DESIGN, INSTALLATION, AND MONITORING OF A NEW DOWNHOLE HEAT EXCHANGER

A.D. Chiasson[1], G.G. Culver[1], D. Favata[2], S. Keiffer[3]

[1]Geo-Heat Center, Oregon Institute of Technology, Klamath Falls, OR, USA
[2]Alternative Geothermal Solutions, Oklahoma City, OK, USA
[3]Facilities Services, Oregon Institute of Technology, Klamath Falls, OR, USA

ABSTRACT

The downhole heat exchanger (DHE) is used to provide space heating and domestic hot water from a single geothermal well. The most common construction of DHEs has been black iron, which is subject to failure by corrosion. This paper describes the design, installation, and monitoring of a new type of DHE constructed of cross-linked polyethylene plastic (PEX), a material known for its relatively high temperature and pressure rating, durability, and chemical resistance. The PEX DHE was installed as a retrofit at a residence in Klamath Falls, OR and a data logger was used to record system temperatures at 5-minute intervals for the 2004-2005 heating season. Observations thus far show the PEX assembly to be an acceptable DHE.

Keywords: *downhole heat exchanger, DHE, PEX, direct use*

INTRODUCTION

A downhole heat exchanger (DHE) is a closed-loop pipe with a “U-bend” at the bottom, and is installed in geothermal wells to provide space heating and domestic hot water. Their most widespread use is in the United States, Turkey, and New Zealand, with less common and/or experimental uses reported in Iceland, Hungary, Russia, Italy, Greece, and Japan. In the United States, the most concentrated uses of DHEs are in Klamath Falls, OR and Reno, NV.

In Klamath Falls, OR, over 500 DHE installations are believed to exist, mostly in residences, schools, and in a bridge deck snow melting application. The most common construction of DHEs is black iron pipe due to its low cost and relative ease of installation. The drawback, however, is that black iron eventually fails by corrosion. A 1974 study of DHEs in Klamath Falls (Culver et al., 1974) revealed that their lifetime then ranged from 5 to 22 years, with an average of 14.1 years. DHEs in artesian wells were found to last longer, about 30 years. Based on some recent experiences in Klamath Falls, some DHEs experience failure due to corrosion in less than two years. With the cost of black iron pipe approximately doubling in the past few years, and the continued uncertainty in predicting DHE lifetime, it still remains desirable to find alternatives to black iron DHEs. Several DHE materials of construction have been tried throughout their history, but a low-cost, maintenance-free DHE has been elusive.

The overall objective of this work has been to examine the viability of making use of cross-linked polyethylene (PEX) plastic in DHEs. This main objective consisted of three parts: (1) developing a method of reliably installing a PEX DHE in an existing well, (2) developing a preliminary design calculation method to determine the required PEX tubing length in DHE retrofits, and (3) initiating a long-term performance monitoring program of PEX DHEs. This paper describes the method used to install a PEX DHE and determine its required length, and presents the results of temperature monitoring of the first heating season.

BACKGROUND

A Brief History of DHE Materials

A history of DHE materials has been recently described by Culver (2005), and much of the discussion below comes from that paper. A schematic of a typical DHE system in Klamath Falls, OR is shown in Figure 1.

The first DHE installed in Klamath Falls, OR was in 1931, and was perhaps the first DHE installed in the world. It was constructed of black iron pipe, and corrosion of the pipe eventually occurred most commonly near the water level in the well. Early efforts to combat corrosion consisted of using zinc-galvanized pipe, installing a section of brass pipe at the water line, and dumping motor oil down the well.

The use of galvanized pipe proved unsuccessful, as it is now known that geothermal waters leach zinc, and at temperatures above 135°F (57°C), the anode-cathode relationship of Zn and Fe reverses. The use of brass pipe at the water line was a bit more successful, but it was often difficult to predict long-term water level changes and the brass pipe section did not always remain straddled across the water table. Constructing the entire DHE of brass was not cost-effective. The practice of dumping motor oil down wells was discouraged for obvious environmental reasons, but it seemed to have some effect in hindering corrosion at the water-air interface in the well. Thus, the practice of dumping paraffin down the well became common and Swisher and Wright (1990) showed that this practice did in fact reduce corrosion. Swisher and Wright (1990) also recommended the sealing of wells to prevent oxygen intrusion into the well.

The above practices did not address corrosion of the DHE below the water level in the well. This type of corrosion is not as well understood, and could be partially caused by stray currents from poorly grounded electrical systems (electrical grounding to water lines was a common practice in older homes). Corrosion of DHEs near the well bottom could also be attributed to interactions with naturally-occurring metals in groundwater, dissolved from the surrounding rock.

Some attempts to solve corrosion problems of DHEs below the groundwater level consisted of using sacrificial anodes and coating the black iron pipe with mastic plus an extruded polyethylene cover. The benefits of sacrificial anodes were inconclusive. The use of mastic was unsuccessful because above about 150°F (65.5°C), the material becomes brittle, resulting in cracking.

In Reno, NV, different non-metallic pipe materials were tried in the early 1980s such as polyethylene, polybutylene, CPVC, and fiberglass epoxy. Polyethylene, polybutylene, and CPVC were not successful as the pressure rating of these materials is severely de-rated above temperatures of 140°F to 160°F (60°C to 71°C). The use of fiberglass epoxy pipe in DHEs has been more successful, as this material has a high temperature and pressure rating as well as excellent corrosion resistance. However, care must be taken in these installations because fiberglass pipe is joined with a threaded connection, and failures have been observed near these joints in the past. According to Culver (2005), DHE materials in the Reno, NV area are trending toward stainless steel, which is about three times the cost of black iron.

Project Background

A black iron DHE at a 1,500 ft^2 (140 m^2) residence in Klamath Falls failed in October 2004 due to corrosion near the air-water interface in the well. Corrosion of the black iron had resulted in the formation of pinholes in the pipe and subsequent excessive leakage of municipal water into the well (municipal water is typically tied into DHE's with a pressure-regulating valve to provide operating pressure to the system). The homeowner reported that the DHE had just been replaced 1.5 years prior. The length of the black iron DHE was 160 ft (48.7 m) with a nominal diameter of 1½ in. (38 mm).

A review of existing information on the well revealed that there was no well log or driller's report. The Geo-Heat Center had been involved with various studies on this particular well since the 1970s and there was anecdotal information that the well was probably installed in the 1940s or 1950s. The well has an 8-in. (203 mm) nominal diameter steel surface casing, which is believed to extend to only about 15 ft (4.6 m) below grade. Based on numerous temperature profile measurements performed on this well, the average well water temperature is about 200^{o}F to 205^{o}F (93^{o}C - 96^{o}C). Historical static water levels have consistently been about 90 ft (27.4 m) below grade and the well depth is 322 ft (98 m) below grade. Therefore, the usable (submerged) length of the old black iron DHE was approximately 70 ft (21 m).

The heating system in the residence is a forced-air unit with a hot water hydronic coil. The air-handling unit and air supply and return ducts are installed in a crawl space. Water flows to and from the DHE in the well by natural convection (thermosyphon), so no pump is installed. Domestic hot water is supplied by an electric hot water tank in the house, not the geothermal well.

Heat Transfer in DHEs and Existing Design Methods

The heat transfer processes governing DHE performance are complex. The main heat transfer mechanism is vertical convection of groundwater in the well (as shown in Figure 1), but its exact nature is governed by the well construction details. Culver and Lund (1999) describe current methods of well completion to enhance groundwater convection in the well.

At present, there is no good design procedure for DHEs (Culver and Lund, 1999). There is an old rule of thumb of 1 ft of coil per 1,500 Btu/hr of heat output, but this is specific to the Klamath Falls area, since it has built-in assumptions of groundwater temperature and degree of convection mixing in the well bore. Culver and Lund (1999) summarize the latest design procedure, which uses a *mixing ratio* to approximate the ratio of cooler water leaving the well to hotter water entering the well through convection. However, this parameter is an empirical one and is difficult to determine.

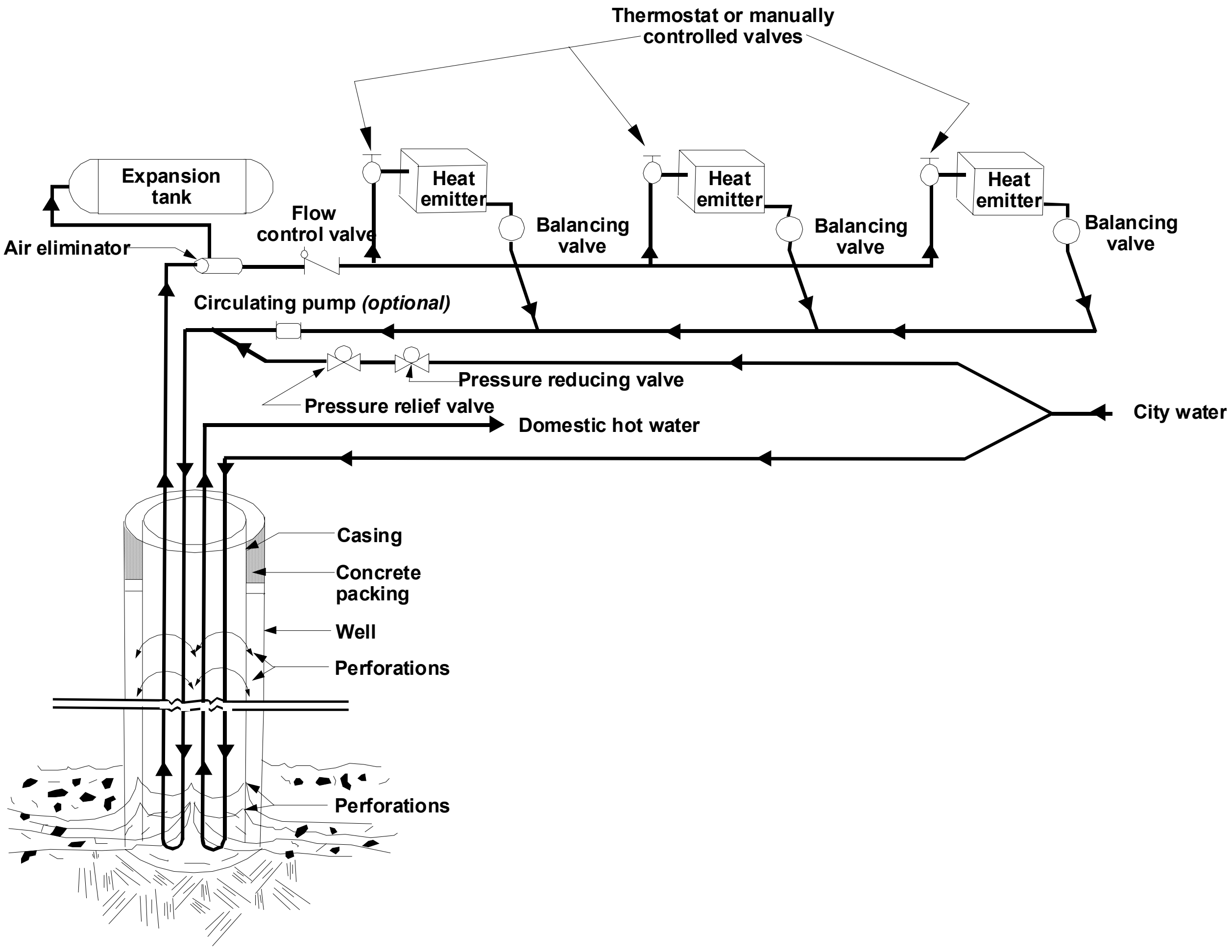

Figure 1. Typical downhole heat exchanger (DHE) system (Klamath Falls, OR).

METHODOLOGY

DHE Material

Figure 2 is a photograph of the PEX DHE. The entire DHE was constructed of PEX materials, including the compression-type fittings and elbows. The compression-type fittings are unique to PEX material; the compression fitting is placed over the end of the pipe to be joined to an elbow (or other fitting) and an expansion tool is used to expand the pipe and compression fitting. The elbow (or other fitting) is quickly inserted into the pipe end, and then the pipe and compression fitting returns to its original shape via the "memory" of the plastic, resulting in an extremely tight fitting.

Polyethylene is available in different forms, depending on the molecular structure. For example, high-density polyethylene (HDPE) is the standard pipe used in geothermal heat pump systems and is color-coded black. Yellow HDPE pipe is being used to replace black iron piping in natural gas pipelines. PEX pipe is readily available and is commonly used in radiant floor heating applications and in potable water plumbing. The "cross-linking" procedure is a chemical process that produces a long molecular chain that results in a more durable material that can withstand a wide range of pressures and temperatures.

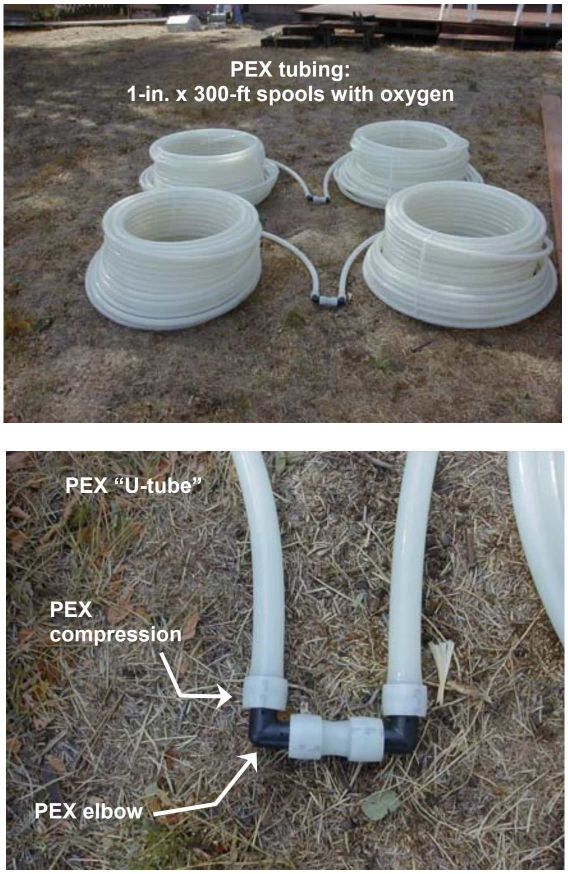

Figure 2. PEX DHE materials.

The main reasons for choosing PEX pipe is it’s relatively high temperature rating, durability, and chemical resistance. A manufacturer of PEX pipe reports that one independent laboratory in Sweden and one in Germany have subjected a test sample of PEX to a temperature of 203^{o}F (95^{o}C) and pressure of 152 pounds per square inch (psi) (1048 kPa) since 1973 (Uponor Wirsbo, 2003). PEX pipe is rated at 100 psi (689 kPa) at 180^{o}F (82^{o}C) and 80 psi (552 kPa) at 200^{o}F (93^{o}C). As a point of reference, HDPE pipe is only rated up to 140^{o}F (60^{o}C).

PEX tubing is available with an oxygen diffusion barrier to prevent corrosion of metal parts of the system. As this installation was a retrofit with metal components remaining in the system, we used PEX with an oxygen barrier as conservative measure.

Design and Installation of the DHE

A schematic of the DHE assembly is shown in Figure 3 and a photograph prior to lowering the DHE into the well is shown in Figure 4. In a DHE retrofit of this type, many theoretical and practical considerations are necessary as described below.

The two main design parameters controlling the PEX DHE sizing included diameter and length of the pipe. The overall DHE consists of two PEX U-tubes in order to maintain an acceptable pressure drop through the flow system and to achieve an adequate heat exchange length. Another practical consideration in the design of a DHE retrofit is the well bore diameter, as this dictates the allowable diameter of the DHE. In this case, the well was reamed out prior to DHE installation and the driller reported that the hole was 8-in (203 mm) diameter to a depth of 270 ft (82 m), but then narrowed to 6-in (152 mm). Since a 1-inch (25.4 mm) PEX U-tube assembly is about 5.75 in. (146 mm) in overall diameter, it was deemed too risky to attempt to push it into a 6-in. (152 mm) diameter hole. Therefore, there was only 180 ft (54.9 m) of water column available for the new PEX DHE (*270 ft of 8-in. hole - 90 ft static water level = 180 ft submerged*).

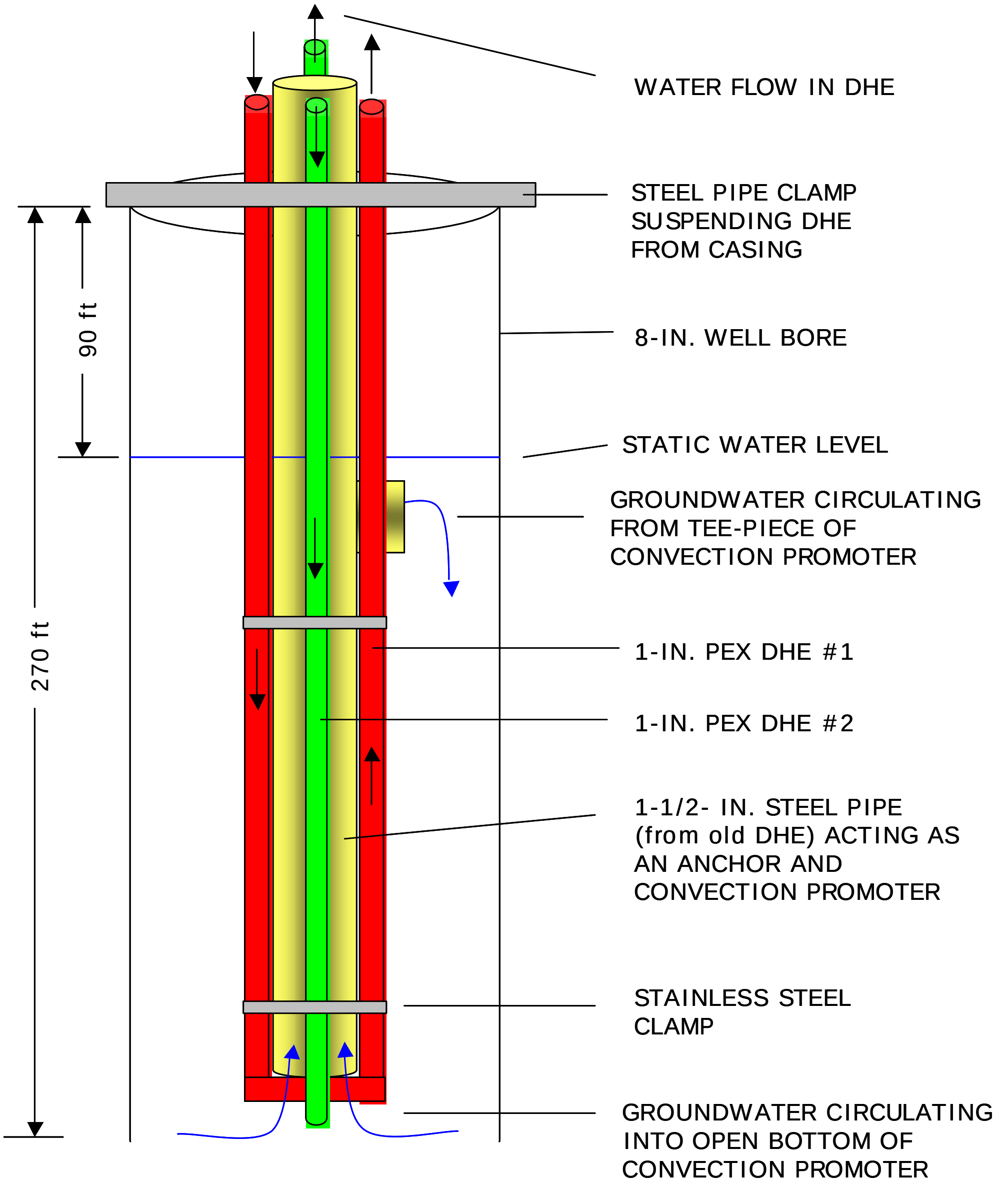

Figure 3. Schematic of the DHE assembly.

Figure 4. PEX DHE prior to installation, showing the two PEX U-tubes fastened to the black iron pipe of the old DHE, which was used as an installation guide, anchor, and convection promoter.

Based on heat loss calculations for the home and thermal properties of the PEX pipe, it was determined that two loops of 180 ft (54.9 m), 1-inch nominal diameter, would be more than adequate to provide heat to the home. For a DHE, the heat extraction rate (*q*) per unit length of pipe is simplified as:

$$q = \frac{1}{R}\left(T_{in} - T_{out}\right) \tag{1}$$

where *q* is in units of But/hr/ft (W/m), *R* is the overall pipe thermal resistance per unit length in units of ^{o}F/(Btu/(hr-ft)) or ^{o}C/(W/m), and T_{in} and T_{out} are the temperatures of fluid inside and outside the pipe. Considering the heat transfer processes involved in DHEs, the key parameter in Equation 1 is the overall pipe resistance. This term combines the effect of internal convection, pipe wall conduction, and external convection and is given by:

$$R = \frac{1}{h_{in} 2 \pi r_{in}} + \frac{\ln\left({r_{out}}/{r_{in}} \right)}{2 \pi k} + \frac{1}{h_{out} 2 \pi r_{out}} \tag{2}$$

where *h* is the convection coefficient, *r* is the pipe radius, *k* is the pipe thermal conductivity, and the subscripts *in* and *out* refer to the inside and outside of the pipe. Using known values of the pipe thermal conductivity for black iron and PEX and typical flow rates in DHEs as reported by Culver and Lund (1999), the overall thermal resistance is computed to be about four times greater for PEX than for black iron. This means that four times the amount of 1-inch PEX DHE is required to transfer heat at the same rate as 1½-inch black iron DHE. Therefore, since the previous black iron DHE had a submerged length of 70 ft (21.3 m), 280 ft (85.3 m) of PEX DHE should be adequate.

Since there was uncertainty in the performance of a double U-loop as compared to a long single loop, it was decided to utilize the full length of available water column in the well as a safety measure. Therefore the resultant DHE was 360 ft (110 m) in total length. The benefit of two parallel sub-loops is that lower pressure drops are maintained through the DHE.

It is interesting to note that the thermal conductivity of black iron is around 30 Btu/hr-ft-^{o}F (52 W/m-^{o}C), while the thermal conductivity of PEX is about 0.25 Btu/hr-ft-^{o}F (0.43 W/m-^{o}C). However, since the pipe thermal conductivity affects only one term in the overall thermal resistance, pipe thermal conductivity values greater than 6 Btu/hr-ft-^{o}F (10.4 W/m-^{o}C) have a negligible effect on the overall thermal resistance value.

A considerable portion of the design phase consisted of devising a method to easily and reliably install the DHE into the well. As it was judged doubtful that PEX U-tubes could simply be pushed into the well (especially through the water column) another scheme was necessary. It was therefore decided to fasten the PEX U-tubes to the leftover black iron pipe from the original DHE to facilitate pushing the PEX tubing into the well. The black iron pipe could then be used as an anchor for the PEX tubing, providing a means to suspend the PEX in the well without stressing the PEX under its own weight.

Another advantage of using the black iron pipe as a guide and anchoring device was that it could be used as a "convection promoter" in the well. The advantages of convection promoters have been examined by Freeston and Pan (1983). Their function is essentially to provide a conduit for water to circulate within uncased wells by natural convection, preventing the formation of stagnant cold water zones. This was done by leaving the bottom of the black iron pipe open and using a tee-piece as one of the pipe couplings below the water level (Figure 3).

The entire installation process took about 3 hours to complete.

Data Logging

Temperature sensors were installed at four locations: inlet and outlet water in the DHE, and supply and return air in the house. Temperatures were recorded at 5-minute intervals using a digital data logging device. Pressure gauges were installed in the supply and return lines of the DHE in order to estimate flow rates. Daily high and low ambient air temperatures for Klamath Falls were obtained from the National Weather Service.

RESULTS

Performance Monitoring

Performance monitoring of the PEX DHE for the 2004-2005 heating season ran from October 18, 2004 to May 2, 2005, and no problems were encountered.

Measured temperatures of the air and water sides of the system are shown in Figure 5. For clarity, plotted in Figure 5 are average hourly temperatures computed from the 5-minutely recorded temperatures. The lowest recorded water temperature exiting the DHE was 174.5°F (79.2°C) when the outdoor air temperature was -3°F (-19.4°C). The supply air temperature at that time was still in excess of 130°F (54.4°C), keeping the house at 74.5°F (23.6°C). The water temperature exiting the DHE was routinely measured at 178 -182°F (81-83°C) through the heating season, keeping the house at 78-80°F (25.5-26.7°C).

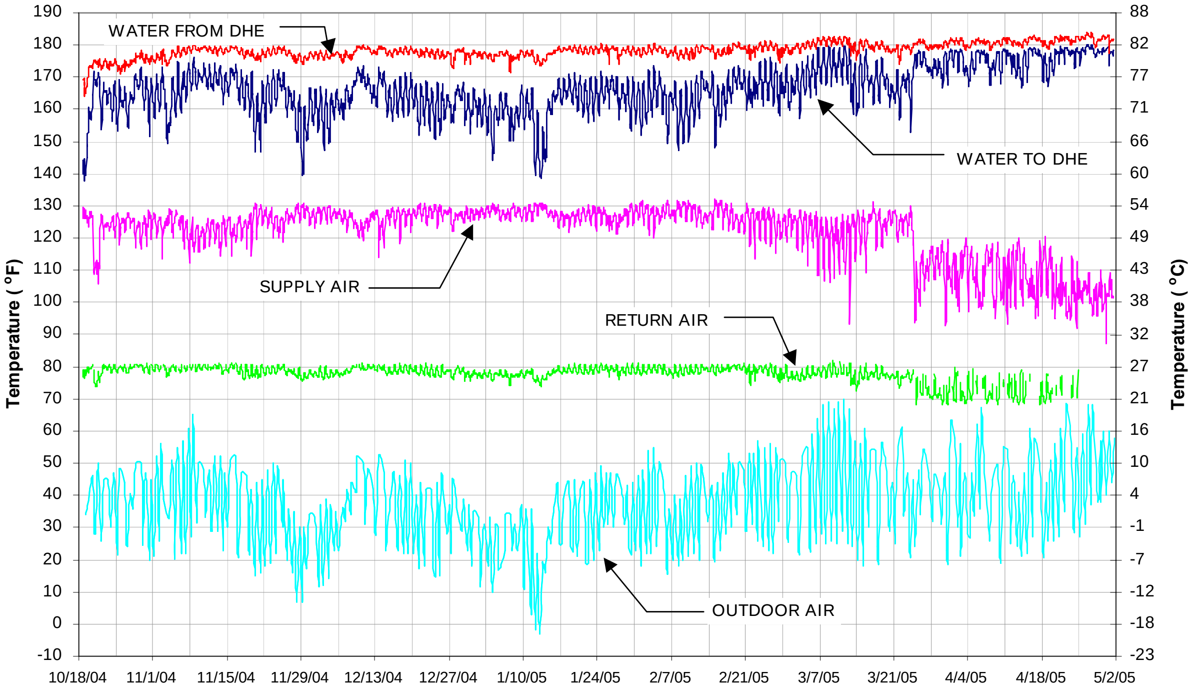

Figure 5. Average hourly system temperatures.

Water flow rates through the DHE were crudely estimated from pressure gauge readings on the system and from published pressure drop values in the PEX manufacturer's catalog. With the air-handling unit *ON*, the pressure differential across the DHE was observed to be about 2.5 to 3 psi (17.2 to 20.7 kPa), which translates to a water flow rate through the DHE of approximately 6 to 7 gpm (0.38 to 0.44 L/s). With the air-handling unit *OFF*, the pressure differential across the DHE was observed to be about 1.5 psi (10.3 kPa), which translates to a water flow rate through the DHE of approximately 3 gpm (0.19 L/s). Using these estimated flow rates and the measured temperature differential across the DHE, the hourly heat output of the DHE was calculated and is shown in Figure 6. A review of this figure shows that the maximum hourly output of the DHE was about 115,000 Btu/hr (34 kW), occurring when the outdoor air temperature was -3°F (-19.4°C). This heat output is much more than necessary for the home itself, but there are significant heat losses in the crawl space where the air-handling unit and ductwork are located.

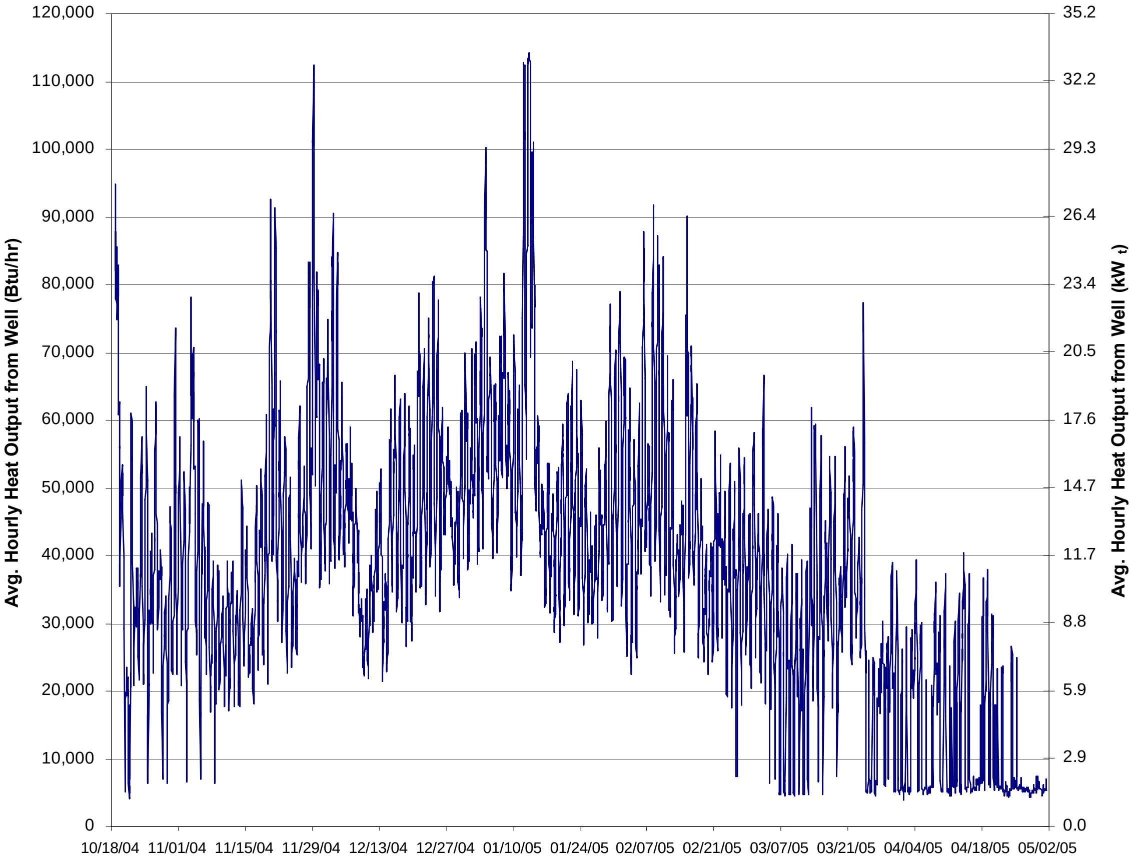

Figure 6. Estimated hourly heat output rate of the DHE.

Economics of a PEX DHE

The ultimate success of any new DHE will be in the economics. At this preliminary stage of the project, it is beneficial to perform a simple economic analysis.

Material costs of 1½-inch black iron pipe are on the order of $3/ft, or $6/ft of DHE (since a DHE consists of two legs). Material cost of 1-inch PEX tubing with the oxygen barrier is on the order of $2.20/ft, and the same tubing without the oxygen barrier is about $1.55/ft. Therefore, if corrodible materials are eliminated from the plumbing system, and one chooses the 1-inch PEX tubing without the oxygen barrier and uses the design described in this paper (i.e. two U-tubes fastened to a 1½ inch black iron guide), the DHE cost would be $9.20/ft (4 x $1.55/ft for the PEX tubing + $3/ft for a 1½ inch black iron guide). Assuming quadruple the length of PEX pipe is required relative to black iron, double the length of the double U-tube PEX DHE would be required.

To put these costs in perspective, consider a new DHE in a well with a 50-ft (15 m) static water level and 100 ft (30 m) of submerged black iron DHE required. Using the above material costs, a 1½ -inch black iron DHE would cost about $900. An equivalent double U-tube PEX DHE would cost $2300. Assumed labor costs are an additional $300 for the black iron DHE and $400 for the PEX DHE. Assuming a future cost of $500 each time the black iron DHE corrodes at the air-water interface in the well (i.e. labor and material costs to replace only two 21-ft sections of corroded pipe), three episodes of this type of corrosion failure would be necessary for the PEX DHE to pay for itself. However, this does not include eventual total replacement of the black iron DHE.

CONCLUDING SUMMARY

This paper has described a new downhole heat exchanger (DHE) constructed of cross-linked polyethylene plastic (PEX), which has been designed, installed as a retrofit in a residence in Klamath Falls, OR, and monitored for one heating season. The PEX DHE has provided more than adequate heat to the home it was designed for, and no operating problems were encountered.

The design and installation procedure described in this paper is mostly applicable to black iron DHE retrofits. Thermal resistance calculations show that about four times more 1-inch nominal PEX tubing is required than 1½-inch nominal black iron. However, monitoring results of this study showed that the PEX can be bundled in a double U-tube assembly and still perform adequately. The double U-tube assembly also results in a lower pressure drop across the DHE. A black iron center pipe can serve as a valuable aid to install and anchor the DHE, and also serve as a convection promoter.

At this stage, the economics of a PEX DHE look favorable if one considers life-cycle costs. Future work involves verification of operation of the convection promoter; measuring and determining the maximum heat output of the DHE; and refining the design and DHE sizing calculations to include application to buildings of new construction.

REFERENCES

Culver, G., 2005. “A Brief History of DHE Materials”. *Geo-Heat Center Quarterly Bulletin*, Vol. 26, No. 1.

Culver, G. and J. W. Lund, 1999. “Downhole Heat Exchangers”. *Geo-Heat Center Quarterly Bulletin*, Vol. 20, No. 3.

Culver, G.G., J.W. Lund, and L.S. Svanevik, 1974. *Klamath Falls Hot Water Well Study*. Prepared for Lawrence Livermore Laboratory, University of California, under contract with Atomic Energy Commission.

Freeston, D.H. and H. Pan, 1983. “Downhole Heat Exchanger.” *Proceedings of the 5th New Zealand Geothermal Workshop*, pp. 203-208.

Swisher, R. and G.A. Wright, 1990. “Inhibition of Corrosion at the Air-Water Interface in Geothermal Downhole Heat Exchangers.” *Geo-Heat Center Quarterly Bulletin*, Vol. 12, No. 4.

Uponor Wirsbo, 2003. “Complete Design Assistance Manual.”