Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Optimum Design of a Space Heating System Using Heat Pump Combined with Downhole Heat Exchanger

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Keywords: Downhole Heat Exchanger, Heat Pump, Space Heating, Optimum Design

ABSTRACT

Downhole Heat Exchangers (DHEs) in the previous applications were often installed in a shallow geothermal well, and they can stand for a moderate heating duty alone without any assistant heating facilities. However, due to the limitation of shallow geothermal resources, DHEs are still not prevalent worldwide. This paper proposes an idea for using DHEs together with a heat pump system, and gives a thermal performance analysis by combining the two sets together for space heating. We have theoretically analyzed the heating performance of the whole system with various configurations in order to get a maximum heat output. It is believed that these results could be helpful for extending the uses of DHEs in places where have not a high geothermal gradient.

1. INTRODUCTION

Downhole Heat Exchangers (DHEs) are different from the Borehole Heat Exchangers (BHEs) in their heat transfer mode underground. DHEs are usually installed vertically in a high permeable geothermal aquifer that natural convection will be the dominate heat transfer mode, while BHEs are often installed in low permeable soil that heat transfer rate depends mainly on heat conduction. It is known that convection is more effective in heat transfer than conduction. The heat output for a single DHE unit (approximately 100m in depth) could be in an order of hundred kilowatts, while a BHE only of several kilowatts.

Since they both are close-looped heat exchangers that there is no mass transfer to or from underground, there will be no water level drawdown or pressure disturbance of aquifers, and no pollution problems at the surface. However, DHEs in the previous application are only limited in a shallow geothermal well with high temperature gradient because the outlet temperature from the DHEs should be suitable for a heating duty, for example, higher than 50℃. This usually requires that the shallow reservoir temperature be much higher. So far, there are many successful installations using DHE for spacing heating world wide (Lund, 1999, Culver, 1999, and Chiasson, 2005). However, because of the site limitation of shallow geothermal resources, DHE projects for space heating can only be found in a few countries, such as New Zealand, U.S., Turkey, Japan.

This paper proposes an improved scheme by combining heat pumps with a DHE unit, which could extend the utilization of DHEs in areas having intermediate- or low-temperature shallow aquifers. The main idea is by decreasing the inlet temperature of circulating water through the DHE. Figure 1 shows the sketch of a novel DHE application system. The return water from the heat user flows through the evaporator and its temperature is further decreased. As we known that the temperature difference between DHE and its surrounding aquifer determines the magnitude of driving force (buoyancy) of natural convection. Generally, the intensity of natural convection in porous media can be evaluated by using a dimensionless parameter Rayleigh number, *Ra*, which can be defined by

$$Ra = \frac{\beta g(T_\infty - \bar{T}_{DHE})H^3}{\nu_f a_m} \text{ or } \frac{\kappa\beta g(T_\infty - \bar{T}_{DHE})H}{\nu_f a_m} \quad (1)$$

where H is the aquifer thickness, β is the volumetric thermal expansion coefficient, κ is the aquifer permeability, ν_f and a_m are the kinematic viscosity of water and thermal diffusivity of matrix, respectively.

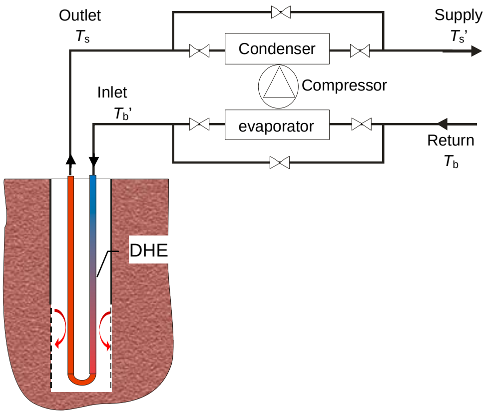

Figure 1: a novel scheme of a DHE unit combined with a heat pump for space heating.

Therefore, the proposed scheme has some merits over a traditional DHE set without heat pumps. First, the intensity of natural convection happened in aquifers could be increased as discussed above that the total heat gain could be increased. Second, the supply temperature to the heat user can be increased so that the size of the terminal radiator can be reduced. The disadvantage is the additional investment of a heat pump system, and possibly a low COPh for the heat pump system.

In order to compare the thermal performances of two DHE space heating systems with and without an auxiliary heat pump, we perform a theoretical analysis in this paper. Some conclusions are summarized and discussed.

2. DHE SPACE HEATING MODEL

The DHE space heating system is much different from those of burning fossil fuel. The supply temperature of hot water to heat users is mainly determined by the heat transfer performance of DHE. The total heat transfer coefficient of DHE depends largely on the outside film heat transfer coefficient since the thermal resistance of outside is much higher than that of inside the U-shaped tubes. Therefore, it is necessary to construct a model to perform a theoretical analysis for predicting or calculating the heat output of a DHE heating system. The model illustrated in Fig. 1 is based on the following assumptions: (1) the pipe heat loss upstream and downstream of the radiator is ignored; (2) the radiated heat from the sun to the building and any other heat sources inside the building are ignored; (3) the space heating system is thermostatic, i.e. the indoor temperature lag resulting from the heat storage effect of the building is not considered. Therefore, the energy conservation equations or the total heat transfer rate through different thermal boundaries can be given, which are:

(a) The heat loss from the building to the atmosphere , Q_1, can be calculated by:

$$Q_1 = C_q A_t (T_r - T_a) \tag{2}$$

Where A_t is the total heated floor area, T_r and T_a are the indoor and outdoor temperatures, respectively. C_q is a specific heating load per floor area and per temperature difference for a building, which can reflect the perfectiveness of thermal insulation of the building. It is noticed that the thermal resistance inside the radiator is much smaller compared with that of outside, and is ignored in this model.

(b) The heat transferred from the terminal radiators to the air in rooms, Q_2, is given by:

$$Q_2 = \alpha A_2 \left(\frac{T_s^{'} + T_b}{2} - T_r \right)^{1+\gamma} \tag{3}$$

Where α, γ are two empirical constants depending on the type of radiators. A_2 is total heat transfer area of radiators.

(c) The heat loss of circulating water though the radiators can also be calculated by

$$Q_3 = GC_p (T_s^{'} - T_b) \tag{4}$$

(d) The heat extracted at DHE side underground can be written as

$$Q_4 = A_1 K \left(T_\infty - \frac{T_s + T_b^{'}}{2} \right) = A_1 K \Delta T \tag{5}$$

Where K is the total heat transfer coefficient of DHE, and A_1 is the effective heat transfer area of DHE, ΔT is the mean temperature difference between the fluid far from the DHE in the aquifer and the averaged temperature of inlet and outlet temperatures of DHE. The outside heat transfer coefficient of DHE was calculated by using a correlation function obtained in our laboratory (Chen Y, 2009).

It is also noticed that $Q_1 = Q_2 = Q_3 = Q_4 + P$, in which P is the electric power input for the heat pump. Therefore, we have five unknowns (Q_1, $T_s^{'}$, $T_b^{'}$, T_s, T_b) but only four equations (2)-(5). An additional equation is needed to make these equations complete. Here an empirical correlation of COP_h for a heat pump proposed by Harrison et al. (1990) is added, which is

$$COP_h = 10.376 - 0.24(T_s^{'} - T_b^{'}) + 0.00187(T_s^{'} - T_b^{'})^2 \tag{6}$$

After some arrangement, a final equation can be derived, which includes only Q ($=Q_1$), and is written as,

$$Q = \alpha A_2 \left(T_\infty - \frac{Q}{A_1 K} - \frac{Q}{C_q A_t} - T_a + \frac{P}{A_1 K} + \frac{COP_h P}{GC_p} - \frac{P}{2GC_p} \right)^{1+\gamma} \tag{7}$$

It is more convenient to solve the nonlinear equation above numerically because it is difficult to get an analytical solution.

3. INPUT PARAMETERS AND CALCULATION PROCEDURE

The given parameters are listed in Table 1, which includes the parameters of a geothermal reservoir, terminal heat radiators, the building to be heated, and a heat pump. In order to decrease the temperature requirement of geothermal reservoirs, we select the reservoir temperature to be 65℃, and a heat pump having a electric input power of 6.0 kW.

The Newton's iteration method was used in solving equation (7). However, it is noticed that COP_h and K are functions of unknown temperatures ($T_s^{'}$, $T_b^{'}$) and ($T_s^{'}$, T_b), respectively. Therefore, firstly COP_h and K are also given by guess values. The calculation scheme is as follows

(1) given guess values COP_h, K;
(2) find a Q according to equation (7);
(3) calculate $T_s^{'}$, $T_b^{'}$, T_s, T_b;
(4) calculate new COP_h and K;
(5) go to step (1) to find a new Q
repeat steps (2)-(5) until a certain accuracy.

4. RESULTS AND DISCUSSIONS

4.1 DHEs without Heat Pumps

The previous DHEs were mostly installed in shallow geothermal aquifers with a temperature higher than, say 90℃ (Lund, 1999), so that DHEs alone can stand for a moderate heating duty. Figure 2 shows the supply temperature, T_s, the return temperature, T_b, the room temperature, T_r, and the supplied heat Q, at a constant flowrate of circulating water, G = 2.0kg/s, and an outdoor temperature of T_a = -10℃. The results can be obtained easily by putting P = 0 in eq. (7). It shows that the maximum DHE exiting temperature T_s, is less than 48℃, and total supplied heat does not increase much with the size of radiator, A_2. This is because that the supply temperature is relatively too low for this type of terminal radiator.

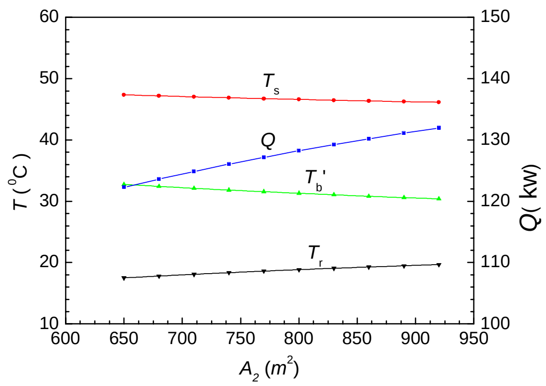

Figure 2: DHE performance without a heat pump for space heating.

4.2 DHEs with Heat Pumps

If an auxiliary heat pump is installed in the system, the supply temperature, T_s, can be increased significantly, so that the supplied heat Q, can also be increased due to an increase of temperature drop in equation (3). Except of the size of radiators, the other given parameters are the same as in the case without heat pumps. It is shown as in figure 3 that the size of radiators can be reduced approximately to a half without lowering the room temperature. For a same size of terminal radiator, say A_2 = 800 m^2, the total heating loads are 128.2 kW, and 142.7 kW for the systems without and with a heat pump, respectively. Therefore, the supplied heat difference between these two cases (14.5 kW) is about 2.4 times of the electric input power (6.0kW), which means about 8.4 kW additional heat is extracted from the aquifers by adding the heat pump.

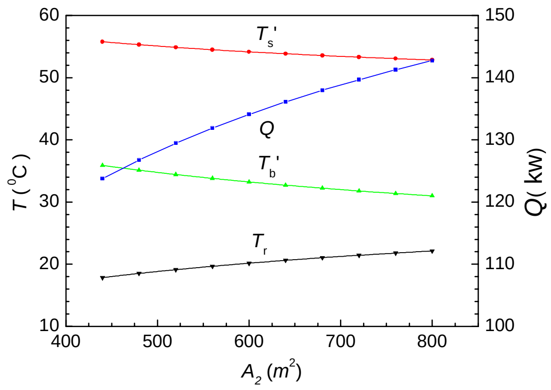

Figure 3: DHE performance with a heat pump for space heating.

4.3 Optimum Design of a DHE Space Heating System

For a specific DHE system, there exists a most economically or technically optimum heating capacity. So far, it is still difficult to realize an optimum design of a DHE space heating system because the heat transfer mechanism of DHE in aquifers is not well understood. But, there is no doubt that at the optimum running condition the heat transfer rate at the terminal heat radiator side should be in good matching the capability of the DHE extracting heat subsurface.

As shown in Figs 2 and 3, the DHE with a heat pump can provide much more heat than that without a heat pump. The size of terminal heat radiators can be reduced so that the capital investment on this part can be saved, which indicates that the scheme having the additional expense on heat pumps somehow can get some compensate from the other part. This can result in the total price of a DHE-heat pump system to be acceptable in a real application.

In order to compare the thermal performance for the two DHE space heating systems at running, we have to determine the size of terminal radiator, A_2. A_2 are given by 700 m^2 and 480 m^2 for the DHE without and with a heat pump, respectively. It is shown in figures 4 and 5 that the supplied heat Q changes with the circulating water flow rate G. The supplied heat Q was obtained by solving equation (7) at various G, in which A_2 is a known value. It can be seen that for the both cases the supplied heat increases with increasing the circulating water flowrate, but not so sensitive with the flowrate change. The supplied heat increment by increasing flowrate is less for the case with a heat pump than that without a heat pump, which means that the adjustment of running conditions corresponding to the change of outdoor temperature by changing flowrate is limited. An effective way in adjustment is on the heat pump, for example, by using variable frequency heat pumps, multi-module heat pumps, etc..

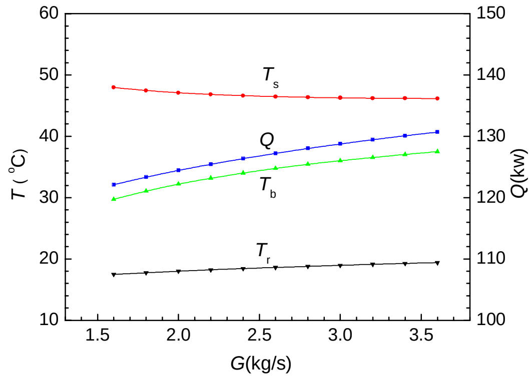

Figure 4: Supplied heat and temperatures versus circulating water flowrate for the case without a heat pump.

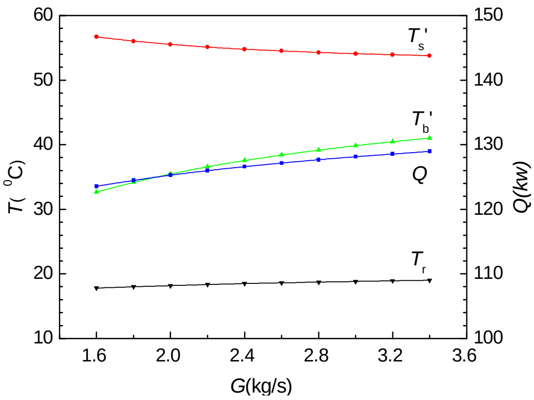

Figure 5: Supplied heat and temperatures versus circulating water flowrate for the case with a heat pump.

5. CONCLUSIONS

This paper performed a thermal analysis for a novel space heating scheme using DHEs and heat pumps. This scheme is quite different from the convectional way in the application of heat pumps because it has only one fluid stream flowing through both evaporator and condenser. It is a bad idea or even not workable for a convectional heat pump system, however, it could be feasible for a DHE space heating system according to the analysis of the paper. Using the parameters given in this paper, the combination of DHEs with heat pumps can supply more heat to the users; and the COPh could be over 2.5. It is considered that the heat transfer performance of DHEs is the major factor on selecting the novel scheme of space heating.

ACKNOWLEDGEMENT

The work was supported by the Ministry of Science and Technology of China through the national 863 key project fund under contract 2007AA05Z462.

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Table 1: Parameters Used in the Calculation of DHE and Heat Pump Space Heating System

Parameter	**Value**	**Unit**
DHE heat transfer area, A_1	18.84	m^2
Aquifer temperature, T_∞	65	℃
Floor area, A_t	2000	m^2
Specific heat load of building, C_q	2.22	(℃m^2)$^{-1}$
Power input of heat pump, P	6.0	kW
Design outdoor temperature, T_a	-10	℃
Design water flowrate, G	2.0	kg/s
Empirical constants of radiator α, γ	2.35, 0.35	-