A Numerical Investigation of a Horizontal Spiral Coil Ground Heat Exchanger (HSGHE) for a Geothermal Heat Pump Using Variable Fin Characteristics

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Abstract

Ground Heat Exchanger (GHE) is one of the most efficient sources of renewable energy where the heat from the fluid is either taken from or given to the ground. In this study, the increase in the Heat Transfer Rate (HER) of a Horizontal Spiral coil Ground Heat Exchanger (HSGHE) with fin has been analyzed and the difference between with and without fin GHE has been evaluated with the help of numerical analysis using the ANSYS 19 software. To compare the thermal performances, different shapes (rectangular and circular) of fin, sizes of fin length, and number of fins per turn of GHE coil were investigated with varying fin materials to evaluate an optimum outlet fluid temperature and HER for the HSGHE. The proposed model extracts heat from the working fluid and releases it to the ground, thus creating a cooling effect. Four pitch lengths of 0.03m, 0.04m, 0.05m, and 0.06m are considered. Three different fin materials: polyethylene, copper, and aluminum are used to evaluate the optimum fin material. It has been found from the analysis that the circular fin model with 0.04m pitch length of copper material increases the HER by 14.5% than the without fin model. The fin numbers were also varied from 4 to 8 fins per turn to observe the effect of the number of fins on HER. It has been observed that if the number of fins increases from 1 to 6 per turn of the spiral GHE coil, HER increases gradually. However, 7 or 8 fins per turn decreases the HER than the 6 fins per turn model. The effect of the fin length on the HER has also been investigated.

Keywords
Horizontal Spiral-coil Ground Heat Exchanger (HSGHE), Heat Exchange Rate (HER), Heat pump, Spiral coil, Heat transfer rate.

1. Introduction
Recently renewable energy sources have become a great alternative way to energy supply. Among them, the geothermal heat pump is one of the vital sources. The ground source heat pump (GSHP) is one of the most potential technologies for building heating and cooling and it is a great source of renewable energy utilization (Yuan et al. 2012). In household buildings, offices, and many other places where there is a requirement for a good amount of heating and cooling operation, this type of geothermal heat pump can provide a good performance and can be an easy source of energy also (Beier 2014). Although having higher upfront costs, GSHPs are the most productive heating and cooling technology because they use up to 50% less electricity than conventional heating and cooling systems (Sarbu and Sebarchievici 2014). The GSHP can be of different orientations. They are- horizontal, vertical, radial, open loop, Direct Exchange (DX), etc. Concerning the traditional air source heat pump, the HSGHE uses the shallow ground as a heat source or sink for the heat pump and it greatly increases the performance and efficiency (Yuan et al. 2016). One of the most important parts of a ground source heat pump system is its ground heat exchanger (GHE). The heat exchanger can be of vertical and horizontal types according to their orientation. The GHE coil can be of different shapes such as - spiral, slinky, U-tube, W-tube, and more. Fuiji et al. (2013) showed a performance prediction method for horizontal slinky coil GHE. The results showed good agreement between measured and simulated values. However, the main advantages of using the HSGHE is its easy construction and low cost and also a huge reduction of land area than the traditional straight GHE (Yang et al. 2019). Including a fin around the coil surface will transfer more heat to and from the ground. The horizontal orientation has been chosen over the vertical one because the bore required for the installation is very costly. The horizontal heat exchanger can be easily installed as it requires less boring depth. As the spiral coil has a greater pipe density, the horizontal spiral coil GHE can exhibit better heat transfer performance.

2. Literature Review
Park et al. (2012) demonstrated an experimental and numerical study on the thermal performance of the HSGHE with the help of a thermal response test (TRT) in a dry sand room. For different screw pitches and heat source models and conditions, the average fluid temperature and other thermal performance parameters were evaluated. Similar types of experiments were also done on vertical heat exchangers but the results were different. Dehgan and Kukrer (2016) presented a U-type coil heat exchanger for vertical orientation and showed its thermal characteristics. The drilling in this case was done in such a way to save at least 20% of the cost. Vertical Spiral coil heat exchangers provide a good amount of heat transfer but the cost associated with their installation is much greater than the horizontal one. The fin attachment with the vertical spiral coil heat exchanger showed a good amount of increase in temperature difference which enhanced the heat transfer rate by 31% (Saeidi et al. 2018). Also, different shapes of fins were used in this case, and for each fin, the heat transfer rate was calculated.

For the spiral coil type heat exchanger, the pitch length has great importance. For a specific pitch length, there is a specified fluid velocity that provides an optimum result (Minjun et al. 2016). Spiral coil pitch variation was shown by Jalaluddin and Miyara (2015) where pitch length was taken at 0.05, 0.1, and 0.2 and for the pitch length of 0.05, the heat exchange rate increased by 69.2% for laminar flow in comparison to straight pipe in the borehole. A ring-coil source model was developed which showed the impact of the coil pitches but that model was different from the spiral coil one (Man et al. 2010). In another study, it is manifested through simulation that the Nusselt number and heat transfer coefficient are higher in the case of a circular tube when compared with a rectangular tube (Bisht et al. 2014). To understand the behavior of GHE, these properties must be known and these are the key factors for the heat transfer performance of the ground heat exchangers (Florides et al. 2013). A helical coil source model has been developed to consider the effects of 3D shape and radial dimension (Park, S. et al. 2013).

3. Method

3.1 Model Analysis

For designing the spiral GHE, 04 models were constructed by varying the pitch length of the spiral coil. They were named as Model-01 (0.03m pitch length), Model-02 (0.04m pitch length), Model-03 (0.05m pitch length) and Model-04 (0.06m pitch length). The design and simulation of the GHE was done in SOLIDWORKS 2018 and ANSYS 19. The GHE model was simulated in the cooling mode where the inlet water temperature was at 300K. The initial soil temperature is assumed to be constant at 290K. The flow velocity of the circulated water was set to a value of 0.1 m/s.

Table 1. Geometric parameters of the GHE coil.

Parameters	**Value (m)**
Outer diameter, d_o	0.012
Inner diameter, d_i	0.009
Pitch length for spiral-tube GHEs, p	0.03, 0.04, 0.05, 0.06
Diameter of soil	0.2
Spiral diameter, D	0.0813
Coil Length	0.4

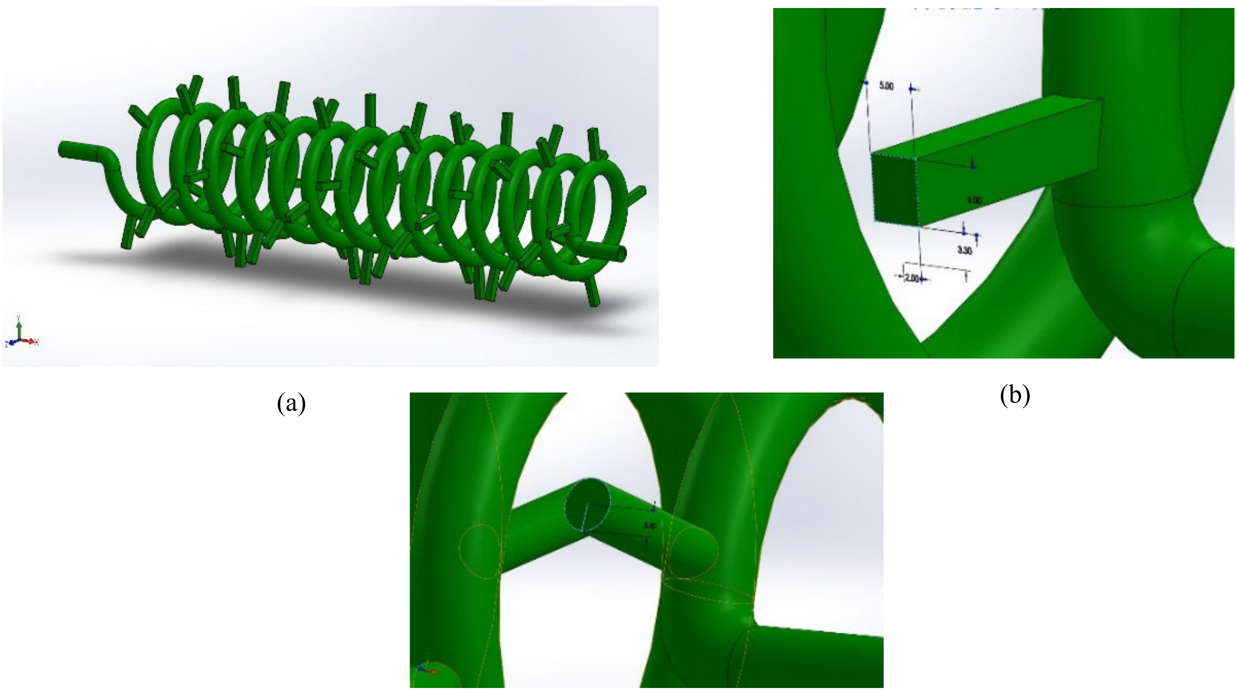
Table 2. Geometric parameters of the Fin

Type of Fin	**Length (m)**	**Width (m)**	**Height (m)**	**Diameter (m)**	**Number of Fins**
Rectangular	0.005	0.006	0.07	N/A	60
Circular	N/A	N/A	0.07	0.0035	60

Table 3. GHE coil Material properties used for Fin

Material Name	**Density (Kg/m^3)**	**Specific Heat (J/Kg.K)**	**Thermal Conductivity (W/m-K)**
Polyethylene	920	2300	0.35
Copper	8978	381	387.6
Aluminum	2719	871	202.4

The geometric parameters of the GHE coil and Fins are shown in Table 1 and Table 2. The Fin materials that were varied during the simulation is shown in Table 3. Keeping some assumptions like- the soil is considered uniform, and its properties are constant, ignoring the contact thermal resistance between the HSGHE and soil, and primary temperature of soil and HSGHE are the same into consideration (Yang et al. 2019). The fluid inlet velocity was taken to be 0.1 m/s with a temperature of 300K, whereas, the GHE coil and soil domain had the temperature of 290K. Energy equation and the standard K-epsilon model were used to get the most precise result during the numerical analysis. The GHE coil structure is demonstrated in Fig 1(a). Also, Fig 1(b) and 1(c) shows the closer look of the rectangular and circular fin geometry.



(a) (b) (c)

Figure 1. (a) GHE coil with fin attachment. (b) Rectangular fin model. (c) Circular fin model.

3.2 Governing Equation

To calculate the experimental heat exchange rate of the GHE to analyze its performance, the following equation is used:

$$\boldsymbol{Q = mC_p(T_i - T_o) \ldots (1)}$$

where *m* is the flow rate of inlet water (kg/s), Cp is the specific heat of water (J/(kg·K)), T_i and T_o are the inlet and outlet temperatures of water.

The heat transfer process in this study mainly includes thermal convection between circulating fluid and pipe wall and thermal conduction in the soil. The heat transfer in the soil can be taken as pure conduction because the soil is considered as a continuous solid and the energy equation is:

$$\boldsymbol{\frac{\delta_T}{\delta_t} = \alpha_s \nabla^2 T + \frac{q_v}{\rho_s C_p} \ldots\ldots\ldots\ldots (2)}$$

Where T is the soil temperature, t is the time, $\boldsymbol{\alpha_s}$ is the thermal diffusivity of soil, ρ_s is the density of soil, C_p is the specific heat of soil, q_v is the source term.

3.3 Mesh Independency Test

It is a test where the solution does not change significantly when the mesh is changed or made finer. With default coarse mesh, the outlet temperature varied much than finer mesh. For the rectangular fin model, it can be seen that for mesh-2, mesh-3 and mesh-4, the outlet temperature change is smaller than mesh-1. So, the value of mesh-3, 298.804K, is taken for further calculation.

Table 4. Mesh Independency Test

Mesh Number	Element Number	Node Number	Outlet Temperature (K)
Mesh 1 (Size – 0.2)	12,00,932	2,66,088	299.031
Mesh-2 (Size- 0.15)	15,07,258	3,70,122	298.927
Mesh-3 (Size- 0.1)	16,51,445	4,40,462	298.804
Mesh-4 (Size- 0.08)	16,52,831	4,40,730	298.801

3.4 Validation of the proposed model

The designed model is validated with the historic design from (Jalaluddin at el. 2015). The Outlet temperature of the spiral coil heat exchanger and the heat exchange rate is being shown in the graph from the validation. The Soil temperature was 310K and the inlet fluid temperature was 290K. The pitch lengths were 0.05m, 0.1m, and 0.2m. Both field of study were same. The difference is very minimal, about 0.02-0.1% for outlet temperature and 1-5% for HER and is in the higher side as the model had to be reduced in dimensions for computational purposes.

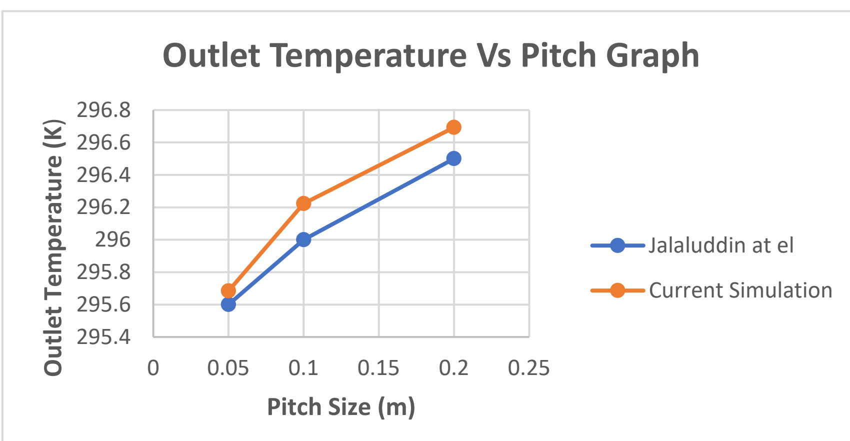


Figure 2. Numerical Validation of the proposed model

3.5 Convergence of solution

The solution converged at 52 iterations where the residual value was taken to be 10^{-3}. Total iteration of 1000 was taken with the residual value of 10^{-3} for more precise calculation.

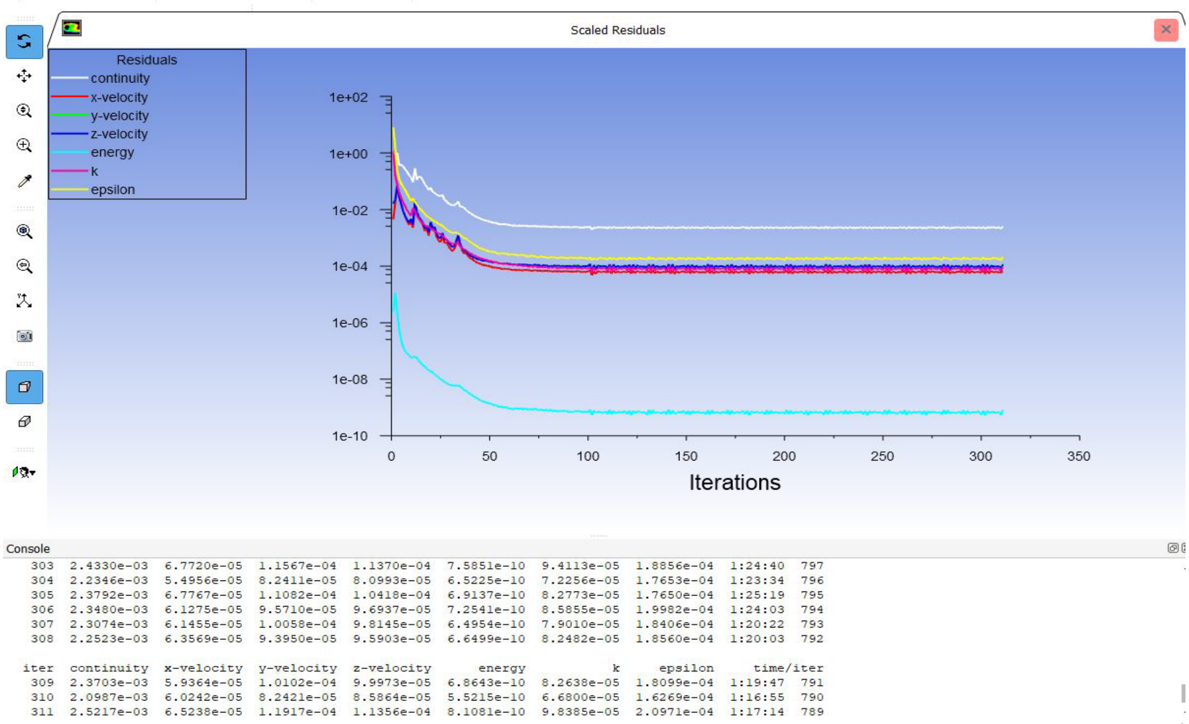


Figure 3. Solution convergence

4.0 Results and Discussion

4.1 Effect of Fin and Coil Material on the Outlet Fluid Temperature and Heat Exchange Rate (HER):

Table 5 shows the outlet fluid temperature of the GHE coil with and without fin configuration. A higher outlet temperature indicates a lower heat transfer characteristic. The GHE coil without fin has the lowest outlet fluid temperatures of 298.889K (Copper Material) for pitch 0.04m (Model-02). With increasing pitch length (i.e.- Model 03 and 04), the outlet fluid temperatures increased. Due to increased pitch length, the heat transfer area is reduced for the same length of the coil. Model-01 also has a higher temperature than Model-02. This is because 0.03m pitch creates higher thermal interference in the GHE coil. It can be observed that the fin arrangement (rectangular and circular) shows comparatively lower outlet temperature than without the fin model which indicates the increase in heat transfer characteristics.

Table 5 also shows the HER of the corresponding models with different pitch lengths. It is fathomable that with lower outlet fluid temperature, the temperature gradient of the fluid will be higher, which will ultimately increase the HER. Likewise, it can be seen that for pitch length 0.04m (Model-02), the outlet fluid temperature was the lowest. Thus, the HER is higher than all other orientations. For Model-02, the HER for the rectangular fin section is around 176W whereas, for the circular fin model, it is around 184W. It indicates that, with a circular fin, the HER increases by about 4.5% than a rectangular fin attachment. Because of the upper hand of shape, circular fin provides better heat transfer characteristics than rectangular fin. It is also noticeable that with fin configuration, GHE coil provides a higher HER than without fin arrangement.

Table 5. Numerical Data of Outlet Temperature and Heat Exchange Rate for four designed GHE model with rectangular fin, circular fin and without fin attachment. (Model-01 (0.03m pitch length), Model-02 (0.04m pitch length), Model-03 (0.05m pitch length) and Model-04 (0.06m pitch length)

Coil Material	**Model**	**Outlet Temperature (K)**			**Heat Exchange Rate (W)**		
		Rectangular Fin	Circular Fin	Without Fin	Rectangular Fin	Circular Fin	Without Fin
Polyethylene	Model-01	299.309	299.291	299.326	98.252	100.811	95.835
	Model-02	299.232	299.219	299.312	109.200	111.048	97.825
	Model-03	299.363	299.342	299.388	90.573	93.559	87.019
	Model-04	299.400	299.391	299.406	85.312	56.592	84.459
Copper	Model-01	298.791	298.735	298.954	171.905	179.868	148.729
	Model-02	298.759	298.700	298.889	176.455	184.844	157.970
	Model-03	298.804	298.782	299.014	170.056	173.184	140.197
	Model-04	298.843	298.814	299.041	164.511	168.634	136.358
Aluminum	Model-01	298.855	298.824	298.995	162.805	167.213	142.899
	Model-02	298.810	298.793	298.963	169.203	171.621	147.448
	Model-03	298.928	298.872	299.080	152.425	160.388	130.812
	Model-04	298.937	298.826	299.108	151.145	171.620	126.831

Between circular and rectangular fin arrangements, circular fin with a pitch length of 0.04m (Model-02) shows the best performance for all the three coil materials. Among the three materials, Copper demonstrated the best results for all models because of its higher thermal conductivity. Figure 4(a) and 4(b) shows the variation of outlet temperature and heat exchange rate with different fin orientation with copper as the coil material. It is observed that copper has the lowest outlet temperature and the highest HER. Figure 5 shows the temperature contour for GHE coil with circular fin attachment.

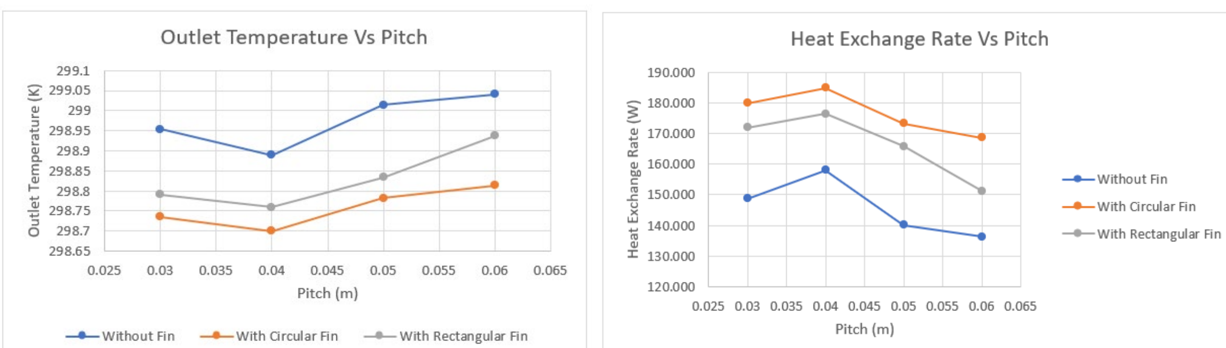


Figure 4. (a) Variation of outlet fluid temperature with the pitch for with and without fin models for Model-02 with copper coil material. (b) Variation of Heat Exchange Rate with the pitch for with and without fin models for Model-02 with copper coil material.

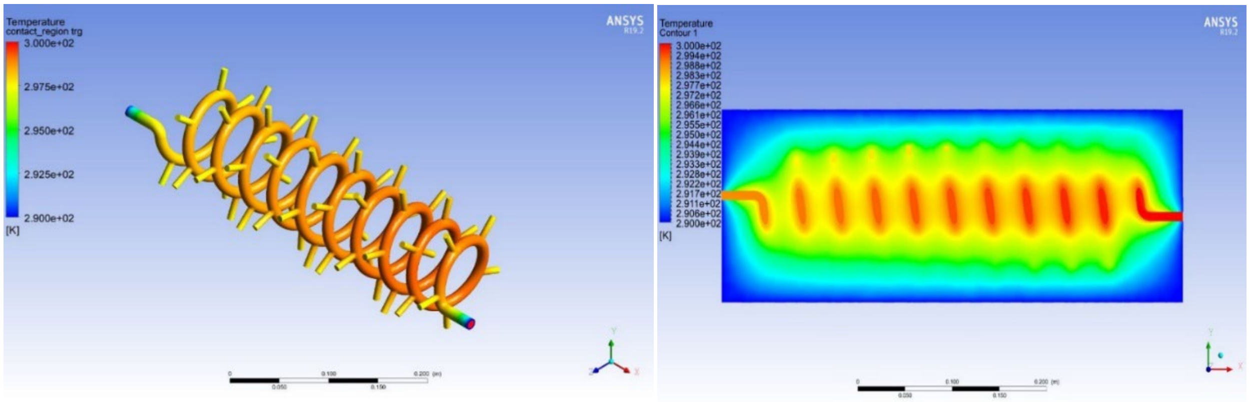


Figure 5. Temperature contour of the GHE coil with pitch=0.04m with circular fin.

4.2 Effect of Number of Fins and Fin Size on HER:

From Figure 6, it can be observed that initially with the increase of fin number per turn on the GHE coil, the HER increases. For 4, 5, and 6 fins per turn, the HER is 168.624W, 173.305W, and 184.844W respectively. This is because the heat transfer surface area increases with the increasing in numbers. But when fin numbers are 7 and 8 per turn, the HER decreases to 179.862W and 177.507W. This nature of decreasing HER can occur due to thermal interference. As the fin numbers were increasing, the distance between the fins was decreasing. Thus, each fin was not able to dissipate heat efficiently which results in lower HER. As the highest HER from the model was 184.844W which was with 6 fins per turn, this type of GHE coil configuration with fin can be used to extract heat effectively.

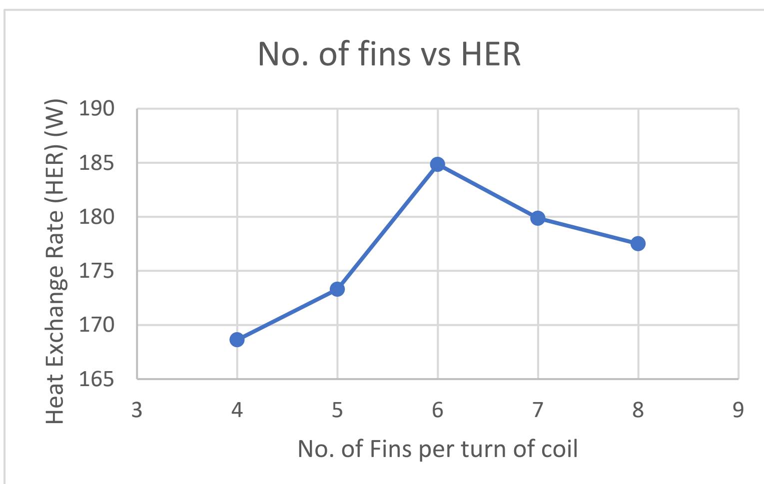


Figure 6. Variation of HER with the number of Fins per turn.

As the circular fin showed better performance than the rectangular fin, the length of the circular fin has been taken into consideration for observing the change of the Heat Exchange Rate (HER) of the GHE coil. For the circular fin, the diameter was taken to be 0.0035m and the length was 0.07m (Table-2). So, keeping the diameter constant, the length was varied from 0.05m to 0.1m in Figure 7. Though the HER value increased with increasing fin length, the values were quite close to each other. For instance, HER value 0.07m, 0.08m, and 0.1m fin length was 184.844W, 184.903W, and 184.952W respectively. So, the increase in HER is not significant enough. This type of nature in HER value can occur due to continuous heat dissipation from the fin and thus after a certain length of fin length, the HER does not increase significantly.

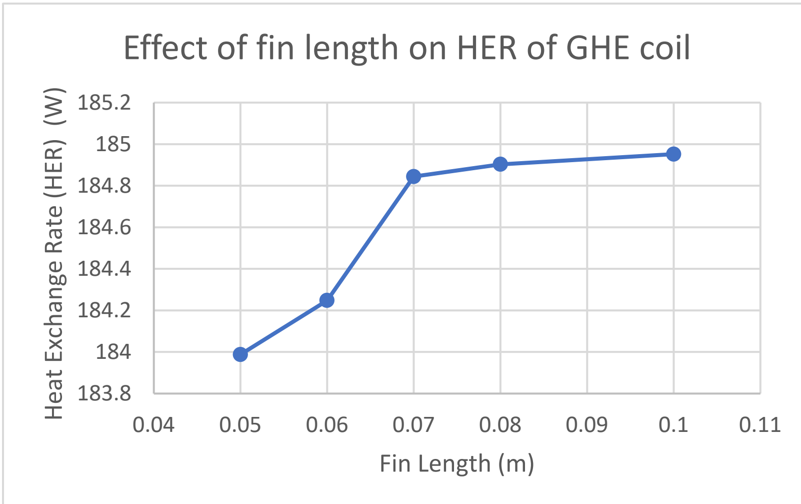


Figure 7. Variation of HER with the length of the Fin.

5. Conclusions

Horizontal Spiral coil Ground Heat Exchanger for Ground Source Heat Pump is an effective technique for extracting heat from working fluid and releasing it to the ground. With the inclusion of fins on the GHE coil periphery, the HER of the GHE increases significantly. In this research, two different shapes of the fins, circular and rectangular, were evaluated, and between them, in terms of HER, the circular fin model (184.844W) showed better results than the rectangular fin model (176.455W). By varying pitch length, it was observed that lower pitch length provides better HER and 0.04m pitch length has the optimum heat transfer characteristics. Six (06) fins per turn of the GHE coil provided a HER of 184.844W, which decreases if the fin number is increased more than 6. Copper as fin material provided more satisfactory HER than aluminum and polyethylene. Moreover, increasing the fin length beyond 0.07m did not provide a satisfactory increase in the HER value. The HER increased by about 14.5% for the copper-made circular fin with 0.04m pitch length (Model-02) than without fin model.

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Torikul Islam received B.Sc. degree in biomedical engineering from Khulna university of engineering & Technology, Khulna, Bangladesh. He is currently pursuing the Ph.D. degree in Biomedical engineering with New Jersey Institute of Technology, Newark, NJ, USA. He worked as Research Fellow at Photonics Research Group, KUET. He also founded Bio-neural Intelligence and Research Advancement Laboratory. He is a Graduate Research Assistant at Sensorimotor Quantification and Rehabilitation Lab, NJIT, USA. His field of interest Biomedical Engineering, Neuro Engineering, Bio-Photonics, Biomaterials, Biomedical signal and Image processing, Numerical Analysis. He has published 3 peer-reviewed journal articles and 5 peer-reviewed international conference papers.