HEAT EXCHANGERS

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INTRODUCTION

Most geothermal fluids, because of their elevated temperature, contain a variety of dissolved chemicals. These chemicals are frequently corrosive toward standard materials of construction. As a result, it is advisable in most cases to isolate the geothermal fluid from the process to which heat is being transferred.

The task of heat transfer from the geothermal fluid to a closed process loop is most often handled by a plate heat exchanger. The two most common types used in geothermal applications are: bolted and brazed.

For smaller systems, in geothermal resource areas of a specific character, downhole heat exchangers (DHEs) provide a unique means of heat extraction. These devices eliminate the requirement for physical removal of fluid from the well. For this reason, DHE-based systems avoid entirely the environmental and practical problems associated with fluid disposal.

GASKETED PLATE HEAT EXCHANGERS

The plate heat exchanger is the most widely used configuration in geothermal systems of recent design. A number of characteristics particularly attractive to geothermal applications are responsible for this. Among these are:

1. Superior thermal performance.
2. Availability of a wide variety of corrosion resistant alloys.
3. Ease of maintenance.
4. Expandability and multiplex capability.
5. Compact design.

Figure 1 presents an introduction to the terminology of the plate heat exchanger. Plate heat exchanger, as it is used in this section, refers to the gasketed plate and frame variety of heat exchanger. Other types of plate heat exchangers are available; though among these, only the brazed plate heat exchanger has found application in geothermal systems.

As shown in Figure 1, the plate heat exchanger is basically a series of individual plates pressed between two heavy end covers. The entire assembly is held together by the tie bolts. Individual plates are hung from the top carrying bar and are guided by the bottom carrying bar. For single-pass circuiting, hot and cold side fluid connections are usually located on the fixed end cover. Multi-pass circuiting results in fluid connections on both fixed and moveable end covers.

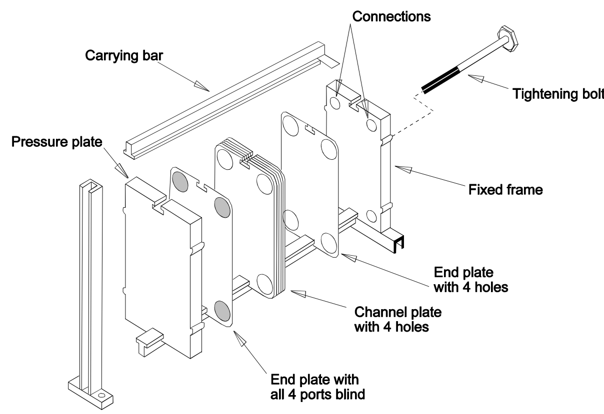

Figure 1. The plate heat exchanger.

Figure 2 illustrates the nature of fluid flow through the plate heat exchanger. The primary and secondary fluids flow in opposite directions on either side of the plates. Water flow and circuiting are controlled by the placement of the plate gaskets. By varying the position of the gasket, water can be channeled over a plate or past it. Gaskets are installed in such a way that a gasket failure cannot result in a mixing of the fluids. In addition, the outer circumference of all gaskets is exposed to the atmosphere. As a result, should a leak occur, a visual indication is provided.

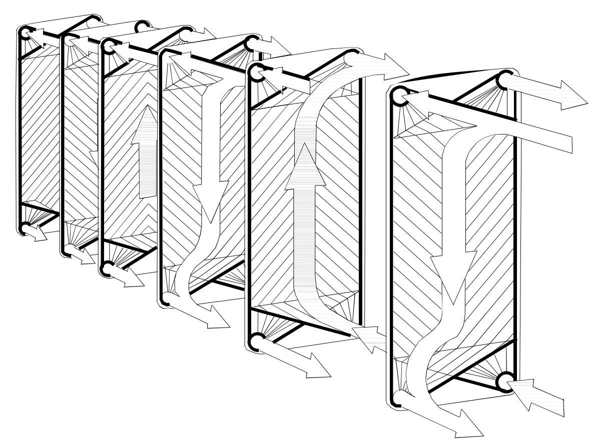

Figure 2. Nature of fluid flow through the plate heat exchanger.

General Capabilities

In comparison to shell and tube units, plate and frame heat exchangers are a relatively low pressure/low temperature device. Current maximum design ratings for most manufacturers are: temperature, 400°F, and 300 psig.

Above these values, an alternate type of heat exchanger would have to be selected. The actual limitations for a particular heat exchanger are a function of the materials selected for the gaskets and plates; these will be discussed later.

Individual plate area varies from about 0.3 to 21.5 ft^2 with a maximum heat transfer area for a single heat exchanger currently in the range of 13,000 ft^2. The minimum plate size does place a lower limit on applications of plate heat exchangers. For geothermal applications, this limit generally affects selections for loads such as residential and small commercial space heating and domestic hot water.

The largest units are capable of handling flow rates of 6000 gallons per minute (gpm) and the smallest units serviceable down to flows of approximately 5 gpm. Connection sizes are available from 3/4 to 14 in. to accommodate these flows.

Materials

Materials selection for plate heat exchangers focuses primarily upon the plates and gaskets. Since these items significantly effect first cost and equipment life, this procedure should receive special attention.

Plates

One of the features which makes plate-type heat exchangers so attractive for geothermal applications is the availability of a wide variety of corrosion-resistant alloys for construction of the heat transfer surfaces. Most manufacturers will quote either 304 or 316 stainless steel a the basic material.

For direct use geothermal applications, the choice of materials is generally a selection between 304 stainless, 316 stainless, and titanium. The selection between 304 and 316 is most often based upon a combination of temperature and chloride content of the geothermal fluid. Should oxygen be present in as little as parts per billion (ppb) concentrations, the rates of localized corrosion would be significantly increased (Ellis and Conover, 1981). Should the system for which the heat exchanger is being selected offer the potential for oxygen entering the circuit, a more conservative approach to materials selection is recommended.

Titanium is only rarely required for direct use applications. In applications where the temperature/chloride requirements are in excess of the capabilities of 316 stainless steel, titanium generally offers the least cost alternative.

The first cost premium for titanium over stainless steel plates is approximately 50%.

Gaskets

As with plate materials, a variety of gasket materials are available. Among the most common are those shown in Table 1.

Table 1. Plate Heat Exchanger Gasket Materials

Material	Common Name	Temperature Limit (°F)
Styrene-Butadiene	Buna-S	185
Neoprene	Neoprene	250
Acrylonitrile- Butadiene	Buna-N	275
Ethylene/Propylene	EPDM	300
Fluorocarbon	Viton	300
Resin-Cured Butyl	Resin-Cured Butyl	300
Compressed Asbestos	Compressed Asbestos	500

Testing by Radian Corporation has revealed that Viton shows the best performance in geothermal applications, followed by Buna-N. Test results revealed that neoprene developed an extreme compression set and Buna-S and natural rubber also performed poorly (Ellis and Conover, 1981).

Although Viton demonstrates the best performance, its high cost generally eliminates it from consideration unless its specific characteristics are required. Buna-N, generally the basic material quoted by most manufacturers, and the slightly more expensive EPDM material are generally acceptable for geothermal applications.

Performance

Superior thermal performance is the hallmark of plate heat exchangers. Compared to shell-and-tube units, plate heat exchangers offer overall heat transfer coefficients 3 to 4 times higher. These values, typically 800 to 1200 Btu/-hr·ft^2 °F (clean), result in very compact equipment. This high performance also allows the specification of very small approach temperature (as low as 2 to 5°F) which is sometimes useful in geothermal applications. This high thermal performance does come at the expense of a somewhat higher pressure drop. Selection of a plate heat exchanger is a trade-off between U-value (which influences surface area and hence, capital cost) and pressure drop (which influences pump head and hence, operating cost). Increasing U-value comes at the expense of increasing pressure drop.

Fouling considerations for plate heat exchangers are considered differently than for shell-and-tube equipment. There are a variety of reasons for this; but, the most important is the ease with which plate heat exchangers can be disassembled and cleaned. As a result, the units need not be over-designed to operate in a fouled condition. Beyond this, the nature of plate heat exchanger equipment tends to reduce fouling due to:

- High turbulence,
- Narrow high-velocity flow channels which eliminate low flow areas found in shell-and-tube equipment, and
- Stainless steel surfaces that are impervious to corrosion in most groundwater applications

Costs

For most geothermal systems, the plate heat exchanger can constitute a large portion of the mechanical room equipment cost. For this reason, it is useful to have a method of evaluating the capital cost of this component when considering the system design.

Final heat exchanger cost is a function of materials, frame size and plate configuration.

Figure 3 presents a plot of plate heat exchanger costs in 1996 dollars/ft^2 of heat transfer area based on a number of manufacturer's quotes for various geothermal applications. Since heat transfer area takes into account duty, temperature difference and fouling, it is the most useful index for preliminary costing.

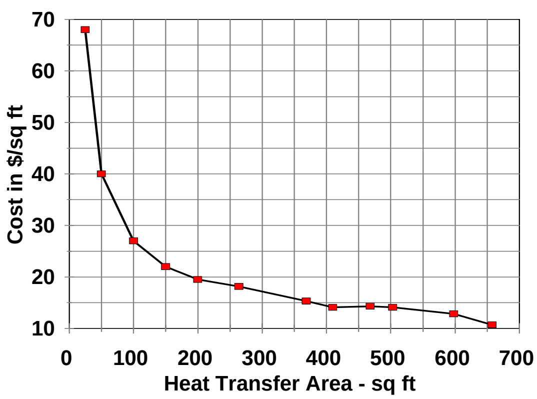

Figure 3. Plate heat exchanger cost for Buna-N gaskets and 316 stainless steel plates (1996).

BRAZED PLATE HEAT EXCHANGERS

Construction

The brazed plate unit as shown in Figure 4 eliminates the end plates, bolts, and gaskets from the design. Instead, the plates are held together by brazing with copper. This results in a much less complicated, lighter weight and more compact heat exchanger. The simpler design also results in greatly reduced cost.

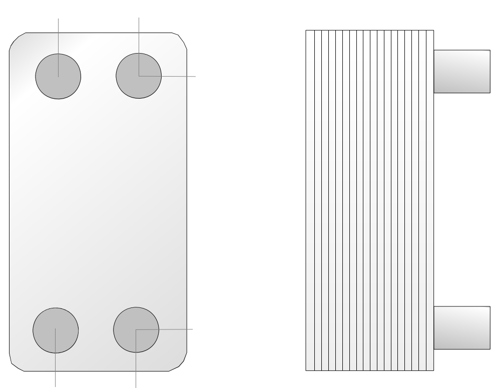

Figure 4. Brazed plate heat exchanger.

On the negative side, the brazed plate approach eliminates some of the advantages of the plate-and-frame design. In terms of maintenance, the brazed plate units cannot be disassembled for cleaning or for the addition of heat transfer plates as bolted units can.

Most importantly, however, the brazing material is copper. Since most geothermal fluids contain hydrogen sulphide (H_2S) or ammonia (NH_3), copper and copper alloys are generally avoided in geothermal system construction. The situation with brazed plate heat exchangers is especially critical due to the braze material and length (a few tenths of an inch) of the brazed joints.

Application Considerations

In addition to the material related questions, there are also issues related to the standard configuration of brazed plate heat exchangers.

Physical size of the exchangers limits application flow rates to approximately 100 gpm (athough one manufacturer produces units capable of 200 gpm). Maximum heat transfer area is limited to 200 ft^2. Heat transfer rates are similar to those of plate-and-frame heat exchangers and range from 800 - 1300 Btu/hr ft^2 ^{o}F in most applications.

The major design considerations for brazed plate exchangers is that standard units are manufactured in only single-pass flow arrangements for both hot and cold fluids. This influences the ability of the exchanger to achieve close approach temperatures in certain applications.

Heat Exchanger Equipment Cost

As discussed above, the low cost of the brazed plate heat exchanger is its most attractive feature. Since heat exchanger cost is influenced by a host of factors including hot- and cold-side fluid flows and temperatures, it is most useful to discuss costs in terms of heat transfer area.

Figure 5presents cost data for brazed plate heat exchangers. As indicated, a similar curve to the one shown earlier for plate-and-frame, holds for these units; however, it is offset toward lower costs.

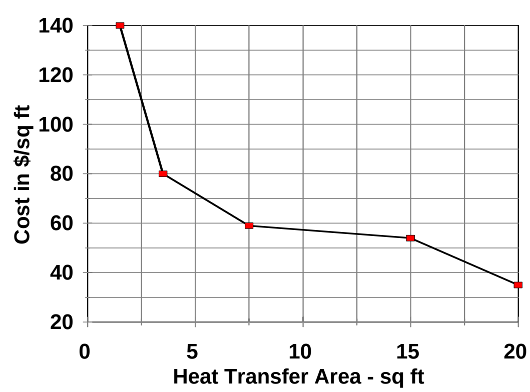

Figure 5. Brazed plate heat exchanger.

Based on limited testing, brazed plate heat exchangers should demonstrate a minimum service life of 12 years in fluids of less than 1 ppm H_2S and 10 years in fluids of 1 to 5 ppm H_2S.

Based on calculations of capital cost, service life, maintenance and installation cost our study (Rafferty, 1993) suggests that the selection of the brazed plate exchanger is valid when the capital cost is 50% or less of the plate-and-frame exchanger. This relationship was determined for fluids of < 5ppm H_2S.

DOWNHOLE HEAT EXCHANGERS

The downhole heat exchanger (DHE) is of a design that eliminates the problems associated with disposal of geothermal water since only heat is taken from the well. These systems can offer significant savings over surface heat exchangers where available heat loads are low and geologic and ground water conditions permit their use.

The use of a DHE for domestic or commercial geothermal space and domestic water heating has several appealing features when compared to the alternative geothermal heat extraction techniques. It is essentially a passive means of exploiting the geothermal energy because, in marked contrast to the alternative techniques, no water is extracted or flows from the well. Environmental and institutional restrictions generally require geothermal water to be returned to the aquifer from which it was obtained. Therefore, techniques involving removal of water from a well require a second well to dispose of the water. This can be a costly addition to a small geothermal heating project. The cost of keeping a pump operating in the sometimes corrosive geothermal fluid is usually far greater than that involved with the maintenance of a DHE.

The principal disadvantage with the DHE technique is its dependence on the natural heat flow in the part of the hot aquifer penetrated by the well. A pumped well draws in hot water and the resultant heat output is normally many times the natural value. This limitation on the potential heat output of a DHE makes it most suitable for small to moderate-sized thermal applications.

DHE outputs range from supplying domestic hot water for a single family at Jemez Springs, New Mexico to Ponderosa High School in Klamath Falls, Oregon. The single family is supplied from a 40 ft well and the school at over one MWt from a 560 ft, 202ºF, 16 in. diameter well. The DHE's are also in use in New Zealand, Austria, Turkey, the USSR and others. A DHE producing 6 MWt has been reported in use in Turkey.

Typical Designs

The most common DHE consists of a system of pipes or tubes suspended in the well through which clean water is pumped or allowed to circulate by natural convection. Figure 6 shows a U tube system typical of some 500 installations in Klamath Falls, Oregon. The wells are 10 or 12 in. diameter drilled 20 or more ft into geothermal fluids and an 8 in. casing is installed. A packer is placed around the casing below any cold water or unconsolidated rock, usually

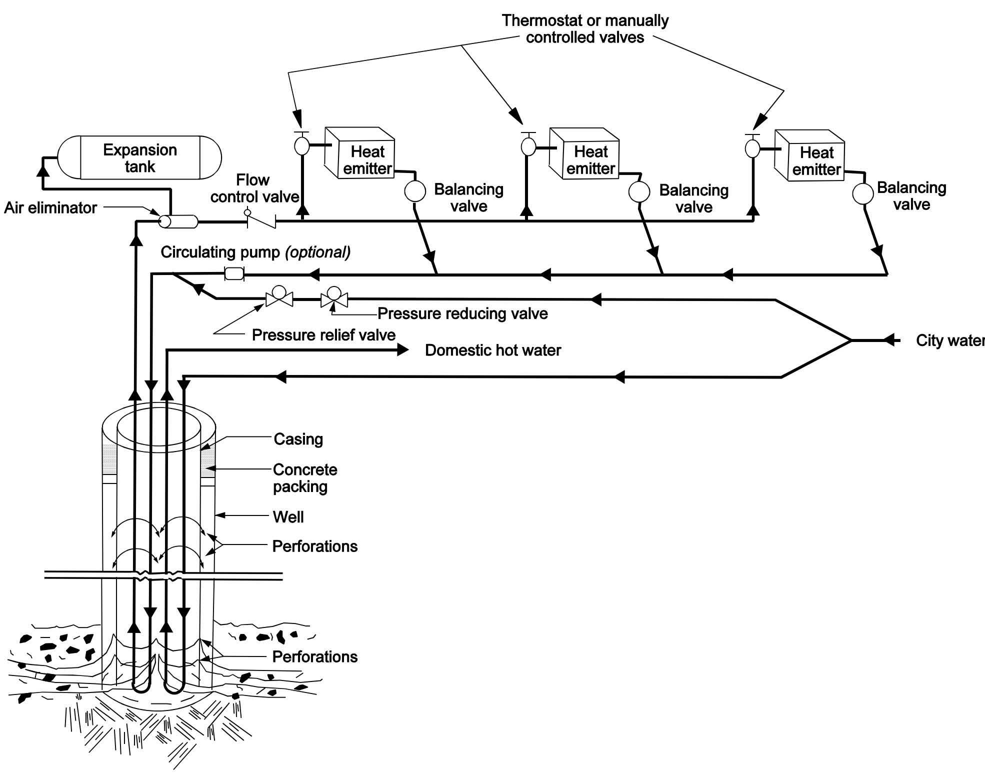

Figure 6. Typical hot-water distribution system using a downhole heat exchanger (Culver and Reistad, 1978).

20 to 50 ft, and the well cemented from the packer to the surface. The casing is torch perforated (0.5 x 6 in.) in the live water area and just below the static water level. Perforated sections are usually 15 to 30 ft long and the total cross-sectional area of the perforations should be at least 1-1/2 to 2 times the casing cross section. Because fluid levels fluctuate summer to winter the upper perforations should start below the lowest expected level. A 3/4 or 1 in. pipe welded to the outside of the casing and extending from ground surface to below the packer permits sounding and temperature measurements in the annulus and is very useful in diagnosing well problems.

The space heating DHE is usually 1-1/2 or 2 in. black iron pipe with a return U-bend at the bottom. The domestic water DHE is 3/4 or 1 in. pipe. The return U bend usually has a 3 to 5 ft section of pipe welded on the bottom to act as a trap for corrosion products that otherwise could fill the U-bend, preventing free circulation. Couplings should be malleable rather than cast iron to facilitate removal.

Materials

Considering life and replacement costs, materials should be selected to provide economical protection from corrosion. Attention should be given to the galvanic cell action between the DHE and the well casing, since the casing could be an expensive replacement item. Experience indicates that general corrosion of the DHE is most severe at the air-water interface at the static water level. Stray electrical currents can cause extreme localized corrosion below the water. Insulated unions should be used at the wellhead to isolate the DHE from stray currents in the buildings and city water lines. Galvanized pipe is to be avoided; since, many geothermal waters leach zinc and usually above 135°F, galvanizing loses its protective ability.

Considerable success has been realized with non-metallic pipe, both fiberglass-reinforced epoxy and polybutylene. Approximately 100,000 ft of fiberglass reportedly has been installed in Reno at bottom-hole temperatures up to 325°F. The The only problem noted has been national pipe taper (NPT) thread failure that was attributed to poor quality resin in some pipe. Another manufacturer's pipe, with epoxied joints, performed satisfactorily. Before installing any FRP pipe, check with the manufacturer giving them temperature, water chemistry, and details of installation. Also check on warranties for the specific conditions.

Average DHE life is difficult to predict. For the approximately 500 black iron DHEs installed in Klamath Falls, the average life has been estimated to be 14 years. In some instances, however, regular replacement in 3 to 5 years has been required. In other cases, installations have been in service over 30 years with no problems. Stray electrical currents, as noted above, have undoubtedly been a contributing factor in some early failures. Currents of several tens of milli-amps have been measured. In others, examination of the DHEs after removal reveals long, deeply corroded lines along one side. This may be caused by themal expansion and contraction of the DHE against the side of the well bore where the constant movement could scrub off protective scale, exposing clean surface for further corrosion.

Corrosion at the air-water interface is by far the most common cause of failure. Putting clean turbine oil or paraffin in the well appears to help somewhat, but is difficult to accurately evaluate. Use of oil or paraffin is frowned on by the Enviornmental Protection Agency since geothermal water often commingles with fresh water.

DHE wells are typically left open at the top; but, there appears to be no reason they could not be sealed air-tight. Once the initial charge of oxygen is used up in forming corrosion products, there would be no more oxygen available because there is essentially no dissolved oxygen in the geothermal fluid. Swisher and Wright (1986) measured corrosion rates of mild steel in geothermal water under aerobic and anerobic conditions in the lab. They found aerobic corrosion rates of 260-280 micrometer/year with completely emersed specimens with paraffin on the water, 830 micrometer/year above the paraffin on partially emersed specimens and only 11 micrometer/year under anerobic conditions.

Convection Cells

Although the interaction between the fluid in the well, fluid in the aquifer, and the rock surrounding the well is poorly understood, it is known that the heat output can be significantly increased if a convection cell can be set up in the well. There is probably some degree of natural mixing (i.e., water from the aquifer continuously enters the well, mixes with the well fluid, and fluid leaves the well to the aquifer). There are two commonly used methods of inducing convection.

The first method may be used when a well is drilled in a stable formation, and will stand open without a casing. This allows an undersized casing to be installed. If the casing is perforated just below the minimum static water level and near the bottom or at the hot aquifer level, a convection cell is induced and the well becomes very nearly isothermal between the perforations (Figure 7). Cold surface water and unstable formations near the surface are cemented off above a packer. If a DHE is then installed and heat extracted, a convection cell is established with flow down the inside of the casing and up the annulus between the well wall and casing. The driving force is the density difference between the fluid surrounding the DHE and fluid in the annulus. The more heat extracted, the higher the fluid velocity. Velocities of 2 ft/s have been measured with very high heat extraction rates; but, the usual velocities are between 0.04 and 0.4 ft/s.

The second method is used where a different situation exists. In New Zealand where wells do not stand open and several layers of cold water must be cased off, a system using a convection promoter pipe was developed (Figure 8). The convector pipe is simply a pipe open at both ends, suspended in the well above the bottom and below the static water level. An alternate design involves the pipe resting on the bottom, and having perforations at the bottom and below static water level. The DHE can be installed either in the convector or outside the convector; the latter being more economical since smaller convector pipe is used (Freeston and Pan, 1983; Dunstall and Freeston, 1990).

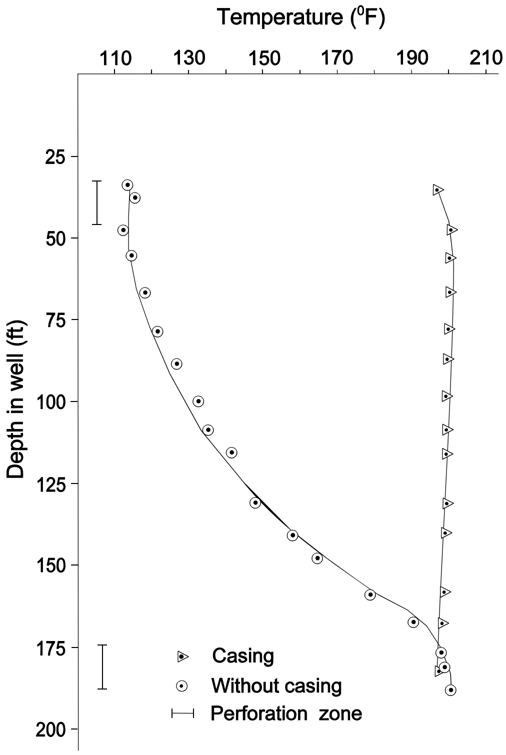

Figure 7. Temperature vs. depth with and without casing (Culver and Reistad, 1978).

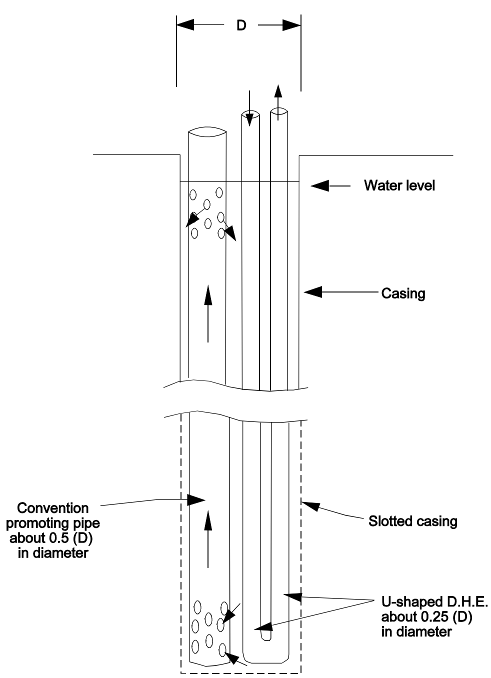

Figure 8. Convection promoter pipe with DHE (Allis and James, 1979).

Both lab and field tests indicate that the convection cell velocities are about the same in undersized casing systems and convector pipe systems.

Optimum conditions exist when frictional resistance because of wetted surfaces (hydraulic radius) is equal to both legs of the cell and DHE surface area is maximized, providing maximum heat transfer. For designs using undersized casing and DHE inside the convector, this occurs when the casing or convector is 0.7 times the well diameter. When the DHE is outisde the convector, the convector should be 0.5 times the well diameter. The full length U-tube DHE diameter is 0.25 times the well diameter in all cases. Partial length or multi-tube exchangers will have different ratios (Allis, 1979; Allis and James, 1979).

Design Considerations

Downhole heat exchangers extract heat by two methods: extracting heat from water flowing through the aquifer, and extracting stored heat from the rocks surrounding the well.

Once the DHE is extracting heat and a convection cell is established, a portion of the convecting water is new water entering the well from the aquifer, the same amount of cooled water leaves the well and enters the aquifer.

The ratio of convecting water to new water has been termed the mixing ratio and is defined as:

$$Rm = 1 - \frac{m_a}{m_t}$$

where:

Rm = mixing ratio
m_a = mass flow of new water
m_t = total mass flow of convecting water.

Note that a larger mixing ratio indicates a smaller proportion of new water in the convection cell.

Mixing ratios vary widely between wells even in the same aquifer and apparently depend on permeability. As more heat is extracted, the mass flow rate in the convection cell increases; but, the mixing ratio appears to remain relatively constant up to some point, then increases with further DHE loading. This is interpreted as the permeability, allowing new hot fluid to enter the well or, more probably, allowing used cool fluid to sink into the aquifer near the well bottom. At some combination of density difference and permeability, the ability to conduct flow is exceeded and the well rapidly cools with increasing load.

The theoretical maximum steady state amount of heat that could be extracted from the aquifer would be when the mixing ratio equals zero. That is, when all the water makes a single pass through the convection cell and out the well bottom. Mixing ratios lower than 0.5 have never been observed and usually range from about 0.5 to 0.94. The theoretical maximum steady heat extraction rate can be estimated if the hydraulic conductivity and hydraulic gradient are known and it is assumed there is some temperature drop of the water.

Many DHE wells in the Moana area of Reno are pumped to increase hot water flow into the well. Pumping rates for residential use is limited to 1800 gal/day and the pump is thermostatically controlled. The system is designed to switch on the pump if the DHE temperature drops below some predetermined level, usually approximately 120°F. This method permits use of a well that would not supply enough heat using a DHE alone, yet minimizes pumped fluid and pumping costs. It is, however, limited to temperatures at which an economical submersible or other pump can be used.

Unfortunately, at the present time, there is no way to relate mixing ratio and permeability. With good permeability similar to well-fractured basalt, the mixing ratio might be approximately 0.5, in coarse sand approximately 0.8, and in clayey sand 0.9 to 0.94.

At the time the term mixing ratio was introduced, it seemed to be a logical hypothesis because all known DHE wells had (and most still have) perforations, at least in the hot aquifer zone. Some new fluid could enter the well, mix with fluid in the well and some used water exit the well. The mixing ratio is really a term for energy input into the well. Although perforations undoubtedly help, a solidly cased well with a DHE will provide heat. The energy output is then limited by the conduction of the rock and casing, allowing energy to flow into the well.

In Klamath Falls, it has been experimentally verified that when a well is drilled, there is negligible convective flow in the well bore. When undersized perforated casing is installed, a convection cell is set up, causing flow up the inside of the casing and down the annulus between the casing and well wall. When a DHE is installed and heat is extracted, the convection cell reverses with the flow downward in the casing (around the DHE) and up the annulus. Similar circulation patterns were noted in New Zealand using convection promoters.

DHEs are principally used in space and domestic water heating applications: homes, schools, small com-mercial buildings and greenhouses, with the resulting inter-mittent operation. When the heating system is not calling for heat, and if a convection cell can exist, it functions to store heat in rocks surrounding the well; especially those cooler rocks nearer the surface that would normally be at the natural temperature gradient for the locale. The under-sized casing or convection promoter then acts to increase thermal storage.

Referring again to Figure 7, it can be seen that up to the upper perforations, the well becomes very nearly isothermal, with the upper portion approaching the aquifer temperature and the rock temperature increasing significantly. When a DHE is turned on, the water in the well cools rather rapidly; the rate depending on the mixing ratio. As the water continues to cool, the convection cell extracts heat from the surrounding rocks.

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