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Development of an efficient numerical model and analysis of heat transfer performance for borehole heat exchanger

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ABSTRACT

Knowledge of borehole heat exchanger efficiency is necessary to optimize the design and performance of ground source heat pump systems. To evaluate the heat transfer performance of the wildly-used vertical U-pipe BHE, a novel one-dimensional numerical model was developed to assess the thermal transfer performance of the BHE from short-term (thermal response test) to long-term (a heating period) for engineering application. The proposed numerical model took into account the internal capacity of the borehole and the thermal resistance between the two legs of U-pipe which are often negligible in traditional one-dimensional numerical models. A thermal response test data from a case at Vorbasse, Denmark and the data from the TRNSYS model were used to validate the feasibility and reliability of the presented model. Then, both a short-term thermal response and a long-term temperature development of the fluid in BHE and surrounding ground were simulated and analyzed based on the model. Additionally, this study did a sensitivity analysis to see what effect the parameters have on the BHE efficiency. Hereby the impact of given assumptions can be able to estimate and the results can serve for the optimum design and control of GSHP systems.

1. Introduction

Buildings account for approximately 40% of total energy use and 36% of carbon dioxide emissions in the Europe Union, as similarly do the rest of the world [1]. Specifically, about 54% of the total energy consumption of a building is used for heating [2]. Ground source heat pump (GSHP) systems, as an energy-efficient and environment-friendly heating and cooling technology, have been increasingly popular to provide air-conditioning and domestic hot water for buildings in the last decades [3]. A GSHP system mainly consists of a conventional heat pump coupled with a borehole heat exchanger (BHE) where water or a water/antifreeze mixture absorbs heat from the ground or release heat to the ground. The efficiency of the BHE has a significant impact on the overall performance and efficiency of the GSHP system. Therefore, the performance evaluation of BHE can play an important role in realizing optimal design and good performance of GSHP systems.

To better estimate thermal transfer performance of the BHE, a number of heat transfer models have been found in the literature, which can be divided as analytical and numerical models [4].

The conventional analytical models include the infinite source model, infinite cylindrical source model and finite source model [5]. These models are robust tools still widely used today to analyze short-time thermal response results and compute the ground transient heat conduction. However, these models do not take into account the internal capacity of the borehole and thermal resistance between the two legs of U-tube, and for that are known to lack accuracy [6]. Nian and Cheng [7] contributed to an improved cylindrical source model considering the effect of borehole heat capacity mainly involves fluid, grout and pipes heat capacity. Results showed that the improved model agreed well with the experimental data compared with the conventional analytical models during short time. Madiseh et al. [8] proposed a simple one-dimension analytical model that could successfully estimate transient thermal transfer performance of the BHE in the GSHP systems and assess the thermal responses from short-term to long-term.

Neglecting the thermal resistance between the two legs of U-tube and assuming linear distribution of the fluid temperature will

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Nomenclature

BHE	borehole heat exchanger
Bi	Biot number
$c_{p,f}$	fluid specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)
$c_{p,s}$	soil specific heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)
$c'_{p,f}$	fluid volumetric specific heat ($kJ \cdot m^{-3} \cdot K^{-1}$)
D_0	outer diameter of U-shaped pipe (m)
D_{ed}	equivalent outer diameter of U-shaped pipe (m)
Fo	Fourier number
GSHP	ground source heat pump
h_i	heat transfer coefficient in the BHE ($W \cdot m^{-2} \cdot K^{-1}$)
h_{eq}	heat transfer coefficient from the fluid to the outside wall of the U-pipe ($W \cdot m^{-2} \cdot K^{-1}$)
L	borehole depth (m)
$m_{p,f}$	fluid mass flowrate ($kg \cdot s^{-1}$)
MAE	mean absolute error
MAPE	mean absolute percentage error
ME	maximum absolute error
Nu	Nusselt number
Pr	Prandtl number
Q	q heating/cooling load (W) heat transfer rate per meter ($W\ m^{-1}$)
r	radius coordinate (m)
r_i	inner radius (m)
r_o	outer radius (m)
R_0	distance from the center of borehole to the boundary in the radius coordinate (m)
R_f	film resistance ($m \cdot K \cdot W^{-1}$)
R_{pw}	wall resistance of two pipe ($m \cdot K \cdot W^{-1}$)
R_s	soil resistance ($m \cdot K \cdot W^{-1}$)
R_{sc}	total thermal resistance between the two legs of U-tube ($m \cdot K \cdot W^{-1}$)
Re	Reynolds number
RMSE	root mean squared error
TM	simulated period (s)
TRT	thermal response test
T	soil temperature (°C)
t	temperature (°C)
t_0	undisturbed underground-temperature (°C)
x_s	distance between the center of borehole and the center of the pipe (m)
α	thermal diffusivity ($m^2 \cdot s^{-1}$)
ρ	density ($kg \cdot m^{-3}$)
λ	thermal conductivity ($W \cdot m^{-1}\ K^{-1}$)
τ	time from start (s)
$\Delta\tau$	time-step (s)
b	borehole
f	fluid
g	ground
i	inner
in	inlet
j	the node of jth in the radial direction
o	outer
out	outlet
p	pipe
s	soil

result in some errors in the conventional analytical models. Therefore, Zhang et al. [9] calculated the average fluid temperature as a function of inlet and outlet fluid temperature and introduced a transient thermal resistance, and developed a model that could predict both short-term and long-term responses. Beier and Spitler [10] developed a weighting factor for the inlet and outlet fluid temperatures that could be combined with one-dimensional radial models in order to account for the variations in temperature with depth. However, these models neglect the internal capacity of the borehole, which may not be appropriate.

Some articles have presented study on the numerical models for BHEs and surrounding ground mass that are based on 1D (one-dimensional), 2D (two-dimensional), 3D (three-dimensional) finite-element or finite-volume methods [11]. Austin et al. [12] used a 2D numerical model to determine the thermal conductivity of the surrounding ground. Qian and Wang [13] proposed a 2D model to calculate the ground temperature distribution and the coefficient of performance of GSHP systems. Rees and He [14] built a 3D numerical model to represent both conduction and fluid circulation processes over both short and long timescales. These models take into account the internal capacity of the borehole and also support variations in the heat injection rate [15]. However, these numerical models are unsuitable for engineering application due to its complexity, long computational times and poor universality. Some simplified 2D and 3D models called thermal resistance capacity models were proposed based on the electrical analogy [16,17], but many thermal resistance capacity models ignore the heat capacity of the U-tube. Compared with the 2D and 3D models, 1D models, taking the advantage of short computational times and high universality, have attracted some researchers' interest [18–20]. These presented 1D models assumed that the fluid temperature linearly varies with the flow direction and not take into account the thermal resistance between the two legs of U-tube.

The objective of the present work is to develop a numerical model to assess the thermal transfer performance of the wildly-used vertical U-pipe BHE from short-term to long-term for engineering application. Therefore, a 1D numerical model for the BHE was proposed by considering the internal capacity of the borehole and the thermal resistance between the two legs of U-tube on the basis of the finite-element method. A thermal response test (TRT) data from a case at Vorbasse, Denmark and the data from the TRNSYS model were compared with the data from the proposed model to verify the reliability and feasibility of the model. Then, this model was used to evaluate both short-term and long-term heat transfer development of the BHE and surrounding ground temperature. Additionally, this study did a sensitivity analysis to see how parameters affect the efficiency of the BHE. Hereby the impact of given assumptions can be estimated and the results can serve for the optimum design and control of GSHP systems.

2. Model

2.1. Model description

Actually, the heat transfer process in a BHE is rather complicated and involves a number of uncertain factors, such as the ground thermal properties, the ground water flow and the building loads [21]. For simplification, some assumptions made in the model are listed as follows.

(1) U-pipe type heat exchanger is replaced by an equivalent single-tube heat exchanger. An equivalent diameter can be

expressed as $D_{ed} = \sqrt{n}D_0D_{ed} = \sqrt{n}D_0$, where D_0 is the outer diameter of U-shaped pipe and n is 2 for single-U pipe and 4 for double-U pipe, respectively [22,23].

(2) The heat transfer from the BHE is radial and there is no variation along the angle direction.
(3) The thermal properties of the borehole and surrounding soil are homogeneous, isotropic and independent of temperature [23–25].
(4) The undisturbed underground temperature is uniform.
(5) The thermo-migration caused by moisture migration is negligible.
(6) The heat transfer between the BHE and soil with perfect contact is of pure heat conduction and has no contact resistance [26].
(7) No heat transfer between soils in the vertical direction [27].

Fig. 1 shows the cross section of a vertical borehole heat exchanger with a single U-tube and simplified model diagram. As seen in Fig. 1, R_0 is the distance from the center of borehole to the boundary in the radius coordinate and L is the depth of borehole. On the basis of the above assumptions, the single U-pipe or double U-pipe can be considered as an equivalent pipe and the temperature distribution of the ground surround the BHE is axis-symmetric. In addition, time is one of main factors to affect the temperature distribution of the ground surrounding the BHE. Therefore, A one-dimensional equation for temperature distribution of the ground in the cylindrical coordinate can be given in Eq. (1) [28] which is the basis for simulation of the vertical BHE.

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}=\frac{1}{\alpha_s}\frac{\partial T}{\partial \tau} \tag{1}$$

where T is the soil temperature, τ is the time from start, r is the radius coordinate, α_s is the soil thermal diffusivity, which is defined as the soil thermal conductivity λ_s divided by soil density ρ_s and soil specific heat capacity $c_{p,s}C_{p,s}$.

Initial condition in the Eq. (1) is $t|_{\tau=0} = t_0$, where t_0 is the undisturbed underground-temperature.

Boundary condition in the Eq. (1) is $\frac{\partial T}{\partial r}\Big|_{r=R_0} = 0\frac{\partial T}{\partial r}|_{r=R_0} = 0$,

where R_0R_0 is the distance from the center of the borehole to the boundary in the radius coordinate, which is assuming at 10 m in this study.

Solutions to Eq. (1) are obtained by using finite-difference method to discretize time and space. Then, the unknown temperature can be solved as:

$$t_j^{n+1}=\left(1+\frac{1}{2j}\right)Fo\cdot t_{j+1}^n+(1-2Fo)t_j^n+\left(1-\frac{1}{2j}\right)Fo\cdot t_{j-1}^n \tag{2}$$

Where j is the jth node in the radial direction (j > 1), n is the nth time level, t_j^n is the soil temperature at the jth node in the radial direction and the nth time level, Fourier number $Fo = \frac{a_s\Delta\tau}{\Delta r^2}$, $\Delta\tau$ is the time step, Δr is the space step in the radial direction.

The temperature in the outside U-pipe wall can be calculated as:

$$t_1^{n+1}=2Fo\left(t_2^n+Bit_f^n\right)+(1-2FoBi-2Fo)t_1^n \tag{3}$$

where t_o is the soil temperature in the outside U-pipe wall, Biot number $Bi = \frac{h_{eq}\Delta r}{\lambda_s}$, in which h_{eq} is the equivalent heat transfer coefficient from the fluid to the outside U-pipe wall.

The initial condition is $t_1|_{\tau=0} = t_0$.

The equivalent heat transfer coefficient from the fluid to the outside wall of U-pipe can be calculated as [27]:

$$h_{eq}=C_oN_t\left[\frac{r_0}{r_ih_i}+\frac{r_0}{\lambda_p}\ln\left(\frac{r_0}{r_i}\right)\right]^{-1} \tag{4}$$

where $C_o = 0.85$ when $N_t = 2$ (single U-tube), $C_o = 0.6$ when $N_t = 4$ (double U-tube), r_i is the inner radius of the U-tube (m), r_o is the outer radius of the U-tube (m), λ_p is the pipe thermal conductivity, h_i is the heat transfer coefficient in the BHE, which is can be calculated as:

$$h_i=Nu\frac{\lambda_f}{2r_i} \tag{5}$$

where λ_f is the fluid thermal conductivity in the U-tube and Nu is the Nusselt number.

The Nusselt number Nu for turbulent flow was then found using the Dittus-Boetler relation as shown in Eq. (6).

$$Nu=0.023Re^{0.8}Pr^k \tag{6}$$

where Re is the Reynolds number, Pr is the Prandtl number of the fluid in the BHE, $k = 0.4$ for heating and $k = 0.3$ for cooling.

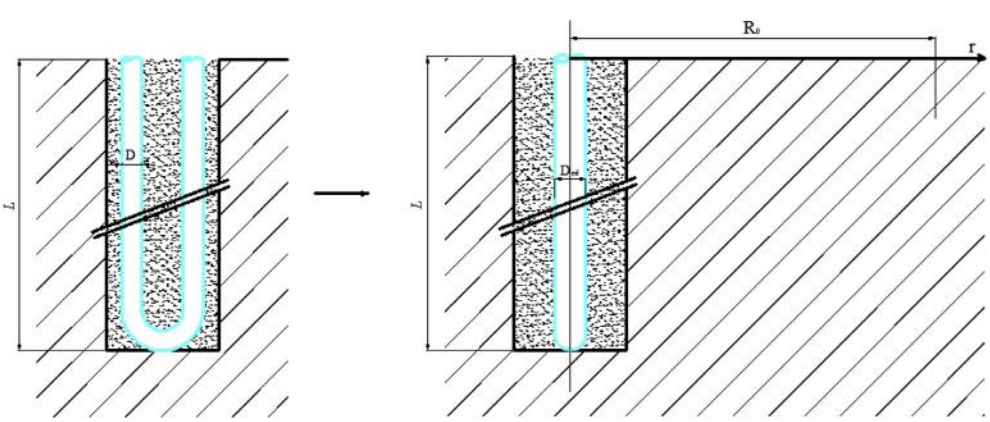

Fig. 1. Cross section of a vertical borehole heat exchanger with a single U-tube and simplified model diagram.

The heat balance equation in the equivalent U-tube can be described by:

$$\rho_f c_{p,f} \pi r_i^2 L \frac{\partial t_f}{\partial \tau} = m_{g,f} c_{p,f} \left(t_{out,f} - t_{in,f}\right) - 2\pi r_i L h_{eq} \left(t_f - t_1\right) \tag{7}$$

where ρ_f is the fluid density in the BHE, $c_{p,f}$ is the fluid specific heat, t_f is the fluid temperature, $m_{p,f}$ is the fluid mass flowrate, $t_{out,f}$ is the fluid outlet temperature in the BHE, $t_{in,f}$ is the fluid inlet temperature in the BHE, t_1 is the soil temperature in the outside U-pipe wall.

A discretized Eq. (8) is obtained as shown below.

$$t_f^{n+1} = \frac{QM}{2\pi r_i L h_{eq}} + (1-M) t_f^n + M t_1^n \tag{8}$$

where the heating or cooling load $Q = m_{g,f} c_{p,f}(t_{out,f} - t_{in,f})$, the non-dimensional parameter $M = \frac{2\pi r_i L h_{eq} \Delta\tau}{\rho_f c_{p,f} \pi r_i^2 L} = \frac{2 h_{eq} \Delta\tau}{\rho_f c_{p,f} r_i}$.

When the fluid inlet temperature $t_{in,f}$ is a known parameter and Q is a variable. Eq. (9) can be written as:

$$t_f^{n+1} = \left(1 - M + \frac{M m_{g,f} c_{p,f}}{\pi r_i L h_{eq}}\right) t_f^n + M t_1^n - \frac{M m_{g,f} c_{p,f}}{\pi r_i L h_{eq}} t_{in,f} \tag{9}$$

The temperature difference between the downward and upward leg of U-tube in borehole would inevitably lead to the thermal short-circuiting in the U-tube. ASHRAE [29] recommended a 4–6% increase in the effective thermal resistance of ground for a daily heat pulse to account for thermal short-circuiting. Beier [30] done a sensitivity analysis and obtained the errors in total thermal resistance are less than 5% requires the ratio ($m_{p,f}\ c'_{p,f}/L$ > 11 W/(m·K)) for typical in-situ tests. In this case, the ratio of 9.87 W/(m·K) is lower than 11 W/(m·K). Therefore, the thermal short-circuiting was taken in account in this study. Kavanaugh proposed a method to calculate the outlet fluid temperature of the BHE considering the thermal resistance to short-circuiting between the two legs of U-tube [31]. The correction can be used for single or double U-tubes.

$$t_{out,f} = t_f + \frac{Q}{2 m_{g,f} c_{p,f}} \left(1 - \frac{1}{m_{g,f} c_{p,f} R_{sc}}\right) \tag{10}$$

where R_{sc} is the total thermal resistance between the two legs of U-tube.

The expression of R_{sc} is as follows [32].

$$R_{sc} = 2R_f + 2R_{pw} + R_s \tag{11}$$

where the film resistance $R_f = \frac{4}{3\pi r_i h_i L}$, the wall resistance of two pipe $R_{pw} = \frac{4\ \ln(r_o/r_i)}{3\pi\lambda_p L}$, the soil resistance $R_s = \frac{\cosh^{-1}\left(\frac{x_s + 2r_o}{2r_o}\right)}{\pi\lambda_s L}$ and x_s is the distance between the center of borehole and the center of the pipe.

2.2. Iterative process of model

An iterative process of the proposed model was developed in Visual Basic. Its objective is to obtain the temperature variations in the BHE and surrounding soil. The flowchart is shown as the following (Fig. 2). In the Fig. 2, *IT* is the number of iterations, which is defined as simulated period (*TM*) divided into the time step ($\Delta\tau$) and N is the interval count of radial direction, which is defined as the distance from the center of the borehole to the boundary in the radius coordinate (R_0) divided into (Δr).

3. Result and discussion

3.1. Model validation

In order to verify the accuracy of the proposed model, it was used to evaluate the fluid temperature in the BHE and compared with the experimental data from a TRT. The TRT was conducted on-site (Grønnegade 11, 6623 Vorbasse Denmark) on a completely installed BHE from 11 November 2016 to 18 November 2016. The TRT data was used to get an understanding of the underground and obtain the important parameters to design the GSHP system. Some parameters including the undisturbed underground-temperature, the thermal conductivity of soil were applied as the input of the presented model. Table 1 shows the input parameters of the model.

The fluid temperatures based on the presented model were compared with the data from the TRT as well as the TRNSYS model to verify the reliability and feasibility of the model. Fig. 3 shows the comparison result between the experimental data and the simulated fluid temperatures by the presented and the TRNSYS model. From Fig. 3, compared with the results of the TRNSYS model, the fluid temperatures based on the TRT data and the presented model are a little different at the starting conditions. Some of this is due to the fact that some starting conditions were ignored in this simplified one-dimensional numerical model. For example, the fluid and soil temperature in the initial condition is the undisturbed underground-temperature at $\tau = 0$, which is simplified. In addition, the TRT system of the BHE is in a transient state where fluid and grout thermal capacities affect the fluid temperature during the first 10–20 h. It can partly result in the little different between the experimental and simulated data. After the first 50 h, the temperatures calculated by the presented model are approximately equal to the measured data and the presented model actually is better than that the TRNSYS model. The maximum temperature difference between the experimental data and simulated values of the proposed model is 0.85 °C which is can be accepted in the engineering application. Hence, the validation showed good agreement between the simulated value of the proposed model and experimental fluid temperatures from the borehole over a time period. Besides, root mean squared error (RMSE), maximum absolute error (ME), mean absolute error (MAE) and mean absolute percentage error (MAPE) defined by Zhang et al. [3] were used to evaluate the performance of the presented and the TRNSYS model. Table 2 shows a detailed comparison of the errors of the fluid temperatures calculated by the presented and the TRNSYS model for the in-situ test after the first 50 h. It is observed that errors of the presented model are smaller than that of the TRNSYS model, which shows an even stronger precision of the presented model.

3.2. Borehole and surrounding ground temperature variation

The model was used to calculate both the short-term and long-term temperature heat transfer development of the circulating fluid in BHE and surrounding ground. The input parameters of the model are based on the Table 1.

Fig. 4 shows the temperature variation of the circulating fluid and surrounding ground over a period of 165 h in the model. The fluid temperature rapidly increases at first 40 h, and then the fluid temperature increases slowly to 21.65 °C at 165 h. However, the surrounding ground temperature changes very little at first 10 h. The temperature of surrounding ground 0.5 m from the borehole gradually rises after 10 h and up to 13.57 °C at 165 h. The temperatures of surrounding ground 1 m or exceeding 1 m away from the borehole are almost the same as the undisturbed underground-temperature. That may be due to the minimal power draw from the surrounding compared to its capacity. The effective radius of the

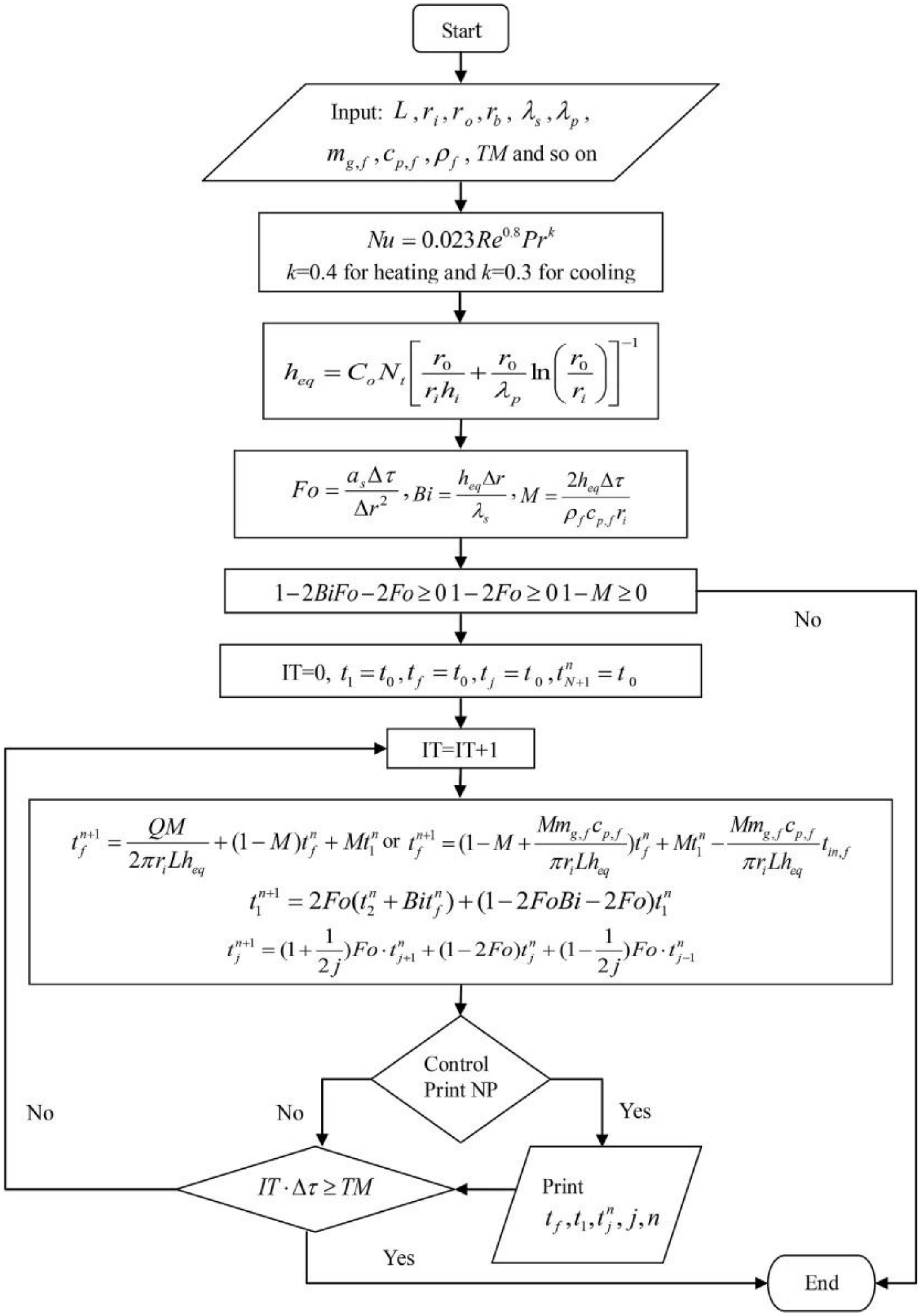

Fig. 2. Flowchart for calculating the temperature variations in the BHE and surrounding soil.

BHE is only 0.5 m in the short-term time scales.

The temperature variation of the circulating fluid and surrounding ground over a heating period in the model is given in Fig. 5. The fluid temperature increases with time and reaches 29.97 °C after a heating period. The heat of the circulating fluid in the U-tube is continuously transmitted to the surrounding ground because the temperature gradient between the fluid and the surrounding ground. The farther distance is from the borehole center, the smaller is the temperature gradient of the soil and the lower the ground temperature becomes. Due to the effect of circulating fluid temperature, the surrounding ground at the site less than 0.5 m from the borehole rise sharply with time. The temperature difference between the surrounding ground temperature and circulating fluid temperature is relatively sharp, but after

Table 1
Input parameters from test to be used in the presented model [33].

Parameter	Unit	Value
Undisturbed underground-temperature	°C	7.9
Heating power	W	4571
Borehole depth	m	96
Borehole diameter	mm	178
U-Tube Pipe	mm	32
Pipe thermal conductivity	$W \cdot m^{-1} K^{-1}$	0.42
Thermal conductivity (RAUGEO fill rot)	$W \cdot m^{-1} K^{-1}$	2.00
Thermal conductivity (soil)	$W \cdot m^{-1} K^{-1}$	2.80
Heat capacity (Water/30% IPA)	$kJ \cdot kg^{-1} K^{-1}$	3.705
Density (Water/30% IPA)	$kg \cdot m^{-3}$	935.5
Fluid flow	$L \cdot min^{-1}$	16.40

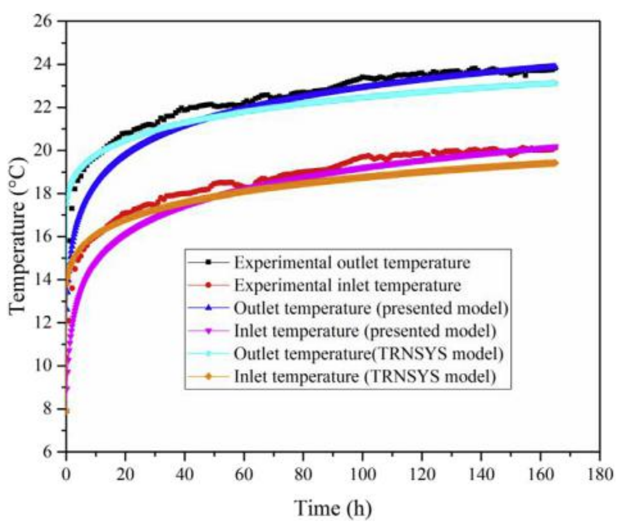

Fig. 3. Comparison between the experimental data and the simulated fluid temperatures by the presented and TRNSYS model.

about 50–100 h, the temperature differences at the site of 0.1 m, 0.3 m and 0.5 m decrease with time and keep at 4–6 °C, 7.5–9.5 °C and 9–12 °C respectively. The temperature of surrounding ground 1 m from the borehole gradually rises after about 100 h and the temperature of surrounding ground 1.5 m from the borehole gradually rises after about 220 h. The temperature of surrounding ground 2.5 m from the borehole is even the same as undisturbed underground-temperature. Therefore, the temperature of surrounding ground 2.5 m or exceeding 2.5 m from the borehole has little change even the BHE during a heating period. The finding for 2.5 m is in line with the minimum borehole spacing for the suggested 5 m value in practice [34,35].

3.3. Sensitivity analysis

In this section, a quantitative study on these sensitivity coefficients for a BHE with vertical U-pipe was done. The aim of sensitivity analysis is to see what effect different aspects

Table 2
Errors with the inlet and outlet fluid temperature simulated by the presented and the TRNSYS model.

Model	RMSE (°C)		MAE (°C)		ME (°C)		MAPE (%)	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Proposed model	0.67	0.68	0.57	0.58	0.84	0.85	3.53	2.98
TRNSYS model	0.70	0.71	0.80	0.81	1.17	1.18	4.03	3.40

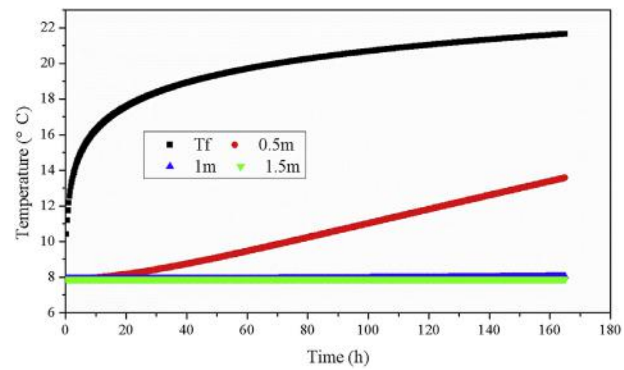

Fig. 4. Temperature variation of the circulating fluid and surrounding ground over a period of 165 h.

(parameters) have on the efficiency of the BHE. Hereby the impact of given assumptions on the performance of the system can be estimated. The heat transfer rate per meter from surrounding soil to the BHE will therefore be monitored while each parameter is varied. Based on these analyses and evaluation, some important parameters and the relationships between them can be identified.

Fig. 6 shows the variation of the heat transfer rate per meter with different parameters. Fig. 6(a) gives how the thermal conductivity of soil affects the heat transfer rate from surrounding soil to BHE, according to simulations. From Fig. 6(a), it is seen that a higher thermal conductivity results in a higher heat transfer rate per meter because that high thermal conductivity has negative effect on the heat transfer in the soil and from soil to fluid. The results suggest that there is a good logarithmic correlation between these two parameters with correlation coefficient of 0.9999. The first-order derivative of the heat transfer rate per meter with respect to the variation thermal conductivity ($\frac{19.456}{x+0.521}$) is more than 0 and decreases with the increase of thermal conductivity. It means that heat transfer rate per meter increases with the thermal conductivity temperature rising and the strength of the heat transfer rate decreases with the increased thermal conductivity. About every 0.1 $W\,m^{-1}\,K^{-1}$ increase of the soil thermal conductivity, heat transfer rate per meter increases by nearly 2.78% at low thermal conductivity and the value is nearly 1.58% at high thermal conductivity.

Fig. 6(b) shows the correlation between the heat capacity of soil and heat transfer rate per meter. It can be seen that a higher thermal capacity of soil will achieve a higher heat transfer rate per meter. The results of regression analysis suggest that there is a good linear correlation between these two parameters. However, the soil

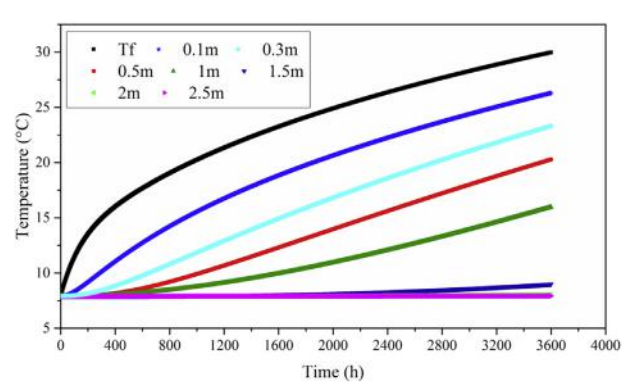

Fig. 5. Temperature variation of the circulating fluid and surrounding ground over a heating period.

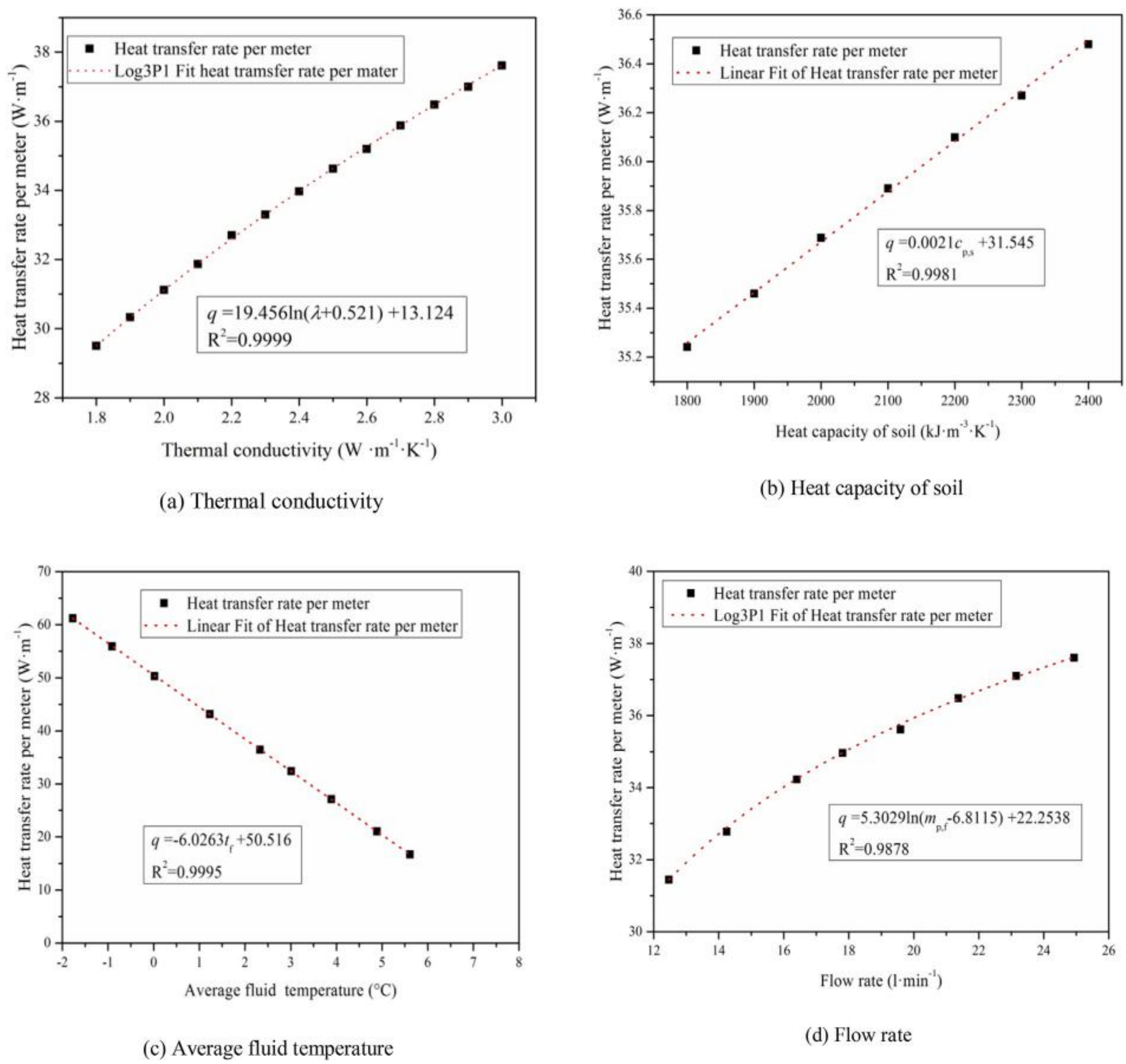

Fig. 6. Variation of the heat transfer rate per meter with different parameters.

thermal capacity has little significant impact on the heat transfer rate per meter compared with the thermal conductivity. Fig. 6(c) below shows the correlation between the average fluid temperature and the heat transfer rate per meter. According to the Fig. 6(c), the fluid temperature has a significant impact on heat transfer rate per meter. The results of regression analysis suggest that there is a good linear correlation between these two parameters. The heat transfer rate per meter rapidly decreases from 61.19 W/m to 16.71 W/m when the fluid temperature increased from −1.77 °C to 5.61 °C. Since the undisturbed underground temperature is 7.9 °C, there is nearly no heat transfer with a fluid temperature of 8 °C. Fig. 6(d) gives the correlation between the flow rate and the heat transfer rate per meter. It can be seen that a higher fluid flow rate results in a higher heat transfer rate. There is a good logarithmic correlation between these two parameters. However, the effect of increased flow rate decreases with higher flow rate. This means that it does not benefit efficiency of the BHE a great deal to increase the flow rate from 53.43 l min^{-1} (based on the regressive equation ($q = 5.3029 \cdot \ln (m_{p,f}$-6.8115)+22.2538) to higher flow rate.

The sensitivity analysis results of the heat transfer rate per meter with different parameters are presented in Table 3. Table 3 gives the variation range and average value of the heat transfer rate per meter with the increase of soil thermal conductivity (every 0.1 W m^{-1} K^{-1}), heat capacity of soil (every 100 kJ m^{-3} K^{-1}), average fluid temperature (every 1 °C) and flow rate (every 1 l min^{-1}) under given range. It is clear that the fluid temperature is more sensitive than other parameters. Every 1 °C increase of average fluid temperature can cause an average −6.03 kW m^{-1} increase of the heat transfer rate per meter. The minus value means that there is a strong negative correlation between the fluid temperature and the heat transfer rate per meter when the fluid temperature is lower than the undisturbed underground temperature. The thermal conductivity obtained from the TRT is also a very sensitive parameter. The heat transfer rate per meter increases by about 0.67 W for every 0.1 W m^{-1} K^{-1} increase in the soil thermal conductivity. Therefore, it should have to be sure to get very precise values if the engineering is made with only narrow safety margins. There are three heat flows including the heat flows in the soil, from soil to fluid and in the fluid and away in BHE and surrounding ground. All the energy flows will be affected by the fluid

Table 3
Sensitivity analysis result heat transfer rate per meter with different parameters.

Parameters	Range	Heat transfer rate per meter (kW·m^{-1})	
		Range	Average value
Thermal conductivity (W·m^{-1} K^{-1})	1.8–3.0	0.56–0.82	0.67
Heat capacity of soil (kJ·m^{-3}·K^{-1})	1800–2400	0.22–0.19	0.21
Average fluid temperature (°C)	−1.77–5.61	−6.35∼-5.70	−6.03
Flow rate (l·min^{-1})	12.41–24.97	0.32–0.71	0.49

temperature variation. Thus also the importance of the thermal conductivity in the soil as this is a limiting factor compared with the fluid temperature. Increasing the fluid flow rate will affect heat flow in the fluid and away but will have smaller effect on the heat flows in the soil and from soil to fluid. The heat flows in the soil and from soil to fluid as these only will be the result of a small increase in the temperature difference between the fluid and the soil. Thus the increase in heat transfer rate for higher flow rates, but only until heat flow in the soil or heat flow from soil to fluid becomes the limiting factor. Also the marginal change in fluid temperature due to increased flow rate will decrease with higher flow rates.

4. Conclusions

In this paper, a novel 1D numerical model associated to vertical configurations on the basis of a finite-element method was developed to simulate the heat transfer between a vertical BHE and the surrounding ground. An experimental data from a case at Vorbasse, Denmark was used to validate the feasibility and reliability of the proposed model. Then, this model was used to estimate the fluid temperature and surrounding soil temperature filed with short and long-term operation time. In addition, this study did a sensitivity analysis to see what effect the parameters have on the efficiency of the BHE. The following conclusions can be drawn:

1) There is little difference between the fluid temperatures based on the presented model and the experimental data under the starting conditions. After the first 50 h, the maximum temperature difference between the experimental and simulated values is 0.5 °C which is can be accepted in the engineering application and the reliability and feasibility of the proposed model is validated.
2) The fluid temperature rapidly increases in first 50 h and the surrounding ground temperature changes very little at first 10 h. The fluid temperature has almost no effect on the surrounding ground 1 m or exceeding 1 m away from the borehole in a TRT.
3) The long-term (about a heating period) heat transfer results show that the farther to the borehole, the longer is the ground temperature response time. The finding for 2.5 m is in line with the minimum borehole spacing for the suggested 5 m value in practice.
4) The fluid temperature is more sensitive than other parameters. Every 1 °C increase of average fluid temperature can cause an average −6.03 kW m^{-1} increase of the heat transfer rate per meter. Additionally, the thermal conductivity obtained from the TRT is also a very sensitive parameter. The heat transfer rate per meter increases by about 0.67 W for every 0.1 W m^{-1} K^{-1} increase in the soil thermal conductivity.
5) The effect of increased the fluid flow rate decreases with higher fluid flow rate and it does not benefit efficiency of the BHE a great deal to increase the fluid flow rate from a specific value (3000 kg h^{-1} in this study) to higher flow rate.

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