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COMPUTATIONAL INVESTIGATION ON THE EFFECT OF VARIOUS PARAMETERS OF A SPIRAL GROUND HEAT EXCHANGER

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ABSTRACT

Shallow Geothermal Energy, a Renewable Energy Source, finds application through Ground Source Heat Pumps (GSHPs) for space heating/cooling via tubes directed into the ground. Vertical Ground Heat Exchangers (GHEs) of various configurations (mainly U-tubes) extract/reject heat into the ground. Spiral type GHEs constitute an alternative to reduce the depth and hence the cost of GSHP systems. Such GHEs are used in energy piles, which are reinforced concrete foundations with helical pipes whereby heating/cooling is provided. Testing GHEs through experimental set-ups is expensive and time consuming. Hence, a computational investigation is preferred. To this end the current paper introduces a 3D mathematical model, based on the convection-diffusion equation, in COMSOL Multiphysics. The related parameters are adjusted, and the model is validated, against experimental data. The validated model is subsequently adapted to match the Cyprus moderate Mediterranean conditions. A parametric investigation of the important implications in the design of GHEs is also conducted.

Keywords: Ground Heat Exchanges, Spiral GHE, COMSOL validation

1. INTRODUCTION

Renewable Energy Systems (RES) have increased in popularity in recent years through a global effort to divert away from fossil fuels and reduction of CO2. Such a system is Ground Source Heat Pump (GSHP), which takes advantage of the Geothermal Energy stored in the sublayers of the earth. GSHP systems are used for space heating and cooling, where heat is either extracted or rejected to the earth using a network of tubes directed into the ground.

There are two main categories of Ground Heat Exchanger (GHE) types: the horizontal and the vertical types. The most commonly used ones are the vertical types, which require less space and have higher performance that the horizontal types (Aresti, Christodoulides and Florides, 2018). The main configuration of vertical types are the U-tube and double U-tube GHEs. In recent years a different configuration has become popular, namely the spiral or helical type GHE. Spiral GHEs was introduced to reduce the GHE depth and has been used in foundation piles, identified as "energy piles" (Carotenuto *et al.*, 2017). Spiral GHEs, due to their high efficiency, can be coupled with GSHP systems for heating and cooling a building. The overall aim of this configuration is to reduce the initial capital and the cost of the GSHP system and to make it more attractive for investment. In particular, energy piles are reinforced concrete foundations with helical pipes, whereby the buildings foundations are utilized to provide space heating and cooling. Typical sizing of the energy piles is considered between 20–40m depth and 0.4–1.5m diameter as reported by Brandl (2013).

Investigation of the spiral coil configuration was performed by Bezyan et al. (2015) using the FLUENT software. A validation against a U-tube configuration was achieved by the authors by comparing the outlet temperatures. The authors compared three different configuration models: the U-tube, the double U-tube (or W-shaped) and the spiral coil, with the spiral configuration providing the highest efficiency in heat transfer rate and energy output. A similar comparison was also performed by Zhao et al (2016). The authors used the COMSOL software to perform computational investigations. The results indicated that the spiral-shaped GHE was estimated to have the better thermal performance than the other GHE configurations in long-term and short-term thermal loads. Further experimental and numerical studies have been conducted by several researchers with the aim to maximize efficiency and to identify the most accurate way for effective energy piles design (e.g., Gao et al. 2008; de Moel et al. 2010; Suryatriyastuti, Mroueh and Burlon, 2012; Brandl 2013; Gashti, Uotinen and Kujala 2014; Yoon et al. 2015; Fadejev et al. 2017)

Energy piles have yet to be applied in Cyprus and, thus, a preliminary assessment considered and investigated before application would be useful. The aim of this paper is to study the effect of the different aspects on the spiral

GHE configuration using a computational modeling approach under the moderate climate conditions of Cyprus.

2. COMPUTATIONAL MODELING

To examine different parameters of a GHE, one can perform either experimental or computational investigations. In general, the sheer experimental set-up and testing of a GHE is expensive and time consuming, therefore a computational investigation is preferable. Here a numerical model using the COMSOL Multiphysics software that is based on the convection-diffusion equation is introduced. The three-dimensional conservation of the transient heat equation for an incompressible fluid is used:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \cdot \nabla T + \nabla \cdot q = Q \tag{1}$$

where ρ is density, c_p is the specific heat capacity at constant pressure, T is the temperature, t is time, u is the velocity, Q is the heat source, and q comes from the Fourier's law of heat conduction. The second term, implicating velocity is only referring to the domain where underwater flow is present and does not apply to the rest of the domains.

The three-dimensional model consists of the spiral pipe domain, the grout domain (borehole, well or pile foundation) and the ground domain.

Modeling a GHE at full scale can be challenging since there is a high scale difference between one dimension (vertical z-axis) and the other two (x- and y-axes). Due to the unbalanced dimensions, meshing the model with equilateral cells will require high computational time and memory.

Existent computational methods could overcome this issue by either applying a coordinate scaling system (Aresti, Florides and Christodoulides, 2016) or by applying parallel computational running with a simplified version (see Equation 2) on the pipes and Equation 1 on the rest of the system, as emended in the software:

$$\rho A c_p \frac{\partial T}{\partial t} + \rho A c_p u e_t \cdot \nabla_t T = \nabla_t \cdot \left(A k \nabla_t T \right) + \frac{1}{2} f_D \frac{\rho A}{d_h} |u| u^2 + Q \tag{2}$$

where A is the area of the pipe, ue_t is the tangential velocity, f_D is the Darcy's friction factor based on Churchill friction model and d_h is the diameter of the pipe.

Figure 1 illustrates the geometry of the model serving as a study-case, where the spiral coil can be observed as a line in a 3D environment.

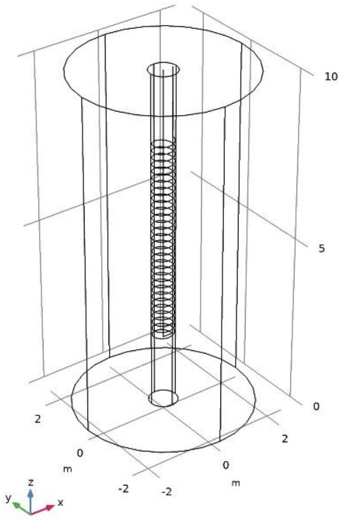

Figure 1: The geometry of the model.

3. VALIDATION AND RESULTS

The related parameters are adjusted to present actual parameters taken from experimental data by Dehghan (2017). Experimental data were obtained using a Thermal Response Test (TRT), which is the most commonly used method to determine the thermal characteristics of the ground (see, for example, Mogensen 1983; Christodoulides et al. 2016). Therefore, the computational model is validated against available experimental data, as shown in Figure 2. It can be observed that the computational results are less compatible during the first 10 hours of the model run. This can be due to the lack of detailed information from the experimental results, as only average values were provided. The rest of the graph though, indicates a very good agreement between the experimental and computational data.

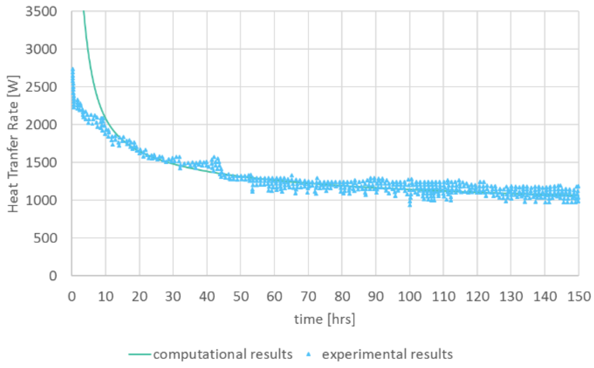

Figure 2: Experimental validation of computational model for a spiral GHE.

The model could be then modified to incorporate a theoretical case scenario of an energy pile system installed in a building in Cyprus for different climate conditions. The validated model is subsequently adapted to match the Mediterranean conditions in Cyprus. The new model is designed with a 10m depth and a 0.4m diameter. The selected model geometry (also seen in Figure 1) consists of a 10m depth pile, a 6m depth spiral coil, a 0.8m pile diameter and a 5m domain diameter. A similar configuration is described at the new public library in Limassol, Cyprus, where a spiral coil is incorporated in a well. In order to obtain more accurate and realistic results, ground temperature data were considered, as in Figure 3, where it can be observed that the temperature below a depth of 7m is constant at 22°C. The same temperatures are observed in a similar case in Limassol by Florides, Pouloupatis and Kalogirou (2011).

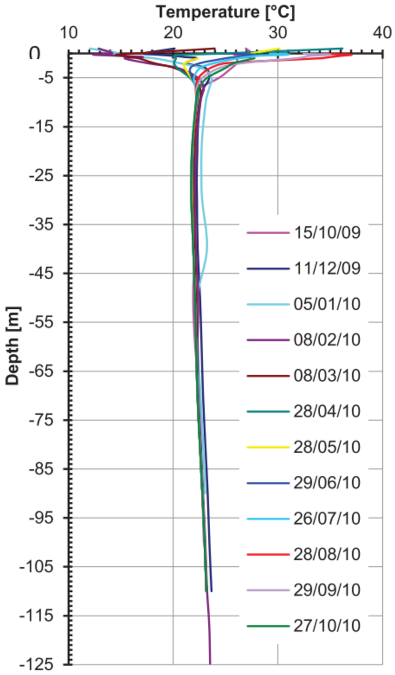

Figure 3: Recorder ground temperature at Lakatamia, Cyprus for a day from each month of a year (Pouloupatis, Florides and Tassou, 2011)

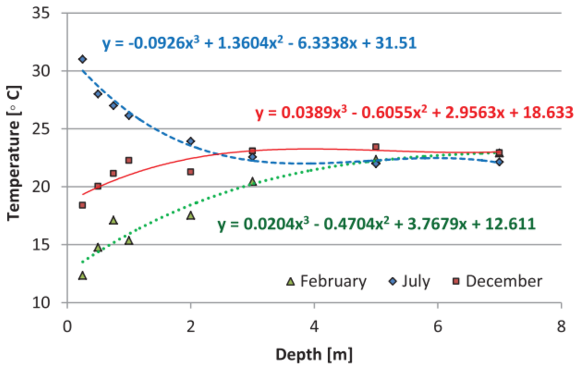

Figure 4: Recorded underground temperature at the Lakatamia shallow zone (0–7m), shown is the best-fit equation

Stylianou et al. (2019) have analyzed the data of Figure 3 and have illustrated a shallow zone temperature gradient (Figure 4) to be used in the computational model. The equation of the ground temperature is input as initial temperature in the computational model. The case of summer was examined for the month of July. Furthermore, the ground characteristics of the case study in Limassol are considered. The ground examined to consist of marl, chalk and gravel, with the complete model material properties described in Table 1.

Table 1: Material properties

Material	k $Wm^{-1}K^{-1}$	ρ kg m^{-3}	c_p J Kg^{-1} K^{-1}	Description
Ground	1.4	2300	950	Marl, chalk and gravel
Grout	1.628	2500	837	Reinforced concrete
Pipes	0.42	1100	1465	HDPE
Water	0.6	998.2	4182	water

The configuration of the energy pile and the dimensional characteristics are defined in Table 2.

Table 2: Model dimensional characteristics and operating parameters

Dimensional Characteristics	
Energy Pile length	10 m
Energy Pile diameter	0.8 m
Spiral coil diameter	32 mm
Pipe (coil) thickness	3 mm
Operating Parameters	
Fluid flow rate	15 l/min
Inlet temperature	60 ºC

Following the model set-up, the spiral pitch was varied from 0.1m to 0.5m by 0.1m increments. With the spiral pitch changed, the length of the pipe also changed since the depth of the pile was kept the same. The results can be seen in Figure 5.

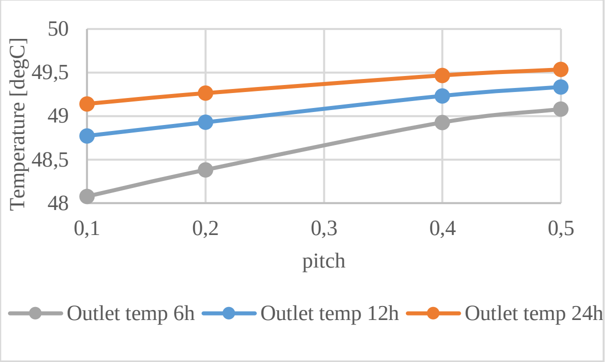

Figure 5: Spiral pitch effect on outlet temperature at different operating durations

The results obtained demonstrate that the higher the pitch, the higher the outlet temperature of the pipe. Similar results were obtained by Park et al. (2015) and Park et al. (2016).

By investigating the higher operating time duration (24h), it can be seen that the effect of the spiral pitch on the outlet temperature is decreased. This is an expected result since for long enough durations of the heat injected into the system, the pile steady state independent of the pitch.

Further examination of the heat transfer rate can be carried out as seen in Figure 6. The heat transfer rate decreases with the increase of the pitch and it becomes almost steady with time; in this case after10 hours of continuous heat injection.

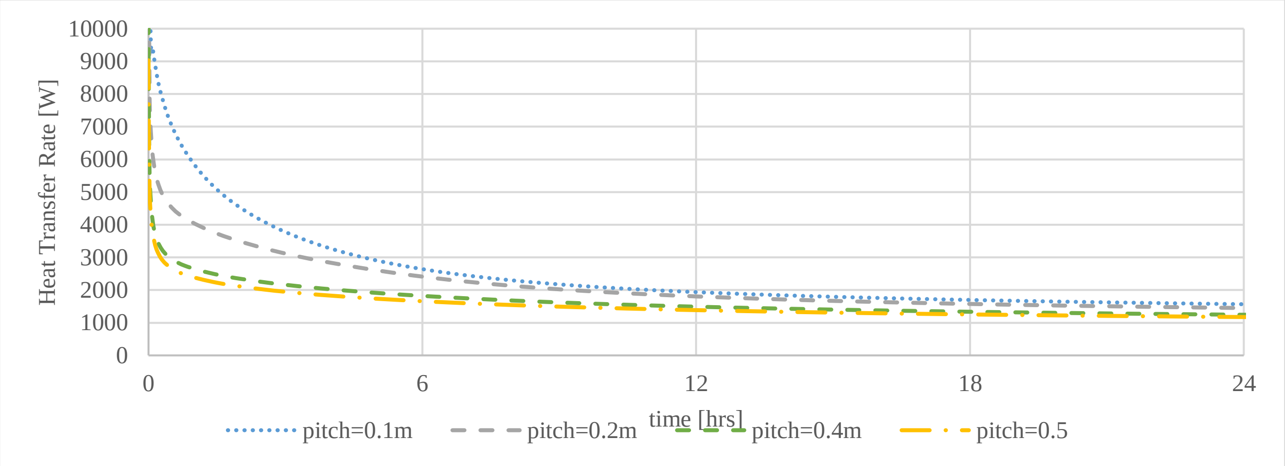

Figure 6: Heat transfer rate versus time

The results above can later be adapted to calculate the efficiency of the pump. As mentioned by Pouloupatis et al. (2017), the lower the outlet temperature of the coil (entering the pump), the higher the pump efficiency. In any design case the system engineer should try and limit the borehole numbers to reduce the initial cost. But in the case of energy piles there is a specific number of piles that can be adapted based on the civil engineer's plans. Therefore, it is important to incorporate a spiral coil in a single pile with the correct length and pitch angle.

4. CONCLUSION AND FUTURE WORK

A computational model of an energy pile with spiral coil (or helix coil) has been presented and discussed. The computational model has been validated against experimental results from the literature, before it was modified to match a close to realistic scenario of an energy pile placed in Cyprus under moderate climate. The parameters affected by the location were incorporated from the literature.

An investigation of the important implications of the design of GHEs has also been conducted. Such variables are the spiral pitch length (presented in this work), the spiral tube diameter and the coil diameter.

For future, other combinations of parameters should be investigated so as to obtain a complete understanding of the effect of the spiral parameters. The diameter and the depth of the spiral coil GHE, since utilized in the building's foundation piles, are constrained by the piles. Hence there are limitations on the actual size of the pile diameter and depth (containing an iron cage for reinforcement) as a function of the building's strength.

Further conclusions based on extended results will lead to recommendations for engineers.

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