FIELD TEST OF HIGH EFFICIENCY RESIDENTIAL BUILDINGS WITH GROUND-SOURCE AND AIR-SOURCE HEAT PUMP SYSTEMS

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Abstract: This paper describes the field performance of space conditioning and water heating equipment in four single-family residential structures with advanced thermal envelopes. Each structure features a different, advanced thermal envelope design: structural insulated panel (SIP); optimum value framing (OVF); insulation with embedded phase change materials (PCM) for thermal storage; and exterior insulation finish system (EIFS). Three of the homes feature ground-source heat pumps (GSHPs) for space conditioning and water heating while the fourth has a two-capacity air-source heat pump (ASHP) and a heat pump water heater (HPWH). Two of the GCHP-equipped homes feature horizontal ground heat exchange (GHX) loops that utillize the existing foundation and utility service trenches while the third features a vertical borehole with vertical u-tube GHX. All of the houses were operated under the same simulated occupancy conditions. Operational data on the house HVAC/Water heating (WH) systems are presented and factors influencing overall performance are summarized.

Key Words: ground-source heat pumps, air-source heat pumps, water heating, thermal envelopes, energy efficiency, space conditioning

1 INTRODUCTION

Although GSHPs are in principle one of the most efficient residential space conditioning and water heating systems available (IGSHP 2010), installation costs, local regulations, and lack of well-characterized performance data under actual conditions are some of the barriers facing this technology (Ally 2006). In 2010, U.S buildings share of primary energy consumption was 39.7% (EIA 2009). Buildings also represent 40% of the European Union's (EU) energy consumption and carbon production (Baden, Waide et al. 2006). U.S. green-house-gas (GHG) emissions from the building sector exceed those of both the industrial and transportation sectors and therefore, buildings represent a compelling opportunity for reducing emissions (Metz, Davidson et al. 2007). Clearly, building energy efficiency is a key element in addressing the environmental and energy challenges confronting developed (and emerging) countries. In October 2010, the energy efficiency requirements in the 2012 International Energy Conservation Code (IECC) will increase by 30 per cent over the 2006 IECC levels offering an opportunity to achieve a 50 per cent increase in energy savings in new US buildings by 2015 (DOE 2010). To achieve these objectives, data from buildings with cost-effective novel designs, improved envelopes, and efficient ways to use renewable energy are vital.

In this paper we present the performance of three GSHP systems for space conditioning and water heating (HVAC/WH) and a fourth HVAC/WH system consisting of a high-efficiency air-source heat pump (ASHP) and an air-source heat pump water heater (HPWH) in tight, well-insulated residential structures. This information will be used for comparison with the performance of ground- and air-source integrated heat pump systems to be tested in the same buildings in future years. From this research project, detailed measurements will enable original equipment manufacturers (OEMs) to prioritize design improvements for additional efficiency gains. A comparison of GSHP versus ASHP performance for space conditioning shall enable stakeholders to make tradeoffs between cost and performance for their geographical locations. Similar tradeoffs exist for water heating. Nearly full year data is available from two of the four houses with GSHP systems and horizontal loop ground heat exchangers (GHX) that were installed next to the house foundation during construction. The third house with PCM insulation contains a vertical loop GHX, connected to the same type GSHP systems as in the SIP and OVF houses. This allows a comparison between the vertical and horizontal loops. The fourth house with EIFS envelope system contains a high-efficiency ASHP for space conditioning and a HPWH for water heating. Data at key state points throughout the HVAC/WH systems are collected every fifteen seconds and averaged over a fifteen minute period for subsequent analyses. A weather station located at the SIP house collects site weather data (solar insolation, temperature, humidity, rain, wind, etc.).

Some limitations of this study are that the envelopes and ground loop designs differ in some characteristic way: the SIP and the OVF houses are identical in architectural design and size (345 m^2; 3700ft^2) but differ slightly in air leakage rates; the horizontal ground loop in the SIP house is smaller than the loop in the OVF house; the vertical ground loop in the PCM house is shorter than either of the horizontal loops; the PCM house and the EIFS houses are 252m^2 (2600ft^2) but the former has a vented crawl space and the latter has a sealed and conditioned crawl space; the Home Energy Rating Systems (HERS) index for all of the houses are slightly different; and the houses have different types of roofs. These design differences were deemed important for other aspects of the research project dealing with building envelopes, foundations, the influence of variances in the horizontal ground loops, and modeling issues (not discussed in this paper). In a project of this scope, the goal was to maximize the information at minimum cost and hence some compromises were inevitable for each major segment of the research. In this paper, we report on the HVAC/WH systems' performance.

The four houses are located in Oak Ridge, Tennessee, Latitude 36.0^{o}N and Longitude 84.3^{o}W. Long term (1971-2000) average heating and cooling degree days for Oak Ridge are 2218 °C-days (3993 °F-days) and 1301 °C-days (723 °F-days) (http://cdo.ncdc.noaa.gov/climatenormals/clim20/tn/406750).

Section 2 of this paper describes the envelope characteristics, ground loops, and HVAC/WH systems. Section 3 describes the performance of the HVAC/WH systems. Concluding observations are in Section 4.

2 Envelope: structural and design characteristics

The four distinct envelope features and overall dimensions are summarized in Table 1. The houses have weather resistive barriers to limit moisture infiltration and all have identical orientation to ensure the same solar insolation. These houses were built under a partnership between the Oak Ridge National Laboratory, the U.S. Department of Energy, builders, and equipment manufacturers. The houses are owned by the builder and will be sold at market value once a three-year experimental program is completed.

The SIP house roof is a standing seam metal with an infrared reflective (IRR) paint yielding a solar reflectance of 0.30 and thermal emittance of 0.85. The roof assembly has an overall thermal resistance of about R_{SI}-8.8 (R_{US}-50). The walls are 0.14m (5 1/2-in) thick and have thermal resistance of R_{SI}-3.7 (R_{US}-21). Windows are triple pane with a U-factor of 1.64 $W/m^2 \cdot K$ (0.29 $Btu/h \cdot ft^2 \cdot {}^oF$) and a solar heat gain coefficient (SHGC) of 0.25.

The OVF house has the same type roof as the SIP. Its walls are made of 2 x 6 Douglas-fir installed at 0.61m (24-in) on center with the gaps filled with 0.013 m (1/2-in) sprayed-in polyurethane foam and R_{SI}-3.3 (R_{US}-19) fiberglass batt insulation to give an overall thermal resistance of R_{SI}-3.7 (R_{US}-21). Its windows are triple pane with argon gas fill and have the same U-factor and SHGC as the SIP house.

The PCM house has a double wall assembly of two 2 by 4 stud, 0.41m (16-in) on center walls and fiberglass insulation embedded with phase change materials. The PCM acts as a thermal buffer. As the ambient temperature rises, the PCM absorbs thermal energy which would otherwise have penetrated directly to the house interior. When the temperature falls, the PCM material releases heat to the interior of the house, keeping it warmer than it otherwise would have been. The roof is of IRR painted metal shake design with a solar reflectance of 0.34 and a thermal emittance measured at 0.85. Windows are glazed, argon gas filled triple pane vinyl units with a U factor of 1.25 $W/m^2 \cdot K$ (0.22 $Btu/h \cdot ft^2 \cdot {}^oF$) and an SHGC of 0.17.

The EIFS house has an IRR asphalt shingle roof with a solar reflectance of 0.26 and a thermal emittance of 0.88. The roof assembly includes a radiant barrier facing into the attic plenum, two low-e surfaces, and passive ventilation from soffit to ridge. Exterior wall insulation consists of 0.13m (5-in) extruded polystyrene (EPS) cladding on the outside of the wall studs designed to reduce thermal bridging losses. The wall assembly is lightweight, highly energy efficient and vapor permeable. Details of the wall construction for this house and the other three are described elsewhere (Miller, Karagiozis et al. 2010). South-facing windows in the EIFS house have U and SHGC values of 1.36 $W/m^2 \cdot K$ (0.24 $Btu/h \cdot ft^2 \cdot {}^oF$) and 0.50, respectively, whereas north-facing windows have U and SHGC values of 1.02 $W/m^2 \cdot K$ (0.18 $Btu/h \cdot ft^2 \cdot {}^oF$) and 0.22, respectively.

The HERS rating for the four houses are summarized in **Table 2** (Jackson 2011). Blower door tests show that all homes are tight as compared to a conventional Builders House. Ventilation rates exceed ASHRAE 62.2 (2009) standards which require a minimum of 0.033 m^3/s (i.e. 0.11 ACH) for a three-bedroom house (Miller, Karagiozis et al. 2010).

2.1 Description of GHX Loops and HVAC/WH Systems in SIP, OVF, and PCM houses

The SIP and OVF houses each have one horizontal loop GHX part of which is placed in the house foundation excavation and utility service trenches. Both GHX loop have three parallel circuits (6 pipes) made of high density polyethylene (HDPE). The total pipe length in the SIP and OVF houses are 559 m and 796 m, respectively. Part of each loop is buried in a "rain garden" designed to capture water from rainfall runoff and keep the soil surrounding those loop segments as moist as possible for improved heat transfer. The benefit of the rain garden concept is part of another study during this project and is not discussed further. The PCM house has one vertical GHX loop 94.5 m deep with a single HDPE u-tube pipe loop. Each GHX loop contains a mixture of 20% (by volume) propylene glycol and 80% water brine solution. Each house's GSHP system has two heat pumps connected to the same GHX. One, dedicated to space conditioning, is a 7.56 kW (2.16 ton) nominal cooling capacity water-to-air heat pump (WAHP), connected to a zoned central air distribution system – four zones in the

SIP and OVF houses and two in the PCM house. The other, dedicated to water heating, is a 5.275 kW (1.5 ton) capacity water-to-water heat pump (WWHP). A schematic of the WAHP and the WWHP showing their connections to the ground loop and the locations of various sensors and transducers is shown in Figure 1 .

3 HVAC/WH System Performance

In all four houses, the thermostat set point temperatures are 21.67°C (71°F) for heating and 24.44°C (76°F) for cooling and were maintained within 1°C (1.8°F). The monthly relative humidity (RH) (averaged for all 4 zones) within those houses were maintained at around 47% with the lowest value of 36% in January. There was a one-day spike in RH to 68% in July due to doors and windows left open to vent off-gases from a sealant applied to the basement floor. The purpose of mentioning the RH values is to emphasize that the temperatures and RH were well within comfort levels as defined by (ASHRAE 2001). The set point temperatures and RH ensure excellent comfort levels in the houses. The performance of the WAHPs for space conditioning is evaluated on the basis of the amount of energy delivered or removed and energy consumed, neglecting standby power use, as the outdoor air temperature (OAT) and the entering water temperatures (EWT) vary. For the SIP and OVF houses, OATs and EWTs are shown in Figure 2. The data were collected at 30 second intervals and averaged over a 15 minute period. The lowest EWT (~ 1°C) occurred in February for both houses. Most of the annual heating load occurred from January to the middle of March.

3.1 Horizontal GHX loops: SIP and OVF houses

Comparisons of the WAHP performance in the SIP and OVF houses are shown in Figure 3 and Figure 4. In the 2009/2010 heating season delivered energy and electrical energy consumed per day peaked in February for both houses, but their magnitudes differ. Almost no electric back up heating was required during the entire heating season in either house (zero kWh for the SIP house and only 66 kWh for the OVF). The SIP house required slightly less energy to heat than did the OVF house most likely due to its tighter envelope (ACH =0.74 vs. 1.24, respectively, Table 2) with better thermal performance. In the 2010 cooling season, the energy removed from conditioned space in both houses peaked during July-August and its magnitude is slightly greater for the OVF house than for the SIP house, again reflecting the differences between their envelope characteristics. Although the GHX loop in the OVF house is significantly larger than the SIP house, the EWTs are very close (most likely due to the greater heat extraction and rejection loads imposed on the OVF GHX because of its greater heating and cooling loads which in turn, is envelope dependent).

3.2 Vertical GHX loop: PCM house

The PCM house became operational in August 2010. The performance of the WAHP connected to the vertical ground loop is shown in Figure 5. Since limited data is available, heating and cooling data are plotted together. Delivered energy and the energy consumed for the heating and cooling seasons are less than that for the SIP or OVF houses because primarily, the PCM house is smaller. However, delivered energy also depends on envelope characteristics. The cooling mode EWT for the PCM house is about 2-4°C lower than those for the SIP and OVF houses which would tend to improve the WAHP performance. The lower Aug-Oct EWTs in the PCM house could be due in part to the fact that operation of the GSHP did not commence until August and the impact of heat rejection to the ground from May-July was therefore not felt. In November 2010 the EWT in the PCM house (vertical ground loop) was about 6°C lower than for either of the horizontal loops in the SIP and OVF houses which would tend to decrease its heat pump performance relative to the other two. Again, not having a full summer's GHX heat rejection load could have caused at least part of this decrease.

3.3 Air Source heat pump: EIFS house

The EIFS house also became operational in late August 2010. The performance of the ASHP is shown in

Figure 6. Since limited data is available, heating and cooling data are plotted together. In September, 2010 the EIFS house had the lowest cooling load (23 kWh/day) of all the four houses. The heating load for the month of November in the SIP, OVF, PCM and EFIS houses were 20.8, 31.9, 24.8, and 23.2 kilowatt-hours per day, respectively. Analysis of November's data for the EIFS house showed that the installer had, inappropriately, installed a balance point sensor. This was set to provide heat solely from the auxiliary resistance heating elements at OATs of ~1.7°C (35°F) or lower. This resulted in higher energy consumption for the ASHP and a lower COP than otherwise would have been the case. The balance point sensor was disconnected at the end of November 2010.

3.4 Water heating

Hot water use in each of the four houses is shown in Figure 7. The water usage in all four houses was controlled in an effort to closely match the Building America benchmark criteria for a three-bedroom house (Hendron 2007). WWHP performance parameters for the SIP and OVF houses are shown in Figure 8. Note the similar EWTs and energy consumed for generating hot water in these two houses. In August 2010, a small refrigerant leak was found at the base of the TXV in the SIP WWHP unit causing the loss of nearly 50% of the unit's refrigerant charge of 1.59kg (56 oz). It is not known whether the leakage had been occurring slowly since initial installation in December 2009 or if it developed suddenly in mid-summer 2010. Upon recharging with R401A, the delivered capacity improved. The impact of this leak on the unit's performance before August 2010 when the leak was identified and fixed has not been quantified.

The COP of the OVF WWHP remained consistently lower than that of the SIP WWHP because the former had a smaller brine pump that was unable to pump sufficient brine especially when its WAHP was running simultaneously. The lower brine flow caused its COP and capacity (not shown) to suffer. This is a clear case when an inadequately sized pump can adversely impact the COP.

Performance parameters of the WWHP in the PCM house and the HPWH in the EIFS house are shown in Figure 9. The delivered energy for the WWHP in the PCM house increases because the cold water supply temperature decreases as winter approaches and consequently, more energy is needed to reach the water set point temperature of 49^{o}C (120°F). The energy consumed to meet the delivered energy also increases. The WWHP, thus, operates under two adverse conditions during winter – lower supply water temperatures and lower EWTs. In contrast, the HPWH energy consumption (EIFS house) is penalized only by the supply water temperature since it draws heat from conditioned space, maintained constant by the thermostat.

The HPWH in the EIFS house can operate in either heat pump or resistance mode. For the months of October, November and December, the EF in the heat pump and resistance modes are, 2.68, 2.64, 2.7 and 0.87, 0.88 and 0.89, respectively.

4 Results and Concluding Observations

Based on our evaluation of the performance of GSHPs for space conditioning and for water heating over nearly a year in the SIP and OVF houses operated under simulated occupancy conditions, we summarize the results as follows.

- The 7.56 kW (2.16-ton) WAHPs were sufficient to heat and cool the 345 m^2 houses and maintain the thermostat set points of 21.7°C (71°F) in the winter and 24.4°C (76°F) in the summer. Almost no backup electric resistance heating was required for either house. February was the coldest month requiring 101 kWh and 124.8 kWh of delivered heat per day while consuming 29.4 kWh and 36.7 kWh per day for the SIP and OVF houses, respectively. The lowest monthly COP in the winter was 3.43 and 3.40 for the SIP and OVF houses. The peak cooling month was August - 77.2 kWh and 78.6 kWh per day while using 20.5 kWh and 21.5 kWh of energy, respectively. The lowest COP in the cooling season (August) was 3.77 and 3.65 in the SIP and OVF houses, respectively. The COPs are monthly averages calculated using the total energy consumed by the GSHP during operation, which includes the fan, controls, brine pump, and the compressor energies, but excludes stand-by losses.

- For water heating in the SIP and OVF houses 5.275 kW (1.5-ton) WWHPs serviced a 303 L (80 gallon) HW tank providing ~220 L/day of hot water at 49°C. The monthly average COP for water heating varied from a low of about 2.6 to a high of 3.71 for the SIP house. For the OVF house, the COP for water heating varied from a low of 2.24 to a high of 2.81. WWHP in the OVF had lower COPs because of an undersized brine pump.

Unfortunately we have only a limited set of performance data for the ASHP and HPWH in the EIFS house. Base on this limited set we can make the following observations.

- The COP of the AAHP for the month of December, the coldest moth for which we have detailed data was 2.3, considerably lower than the COPs demonstrated by the WAHPs in the SIP and OVF houses – due primarily to the difference in evaporator source temperatures experienced by the systems (OAT vs. EWT). The HPWH COP was ~2.7 in December when the HPWH operated in the heat pumping mode. When operating in electric resistance mode, the COP of the HPWH unit was ~0.9.

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Table 1. Test House Thermal Envelope Systems and Floor Areas

		Floor area, m^2			
House	**Envelope system**	**Basement**	**1st Floor**	**2nd Floor**	**Total**
1	SIP	141	141	63	345
2	OVF	141	141	63	345
3	PCM	NA	167	85	252
4	EIFS	NA	167	85	252

Table 2: HERS ratings and infiltration rates as compared to IECC (2006)

	SIP	OVF	PCM	EIFS	Builders House[1]
ACH[2] @50 Pa	0.74	1.24	3.5	2.3	5.7
HERS[3]	44	45	46	51	101

[1]IECC (2006)
[2]Air exchanges per hour (ACH) measured by blower door tests conducted at 50 Pa
[3]Home Energy Rating System – lower numbers indicate more energy efficient construction

Table 3: Energy subsystems used in the SIP, OVF, PCM and EIFS houses

Subsystem	SIP	OVF House	PCM House	EIFS House
HVAC	WAHP ▪ 2-ton capacity ▪ Variable speed blower ▪ Cooling COP[b] 5.4 ▪ Heating COP[c] 4.0 ▪ Horizontal loop 1815 ft (553-m ▪ R410A	WAHP ▪ 2-ton capacity ▪ Variable speed blower ▪ Cooling COP[b] 5.4 ▪ Heating COP[c] 4.0 ▪ Horizontal loop 2610 ft (796-m) ▪ R410A	WAHP ▪ 2-ton capacity ▪ Variable speed blower ▪ Cooling COP[b] 5.4 ▪ Heating COP[c] 4.0 ▪ Vertical well depth 310-ft (94.5-m) ▪ R410A	Air-source heat pump ▪ 2-ton dual capacity ▪ Variable speed blower ▪ SEER[d] 18.4 ▪ HSPF[d] 9.1
Hot water	WWHP ▪ 1½-ton capacity ▪ COP[a] 3.1	WWHP ▪ 1½-ton capacity ▪ COP[a] 3.1	WWHP ▪ 1½-ton capacity ▪ COP[a] 3.1	Heat Pump Water Heater ▪ 0.9 Energy factor, electric resistance ▪ 2.4 Energy factor, heat pump
ERV[e]	TRE[f] 52% ASE[g] 75% Single-speed blower	TRE 52% ASE 75% Variable speed blower	NA	NA
Lighting	CFL	CFL	CFL	LED

[a] WWHP COP based on source entering water temperature (EWT) of 0°C (32°F) and load EWT of 37.8°C (100°F).
[b] WAHP Full Load Cooling based upon 27°C (80.6°F) DB, 19°C (66.2°F) WB entering air and EWT of 25°C (77°F)
[c] WAHP Full Load Heating based upon 20°C (68°F) DB, 15°C (59°F) WB entering air temperature and EWT of -1.1°C (30°F)
[d] Air-source Heat Pump SEER rated at 35°C (95°F); HSPF rated at 8.3°C (47°F)
[e] Energy Recovery Ventilator
[f] Total Recovery Efficiency (TRE) at 35°C (95°F)
[g] Apparent Sensible Effectiveness (ASE) at 0°C (32°F)

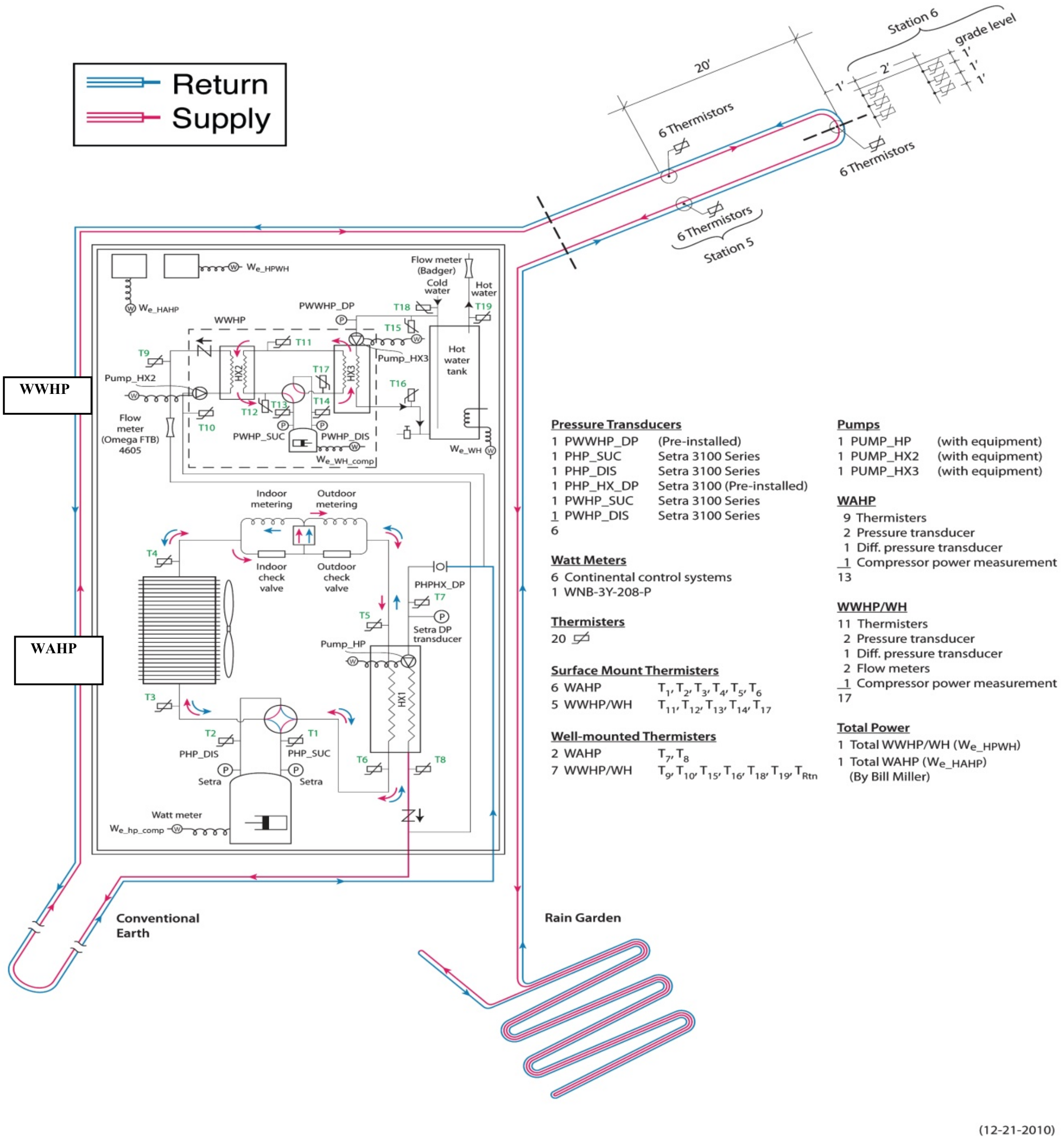

Figure 1: Schematic of WAHP and WWHP connections to the ground loop and locations of various sensors and transducers for data collection

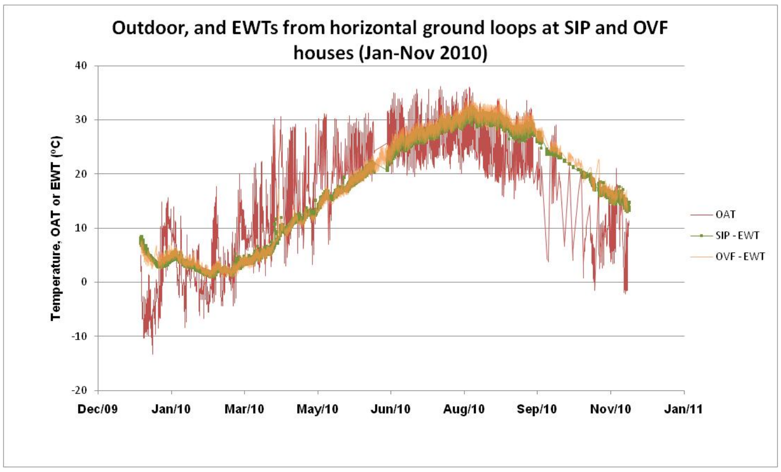

Figure 2: Monthly variation of OAT, EWT for SIP and OVF houses, Oak Ridge, Tennessee

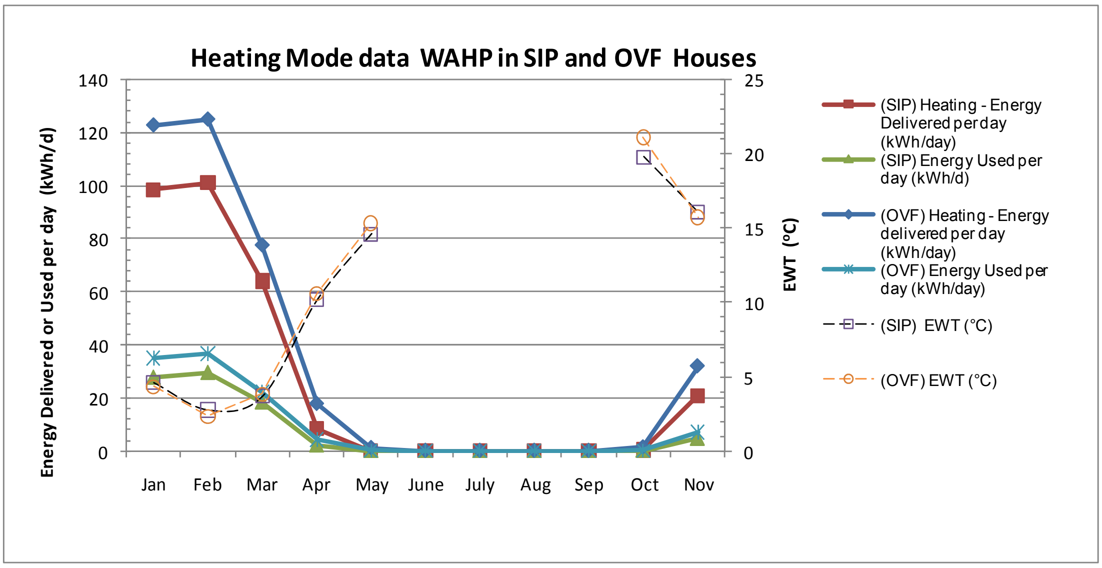

Figure 3: Comparison of WAHPs in SIP and OVF houses in heating mode

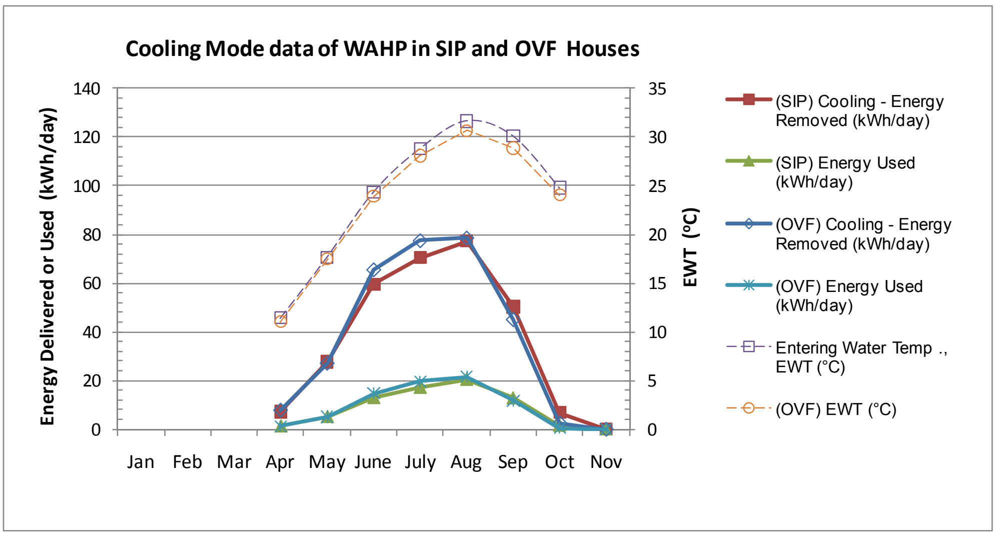

Figure 4: Comparison of WAHPs in SIP and OVF houses in cooling mode

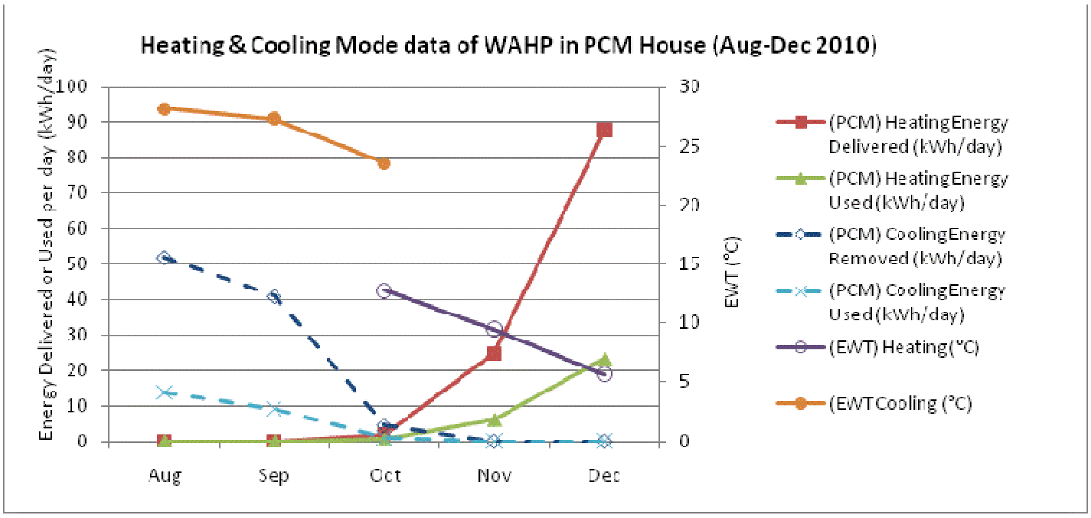

Figure 5: Heating and cooling mode data of WAHP connected to vertical ground source in PCM house. Solid and dashed lines represent heating mode and cooling mode data, respectively.

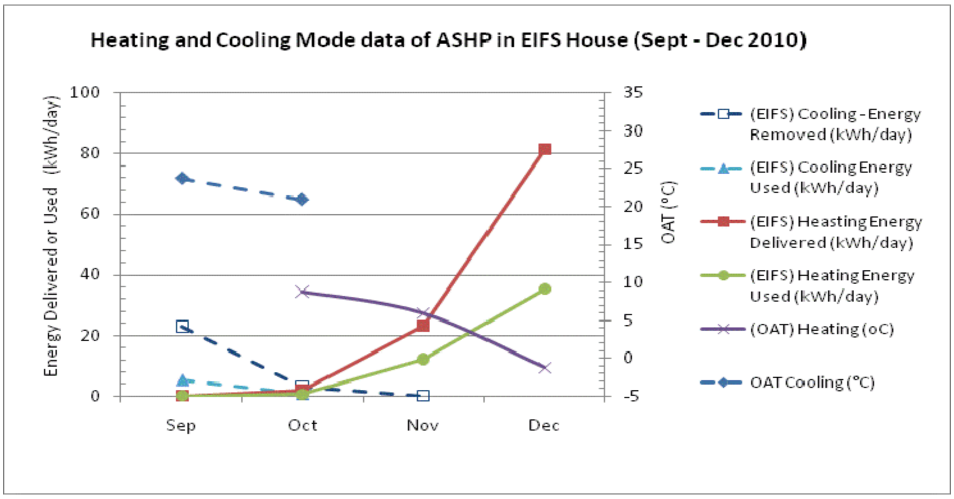

Figure 6: Performance data of ASHP in EIFS house. Solid and dashed lines represent heating and cooling mode data.

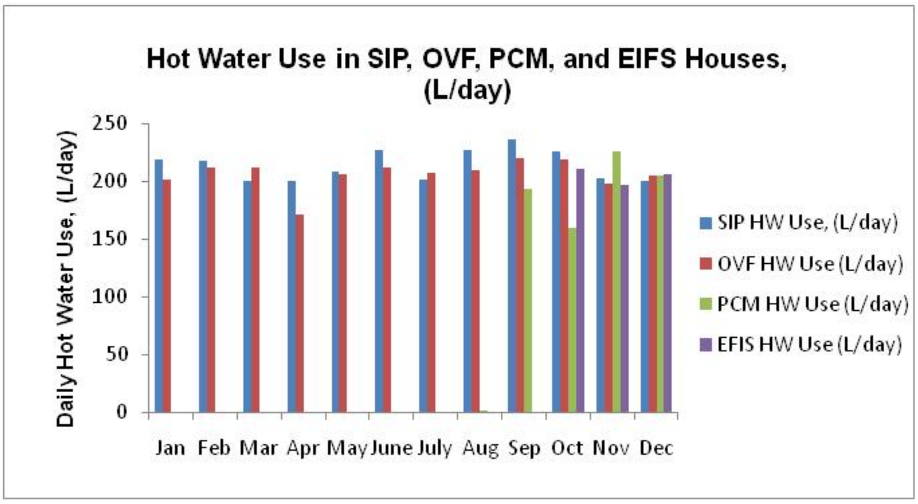

Figure 7: Extent of hot water use per day in the SIP, OVF, PCM and EIFS houses

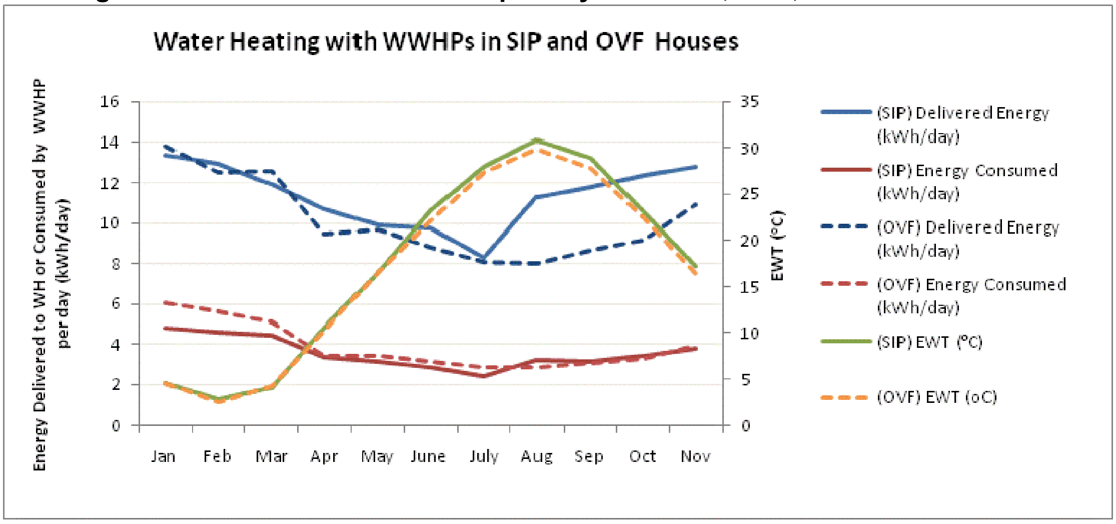

Figure 8: WWHP performance parameters and EWT for the SIP and OVF houses, each with their respective horizontal ground loops.

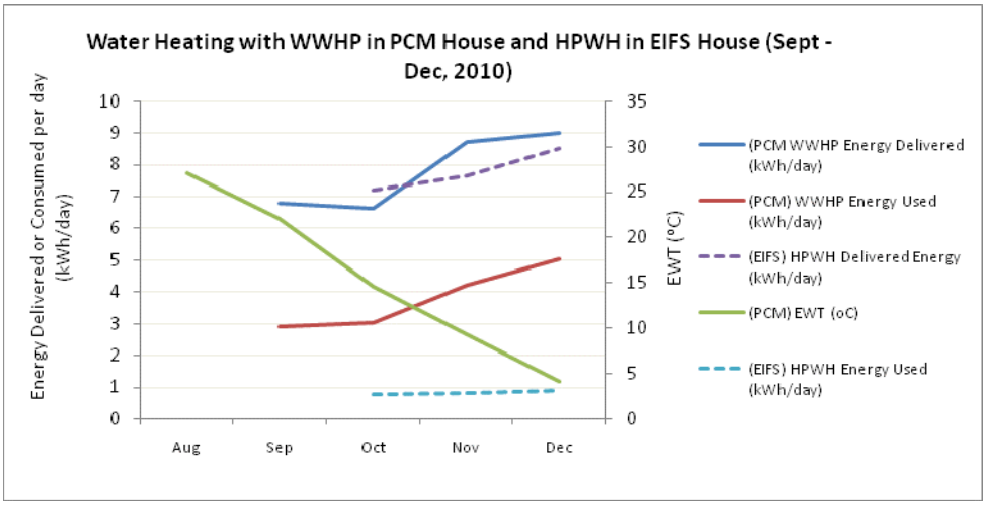

Figure 9: Performance parameters of the vertical loop WWHP in the PCM house and the HPWH in the EIFS house.

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