Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Design of the BHP System Considering the Heat Transport of Groundwater Flow

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Keywords: Geothermal heat pump, Groundwater flow, System design, BHP system

ABSTRACT

It is well known that groundwater exists abundantly in Japan. Various ways to use groundwater as a heat source of BHP system are imaginable. However, the direct pumping of groundwater would cause some troubles such as ground subsidence. Therefore, this study focused on the closed-loop-type BHP system (a conventional ground-coupled heat pump system with borehole), and designed its system, considering the heat transport of groundwater flow. Such a design remarkably saves the depth of borehole (i.e., the cost of drilling) compared to that assuming only the heat conduction under the ground.

In order to evaluate the transport rate of heat from groundwater to the borehole (heat exchanger), the relations of borehole temperature to the heat extraction rate and groundwater flow-velocity have been examined by using a two-dimensional numerical model in this study. The calculated result clarified the upper bound of heat extraction rate (i.e., maximum heat load). Its upper bound is limited by the freezing point either of circulation fluid in U-tube or groundwater. Using the upper bound, we can roughly predict the borehole length required in the BHP system. In the results, the case larger than 10^{-5} m/s in Darcy flow-velocity of groundwater was able to save the length of heat exchanger compared to that of the BHP system design assuming only the heat conduction.

The applicability of the calculated results was confirmed in a test site of BHP system in Omachi business office of Chubu Electric Power Co., Inc., Japan. The BHP system has installed double U-tubes into a borehole of 100 m in depth. In the test site, the flow-velocity of groundwater was estimated to be 10^{-4} m/s in Darcy flow velocity. In the steady state of heat extraction test, the BHE system supplied heat to the ground facility at least up to 20 kW (209 W/m). The results showed good agreement with the calculated results.

1. INTRODUCTION

The ground-coupled heat pump is popular as a heat supply system in Europe and US, because the system has large advantage for the control of CO_2 emission and the effective use of electric power. However, this system doesn't come into wide use in Japan very much. Since in Japan the land for residence is relatively limited, most of the cases would require borehole to install the system, while the cost of drilling is still expensive compared to EU and US. This matter estimates the initial cost to be larger compared to that of conventional heat supply system. On the other hand, groundwater exists abundantly in Japan. Therefore, this study focused on the heat transport of groundwater to obtain a more reliable design of the ground-coupled heat pump system with borehole (hereinafter referred to as BHP system).

In order to use groundwater as a heat source for the BHP system, it may be possible to select also the direct pumping of groundwater. However, such pumping would cause some troubles such as ground subsidence. Therefore, this study selected the closed-loop-type's BHP system (a conventional ground-coupled heat pump system with borehole), and examined a more appropriate design of borehole depth in consideration of the heat supply rate due to groundwater to the borehole.

So far, some researchers (e.g., Cheng, 1982, Kimura et al., 1988, Fujii, 2002) have examined the modeling about heat extraction from groundwater around borehole. However, it is not sufficiently clear to connect such modeling with design of closed-loop-type's BHP system. On the other hand, some useful computer cords for the design aid of BHP system have been already proposed. For example, EED (Sanner et al., 1999) is very useful and is widely used. However, such cords suppose only conduction of heat as main process of underground heat transport.

When the heat conduction is dominant under the ground, we must also consider the balance of heat demand between winter and summer seasons (e.g., Rybach and Eugster, 1998, Eugster and Rybach, 2000, Morita et al., 2000, Morita et al., 2003). The BHP system can store heat in the limited region around borehole. However, if groundwater flow rate is large enough, the BHP system might not be able to store efficiently the heat in the region around borehole. Therefore, this study focused on maximum heat load (demand from ground facility), q_{max} (W), for the year, and examined the thermal response (the transition time period and the temperature in the steady state) of the BHP system, using a two-dimensional numerical model.

On the basis of the calculated results, the borehole depth required for heat extraction has been discussed. (Here, the freezing point either of circulation fluid in U-tube or groundwater was considered as a constraint for the design of the BHP system.) To confirm the variability of the system design considering groundwater flow, the calculated result was applied into the site test results of the BHP system in Omachi business office of Chubu Electric Power Co., Inc., Nagano, Japan.

2. MATHEMATICAL MODEL

Figure 1(a) shows a schematic of groundwater flow and a well (heat exchanger). In the well, a U-tube (usually double-U-tube) is installed and is connected with the heat pump for heat supply to a ground facility. Although groundwater flow does not always take such a uniform flow velocity depending on the distributions of permeability and pressure gradient, this study assumed a uniform flow of groundwater past the well. In such a case, we may be able to regard the heat transport as a two-dimensional problem, as shown in Fig.1(b). Further, this study modified the region of heat extraction, as shown in Fig.2, where the flow system is assumed to be symmetrical in the flow direction (*x*-axis). Fig.2 also shows the other boundary conditions. In this system, the direction of groundwater flow is one-dimensional and the heat transport is two-dimensional.

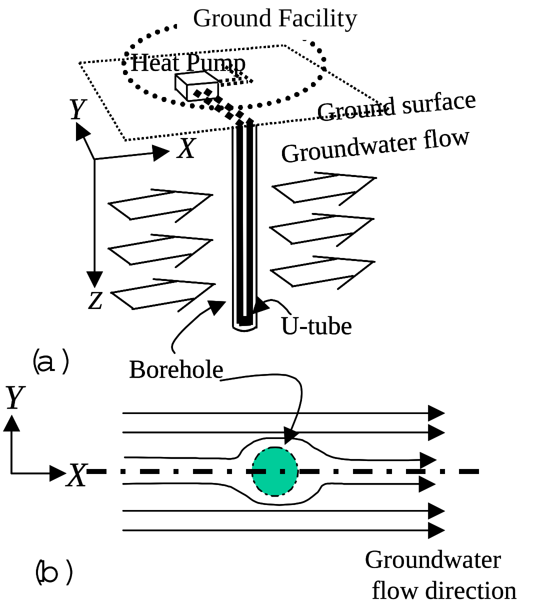


Figure 1 Schematics of groundwater flow and ground-coupled heat pump with borehole (BHP): (a), and schematic of groundwater-flow around borehole: (b). (The circle in Fig.1 (b) is the cross-section of borehole including U-tubes and the arrows are imaginary stream lines.)

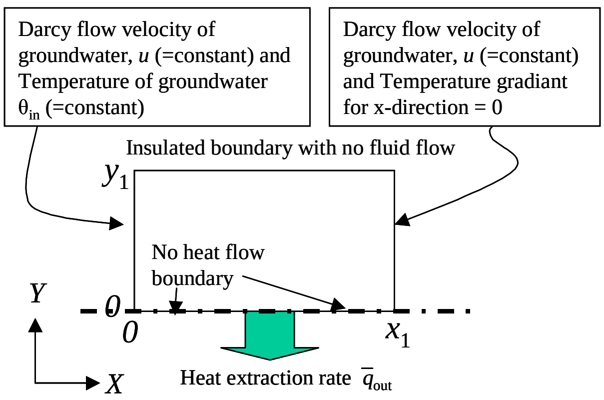


Figure 2 Boundary conditions ($\bar{q}_{out}$ is the average heat flux of heat extraction to the inside of borehole.)

The fundamental equation of heat balance yields

$$(\rho c_p)_e \frac{\partial \theta}{\partial t} = -(\rho c_p)_f u \frac{\partial \theta}{\partial x} + \lambda_e \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right) \quad , \qquad (1)$$

where θ is temperature (K), t is time (s) ρ is density (kg/m^3), c_p is specific heat (J/(kg·K)) (ρc_p is heat capacity), t is time, u is Darcy fluid flow velocity (m/s), λ_e is effective thermal conductivity (W/(m·K)), and the subscripts, 'e' and 'f', mean 'effective' and 'fluid', respectively.

For the boundary condition of heat extraction, this study assumes

$$-\lambda_e \frac{\partial \theta}{\partial y} = -\bar{q}_{out}, \qquad (2)$$

where $\bar{q}_{out}$ is the average value of heat extraction rate (W/m^2), as shown in Fig.2.

The dimensionless variables and parameters are defined by

$$T = \frac{t}{t^*}, \ \left(t^* = \frac{u}{x_1}\frac{(\rho c_p)_e}{(\rho c_p)_f}\right), \ X = \frac{x}{l}, \ Y = \frac{y}{l},$$

$$\Theta = \frac{\theta - \theta_{LB}}{\theta_{in} - \theta_{LB}}, \ P_e = \frac{ul}{k_h},$$

where t^* is the characteristic time (s) as defined above (Note that t^* includes the ratio of heat capacity), l is the characteristic length (m) defined by the half length of outer circumference of the well, k_h is thermal diffusivity (=$\lambda_e/(\rho c_p)_f$), θ_{in} is the temperature of inflow groundwater, i.e., the temperature on the axis of x=0, and θ_{LB} is the lower limit temperature kept for the performance of the BHP system. About its value, we can suppose two kinds of temperature. One is the freezing point of groundwater itself. The other is the outside surface temperature of borehole corresponding to the condition that the circulation fluid in the U-tube freezes. Using the dimensionless variables and parameters, we can deform equation (1) to

$$\frac{\partial \Theta}{\partial T} = -\frac{\partial \Theta}{\partial X} + \frac{1}{P_e}\left(\frac{\partial^2 \Theta}{\partial X^2} + \frac{\partial^2 \Theta}{\partial Y^2} \right). \qquad (3)$$

Similarly, equation (2) is deformed to

$$\frac{\partial \Theta}{\partial Y} = Q_{out}, \quad Q_{out} = \frac{\bar{q}_{out} l}{\lambda_e(\theta_{in} - \theta_{LB})}. \qquad (4)$$

Using the upwind differential explicit method in FDM (finite difference method), the fundamental equations were solved numerically. As shown in equations (3) and (4), this problem can be described by two parameters, that is, the Peclet number, P_e, and the dimensionless heat-extraction-rate, Q_{out}.

Table 1 shows an example of parameter sets. The heat extraction rate unit borehole length is set at 20 W/m. This may be a general value of BHP (with U-tubes) obtained from the underground controlled by heat conduction (Eugster, 1999, and Niibori, 2002). In this case, the dimensionless heat extraction rate Q_{out} is estimated to be 0.8 through equation (4). As for the flow velocity of groundwater, this study assumes a range of from 10^{-6} m/s to 10^{-4} m/s in Darcy flow velocity. Then, the Peclet number, P_e, is estimated to be from 0.48 to 48. When the Peclet number is smaller than 1, the heat transport is controlled mainly by heat conduction, as clarified in the fundamental equation (3). Therefore, this study focuses on the range larger than 1 in P_e. About t^*, the value is 3.5 hours, when u=1.0x10^{-5} m/s. (t=t^* corresponds to T=1 in dimensionless time.) Further, to know the practical temperature of θ_{LB}, this study assumes a condition that the circulation fluid in

U-tube does not include an antifreezing solution. From the overall coefficient of heat transmission in the borehole heat exchanger with U-tubes (Eugster, 1999), the temperature difference between inside and outside of U-tube is approximately estimated to be 5 °C in the steady state of the heat extraction. Therefore, the constraint temperature, θ_{LB}, was assumed to be 278 K (higher by 5 K than the freezing point of water, 273 K).

Table 1 Reference values of parameters in this study

Parameter, Symbols and Values
Initial temperature of ground θ_{in} : 285 K
Constraints of temperature θ_{LB} : 278 K
Effective thermal conductivity λ_e : 2.1 W/(m¥K) [1)]
Heat extraction rate unit borehole length $q_B{}^*$: 20 W/m [1)]
Diameter of borehole d_{outer} : 0.152 m
Heat extraction rate q_{out} (= $q_B{}^*$ /($d_{outer}\pi$)) : 42 W/m^2
Characteristic length (the half length of outer circumference of the well) l (= ($d_{outer}\pi$)/2) : 0.239 m
Effective heat capacity of formation saturated with groundwater $(\rho c_p)_e$: 2.2x10^6 J/(m^3¥K) [2)]
Heat capacity of groundwater $(\rho c_p)_f$: 4.18x10^6 J/(m^3¥K)
Thermal diffusivity k_h(= λ_e/ $(\rho c_p)_{,t}$) : 5.0x10^{-7} m^2/s
Dimensionless heat extraction rate Q_{out} (Note eq. (4)) : 0.8
Darcy flow velocity u: 1.0x10^{-6}<u< 1.0x10^{-4} m/s
Peclet number Pe : 0.48< Pe< 48
Characteristic time t^* : 3.5 hours (at u=1.0x10^{-5} m/s)

[1)] Eugster (1999) , [2)] Eugster (1999), Morita et al. (2003)

3. RESULTS AND DISCUSSION

3.1 Calculation Results

Figure 3 shows an example of the calculated temperature distribution in the steady state, where Q_{out} is set at *0.8* based on Table 1. The calculation region is X_1=5 (=x_1/l) and Y_1=5 (=y_1/l), and the heat extraction range is 2.0$\le X_1 \le$3.0 at Y=0. Through the pre-calculations, it was confirmed that the temperature at the heat extraction region (2.0$\le X_1 \le$3.0, Y=0) does not depend on the set of calculation region (0<X<X_1, 0<Y<Y_1). When P_e=50, the spatial region cooled by heat extraction is remarkably limited compared to that of P_e=10 or P_e=1. This means that the heat supply to the borehole is controlled mainly by heat transport due to groundwater flow.

Figure 4 shows the average temperatures in the heat extraction region (2.0$\le X_1 \le$3.0, Y=0), where the vertical axis is the dimensionless temperature and the horizontal axis is dimensionless time. In order to confirm the thermal effect of groundwater flow, this study changed Q_{out} from 0.8 to zero when the temperature distribution attains to the steady state. (This timing corresponds to the time when the relative error of temperature in the numerical computation attains to 1.0x10^{-7} at arbitrary grid-point.) As shown in Fig.4, the thermal response (the transition time period and the temperature in the steady state) strongly depends on the value of Peclet number proportional to the flow velocity of groundwater, u. From the calculated results in use of dimensionless time, T(=t/t^*), we can know the practical time required to recover the temperature. For example, the characteristic time, t^*, is shorter than 3.5 hours, when u is larger than 10^{-5} m/s. Then, the time required for recovering is within the range of several hours, as shown in the curve of P_e=10 after setting Q_{out} to zero (Fig.4).

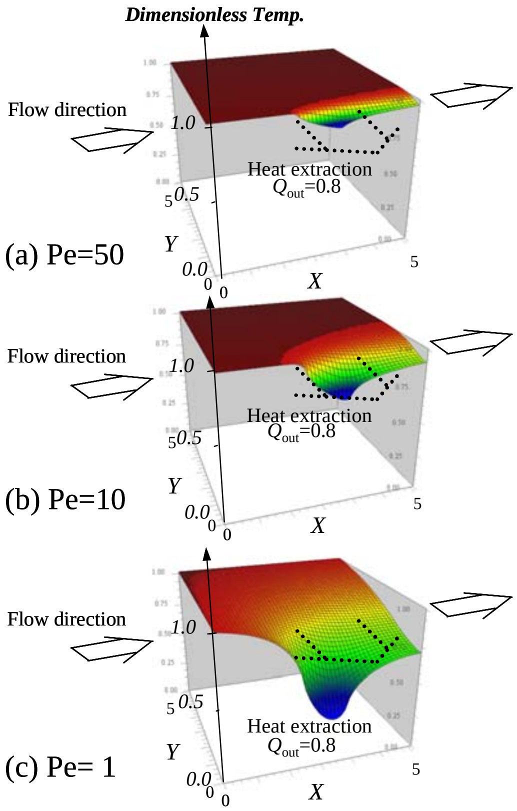


Figure 3 Examples of the calculated results of temperature distribution in the steady state, when Q_{out}=0.8 whose value is based on Table 1. (Heat extraction region is 2.0$\le X \le$3.0, Y=0, and the calculation region is X_1=5.0 and Y_1=5.0.)

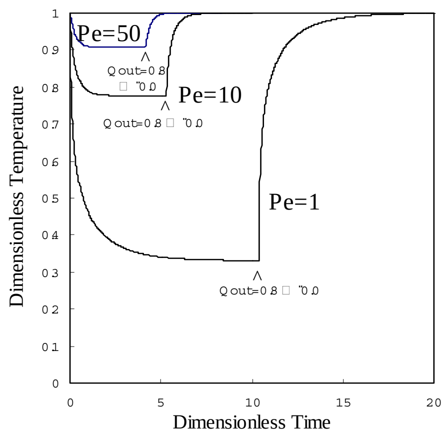


Figure 4 Thermal responses of the average temperature in the region of heat extraction, i.e., 2.0$\le X \le$3.0, Y=0. Here, in order to know easily the recovery time, the dimensionless heat extraction rate, Q_{out}, was hypothetically changed from 0.8 to zero when the temperature distribution attains to the steady state.

In general, the heat demand of ground facility fluctuates, depending on time period. Further, the heat demand depends also on season (e.g., Rybach and Eugster, 1998, Eugster and Rybach, 2000, Morita et al., 2000, Morita et al., 2003). For the design of the BHP system, we must usually consider the storage of heat in the underground region around borehole. However, when $P_e \ge$10 (u is larger than 10^{-5} m/s), it may be possible to ignore such a heat balance for the design of BHP system. That is, we can focus on just the maximum value of heat load (heat demand from ground facility), q_{max} (W), for the year. Then, a critical constraint for the design of the BHP system is the condition that either temperature of circulation fluid in U-tube or groundwater does not attain to the freezing point. (Further, in the practical design of BHP system, we will pay attention also to the coefficient of performance of heat pump (COP).)

3.2 Application of the Model to the Test Site To confirm the variability of the system design concept considering groundwater flow, the calculated result was applied into the site test results of the BHP system in Omachi business office of Chubu Electric Power Co., Inc., Nagano, Japan. Iwata et al. (2002) and Niibori et al. (2002) reported that in this test site the flow velocity was estimated to be 10^{-4} m/s from the temperature data measured at the observation well in the heat extraction test. The observation well is located at 1 m downstream from the borehole heat exchanger (BHP). The BHP system has a borehole of 100 m in depth, where so-called double U-tubes were installed. The U-tubes are connected to the heat pump (HP), then the HP supplies heat to a part of third floor (210 m^2) in the business office.

The ground water table was observed at 30 m depth from the ground surface. The borehole was not grouted in the test stage of heat extraction. (In general, the grouting is conducted for the efficient heat transfer between the circulation fluid in U-tube and underground.) The temperature values were monitored at 10 m depth-interval by the thermo sensor fixed at the outside of U-tube. The circulation fluid in U-tube was an antifreeze liquid of ethylene glycol (its volume content: 30%).

Figure 5 shows the temperature distribution in depth direction (Iwata et al., 2002, Iwata et al., 2004). The heat extraction test was conducted on 9th Feb. 2002. The atmosphere temperature was 0 °C at the beginning of the test. In the site test, the heat rate of 20 kW (209W/m) in the steady state was extracted forcibly through the BHP system from the underground. Such a heat load was made by fully opening all windows of the office. As shown in Fig.5, the temperature in the borehole immediately decreased. Then about 100 min later, the temperature distribution attained to the steady state as shown in Fig.5(c). The heat extraction was conducted until 420 min (7 hours). After stopping the heat extraction, temperature was monitored continuously. As shown in Fig.5(d), the temperature distribution recovered within 4 hours (240 min) almost to the initial distribution.

Figure 6 shows the temperature at 100 m in depth. In this site, the heat extraction test as shown in Fig.5 was conducted two times. The results of Fig.5 correspond to the first test in Fig.6. In addition, Fig.6 also shows the atmosphere temperature. As mentioned above, the atmosphere temperature at the beginning of the first test was 0 °C, then its temperature at the end of the first test decreased down to -4 °C. The atmosphere temperature may affect the temperature of the borehole particularly above the water table (0 to -30 m in depth), because air exists (around the U-tubes) inside the borehole above the water table. On the other hand, the temperature at 100 meter depth decreased with heat extraction and attained a steady state. Then, after stopping the heat extraction, the temperature immediately recovered to the initial temperature, i.e., to 12.6 °C. Moreover, such a recovery was also confirmed in the second test of heat extraction.

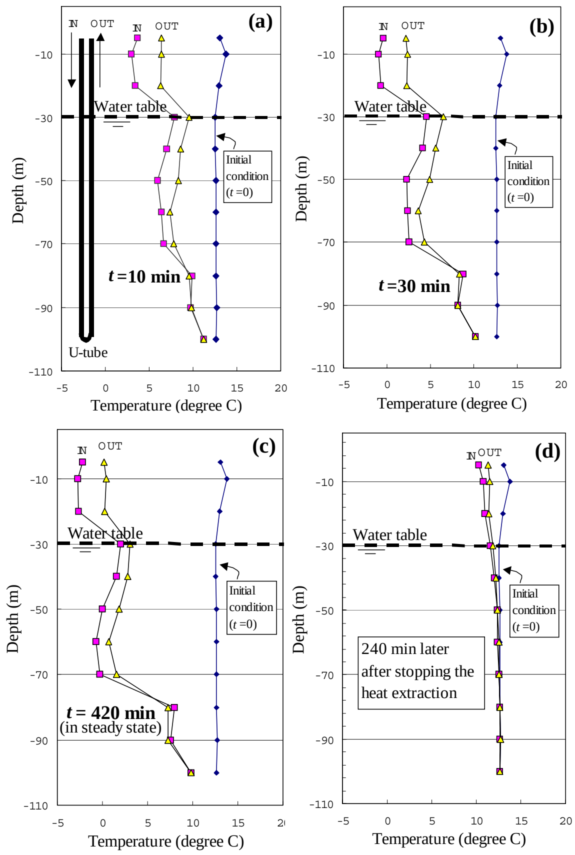


Figure 5 Temperature distributions in depth during the heat extraction test in Omachi, Nagano Japan. (a) 10 minutes later, (b) 30 minutes later, (c) 420 minutes later and, (d) 240 minutes later after stopping the heat extraction.

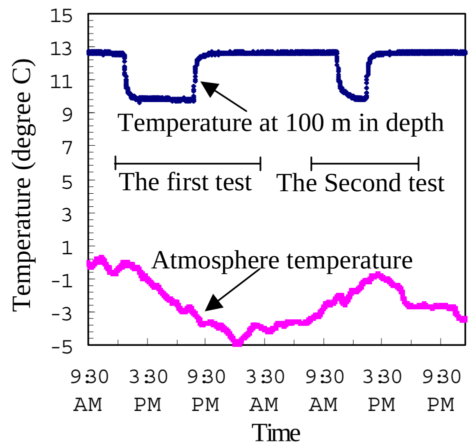


Figure 6 Temperatures traced in the site test. (The experimental results of Fig.5 correspond to the time period of "The first test" in this figure.)

Figure 7 shows the comparison of the monitored temperature with the calculated results of equations (3) and (4). The dimensionless parameter was estimated to be 6.6 in Q_{out} and 55 in P_e, based on Table 2 (Iwata et al., 2002, Niibori et al, 2002, Iwata et al, 2004). Here, the constraint temperature for the BHP system, θ_{LB}, was assumed to be a freezing point of groundwater (approximately 0 °C), because the circulation fluid in U-tubes includes an antifreeze liquid in the BHP system, as mentioned above.

Since the water table is located at -30 m in depth, the effective depth of heat extraction, d_e, was assumed to be 70 m (minus 30 m from the borehole depth 100 m). This study used the d_e to evaluate the net value of heat extraction flux through the heat exchanger, as shown in Table 2.

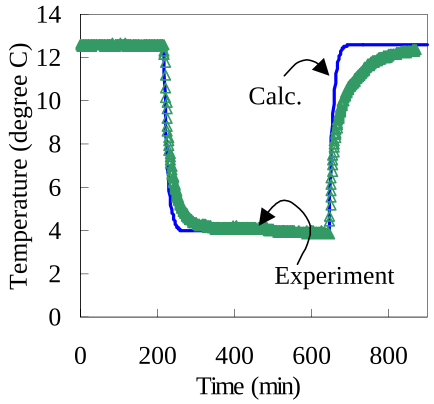


Figure 7 The monitored temperature in the first test of the heat extraction in Omachi, Nagano, Japan, and the calculated results using equations (3) and (4). (The temperature data in this figure is plotted as the average value in the range of from -30 meter to -100 meter in depth.)

Table 2 The values of parameters for the site test in Omachi, Nagano, Japan (Iwata et al., 2002, Niibori et al, 2002, Iwata et al., 2004).

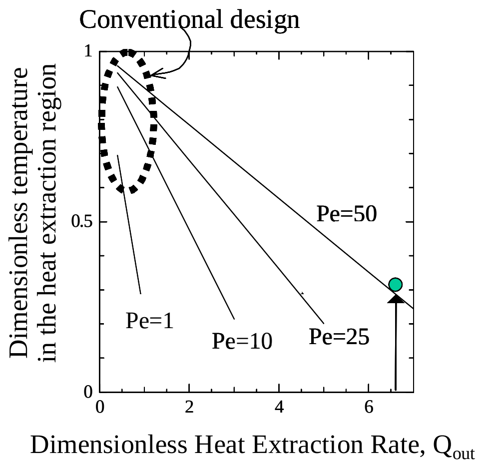
Parameter, Symbols and Values
Initial temperature of ground θ_{in} : 285.6 K (12.6 °C)
Constraints of temperature θ_{LB} : 273 K (0 °C)
Effective thermal conductivity λ_e : 1.8 W/(m¥K)
Heat extraction rate unit borehole length q_B^* : 209 W/m
Borehole depth d_B: 100 m
Effective heat extraction distance d_e : 70 m
Diameter of borehole d_{outer} : 0.152 m
Heat extraction rate q_{out} (= $(d_B / d_e) q_B^* / (d_{outer}\pi)$) :626 W/m^2
Characteristic length (the half length of outer circumference of the well) l (= $(d_{outer}\pi)/2$) : 0.239 m
Effective heat capacity of formation saturated with groundwater $(\rho c_p)_e$: 2.2x10^6 J/(m^3¥K) *)
Heat capacity of groundwater $(\rho c_p)_f$: 4.18x10^6 J/(m^3¥K)
Thermal diffusivity k_h(= $\lambda_e / (\rho c_p)_{,t}$) : 5.0x10^{-7} m^2/s
Dimensionless heat extraction rate Q_{out} (Note eq. (4)) : 6.6
Darcy flow velocity u: 1x10^{-4} m/s
Peclet number Pe : 55
Characteristic time t^* : 21 minutes

*) Eugster (1999), Morita et al. (2003)

The temperature data plotted in Fig.7 is the average value in the region of from -30 m to -100 m in depth. The calculated result shows good agreement with the temperature data, while the groundwater inside the borehole (around the U-tubes) may play a role as a thermal buffer material in the range of from -30 m to -100 m in depth.

3.3 A design concept of BHP system considering the groundwater flow velocity

Figure 8 shows the calculated results of the average dimensionless temperature in the heat extraction region ($2.0 \leq X \leq 3.0, Y=0$) in the steady state, where the horizontal axis is the dimensionless heat rate Q_{out}. The zero in dimensionless temperature corresponds to the constraint temperature for the BHP system, θ_{LB}, defined in this study. We must design the BHP system at least under the condition that the average temperature in the heat extraction region is not close to zero in dimensionless temperature. For example, if the flow velocity of groundwater, u, and the maximum heat demand, q_{max} (W), are given, we can estimate the Peclet number, then select an upper bound of Q_{out} so that the dimensionless temperature in Fig.8 does not attain to zero. Its value of Q_{out} yields a suitable length of borehole required against the maximum heat demand, q_{max} (W). That is, the calculation is the reverse procedure that Q_{out} was obtained in Table 1 or Table 2. From the selected value of Q_{out}, we obtain the heat extraction rate unit borehole length, q_B^* (W/m). Then, the q_B^* (W/m) and the q_{max}(W) give the length (m) of borehole required.



Heat extraction test in Omachi site, Q_{out}=6.6 Pe=55.

Figure 8 The dimensionless average temperature in the range of heat extraction ($2.0 \leq X \leq 3.0$, Y=0). ("Conventional design" means the design of BHP system considering only heat conduction.)

When the heat transport is mainly controlled by heat conduction, we can use the conventional useful computer cords for the design aid of BHP system, such as EED (Sanner et al., 1999). EED gives us the most suitable length of borehole against the heat demand, considering also the peak loads in winter and summer. From the calculated results, we can evaluate the value of Q_{out} defined by this study. Its values is always smaller than 1.0. As shown in the dotted circle in Fig.8, the temperature in the range of Q_{out} smaller than 1.0 does not strongly depend on Peclet number. That is, EED does not expect heat transport due to groundwater flow. On the other hand, in the design of BHP system for the case such as Omachi site, we can count the heat of groundwater flow.

4. CONCLUSIONS

This study examined the relation of borehole temperature to the heat extraction rate and groundwater flow-velocity, in order to evaluate the transport rate of heat from groundwater to the borehole, using a simple two-dimensional mathematical model. The results suggested that the case larger than 10^{-5} m/s in Darcy flow-velocity saves the borehole length compared to that of the BHP system design assuming only the heat conduction.

The applicability of the calculated results was confirmed in the heat extraction tests in Omachi business office of Chubu Electric Power Co., Inc., Nagano, Japan. The groundwater flow velocity is 10^{-4} m/s. The BHP system with 100 m depth borehole can supply the heat to the ground facility at least up to 20 kW (209 W/m). The results showed good agreement with the calculated results.

In order to design the BHP system considering the heat transported from groundwater flow, this study proposed the upper bounds of heat extraction rate. Its values are limited by the freezing point either of circulation fluid in U-tube or groundwater. Using the upper bounds (that strongly depend on the flow velocity of groundwater), we can obtain more reliable length of borehole, compared to the conventional design assuming only the heat conduction in the region around the borehole (heat exchanger).

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