#204 with 6 GPM design flow rate) was running continuously and the other 2-ton unit (#104 with 6 GPM design flow rate) was turned on and off at different times. When only one 2-ton unit was turned on, the PLR was 0.2 and with both running the PLR was 0.4. As shown in Figure 26(a), DP1 was automatically modulated and kept below the initial DP1 set point, which was 14.8 ft and needed to deliver the designed flow to each heat pump unit when all of them were running. The WSTDs were maintained between 7.5 and 10.5°F during the test, as shown in Figure 26(b). Since the DP1 set point is automatically adjusted, WSTDs can be maintained within the same range no matter whether the individual WSHP units run in heating or cooling mode. In contrast, with the conventional fixed DP control, WSTDs will be lower in heating mode (indicating overflow) than in cooling mode since the water side heat transfer rate is smaller when the individual zone heat pumps run in heating mode. Figure 26(c) shows that the smart pumping control resulted in a lower pumping power than that resulting from the fixed DP control. The maximum pumping power reduction was 19% during this test. Cumulatively, the pump consumed 14% less electricity compared with that resulting from the fixed DP control for meeting the same flow demands. As discussed in section 3.3.3.1, more pumping energy savings could be achieved for DGSHP systems with a larger piping system (i.e., with higher hydraulic resistance).



(a)



(b)



(c)

Figure 26. A sample of lab test results of the smart pumping control.

3.3.4 Conclusions and Recommendations

Both computer simulations and lab tests indicate that the conventional pumping control of DGSHP systems, which is to maintain a constant DP across either the supply-return mains of the hydronic piping system, or the hydraulically furthest zone heat pump unit at the piping system, results in excessive pumping or significant underflow under part-load conditions. It unnecessarily increases the pumping energy and can potentially result in failure of individual zone units. The newly developed smart pumping control can deliver the needed water flow to each zone WSHP unit with less pumping energy by automatically adjusting the DP set point based on the system flow demand.

Lab tests of the smart pumping control indicate that 14% of the pumping energy can be saved in the small-scale experimental DGSHP system. A simulation-based case study indicates that the annual pumping energy consumption of a typical DGSHP system serving a medium-size office building can be reduced by 62% with the smart pumping control compared with the conventional control, which maintains a fixed DP across the supply-return mains of the piping system.

It is recommended that the smart pumping control be implemented at an existing commercial DGSHP system to demonstrate its benefits. Wireless temperature sensors with lower cost, more robust communication and better reliability need to be identified or developed, which will improve the performance and cost-effectiveness of the smart pumping control. In addition, since the efficiency of a zone WSHP unit is affected by the water flow rate, the smart pumping control could be further developed to minimize the total power consumption of both the individual heat pump units and the central pump.

4. SUBJECT INVENTIONS

The conventional variable speed pumping control for DGSHP systems results in excessive pumping or significant underflow under part-load conditions. It unnecessarily increases the pumping energy consumption and can potentially result in premature failure of individual zone heat pump units. The high pumping energy use resulting from the excessive pumping leads to a lower-than-expected operational efficiency of DGSHP systems, especially when building heating and cooling loads are not at peak. Reducing pumping energy use is crucial for improving the operational efficiency of DGSHP systems.

The invention (patent pending, Invention Disclosure #: 201403380, DOE S number: S-138,004) developed through this study is a new control system for the variable speed pump used in DGSHP systems. This new control can dynamically adjust the DP set point at real time based on the on/off status of each GSHP unit and deliver only the needed water flow to each operating zone heat pump units. The on/off status of the individual zone units can be obtained from the building's energy management system, or additional measurements of the air- or water-side temperatures at each unit.

This new control system can reduce or even eliminate overflow or underflow in any zone unit of a DGSHP system. In addition, unlike the conventional pumping control systems, this new control system does not require any bypass flow. Therefore, it has potential to significantly reduce pumping energy and thus improve the operational efficiency of DGSHP systems. This new control system may also be used to identify abnormal operation of individual zone units and the circulation pump.

Computer simulation predicts that significant pumping energy savings can be achieved with this new pumping control. A simulation-based case study indicates that the annual pumping energy consumption of a typical DGSHP system serving a medium-size office building can be reduced by 62% with the new pumping control compared with the conventional control, which maintains a fixed DP across the supply-return mains of the piping system.

The convenience and cost effectiveness of implementing this new pumping control, especially for retrofitting existing pumping control, could be improved by using wireless temperature sensors that have low cost, reliable measurement, and robust communication. Besides, by integrating with performance modeling of GSHP units and proper optimization algorithms, this control system can be further developed to minimize the total energy consumption of the entire DGSHP system.

5. COMMERCIALIZATION POSSIBILITIES

As described before, this newly invented pumping control system can effectively address the shortcomings of the conventional pumping controls. Although this project focus on its application in DGSHP systems, this pumping control system can be used in other HVAC systems that use hydronic pumping systems, and even some industry processes involve hydronic pumping. It is estimated that this new pumping control system can reduce pumping energy use of existing HVAC systems by 50%. Based on this and other information from DOE's Building Energy Data Book (DOE 2009), it is estimated that this new pumping control system can save 51 Trillion BTU primary energy each year in the US, which also means an annual reduction of 3.4 million tons of CO_2 emissions.

The new pumping control system has been introduced in the annual conference of American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) in 2016. Similar pumping control (e.g., the Grundfos Hydro MPC integrated pumping systems[1]) has been presented in a major trade show in early 2017. ClimateMaster expressed interest in commercializing the new pumping control system developed in this study. It is planned to install the new pumping control system in an existing commercial DGSHP systems to demonstrate its benefits. Field demonstration of the new pumping control could also be held in China, where 1.1 billion square meters (12 billion square foot) more buildings will be conditioned with GHP systems from 2016 through 2020 per China's Economic and Social Development Plan for the 13th Five-Year Period[2].

6. PLANS FOR FUTURE COLLABORATION

The research team plans to work with ClimateMaster to further improve the new pumping control systems. The planned collaborations include (1) development of new wireless temperature sensors that have low cost, reliable measurement, and robust communication; (2) integration with performance modeling of GSHP units and proper optimization algorithms to minimize the total energy consumption of the entire DGSHP system; and (3) field demonstration of the new pumping control systems applied in commercial DGSHP systems.

7. CONCLUSIONS

GSHPs are a proven technology that utilizes clean and renewable geothermal energy, as well as the massive thermal storage capacity of the ground, to provide space conditioning and water heating for both residential and commercial buildings. It has a higher energy efficiency than conventional space conditioning and water heating systems. It is estimated that a reduction of 0.6 Quad Btu in primary energy consumption and 36 million tons in carbon emissions will be realized each year if GSHP achieves a 10% market share in the United States. However, the current market share of GSHPs in the United States is less than 1%. To enable wider adoption of GSHPs, the cost-effectiveness of GSHP applications needs to be improved.

This project aimed to improve the operational efficiency of GSHP systems by developing smart controls at the component and system levels. Close collaboration with the US industry partner, ClimateMaster, through this CRADA project resulted in the following achievements:

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[1] http://us.grundfos.com/products/find-product/hydro-mpc1.html

[2] The 13th Five-Year Period for Economic and Social Development was jointly developed by the National Development and Reform Commission, the Ministry of Land and Resources, and the National Energy Bureau (http://www.mlr.gov.cn/xwdt/jrxw/201702/t20170207_1439676.htm).

- a first-of-its-kind flexible test facility capable of supporting development and verification of various emerging technologies for GSHP or DGSHP applications in a low-risk and realistic real-building environment,

- an innovative flow-demand-based control for DGSHP system variable speed loop pumps, which can dynamically adjust the DP set point at real time and deliver only the needed water flow to each operating individual zone heat pump in the system. This newly invented pumping control (patent pending, Invention Disclosure #: 201403380, DOE S number: S-138,004) has potential to reduce pumping energy by 60% in typical DGSHP systems.

- a better control for GS-IHPs, which avoids the power surges resulting from the SSC&WH operation and significantly reduces or even eliminates the operation of the electric elements. Experimental test results also indicated that this new control improved the combined COP of the GS-IHP for space cooling and water heating by 10% compared with the existing control when the ground source supply temperature was below 75ºF.

In addition to supporting the optimization and field verification needs of this project, the flexible test facility built during this project provides a first-of-its-kind facility capable of supporting other valuable research to further improve the energy efficiency of DGSHP or GSHP systems over their expected service life and reduce costs (e.g., fault detection and diagnostics, improved control through application of low-cost wireless sensors, etc.) .With this facility, various emerging technologies can be developed and verified in a low-risk realistic real-building environment.

Further support from the US Department of Energy and industrial partners is desired to commercialize the new control systems developed in this project. It is an essential component of the next-generation of GSHP systems, which will be more cost-effective and capable of meeting all the space conditioning and water heating demands; and can optimize its operation based on thermal loads in real time.

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