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# Optimal Design and Operation of a Geothermal District Heating System Using Deep Downhole Heat Exchanger Coupled with Heat Pump

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## ABSTRACT

In this paper, a method for arriving at an optimum design and operation of a geothermal district heating system equipped with deep downhole heat exchanger and heap pump was introduced. A theoretical heat transfer model at steady state was proposed by ignoring the heat loss of transmission pipeline and the heat storage effect of installed facilities and buildings. It shows that there is an optimum ratio of hot geothermal water flowrate to the cold circulating water flowrate through PHE or the evaporator of heat pump. In addition, based on the heat balance equations, and the given costs of PHE, terminal radiator and heat pump, the installation of those main facilities with a minimum capital investment can be obtained.

**Keywords:** geothermal district heating, deep downhole heat exchanger, heat pump, optimal design, optimal operation

## NONMENCLATURE

| | |
|---|---|
| *Abbreviations* | |
| COP | Coefficient of performance |
| DBHE | Deep borehole heat exchanger |
| DDHE | Deep downhole heat exchanger |
| HP | Heat pump |
| PHE | Plate heat exchanger |
| *Symbols* | |
| $G_c$ | Circulating water flowrate through condenser |
| $G_h$ | Geothermal water flowrate |
| $G_m$ | Circulating water flowrate through evaporator |
| $N_p$ | Number of Plates of PHE |
| Q | Heat load |
| W | Heat pump input power |

## 1. INTRODUCTION

In recent years, geothermal resources have been exploited for space heating in many counties (Lund, 2020), for example, by using shallow borehole heat exchangers, deep doublet well systems with production and reinjection wells, etc.. However, due to some difficulties that might be encountered in fully reinjection, particularly for the well drilled in a sandstone aquifer, the deep downhole (or borehole) heat exchanger has become a promising alternative. The related studies have been increasing in recent years. It is noticed that comparing with the geothermal heating system of a doublet system, the system using deep borehole heat exchangers has a low heat output and supply temperature. Therefore, the auxiliary equipment of heat pump has to be installed in general. Recently, an in-situ test of deep open looped coaxial heat exchanger shows that such a system can deliver a much higher heat output comparing with DBHEs (Dai et al, 2019). Nevertheless, the outlet temperature of geofluid from the well is still too low to be directly supplied to the building, and a heat pump has to be coupled with. Therefore, that how to determine the sizes of heat pump, terminal radiator, and corresponding PHE in such a system is raised. The objective of this paper is to propose a theoretical model for reaching a reasonable design of such a district heating system. In order to find an optimal design, the characteristics of heat supply from a deep open looped downhole heat exchanger to the building has to be analyzed, for example, how the heat output changes with the flowrates of geofluid, circulating water through evaporator and/or condenser of heat pump etc.

## 2. THE SETUP OF DISTRICT HEATING SYSTEM

### 2.1 Heat balance equations and solution method

A simple geothermal district heating system with both HP and DDHE is shown as in Fig. 1. In this paper, the minimum design ambient temperature is given by -9°C. When the ambient temperature gets higher, the flowrate of geofluid can be correspondingly decreased in order to keep the indoor temperature not too high over the lowest limit, i.e. 18 °C.

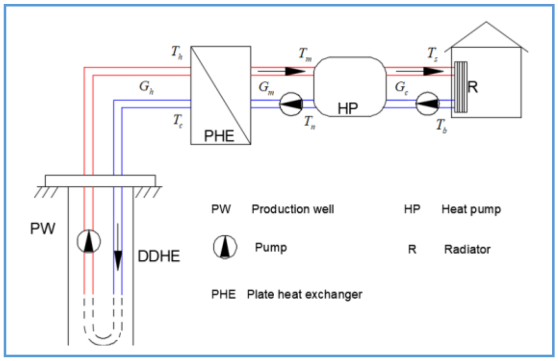


*Fig. 1 The geothermal district heating system coupled with HP and DDHE*

In order to perform a theoretical analysis for the district heating system as shown in Fig. 1, the following assumptions were made:

(1) The characteristic of heat extraction of DDHE is known in advance, i.e., the correlation of heat output with the inlet temperature and flowrate of circulating geofluid through the DDHE is given.

(2) Take no account of heat peak loading auxiliaries, such as boiler or other heat supply sources.

(3) Ignore the heat losses through PHE, HP and pipeline to environment.

(4) Ignore the radiant heat of the sun and other heat sources in the building.

(5) Indoor temperature lag caused by building heat storage is not taken into account.

There are seven heat transfer processes that can be divided: (1) heat source of DDHE, $Q_1$, (2) the released heat of geofluid, $Q_2$, (3) the heat exchanged at PHE, $Q_3$ (4) the absorbed heat of the clean circulating water at PHE or the supplied heat to the evaporator of heat pump, $Q_4$ (5) the negative thermodynamic cycle of heat pump, (6) the released heat of clean circulating water through the condenser of heat pump, $Q_5$ or the heat emitted to the house from the terminal radiator, $Q_6$ and (7) the heat transferred from the building to the outdoor circumstances, $Q_7$. According to the above assumptions, the first three heat transfer rates should be equal under steady operation of the geothermal system, and the last four heat transfer rates should be equal, which are increased by the input electric power of the heat pump.

Different from the thermal analysis conducted by Dai and Liang (1999), two empirical formulas of DDHE and COP of heat pump were added in the present paper. While the COP of heat pump is introduced, the heat transfer rate at the heat pump can be written by：

$$Q_5 = COP \cdot W \tag{1}$$

Where COP is the coefficient of performance related to the two averaged temperatures of circulating water on both sides of evaporator and condenser. The specific fitting expression from a test is given by:

$$COP = 9.376 - 0.24\theta + 1.87 \times 10^{-3}\theta^2 \tag{2}$$

$\theta$ is the temperature difference between the average temperatures of circulating water through condenser and evaporator of heat pump, i.e.

$$\theta = \frac{T_s + T_b}{2} - \frac{T_m + T_n}{2} \tag{3}$$

The above seven heat transfer processes constitute the main bases for the theoretical analysis to find the best operation parameters, and the most economical investment mode under the condition of required demand of building heating. From the above analysis, it can be seen that:

$$Q_1 = Q_2 = Q_3 = Q_4 \tag{4}$$

$$Q_4 + W = Q_5 \tag{5}$$

$$Q_5 = Q_6 = Q_7 \tag{6}$$

Through the above analysis, we can obtain the upstream and downstream fluid temperatures through PHE, HP and terminal radiator. The derived temperature equations at each section shown in FIG. 1 can be given by,

$$T_m = T_h - \frac{Q_2}{C_p(S-1)}\left(\frac{S}{G_h} - \frac{1}{G_m}\right) + \frac{Q_2}{C_p G_m} \tag{7}$$

$$T_n = T_h - \frac{Q_2}{C_p(S-1)}\left(\frac{S}{G_h} - \frac{1}{G_m}\right) \tag{8}$$

$$T_s = T_a + \left(\frac{Q_6}{A_r \alpha}\right)^{\frac{1}{1+\beta}} + \frac{Q_6}{C_q V} + \frac{Q_6}{2C_p G_c} \tag{9}$$

$$T_b = T_a + \left(\frac{Q_6}{A_r \alpha}\right)^{\frac{1}{1+\beta}} + \frac{Q_6}{C_q V} - \frac{Q_6}{2C_p G_c} \tag{10}$$

$$T_r = \frac{Q_6}{C_q V} + T_a \tag{11}$$

$$T_c = T_h - \frac{Q_2}{C_p G_h} \tag{12}$$

The six temperatures ($T_m$, $T_n$, $T_s$, $T_b$, $T_r$ and $T_c$) together with the heat output of $Q_3$ or $Q_4$ can be obtained using the closed set of seven equations (Eq. (2), and Eqs. (7)-(12)). Since it is still difficult to solve the transcendental equation, Newton's method was adopted for finding the root of heat output of $Q_4$. The derived iteration formula is given as follows,

$$Q_{n+1} = Q_n - \frac{Q_n - (8.376 + 0.24\theta - 0.00187\theta^2)W}{1 - W(0.24 + 0.00374\theta)\dfrac{\partial\theta}{\partial Q_n}} \tag{13}$$

in which $\frac{\partial\theta}{\partial Q_n}$ can be written as:

$$\frac{\partial\theta}{\partial Q_n} = \frac{1}{C_q V} + \frac{1}{(1+\beta)}\left(\frac{Q_{n+1}}{A+\alpha}\right)^{-\frac{\beta}{1+\beta}} + \frac{\dfrac{S}{G_h} - \dfrac{1}{G_c}}{C_p(S-1)} - \frac{1}{2G_m C_p} \tag{14}$$

According to the above theoretical analysis, an optimal operation mode can be calculated while the sizes of PHE, HP and terminal radiator were given. The vice versa, an optimal design (selection the sizes of PHE, HP and terminal radiator) can be carried out for a given heating duty. Some parameters used in the analysis are given in Table 1:

*Table 1: Parameters used in the thermal analysis*

| | |
|---|---|
| Geothermal water flow | 50t/h |
| Plate Heat Exchanger | Arrangement、one pass counter current, Effective heat area per plate: 0.8 m$^2$<br>plate spacing: 3 mm, Plate thickness: 0.5 mm, effective width of plate: 0.3m, Material of Plate: Stainless steel<br>Thermal conductivity of plate:16.28 W/(m·°C), Fouling thermal resistance:0.00017 (m·°C)/W |
| Heat Pump | 180 kW |
| Terminal Radiator | Cast iron, Effective heat transfer area: 6500 m$^3$ |
| Building | 31000 m$^3$ |

## *2.2 Optimal operation parameters*

Eqs.(7) to (13) can be solved at given heat transfer areas of plate heat exchanger, $A$, terminal radiator, $A_r$, heat pump input power and the flow rates of geothermal side, $G_h$, and circulating water, $G_C$, $G_m$. The outlet temperature of geothermal water, $T_c$, and the heat output $Q$ can also be obtained at different ambient temperature $T_a$. It was found that by adjusting the circulating water flow rate, $G_c$, a maximum heat output of the whole heating system can be got. In other words, there is an optimal set of operating parameters for the geothermal indirect heat extraction and heat pump coupling heating system.

It can be seen from Fig. 2(a) that the total heat load increases with the decrease of the ambient temperature $T_a$, and the maximum heat load exists when $G_m$ is around 22.5 kg/s, that is, the flow rate $G_h/G_m$ is 0.6. A similar phenomenon has been observed in indirect geothermal heating systems without heat pump (Dai, 1997). But in this case, the optimal flow ratio is 0.60 instead of 0.83 (Dai and Liang, 1999). As shown in Figure 2(b), by changing the circulating flow rate of $G_c$, the heat load does not change too much under a fixed $G_m$, which indicates that $G_m$ plays a dominant role in the system.

## *2.3 Optimal selections of PHE and terminal radiator*

Figure 3 shows that at the case of optimal operating parameters of $G_h$, $G_m$ and $G_c$. there can be many selections for the number of plates, $N_p$, of PHE and the area of terminal radiator, $A_t$, with the limit of satisfying the room temperature over 18 ℃ (see the dashed line). For example, the pair values of ($N_p$, $A_t$) can be given by (50,6600) or (60, 6400). Therefore, the lowest capital investment can be predicted by balancing the values $N_p$ and $A_t$ with the consideration of the costs of PHE and terminal radiators. It is noticed that the cost of heat pump also influences the optimal design of PHE and the terminal radiator. Equation (13) can be used for a thermal analysis theoretically to find the optimum design of such a space heating system. It shows that while maintaining the indoor temperature $T_r$ over 18℃at the design outdoor temperature of -9 ℃ with the given parameters in Table 1, the COP of the heat pump is in a range from 3.5 to 3.8.

Figure 4 shows the initial capital investment of PHE, $C_p$, and the terminal radiator, $C_h$, at given cost of per heat transfer area, respectively, and the total of $C_t$ is $C_p$+$C_h$,.

## 3. CONCLUSIONS

In this paper, the thermal analysis of the district heating system coupled with geothermal indirect heat extraction and heat pump is carried out. The results show that there is an optimal flow ratio on the hot and cold side of plate heat exchanger with heat pump coupling. In addition, the change of flow rate at the evaporator side plays a dominant role in the total supplied heat or heating power, while the change of flow rate at the condenser side has little influence on the total supplied heat or heating power. After the input parameters are determined, the number of plates of PHE and the area of the terminal radiator inside the building can be selected optimally. There could be many design options meeting the required heat load for a specific district heating system. In order to minimize the total cost of plate heat exchanger and terminal radiator, the optimization design is carried out. The proposed analysis method can also be extended to the selection of heat pump and the overall economic feasibility study by taking into account of the electricity consumption in a lifetime period.

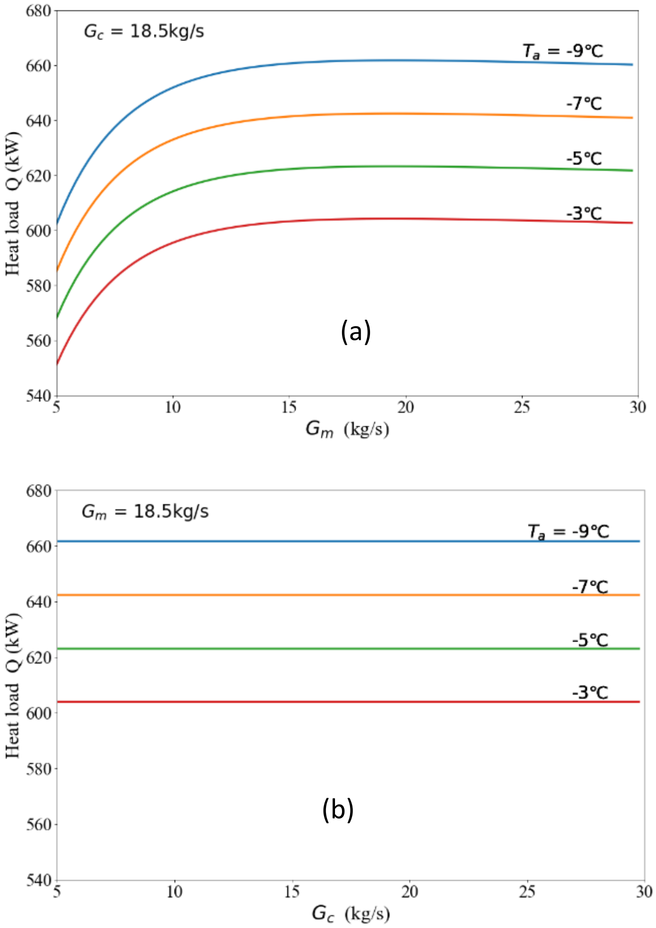
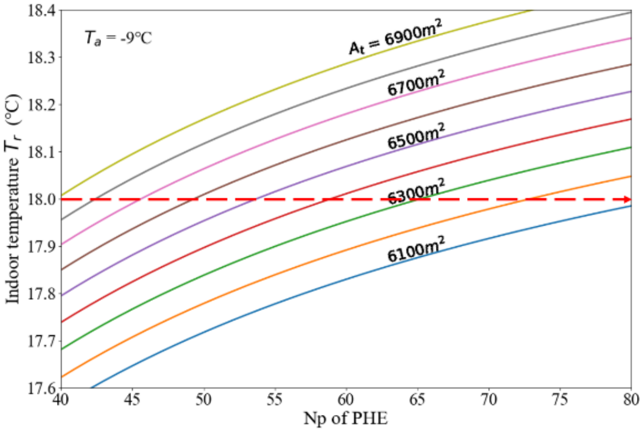


*Fig. 2 The heat load for the geothermal district heating system coupled with HP and DDHE at various circulating flowrates of $G_m$ (a) and $G_c$ (b)*



(c)

*Fig. 3 The calculated indoor temperature with various $N_p$ and $A_t$*

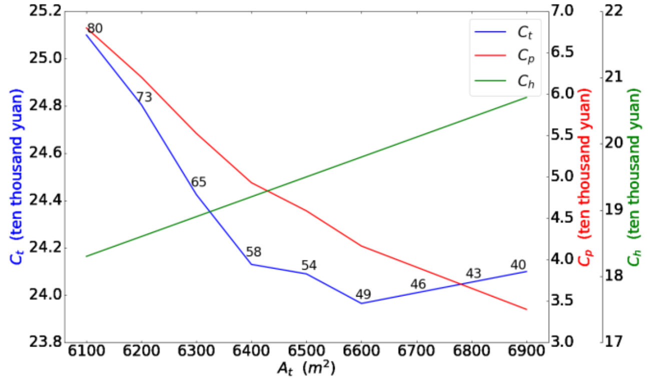


*Fig. 4 The capital investment at various $N_p$ and $A_t$*

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