DESIGN AND INSTALLATION OF A NEW DOWNHOLE HEAT EXCHANGER FOR DIRECT-USE SPACE HEATING

Andrew Chiasson, P.E.
Geo-Heat Center

INTRODUCTION

The downhole heat exchanger (DHE) is used extensively in Klamath Falls, OR, in over 500 installations to provide space heating and domestic hot water from a single well. The most common construction of DHEs is black iron pipe due to its low cost and relative ease of installation. Several DHE materials of construction have been tried throughout their history, (see article by G. Culver, this issue) but a low-cost, maintenance-free DHE has been elusive.

Steel DHEs exhibit failure due to corrosion, usually at the air-water interface in the well. A 1974 study of DHEs in Klamath Falls (Culver, et al., 1974) revealed that the lifetime of a DHE in Klamath Falls at that time ranged from between 5 and 22 years, with an average lifetime 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 steel DHEs. This article describes the installation of a DHE made of cross-linked polyethylene (PEX) plastic.

BACKGROUND OF THE PROJECT

A black iron DHE at a 1,500-ft^2 (140-m^2) residence in Klamath Falls failed in October 2004 due to corrosion (Figure 1). The homeowner reported that the DHE had just been replaced 1.5 years prior. Corrosion of the steel 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 length of the steel DHE was 160 ft (48.7 m) with a nominal diameter of 1½ in. (38 mm).

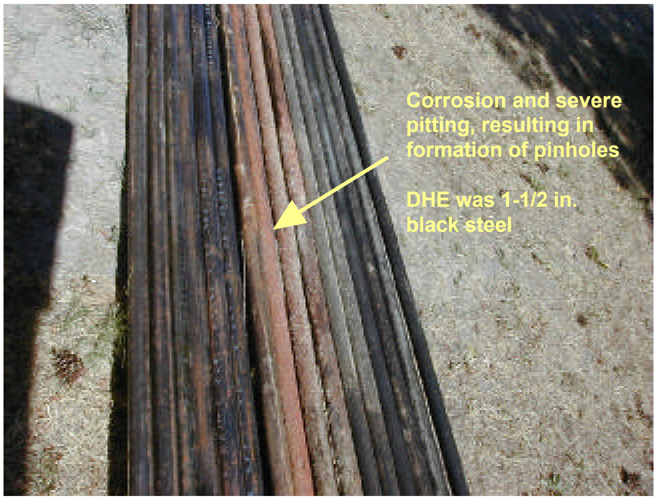

Figure 1. Corrosion o the DHE resulting in the formation of severe pitting and pin holes.

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. Figure 2 shows one of the several temperature measurement profiles taken on this well. The average well water temperature at the time of measurement, as shown in Figure 2, was 205°F (96°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 steel DHE was approximately 70 ft (21 m).

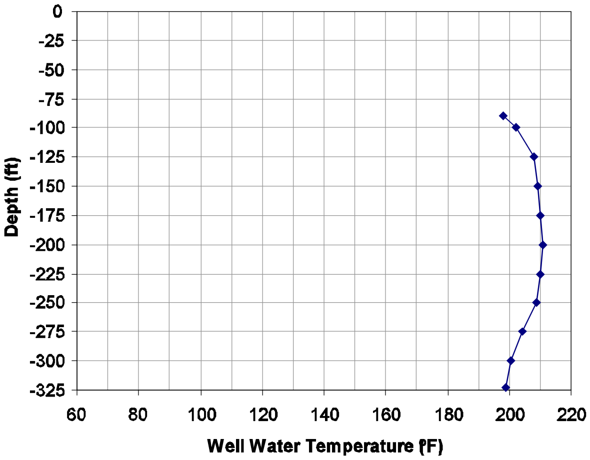

Figure 2. Well temperature profile taken in August 1976.

The heating system in the residence is a forced-air unit with a hot water hydronic coil (Figure 3). 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 nstalled. Domestic hot water is supplied by an electric hot water tank in the house, not the geothermal well.

Figure 3. ***Air-handling unit with hot water coil installed in the crawl space.***

NEW DHE INSTALLATION

PEX Pipe

The new DHE installed in the well is constructed of cross-linked polyethylene plastic (PEX) pipe. Polyethylene is available in different forms, depending on the molecular structure. 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 steel 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.

The main reasons for choosing PEX pipe is it's temperature rating, durability and chemical resistance. A manufacturer of PEX pipe reports that an independent laboratory in Sweden has subjected a test sample of PEX to a temperature of 203°F (95°C) and pressure of 152 pounds per square inch (psi) (1048 kPa) since 1973. PEX pipe is rated at 100 psi (689 kPa) at 180°F (82°C) and 80 psi (552 kPa) at 200°F (93°C). HDPE pipe, for the sake of comparison, is only rated up to 140°F (60°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 Assembly of the DHE

The two main design parameters controlling the PEX DHE sizing included length and diameter of the pipe. The length is the most important parameter affecting the overall heat extraction rate from the well. The pipe diameter was sized to make sure that the pressure drop was similar to that of the previous system, which was known to thermosyphon without difficulty and provide adequate heat to the home.

Another consideration in the design of the DHE was the wellbore diameter. Prior to DHE installation, the well was reamed out 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-in. (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. Based on heat loss calculations for the home and thermal properties of the PEX pipe, it was determined that two loops of 180 ft (*270 ft of 8-in. hole - 90 ft static water level = 180 ft submerged*), 1-in. nominal diameter, would be more than adequate to provide heat to the home.

Details of the design procedure will be forthcoming in a future paper, but a brief discussion is presented here. For a DHE, the heat extraction rate (q) per unit length of pipe is simplified as:

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

where q is in units of But/hr/ft (W/m), R is the overall pipe thermal resistance per unit length in units of °F/(Btu/(hr-ft)) or °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 (Figure 4), 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:

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

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 steel and PEX and typical flow rates in DHEs as reported by Culver (1999), the overall thermal resistance is computed to be about four times greater for PEX than for steel. This means that four times the amount of 1-inch PEX DHE is required to transfer heat at the same rate as 1½-inch steel DHE.

It is interesting to note that the thermal conductivity of steel is around 30 Btu/hr-ft-°F (52 W/m-°C); while, the thermal conductivity of PEX is about 0.25 Btu/hr-ft-°F (0.43 W/m-°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-°F (10.4 W/m-°C) have a negligible effect on the overall thermal resistance value.

Figure 5 shows photographs 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.

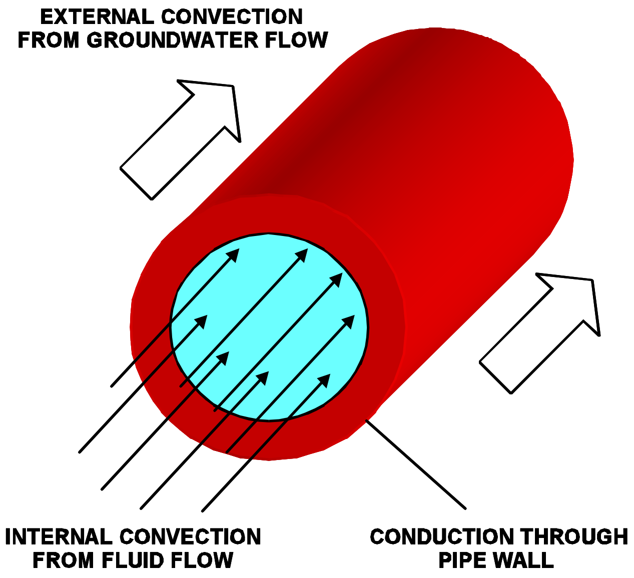

Figure 4. Heat transfer processes in a single pipe of a DHE.

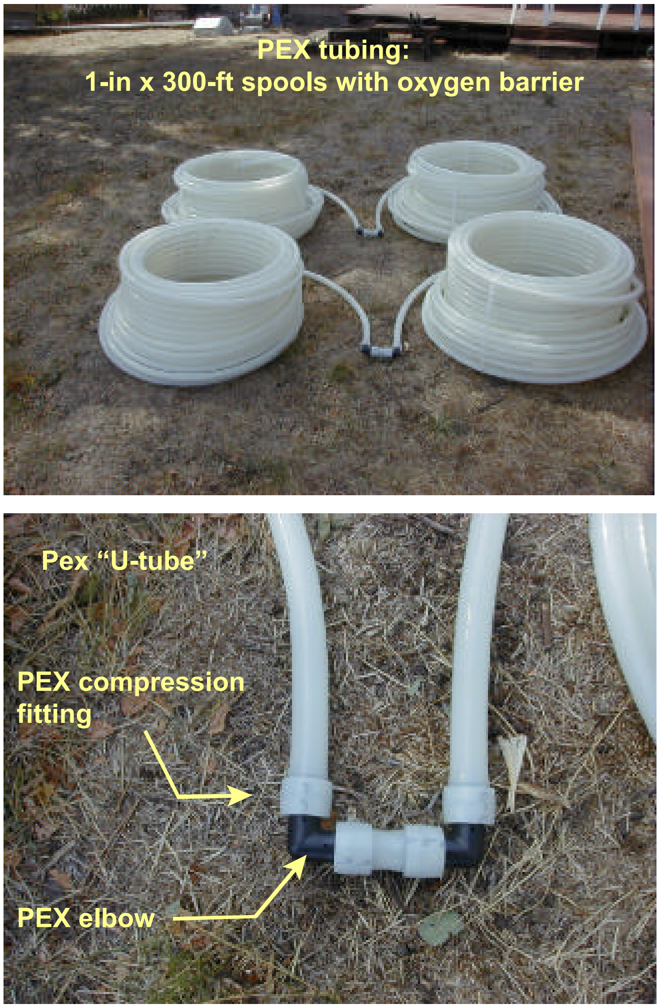

Figure 5. PEX downhole heat exchangers prior to installation.

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 steel pipe from the original DHE to facilitate pushing the PEX tubing into the well. The steel 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 steel 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 the well by natural convection, preventing the formation of stagnant cold water zones. This was done by leaving the bottom of the steel pipe open and using a tee-piece as one of the pipe couplings below the water level. A schematic of the downhole assembly is shown in Figure 6.

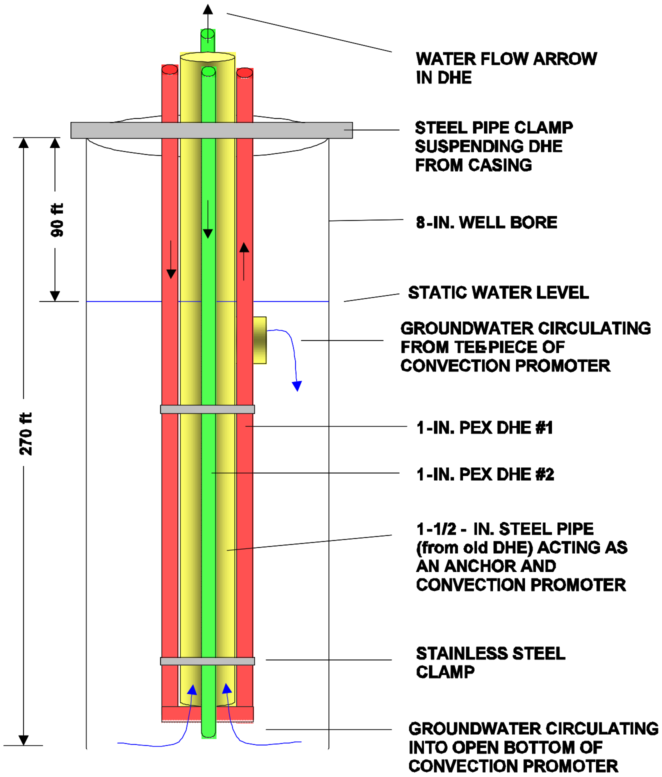

Figure 6. Schematic of PEX assembly.

Installation of the DHE

Photos of the installation procedure are shown in Figures 7 and 8, showing the process of lowering the DHE assembly into the well. The DHE was successfully installed to a depth of 252 ft (76.8 m). The entire installation process took about three hours to complete.

Figure 7. ***PEX DHE prio to installation, showing the two PEX U-tubes fastened to the steel pipe from the old DHE, which was used as an installation guide, anchor and convection promoter.***

Figure 8. ***Process of lowering the DHE assembly into the well, showing fastening of the PEX tubing to the steel pipe guide with stainless steel clamps.***

Figure 9 shows the final installation prior to enclosing the piping and instrumentation. The instrumentation consists of pressure gauges, temperature gauges, and temperature probes at four locations: inlet and outlet water in the DHE, and supply and return air in the house. The temperatures measured by the probes are recorded by a data logger at 5-min. intervals.

Preliminary Performance Monitoring

Performance monitoring of the PEX DHE began on October 18, 2004 and is on-going. Results of the full heating season will be the subject of a future article. So far, the lowest recorded water temperature exiting the DHE was 174.8°F (79.3°C); when, the outdoor air temperature was 7°F (-13.9°C). The supply air temperature at that time was still in excess of 125°F (51.7°C), keeping the house at 74.5°F (23.6°C). The water temperature exiting the DHE is routinely measured at 178 -180°F (81-82°C), keeping the house at 78-80°F (25.5-26.7°C). No problems have been encountered, thus far.

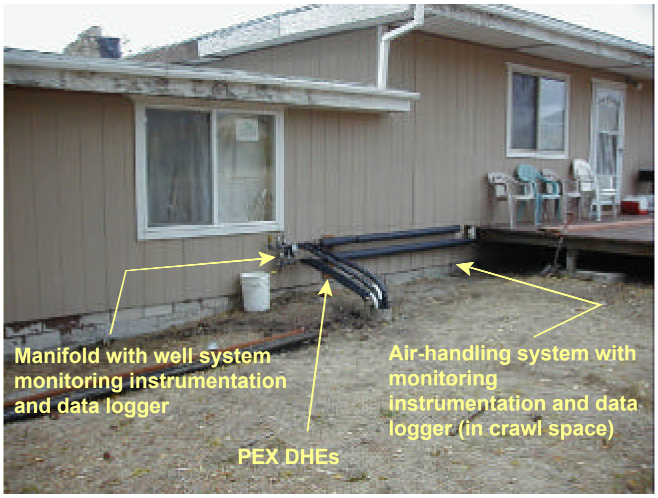

Figure 9. ***Final installation showing insulated piping and manifold prior to installing pipe enclosure.***

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-in. 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-in. 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-in. PEX tubing without the oxygen barrier and uses the design described in this article (i.e., two U-tubes fastened to a 1½-in. steel guide), the DHE cost would be $9.20/ft (4 x $1.55/ft for the PEX tubing + $3/ft for a 1½-in. steel guide). Assuming quadruple the length of PEX pipe is required relative to steel, 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 steel DHE required. Using the above material costs, a 1½ -in. steel DHE would cost about $900. An equivalent double U-tube PEX DHE would cost $2300. Assumed labor costs are an additional $300 for the steel DHE and $400 for the PEX DHE. Assuming a future cost of $500 each time the steel 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 steel DHE.

Lessons Learned

Thus far, the PEX DHE has performed better than expected. Admittedly, more tubing was installed than necessary as a conservative measure, and more refinement is needed in the design calculations.

The use of a pipe reel would have greatly expedited the installation process. Pipe reels are routinely used for installing ground loops in the geothermal heat pump industry. As these installers know, managing polyethylene tubing once it is uncoiled can be very difficult, particularly in cold weather.

The use of pipe conduit bends on the PEX tubing at the well casing top is necessary. Without these, the PEX will easily kink over the well casing, restricting flow and possibly causing a leak.

THE FUTURE OF PEX DHEs

The future of PEX DHEs may not just lie in corrosion protection, but in a total maintenance-free DHE. It is conceivable that a PEX DHE could be installed directly in a borehole, similar to that for heat pump applications, and gravel-packed in place. This would eliminate the need for the extra "steel guide" described above and would eliminate the need for a traditional water well as in current applications. Certainly, more heat exchange length would be required for the DHE, but the extra cost may offset future maintenance items. An expensive maintenance item for geothermal well owners in Klamath Falls is the bailing of sediment and rock fragments from the well that accumulate over time. The presence of sediment around a steel DHE also accelerates corrosion. The direct-burial of PEX DHEs in vertical boreholes will be addressed in a future article.

REFERENCES

Culver, G., 1999. "Downhole Heat Exchangers." *Geo-Heat Center Quarterly Bulletin*, Vol. 20, No. 3.

Culver, G. G.; Lund, J. W. 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.