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Borehole heat exchanger with nanofluids as heat carrier

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ABSTRACT

This paper presents numerical study on the use of nanofluids to replace conventional ethylene glycol/water mixture as heat carrier in a BoreHole Heat Exchanger. Nanofluids contain suspended metallic nanoparticles: increasing their concentration, in comparison to the base fluid, the thermal conductivity increases and the volumetric heat capacity decreases. The first effect is positive for the reduction of borehole thermal resistance, since it causes the grow of fluid convective heat transfer coefficient, while the second one is detrimental, due that it decreases the heat transfer between fluid and borehole wall.

A numerical model based on energy and momentum balances is used to evaluate which is the best nanofluid with low nanoparticles volumetric concentration (0.1%–1%) that ensures the highest decreases of borehole thermal resistance and minimum increases of pressure drop among silver, copper, aluminium, alumina, copper oxide, graphite and silicon oxide. Moreover, a simple economic analysis was done.

Results show that copper is characterized by highest borehole thermal resistance reduction, that reaches the value of about 3.8%, in comparison to that of base fluid, when nanoparticles volumetric concentration is 1%, but also the second one highest pressure drop. In this case, the cost of copper-based nanofluid is about 10 € m^{-1}, i.e. about 12% of total cost of BoreHole Heat Exchange – Ground Source Heat Pump system.

1. Introduction

Renewable energy sources represent a viable alternative to meet the growing global energy demand and, at the same time, to prevent the occurrence of irreversible Earth's climate change (IEA, 2015; Esen and Yuksel, 2013).

In 2013, world Total Primary Energy Supply (TPES) was 13′555 million tones of oil equivalent (Mtoe) of which 13.5%, or 1′829 Mtoe, was produced from renewable energy source (IEA, 2015). Due to its widespread non-commercial use (i.e. residential heating and cooking) in developing countries, solid biofuels is by far the largest renewable energy source, representing 10.4% of world TPES and 73.4% of global renewables supply. The second-largest is hydroelectric power, which provides 2.5% of world TPES and 17.8% of renewables. Geothermal, solar, wind, biogases make up the rest of the renewables energy supply (IEA, 2015).

Although, as shown, geothermal energy is not the most exploited renewable source, the geothermal thermal power installed is growing at a sustained rate of 4% to 5% yearly ((Stathis) Michaelides, 2015).

It is customary to divide geothermal energy in three areas, regarding to the temperature of the Source: 1) high-enthalpy (temperature of source above 423 K), in this case geothermal energy is converted into electricity (Zheng et al., 2015); 2) medium and low-enthalpy (temperature of source between 305 and 423 K), in this case geothermal energy is used directly, for space heating, swimming pool heating, agricultural and industrials uses, etc. (Bloomquist, 2003); 3) thermal baths, for therapeutic and recreational aims.

In the recent years, direct uses of geothermal energy are witnessing a rapid growth worldwide (Canelli et al., 2015). Lund and Boyd (Lund and Boyd, 2016) published the review about direct utilization of geothermal energy in the world, highlighting that in 2015 the total worldwide thermal power installed was 50′528 MW_{th} and the annual energy used was 326′868 TJ. While Ground Source Heat Pumps (GSHPs) covers about 70.9% of the installed thermal power, recently other applications are being developed, such as swimming pool heating (20.2%), space free heating/cooling (14.9%), agricultural drying (1.76%), industrial uses (0.34%), etc.

Many papers are available in the literature regarding GSHP: Esen et al. (Esen et al., 2017) studied the performance of solar-assisted GSHP coupled with slinky (spiral loop) ground heat exchanger; Balbay and Esen (Balbay and Esen, 2013, 2010) evaluated the potential of GSHP as system for snow melting and de-icing on pavements and bridge slabs; Esen et al. (Esen et al., 2008) used the artificial neural networks to predict performance of a horizontal ground-coupled heat pump, with

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Nomenclature

A_{int}	Pipe inner area, m^2
C_e	Specific cost, € kg^{-1}
C_{el}	Cost of electric energy, €
C_p	Heat capacity, J kg^{-1} K^{-1}
C_1	Specific cost of electric energy, € k Wh^{-1}
ELT	Heat pump entering liquid temperature, K
f	Friction factor, –
F_{sc}	Short circuit loss fraction between supply and return tubes in BHE
h	Convective heat transfer coefficient, W m^{-2} K^{-1}
K	Thermal conductivity, W m^{-1} K^{-1}
L	Borehole length, m
LLT	Heat pump leaving liquid temperature, K
$\dot{m}$	Fluid mass flow rate, kg s^{-1}
Mo	Mouromtseff number
r	Pipe radius, m
p	Power in p-linear average, –
P	Pressure, Pa
PLF_m	Part-load factor during design month
Q	Heat input rate, W
Q_a	Net annual average heat transfer to the ground, W
Q_{evap}	Heat pump evaporate rate from ground, W
R	Thermal resistance, m K W^{-1}
R_b	Borehole thermal resistance, m K W^{-1}
R_f	Convective film resistance, m K W^{-1}
R_{ga}	Effective thermal resistance of the ground in annual pulse, m K W^{-1}
R_{gm}	Effective thermal resistance of the ground in monthly pulse, m K W^{-1}
R_{gst}	Effective thermal resistance of the ground in short-term pulse, m K W^{-1}
R_{pw}	Pipe wall thermal resistance, m K W^{-1}
R_w	Grout thermal resistance, m K W^{-1}
R_{12}	Thermal resistance between the fluids in the two pipes, m K W^{-1}
t	Time, s
T	Temperature, K
T_{pp}	Long-term ground temperature penalty, K
u	Fluid velocity, m s^{-1}
V	Liquid volume, m^3
w	Volumetric mass flow rate, m^3 s^{-1}
x_s	Distance between the center of pipe and the center of borehole, m
z	Depth, m

Greek letters

α	Ground thermal diffusivity, m^2 s-1
γ	Eulero constant, –
η_p	Efficiency of circulation pump, –
ϕ	Volumetric concentration, %v
ρ	Density, kg m^{-3}
μ	Viscosity, Pa s
ω	Mass concentration, %kg
ΔP_d	Pressure drop, Pa
ΔT_{in}	Temperature difference between T_{in} and T_g, K
ΔT_{out}	Temperature difference between T_{out} and T_g, K
ΔT_p	P-linear average temperature, K
ΔR_b	Decreases of borehole thermal resistance in comparison to that of water, %

Subscripts

b	Borehole
1,2	Pipe number
ext	External
f	Fluid
g	Ground
in	Inlet
int	Internal
nf	Nanofluid
np	Nanoparticle
out	Outlet
p	Pipe
s	Solid particle

Acronyms

BHE	Borehole heat exchanger
GSHP	Ground source heat pump
GRT	Ground response test
HC	Heat carrier
TPES	Total primary energy supply

the aim to improve forecasting performances, essential pre-requisite for the optimal control and energy saving operation of GSHP; Allaerts et al. (Allaerts et al., 2017) experimentally analyzed the performance of a GSHP in combination with different low temperature heating located in a Belgium school building; Biglarian et al. (Biglarian et al., 2017) developed a numerical model to simulate Borehole Heat Exchanger (BHE), achieving good forecasting in both short and middle term; several ground heat exchangers configurations were studied, albeit the two major types are open loop and close loop [*e.g.* (Kaushal, 2017)].

Although in the above reported literature there are the proofs that GSHPs could represent a valid environmental-friendly alternative as heating/cooling system in buildings, efforts are still needed to improve their performance, since the diffusion of these systems is still limited by their high initial costs, negatively affect by drilling costs for vertical Borehole Heat Exchanger, which is the most applied heat exchanger configuration (Esen et al., 2006). In order to mitigate this negative aspect and to make GSHPs more competitive compared to based-fossil fuels technologies, in this work it is investigated the possibility to improve the heat transfer coefficient of heat carrier in the BHE replacing conventional ethylene glycol/water mixture (follow water) with fluids containing nanoparticles (nanofluids).

Nanofluids are two phase systems comprising a carrier medium (liquid or gas) and dispersed nanoparticles, that are particles with characteristic dimensions within 1–100 nm. The typical carrier media are water, organic liquids (ethylene glycol, oils, biological fluids), polymer solutions, *etc*. Solid species usually represent nanoparticles of chemically stable metals or metal oxides. Results of investigations performed in the past decade in the United States, Japan, South Korea, China, Australia, and some other countries showed that the efficiency of various heat exchangers employing nanofluids is much greater than that of analogous systems with conventional cooling agents.

It is important to understand how the physical and thermal properties of nanofluids impact the heat transfer performance. In the past decade, many investigators studied various features of nanofluids. Review paper by Yu et al. (Yu et al., 2012) provided an overview of the thermophysical properties of nanofluids and how the addition of nanoparticles impacts on the heat transfer performance. Although an increase in thermal conductivity and changes in other physical properties such as density, heat capacity and viscosity are important indications to infer an improved heat transfer behavior, the heat transfer coefficient is