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Investigating the effects of geometric parameters on finned conical helical geothermal heat exchanger and its energy extraction capability

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ABSTRACT

With the onset of the warm and cold season, the temperature inside the building goes far away from the human comfort condition, so an optimal energy source is needed to reach the desired temperature. Naturally, the earth is a massive source of heat that is easily accessible under the buildings, yards, and squares of the city; therefore, the geothermal heat exchangers can be used in depth of the ground to drain the heat from the earth. In optimizing heat transfer equipment to achieve higher energy efficiency, the focus is on reducing the size of the heat exchanger on the one hand and increasing the intensity of heat transfer area on the other hand. Helical heat exchangers are compact and can be used in geothermal systems to receive energy. In this paper, a conical coil tube geothermal heat exchanger is simulated according to the environmental conditions of Tehran, the capital city of Iran, and the potential of using such system is examined by changing the geometric parameters and operational requirements. The coil diameter, coil pitch and the angle of conic of the helical tube are varied for the heat exchanger buried at a depth of 3*m* from the earth surface. The soil temperature profile is obtained from the air temperature data Synoptic Meteorological Station. Design parameters are coil diameter, coil pitch, cone angle, length to width ratio of the fin, number of fins and Reynolds number. Taguchi algorithm is applied to find the best geometric parameters. Finally, different volume fractions of Al_2O_3 nanoparticles are added to the optimized geometry to enhance the heat transfer rate. Results indicate that the optimized geometry considering thermal-hydraulic performance in the range of this study is $\theta = 0°,\ D_c = 1000\,mm,\ P_c = 60\,mm,\ Re = 3000,\ R = 1\ and\ Fn = 6$ for cone angle, coil diameter, coil pitch, Reynolds number, length to width ratio of fin and number of fins respectively. Changing the objective to increase heat transfer (Nusselt number) the optimized values alter to $\theta = 3.14°,\ D_c = 1000\,mm,\ P_c = 80\,mm,\ Re = 4993,\ R = 1.5\ and\ Fn = 6$. Heat flux on the surface of the tube increases to 18% for 0.5% volume fraction of nanoparticles.

1. Introduction

The use of geothermal energy in Iran is very far away so that people in traditional ways used this power in places where there were spa springs for use in water treatment and recreation. The population growth, urban development, and the energy economy in Iran have made the production of 90,000,000 MW of electricity in 2020 inevitable. About 98% of current generation capacity (29,000 MW) of country's power plants rely on fossil fuels. However, the limitation of fossil fuels, domestic consumption growth on the one hand, and the environmental sustainability criteria and standards, on the other hand, have made the use of renewable energy inevitable.

So far, areas of Iran that have the potential to utilize geothermal energy have been studied, and research projects in this field are being implemented. In Iran, it is possible to use geothermal energy sources in Damavand, Sabalan, Mako, Khoy, and Sahand. Currently, studies on the construction of the first geothermal power plant in the country are underway by the Renewable Energy and Energy Management Organization of Iran, affiliated to the Ministry of Energy in the Meshkin Shahr area (Noorollahi et al., 2009).

Environmental comfort, economy, and energy consumption are one of the most important considerations regarding buildings. In most educational, commercial, office and residential buildings, air conditioning systems are widely used to provide residents with the comfort and health of the demand, which is increasingly growing over time. Today, developed countries are trying to use renewable energy systems in the air conditioning industry for heating and cooling of buildings. One of these systems, which has undergone extensive research over the 1970s in most parts of the world, is underground pipes. The temperature of the soil at a depth of 4–6 meters would be as much as the

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Nomenclature

c_p	Specific heat capacity, $J/kg.\ K$
d	Tube diameter, mm
D_c	Coil diameter, mm
f	Friction factor
Fn	Number of fins
h	Heat transfer coefficient, $W/m^2.\ K$
j	Colburn factor
jf	Thermal-hydraulic performance
k	Thermal conductivity, $W/m.\ K$
L	Tube length, mm
Nu	Nusselt number, $h.\ D_h/k$
p_c	Coil pitch, mm
Pr	Prandtl number
Δp	Pressure drop
q''	Heat flux, W/m^2
R	Width to height ratio
Re	Reynolds Number
T	Temperature, K
t	Time, $hour$
V	Velocity, m/s
y	Depth, m

Greek letters

ρ	Density, kg/m^3
μ	Viscosity, $kg/m.\ s$
φ	Nanofluid volume fraction, %

subscripts

nf	nanofluid
p	nanoparticle
w	Water

Abbreviations

HP	Heat Pump
GHP	Ground Heat Pump
GHEX	Ground heat exchanger
SN	Signal to Noise

average air temperature of the year (Abbaspour-Fard et al., 2011). In this system, ambient air enters underground pipes and after exchanging heat with soil, for ventilation and reducing the amount of thermal load of the building is used. This system, most of the time includes one or more tubes of specific length and radius that are used to cool the air passing through it in the summer or pre-heating of the air passing through it in the winter. The physical phenomenon is straightforward. Soil temperatures are usually lower in the summer and higher in the winter than the ambient air so that the soil can be used as a heat and cold absorbent throughout the year. The prototype is underground metro stations in cities which the ground and underground temperatures can be compared there (Abbaspour-Fard et al., 2011).

In the extraction of geothermal energy, the use of heat exchangers is inevitable. The most straightforward type of heat exchanger is tubular ones, which can be installed horizontally and vertically in the ground and transmit heat to the surface. One of the types of heat exchangers is curved pipe heat exchangers, in which due to the nature of pipes, secondary flow in the perpendicular direction of the current is made and the heat transfer rate is much higher than the straight tubes. Several researchers made efforts to drive correlations for the heat transfer rate and pressure drop in the helical tubes. Some proposed Nusselt number correlations (Dravid et al., 1971) while others investigate both Nusselt number and friction factor (Kubair and Kuloor, 1966; Patankar et al., 1983; Xin and Ebadian, 1997). Dravid et al. (Dravid et al., 1971) presented a relationship for the asymptotic Nusselt numbers according to the results obtained on their investigation of the effect of secondary flow on the Nusselt number in the laminar regime. Kubiar and Kuloor (Kubair and Kuloor, 1966) experimentally studied the heat transfer rate and pressure drop of the glycerol flowing inside a vertical helical coil at constant wall temperature. The flow regime was laminar, and finally, correlations were proposed. Rahul et al.(Rahul et al., 1997) presented a relationship for outside Nusselt number of a helical tube. Their results indicate that the pitch of coil significantly affects the outside heat transfer coefficient. Jamshidi et al. (Jamshidi et al., 2013) found the optimum coil diameter, coil pitch and flow rates in shell and tube side to enhance the heat transfer rate in a helical tube heat exchanger. They found that higher coil diameter, lower coil pitches and higher flow rates in shell and tube sides can be a good choice for these kinds of heat exchangers. As helically coiled heat exchangers are widely used in industry, investigations were made to enhance the heat transfer rate in these tubes (Kurnia et al., 2016; Promthaisong et al., 2017), while some changed the cross-section shape of tubes, others used Nanofluid as working fluid (Huminic and Huminic, 2011, 2016; Jamshidi et al., 2012b; Karami et al., 2016; Bhanvase et al., 2018). Thermo-physical properties of the fluid are essential in many engineering applications. Conventional heat transfer liquids such as water, oil, and ethylene glycol have low thermal conductivity. Therefore, there exists a substantial motivation to overcome these disadvantages to develop more compact heating and cooling systems with high performance. One way to overcome this problem is adding solid particles with high thermal conductivity to the base fluid. An innovative technique to improve the heat transfer is using the Nano-scale particles in the base fluid. Fluids with nanoparticles suspended in them are called Nanofluids (Choi, 1995). Nanofluids introduce a unique approach for treating more efficient heat removal in thermal-fluid systems (Sheikholeslami and Ganji, 2014, 2018; Sheikholeslami et al., 2017a, b). Several review papers introduce correlations for the thermo-physical properties and the heat transfer coefficients of Nanofluids at different flow conditions (Huminic and Huminic, 2012; Kakaç and Pramuanjaroenkij, 2009; Murshed et al., 2008; Solangi et al., 2015; Jamshidi et al., 2012a; Alawi et al., 2018; Yang et al., 2017). There are two techniques for simulating nanofluids, single-phase model and two-phase model. Ziad Saghir et al. (Saghir et al., 2016) compared two-phase and single-phase model for the nanofluids in a square cavity. They concluded that the two-phase model provides a better understanding about liquid and solid parts in the mixture, however, single-phase model with 1% discrepancy from the experimental results predicts more accurate heat transfer rate. Esfandiary et al. (Esfandiary et al., 2016) studied forced convection in a pipe in turbulent regime. They stated that the results based on single-phase model are near to the results obtained by the experimental results. The solid particles in the base fluid are very small so despite the fact that Nanofluids are two-phase mixtures, they can be considered a single phase fluid (Rea et al., 2009). Therefore, it is reasonable to consider Nanofluids with low volume fractions of particles as a single phase flow.

Studies in the field of geothermal heat exchangers can be classified according to the method of investigation as well as the shape of the heat exchanger. Some researchers investigated the geothermal heat exchangers using experimental methods. (Kim et al., 2016) installed a horizontal helical heat exchanger in the ground and compared the thermal response received from the pilot system and their numerical results. The water temperature obtained from numerical results was slightly lower than the water temperature of the experimental ones. The results show that the use of installed heat exchangers can provide the