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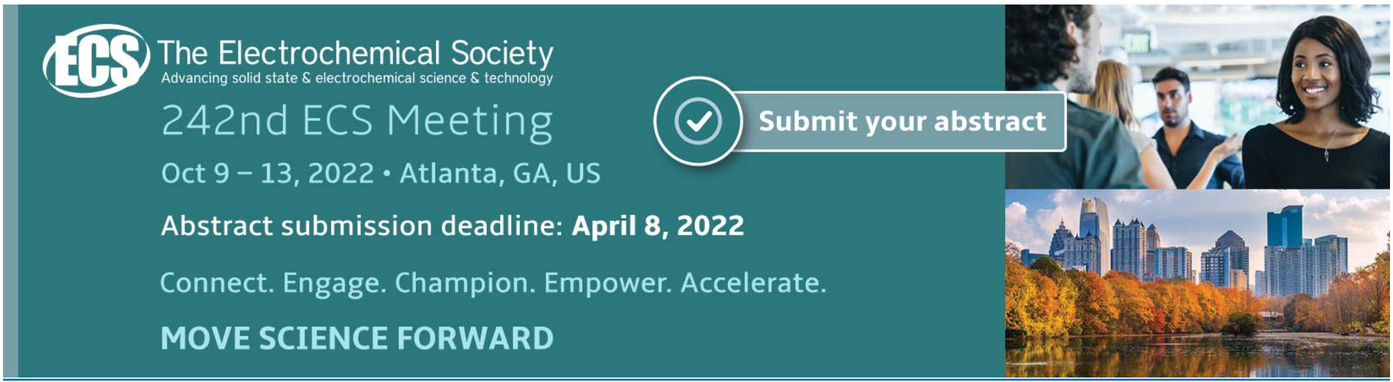

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Nanofluid suspensions as heat carrier fluids in single U-tube borehole heat exchangers

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Abstract. The borehole heat exchanger (BHE) is a critical component to improve energy efficiency and decreasing environmental impact of ground-source heat pump systems. The lower thermal resistance of the BHE results in the better thermal performance and/or in the lower required borehole length. In the present study, effects of employing a nanofluid suspension as a heat carrier fluid on the borehole thermal resistance are examined. A 3D transient finite element code is adopted to evaluate thermal comportment of nanofluids with various concentrations in single U-tube borehole heat exchangers and to compare their performance with the conventional circuit fluid. The results show, in presence of nanoparticles, the borehole thermal resistance is reduced to some extent and the BHE renders a better thermal performance. It is also revealed that employing nanoparticle fractions between 0.5% and 2 % are advantageous in order to have an optimal decrement percentage of the thermal resistance.

1. Introduction

Ground-Source Heat Pumps (GSHPs) are becoming increasingly a rather widely used technology for building climatization. The annual use of thermal energy produced by GSHPs increased by about 40% from 2010 to 2015, with an annual growth rate of 7% [1]. GSHPs are economically advantageous and more eco-friendly than traditional heating systems. The development of GSHPs could yield a remarkable reduction in primary energy use and in the emission of greenhouse gases.

A GSHP system typically consists of a heat pump, a vertical or horizontal ground heat exchanger and a distribution system. The most diffuse GSHP systems employ vertical ground heat exchangers, also called Borehole Heat Exchangers (BHEs). The main superiority of vertical U-tube BHEs is their higher coefficient of performance. They require less ground area and offer better performance, due to smaller seasonal swing in the ground mean temperature. However, the central dilemma to employ these wide spreading systems is their financial cost, including high drilling cost and set-up expenses, compared with traditional heating and cooling systems. Cost sensibility analyses showed that most influential parameters to minimize the total cost for a GSHP system are the depth and number of boreholes. Indeed, a better thermal performance of BHEs leads to a lower total required borehole length and consequently to a lower total installation cost [2,3]. The borehole thermal resistance is a key performance characteristic of the BHE; the lower the thermal resistance the lower required borehole length. Hence, many innovative designs have been recently proposed in order to reduce the borehole thermal resistance and improve the performance of BHEs – e.g. thermally enhanced grouting material and High-Density Polyethylene (HDPE) pipes, and various novel configurations of the BHEs. While such novel designs enhance the heat transfer to some extent, most of them are not cost-effective designs; they require higher set-up expenses, including higher production and installation cost, compared with simple deeper boreholes.

The aim of the present study is to fill this gap by proposing the nanofluid suspension as a heat carrier fluid in single U-tube borehole heat exchangers in order to mitigate the problem of low-thermal-conductivity of conventional water/ethylene glycol mixture. In fact, nanoparticles can be utilised as the primary circuit fluid to improve thermal properties of the base fluid. By means of a series of 3D finite element simulations, we analyse the possibility of lowering the borehole thermal resistance by employing the nanofluid suspension as a heat carrier fluid.

2. Mathematical model

The case under study is a single U-tube BHE surrounded by the ground, composed of a HDPE U-pipe sealed with grouting material. A customary BHE with length L=100 m and dimeter D_b=16 cm was considered. The U-tube has an internal diameter D_i=32.6 mm and external diameter D_e=40 mm and an intermediate value of shank spacing (centre-to-centre) was considered, namely S=95 mm. The ground around the BHE was modeled as a cylinder coaxial with the borehole, with diameter of 10 m and length equal to that of the BHE. Sketch of the BHE cross section is illustrated in Figure1(a).

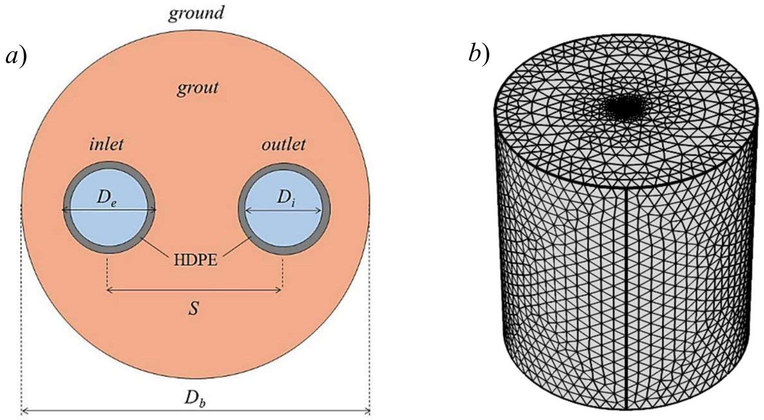

Figure 1. Sketch of considered cross section (a) and illustration of the mesh adopted (b).

The summer-cooling condition was considered with the reference inlet fluid temperature equal to T_{in}=30 °C. It was assumed that fluid flows with uniform velocity and two volume flow rates, V=15 and 20 litres per minute (L/min) were considered, with fluid velocity u_f = 0.3 and 0.4 m/s. Values of thermophysical properties are reported in Table 1. For numerical modelling of nanofluids, dispersion method was worked out [4]. A copper-based (Cu) suspension was employed as the heat carrier with volume fraction ϕ varying from 0.1% to 2.0%. As shown in Ref. [5], suspensions with Cu nanoparticles are characterized by highest heat transfer enhancement with reasonable production costs for geothermal applications, compared with other nanofluid suspensions. Corresponding values of thermophysical properties of Cu-water nanofluid were estimated through Equations (5, 12, 19, 20, 24) of Ref. [6].

As a boundary condition, lateral and bottom surfaces of the ground were considered as adiabatic. At the external boundary of the computational domain, the surface at z = 0 of the BHE was considered as adiabatic, while that of the ground was considered as isothermal, with T=24°C. As initial condition, the temperature was set equal to the undisturbed ground temperature, both for the ground and the BHE [7].

A 3D transient finite element code, implemented through COMSOL Multiphysics, was employed to solve the conjugate heat transfer problem. Finite element method (FEM) is an accurate and flexible method to deal with heat transfer problems for geothermal applications [7-9]. The employed numerical code is the same as that adopted in the previous work [6]. The direct PARDISO time-dependent solver with absolute tolerance of 10^{-4} was utilised to solve the heat transfer problem with duration of 100 h. The computational domain was meshed with unstructured tetrahedral elements. The mesh independence of the results was ensured by performing preliminary computations. The selected mesh for final computations, illustrated in Figure 1(b), contains 1.48 m tetrahedral elements.

3. Validation of the numerical model

In order to validate the employed numerical code, values of the mean fluid temperature, $T_{f,m}$, obtained through simulations for the case under study, are compared with those yielded by applying correlations proposed in Ref. [9] to evaluate $T_{f,m}$ for single U-tube BHEs. Figure 2 shows a comparison between the time evolution of $T_{f,m}$ obtained through the numerical simulation and that determined through correlations [9]. The Mean Square Deviation (MSD) of the numerical results from those obtained by correlations is equal to 0.32℃ and the normalized-MSD is 1.21%, which can be considered as a satisfactory discrepancy.

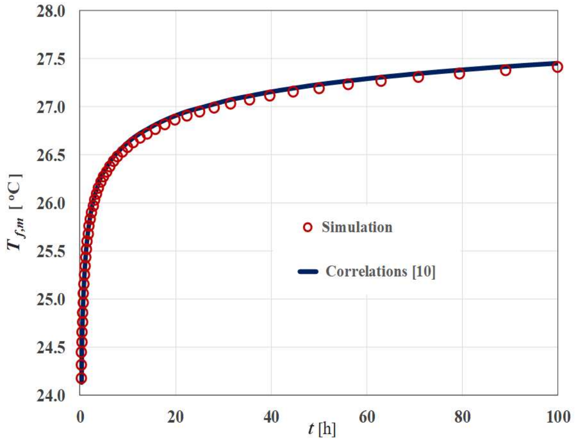

Figure 2. Validation of the numerical model.

Table 1. Thermophysical properties.

Title	Soil	Grout	HDPE	Water
ρ [Kg m^{-3}]	1600	1600	1000	995.7
c_p [J Kg^{-1} K^{-1}]	1000	1562.5	1824	4179.8
k [W m^{-1} K^{-1}]	2.2	1.8	0.5	0.6155
μ [Pa s]	-	-	-	0.00079

4. Results

Variations of the Nusselt number with various volume concentration of nanofluids is illustrated in Figure 3(a), for V=15 L/min. As is evident, a higher percentage of ϕ yields a higher Nusselt number. Figure 3(b) displays plots of the power rejected to the ground per unit borehole length versus time for V=15 and 20 L/min, for both water and nanofluid with ϕ=1.0%. Plots show that the power is descending function of time and that nanofluids render higher values of the power rejected to the ground in comparison with the water, for both volume flow rates.

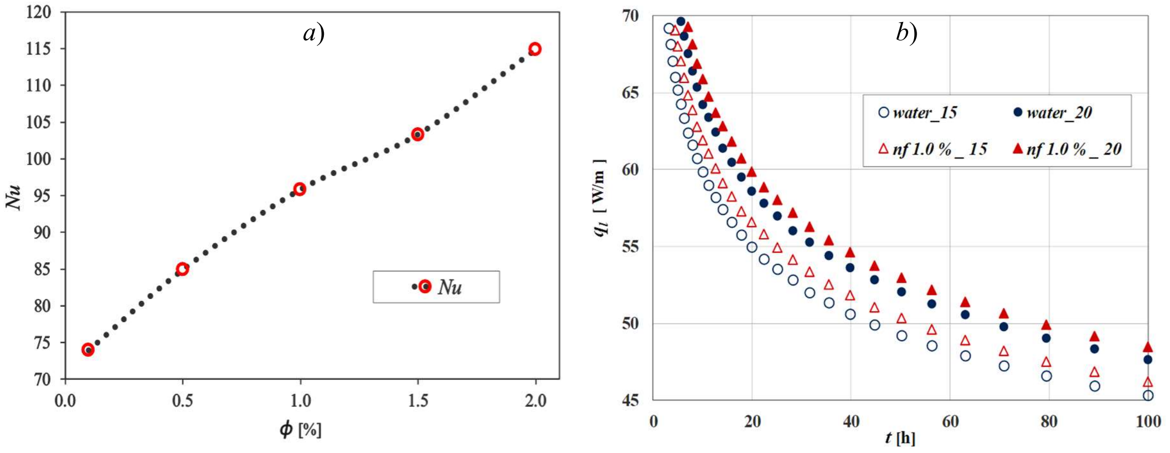

Figure 3. Nusselt number for various values of ϕ (a); power rejected to the ground versus time (b).

Figure 4 demonstrates effects of employing nanofluids as a circuit fluid on the borehole thermal resistance, defined as $R_b=(T_{f,m}-T_{b,m})/q_l$. Figure 4(a) shows variations of the dimensionless thermal resistance, $R^*= R_{b,water} / R_{b,nf}$, with ϕ versus logarithmic-scale of time; a higher particle concentration leads to a lower thermal resistance, with highest reduction of 3.3% to 4.2 % for ϕ=2.0%. It can be observed that the decrement rate of R_b does not alter linearly with increasing ϕ; for values of ϕ higher than 1%, the decrement rate of R_b decreases, in comparison with lower values of ϕ. Taking into account the economic point of view and probable rheological problems for higher volume fractions, it can be asserted that the best range of ϕ to have an optimal decrease rate of R_b, for Cu-water nanofluid, is between 0.5% and 2.0%. It is also noticeable that, for values of ϕ higher than 0.5%, the required time for R^* to reach a steady value increases to some extent.

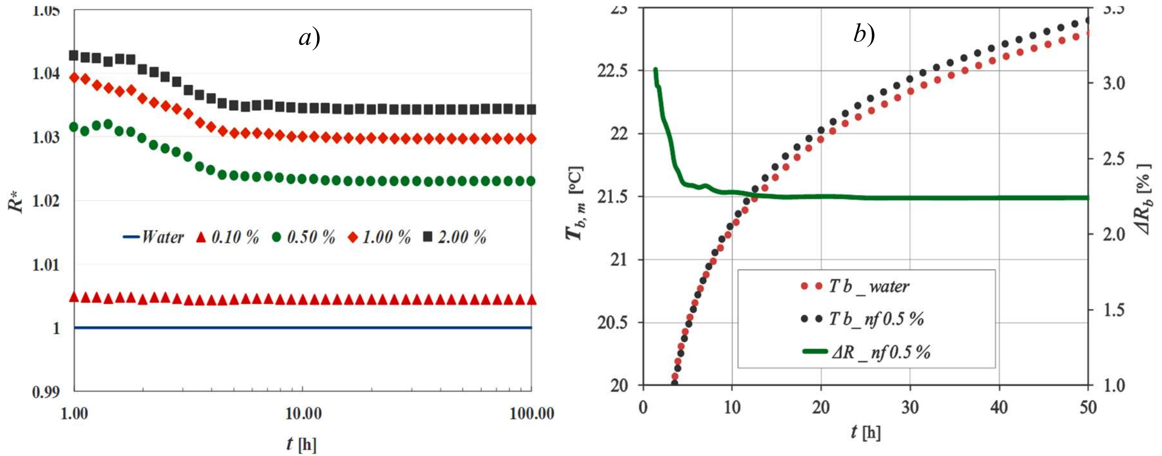

Figure 4. Dimensionless thermal resistance versus time (a); time evolution of $T_{b,m}$ and ΔR_b (b).

Figure 4(b) illustrates temperature increment of the BHE mean surface, $T_{b,m}$, in presence of 0.5% suspension over period of 50 h. It shows that using nanofluid slightly increases $T_{b,m}$, in particular after 20 h. Furthermore, the plot of the decrement percentage of R_b with reference to the base fluid, namely ΔR_b, shows an almost 2.3% decrement of R_b in steady-flux period, i.e. after 10 h of operation.

5. Conclusions

In the present paper, effects of utilising nanofluid suspensions on thermal performance of single U-tube geothermal heat exchangers and on reducing the borehole thermal resistance were evaluated through a series of finite element simulations. The results obtained by numerical code was validated by comparing with those determined through correlations. The results showed that, in presence of nanoparticles, the BHE renders higher power rejected to the ground and a better thermal performance. It can be concluded that the suspension of nanofluids could reduce the BHE thermal resistance to some extent and that concentrations between 0.5% to 2 % are advantageous to have an optimal decrement percentage of thermal resistance. A more detailed investigation to examine the performance of GSHPs coupled to BHEs with nanofluids as a heat carrier fluid would be precious.

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