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AN EXPERIMENTAL SIMULATION ON HEAT TRANSFER CHARACTERISTICS OF A DOWNHOLE HEAT EXCHANGER

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ABSTRACT

The heat transfer characteristics of a downhole heat exchanger (DHE) were studied experimentally in a laboratory scale. The permeable aquifer was simulated by using a rectangular tank filled with glass beads of diameter ranging from 3 to 5 mm. The downhole heat exchanger was modeled by a U-shaped copper tube. We have simulated various configurations of DHE by changing the geometrical parameters of U-tube and downhole, and different operating conditions at various inlet water temperatures, mass flow rates through the DHE. In addition, the experimental system was specially designed that capable of simulating an aquifer with flowing water. The results show that the temperature difference between the reservoir and the inlet water of U-tube is a dominant factor on heat extracted. However, the total amount does not necessarily follow a linear relation. The mean outside heat transfer coefficient of the two legs can achieve a maximum value at a moderate temperature difference.

INTRODUCTION

Without pumping geothermal fluid out of aquifers and that related disposal problems, Downhole Heat Exchanger (DHE) has always been an attractive mining heat option in geothermal uses. Compared with borehole heat exchanger (BHE), DHE obviously holds a more effective heat transfer mode by natural convection than BHE that by conduction. Because natural convection is strongly temperature-flow coupled, the outside heat transfer coefficient of the two U-tube legs has never been easily and precisely determined. DHE is recommended to be installed in a high permeable zone with liner casing or without casing of the well so that natural convection can be induced.

The natural convection happened inside the wellbore and its surrounding porous media is a complicated phenomenon. There have been a number of efforts tried in the past in order to have a high intensity convection cell outside the U-tube. An early research on DHE were carried out in New Zealand, which indicated that a promoting pipe can be used to induce vertical natural convection in the well, and different configurations of promoting pipe and DHE were studied in a laboratory model to find the optimum pipe diameter (Allis and James, 1979). The experiment work conducted at University of Auckland concluded that the diameter (cm)-to-length (m) ratio of the promoting pipe should be larger than one in order to get the maximum heat output (Freeston and Pan, 1983). Moreover, a series of test were carried out on a U-tube DHE in Rotorua to study the fluid temperatures inside the heat exchanger tubes (Dunstall and Freeston, 1990). For practical applications, existing design procedure was presented to estimate the steady-state heat flow, referring to the mixing ratio determined for a specific aquifer by well testing (Culver and Reistad, 1978). Recently, a lumped parameter model was proposed to estimate the operating limits of the DHE (Carotenuto and Casarosa, 1997, 2000), in which the mixing ratio is a known parameter by interpolating. However, the flowing and heat transfer interaction between the water in the well and that in the aquifer is poorly understood. The effects of numerous factors on the convective flow and heat transfer in the well and that in the aquifer need a deeper investigation, such as the geometric configurations of downhole exchanger and well, the flow rate through the exchanger, and the temperature difference between the water in the exchanger and that in the aquifer,. The necessary conditions to generate a co-active convective heat transfer between the well and the aquifer, as well as the heat transfer in DHE need to be studied in detail.

SYSTEM DESCRIPTION

A rectangular glass tank having a size of 900×500×1000 mm3 was fabricated to simulate the DHE system. Several types of U-tube made of copper were used as DHEs, which have an inner diameter of 3 mm, 6 mm, 10 mm, and a distance between the two legs of 10 mm, 15 mm, 20 mm, respectively. The well was made of plexiglass pipe. Three types of wells having respectively a diameter of 80 mm, 60 mm and 40 mm were tested. Except of the part in the air, the well wall was penetrated uniformly with 3 mm-holes to simulate the bare well or liner casing. The saturated aquifer was simulated by using glass beads in diameter of 3-5 mm, which filled up the glass tank to about its half height, that is, 500×500×1000 mm3 in space. The outer part of the system is kept at a constant temperature to simulate the undisturbed aquifer. The experiment system was specially designed that can provide different seepage velocities in the porous aquifer. Figure 1 shows some parts of the experiment system.

(*a*)

(*b*)

Fig. 1: The Experiment setup and main components
(*a*) *testing points and simulated aquifer*
(*b*) *simulated wellwall*

About forty T-type thermocouples were located at three different heights in the porous layer, and at each height they were distributed evenly in three concentric circles around the well. During the experiment, the flow rate through the U-shape DHE and that through the porous aquifer were measured by water weighting. Together with the water temperatures at the inlet and outlet of the U-tube, the temperatures at different locations in the porous aquifer were collected by an Angilent Data Logger. Therefore, the heat flow rate of the DHE, the temperature variation in the aquifer can be monitored under different operating conditions.

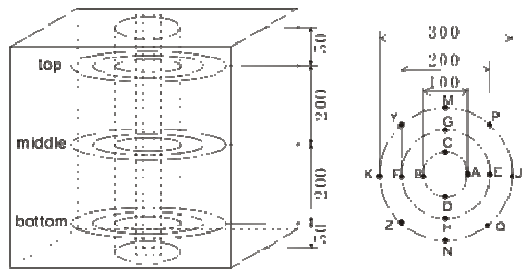

Fig. 2: Distribution of the testing points in porous aquifer

PROCESSING OF EXPERIMENTAL DATA

The heat extraction rate Q [W] was calculated according to Eq. (1).

$$Q = \dot{m} c_p \left(T_{ou} - T_{in} \right) \tag{1}$$

where, $\dot{m}$ is the mass flow rate through the U-shaped DHE [kg s-1], T is temperature [K or □], c_p is the specific heat of water at constant pressure [J $kg^{-1}K^{-1}$] and the subscripts "ou" and "in" denote the outlet and inlet of the U-shaped DHE, respectively. The outside convective heat transfer coefficient h_o [$Wm^{-2}K^{-1}$] is a function of the overall heat transfer coefficient K [$Wm^{-2}K^{-1}$] and the inside convective heat transfer coefficient h_i [$Wm^{-2}K^{-1}$], which refers to the heat flux through the U-tube wall q [Wm^{-2}], the water flow rate in the U-tube v_u [ms^{-1}], the geometry of the U-tube, and the logarithm mean temperature difference (LMTD) between the water in the porous aquifer and that in the U-tube, $\overline{\Delta T}$. It is worthy to note that h_o indicates the status of heat transfer outside the U-shaped DHE, which includes the effects of both the convection in the well and the convection in the porous aquifer. Eq. (2) gives the definition of h_o.

$$h_o = \left(\frac{1}{\kappa} - \frac{1}{h_i} \frac{d_o}{d_i} - \frac{d_o}{2\lambda} \ln \frac{d_o}{d_i} \right)^{-1} \tag{2}$$

$$\kappa = \frac{q}{\overline{\Delta T}} \tag{3}$$

where, d is the U-tube diameter [m], λ is the thermal conductivity of copper [Wm-1K-1], subscripts "o" and "i" denote the outside and inside of the U-tube respectively.

RESULTS AND DISCUSSIONS

In this paper, we briefly discuss four influencing parameters on the total heat output, i.e. the seepage water velocity in the aquifer, the temperature difference between the U-tube inlet and the aquifer far away from the DHE, ΔT, the flow rate through the U-tube, and some geometric parameters of both the U-tube and the well.

Effect of seepage velocity in porous aquifer

Figures 3 and 4 show, respectively, the heat extraction rate, Q, and the outlet temperature, T_{ou}, against time under different seepage velocity, v_s. During the experiment, the temperature of undisturbed aquifer, T_p, was kept at 40 ℃, by circulating water through a temperature controlled water bath. The inlet water temperature and the flow rate of the U-tube, T_{in} and v_u, were 15℃ and 0.12m/s respectively. As shown in Fig. 3 and 4, both the heat extraction rate and the water outlet temperature can reach a steady state in a shorter period under a higher seepage velocity. In the initial 10 minutes of running, the fluctuation of Q is obviously smaller under a higher v_s than that under a low v_s. This is because a higher seepage velocity results in a better thermal recovery in the surrounding aquifer. Given a continuous heat extracting, the propagation of the temperature drop in the neighbor region of the U-tube is inhibited more easily by the upstream geothermal fluid under a high seepage velocity. The temperature profile around the U-tube was kept at a value closer to the initial level than that of the lower v_s. Therefore, the driving force for convective heat transfer, namely, the temperature difference, can provide a more stable and a higher outlet temperature in utilization.

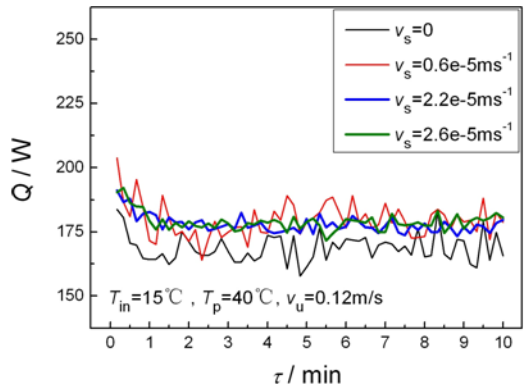

Fig. 3: Heat extraction rate under different seepage velocity

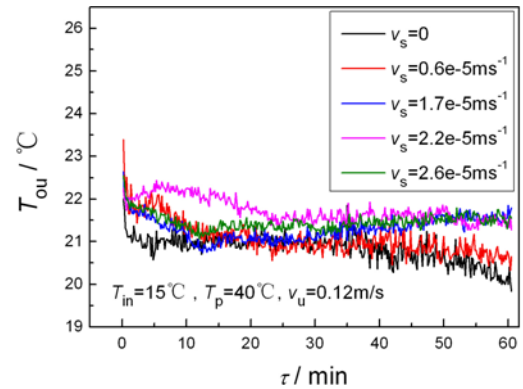

Fig. 4: Outlet temperature of U-tube exchanger under different seepage velocity

It is also indicated that while v_s is larger than 0.6×10^{-5} m/s the total obtained heat is about 20% larger than the case with zero seepage velocity, and the outlet temperature is about 1□ higher, as shown in Fig. 5 and 6.

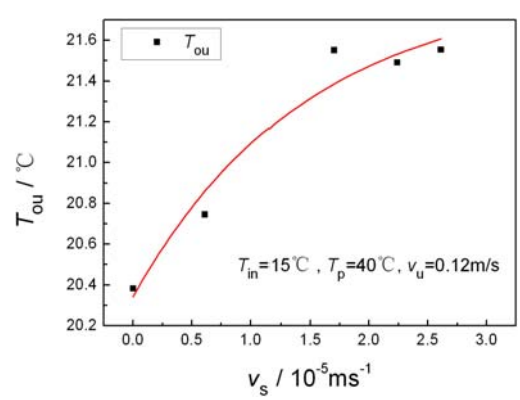

Fig. 5: Outlet temperature variation with seepage velocity

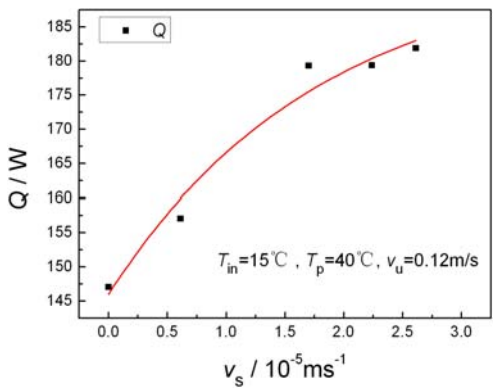

Fig. 6: Heat extraction rate variation with seepage velocity

At a constant flow rate of the U-tube, the thermal performance of the DHE does not show a linear improvement with an increase of seepage velocity. Both the total heat output, Q, and the outside convective heat transfer coefficient, h_o, follow approximately a type of exponential function of v_s, as shown in Fig.6 and Fig. 7.

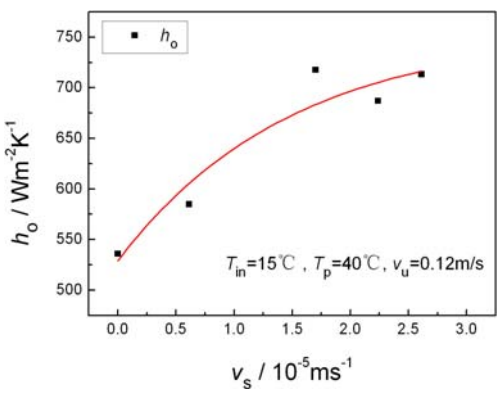

Fig. 7: Outside heat transfer coefficient under different seepage velocity

Moreover, the effect of seepage velocity gets more apparently at a larger ΔT. Otherwise, given a small ΔT, the temperature increase in the U-tube, ΔT_u, is almost the same at different seepage velocity (see Fig. 8). This indicates that the influence of ΔT is stronger than that of v_s. However, while ΔT becomes relatively larger, a mixed convection may arise, which is a favorable heat transfer mode for heat output. This can be reasonably explained according to the distinct temperature curves with time, as shown in Fig. 9. Although flow regime is important for convective heat transfer, the temperature difference is the only driving force for natural convective heat transfer. It may play a more influential role in mixed convection. Actually, the groundwater flows at a very low speed, usually in the range of 2.2e^{-12} -3.0e^{-5} m/s. Thus, the temperature difference is a more important factor.

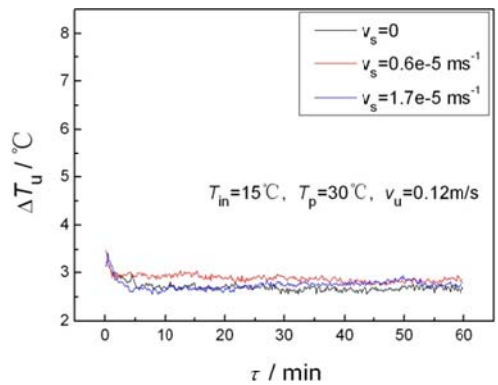

Fig. 8: Effect of seepage velocity under small ΔT

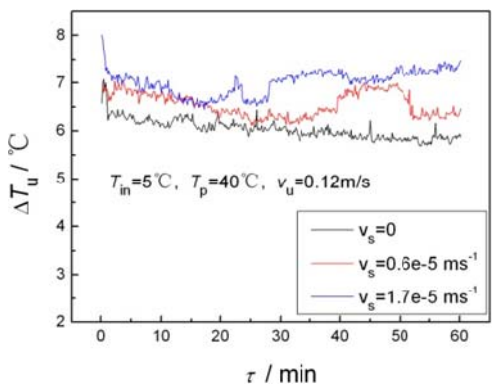

Fig. 9: Effect of seepage velocity under large ΔT

Effect of temperature difference, ΔT

Figure 10 shows the case of zero seepage velocity and the water velocity in U-tube is 0.12m/s. The heat output, Q, can reach its steady state after about one hour for various ΔT.

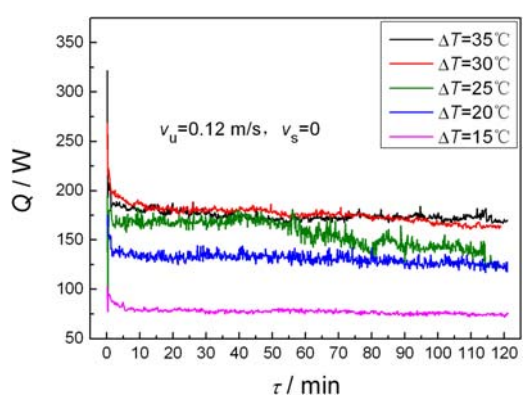

Fig. 10: Heat extraction rate under different average temperature difference

Figure 11 shows the variation of the total heat output, Q, with ΔT at a steady state, the curve indicates an exponential increase. The maximum heat extracted is about 175W for the case with maximum ΔT of 35□. When the temperature difference, ΔT, was raised from 30 □ to 35 □, the temperature rise in the U-tube, ΔT_u, changed little. The increment of ΔT_u with ΔT was limited for the case with a large ΔT. This can be understood more easily if we plot the relation of heat transfer coefficient outside U-tube against ΔT, (Fig. 13), which shows that there was a maximum heat transfer coefficient while ΔT was controlled at 25□.

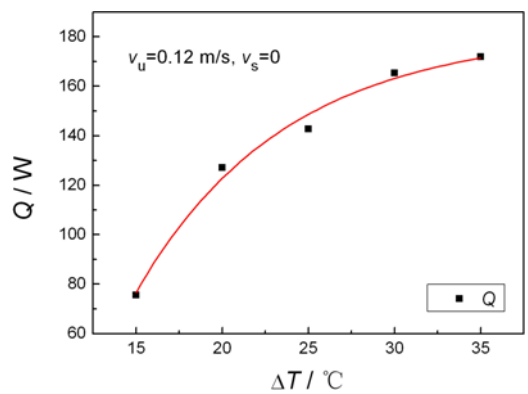

Fig. 11: Heat extraction rate variation with temperature difference

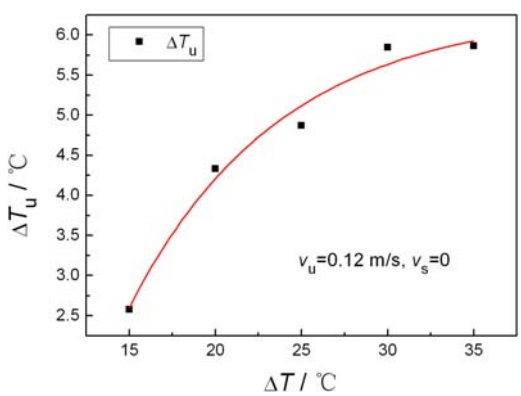

Fig. 12: Temperature rise in U-tube exchanger with temperature difference

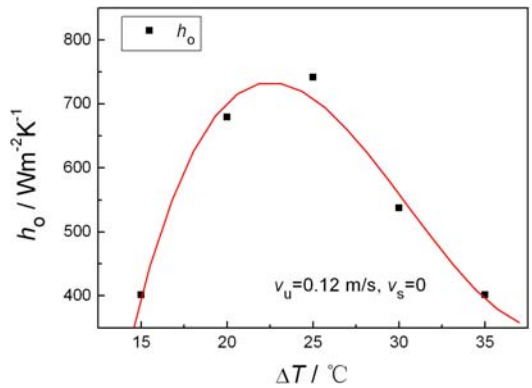

Fig. 13: Outside heat transfer coefficient under different average temperature difference

The tendency in the curve of outside convective heat transfer coefficient, h_o, is distinct from that in Fig. 5. The maximum value of h_o occurs at a moderate ΔT. For a given undisturbed aquifer temperature, T_P, larger ΔT means a lower inlet water temperature, T_{in}, and in turn a sharper temperature rise in the leading section of the U-tube. In the following parts of the U-tube, say, the central and end section, the temperature rise is smaller. That is, the fluid temperature distribution is not uniform along the U-tube exchanger. In the porous aquifer, the temperature difference on the top is larger than that at the bottom.. As to the convective heat transfer in the aquifer, there may be a coupling relationship between the uniformity of temperature distribution and the magnitude of the averaged temperature difference. Moreover, the uniformity may be a more important one of the two influential factors. Thus, a moderate ΔT will lead to a favorable temperature distribution along the U-tube and then an improved heat transfer performance. Therefore, a proper ΔT according to the thermal properties of aquifer might be a crucial point for a DHE design.

Effect of flow rate through U-shaped DHE, v_u

A series of experiments were conducted by varying the flowrate through the U-tube while the other parameters were kept or controlled at constant values. The initial temperature of the aquifer, T_p, was given by 40 □, and the inlet water temperature of the U-tube, T_{in}, was controlled at 15 □.The seepage velocity was zero. In fact, in most of cases, the water flows in aquifer with a very low velocity (at the level of 10^{-7} - 10^{2} m/y).

As shown in Fig. 14, the heat extraction rate, Q, can reach its steady state within two hours when the flow rate of the U-tube was lower than 0.38 m/s.

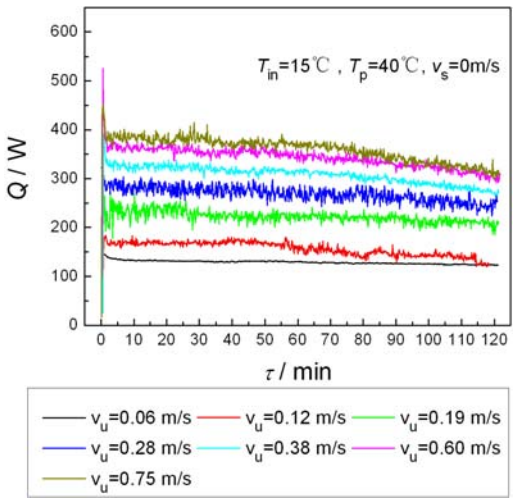

Fig. 14: Heat extraction rate with operating time

Compared with Fig. 13, the heat transfer performance of the DHE can be further improved by increasing the flow rate through the U-tube at a moderate ΔT, as shown in Fig. 15. This is mainly because of the improved inside convective heat transfer by increasing water velocity in the U-tube. Although the outlet temperature of the U-tube, T_{ou}, dropped with the flow rate, the heat extraction rate was still raised. Both the extracted heat rate, Q, and the outlet water temperature, T_{ou}, shows a similar exponential curve with the velocity in the U-tube, (Fig. 16 and 17).

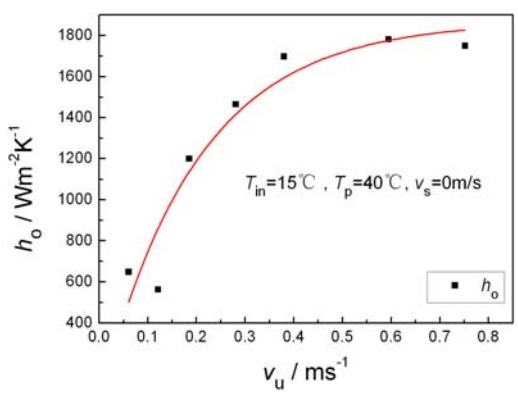

Fig. 15: Outside heat transfer coefficient under different flow rate in U-tube exchanger

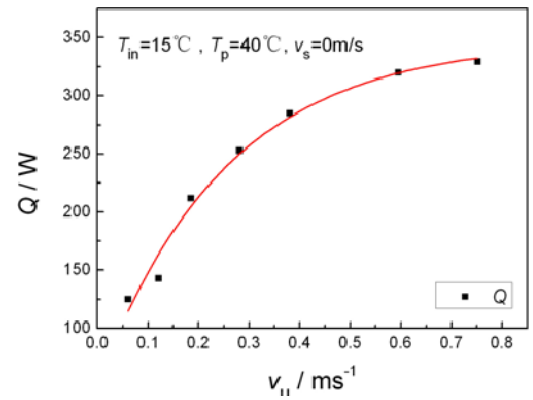

Fig. 16: Heat extraction rate under different flow rate in U-tube exchanger

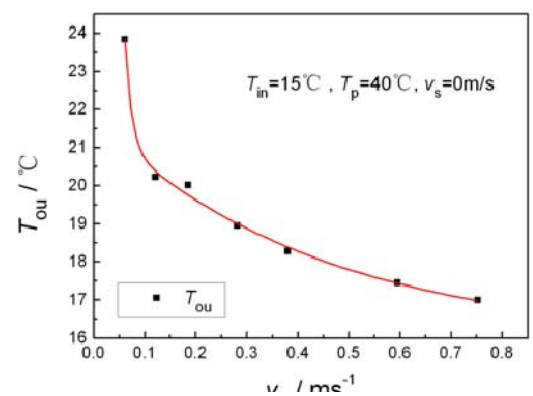

Fig. 17: Outlet temperature variation with flow rate in U-tube exchanger

Effect of geometric condition, ζ

The heat transfer performance of a DHE is related to both the heat transfer area and the free flowing space where the convective cells take place. Therefore, a U-tube heat exchanger with a larger diameter and a larger borehole is more likely favorable to a DHE system. In order to correlate the geometric factor on the heat transfer characteristics for a DHE system, we introduce a parameter denoted by, ζ, which stands for the ratio of borehole volume to the heat transfer area, The parameter, ζ, can be given as

$$\zeta = \frac{\pi D^2 H}{8\pi d_u H} = \frac{D^2}{8 d_u} \tag{4}$$

where D is the borehole diameter (m), d_u is the U-tube exchanger diameter (m), and H is the height of the DHE. In the experiment, the mass flow rate in the U-tube was about 40 kg/h, and a moderate temperature difference was applied, that is, ΔT =25℃. As shown in Fig. 18, small ζ is beneficial to the heat extraction rate for each borehole diameter group. In other words, heat transfer area is still the dominant

factor compared with free volume. However, there seems to have a critical point that in each Q-ζ bar group the heat extraction rate follows down-up tendency with the parameter ζ. No significant drop was observed in heat extraction rate between the two extreme cases for all the three groups. It means that we can achieve approximately an equal heat output with different borehole-U-tube matching. From the economic point of view, this should be taken into consideration in a decision making.

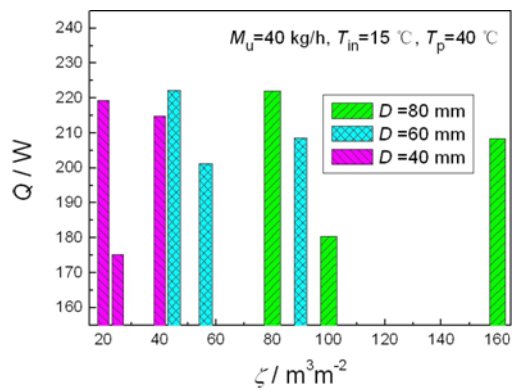

Fig. 18: Heat extraction rate with available free volume

CONCLUSION

A series of experimental tests were carried out in our laboratory for simulating a downhole heat exchanger system. The results show that the heat extraction rate holds an exponential relation with seepage velocity, temperature difference for heat transfer and flow rate in the U-tube exchanger. The outside convective heat transfer coefficient can achieve the maximum value at relatively small v_u under a moderate LMTD temperature difference, and can be further improved by increasing the velocity in the U-tube. It is noticed that the heat transfer characteristics for a real DHE system is very complicated. These experimental results can not be transplanted directly for a DHE design. This is because not only of the size but the heterogeneous structure for most of aquifers. Nevertheless, the results should be helpful for understanding the phenomena happened deep down in the DHE, since these phenomena are governed by the same equations for both cases.

ACKNOWLEDGEMENTS

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