International Journal of Industrial Electronics and Electrical Engineering, ISSN(p): 2347-6982, ISSN(e): 2349-204X
Volume-6, Issue-9, Sep.-2018, http://ijieee.org.in

BOREHOLE GROUND HEAT EXCHANGERS AND THE FLOW OF UNDERGROUND WATER

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Abstract - Vertical Ground Heat Exchangers (GHEs) in boreholes are a major form of Geothermal Energy applications. When water flowing underground past the borehole the heat injection rates of the GHE are subject to change. Here, we construct a mathematical model for such regimes. Then, based on the Finite Element Method we construct a corresponding computational model, which is validated with experimental data of a Thermal Response Test carried out in Lakatameia, Cyprus. Finally, using the validated model, the thermal behavior of borehole GHEs is investigated by studying the effect of the (a) BH radius, (b) U-tube diameter, (c) U-tube leg and BH centers distance, (d) grout thermal conductivity and (e) underground water velocity.

Keywords - Ground Heat Exchangers, borehole, undergroundwater flow, geothermal energy, computational modeling

I. INTRODUCTION

Geothermal energy, although of high installation cost, is a fast growing Renewable Energy Source as it can find applications everywhere. One of the standard approaches for lower and mid-depth applications is the borehole vertical Ground Heat Exchanger (GHE). In particular, GHE technology is of higher efficiency for air-conditioning (A/C) compared to conventional systems. GHE systemsuse pipes (tubes)inside a borehole (BH)as heat exchangers in the ground. The underground environment provides lower temperature for cooling and higher temperature for heating and experiences less temperature fluctuation than ambient air, with the underground temperature being approximately equal to the mean annual atmospheric temperature of the year [1–2]. Fluid circulates through pipes, resulting in indirect thermal contact between the fluid and the subsurface. The whole GHE system is controlled by the effective area and can be limited by the equipment involved, e.g. type and size of pipes, the grouting material [3], the velocity of the circulating fluid[4], the thermal conductivity of the subsurface [5–7], the presence of underground water due to the presence of an aquifer [8–9], and so on. An aquifer is the saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients [10].

It is thus necessary to use simulations and validation tools for the parametric analysis of the above-mentioned factors that can lead to the optimization of the GHE system.

The present study deals with the calculation of heat injection rates of GHEs, as these are affected by the(i) BH radius, (ii) U-tube diameter, (iii) U-tube leg and BH centers distance,(iv) grout thermal conductivity and (v) undergroundwater velocity. To validate the proposed methodology, a study case was set up in an area with high potential in geothermal usage and a Thermal Response Test (TRT) was carried out.The TRT is a method determining the thermal characteristics of the groundbased on injecting heat in the BH at constant power, while the mean BH temperature is recorded continuously during the test [11]. The area chosen wasLakatameia, near Nicosia – the capital city of Cyprus.

Regarding the computation of the temperature of the fluid circulated in the U-tubes of a GHE, various analytical and numerical models exist such as the line- and the cylindrical-source models [12–13] and models based on finite element methods (FEM) [14–15]. For the utilization of numerical methods a number of commercial and freeware software programs, suitable for GHE system design can be found in the market. In the present analysis the FlexPDE software was used, with the help of FEM, to numerically solve a system of partial differential equations (PDE) governing the energy flow and the temperature change in and around a BH. FlexPDE is a general-purpose software that can solve steady-state, time-dependent and free boundary problems.FlexPDE builds a mesh, constructs a system FEM, solves it, and presents an easy to use graphical output.

A study case of a real BH located in Lakatameia was set-up in the FlexPDE environment.First the experimental data related to the above-mentioned BH are collected. Then a mathematical model governing vertical GHE systems in the presence of an aquifer is presented. Based on these the computational model in FlexPDE is constructed and validated. Consequently, a parametric analysis of the GHE is attempted and a discussion of the results is given.

II. METHODOLOGY AND NUMERICAL MODEL

2.1. Experimental data

The study under consideration here is a geothermal system of a BH GHE with a surrounding rock mass crossed by an aquifer. The temperature of the ground in the Lakatameia BH, chosen as a study case, was measured in the framework of a project for the efficient use of Ground Coupled Heat Pumps in Cyprus [16–17]. According to the project's findings, the ground is divided into three zones: (i) the surface zone, (ii) the shallow zone, (iii) the deep zone. The surface zone is affected by seasonal variations as the depth increases (shallow zone), and at 8 m approx. (deep zone) the underground temperature nearly remains unchanged throughout the year [18]. Similar statements were made in the framework of other studies in various regions of the world [19–21].

The underground temperature in the Lakatameia BH, for depths over 7 m was 22°C, with1°C increase per 100 m (temperatures were recorded for depths of up to 160 m). All recorded temperatures for a day per month at the Lakatameia BH, over a whole year, varying from 11 to 37°Ccan be found in [22–23]. Based on these, one can obtain realistic temperature gradients (best-fit polynomial equations)that can be imposed on the numerical model for the depth profile in FlexPDE.

The Lakatameia GHE (illustrated in Fig. 1) consisted of plastic tubes (polyethylene), with the space between the tubes and the hole (radius 0.1 m) filled with bentonitic clay with cement,as an appropriate grout material for good contact between the tube and the undisturbed ground and to reduced thermal resistance. The vertical GHE was drilled with a 20-cm diameter of drill. Regarding lithology, the the BH consists of marls (Nicosia Formation). The study area is a circle with a 1.4 m radius. The heat exchangers are of the single U-tube configuration. The tubes used are of 160 m length, 0.032 m inner diameter and 0.003 m wall thickness. The distance between the center of the tube and the center of the BH is 0.06 m. The underground water level was at 80 m depth. There were two groundwater flow velocities recorded in the water baring layers: in the majority of them a negligible one at 0.0000000116 m s^{-1} and a high one at 0.00005 m $s^{-1}$for a thickness of about 25 m in layers containing marly sand. The TRT performedat the site [16] for an initial fluid input temperature of 22.85°C, gave an input and output temperature difference of 5.2°C for an input power of 5710 W.

The soil thermal properties (respectively, thermal conductivity, density, specific heat capacity) of the BH are $\lambda = 1.4$ W m^{-1} K^{-1}, $\rho = 2300$ kg m^{-3}, c = 950 J kg^{-1} K^{-1} for the dry ground, $\lambda = 1.5$ W m^{-1} K^{-1}, $\rho = 2600$ kg m^{-3}, c = 100 J kg^{-1} K^{-1} for the saturated ground, $\lambda = 0.9$ W m^{-1} K^{-1}, $\rho = 1500$ kg m^{-3}, c = 800 J kg^{-1} K^{-1} for the dry grout, and $\lambda = 1.1$ W m^{-1} K^{-1}, $\rho = 1700$ kg m^{-3}, c = 850 J kg^{-1} K^{-1} for the saturated grout. The mean value of thermal conductivity was$\lambda = 1.45$ W m^{-1} K^{-1}.

2.2. Mathematical model

Based on the cylinder heat exchange model, described in detail by Carslaw and Jaeger (1959), and having in mind that in a shallow geothermal BH we have heat transfer by conduction and convection, then a one-dimensional heat conservation equation for an incompressible fluid flowing in the tube with a velocity u = dz/dt [m s^{-1}] is described by

$$A_f \rho_f c_f \frac{\partial T}{\partial t} + A_f \rho_f c_f u \frac{\partial T}{\partial z} + A_f \frac{\partial}{\partial z}\left(-\lambda_f \frac{\partial T}{\partial z}\right) + \pi d_{in} h\left(T_f - T_p\right) = 0, \quad (1)$$

where A_f is the fluid cross-sectional area [m^2], λ_f is the fluid thermal conductivity [W m^{-1} K^{-1}], $\rho_f$is the density of the fluid [kg m^{-3}], $c_f$is the specific heat capacity of the fluid [J kg^{-1} K^{-1}], h is the convective heat transfer coefficient of the process [W m^{-2} K^{-1}], T is temperature [K], T_f is the fluid temperature, T_p is the pipe temperature, $d_{in}$is the internal diameter [m] and t is time [s].

Eq. (1) can be used for the fluid in both sides of the tubes of a GHE by changing the sign of velocity u. Taking into consideration that the conduction can take place in all three directions and convection takes place only in one direction, i.e. the direction of the motion of the water in the tubes, then a three-dimensional space heat conservation equation per unit volume may be written as

$$\rho_f c_f \frac{\partial T}{\partial t} + \rho_f c_f u \frac{\partial T}{\partial z} + \frac{\partial}{\partial x}\left(-\lambda_f \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(-\lambda_f \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(-\lambda_f \frac{\partial T}{\partial z}\right) + \frac{4}{d_{in}} h\left(T_f - T_p\right) = 0. \quad (2)$$

Convection was considered to take place in the y-direction due to the motion of underground water and is described by

$$\rho c \frac{\partial T}{\partial t} + \rho c_w v \frac{\partial T}{\partial z} + \frac{\partial}{\partial x}\left(-\lambda_f \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(-\lambda_f \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(-\lambda_f \frac{\partial T}{\partial z}\right) = 0, \quad (3)$$

where λ is the thermal conductivity of the porous matrix, ρc is the volume heat capacity of the soil matrix [J m^{-3} K^{-1}], v is the flow velocity considered anisotropic along the principal axis, T is temperature, T_d for dry soil and T_w for saturated soil, c is specific heat capacity, c_d for dry soil and c_w for saturated soil, and ρ is the density of the porous matrix.

Note that porosity of rocks in underground layers was also considered in our solution. In a porous medium, thermal conductivity $\lambda = (1 - n)\lambda_s + n\lambda_{fw}$ and volume heat capacity $\rho c = (1 - n)\rho c_s + n\rho c_{fw}$ where, n is the porosity and subscripts s and fw refer to the solid and fluid-water phases respectively. Given an underground aquifer crossing a BH, the area around the BH could be separated into a phase of a saturated porous material, with solid particles and water, and a phase of a dry material [24].

Now, the energy conservation equation for the pipe wall becomes

$$\rho_p c_p \frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\left(-\lambda_p \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(-\lambda_p \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(-\lambda_p \frac{\partial T}{\partial z}\right) + \frac{4}{t_p} h\left(T_p - T_f\right) = 0, \tag{4}$$

where t_p is the thickness of the pipe [m].

In addition, the heat equation representing the flow in the ground (per unit volume) is given by

$$\rho_g c_g \frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\left(-\lambda_g \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(-\lambda_g \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(-\lambda_g \frac{\partial T}{\partial z}\right) = 0, \tag{5}$$

where subscript g denotes the ground.

Note that at the boundary between the fluid and the tubes the convective heat flux is hΔT, where h is the convective heat transfer coefficient of the process and ΔT is the temperature difference at the boundary.The convection heat transfer coefficientcan be estimated as $h = \lambda \cdot Nu/D_H$[25], where D_H is the hydraulic diameter (in this case the tube-inside diameter) and Nu is the Nusselt number. The Nusselt number in this case can be expressed through the Dittus–Boelter correlation as$Nu = 0.023Re^{0.8}Pr^n$, where $Pr = \mu c/\lambda$is the Prandtl number, $Re = \rho c d_{in}/\mu$ is the Reynolds number, μ is the dynamic viscosity, and n = 0.4 for heating and 0.33 for cooling.

As the fluid properties are evaluated at the bulk temperature, an iterating process is applied for the equations above.

2.3. Computational model

The Lakatameia BH GHE domain is illustrated in Fig. 1.

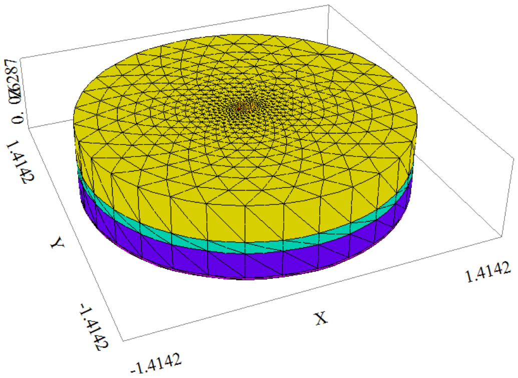

Fig. 1. The FlexPDE model for the energy analysis of the Lakatameia BH: 80 m dry well area shown in yellow; 25 m high water velocity area shown in green; 55 m low water velocity area shown in blue; 5 m base area shown in purple (z-coordinate scaled by a factor of 0.00385).

The desired model was created in the FlexPDE environment, where the soil thermal properties and the GHE characteristics of the BH (see Section 2.1)as well as the best-fit formulas for the realistic temperature gradients for shallow and deep zones have been implemented. As FlexPDE allows for a detailed description of the geometry, boundary layers and boundary conditions, the model tested the response of the GHE for the top layer temperature in the presence of underground water in an aquifer. The heat transfer inside and around the BH was also analyzed.

2.4. Validation of the model

The model above was then validated using the TRT results carried out in-situthe Lakatameia BH in December 2009.As already mentioned, the best-fit equations for the temperature gradient were imposed on the numerical model to match the ground temperatures used in simulations to the actual temperatures of the ground during the experimental measurements. This was achieved through the use of the swage function of FlexPDE. The initial ground temperatures on the vertical BH axis are shown in Fig. 2 and correspond to the actual measured values of the ground. The actual ground temperature in the BH increases up to a depth of 5 m reaching 23.4°C and then decreases slightly up to a depth of 30 m. Then ground temperature increases again, reaching 24.5°C at a depth of 160 m.

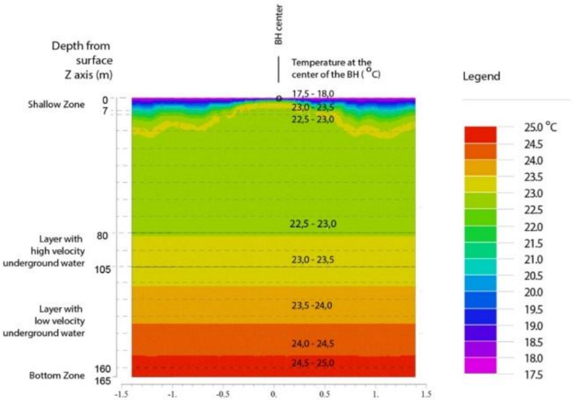

Fig. 2. Initial Ground Temperature on the vertical BH axis(scaled in the z-coordinate by 0.00385)

Note that the geometry of the Lakatameia BH was scaled in the z-coordinate by a factor of 0.00385, the maximum factor that the computer could handle. The reason is simply for saving computational memory and time as the z dimension has an enormous difference in relation to the other dimesions.

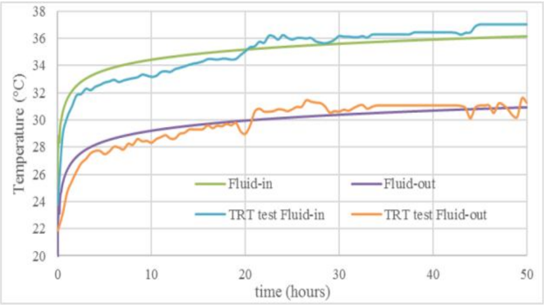

Fig. 3. TRT recorded temperatures (December) at the Lakatameia BH (TRT Fluid-in/out), in comparison with the FlexPDE script calculated values (Fluid-in/out)

Fig. 3 shows the comparison and the good agreement between the TRT and the measured values. This allows one to use the validated model to extract realistic conclusions for the parametric analysis that follows in Section 3.

In general, regarding the temperature distribution at the end of the 50 h run, the grout attaina higher temperature than the surroundings, the middle layer where higher velocity flow is present attains a lower temperature, and the low velocity layer is a little cooler than the top layer.

III. PARAMETRIC ANALYSIS

The next step is to tackle the main goal of this paper, i.e. to perform a parametric analysis of the GHE, based on the model of Section 2. In all cases the power absorbed was kept constant at 5710 W, with the temperature difference between the input and the output circulating water being 5.2 °C for a cooling mode.

3.1. Borehole radius

Four different radiuses of the BH, namely0.08, 0.10, 0.125, 0.15 m were simulated in order to evaluate the effect of this characteristic on the thermal response of the GHE. The clear outcome is that the smaller the BH radius the lower the temperature of the fluid of the GHE (Fig. 4).This is because of the thermal properties of the grout (see Section 2.1) in comparison to the surrounding ground. The accumulation of heat in the bigger radius grout due to its higher resistance results in higher temperature.

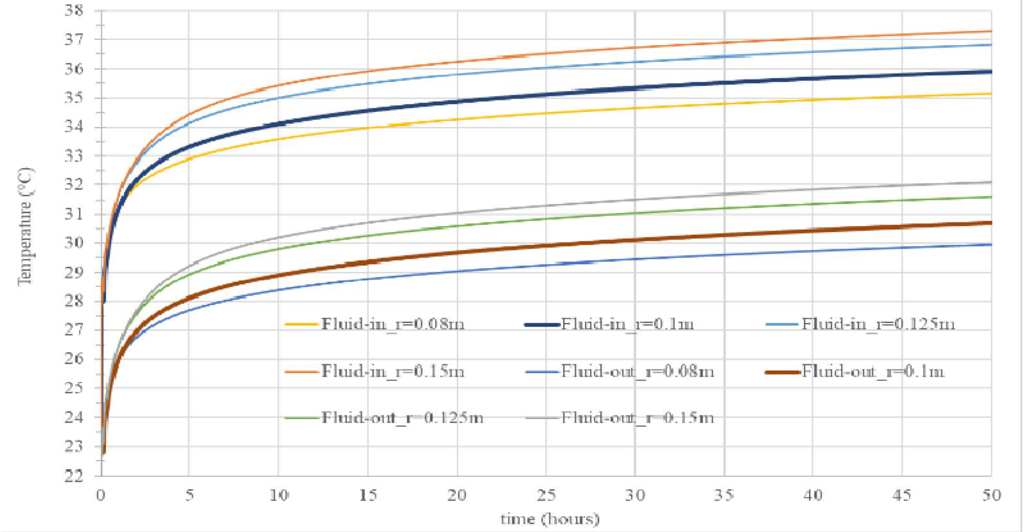

Fig. 4. Temperature evolution of the GHE for various values of the grout thermal conductivity λ

3.2. Grout thermal conductivity

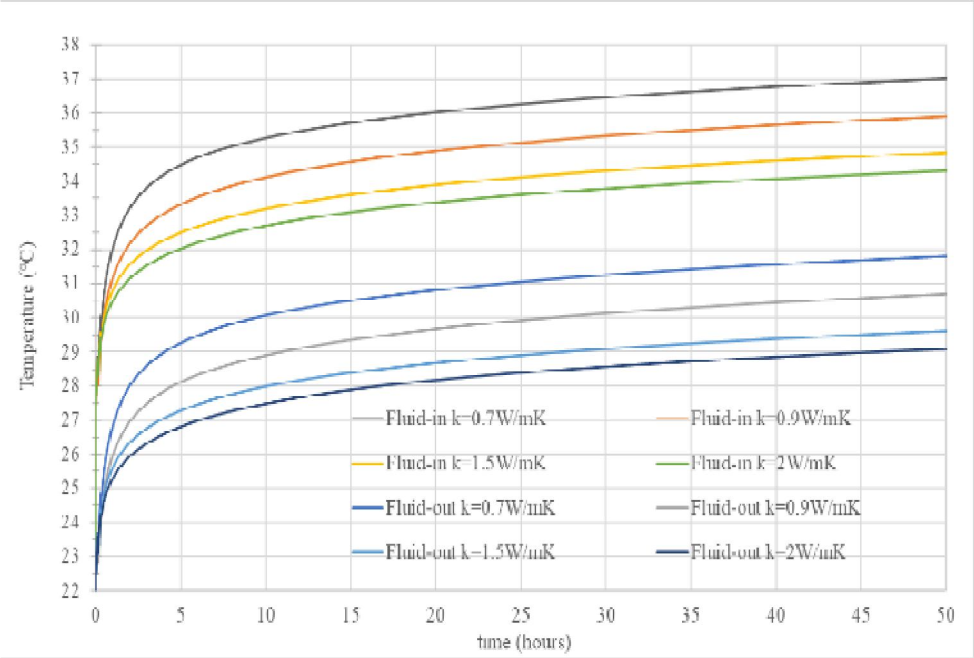

Fig. 5. Temperature evolution of the GHE for various values of the grout thermal conductivity λ

Four different grout materials of thermal conductivity 0.7, 0.9, 1.5 and 2.0 W m^{-1} K^{-1} were simulated in order to evaluate the effect of this characteristic on the thermal response of the GHE. The clear outcome is that when the energy absorbed by the GHE is the same, the lower the grout thermal conductivity the higherthe temperature of the fluid of the GHE (Fig. 5).

3.3. U-tube size

Four different U-tube sizes of external diameters, namely 20, 25, 32 and 40 mm,were simulated in order to evaluate the effect of this characteristic on the thermal response of the GHE. The clear outcome is that,when the energy absorbed by the GHE is the same,the lower the diameter the higherthe temperature of the fluid of the GHE (Fig. 6).

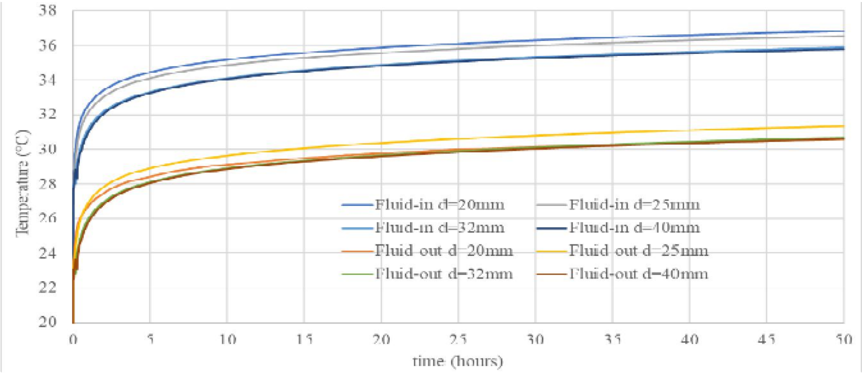

Fig. 6. Temperature evolution of the GHE for various values of the U-tube external diameter

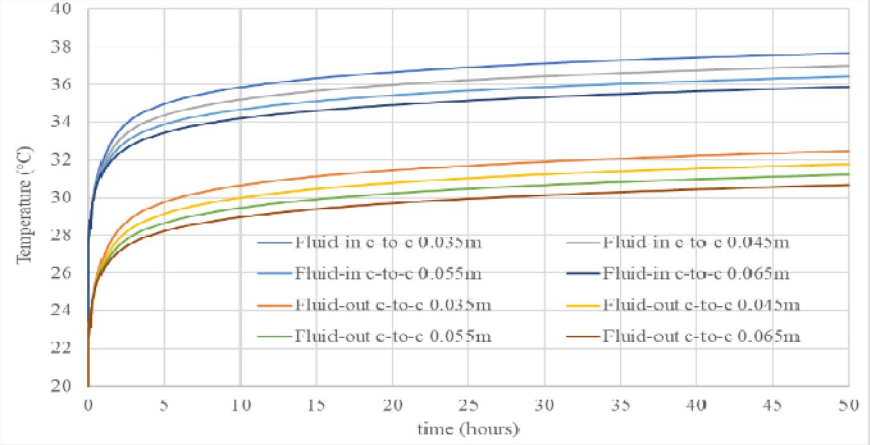

Fig. 7. Temperature evolution of the GHE for various values of the distances between the leg and the BH center

3.4. Distance between leg and borehole centers

Four different distances between the leg and the BH centers (for as symmetric BH), namely 35, 45, 55 and 65 mm,were simulated in order to evaluate the effect of this characteristic on the thermal response of the GHE. The clear outcome is that, when the energy absorbed by the GHE is the same, the lower the center-to-center distance the higherthe temperature of the fluid of the GHE (Fig. 7).

3.5. Underground water velocity

The presence of underground water and an aquifer improves the heat exchange of a GHE with the ground [8–9]. To quantify this, four different underground water flows in the underground layer with the ‘high’ velocity with realistic values of 0.000001, 0.000025, 0.0001 and 0.0002m s^{-1}were simulated in order to evaluate the effect of this characteristic on the thermal response of the GHE. The clear outcome is that, when the energy absorbed by the GHE is the same, the lower the underground water velocity the higherthe temperature of the fluid of the GHE (Fig. 8).

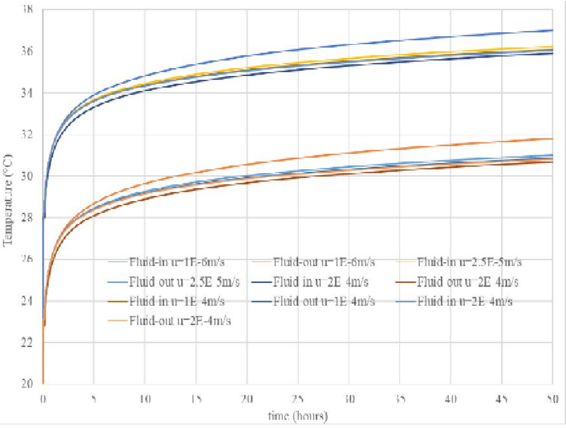

Fig. 8. Temperature evolution of the GHE for various values of the underground water velocityIt turns out that higher underground water velocities (over 0.0003 m s^{-1}) do not lead to extra cooling.

CONCLUSIONS

In the previous Sections, the mathematical model describing the heat transfer in BH GHEs in soils where groundwater flow may be present wasdeveloped. Based on this, the FlexPDE software was used to build an equivalent FEM computational model. The computational model was validated with collected data from a TRT that was carried out in Lakatameia, Cyprus. The validated model allows for the investigation of the heat injection rate of a BH GHE.

A parametric analysis,for the cooling mode of the GHE, that can be a great help for the designing engineer was then performed. Five GHE features were explored as follows.

When all other parameters/factors are kept unaltered decreasing the BH radius improves cooling (and the efficiency of the heat pump of the system), provided an appropriate grout material is used.

In its turn the grout thermal conductivity improvescooling when increased.

Also, the study case shows that increasing the U-tube diameter results in a better cooling effect.

Another finding of the study is that the greater the distance between centers of the tube and the BH, the better the cooling.

Finally, the presence of underground water improves the heat exchange ability, with cooling increased for increased underground water velocities, although a maximal such velocity exists.

The study presented in this paper constitutes an important step toward investigating the importance of the presence of an aquifer in the construction of a BH GHE. Such an investigation can be further extended both for the factors explored here as well as for factors such as the summer and winter mode of operation, the underground temperature variation in depths smaller than 7 m due to daily and seasonal changes, the actual power rejected into or absorbed by the ground and the thermal resistance of the BH.

REFERENCES

[1] J. Busby, “UK shallow ground temperatures for ground coupled heat exchangers”, Geological Society of London, 2015.

[2] R.C. Heath, Basic ground-water hydrology, US Geological Survey, 1983.

[3] P. Christodoulides, G. Florides, P. Pouloupatis, V. Messaritis and L. Lazari., “Ground heat exchanger modeling developed for energy flows of an incompressible fluid”,Int J Mech Aerospace, Inductrial, Mechatron Manuf Eng, vol.6, pp.640-4, 2012.

[4] A. Bidarmaghz, G. Narsilio and J. Johnston, “Numerical Modelling of Ground Heat Exchangers with Different Ground Loop Configurations for Direct Geothermal Applications”, In Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, 2013.

[5] O.J. Svec, L.E. Goodrich and J.H.L. Palmer, “Heat transfer characteristics of in-ground heat exchangers”, International Journal of Energy Research, vol. 7(3), pp.265-278, 1983.

[6] I.I. Stylianou I.I., S. Tassou, P. Christodoulides, I. Panayidesand G. Florides, “Measurement and analysis of thermal properties of rocks for the compilation of geothermal maps of Cyprus”, Renewable Energy, vol. 88, pp.418-429, 2016.

[7] P. Christodoulides, G. Florides and P. Pouloupatis, “A practical method for computing the thermal properties of a Ground Heat Exchanger”, Renewable Energy, vol. 94, pp.81-89, 2016.

[8] R. Fan, Y. Jiang, Y. Yao, D. Shiming and Z. Ma, “A study on the performance of a geothermal heat exchanger under coupled heat conduction and groundwater advection”, Energy, vol. 32(11), pp.2199-2209, 2007.

[9] H. Fujii, Y. Komaniwa, K. Onishi and N. Chou, “Improvement of the capacity of ground heat exchangers by water injection”, Dep, vol. 40, p.50, 2013.

[10] R.A. Freeze and J.A. Cherry, Groundwater, pp.604, 1979.

[11] P. Mogensen, “Fluid to duct wall heat transfer in duct system heat storages”, Document-Swedish Council for Building Research, vol. 16, pp.652-657, 1983.

[12] S. Kavanaugh, “A design method for commercial ground-coupled heat pump”, In ASHRAE Transactions: Symposia (sd-95-13-3), pp. 1095-1100, 1995.

[13] H. Yang, P. Cui and Z. Fang, “Vertical-borehole ground-coupled heat pumps: A review of models and systems”, Applied energy, vol. 87(1), pp.16-27, 2010.

[14] K.C. Lee, “Classification of geothermal resources by exergy”,Geothermics, vol. 30(4), pp.431-442, 2001.

[15] H. Y. Zeng, N.R. Diao and Z.H. Fang, “A finite line-source model for boreholes in geothermal heat exchangers”, Heat Transfer-Asian Research, vol. 31(7), pp.558-567, 2002.

[16] G.A. Florides, P.D. Pouloupatis, S. Kalogirou, V. Messaritis, I. Panayides, Z. Zomeni, G. Partasides, A. Lizides, E. Sophocleous and K. Koutsoumpas, “The geothermal characteristics of the ground and the potential of using ground coupled heat pumps in Cyprus”, Energy, vol. 36(8), pp.5027-5036, 2011

[17] P.D. Pouloupatis, G. Florides and S. Tassou, “Measurements of ground temperatures in Cyprus for ground thermal applications”, Renewable energy, vol. 36(2), pp.804-814, 2011.

[18] G. Florides, P.D. Pouloupatis, S. Kalogirou, V. Messaritis, I. Panayides, Z. Zomeni, G. Partasides, A. Lizides, E., Sophocleous and Koutsoumpas. “Geothermal properties of the ground in Cyprus and their effect on the efficiency of ground coupled heat pumps”, Renewable energy, vol. 49, pp.85-89, 2013.

[19] A. Correia, G. Vieira and M. Ramos, M., “Thermal conductivity and thermal diffusivity of cores from a 26 meter deep borehole drilled in Livingston Island, Maritime Antarctic”, Geomorphology, vol. 155, pp.7-11, 2012.

[20] A.M. Vijdea, C. Weindl, A. Cosac, N.S. Asimopolos and D. Bertermann, “Estimating the thermal properties of soils and soft rocks for ground source heat pumps installation in Constanta county, Romania”, Journal of Thermal Analysis and Calorimetry, vol. 118(2), pp.1135-1144, 2014.

[21] T. Sliwa and M.A. Rosen, “Natural and artificial methods for regeneration of heat resources for borehole heat exchangers to enhance the sustainability of underground thermal storages: a review”, Sustainability, vol. 7(10), pp.13104-13125, 2015.

[22] P. Pouloupatis, Determination of the thermal characteristic of the ground in Cyprus and their effect on ground heat exchangers, Ph.D. thesis, Brunel University London), 2014.

[23] P.D. Pouloupatis, S.A. Tassou, P. Christodoulides and G.A. Florides, G.A., “Parametric analysis of the factors affecting the efficiency of ground heat exchangers and design application aspects in Cyprus”, Renewable energy, vol. 103, pp.721-728, 2017.

[24] R. Al-Khoury, T. Kölbel and R. Schramedei, “Efficient numerical modeling of borehole heat exchangers”, Computers & Geosciences, vol. 36(10), pp.1301-1315, 2010.

[25] L. Aresti, P. Christodoulides and G.A. Florides, “Computational modelling of a ground heat exchanger with groundwater flow”, BULGARIAN CHEMICAL COMMUNICATIONS, vol. 48, pp.55-63, 2016.

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