Vertical and Horizontal Ground Heat Exchanger Modeling

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Abstract: As the cost of energy continues to rise, it becomes essential to save energy and improve overall energy efficiency of air-conditioning systems. In this light, the heat pump becomes a key component in energy saving with great potential. Heat pumps (HP) attain higher efficiencies when they are coupled to ground heat exchangers (GHEs). This is due to the fact that the ground is always cooler in summer and hotter in winter than the ambient air with which the common HPs exchange heat. The basic types of GHE configuration are horizontal or vertical. In the horizontal type the heat exchangers are usually buried in the ground at a depth of about 1–2 m with a number of tubes connected together. These exchangers are affected by the seasonal weather conditions because they are shallowly placed in the ground. Vertical GHE or borehole heat exchangers are widely used when there is a need to install sufficient heat exchange capacity under a confined surface area. Vertical loops are generally more expensive to install and usually have a depth of 20–300 m.

This paper describes the modeling of vertical and horizontal GHEs and compares their efficiency. Simulations with the vertical GHE show, as expected, that when the initial ground temperature rises the mean temperature of the heat exchanger fluid increases as well in a straight line relation. Comparisons between the horizontal and vertical GHEs reveal that under the same operating conditions and centre to centre distances of the tubes, the vertical heat exchanger keeps a much lower mean temperature because the initial ground temperature at the buried tube depth is always higher than that of the vertical GHE. Because of this observation one would assume that the vertical GHE is more efficient than the horizontal. Instead, in a proper design, one could increase the distance between the tube centres and in this way decrease the mean temperature of the tube fluid.

1. INTRODUCTION

It is well known that the fluctuations of the ground temperature decrease as the ground depth increases and from a certain depth and beyond remains constant irrespectively to the ambient environment conditions (Geothermal heat pump consortium, 2010). This relies on the fact that the ground is characterized by high thermal inertia which results to a time delay between the effect of temperature fluctuations at the surface to deeper layers in the ground. The ground temperature below approximately 5 m remains warmer, than the ambient air, in winter and cooler in summer. This characteristic of the ground can be exploited through the use of a system combining a ground heat exchanger (GHE) and a ground heat pump (GHP) as part of a central heating and cooling system in order to use the ground as a heat sink in summer (cooling mode) and as a heat source in winter (heating mode).

In general GHP or ground-source heat pumps (GSHP) are devices that use electricity in order to provide heating and cooling to a conditioned space. The main advantage of these devices, compared to the conventional air source heat pump (ASHP), is that the temperature lift across a GHP is lower for both heating and cooling modes and thus the operating efficiency of the heat pump is higher. It should be noted that the GHPs, despite the fact that are electrically driven, are classified as renewable energy technology since, according to the U.S. Environmental Protection Agency (EPA), these systems are the most efficient technology available with the lowest CO_2 emissions.

Ground Heat Exchangers are the part of the system, where the heat exchange between the heat transfer medium and the ground takes place. Several different heat transfer mediums, such as air, water or water and antifreeze mixture, are used to transfer heat to or from the ground. GHEs usually consist of one or more arrays of pipes installed into the ground horizontally or vertically. The horizontal GHEs require a large area of land in order to be applied. As a result in applications where the land area is confined, this type cannot be used and the only option is to use the vertical GHEs or borehole heat exchangers. The vertical GHEs not only have the advantage of being suitable in applications with confined areas, but they can also use the ground temperature of deeper layers that remains constant through all seasons. In a vertical GHE the pipes installed are usually made of polyethylene or polypropylene, while the remaining space in the hole is filled (grouted) with a pumpable material such as bentonite (Sanner, 2001).

In spite of their many advantages, GHPs are not as popular as ASHPs owing to their having several drawbacks such as their dependence on geological conditions, the high initial cost as well as the lack of reliable and widely accepted calculation models and design methods for the GHEs. A number of commercial programs for calculating the correct sizing (diameter and length) of each type of GHE are available. Some of these are the following: (a) The GeoLink Design Studio that combines geothermal engineering design with annual operating cost comparison and sales proposal software (GeoLink Design Studio, 2013). (b) The Ground Loop Design (GLD), a versatile program that assists the trained geothermal HVAC designer/engineer in sizing equipment, determining the appropriate lengths of the tube required for commercial projects, optimizing the piping configuration for balanced flow and optimal heat transfer, and calculating the annual and lifetime energy/operating/emissions costs associated with the design (Ground Loop Design, 2012). (c) The HYDROTHERM, a computer code for simulation of two-phase ground-water flow and heat transport in the temperature range of 0–200°C (HYDROTHERM, 2011). (d) The LoopLink, professional ground loop design software, designed around the new IGSHPA standards (LoopLink, 2013). (e) The SVHeat that is designed for use by geotechnical/geoenvironmental engineers, geological engineers, and soil scientists (SVHeat, 2013). (f) The TEMP/W, a finite element software product for analyzing thermal changes in the ground due to environmental changes or due to the construction of facilities such as buildings or pipelines (TEMP/W, 2013). (g) The GLHE-PRO, a program offered by the Oklahoma State University and can be used as an aid in the design of vertical bore-hole ground loop heat exchangers (GLHE-PRO, 2012). (h) The CLGS, a menu driven program offered by the Oklahoma State University and can be used for the design of closed-loop ground source heat exchanger (CLGS, 2012). Also, other programs exists and all have their advantages and disadvantages but this is beyond the scope of this paper.

1.1. The Geological map of Cyprus

The island of Cyprus, situated in the eastern Mediterranean serves as an excellent example of a rich grounds variety for the experimental application of GHEs. This section attempts to give an account of the lithologies that are represented in the various formations that make up the various terranes in Cyprus. The topography of the island is controlled by the lithology and tectonic structure of its four geological terrranes (see Figure 1). The Troodos Terrane forms the highest peaks in the central part of the island and the Keryneia Terrane forms the Pentadaktylos mountain chain on the northern coast. A juxtaposed suite of rocks in the southwestern part

of the island is referred to as the Mamonia Terrane. The Circum-Troodos autochthonous sedimentary succession covers all of these geological terranes.

2. THERMAL PROPERTIES OF THE LITHOLOGIES OF CYPRUS

For the direct measurement of the thermophysical properties, thermal conductivity and volume heat capacity of the lithologies found in Cyprus, the Isomet 2104 portable heat transfer analyzer was used for repeating the tests performed with Hukseflux thermal device. The accuracy of the instrument when measuring thermal conductivity in the range of 0.015–0.7 W m^{-1} K^{-1} is 5% of the reading +0.001 W m^{-1} K^{-1}, while in the range 0.7–6.0 W m^{-1} K^{-1} the accuracy is 10% of the reading. Also the instrument has a repeatability accuracy of 3% of the reading +0.001 W m^{-1} K^{-1}. The measurements were performed on various samples in their dry and water saturated state. All results measured with the Isomet 2104 portable heat transfer analyzer with a surface probe are shown in Table 1.

The thermal conductivity of each type of samples is not constant but it varies. This is due to the fact that the specific weight of the collected rocks also varies. Samples collected from the surface appear to be less dense than the ones collected from deeper ground.
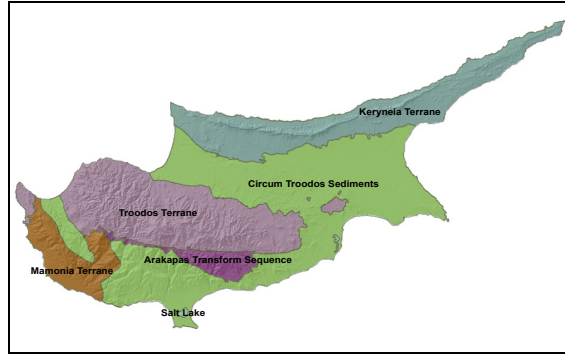

Figure 1. Major geological terranes of Cyprus.

3. MATHEMATICAL MODEL FOR A VERTICAL GHE

Assuming that t is time, the flow velocity $u = u(t)$ and the fluid temperature $T = T(x, y, z, t)$, then a three-dimensional (in x, y, z) conduction is governed by the equation (Florides et al., 2012):

$$\rho_0 c_p \frac{\partial T}{\partial t} + \rho_0 c_p u \frac{\partial T}{\partial z} + \left[\frac{\partial}{\partial x}\left(-\lambda_f \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(-\lambda_f \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(-\lambda_f \frac{\partial T}{\partial z}\right) \right] + \frac{4}{D} h\left(T - T_\infty\right) = 0. \tag{1}$$

where c_p is the specific heat at constant pressure, ρ_0 the fluid density, λ_f the coefficient of thermal conductivity, D the external diameter of pipe and h the convection heat transfer coefficient. Equation (1) can be modified accordingly to model both the pipe and the ground.

To complete the formulation of a geothermal heat exchanger the power flow in the tubes must be defined. Since usually the power supplied to the heat-exchanger and the circulating fluid velocity is constant, the power can be defined as a constant difference between the entering and exiting temperatures of the fluid. One can also consider that at the bottom of the pipe (where the "U"-connection is) the mean temperature of the upward fluid is equal to that of the downward fluid.

The FlexPDE software package is chosen as the numerical solving tool. This is a general-purpose software package for obtaining numerical solutions to partial differential equations in 2 or 3 dimensions based on the Finite Element Method (FlexPDE 6 manual, 2010). It uses an Adaptive Mesh Refinement method. Once the initial mesh is constructed, FlexPDE continues to estimate the solution error, and refines the mesh as necessary to meet the target accuracy. In time dependent problems, an adaptive refinement process will also be applied to the initial values of the variables, to refine the mesh where the variables undergo rapid change. Cells created by this adaptive refinement process can later be remerged.

After the formulation of the problem, an appropriate drawing of the heat exchanger domains must be sketched in the program. Figure 2(a) shows the two pipes of the heat exchanger with an external diameter of 32 mm, a thickness of 3 mm and a length of 100 m which are placed inside the borehole of a diameter of 0.2 m. The total length by width of the simulated area is 1 m × 1 m. There are also four vertical layers and an extra bottom layer with properties that represent the actual parameters present at the Prodromi (Cyprus) borehole. Because the geometry of a ground heat exchanger is extremely inhomogeneous in scale, with a 100 m length and a very small diameter of the, the software package requires an enormous number of cells for adequate modelling. As FlexPDE tries to make mesh cells as nearly equilateral as possible, severely distorted cells increase the numerical difficulty of the matrix solution, especially for thin cylindrical shells. Therefore coordinate scaling was used to reduce the length of the tube to a manageable size. The resulted final 3D-mesh used to check the effect of the layers on the temperature in the tubes of the GHE is shown in Figure 2(b).

Table 1. Thermophysical properties of various ground types in Cyprus.

Ground type	λ W m^{-1} K^{-1}	c_p J kg^{-1} K^{-1}	ρ kg m^{-3}	α ×10^{-6} m^2/s	Condition
Tera limestone	1.22	654	2232	0.835	dry
	1.74	906	2347	0.818	saturated
Koronia limestone	1.51	718	2125	0.989	dry
	1.94	962	2234	0.902	saturated
Lefkara chalk	1.58	729	2304	0.940	dry
	1.70	733	2402	0.965	saturated
Pachna marly chalk	0.75	1020	1591	0.462	dry
	1.22	961	1862	0.681	saturated
Nicosia marl	0.50	806	1832	0.338	dry
	0.99	767	2155	0.598	saturated
Kalavasos gypsum	0.78	784	2075	0.479	dry
	1.19	757	2461	0.638	saturated
Nicosia calcarenite	0.36	296	1359	0.894	dry
	0.80	527	1777	0.854	saturated
Kalavasos gypsum	1.23	717	2301	0.745	dry
	1.19	753	2301	0.686	saturated
Ochre	0.72	690	2174	0.479	dry
Lower pillow lava	0.80	751	1997	0.533	dry
	0.97	805	2020	0.596	saturated
Upper pillow lava	0.82	749	2119	0.516	dry
	0.98	756	2225	0.582	saturated
Lava (Basal Group)	1.45	596	2728	0.891	dry
Gabbro	1.97	675	2749	1.061	dry
Wehrlite	2.65	630	2941	1.430	dry
Harzburgite	2.34	645	2708	1.339	dry
Plagiogranite	2.81	586	2893	1.657	dry
	3.16	703	2893	1.553	saturated
Diabase	3.76	522	3264	2.206	dry
	3.73	603	3264	1.895	saturated
Iron pyrite	9.06	392	4093	5.646	dry
Umber (silicified)	2.97	642	2773	1.668	dry
	3.14	690	2773	1.641	saturated
Pyroxenite	2.02	660	2718	1.126	dry
Serpentinite	2.29	641	2588	0.835	dry

To validate the numerical model above, a test run is carried out in order to check the results with the in-situ Thermal Response Test (TRT) results obtained for the Prodromi borehole installation. The results showd a good agreement, which means that the numerical model can be used to extract realistic conclusions for the conditions specified.

Next, to compare the efficiency of the vertical and horizontal heat exchangers a numerical model of a horizontal GHE was constructed. This model consists of four horizontal tubes of length 50 m each, buried at a usual depth of 1.5 m into the ground. The distance between the tubes can vary. The ground is uniform in all

layers and has the same properties as the top soil at Prodromi area. The tube diameters and other specifications are similar to that of the vertical GHE. This configuration is the spatial analog to the 100 m vertical GHE discussed above since it has the same total length of tubes. A drawing showing the geometry of the horizontal GHE and the resulting final 3D-mesh is illustrated in Figure 3. The three layer regions and the borehole around each of the tubes were used in order to facilitate the mesh generation. The GHE fluid enters the first tube and exits the last one. The tubes are connected in series as indicated in Figure 3(a).

In addition, a temperature gradient is imposed on the depth profile to match the actual temperature of the ground. In June, when the tests were carried out at the Prodromi borehole, the recorded temperatures with respect to depth were at 0.3 m 31°C, at 1.5m 24°C and at 3m 22°C.
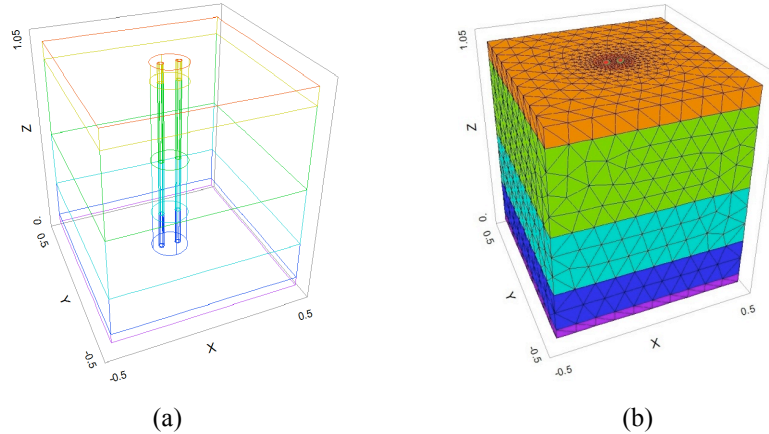

(a)   (b)

Figure 2. (a) A drawing showing the geometry of the vertical heat exchanger. (b) The resulted final 3D-mesh used to check the effect of the layers on the temperature in the tubes of the GHE.

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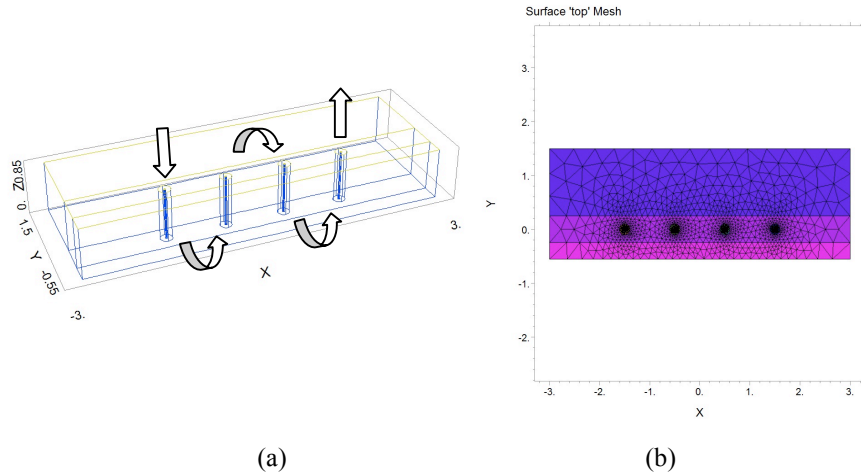
Figure 3. (a) Schematic showing the geometry of the horizontal GHE. (b) The resulting final 3D-mesh used to check the efficiency of the horizontal GHE.

4. RESULTS AND DISCUSSION

In this section follows the evaluation and comparison of the two models discussed above (up to equivalent specifications). Running the numerical model with the above-mentioned specifications and a center-to-center distance of 1 m between the tubes yields the temperature distribution around the tubes after 50 h of operation shown in Figure 4. The Figure presents a section of the soil area passing through the center of a heat exchanger tube showing the temperature distribution in the vertical plane. More heat escapes from the right, hotter part of the tube. The length of the tube is scaled.

Now that the two models are set up under equivalent parameters their results can be compared. Because the surrounding ground temperature of the horizontal GHE is always hotter than that of the vertical, in this case 24.2°C for the horizontal and 21°C for the vertical, it is expected that a vertical GHE will function with greater efficiency.

Figure 5(a) shows that a nearly linear relation exists between the initial ground temperature and the mean fluid temperature of a 100 m vertical heat exchanger under the conditions examined. It must be noted that the center- to-center distance of the tubes of the vertical GHE is of great importance. The nearer the tubes are the hotter the outlet fluid temperature is. This is because in this case, only a fraction of each tube area can exchange heat directly with the ground since a large part of each tube is obstructed by the other tube. Therefore by comparing the outlet fluid temperature of the two GHEs we observe that the vertical GHE has an outlet fluid temperature of 29.7°C after 50 h of operation but the horizontal one only 28.3°C. This is because the drawback of the higher ground temperature (24.2 instead of 21°C) is overcome by the by far greater distance between the four tubes (1 m).
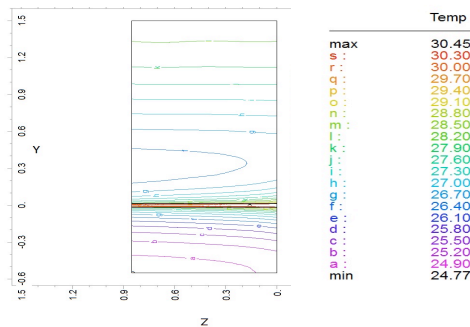

Figure 4. A section of the soil area passing through the center of the heat exchanger tubes showing the temperature distribution in the vertical plane after 50 h of operation.
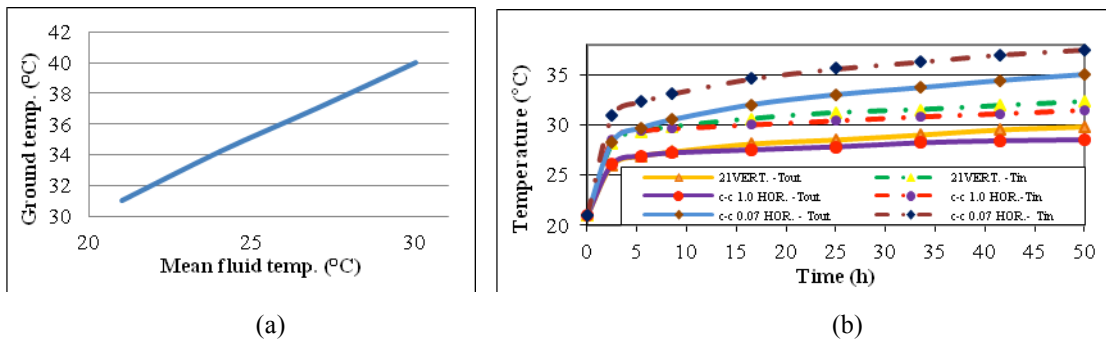

| (a) | (b) |

Figure 5. (a) Effect of initial ground temperature on the mean fluid temperature of a 100 m vertical heat exchanger. (b) Comparison of the inlet and outlet fluid temperature of the vertical and horizontal GHE.

If the distance between the tubes of the horizontal GHE were kept the same as the vertical GHE (0.07 m) then we would see that the temperature of the horizontal GHE would be far too hotter (in this case 38.7°C - Figure 5b). This result is intensified by the fact that the two inner tubes are blocked in a greater extent than the outer tubes.

In the case under investigation (Figure 6a) there is a critical center-to-center (c-c) distance of about 0.7 m, after which no observable effect will result on the mean fluid temperature. In this case the relation is hyperbolic indicating that smaller distances have greater negative effect on the mean fluid temperature.

Finally, a comparison is made between various layer materials to observe the effect of the ground type on vertical and horizontal GHEs. A basic property of the ground is the thermal diffusivity, which is a measure of the rate that the heat moves in a substance and is given as $\alpha = \lambda/(\rho c)$. This means that in a substance with high thermal diffusivity heat moves rapidly through. To check this effect a number of materials were used as shown in Table 1. The results show that diffusivities above 16 m^2/s are not important for the vertical GHE because they will not produce any appreciable effect on the mean fluid temperature of the GHE. Below that value diffusivity is very important because the lower the value the greater the temperature of the GHE. As observed in Figure 6(b) the effect may be an increase of temperature of about 6.5°C for a value of 3.4 m^2/s. For the horizontal GHE the critical value is about 9 m^2/s, while a lower value of 3.4 m^2/s will produce a temperature difference in the mean fluid of about 3.5°C.
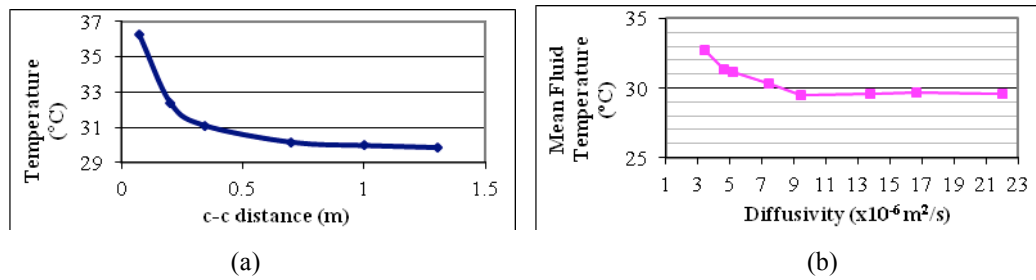
Figure 6. (a) Effect of center-to-center tube distance of a horizontal GHE on the mean fluid temperature after 50 h of operation. (b) Ground diffusivity effect on the mean fluid temperature of the horizontal GHE.

5. CONCLUSIONS

The present study examines the effect of temperature and thermal properties of the ground on vertical and horizontal GHEs. For this purpose two simulation models were constructed, one for each type of GHE, and the FlexPDE simulation software was used for running the models. Cyprus having a large variety of ground types, from volcanic to sedimentary, was used for measuring the thermal properties and initial temperature. Examining the effect of the initial ground temperature on the mean fluid temperature of a vertical GHE it is shown that a nearly linear relation exists under the conditions examined. Usually it is believed that a vertical GHE is more efficient than a horizontal one because, in the cooling mode, the ground temperature below about 10 m is always cooler that the top layer temperature meaning that the horizontal HE is embedded in hotter ground.

The results show that this is not always so: a horizontal GHE will produce a hotter outlet fluid than a vertical one if the center-to-center tube distance is kept the same as that of the vertical GHE. If the center-to-center distance is increased enough then the horizontal GHE may produce a lower temperature than the vertical one. This can easily be done because the width of the horizontal GHE trench can be increased as it is on the ground surface, whereas the borehole diameter of the vertical GHE cannot. It is also observed that there is a critical distance for the center-to-center distance of the horizontal GHE (in the examined case being about 0.7 m), after which no observable effect will result on the mean fluid temperature. Finally, a comparison is made between various layer materials to observe the effect of the ground type on horizontal GHEs.

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