

Experimental and numerical analysis of helical geothermal heat exchanger operating in hot climates

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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, the geothermal heat exchanger systems can be used to refresh the buildings. various configurations especially single U-tube ground heat exchangers have been studied to improve the thermal performance of ground heat exchangers. Although helical type has better thermal performance than the others. The present paper provides experimental and numerical analysis of helical geothermal heat exchanger tested in El-Oued region (Algeria). A PVC pipe was used as a Helicoidally Water-Air Heat Exchanger (HWAHE), with 30 m of length and 0.6 m of diameter. The HWAHE was emerged in the bottom of water well of 5 m of depth. A mathematical model was developed to test thermal efficiency of the system and a parametric analysis was carried out taking into account the length and the radius of the pipe and the velocity of the air in the pipe. The results of performance show that the inlet air temperature has significant effect mainly when the difference in temperature between the ambient air and the water borehole increases. Therefore, the gained temperature gap between the inlet and the outlet air of the exchanger increases with the increasing of air inlet temperature. However, at air velocity of 10 m/s the efficiency of the exchanger reached 89%.

Keywords: Geothermal energy, ground heat exchanger, reheating, cooling, buildings air-conditioning.

1. Introduction

Nowadays, energy shortage, air pollution, and global warming are serious problems for all creatures. The main contributor to global warming is carbon dioxide (CO₂) emission from fossil fuel. The concerns associated with the global growth of energy usage can be significantly reduced through the use of renewable energy sources which is environmentally friendly energy and continuously replenished. For this purpose, many researchers have concentrated on sustainable energy sources such as solar, geothermal energy, wind and biomass. Geothermal energy is known as one the most efficient renewable energies in the world. It is green, sustainable, suitable energy storage and available for whole day. Geothermal energy can be used through a ground heat exchangers which characterized by their large potential for energy saving and low maintenance [1, 2].

The temperature of the soil at a depth of 4–6 meters would be almost constant and as much as the average air temperature of the year. In this system, ambient air enters underground tubes and after exchanging heat with ground, for ventilation and reducing the amount of thermal load of the building is used. the extraction of geothermal energy, is very efficient with the use of heat exchangers. The most straightforward types of heat exchanger are the horizontal and vertical configurations. One of the types of heat exchangers is curved tube heat exchangers, in which due to the nature of tubes, secondary flow in the perpendicular direction of the current is made and the heat transfer rate is much higher than the straight tubes [3].

To understand the thermal performance of the ground heat exchangers, several mathematical models, methods and computer tools were developed and used in the open literature. Bezyan et al. [4] 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.

Zarella et al. [5] 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. Krarti et al. [6] analyzed the heat transfer process in an EAHE and proposed an analytical model for the EAHE system. A physical model to simulate the EAHE was developed and validated by Mihalakakou et al. [7, 8]. Benkert et al. [9] highlighted the lack of optimization criteria when analyzing EAHEs and developed a specific computer tool based on a physical model which was experimentally validated. Bourouis et al. [10] Carried out numerical analysis of earth air heat exchangers at operating conditions in arid climates at Adrar (Algeria) and results showed that a simple EAHE system can provide 246.815 kWh in a period of one year.

This study presents, numerical analysis of ground heat exchanger performance. The model developed was validated using the experimental results on a set-up installed in El Oued region (Southern Algeria).

2. Experimental setup description

The experimental setup steps mainly consist of drilling the borehole, preparation of the exchanger and setting up of the heat exchanger into the water borehole as detailed below. Due to the low solidity of El Oued soil (sandy soil) the borehole was drilled using the Concrete cement rings to avoid falling of the sand, the borehole drilled with 1 m diameter and 5 m depth and then filled with water.

The geothermal heat exchanger has a helical shape. the exchanger made by PVC pipe with 30 m length and 6 cm diameter, it is formed of 12 spires and the space between two consecutive spires is 30 cm as shown in Fig.1. the input parameters used for calculation are given in Table 1.



Fig.1. Set up of the heat exchanger.

Table 1. Physical and thermal parameters used in the study

Material	Density (kg/m ³)	Thermal Capacity (J/kg °C)	Thermal Conductivity (W/m °C)
Air (300 K)	1.1774	1005.7	0.02624
water	1000	4180	0,60
PVC	1380	900	0,16

3. Mathematical modeling

The modeling of HWAHE is established in such a way that the following assumptions are respected: (a) water around the immersed pipe is homogenous; (b) water properties are isotropic and there is a perfect contact between the water and the pipe; (c) air flow is uniform along the length of the immersed pipe; (d) thermophysical properties of the air are constants; (e) the air flow is considered one dimensional [11]. The input parameters used for calculation are given in Table 1.

The energy balance is established as follow:

$$\dot{m}_a c_{pa} \frac{dT_a}{dx} = - \left(\frac{T_a - T_{water}}{R_{total}} \right) \quad (1)$$

where C_{pa} , \dot{m}_a , T_a , T_{water} , and R_{total} are the specific heat capacity of the air, mass flow rate of the air, soil temperature, air temperature and the total thermal resistance respectively. The total thermal resistance (R_{total}) is the contribution of water conductive resistance (R_{water}), pipe resistance (R_{pipe}) and air convective resistance (R_{cv}).

The total thermal resistance given by:

$$R_{total} = R_{pipe} + R_{cv} + R_{water} \quad (2)$$

The thermal resistance of the pipe can be expressed as:

$$R_{pipe} = \frac{\ln \left(\frac{r_e}{r_i} \right)}{2 \pi \lambda_{pipe}} \quad (3)$$

The thermal resistance of the water can be written as follow:

$$R_{water} = \frac{\ln \left(\frac{r_s}{r_e} \right)}{2 \pi \lambda_{water}} \quad (4)$$

The thickness of the water radius is equal to the radius of the pipe ($r_s = 2 \times r_i$) [12].

The convective thermal resistance R_{cv} may be expressed as:

$$R_{cv} = \frac{1}{2\pi r_i h_a} \quad (5)$$

Where r_i , r_e and r_w are the inner and outer radius of the pipe and the water well radius respectively.

By solving Eq. (6) analytically, the air temperature $T(L)$ along the helical heat exchanger is given as follows [10, 13]:

$$T(L) = T_{water} + (T_{in} - T_{water}) \times \exp\left(\frac{-1}{\rho C_{p,air} S_{in} V R_{total}} L\right) \quad (6)$$

where T_{in} , S_{in} , V are the inlet air temperature, inner surface of the pipe and the air velocity respectively.

The efficiency of the HWAHE is defined as the ratio of the air temperature drop between the outlet and the inlet of the HWAHE and the difference between soil and inlet air temperatures:

$$\varepsilon = \frac{T_{outlet} - T_{inlet}}{T_{soil} - T_{inlet}} \quad (7)$$

4. Model validation

The model has been validated for summer weather conditions by taking observations on the actual experimental set-up (as shown in Fig. 1) in the month of May, 2017 at El Oued (Southern Algeria). Comparison of numerical and experimental values of outlet temperature is summarized for air velocity of 10 m/s in Table 3 and presented as plot in Fig. 2. In this validation exercise, inlet condition of air in the model was kept same as measured at the experimental set-up.

It is observed from Table 3 that there is a difference of 7.1–10% between the experimental and numerical data. Thus, the model was considered to be usable to carry our detailed analysis.

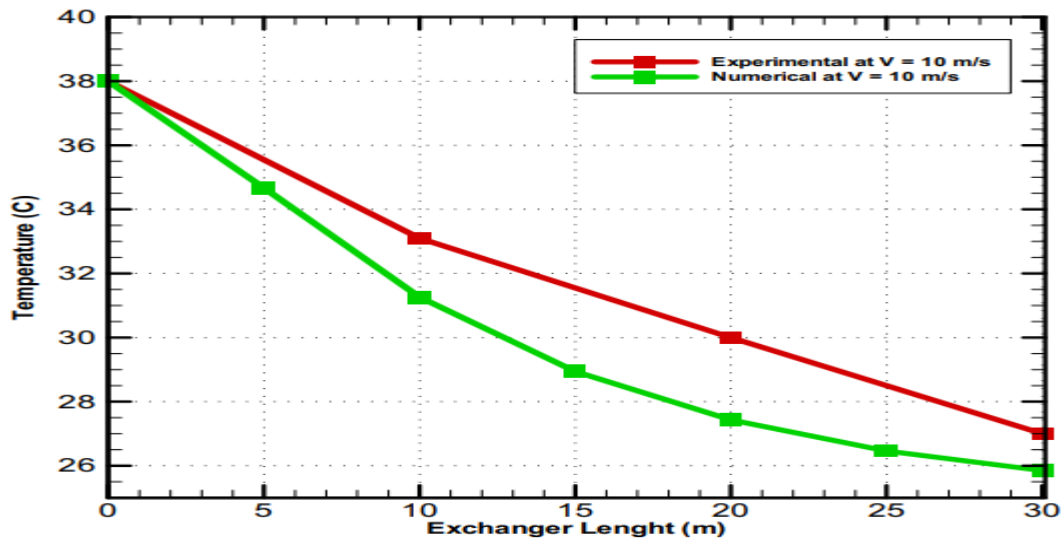


Fig.2. Variation of the air temperature versus the length of the exchanger.

Table 3. Results of model validation against the experimental data at $V = 10$ m/s.

T_{inlet} (°C)	Experimental T_{outlet} (°C)	Numerical model T_{outlet} (°C)	Relative error %
40.3	27.9	25.0	10
38.4	27.2	24.9	8.4
35.6	26.7	24.8	7.1

5. Results and Discussion

5.1. Effect of the air velocity on the performance of the exchanger

The below plot shows the evolution of the air temperature in the exchanger based on the numerical model of equation (6), the evolution of the air temperature in the exchanger from the inlet to the outlet. It is well noted that the temperature of the air decreases from the inlet to the outlet of the exchanger.

Three velocity was entered to the numerical model ($V = 10$ m/s, $V = 15$ m/s, $V = 20$ m/s) to see the influence of the flow rate on the geothermal exchanger behavior, it is clearly shows that when the velocity increases the efficiency of the exchanger decreased due to the gap between the inlet and the outlet air temperature of the exchanger decreased. An

important gap achieved between the inlet and the outlet air temperature of the exchanger such with $V = 10$ m/s the temperature gap reached until 12.2 °C.

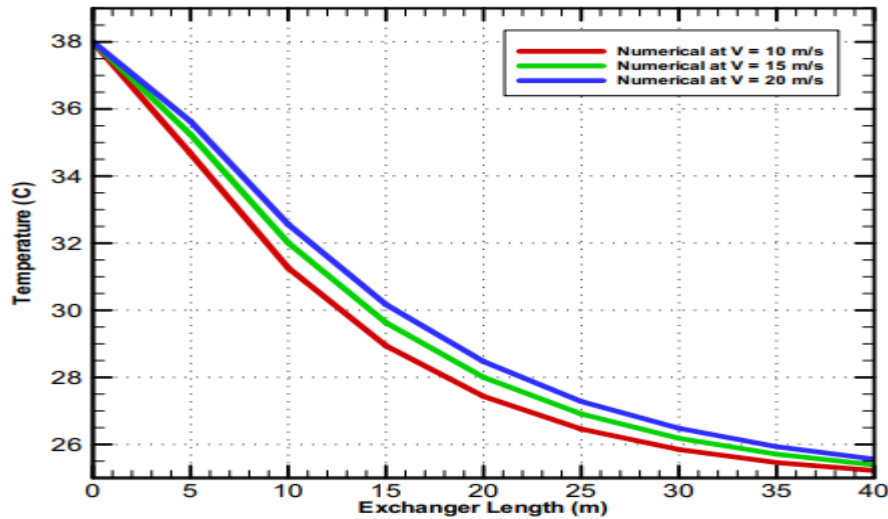


Fig.3. air velocity versus the length of the exchanger.

5.2. Effect of the inlet temperature on the performance of the exchanger

The Experimental measurements shows as described in the below plot that when the temperature difference between the ambient air and the water borehole increase the gained temperature gap between the inlet and the outlet of the exchanger increase too. Moreover, we found that the corresponding temperature differences between the ambient air and the cooled air at the outlet of the exchanger for inlet air temperature of 42 °C and 35.6 °C are respectively 13.9 °C and 8.7 °C. This is due to the fact that when the temperature of the ambient air is greater than that of the water borehole, the thermal losses towards the tube walls are also great. This causes its temperature to drop considerably.

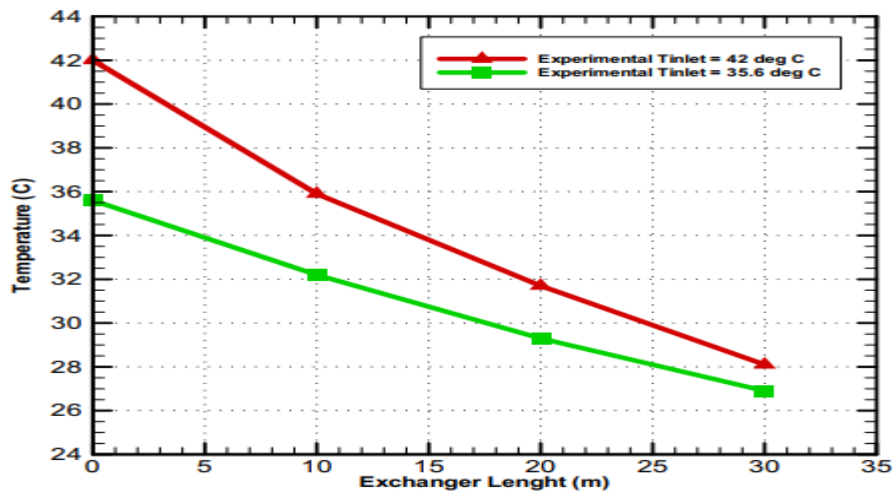


Fig.4. Effect of the inlet temperature versus the length of the exchanger at $V=10$ m/s.

5.3. Effect of the exchanger functioning on the water borehole temperature

In order to evaluate the influence of the exchanger during its functioning period on the water borehole temperature which is basically the soil temperature. The exchanger functioned for a period of 8 hours in the hot time of the day from 10:00 until 18:00 with velocity of 10 m/s, the ambient temperature starts from 34.4 °C at 10:00 and reached its maximum 40.3 °C at 14:00 and then continued to decrease until reached 33.4 °C at 18:00. Therefore, the outlet air temperature was within the interval between 27.9 °C and 25.8 °C for inlet air temperature of 40.3 °C and 33.4 °C respectively.

However, it is clearly shown in the below plot that the water borehole temperature remained constant within the 8 hours of the exchanger functioning and confirmed the feasibility of the geothermal heat exchanger as the soil plays the role of the cold source during the hot season and the hot source during the cold season.

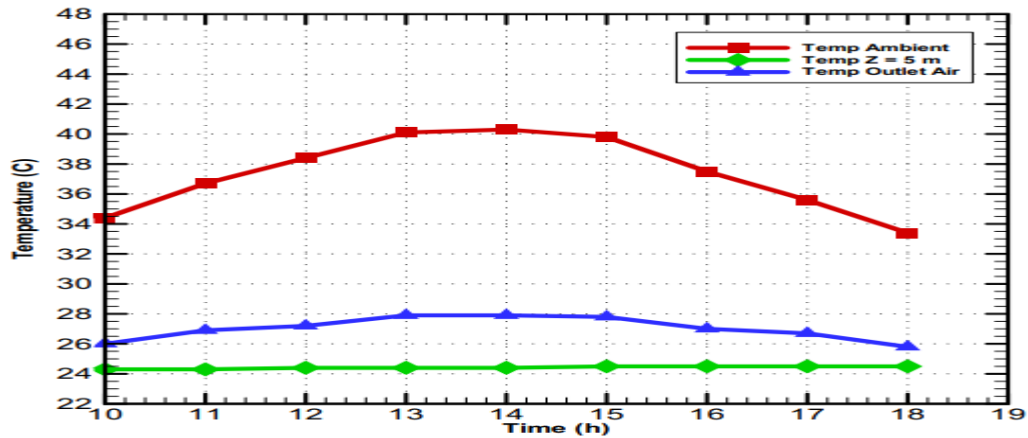


Fig.5. Variation of the ambient, outlet air and water borehole temperatures versus time.

6. Conclusion

This study presented a helical geothermal heat exchanger was immersed in a water borehole of 5 meters depth and tested in El Oued region, Algeria. At the end of this study and through the results obtained, a promising vector in climate engineering as a renewable energy source will have to be unquestionably exploited industrially. The Numerical model presented reflects the evolution of the air temperature as a function of the main parameters. This model can be used in case missing of experimental data to dimension an air / ground exchanger.

The model developed was first validated using experimental data. A parametric analysis was then performed to evaluate and investigate the effect of the length of the buried pipe and the air flow rate on the temperature of the air at the tube exit. The main conclusions are here in summarized.

- The air / ground exchanger alone can achieve thermal cooling comfort, and it can reduce the consumption of electric power as the use of air conditioning means.
- The geometry of helical shape can be used to decrease the area of installation of the geothermal heat exchanger and to assure the maximum of heat transfer from the greater depth of the ground.
- The flow velocity has such an important effect on the functional of the geothermal exchanger. The temperature of the cooled air increases linearly with the speed of the air. Therefore, it is better to choose a speed neither very low nor very high.
- The temperature of the air inside the pipe decreases more in the first section of the exchanger and less in the second section, therefore longer pipe involved low effectiveness and a high drop of the pressure.

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