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Heat Transfer Analysis of Centric Borehole Heat Exchanger with Different Backfill Materials

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ABSTRACT

Thermal performance of BHE's made of a coaxial pipe with fluid inflow into the outer pipe and coming out from the inner pipe were studied. Fluid temperature distribution was calculated, the impact of backfill materials and fluid flow rate on fluid temperature were conducted. When a mixture of capric and lauric acid were used as phase change materials (PCM) for backfilling, the temperature distribution in both solid and liquid phases was calculated for heat injection. The results show that when the backfill materials are soil or PCM respectively, the corresponding temperature difference of fluid are 0.24ºC /0.08ºC, and which decreases as mass flow increases, this is because although both flow rate and transferred heat increase over flow velocity, the flow rate increased faster than the heat, thus, the corresponding temperature difference is smaller. The results also indicate that the larger the Stefan number is, the faster the phase interface moves, and the smaller the total melting time of the PCM backfill is; When the mass flow is 180 L/h, the total melting time is 4h 02min with a Stefan number of 0.15, and the corresponding distances are 0.18 m and 0.50 m, respectively, indicating using PCM could shorten the distance between boreholes.

1.INTRODUCTION

Vertical borehole heat exchangers (BHEs) can be classified into U-pipe type, coaxial pipe type and single U-pipe type. This paper focus on the heat transfer analysis of centric borehole heat exchanger (also called pipe-in pipe) with different backfill materials. The characteristics of the centric type is that heat exchange occurs from either the upstream or downstream flow channel, an inner pipe is placed inside a larger outer pipe, forming an annular cross-section between them (Figure 1). Backfill materials or groundwater fills the space between the outer pipe and the borehole wall. The inner pipe is often thermal insulated in order to avoid thermal short circuiting between the upward and downward flow channel. Hellstor (2002) gives a thorough description of BHE design and experience during the past 30 years.

A vertical borehole may require that some kind of backfill materials, which are used to fill the space between the flow channels and the borehole wall. Laboratory tests to investigate thermal resistance and thermal conductivity of grouts have been reported by Remund and Lund (1993), Kavanaugh and Allan (1999), whereas works on reducing the space between boreholes so as to save available land area have been rather few. Considering the characteristics of air conditioning system of office building, i.e., air conditioning systems only work during daytime, this paper focus on the phase change materials (PCMs) used as backfill materials, temperature distribution, and thermal distribution radius for the different backfill materials.

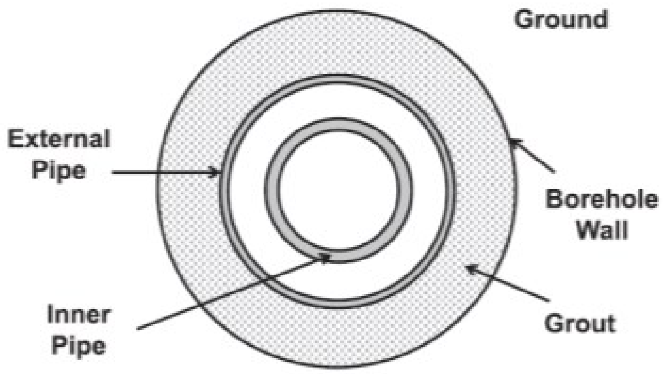

Figure1: Cross section of a centric borehole heat exchanger (Richard, Jose, and Mogensen, 2013)

$$T_{f1} = c_1 + c_2 + T_3 \tag{1}$$

$$T_{f2} = c_1\left(1 + \frac{R_1}{2}c_{pf}\rho_f r_1^3 v_1\right) + c_2\left(1 + \frac{R_1}{2}c_{pf}\rho_f r_1^2 r_2 v_1\right) + T_3 \tag{2}$$

$$\begin{cases} C_1 = \frac{(T_3 - T_{in})u_2}{u_1 e^{K_1 H} - u_2 e^{K_2 H}} \\ C_2 = \frac{(T_3 - T_{in})u_1}{u_2 e^{K_1 H} - u_1 e^{K_2 H}} \end{cases} \quad (3)$$

$$\begin{cases} u_1 = \alpha_3 r_3 - \frac{1}{2}\rho_f c_{pf} r_1^2 v_1 k_1 \\ u_2 = \alpha_3 r_3 - \frac{1}{2}\rho_f c_{pf} r_1^2 v_1 k_2 \end{cases} \quad (4)$$

$$\begin{cases} k_1 = \frac{\alpha_3 r_3}{\rho_f c_{pf} r_1^2 v_1} + \frac{1}{\rho_f c_{pf} r_1^2 v_1}\sqrt{\frac{R_t \alpha_3^2 r_3^2 + 4\alpha_3 r_3}{R_t}} \\ k_2 = \frac{\alpha_3 r_3}{\rho_f c_{pf} r_1^2 v_1} - \frac{1}{\rho_f c_{pf} r_1^2 v_1}\sqrt{\frac{R_t \alpha_3^2 r_3^2 + 4\alpha_3 r_3}{R_t}} \end{cases} \quad (5)$$

2. HEAT TRANSFER ANALYSIS OF COAXIAL BOREHOLE HEAT EXCHANGERS (CBHE)

BHEs will be in quasi-steady state after 12-20 hours operation (Smith and Perry, 1999), so heat transfer process could be analyzed by the quasi-steady state. Since the structure of the CBHE is axially symmetrical, the heat transfer process could be studied as radial one-dimensional. If the underground formation is assumed to uniformly distribute, the soil temperature is only related with the formation depth, thus, the heat transfer of CBHE could be simplified to two-dimensional radial and axial problem. Therefore, the following assumptions were made:

1) Heat transfer is in the quasi-steady state;
2) The fluid temperature and velocity are uniform at any coil section.
3) Casing wall temperature is equal to the water temperature in the same annular cavity
4) The contact thermal resistance between backfill material and outer wall of inner pipe was ignored.

The axis system is shown in Figure 2, and analytical solutions were obtained as follows (Lei, 2011).

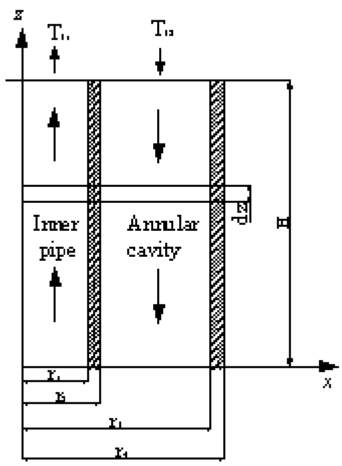

Figure 2: Flow patterns of coaxial borehole heat exchangers

Equations (1)-(3) are the analytical solutions of fluid temperature for CBHE, with fluid inflow into the outer pipe and coming out from the inner pipe.

3.0 HEAT TRANSFER ANALYSIS OF PHASE CHANGE MATERIALS

3.1 Exact Analytical Solution of Phase Change Heat Transfer

Exact analytical solution of phase change heat transfer was proposed by Neumann (1984). However, the Neumann's solution is only available for moving boundary problems in Cartesian coordinates. For phase change heat transfer in the cylindrical coordinates, Paterson (1996) indicated that the exact analytical solution could be obtained if the solution of heat conduction is taken as an exponential function in the form of Equations (1)-(3) are the analytical solutions of fluid temperature for CBHE, with fluid inflow into the outer pipe and coming out from the inner pipe.

1. HEAT TRANSFER ANALYSIS OF PHASE CHANGE MATERIALS

3.1 Exact Analytical Solution of Phase Change Heat Transfer

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Assuming a line heat sink (solidification problem) with the heat intensity of Q (W/m) being placed at liquid, the uniform liquid temperature T_i is higher than the solidification temperature. The heat source began to constantly absorbing heat from t=0, phase change materials start to solidification and the solid-liquid interface moves to the positive *r* direction. Figure 3 schematically illustrated this case.

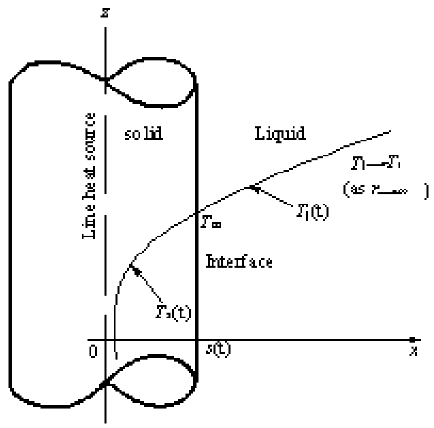

Figure 3: Solidification by a line-heat sink in an infinite medium with cylindrical symmetry

The solutions for the temperature in the solid and liquid phases are given by

$$T_s(r,t) = T_m + \frac{Q}{4\pi k_s}\left[Ei\left(-\frac{r^2}{4a_s t}\right) - Ei(-\lambda_m^2)\right] \quad 0 < r < s(t) \tag{6}$$

$$T_1(r,t) = T_i - \frac{T_i - T_m}{Ei\left(-\frac{\lambda_m^2 a_s}{a_l}\right)} Ei\left(-\frac{r^2}{4a_1 t}\right) \quad s(t) < r < \infty \tag{7}$$

The constant λ_m is determined by the following transcendental equation:

$$\frac{Q}{4\pi} e^{-\lambda_m^2} + \frac{k_s(T_m - T_i)}{Ei(-\frac{\lambda_m^2 a_l}{a_s})} e^{-\frac{\lambda_m^2 a_l}{a_s}} = \lambda_m^2 a_l \rho L \tag{8}$$

$$\lambda_m = \frac{s(t)}{2(a_s t)^{1/2}} \tag{9}$$

3.2 Parameters Nondimensionalization

The dimensionless parameters are defined herein below to obtain better comparison:

$$R = \frac{r}{r_1} \quad R_m = \frac{r_m}{r_1} \quad Ste = \frac{c_p(T_m - T_0)}{L}$$

$$Bi = \frac{hR_0}{\lambda} \quad \tau = \frac{at}{R_0^2} \quad U = \frac{T_m - T}{T_m - T_0}$$

$$W = \frac{T - T_f}{T_0 - T_f} \quad \theta_s = \frac{T_s - T_i}{T_m - T_i} \quad \theta_l = \frac{T_1 - T_i}{T_m - T_i}$$

4. THEORETICAL CALCULATIONS

Phase change materials and sandy-soil used as backfill materials for CBHE were theoretically compared, a mixture of capric and lauric acid were selected as PCM backfill material (Lei, 2011).

4.1 Fluid Temperature Distribution in CBHE

4.1.1 Effect of Backfill Materials on Fluid Temperature Distribution

Figure 4 presents the fluid temperature distribution in CBHE with the flow rate of 250 L/h, and using different backfill materials during heat injection. As shown in Figure 4, the fluid temperature was gradually reduced with fluid flows to the bottom of the CBHE, and increases slightly when the fluid flows back from the bottom. This is due to the heat exchange from downstream flow channel, resulting in fluid temperature gradually decreases and the fluid temperature reaches a minimum at the bottom of the casing. When the fluid flows back from the bottom through the inner pipe, the fluid temperature slightly increases. When the backfill materials are sandy-soil and PCMs, respectively, the corresponding temperature difference between the inner and the outer pipe are 0.24ºC and 0.08ºC.

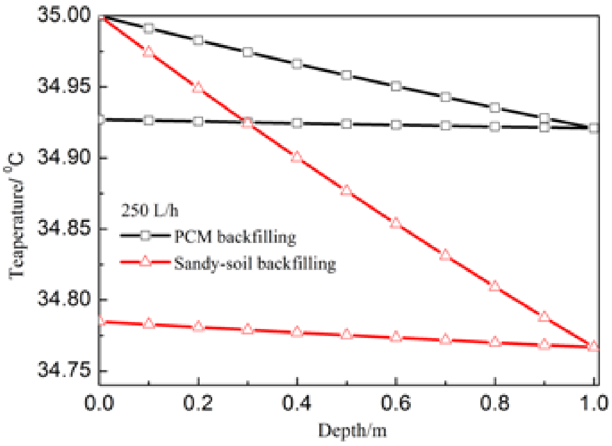

Figure 4: Fluid temperature distribution in CBHE during heat injection

4.1.2 Effect of Flow Rate on Fluid Temperature Distribution

Figure 5 compares the fluid temperature distribution in CBHE when the flow rates were 250 L/h and 180 L/h, with the backfill materials of mixed acid. It is evident that the fluid temperature decreases with the flow rate increases. This is because although both flow rate and transferred heat increase over fluid velocity, the flow rate increased faster than the heat, thus, the corresponding temperature difference is smaller.

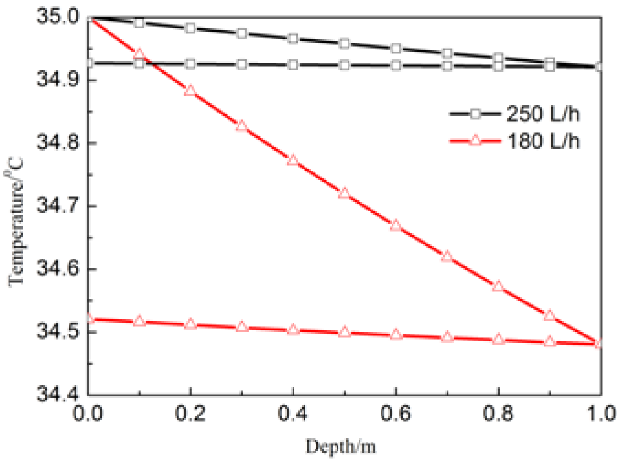

Figure 5: Fluid Temperature Distribution in CBHE during Heat Injection

4.2 Temperature Distribution in Backfill Materials during Heat Injection

The phase change of PCM backfill materials is a melting process during heat injection in summer time. Temperature distribution of the melting process was calculated based on Eq. (4) to (6). Table 1 describes the parameters of mixed acid during heat injection, and Table 2 shows the melting constant λ for different Stefan number by solving the transcendental Eq. (6).

Table 1: Constant parameters

parameter	value	parameter	value
λ_s (W/(m·K))	0.207	a_s (m^2/s)	1.01×10^{-7}
λ_l (W/(m·K))	0.148	a_l (m^2/s)	7.92×10^{-8}
ρ_s (kg/m^3)	962.18	C (kJ/kg·K)	2.11
ρ_l (kg/m^3)	885.82	L (kJ/kg)	138.82

Table 2: λ_m for different Stefan number

	Ste	0	0.07	0.15	0.22
λ_m	250 L/h	0.01	0.310	0.422	0.494
λ_m	180 L/h	0.01	0.337	0.398	0.491

4.2.1 Effect of *Ste* Number on Melting Time

Figure 6 indicates that solid-liquid interface moves faster with the flow rate and Stefan number. This is because the greater the flow rate is, the smaller the fluid temperature difference between inlet and outlet is, thus the larger the logarithmic mean temperature difference between the fluid and PCMs is. Thus enhancing the heat transfer and accelerating the melting process. In addition, natural convection occurs during melting, which speeds up the melting of PCM and enhancing heat transfer.

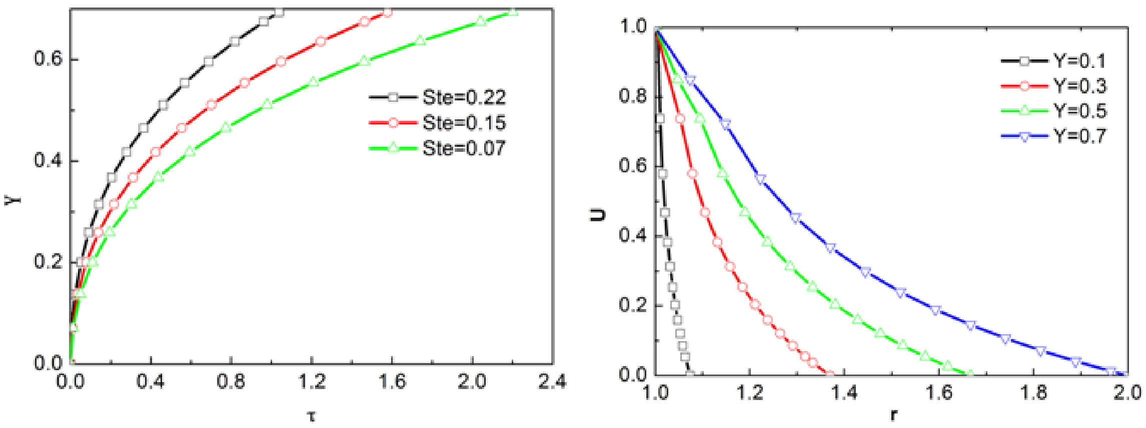

Figure 6: Effect of Ste number on melting time

As shown in Figure 7, when the fluid inlet temperature is larger than the fusion temperature, sensible heat transferred exists between the fluid and the PCMs, the PCMs near to the outer wall will gradually melt, phase interface moves to the positive *r* direction. The larger the Stefan number is, the faster the phase interface moves, the smaller the melting time is. The PCMs totally melts after 4.04 h with a Stefan number of 0.15.

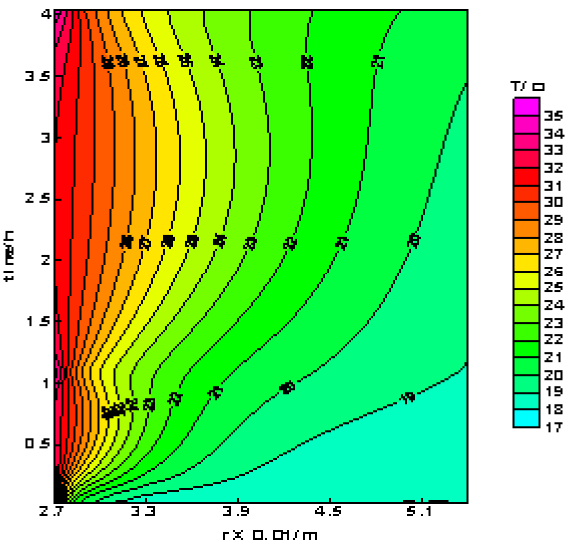

Figure 7: Temperature distribution in the phase change region during melting with a Stefan number of 0.15

4.2.2 Effect of Backfill Materials on Thermal Disturbance Distance

Figure 8 compares the thermal diffusion radius for different backfill materials during heat injection. It can be seen that thermal disturbance distance is independent of the Stefan number, but mainly concerned with the backfill materials. When the mass flow is 180 L/h, the total melting time is 4h 02min with a Stefan number of 0.15, and the corresponding distances are 0.18 m and 0.50 m, respectively, indicating using PCM could shorten the distance between boreholes.

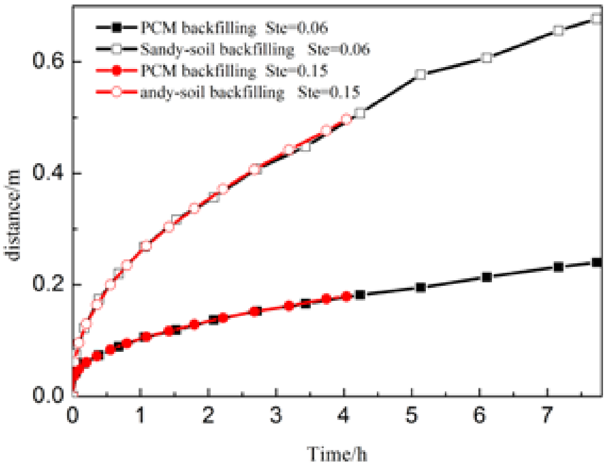

Figure 8: Comparison of thermal disturbance distance.

5.CONCLUSIONS

In this paper thermal performance of coaxial borehole heat exchangers (CBHEs) was theoretically calculated, comparative experiment was carried out for different backfill materials, the following conclusions are made:

1) When sandy-soil and PCMs (a mixture of capric and lauric acid) were respectively used for backfilling, the corresponding temperature difference of fluid are 0.24ºC /0.08ºC, with a Stefan number of 0.15;

2) The larger the Stefan number is, the faster the phase interface moves, and the smaller the total melting time of the PCM backfill is;

3) When the mass flow is 180 L/h, the total melting time is 4h 02min with a Stefan number of 0.15, and the corresponding distances are 0.18 m and 0.50 m, respectively;

ACKNOWLEDGMENT

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NOMENCLATURE

Q	heat intensity, W/m
Ei	exponential integral function
Ste	Stefan number
c_{pf}	specific heat of fluid, kJ/(kg•K)
L	latent heat, kJ/kg
Bi	Biot number
h	convective heat transfer coefficient, W/(m2•K)
t	time, s
a	thermal diffusivity, m2/s
a_s	thermal diffusivity of solid phase, m2/s
a_l	thermal diffusivity of liquid phase, m2/s
λ	soil heat conductivity, W/(m.K)
λ_m	solidification (melting) constant
c_1, c_2	coefficient, defined in equation (3).
u_1, u_2	coefficient, defined in equation (4)
k_1,k_2	coefficient, defined in equation (5)
α_3	convective heat transfer coefficient between the fluid and the inner wall of the outer pipe, W/(m2•K) ;

r_1 internal diameter of centric inner pipe, m

r_2 external diameter of centric inner pipe, m

r_3 internal diameter of centric outer pipe, m

v_1 fluid velocity in inner pipe, m/s

ρ density, kg/m3

ρ_f fluid density, kg/m3

H length of concentric pipe, m

R_t thermal resistance of the centric pipes, K/W

T_m phase-transition temperature, K

T_o ambient temperature, K

T_f fluid temperature, K

T_{f1} fluid inlet temperature, K

T_{f2} fluid outlet temperature, K

T_s temperature of solid phase, K

T_l temperature of liquid phase, K

T_3 inner wall temperature of outer pipe, K

T_{in} initial temperature, K

R dimensionless distance

R_m dimensionless solid-liquid interface location

τ dimensionless time

U dimensionless temperature based on fusion temperature

W dimensionless temperature based on fluid temperature

θ_s, θ_w dimensionless temperature of solid and liquid phase, respectively

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