# DOWNHOLE HEAT EXCHANGER EXPERIMENTS IN A LABORATORY SCALE MODEL WELL

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**SUMMARY** — Some of the factors influencing the performance of Downhole Heat Exchangers (DHEs) in shallow hot water wells were investigated using a model which has been developed at the University of Auckland. Two different materials, copper and PVC, were used to construct two otherwise identical U-tube DHEs, which were tested over a range of DHE flow and cross flow rates. During most tests a PVC convection promoter pipe was fitted in the well, to allow a bulk circulation of the well fluid. Some comparisons are made to results obtained during full scale testing in a shallow Rotorua well.

## INTRODUCTION

Downhole heat exchangers extract heat energy from geothermal reservoirs by circulating a coolant fluid through piping which is installed within the well bore. Generally, no geothermal fluid is withdrawn from the well, eliminating the need for a disposal system and resulting in a relatively low environmental impact. With careful design mineral deposition and corrosion *can* be virtually eliminated, and the single well systems usually have a relatively low capital cost.

DHEs are currently used in at least five countries; Austria, Switzerland, Turkey, the USA and New Zealand. The heat produced is used predominantly for space and water heating of residential homes, but agricultural applications can also be found. DHE outputs vary over a wide range, from domestic systems providing just a few kilowatts for water heating in a single residence, to over 1 MW from a single well at the Ponderosa High School in Klamath Falls, Oregon. One DHE in Turkey is reported to have an output of 6 MWt, but well fluid must be extracted to maintain this rate of output (Culver 1990).

The primary disadvantage of DHE systems is their dependence on natural heat flow, which is normally maintained by a cross flow of hot water at the wells feed zone. A highly permeable resource and a natural hydraulic gradient are usually required to maintain a useful DHE heat load and output temperature.

The characteristics of geothermal aquifers vary widely, with parameters such as downhole temperature, hydraulic gradient, depth to production zones, porosity, and permeability all influencing DHE performance. As a consequence, identicaly completed systems may have performance which varies by an order or magnitude or more, even within the same reservoir (Culver 1989). Simply copying a successful design may yield disappointing results in another area. It is well known that fitting an undersized perforated casing or a convection promoter pipe to the well allows a natural circulation cell to form, and that this can enhance heat transfer to the DHE. The mechanism by which fresh fluid enters the well bore, and the mechanism by which cooled fluid leaves the well, are however not clearly understood. Well completion and DHE construction methods which place a greater surface area of the DHE in contact with the hot fluid, or encourage the natural replacement of cooled fluid, have the potential to increase DHE system performance.

Studies undertaken on a small diameter (100mm) test well in Rotorua (New Zealand) showed that almost all the nett heat transfer occurred at the feed zone (Freeston & Dunstall 1992a). Dye injection tests conducted with a promoter pipe installed in the same well indicated that the convective cell circulation direction was influential on the mixing process which occured at the feed zone level. The influence on heat transfer was inconclusive because of the promoter pipes poor aspect ratio, which limited its heat transfer performance (Dunstall 1992).

In conjunction with field testing, the development of a model well has been continuing at the University of Auckland. The aim of this work has been to develop a better understanding of the processes controlling heat and mass transfer at the feeds zone, where fluid enters and leaves the well. Using a model allows experiments to be conducted under controlled conditions. DHE and reservoir flow rates, as well as feed zone and DHE inlet temperatures can be independently varied and changes to the promoter pipe and DHE configurations *can* be easily made.

This paper describes the results of recent experiments with the model well, in particular the influence of flow direction in the natural circulation cell which becomes established when a convection promoter pipe is installed. Two types of DHE are compared; a copper DHE as tested by Torrens (1991) and a PVC DHE used in the current tests. Some suggestions for improvements to the model for future work are made.

## EXPERIMENTAL EQUIPMENT

The basic set-up of the model well can be seen in Figure 1. The well bore is made from a 5.7 m long 73 mm inside diameter pipe, perforated at the feed zone level, into which the Downhole Heat Exchanger (DHE) is inserted. The

DHE tested in these experiments is a U-shaped PVC pipe with 12.6 mm inside diameter and a wall thickness of 1.3 mm. It is supplied with water from the city supply, through a pressure regulating valve, providing a steady adjustable flow rate.

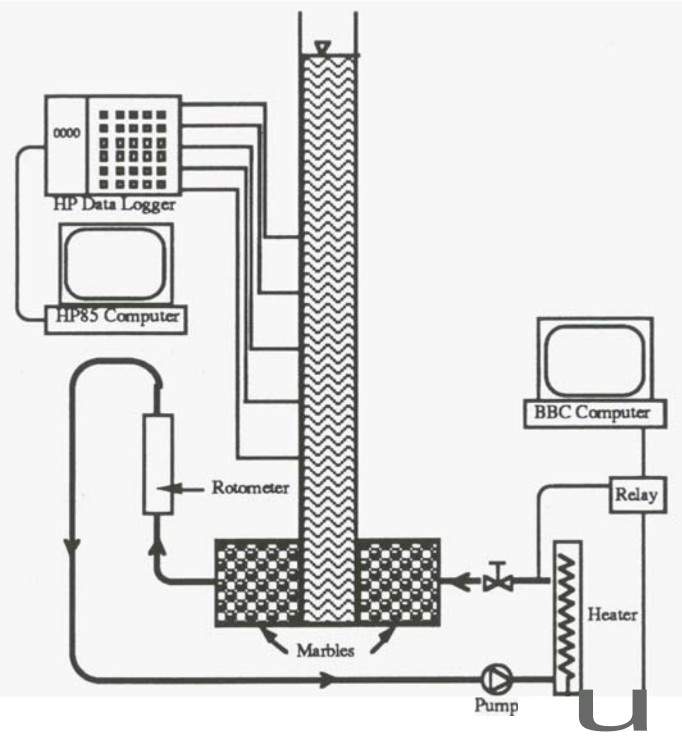



*Figure 1 - The Model Well*

For the most of the experiments, a 32 mm inside diameter PVC convection promoter pipe with a 1.5 mm wall thickness was also inserted in the well, to enhance natural circulation. It is perforated 110 mm above the base and 240 mm below the top end. The total area of each set of perforations is equal to twice the cross sectional area of the promoter.

The 200 mm long perforated section of well pipe is surrounded by a 215 mm I.D. cylinder. Glass marbles, of an average diameter of 15 mm, fill the annulus formed by this base section to simulate permeable reservoir rock. The well is completely filled with water and is insulated with closed cell foam. The well base has an inlet and an outlet through which hot water of an adjustable temperature and adjustable mass flow is pumped in a circuit. A 3 kW electric element heats the water which flows in the well base. The heating element is controlled by a BBC micro computer, which runs a control program, a temperature transducer, and a relay to switch the power for the heater on or off (Torrens 1991). The control system maintains the well base inflow temperature within +/- 0.5 °C of the chosen temperature. Flow rates through the well base and the DHE are adjusted with valves and measured with rotameter flow meters.

Thermocouples, passed through the pipe wall, measure internal fluid temperatures in the DHE and the well. A total of 19 thermocouples are positioned in the well at 1 m spacing down the well, beginning at 0.56 m depth. At each depth two thermocouples are set on opposite sides of the well. The radial temperature distribution is measured at two depths, 2.56 m and 4.56 m, by a group of four thermocouples each set at equal distances around the well. Two thermocouples are set in the inlet and the outlet of the well base to measure the heat input. One thermocouple is located in the centre of the well base.

The DHE temperature profile is measured by nine thermocouples. These are placed in the inlet and the outlet, and at three positions in each leg with 1 m spacing beginning at 2.89 m depth. One thermocouple is set at the U bend of the DHE.

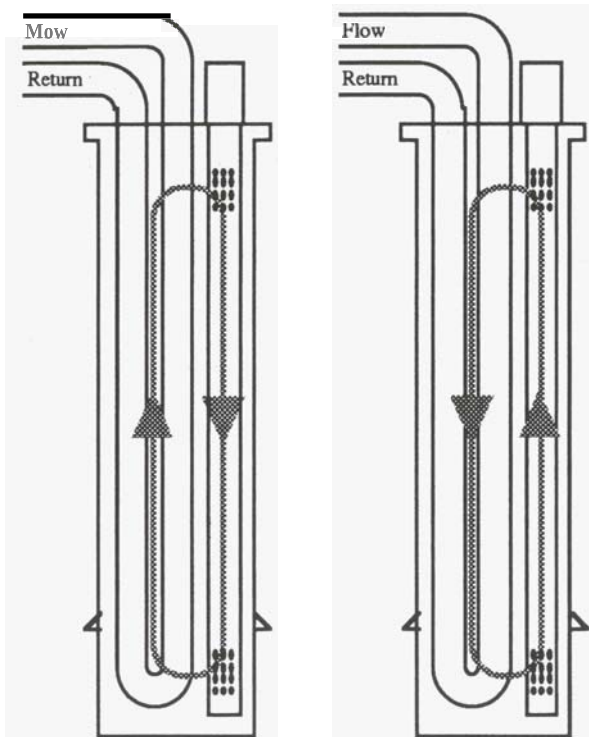
## EXPERIMENTAL PROGRAMME

In each experiment the flow rates of the DHE and the reservoir cross flow were adjusted and the desired cross flow inlet temperature was set in the control program. After one to three hours the system reached thermal equilibrium and steady state temperature measurements were recorded.

The first series of test runs examined heat transfer performance of the PVC DHE over a range of DHE and cross flow rates without the convection promoter pipe installed. Results were compared to the copper DHE, as tested by Torrens (1991).

The promoter pipe was then installed and a number of combinations of DHE flow and cross flow rates were tested to determine the influence of these two parameters on the heat output of the new PVC DHE. Earlier work (Dunstall 1992) indicated that the flow direction of the convective cell influenced the heat output. This was confirmed in these experiments. In total three sets of experiments were performed, initially without a promoter and later with the promoter installed for both circulation directions, over a range of DHE and cross flow rates.

## CIRCULATION DIRECTION




*Forward* *Reverse*

*Figure 2 - Circulation Flow Directions*

Two flow directions are possible in the convective circulation cell (Fig. 2). In the first case hot water rises in the annulus between well and promoter pipe passing over the DHE, where it cools, and flows down in the promoter pipe. This flow direction is called forward, in recognition of the similarity to mud circulation during well drilling (Horne 1980). When hot water rises in the promoter pipe and flows down in the annulus the flow is said to be reversed.

During the experiments both circulation directions were observed. When the system was started the flow initiated in the forward direction, since the aspect ratio in the annulus is more favourable for eddy diffusion (Allis & James 1980). Reverse circulation usually occured at high cross flow rates and once established it remained stable, even at low cross flow rates. It was not possible to sustain forward circulation at cross flow rates higher then 50 ml/s. A forward circulation would switch to a reverse circulation if the flow was disturbed somehow (by quickly changing the DHE flow for example). This shows that reverse circulation is the more stable flow direction.

## RESULTS

### Test Runs Without a Promoter Pipe

Results obtained without a promoter pipe installed were comparable to those obtained by Torrens (1991), who tested a copper DHE. There was a very high vertical temperature gradient in the well and only the base zone of the well maintained a high temperature during DHE operation (Fig. 3).

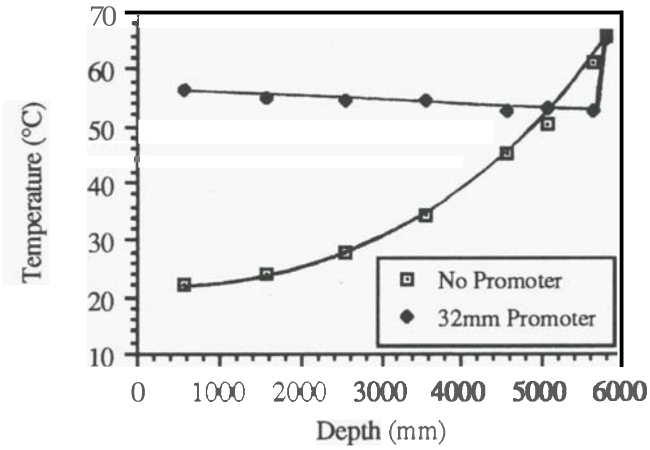



*Figure 3 - Well Temperature Profiles (Crossflow 50 mlfs - DHE flow 20 mlfs)*

Heat output of the DHE was therefore quite low. The maximum heat output was 732 W compared to 1713 W under the same conditions with the promoter pipe in the well. The heat output increased slightly with increasing DHE flow and cross flow rate (Fig. 4). Despite the fact that the thermal resistance of the PVC DHE is orders of magnitude greater than that of the copper DHE the nett heat output was up to 78% of that obtained with the copper DHE under the same conditions, demonstrating the small effect of pipe wall resistance in the overall heat transfer process. This has been demonstrated by Culver (1989), who calculated heat transfer in a fibreglass DHE, and by Dunstall (1992) who investigated the performance of enhanced surfaces in a numerical study of low output wells. As the cross flow rate was increased the importance of wall resistance increased, with the relative output falling as low as 40% at the maximum possible cross flow rate (102 ml/s).

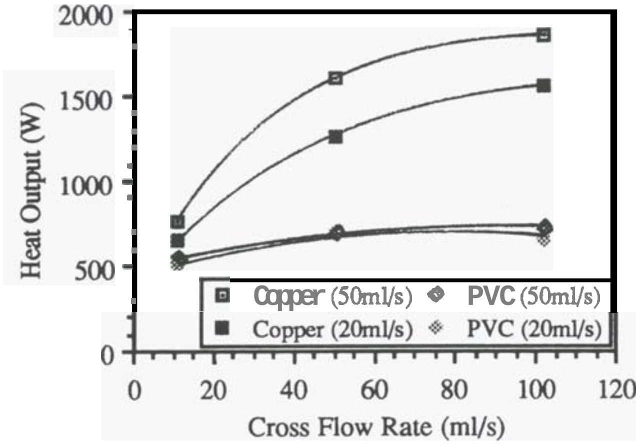



*Figure 4 - Heat Output vs. Crossflow (no promoter)*

### Test Runs With a Promoter Pipe

When the promoter pipe was inserted in the well convective circulation became established, causing a temperature distribution with a low vertical temperature gradient (Fig. 3). The heat output of the DHE is dependent on both the DHE flow and the cross flow rate (Fig. 5 and Fig. 6).

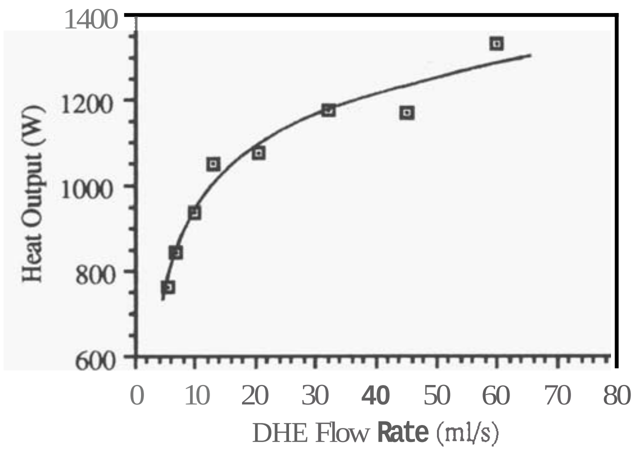



*Figure 5 - Heat Output vs. DHE flow (32mm promoter) (Crossflow rate 15 mlfs)*

The direction of circulation in the convection cell affects the heat output. This can be seen in Figure 6, where the heat output at the two highest cross flow rates was measured whilst the circulation in the well was in the reverse direction, whereas the other measurements were made when the circulation direction was forward. This is further discussed in a later section.

Changes to the cross flow rate affected the heat output less as cross flow increased. While at a cross flow rate of 11 ml/s a change of 1 ml/s caused a change of about 26 W in the heat output, at a cross flow rate of 50 ml/s a change of 1 ml/s caused a change of about 4 W in the heat output.

The relationship between heat output and DHE flow rate is similar (Fig.5). In contrast to tests on a copper DHE conducted by Torrens (1991), the heat output did not

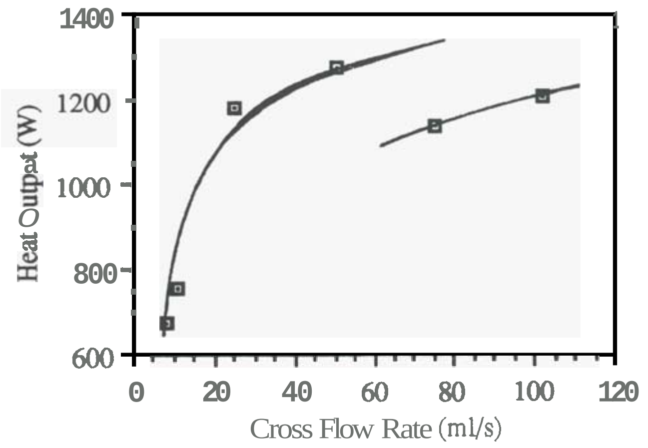



*Figure 6 - Heat Output vs. Crossflow (32mm promoter) (DHE flow rate 10 mlls)*

increase linearly with DHE flow rate. At low DHE flow rates the increase was almost linear but at higher flow rates the change increase in the heat output became much lower. Flattening of the output curve indicates that the DHE / well system is approaching its maximum capacity (Culver & Reistad 1978, Allis 1981, Pan 1983, Dunstall 1992).

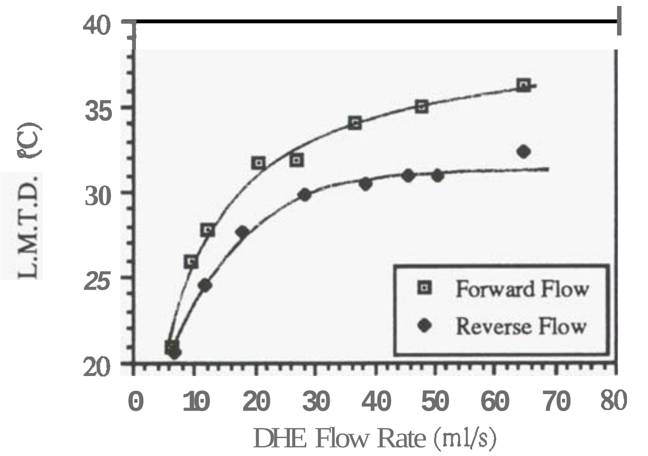



*Figure 7 - L.M.T.D vs. DHE flow (32mm promoter) (Crossflow rate 25.8 mlls)*

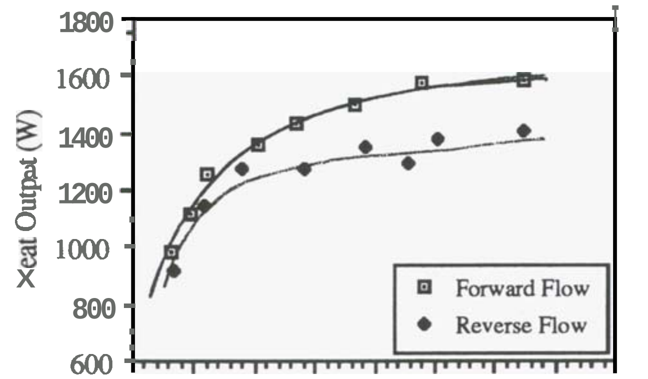



*Figure 8 - Heat Output vs. DHE flow (32mm promoter) (Crossflow rate 25.8 mlls)*

The rate of increase in the heat output reduces at higher flow rates as the mean temperature of the well fluid reduces. This effect can be clearly seen in a plot of the log mean temperature difference between the water in the well and in the DHE (Fig. 7).

This curve tapers off, approaching a limit, with a lower limit in the reverse flow situation. Since the heat output of a heat exchanger is proportional to the log mean temperature difference, the actual heat output vs DHE flow rate has a similarly shaped curve (Fig. 8).

The measurements of the heat output include a greater error than the temperature measurements alone because they also involve flow measurements. The DHE flow is affected by the pressure of the water supply and has small variations over a short time, which introduces some measurement error.

### Comparison Between the Copper DHE and the PVC DHE

At no point did the water temperature in the PVC DHE reach the temperature of the surrounding water in the well, so heat transfer from the DHE back to the well was eliminated. This is in contrast to the temperature profile observed in some cases with the copper DHE in the model well (Torrens 1991) and in a small diameter (100 mm) Rotorua well (Dunstall & Freeston 1990), where the return leg of the DHE lost heat to the well fluid. Loss of heat through the return leg of the DHE was found to be a major limiting factor on DHE performance in the Rotorua well tested by Dunstall (1992). Performance of an annular DHE in the Rotorua well was poor for similar reasons. High heat losses in the return leg pre-heated the down coming fluid, reducing the temperature difference between the DHE and the reservoir, resulting in a substantial fall off in nett performance (Freeston & Dunstall 1992b). The heat output of a high conductivity DHE could therefore be increased by insulating part of the return.

At a low cross flow rate of 11 ml/s the heat output of the PVC DHE was about 83% of the heat output of the copper DHE for all DHE flow rates. If the DHE flow rate was kept the same and the cross flow rate was changed, this percentage decreased with increasing cross flow rate. The relative output decreased from 83% for a cross flow rate of 11 ml/s to 66% for 102 ml/s compared to a copper DHE under the same conditions. A smaller relative reduction in performance for the PVC DHE is noted when the promoter is installed in the well. This is because the DHE heat transfer surface is more lightly loaded under these conditions, due to more even distribution of hot fluid throughout the well. A DHE made from low conductivity material can provide satisfactory performance when the heat loading of the tube area is low, ie when heat transfer resistance in the tube wall is a small part of the total heat transfer resistance.

### Circulation Mass Flow

The mass flow in the well's convective circulation cell was calculated from the DHE heat output and the temperature difference of the water at the top and at the bottom of the well. The mass flow had a variation of 6% over the whole range of DHE flow rates. The variations were irregular and did not show any noticeable trends. When the cross flow rate was varied the circulation mass flow had a variation of 20%, which was also irregular, but showed a trend to increase with increasing cross flow rate. The circulation mass flow rates were between 83 ml/s and 101 ml/s, which is of a similar order to the cross flow rates tested. This means the flow velocity in the annulus was between 28 mm/s and 34 mm/s.

Torrens (1991) investigated well circulation for this model well using a computer program based on the work of Culver and Reistad (1978); results were similar. Torrens noted that a slight increase in the circulation mass flow rate occured with increasing DHE flow, but the value of this increase was within the range of the variation expected from measurement inaccuracies.

## FORWARD VS. REVERSE CIRCULATION

A series of experiments was performed where the cross flow rate was held constant while varying the DHE flow rate. Both circulation directions were tested. When the water in the well circulates in the forward direction, the DHE has a 10% - 20% higher heat output then in the tests with the reverse circulation direction (Fig. 8, Fig. 9, Fig, 10). The percentage difference in heat output increased with increasing DHE flow rate. At high cross flow rates however, the forward circulation is not stable, so comparisons were made at cross flow rates between 15 and 30 ml/s.

In this model well a cross flow rate of 15 ml/s corresponds to a flow velocity of about 11,000 m/year. In a geothermal field like Rotorua, which has high permeability and strong cross flow (Burnell 1992), the cross flow velocity through the well tested by Dunstall (1992) may be as high as 1,000 m/year. The low flow rates investigated in the model are, therefore, probably more indicative of real field conditions than the higher cross flow rates.

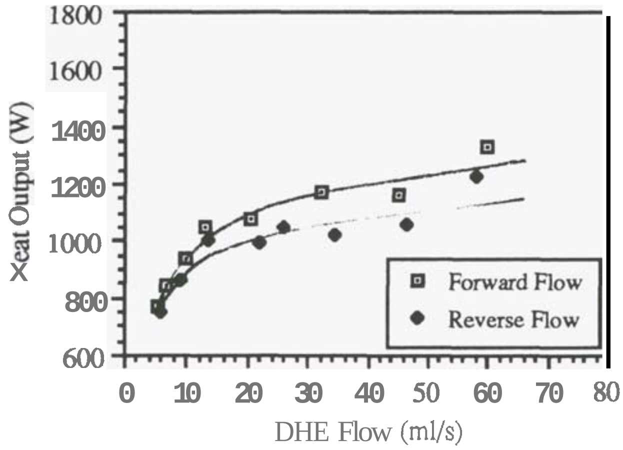



*Figure 9 - Heat Output vs. DHE flow (32mm promoter) (Crossflow rate 15.0 mlls)*

Since the mass flow of fluid supplied to the feed zone is the same for both forward and reverse flow directions the increased performance with forward flow must result from better utilization of the available fluid. Hot fluid enters the well via the annulus so when the flow is in the forward direction it can immediately travel up the well, coming into contact with the full area of the DHE. It is suggested that forward flow allows less mixing of the incoming fresh fluid with recirculated cooled fluid and allows the cooled fluid to exit the well from a high density layer near the well bottom. Since the cooled water is contained within the promoter pipe it is returned to the well base bottom section without the opportunity for substantial mixing. A stratified flow was observed in the outlet pipe, giving some support to this suggestion. The fluid mechanics of the proposed mechanism will be studied in more detail in an attempt to confirm this.

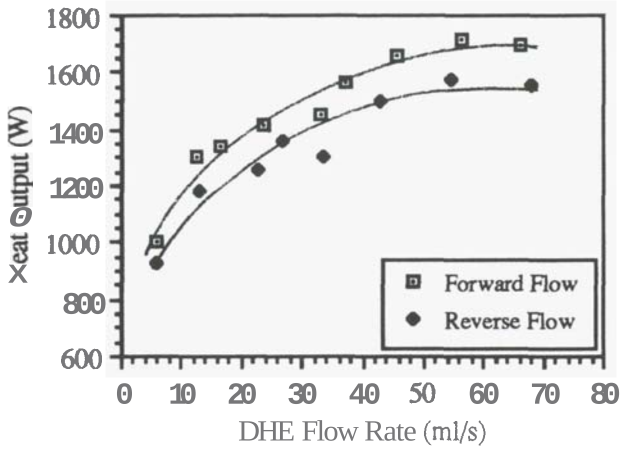



*Figure 10 - Heat Output vs. DHE flow (32mm promoter) (Crossflow rate 31.4 mlls)*

Forward flow in the well bore could be ensured by placing the cold flow leg of the DHE inside the promoter pipe, with the hot return leg in the annulus. The circulation cell driving force resulting from the density difference would then be increased and forward flow would be stabilized.

## PROBLEMS ENCOUNTERED DURING THE EXPERIMENTS

Heat input to the well base section and the heat output through the DHE were determined by measuring inlet and outlet temperatures and flow rates. In some experiments the indicated heat input through the well base was up to 50% or 1000 W higher then the heat output through the DHE. The probable heat loss through the well walls was estimated at about 130 W. Evaporation of the water from the free surface at the top of the well accounts for another 23 W.

A calculation of the power input to the heater showed that the heat supplied to the system was usually between 150 W and 250 W higher than the heat output through the DHE. This result confirmed the heat output measurement, if one takes the heat losses into account, implying an error in the heat balance across the bottom section of the well. This error must then be due to a temperature or a flow measurement.

Calibration of the thermocouples and the flow meters was verified and it was reconfirmed that the system was reaching thermal equilibrium. Measurement of the pipe outlet temperature seemed the only remaining possible source of error. To confirm the temperatures of the water in the outlet pipe of the well base, three thermocouples were glued on the outside of the copper pipe, which was insulated. The thermocouples at the base and top of the pipe showed temperature differences of up to 2.5 °C, caused by a stratification of water in the outlet pipe. The measured temperature was therefore not the mean temperature in the pipe. However, to cause a difference of 1000 W under these conditions the error in the temperature measurement has to be more than 5 °C. The cause of the variation is therefore only partially explained by flow stratification.

A slightly unstable water supply to the DHE also caused some problems in the heat balance calculations, since only spot values of flow rate could be taken, as opposed to the average values of temperature obtained from continuous logging.

## CONCLUSIONS

The heat output of the PVC DHE is quite high compared to the copper DHE, considering its thermal conductivity. This is due to the low percentage of the total heat transfer resistance represented by the tube and the fact that no heat is lost in the return leg.

Cross flow and the DHE flow rate have a strong influence on the heat output of the DHE. Heat output increases with increasing cross flow and increasing DHE flow rate. Both relationships appear nearly linear at low flow rates but the performance improvement tapers off as the flow rate increases.

When the promoter pipe is installed bulk well circulation can be obtained in a forward or reverse direction, with the forward direction yielding a higher heat output. Forward flow is, however, less stable than reverse circulation. In practical applications forward flow may have to be forced, perhaps with a small airlift pump. Alternatively, the system could be designed to ensure forward flow by placing just the cold flow leg of the DHE in the promoter pipe.

The temperature in the PVC DHE was at no point higher then the temperature in the well. Therefore no heat transfer from the PVC DHE back to the well occured. A hybrid DHE, made partially from copper with a PVC return pipe should provide higher heat transfer rates than either of the single material DHEs.

## RECOMMENDATIONS AND FURTHER WORK

Redesigning the well base would improve the model well. Better modeling of the real situation would probably result if the well base zone were wider and not cylindrical. It is suggested that that the inflow and the outflow of the cross flowing water should take place over the whole width of the well base zone, via distribution manifolds, rather than through a single point.

More thermocouples are recommended for the the well base zone. It is anticipated that the mixing process of the hot reservoir water and the circulating water in the well could then be more easily observed.

An attempt will be made to develop a correlation between fluid mechanics parameters and the heat output for this model well using dimensional analysis. Attempts will also be made to extend any resulting correlation to full scale experiments.

Experiments where one leg of the DHE is surrounded by the promoter tube, and where one leg of the DHE is insulated, are continuing or are programmed for the near future.

## ACKNOWLEDGEMENTS

The authors acknowledge the assistance of Auckland University technical staff, in particular Brian Watson and Darryl Visser, for making items of equipment for the model well. Thanks also to Chen Song, who constructed the PVC DHE, and Zhao Feng, who ran a series of preliminary experiments on the effect of circulation direction. Discussions with A/Prof. D.H. Freeston have also contributed greatly to this work.

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