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Ground Heat Exchanger Modeling Developed for Energy Flows of an Incompressible Fluid

Paul Christodoulides, Georgios Florides, Panayiotis Pouloupatis, Vassilios Messaritis, and Lazaros Lazari

Abstract**—**Ground-source heat pumps achieve higher efficiencies than conventional air-source heat pumps because they exchange heat with the ground that is cooler in summer and hotter in winter than the air environment. Earth heat exchangers are essential parts of the ground-source heat pumps and the accurate prediction of their performance is of fundamental importance. This paper presents the development and validation of a numerical model through an incompressible fluid flow, for the simulation of energy and temperature changes in and around a U-tube borehole heat exchanger. The FlexPDE software is used to solve the resulting simultaneous equations that model the heat exchanger. The validated model (through a comparison with experimental data) is then used to extract conclusions on how various parameters like the U-tube diameter, the variation of the ground thermal conductivity and specific heat and the borehole filling material affect the temperature of the fluid**.**

Keywords**—**U-tube borehole, energy flow, incompressible fluid, numerical model

I. Introduction

GEOTHERMAL heat pumps use the ground to reject heat during summer operation or absorb heat in winter operation. A common means of exchanging heat is through vertical ground heat exchangers that mainly consist of a descending and an ascending leg of polyethylene pipe connected at their ends in the ground with a U-joint. A borehole with a diameter of 0.1-0.2m and a common depth of 100 m is drilled in the ground, the heat exchanger is placed in position and the borehole is filled with thermally enhanced bentonite or silica sand. The result is a good contact between the pipe and the ground and therefore a fluid, usually water, circulating in the pipes can be cooled or heated depending on its temperature relative to the adjacent ground. The classic method to model the heat exchange process is through the cylindrical heat source theory proposed by Carslaw and Jaeger [1]. The method is relatively easy to apply and was used by many researchers to model and evaluate the response of ground heat exchangers [2, 3, 4].With the introduction of the finite element method and software for easy use, a number of researchers have used basic formulae to evaluate the ground heat exchanger performance.

P. Christodoulides, G. Florides, P. Pouloupatis, V. Messaritis and L. Lazari are with the Faculty of Engineering and Technology, Cyprus University of Technology, Limassol CYPRUS (e-mail paul.christodoulides@cut.ac.cy).

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Nam and collaborators [5] developed a numerical model to predict heat exchange rates for a ground-source heat pump system. The analytical results agreed well with experimental results and the developed model was used to predict the heat exchange rate for an actual office building in Japan. Cui and collaborators [6] used a finite element numerical model for the simulation of the ground heat exchangers (GHEs) in alternative operation modes over a short time period for ground-coupled heat pump applications. The comparisons with experimental results show a reasonable agreement between the numerical and the measured data. The variation of the U-tube pipe wall temperatures demonstrates that the discontinuous operation mode and the alternative cooling/heating modes can effectively alleviate the heat buildup in the surrounding soil.

Schiavi [7] analyzed simulated thermal response test data in order to evaluate the effect of a three-dimensional model in determining the proper value of the soil thermal conductivity and borehole thermal resistance. These values are necessary for the geothermal energy storage systems' design in real conditions. For the 3D system simulation of the Thermal Response Test the finite element method implemented within the Comsol Multiphysics® environment was adopted. The analysis confirms that the Line Source Model applied to the thermal response test represents a sufficiently accurate approach in the U-tube configuration.

II. Basic Theory

For time-dependent convection-diffusion the representative equation for 3D conduction, but 1D fluid flow, is

$$\frac{\partial \varphi}{\partial t}+u\frac{\partial \varphi}{\partial x}-\frac{\partial}{\partial x}(D\frac{\partial \varphi}{\partial x})-\frac{\partial}{\partial y}(D\frac{\partial \varphi}{\partial y})-\frac{\partial}{\partial z}(D\frac{\partial \varphi}{\partial z})=S, \quad (1)$$

where D is the diffusion coefficient, u is the horizontal velocity, φ is the function under consideration, and S is the source or sink term [8]. Applying (1) for an incompressible fluid flowing in a pipe with a velocity u and with a convection heat transfer coefficient h in W m^{-2} K^{-1} (see Fig. 1), we have (for unit volume)

$$\rho c\frac{\partial T}{\partial t}-\rho cu\frac{\partial T}{\partial z}-\frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x})-\frac{\partial}{\partial y}(\lambda\frac{\partial T}{\partial y})-\frac{\partial}{\partial z}(\lambda\frac{\partial T}{\partial z})$$
$$=\frac{4h}{d_{in}}(T_p-T_f). \quad (2)$$

Here λ is the thermal conductivity of the fluid in W m^{-1} K^{-1}, ρ is the density of the fluid in Kg m^{-3}, c is the specific heat capacity of the fluid in J Kg^{-1} K^{-1} and T is the temperature, with subscripts f, p, i, o denoting fluid, pipe, inlet and outlet respectively.

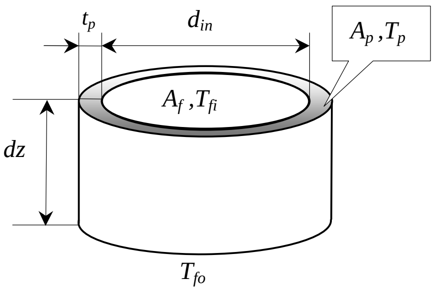

Fig. 1 Geometry of the problem

The convection heat transfer coefficient h can be estimated [9] to be $h = \frac{\lambda}{D_H} Nu$, where D_H is the hydraulic diameter (in this case the tube-inside diameter) and Nu is the Nusselt number. The Nusselt number can be expressed through the Dittus-Boelter correlation as:

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{n}, \tag{3}$$

where Pr is the Prandtl number ($\mu c/\lambda$), Re is the Reynolds number ($\rho c d_{in}/\mu$), μ is the dynamic viscosity, and n = 0.4 for heating (wall hotter than the bulk fluid) and 0.33 for cooling (wall cooler than the bulk fluid). The fluid properties necessary for the application of this equation are evaluated at the bulk temperature.

Equation (2) can be used for both the tubes of a geothermal heat exchanger with care taken on the sign of u, which in one leg is positive and in the other is negative depending on the zero point of the chosen axis system.

Applying an energy conservation equation for the pipe (per unit volume), we get:

$$\rho_p c_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}(\lambda_p \frac{\partial T}{\partial x}) - \frac{\partial}{\partial y}(\lambda_p \frac{\partial T}{\partial y}) - \frac{\partial}{\partial z}(\lambda_p \frac{\partial T}{\partial z}) = \frac{h}{t_p}(T_f - T_p). \tag{4}$$

where t_p is the thickness of the pipe.

In addition, the heat equation representing the flow in the ground (per unit volume) is given by:

$$\rho_g c_g \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}(\lambda_g \frac{\partial T}{\partial x}) - \frac{\partial}{\partial y}(\lambda_g \frac{\partial T}{\partial y}) - \frac{\partial}{\partial z}(\lambda_g \frac{\partial T}{\partial z}) = 0, \tag{5}$$

where the subscript g denotes the ground.

Finally, the power flow in the tubes, which is constant as constant is the fluid flow velocity, is defined through a constant difference between the entering and exiting fluid temperature. Note that at the bottom of the pipe (“U”-connection), the mean temperature of the fluid of the two legs of the pipe are considered to be equal.

III. Discussion of Results

First, the system of equations (2), (4) and (5) is solved by the Finite Element Method using the FlexPDE software.

To validate the results of the theoretical formulation a real case was then tested.

The main features of the tested case and the material thermal properties used are shown in Table 1.

The experimental results were obtained in a borehole 0.20 m in diameter and 100 m in depth drilled at Geroskipou, Cyprus, where a high density polyethylene (HDPE) heat exchanger with the properties specified in Table 1 was fitted. In the tubes the circulating water had a velocity of 0.5 m s^{-1} and the temperature difference between the input and output flow was measured to be 2.7 K. The water was heated with an electric element.

The recorded temperature increase of the flowing water with respect to time is shown in Fig. 2. The line source model, based on the theory describing the response of an infinite line source (explained in [2]) was used to obtain the ground thermal conductivity. Fig. 3 shows that if the mean temperature of the fluid is plotted against the natural logarithm of time, a linear relation exists. The slope of this line can be used to calculate the ground thermal conductivity. In this case it was evaluated to be 1.60 W m^{-1} K^{-1}.

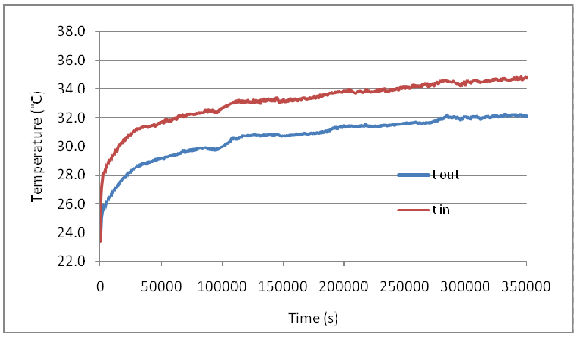

Fig. 2 Recorded heat exchanger input and output fluid temperature with respect to time

A comparison of the simulated fluid temperature to the actual recorded temperatures is indicated in Fig. 4. The results show a good correspondence of the compared temperatures.

The above-mentioned correspondence means that the results of the simulation are realistic and therefore the output of the simulation can be used for further analysis. For instance the variation of the temperature around the borehole ground (surface and bottom) after 4.7 h (17000 s) is shown in Fig. 5.

The vertical temperature profile of the fluid in the heat exchanger is shown in Fig. 6 after 9.3 hours (33500 s), when the heat flow reaches the steady part of the line. Clearly, the temperature decreases linearly from 31.3 to about 29.7°C along the descending-100-m-leg of the heat exchanger, with a further linear decrease to 28.4°C occurring along the ascending-100-m-leg.

TABLE I
INPUT VALUES USED IN THE SIMULATION

Fluid flow rate	14.7 lt m^{-1}
Fluid velocity	0.5 m s^{-1}
Fluid density	1000 kg m^{-3}
Fluid specific heat	4182 J kg^{-1} K^{-1}
Fluid thermal conductivity	0.58 W m^{-1} K^{-1}
Inlet-outlet fluid temperature difference	2.7 K
Power dissipated to ground	2750 W
Soil density	2200 kg m^{-3}
Soil specific heat	2420 J kg^{-1} K^{-1}
Soil thermal conductivity	1.45 W m^{-1} K^{-1}
Borehole diameter	0.2 m
Borehole fill thermal conductivity	1.0 W m^{-1} K^{-1}
Borehole fill density	1500 kg m^{-3}
Borehole fill specific heat	800 J kg^{-1} K^{-1}
HDPE density	950 kg m^{-3}
HDPE specific heat	1800 J kg^{-1} K^{-1}
HDPE thermal conductivity	0.51 W m^{-1} K^{-1}
Length of heat exchanger	100 m
External diameter of heat exchanger tube	0.032 m
Wall thickness of heat exchanger tube	0.0035 m
Centre distance between heat exchanger tubes	0.13 m
Scaling factor	0.01
Convection heat transfer coefficient	2145 W m^{-2} K^{-1}

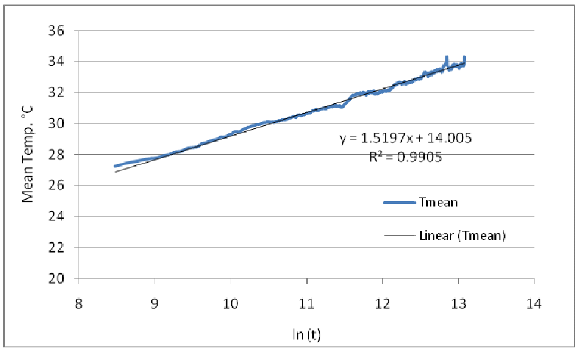

Fig. 3 Mean GHE water temperature variation in respect to the natural logarithm of heating time

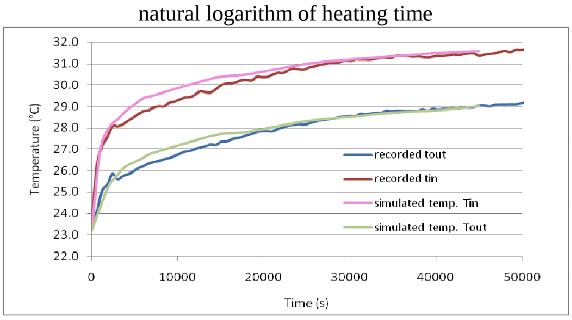

Fig. 4 Comparison of the simulated fluid temperature to the actual recorded temperatures

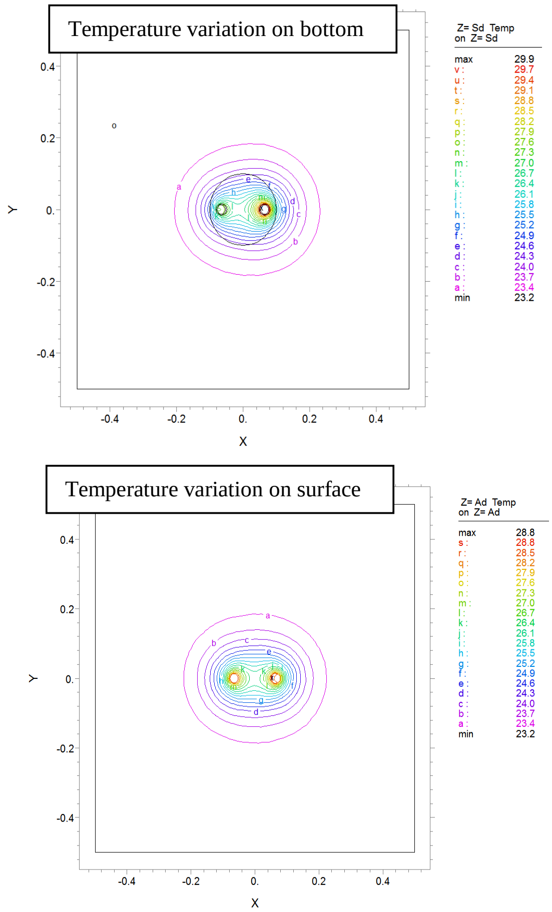

Fig. 5 Variation of the temperature around the borehole ground after 4.7 h of operation

Finally, a cross section of the soil area passing through the center of the heat-exchanger tubes is shown in Fig. 7. Here the temperature distribution in the vertical plane demonstrates how the borehole attains a higher temperature dissipating the heat to the soil, after 12.6 hours of operation. The right tube, with the higher temperature, is the input side with the left tube being the output side.

In the sequel is examined how the input and output temperature of the heat exchanger varies in relation to a series of parameters. In this case the reference soil thermal conductivity and the distance between the centers of the heat-exchanger tubes were chosen to be 1.6 W m^{-1} K^{-1} and 0.13 m respectively, with the rest of the reference parameters values as in Table I, unless specified otherwise.

The first parameter examined is the tube diameter. In this case the fluid was assumed to flow at 14.7 lt min^{-1}, for all cases, with an input power to the heat exchanger of 2750 W. This would give the same temperature difference between the input and output points of 2.7 K.

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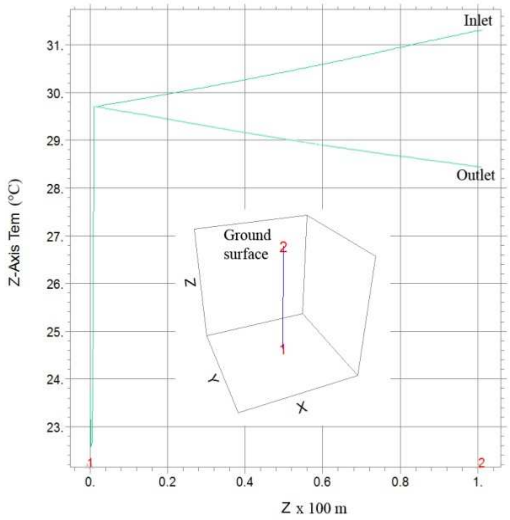

Fig. 6 Vertical temperature profile of the fluid in the heat exchanger (1-bottom, 2-surface) after 9.3 hours of operation

The 25-mm outer-pipe diameter (d_{out}) has a wall thickness (t_p) of 2.5 mm the velocity in the tubes (u) will be 0.78 m/s and the convection heat transfer coefficient (h) is 3205 W m^{-2} K^{-1}. For the 32-mm outer tube diameter the corresponding figures are t_p = 3.5 mm, u = 0.5 m s^{-1}, h = 2145 W m^{-2} K^{-1}. Finally for the 40-mm outer-tube diameter the corresponding figures are t_p = 4 mm, u = 0.305 m s^{-1} and h = 1375 W m^{-2} K^{-1}. The values of the above-mentioned parameters are shown in Table II.

In Fig.8 is shown that the smaller the pipe diameter the hotter the fluid is during the exchanging process at about 40000 s (11.1 hours) the difference between the 25-mm and the 32-mm pipe is about 0.3 K and between the 32-mm and 40-mm pipe is 0.5 K.

Soils vary in thermal conductivity depending on the geological formation in which the borehole is drilled. Thermal conductivity in Cyprus can vary between 0.4 W m^{-1} K for calcarenite to about 3.7 W m^{-1} K^{-1} for diabase. The usual values encountered in geothermal applications are between 1.3 and 2.2 W m^{-1} K^{-1}.

Fig. 9 shows a comparison between three values of soil thermal conductivities, pointing – as expected – that this soil property plays a major role toward dissipating the heat into the ground. At about 40000 s (11.1 hours) the difference between the 2.1- and 1.1-W m^{-1} K^{-1} soil thermal conductivities is about 1.1 K, which is an appreciable difference.

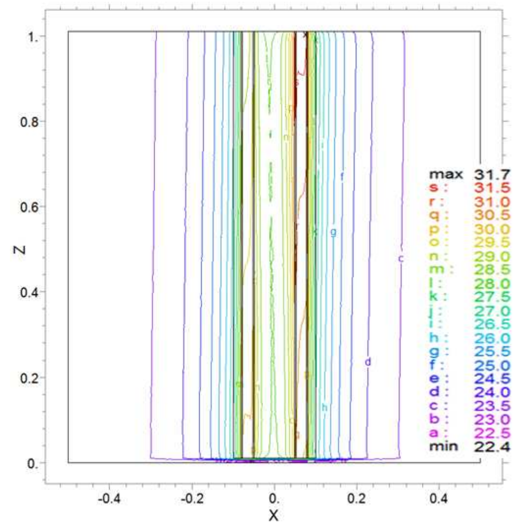

Fig. 7 A cross section of the soil area passing through the center of the heat-exchanger tubes showing the temperature distribution in the vertical plane after 12.6 h of operation

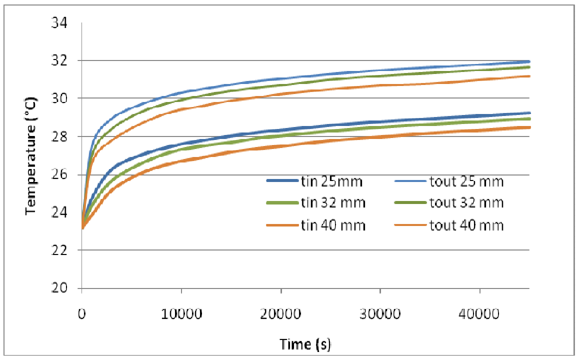

Fig. 8 Difference in input and output temperature in heat exchanger with nominal pipe diameters of 25 mm, 32mm and 40 mm, showing that the bigger diameters maintain lower temperatures for a given flow and power input.

Then, the effect of the variation of the ground specific heat is examined. As it is expected a lower value of the ground specific heat (c_p) affects the output temperature in a reverse exponential manner. Fig. 10 demonstrates that as c_p increases, the temperature-difference decreases. For instance ΔT_1 (for Δc_p = 4200 – 3200) < ΔT_2 (for Δc_p = 2200 – 1200).

TABLE II
PARAMETERS USED FOR THE EXAMINATION OF THE HEAT-EXCHANGER TUBE DIAMETER

d_{out} mm	t_p mm	s_p mm	Flow Rate lt min^{-1}	ΔT K	Power Input W	u m s^{-1}	h W m^{-1} K^{-1}
25	2.5	10	14.7	2.7	2750	0.78	3205
32	3.5	10	14.7	2.7	2750	0.5	2145
40	4	10	14.7	2.7	2750	0.305	1375

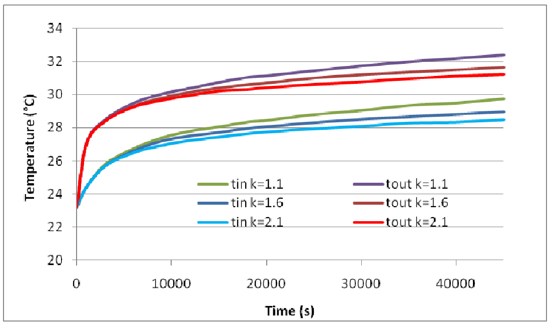

Fig. 9 Difference in input and output temperature in heat exchanger examining the effect of ground thermal conductivity

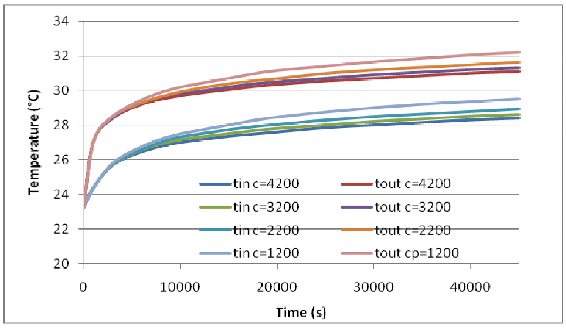

Fig. 10 Difference in input and output temperature of the heat exchanger showing the effect of the variation of the ground specific heat

Finally, the input and output temperature of the water in the U-tube is simulated in order to examine the effect of the borehole filling. Three types of fillings are examined: (i) bentonite with λ = 1.0 W m^{-1} K^{-1}, ρ = 1500 Kg m^{-3}, c_p = 800 J Kg^{-1} K^{-1}, (ii) sand with λ = 1.3 W m^{-1} K^{-1}, ρ = 2600 Kg m^{-3}, c_p = 800 J Kg^{-1} K^{-1}, and (iii) soil with λ = 1.6 W m^{-1} K^{-1}, ρ = 2200 Kg m^{-3}, c_p = 2200 J Kg^{-1} K^{-1}. As shown in Fig, 11 it is obvious that the "best" filling of the three types is soil, then sand and last bentonite. The common practice is to use as filling material either bontonite or sand, as clean soil may be more costly. Therefore, for a better heat exchange with the soil, the borehole size must be minimized so that grout volume is reduced and the geological formation is preserved. Also in the case that regulations require that boreholes are grouted with bentonite (when for instance there is a danger of mixing the flow of water in ground layers and cause pollution), only that portion of the borehole required by the regulations should be grouted. The rest can be filled with sand.

IV. Conclusion

As shown above the development and validation of a numerical model for the energy flow and temperature change in and around a borehole heat exchanger, has led to the examination of how certain parameters affect the heat extraction from the heat exchanger. It has been observed that the larger the U-tube diameter the higher the rate of dissipation of heat to the ground. As expected, the higher the soil thermal conductivity the higher the amount of heat that escapes the U-tube, keeping a lower temperature in the tubes. Moreover, the lower the soil specific heat the higher the increase of the tube temperature. Finally, it has been demonstrated that the choice of the borehole filling is of great importance, showing specifically that bentonite is an insulator and better not be used unless required by regulations; soil itself appears to be a much better filling choice. The present work is based on the modeling of an incompressible fluid flow with regard to energy, temperature and velocity. It remains of great interest the modification of the model to study the effects of higher energy and velocity flows, and even further applications to more extreme regimes.

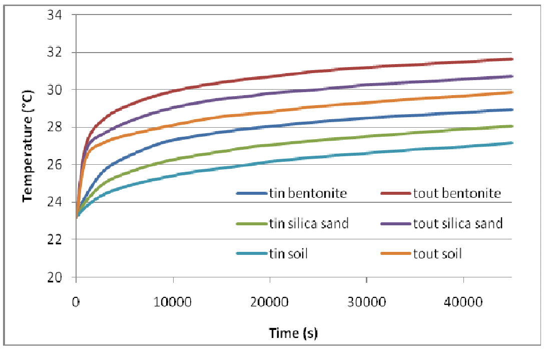

Fig. 11 Difference in input and output temperature of the heat exchanger showing the effect of the filling material of the borehole

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