

FIELD TEST AND EVALUATION OF RESIDENTIAL GROUND SOURCE HEAT PUMP SYSTEMS USING ALTERNATIVE VERTICAL-BORE GROUND HEAT EXCHANGERS

Xiaobing Liu, R&D Staff, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

Richard A. Beier, Professor, Oklahoma State University, Stillwater, Oklahoma, USA

Michael Anderson, Project Manager, Oklahoma Gas and Electric Company, Oklahoma City, Oklahoma, USA

Garen N. Ewbank, Owner, Ewbank Geo Testing, L.L.C., Fairview, Oklahoma, USA

Jeff Munk, R&D Staff, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

Abstract: This paper describes field tests on ten different vertical-bore ground heat exchangers (GHXs). The field tests consist of both short-term thermal response tests on the boreholes and full-year performance measurements on the associated ground source heat pump (GSHP) systems. While providing space conditioning to nearly identical homes, the energy consumptions of these GSHP systems varied significantly—not only due to the various fluid temperatures supplied by each of the GHXs, but also the room temperature set points (especially in winter), and the internal heat gains in the buildings. The measured data were used to verify computer simulations, which later estimated required borehole depths of different GHXs when supplying the same fluid temperature in response to the same building loads. Both the field tests and the computer simulations indicated that the tested alternative GHXs require 14-30% less borehole depth than the conventional single U-tube GHX while delivering the same performance.

Key Words: ground source heat pump, ground heat exchanger, field test

1 INTRODUCTION

A ground source heat pump (GSHP) makes use of low grade and renewable energy stored in shallow sub-surface of the ground, ground water, surface water bodies, or even municipal waste water. Using these resources as heat sinks/sources, GSHP systems provide space conditioning and water heating to residential or commercial buildings. GSHP is one of the most energy efficient technologies for space conditioning and/or water heating. In addition to reducing the energy cost paid by building owners, GSHP can also reduce summer peak electric demand and improve the load factor for electric utilities. The most commonly used ground heat exchanger (GHX) in the United States consists of a vertical borehole with a set of pipes inserted in it. Due to the relatively expensive price for installations of the vertical-bore GHX, the application of GSHP technology is still limited in the United States. If the price of the vertical-bore GHX can be reduced without sacrificing its performance, GSHP systems will be adopted in much larger scale in the United States.

The present study carried out field tests in an attempt to verify the benefits of alternative vertical-bore GHX technologies, and if successful, provide an impetus towards further commercialization of these technologies. Eight combinations of new heat exchanger designs, new grouting materials, and various drilling techniques were selected for the field test. Oklahoma Gas and Electric Company (OG&E), an electric public utility, assembled a group of manufacturers, distributors, installers, and researchers, who installed, tested, and evaluated the performance of the new vertical-bore GHXs.

2 DESCRIPTION OF TESTED GHXS

The new GHXs are eight different combinations of four heat exchanger designs, three grouting materials, and four drilling technologies as summarized in Table 1. The heat exchangers include single U-tube, double U-tube, and two different co-axial pipes. The grouting materials include thermally enhanced grout, super conductive grout, and common bentonite. The drilling technologies include mud rotary, air rotary, mud sonic, and air sonic.

In a single U-tube layout, the circulating fluid flows down one leg of the U-tube and flows up the other. The space between the pipes and the borehole wall is filled with grout to prevent water and contaminants from migrating along the vertical borehole. The double U-tube layout is connected in parallel so that water flow is divided between the two U-tube pipes evenly. As with the single U-tube layout, the space between the pipes and the borehole wall is filled with grout. In a coaxial design, an internal pipe is placed inside a larger external pipe. Grout fills the space between the external pipe and the borehole wall. The fluid may enter the heat exchanger through the internal pipe or the annulus and flows downward, then travels upward through the other pathway. The co-axial pipes tested in this study are engineered with special technologies—the first type (“co-axial #1”) attaches a helix rib on the outside wall of an insulated internal pipe, and the second type (“co-axial #2”) uses a corrugated external plastic pipe with a HDPE internal pipe and stab-type plug-in connections at both ends of the pipe. In all the co-axial pipes tested in this study, the fluid enters through the internal pipe and exits through the annulus.

Two existing conventional GHXs (in units 2 and 8) were included in this study as reference installations. Each of these GHXs uses a vertical single U-tube heat exchanger with a depth of 122 m and conventional bentonite grout. For each of the eight new GHXs, the borehole depth was specified with the intention of making the new GHXs have a thermal performance resembling the performance of the reference installations.

3 IN-SITU THERMAL RESPONSE TESTS

In-situ thermal response tests (TRT) have been carried out on six of the eight new GHXs to provide estimates of soil thermal conductivity (k_s) and borehole thermal resistance (R_b). Based on the line source heat transfer theory (Carslaw and Jaeger 1959), k_s is inversely proportional to the late-time slope of the trend of mean flow temperature of the GHX versus the natural logarithm of time in hours, as expressed in Equation (1).

$$k_s = \frac{Q}{4\pi m L} \quad (1)$$

where Q is the heat input rate, L is the length of the borehole, and m is the late-time slope.

Table 1: Information of the tested new GHXs and the existing reference GHXs

Unit number	1	2	3	4	5	6	7	8	9	10
Pipe type	Co-axial #2	Single U-tube (reference)	Co-axial #2	Co-axial #1	Double U-tube	Double U-tube	Single U-tube	Single U-tube (reference)	Co-axial #1	Single U-tube (small bore)
Grout type	Thermally enhanced	Bentonite	Super conductive	Super conductive	Thermally enhanced	Thermally enhanced	Thermally enhanced	Bentonite	Thermally enhanced	Gravel/ bentonite pellets
Grout thermal conductivity, W/[K·m]	1.5 (catalog data)	0.7 (estimated)	5.1 ^a	3.1 ^a	1.5 (catalog data)	1.4 ^a	1.4 ^a	0.7 (estimated)	1.4 ^a	2.2 ^b
Drilling technique	Mud rotary	Air rotary	Air rotary and mud rotary ^c	Sonic mud	Mud rotary	Mud rotary	Sonic air	Air rotary	Mud rotary	Mud rotary
Borehole diameter, mm	133	133 (estimated)	133	133	133	133	120	133 (estimated)	120	70
Number of boreholes	2 ^d	1	3 ^d	1	1	1	1	1	2 ^d	2 ^e
Total borehole depth, m	92	122	111	65	79	79	97	122	92	110

^a From a lab test of the sample grout obtained at the installation site within 48 hours after the borehole was grouted.

^b Only the top 15 m of this borehole was grouted with gravel/bentonite pellets and the rest was assumed being filled with ground water.

^c Air rotary for one vertical bore and mud rotary for the other two vertical bores.

^d The multiple coaxial pipes in units 1, 3, and 9 are connected in series.

^e The two single U-tube pipes in unit 10 are in two different boreholes and are connected in parallel.

R_b includes all the thermal resistances between the fluid in the pipes and the borehole wall such as the inner-pipe film resistance, pipe wall resistance, grout resistance, and any contact resistances. It can be estimated from the line-source model (Beier and Smith 2002) with Equation (2).

$$R_b = \frac{1}{4\pi k_s} \left[\frac{T_m(t) - T_s}{m} - \ln \left(\frac{4\alpha_s t}{\gamma r_b^2} \right) \right] \quad (2)$$

The temperature $T_m(t)$ may be set as the extrapolated mean flow temperature of the late-time trend evaluated at one hour. Then the time, t , is set equal to one hour. Here T_s is the undisturbed ground temperature, α_s is the ground thermal diffusivity, r_b is the borehole radius, and γ is a constant approximately equal to 1.78.

Beier et al. (2012, 2013) have developed heat transfer models for boreholes with the co-axial and U-tube configurations. The models generate the vertical profiles in the heat exchanger at any given time during the late-time period or constant heat flux period. The calculated dimensionless temperature profiles for co-axial #1 in unit #4 and the single U-tube heat exchanger in unit #10 are shown in Figure 1 for a time near the end of the TRT test (40 hr). The dimensionless temperature (T_D) is given by Equation (3), where T is the flow temperature at a given depth and T_{in} is the fluid temperature entering the GHX. The dimensionless depth is the depth divided by the total depth of the borehole.

$$T_D = \frac{T - T_s}{T_{in} - T_s} \quad (3)$$

As shown in Figure 1, the vertical temperature profile in co-axial #1 differs considerably from the profile in the single U-tube heat exchanger. The internal pipe of co-axial #1 has a polyethylene foam wall that acts as a good thermal insulator and minimizes the heat exchange between the fluid in the central pipe and the annulus. Thus, the higher temperature of the fluid flowing down the internal pipe is nearly unchanged. The temperature of the fluid flowing in the annulus decreases as the fluid moves upward and loses heat to the cooler soil.

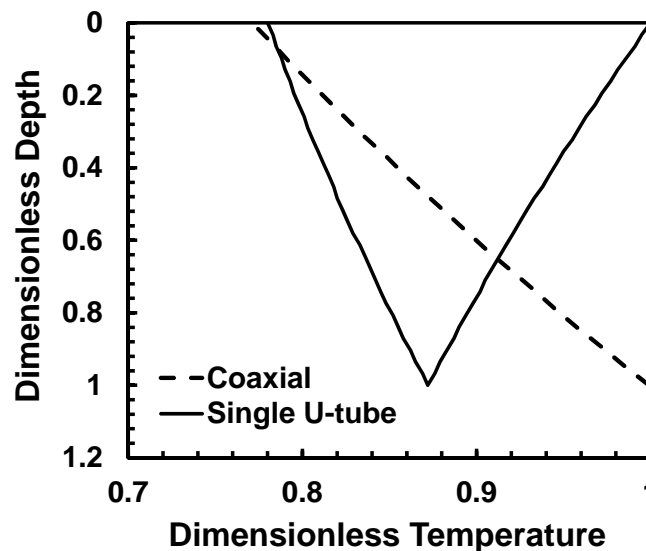


Figure 1: Calculated dimensionless temperature profiles for the coaxial heat exchanger at Unit #4 and the single U-tube heat exchanger at Unit #10 after 40 hours from start of TRT

R_b values of six GHXs have been computed with mean flow temperatures calculated in two different ways: (1) the arithmetic average of the inlet and outlet temperatures of the GHX,

and (2) the mean of the calculated temperature profiles. As shown in Table 2, the results are quite close. These results are also compared with that calculated by GLHEPRO (2008) for the U-tube and coaxial heat exchangers (Table 2). For U-tube heat exchangers Configuration B sets the gap between the pipes equal to the gap between each pipe and the borehole wall. In Configuration C the pipes are spread out and touch opposite sides of the borehole wall. The actual distance of the pipes and the resulting R_b values are assumed anywhere to be between that of configurations B and C. The difference between these two sets of results is within the uncertainty of the in-situ test (Beier and Ewbank 2012).

Table 2: Comparison of calculated borehole thermal resistances

Unit number	3	4	6	7	9	10
Pipe type	Co-axial #2	Co-axial #1	Double U-tube	Single U-tube	Co-axial #1	Single U-tube (small bore)
Mean temperature is approximated with the average of inlet & outlet temp., (K m)/W	0.134	0.091	0.065	0.108	0.122	0.090
Mean temperature is from the modeled temp. profile, (K m)/W	0.121	0.092	---	0.098	0.123	0.084
Results from GHLEPRO, (K m)/W	0.139	0.081	Config. B: 0.105 Config. C: 0.046	Config. B: 0.123 Config. C: 0.086	0.119	---

As shown in Table 2, R_b value of the double U-tube GHX (unit 6) is 30-50% less than any of the other GHXs being tested. R_b values of GHXs in unit 10 (single U-tube in a small 70 mm diameter bore and partially grouted) and unit 4 (co-axial #1 pipe with the super conductive grout) are very close to each other. GHX in unit 7 (single U-tube in a typical 120 mm diameter bore and with thermally-enhanced grout) has slightly bigger R_b value than the above three GHXs. GHXs in units 3 and 9 have highest R_b values among all the six GHXs. It should be noted that the GHX in unit 3 uses co-axial #2 pipe and the super conductive grout, but the GHX in unit 9 uses co-axial #1 pipe and the thermally-enhanced grout. If unit 3 used thermally-enhanced grout, its R_b value would have been even bigger. It indicates that co-axial #2 is worse than the other heat exchangers being tested in terms of heat transfer performance.

4 DATA COLLECTION AND SYSTEM PERFORMANCE MATRIX

Following the short-term TRTs, each of the eight new GHXs were connected to a water-to-air heat pump in a residence. These GSHP systems, along with other two GSHP systems that use the reference GHXs (units 2 and 8 in Table 1), were operated and monitored for one year to test their long-term performance. The ten homes are nearly identical and with about 110 m² of conditioned floor area. Each of these homes has a newly installed identical 7-kW GSHP unit. A15% methanol-water solution is used as heat carrier fluid in all of the GHXs. The flow rate of the heat carrier fluid in each of the GHXs is modulated by a variable-speed circulation pump (which is integrated within the GSHP unit) when the GSHP system is in operation. The variable flow control tends to maintain a constant differential temperature across the GHX and thus avoid excessive pumping power.

The data acquisition system (DAS) for each GSHP system includes a custom designed signal conditioning board and data module measuring the following data: (1) the inlet and outlet fluid temperatures of the GHX, (2) indoor relative humidity and temperature (measured at the return air duct where the heat pump is installed), (3) power draw of the heat pump compressor, the fan, the circulation pump, and the circulation pump for the desuperheater domestic water heater of the GSHP unit, and (4) fluid flow rate of the GHX (readings from the internal flow meter of the GSHP unit). Data were recorded at 1 minute intervals on a notebook and uploaded to a network server through a wireless modem. Hourly ambient dry-bulb temperatures measured at a nearby airport were retrieved from the National Oceanic Atmospheric Administration (NOAA).

The following metrics are determined from the measured data and used to evaluate performance of the GSHP systems: (1) monthly total power consumption of the GSHP system (including the electricity consumed by the compressor and fan of the heat pump, the circulation pump, and the circulation pump for the desuperheater), (2) monthly peak electric demand of the GSHP system, (3) monthly average GSHP system efficiency (coefficient of performance for heating [COP_H] and cooling [COP_C]), and (4) monthly averages of room temperature and supply fluid temperature of the GHX (when the GSHP system was on).

The monthly averaged of COP_H and COP_C of a GSHP system are determined as the ratio of the cumulative heating/cooling output to the associated total electric consumption of the GSHP system during a particular month. The heat and cooling outputs (Q_H and Q_C) of the GSHP system are calculated at each minute with ground loop side measurements and associated power consumptions as shown in Eqs. (4) and (5), respectively:

$$Q_H = C \times \dot{m} \times (T_{out} - T_{in}) + P_{HP} \quad (4)$$

$$Q_C = C \times \dot{m} \times (T_{in} - T_{out}) + Q_{DSH} - P_{HP} \quad (5)$$

where, C and \dot{m} are the specific heat and the mass flow rate of the heat carrier fluid, respectively; T_{out} is the fluid temperature leaving the GHX; P_{HP} is the power draw of the entire GSHP system; and Q_{DSH} is the heat transfer rate through the desuperheater of the heat pump for preheating domestic hot water¹.

5 SUMMARY OF MEASURED PERFORMANCE METRICS

As a result of several severe weather events and the resulting power outages, some data are missing in a few test homes during the test period. In addition, the flow meters for measuring the ground loop fluid flow rate in three tested homes (units 4, 6, and 7) were unable to produce valid measurements through most of the test period, despite several flow meter replacements and repairs. As a result, the monthly COP_H and COP_C of the GSHP systems in these test homes could not be determined for most months during the test period. Liu and Munk (2013) provides details of the measured data and performance metrics.

5.1 Heating Season Performance

During the heating season (December 2011 through February 2012), the ambient dry-bulb temperature averaged 6°C and fluctuated between -8 and 23°C. The monthly average room temperatures in the ten homes were different and ranged from approximately 19 to 26°C.

¹ Q_{DSH} was not directly measured in this study but is estimated based on the catalog data of the heat pump manufacturer. Q_{DSH} is about 10% of cooling capacity of the heat pump when the heat pump entering fluid temperature is around 44°C, which is the monthly average GHX LFT at most of the ten homes during cooling season.

However, for each individual home, the room temperature was maintained at a relatively constant level (less than 1.1°C variance) during the entire heating season. Detailed minutely measurements indicated that the GSHP systems were able to maintain room temperatures at the thermostat setpoint specified by the homeowners during the heating season. The monthly average GHX leaving fluid temperatures (LFTs, which is also the entering fluid temperature to the GSHP unit) of the ten GSHP systems were within 10–15°C. The GHX LFTs decreased slightly (by less than 3°C) during the time period.

The monthly COP_H of the GSHP systems ranged from 3.8 to 4.5 during the heating season (with 10–15°C entering fluid temperature) and the COP_H of a particular GSHP system decreased only slightly (less than 10%) during the time period. These numbers are slightly lower than the COP_H (4.6 at the “full load” condition and 4.9 at the “part load” condition) of the GSHP unit provided in the manufacturer’s catalog when the entering fluid temperature is at 10°C. The difference is thought to be due to the different pump power and fan power from those used in the catalog data.

Fig. 2 shows that with the nearly identical average GHX LFTs in units 1 and 5 (13°C), the 5°C higher average room temperature in unit 5 resulted in a 12.5% decrease in COP_H compared with that of unit 1. Since the double U-tube GHX used in unit 5 has a much lower R_b value than the co-axial #2 GHX used in unit 1, the GHX LFT in unit 5 was about the same as that of unit 1 although the heating loads of unit 5 were bigger (due to the higher room temperature) and the borehole depth is shorter (79 vs. 92 m). It confirms that the double U-tube GHX had better heat transfer performance than the co-axial #2 GHX.

Because of the narrow variation in average GHX LFTs and the different room temperatures among the test homes, there is not a clear relationship between GHX LFT and COP_H showing in Fig. 2. However, detailed 1-minute measurements clearly showed that COP_H decreased with the decrease of the GHX LFT during operation cycles in each individual home, in which the room temperature was maintained nearly constant.

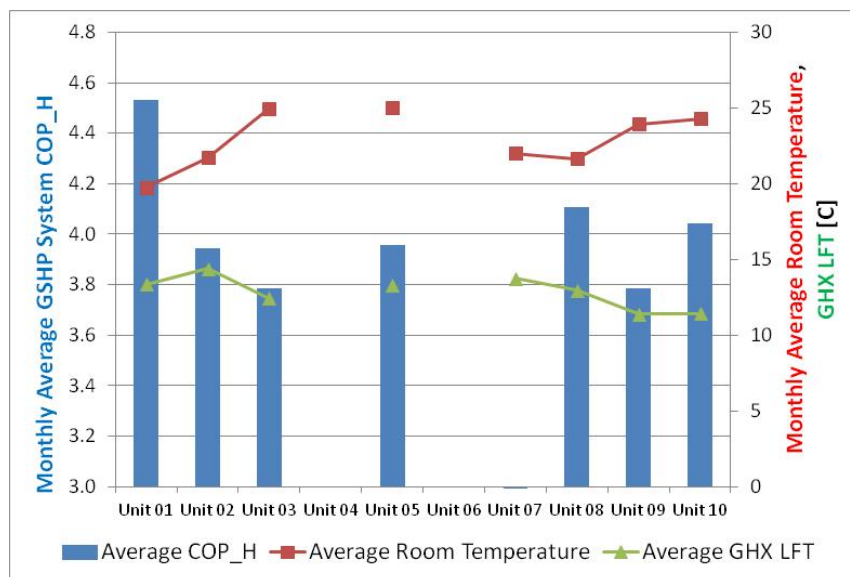


Figure 2: Monthly average COP_H of the GSHP systems and the associated average room temperatures with GHX LFTs at each of the test homes in February 2012

The total GSHP system power consumption varied significantly during the heating season, although the locations, sizes, and construction of the homes are almost identical. The total GSHP system power consumption in unit 3 (over 350 kWh in February 2012) was more than double that in unit 8 (under 150 kWh in the same month) as shown in Fig. 3. Further analysis

indicated it was the difference in room temperatures of the test homes that resulted in the large discrepancies in total GSHP system power consumption. Fig. 3 demonstrates a clear relationship between the average room temperature and the total power consumption of the GSHP systems: the higher the monthly average room temperature (when heating was on), the higher the power consumption. The 6°C lower average room temperature in unit 1 resulted in a 59% reduction in total GSHP system power consumption compared with unit 3. Measured data indicates that the monthly peak electricity demand of the GSHP systems varied from 1.8 to 2.2 kW during the heating season.

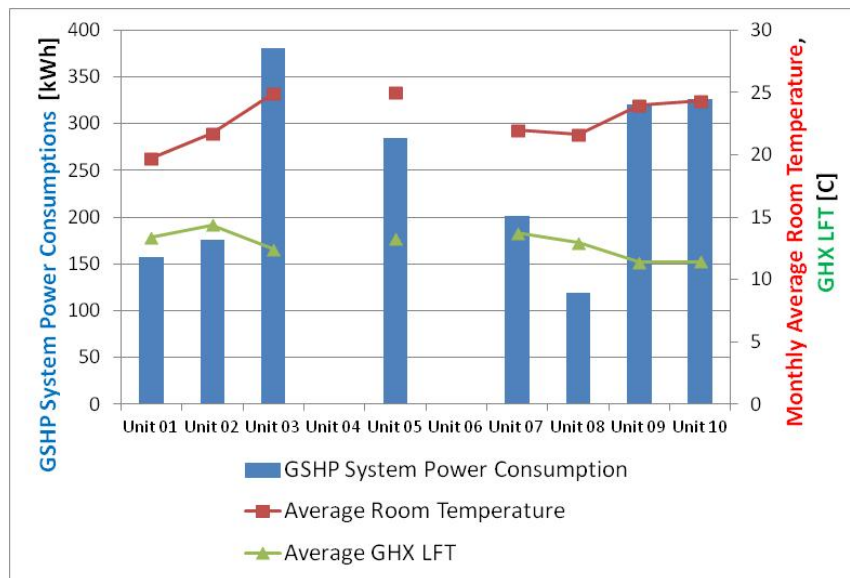


Figure 3: Monthly total GSHP system power consumption and coincident average room temperature with GHX LFT at each of the test homes in February 2012

5.2 Cooling Season Performance

During the cooling season (June 2012 through August 2012), the average ambient dry-bulb temperature was 29°C and fluctuated from 12 to 44°C. There were 18 straight days where temperatures reached 38°C or greater during the second hottest summer on record in the region. The monthly average room temperatures in all of the ten homes were maintained within similar range by the GSHP systems during the cooling season—approximately 23°C with a deviation of less than 1.7°C. However, the monthly average and maximum GHX LFTs in the ten homes varied much more widely in the summer than in the winter. While the average GHX LFT was maintained nearly constant at around 24°C in unit 10, it reached 38°C in July in unit 9 and even higher in August. Except in unit 10, the monthly average GHX LFT at all other homes increased over the first two months and leveled or dropped slightly in August. The temperature increase was less than 3°C except in units 4 and 9, where the increase was 5.6°C and the maximum GHX LFT exceeded 35°C. The 65 m deep co-axial #1 GHX in unit 4 apparently is too short for the given cooling loads although the super conductive grout was used (Table 1). Unit 9 had unexpected high internal heat gains due to higher than normal occupancy and energy uses in this home.

Seven of the ten test homes collected enough data to calculate the monthly COP_C of the GSHP systems. The monthly COP_C ranged from 4.3 to 5.5 during the three summer months except in units 1 and 9. These numbers are slightly lower than the COP_C (4.9 at the “full load” condition and 5.7 at the “part load” condition) provided in the manufacturer’s catalog when the entering fluid temperature is at 26.7°C. The difference is thought to be due to the different pump power and fan power from those used in the catalog data. Another

reason could be that the room temperature (approximately 23°C) was lower than the rating condition (26.7°C), at which the catalog data were obtained.

Since the room temperatures in these homes were maintained within a similar range during the cooling season, the difference in the COP_C values is mainly the result of different GHX LFTs at each home. Fig. 4 plots the monthly COP_C, room temperature, and GHX LFT in July 2012. Apparently, the low COP_C values are associated with high GHX LFTs: unit 10 had the lowest average GHX LFT (24°C) and the highest COP_C (5.3), whereas unit 9 had the highest average GHX LFT (38°F) and the lowest COP_C (2.7). It should be noted that, since the GHX in unit 9 was undersized for the unexpected high cooling loads in this home, its low COP_C is not a representative of a properly designed GSHP system.

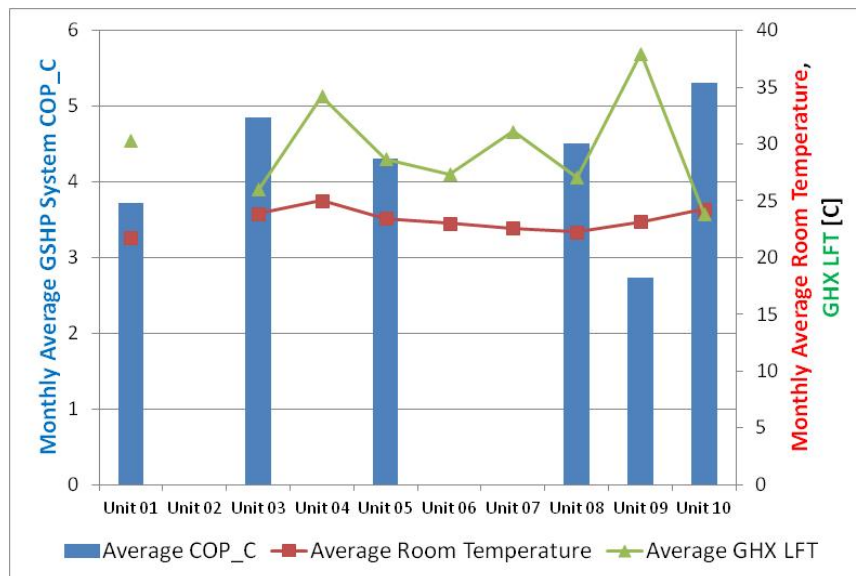


Figure 4: Monthly average room temperatures and GHX LFTs with resulting monthly average GSHP system COP_C at each of the test homes in July 2012

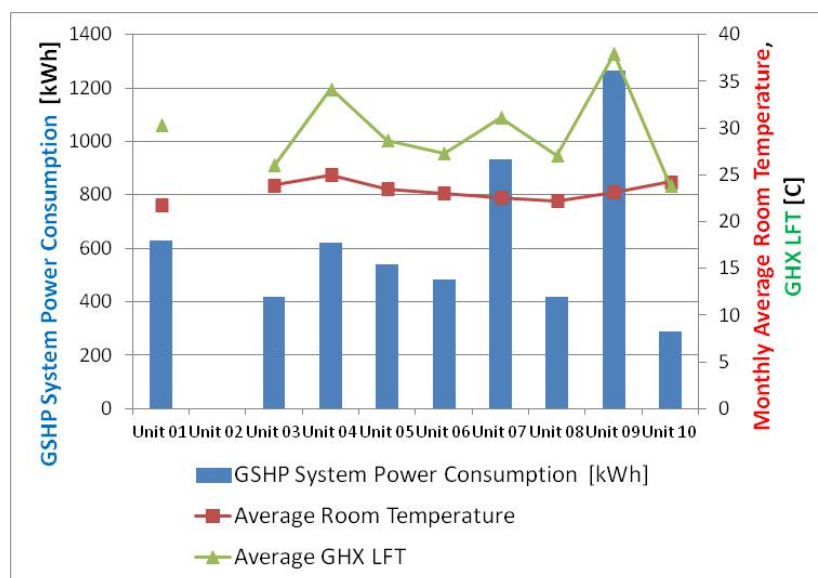


Figure 5: Monthly total GSHP system power consumption and coincident average room temperature with GHX LFT at each of the test homes in July 2012

As shown in Fig. 4, the GHX LFT, room temperature, and COP_C in units 5 and 8 were very close to each other. Thus, the double U-tube GHX in unit 5 performed nearly equal to the

reference conventional GHX in unit 8, but with 35% shorter borehole depth. As discussed earlier, the GHX used in unit 10 has the second lowest R_b value and it is only higher than that of the double-U GHX. However, the total depth of the GHX in unit 10 is 39% deeper than the double U-tube GHX (Table 1). The GHX in unit 10 appears oversized for the given loads and thus resulted in lower GHX LFT than the double U-tube GHXs in unit 5.

The GSHP system power consumption varied widely during the cooling season, although the average room temperature in these homes was maintained at about the same level. Fig. 5 indicates the large variation in GSHP system power consumption is the result of the different GHX LFTs in these systems. The GSHP system power consumption in unit 9 was more than four times that of unit 10. Since the COP_C of the GSHP system in unit 9 is about half of that in unit 10, the fourfold difference in total energy consumption is due not only to the difference in COP_C but also to the different cooling loads of the two systems. The minute-level measured data show that the GSHP system in unit 9 ran at full speed much more frequently than the GSHP system in unit 10. The peak electric demands of the GSHP systems (with valid electric power measurements) varied from 1.6 to 2.6 kW during the cooling season. The highest peak demand was from unit 9, of which the GHX was undersized for the unexpected high cooling loads.

6 ANALYSIS OF DRILLING DEPTH REDUCTION POTENTIAL OF THE NEW GHXS

To assess how much the new GHXs can reduce the required drilling depth, a computer model of one of the homes—unit 3—was developed with eQUEST software, which has reliable simulation capability for GSHP systems (Liu 2008). The model-predicted annual GSHP system power consumption was very close to the measured data in unit 3 with less than 10% difference.

Simulations with the eQUEST model were conducted to determine the required borehole depths of the new GHXs and a conventional vertical-bore GHX for maintaining the GHX LFT under the same maximum level (around 34°C) in response to the identical building loads and the same ground thermal conductivity and undisturbed ground temperature.

The new GHXs are modeled with their borehole diameters and the R_b values estimated from the TRT tests (Table 2). The conventional GHX uses a 25 mm outer diameter single U-tube inserted in a 210 mm diameter vertical bore and is grouted with bentonite (0.7 W/m-K). The separation of the two legs of the U-tube is assumed to be 38 mm. Its R_b value is calculated with an analytical solution described by Hellström (1991), which has been implemented into the eQUEST software, and the result is 0.175 (m-K)/W. The R_b value is also calculated with GLHEPRO as a weighted average of the values corresponding to configurations B and C. Assuming the weighting factors for configurations B and C are 80% and 20%, respectively, the resulting R_b value is 0.174 (m-K)/W, which is nearly identical to the value calculated by eQUEST.

Table 3 summarizes key parameters of the simulations and the predicted borehole depth reductions resulting from three new GHXs, which represent three different levels of borehole thermal resistances (Table 2).

As shown in Table 3, the double U-tube GHX reduces the required borehole depth by 30% compared with the conventional GHX. The single U-tube GHX with small diameter borehole and top-only grouting (the rest is in water) reduces the required borehole depth by 23%. The GHX with co-axial #1 pipe and superpermeable grout (unit 4) has similar borehole resistance to the single U-tube GHX with small diameter borehole and thus can also reduce

the depth by 23% (not listed in Table 3). The GHX with co-axial #1 pipe and the thermally enhanced grout (unit 9) reduces the required borehole depth by 14%.

Table 3: Comparison of calculated borehole thermal resistances

Undisturbed ground temperature, °C	17.2			
Ground thermal conductivity, W/(K m)	3.2			
GHX type	Conventional	Co-axial #1	Single U-tube	Double U-tube
Grout type	Bentonite	Thermally enhanced	Bentonite (on the top 50 ft of borehole and the rest is in water)	Thermally enhanced
Grout thermal conductivity, W/(K -m)	0.7	1.4	0.7	1.4
Borehole diameter, mm	133	121	70	133
Borehole resistance, (K-m)/W	0.17	0.13	0.09	0.065
Borehole depth, m	110	96	85	78
Max loop LFT, °C	34	34	34	34
Percent reduction in borehole depth, %		14%	23%	30%

For a given R_b value and building load, the resulting borehole depth depends on the ground thermal conductivity value. As the ground thermal conductivity increases, the ground thermal resistance decreases relative to the borehole thermal resistance. Then, the total thermal resistance is more sensitive to changes in the borehole thermal resistance. The percentage of borehole depth reduction resulting from the double U-tube GHX increases to 32% if the ground thermal conductivity value is a bit higher [3.8 W/(m-K)] and it decreases to 24% at a place with poor ground thermal conductivity [2.1 W/(m-K)]. The reduction in bore depth depends on parameters of a particular installation and must be determined for each case.

7 CONCLUSIONS

Eight different new vertical-bore GHXs were evaluated through both the short-term TRT tests on the R_b value of each GHX and the full-year performance measurements on the associated GSHP systems.

Based on data collected from the TRT tests, R_b values were evaluated for the new GHXs. The ranking of these GHXs in the ascending order of R_b values is: (1) double U-tube with thermally enhanced grout, (2) single U-tube with small diameter borehole and top-only bentonite grouting (the rest is in water), (3) co-axial #1 with super conductive grout, (4) single U-tube with thermally enhanced grout, (5) co-axial #1 with thermally enhanced grout, and (6) co-axial #2 with super conductive grout. The double U-tube GHX has best heat transfer performance while the co-axial #2 is the worst among the new GHXs being tested.

The full-year performance data show that the GSHP systems maintained the room temperature at the setpoint specified by individual homeowners except in unit 9, where the building cooling load exceeded the capacity of the 2 ton GSHP system. Heating COPs (COP_H) of the GSHP systems were close to each other (3.8 to 4.5) and the differences were attributed to individual homeowners' thermostat settings; the cooling COPs (COP_C) of the GSHP systems varied from 4.3 to 5.5 excluding units 1 and 9, of which the GHX was apparently undersized for the experienced cooling loads. The discrepancy in COP_C was a result of the variation of GHX LFTs during the cooling season.

While the homes are nearly identical, the energy consumptions of the GSHP systems varied significantly depending on GHX LFTs and room temperature (especially in winter, when the

room temperature significantly affects the heating loads of these homes). It indicates that GHX design and implementation, as well as the thermostat control (i.e., setback when the home is not occupied), are major keys to the success of a GSHP system.

Both the full-year performance data and the computer simulations agreed that the double U-tube GHX requires 30% less borehole depth compared with a conventional single U-tube GHX while retaining the same performance at the given building load and ground conditions. The other new GHXs being tested also show the potential to reduce the required borehole depth, although the reductions are smaller (14-23%). A larger reduction in required borehole depth can be expected at locations where the ground thermal conductivity is higher.

8 ACKNOWLEDGEMENTS

This work was sponsored by the U.S. Department of Energy Building Technologies Program via US-China Clean Energy Research Center for Building Energy Efficiency (CERC-BEE) and Oklahoma Gas and Electric Company (OG&E). Special thanks to: ClimateMaster for its donation of heat pump equipment and technical support; Ewbank and Associates for conducting TRT tests; the International Ground Source Heat Pump Association (IGSHPA) for providing DAS in the test homes, and the homeowners for allowing us conducting field tests.

This manuscript has been authored by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy.

9 REFERENCES

- Beier R.A. and Smith M.D. 2002. "Borehole thermal resistance from line-source model of in-situ tests". *ASHRAE Transactions*, Vol. 90, Part 2, pp. 212-219.
- Beier R.A., Acuña J., Mogensen P., and Palm B. 2012. "Vertical temperature profiles and borehole resistance in a U-tube borehole heat exchanger", *Geothermics* 44: 23-32.
- Beier R.A., Acuña J., Mogensen P., and Palm B. 2013. "Borehole resistance and vertical temperature profiles in coaxial borehole heat exchangers", *Applied Energy*, 102: 665–675.
- Beier, R.A., and E.N. Ewbank. 2012. In-Situ Test Thermal Response Tests Interpretations: OG&E Ground Source Heat Exchange Study, International Ground Source Heat Pump Association. http://www.igshpa.okstate.edu/geothermal/research/In_situ_TRT_report.pdf
- Carslaw H.S. and Jaeger J.C. 1959. *Conduction of Heat in Solids*. 2d ed. New York: Oxford University Press.
- GLHEPRO 4.0 for Windows, 2008, User Guide, School of Mechanical and Aerospace Engineering, Oklahoma State University, Distributed by IGSHPA, Stillwater, Oklahoma.
- Hellström G. 1991. *Ground Heat Storage: Thermal Analysis of Duct Storage Systems: Theory*, University of Lund, Sweden.
- Liu, X. 2008, "Enhanced design and energy analysis tool for geothermal water loop heat pump systems," in *Proceedings of the 9th International Energy Agency Heat Pump Conference*, May 20–22, 2008, Zurich, Switzerland.
- Liu, X., and J. Munk 2013. *Field Test and Evaluation of Residential Ground Source Heat Pump Systems Using Emerging Ground Coupling Technologies*, ORNL/TM-2013/39, Oak Ridge National Laboratory.