Energy Conversion and Management 168 (2018) 296–307

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Numerical simulation of a novel spiral type ground heat exchanger for enhancing heat transfer performance of geothermal heat pump

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ARTICLE INFO

Keywords:
Ground source heat pump
Spiral pipe
Pitch
Ground heat exchanger

ABSTRACT

The spiral type one is more prominent of which the vertical type ground heat exchange (GHE) is the most common in ground source heat pumps (GSHP) and on the purpose of this study as well. The present paper provides numerical simulation for 1D-3D model of the ground source heat pumps in cooling mode by using COMSOL environment. In contrary to popular spiral models, this model is designed with a low depth and high diameter with special metal rods (Fins). The simulated spiral pipe has 10 m in depth and 1 m in diameter. In order to compensate the reduction in heat transfer due to the lower depth, the effect of different parameters such as velocity, pitch, thermal conductivity and specific heat capacity in backfill material and ground on the heat performance is investigated. Furthermore, different velocity range is recommended for several pitches. Also, as a novelty, an innovative design is modeled consisting of diverse type of horizontal aluminum rods (Fins) in the soil connected to the pipe completely (Finned pipe). The fins not only hold the pipe inside the ground firmly but also improve the heat transfer rate due to the area increase and the high thermal conductivity system up to 31%.

1. Introduction

The energy issue is one of the most important concerns among nations which made them to develop the renewable energies widely [1,2]. There exist a variety sources of renewables and the relating technologies, amongst, the geothermal heat pump is considered as the aim of this paper. Turning to details, the ground heat exchanger has vital importance depending on different conditions of heat pump type [3].

Ground source heat pumps (GSHP) are recognized as one of the most high-efficiency renewable energy system which is expanding gradually. One of the most important parts of the GSHP system is its ground heat exchange (GHE).

One of the most important part of heat pump systems is the heat exchanger that can be changed much more than the other parts [4]. Therefore, this change may exert an strong influence on the efficiency. Also, by changing in the coil type and material, the fundamental alteration will occur in the initial price.

There are two main types of the ground heat exchanger for geothermal heat pumps: vertical and horizontal closed loop types. In this matter, the vertical type has several types such as u-type and spiral that is utilized owing to some circumstances in which the borehole drilling cost is of significance. In many countries, particularly Iran, the drilling is costing a fortune where the spiral type supports long pipe length with shallow boreholes depth is the best solution. Furthermore, for the countries where the tube and installation cost is more than the drilling cost, the u-tube type can be suitable decision.

To shed more lights on the economic issue, the vertical type occupies less area which has a maximum performance in cold regions [5]. It is highly offered to use spiral type due to low costs in comparison with slinky and U-tube GHEs [6].

Recently, other studies have been done to reduce ground heat exchanger costs, including Dehghan et al. [7] which assessed a new u-type model. The presented model was concurred to avoid the wrong drilling and eliminate at least 20% of GSHP costs. Likewise, Farabi-Asl et al. [8] conducted an investigation which resulted in 22–36% saving for GSHP system costs by the utilization of water pumping and injection.

Bezyan et al. [9] Indicated that the best ground coil shape is spiral due to analyzing three different tube types of 1-w-shape, 1-u-shape, and spiral type with inlet temperature 35 °C in cooling mode of water. Afterwards, their results showed that decrease the outlet temperature difference for spiral, u-shape, and w-shape is 7.74, 4.328, and 4.965 °C respectively. Which the largest difference between the inlet and outlet fluid temperature comes from the spiral type pipe.

So, they reassure that the spiral type tubes are the best choice among others.

Carotenuto et al. [10] applied a simulation by comparing different

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https://doi.org/10.1016/j.enconman.2018.05.015
Received 10 February 2018; Received in revised form 3 May 2018; Accepted 4 May 2018

designs. They also evaluated the heat transfer process using the mixed 1D-3D approach. By comparing three types of double-u-shaped, triple-u-shaped and spiral coil tubes, the most significant difference in temperature was observed in the spiral tube at 5.38 °C after 6 h, and the lowest was for the triple-shape with 2.55 °C. It was also pointed out in this study that the tube length is much more important than tube diameter.

Zarrella et al. [11] has come to the conclusion that the spiral pipe is technically more advantageous than the u-tube. Further, at the same condition, in terms of thermal performance, the spiral resulted better than the u-tube and triple tube. Also, when the pitch rises from 0.15 to 0.3, the pick load is reduced by about 14%. In a similar study for the same initial and boundary conditions, the performance of spiral tubes was better than u and w shape [12]. The reduction in the heat exchange surface when the borehole diameter was smaller needed to be balanced by a thermally enhanced backfill material [13]. That the change in pipe diameter does not have much effect on the system performance [14]. Heat exchange changes by inlet temperature linearly [15,16].

Decreasing the price of circulating pump and increasing the cost of ground heat exchanger by increasing the number of boreholes affects the total cost values [17].

An increase in GHE length for both cooling and heating causes the number of heat pumps to be reduced and as a consequence of which the electricity consumption drops [18]. The use of geothermal in general, especially in large cities, is a convenient replacement for fossil fuels to supply heating and cooling. Moreover, using a renewable source can reduce pollutant in those cities [19].

There are several references evaluated the velocity change in the tube and presented ranges along with some limitations for the velocity. For instance, the velocity range of 0.4–0.7 m/s and 0.4–0.5 m/s are recommended for single u-tube with 32 mm diameter and double-u tube with 25 mm diameter respectively [20]. In another study, the proposed fluid velocity for single u-tubes is 0.4–0.7 m/s and the Reynolds number is between 12,000 and 21,000 [21]. The inlet velocity 0.3–0.7 m/s corresponding to result in a improved performance for coaxial deep [22]. According to these articles, the velocity should not be very high or very low and should be within a certain range. As a matter of fact, by changing the pitch value in spiral and slinky types, there can be significant changes in the heat transfer between soil and the pipe, generally, reducing the pitch size increases the heat transfer. But there exists some limitations which can be reduced by increasing the pitch and pipe length, and improving soil interactions. In this regard, too much reduction in pitch size can cause the thermal interference through the rings and also the heat transfer per unit length are decreased [23,24] also pressure loss increases by decreasing pitch [25].

There are different methods that can explore heat transfer procedure such as, computational methods (Using software like COMSOL, FLUENT), analytical modeling and experimental study [26]. The list of papers including the use of spiral pipe with details and results is reviewed in Table 1.

Although varying the pitch size does not influence on the duration of the installation [35], Park et al. [36] have been economically calculated the pitch impact and they proposed that it is better to use pitchs higher than 200 mm. In another study which was conducted using nanofluid, the thermal conductivity increase for inlet fluid and its impact on tube length reduction was analyzed. The Al_2O_3/water nanofluid outcomes were presented only less than 1.3% reduction for borehole length [37]. increase in thermal conductivity leads to an increase in the efficiency of GHE and its effect backfill material is more than ground in [38].

In many studies, the numerical simulation is applied using Comsol (3D model). On the other hand, another model for in-ground geothermal pipes is 1D-3D which recommended by Comsol [39]. In this model, the pipe is considered as a line in the borehole and the soil is determined as a 3 dimensional model. There are some new published papers regarding this field such as using the model for the horizontal

Table 1
Studies including the use of spiral pipe is reviewed.

Authors	Methods	Time	Pitch (m)	The details and results
Jalaluddin et al. [27,10]	Simulation (ANSYS FLUENT)	72 h	0.05, 0.1, 0.2	Heat transfer rate (HTR) of the spiral pipe with pitch = 0.05 m increased about 34.9% in the turbulent flow and 69.2% in the laminar flow the spiral pipe provides a better HTR than the straight pipe
Zhao et al. [28]	Simulation (COMSOL)		0.25, 0.5, 1.0, 2.0	A rise of spiral pitch results in a decrease of the COPs from 0.77 to 16.49% A reduction of spiral pitch could increase the energy efficiency
Dehghan [6]	Simulation (COMSOL)	2400 h	0.1	Major diameter and Pitch of spiral GHEs are suggested to be 0.45 m and 0.1 m respectively It is highly recommended to use spiral type due to their low costs in comparison with other types of GHE such as slinky and U-tube
Yang et al. [29]	Experimental	10 h	0.1	The decrease of the spiral pitch, the steady value of soil excess temperature increases and the corresponding steady time become longer reducing the spiral pitch can increase the total heat release rate of the coil pipe, but also result in the decrease of heat release rate per unit pipe length
Wang et al. [30]	Ansys CFX analytical modeling		1 m	A new analytical solution was developed taking the Laplace method to account. The difference between borehole and surrounding soil thermal properties for the geothermal heat exchanger with the spiral pipe was studied carefully. This new tool has proven to be an appropriate one for designing and assessing energy pile system
Zhao et al. [12]	Experimental and Simulation (COMSOL)	43 h	0.25 m	The spiral pipe heat transfer gives the lowest temperatures in circulating fluid and the minimum average internal thermal resistances under the same initial conditions and boundary conditions He spiral pipe heat transfer gives the better thermal efficiency than the W-shaped, U-shaped
Leroy et al. [31]	Simulation	2000 h	0.4 m	The expansion of a new contribution to previously developed spiral heat source models
Luo et al. [32]	Experimental	1200 h	0.3 m	Thermal performance of spiral pipe can reach 10–15% upper than single-W type Cost-benefits study expressions that triple-U type has the highest economic performance, followed by, spiral, double-W and double-U
Carotenuto et al. [10]	Simulation (COMSOL)	6 h	0.1, 0.25, 0.5, 0.7	Using a pitch of 0.25 m instead of 0.70 m, an increase of HT efficiency of 68% can be obtained The use of a pitch size smaller than 0.25 m should be avoided due to extreme pressure drops and to a less heat exchanger enhancement
Dehghan [33]	Experimental and Simulation (COMSOL)	3 months	0.1	Different configuration of spiral GHEs was compared. The nine spiral GHE configuration (N = 9) suggested out of models including N = 1,2,3,4,5,9. The proper distance between spiral GHEs was calculated to be at least 6 m (dp 6 m)
Yoon et al. [34]	Experimental and Simulation (COMSOL)	65 h	0.05 m	The finite line source model was suggested for the evaluation of the ground thermal conductivity. The comparison of this model with the spiral type has also been studied