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Borehole Resistance and Heat Conduction Around Vertical Ground Heat Exchangers

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Abstract: Borehole thermal resistance in Ground Heat Exchanger (GHE) installations is affected by several parameters such as geometrical attributes of heat exchanger in the borehole, pipes' characteristics and grout's thermal conductivity. A study is carried out to compare the values computed by Ground Loop Design (GLD) Software, GLD 2009, with three analytical solutions for U-shaped tubes. The analysis is focused on dimensionless ratios of borehole geometrical parameters (borehole diameter to outside pipe diameter and shank spacing to borehole diameter) and pipes according to Standard Dimension Ratio (SDR) and on eight common grouts. Finally, the effect of heat conduction in the borehole is examined by means of finite element analysis by Heat Transfer Module of COMSOL Multiphysics. A two-dimensional (2-D) steady-state simulation is done assuming working fluid temperatures for winter and summer conditions and typical Greek undisturbed ground temperature in a field of four ground vertical U-tube heat exchangers surrounded by infinite ground. The temperature profile is presented and the total conductive heat flux from the pipe to the borehole wall per meter of length of ground heat exchanger is computed for pipes SDR11 (the outside diameter of the pipe is 11 times the thickness of its wall), SDR9 and SDR17 for summer working conditions and three different configurations. It is attempted to reach to comparative results for borehole thermal resistance value through different types of analysis, having considered the major factors that affect it and giving trends for the influence of each factor to the magnitude of its value.

Keywords: Geothermal, Borehole, Borehole Thermal Resistance, Ground Heat Exchanger, Heat Conduction, Standard Dimension Ratio.

1. INTRODUCTION

Geothermal energy [1, 2] is conceived as a clean and cost effective form of energy with various applications for space heating and cooling. Ground Source Heat Pump (GSHP) systems, which are established to exploit the undisturbed ground temperature, consist of several parts with the Ground Heat Exchanger (GHE) to be the most important of them. GHE's major role is not only its contribution to the system's operation but also its contribution to the energy saving.

Several attempts [3, 4], which utilize analytical and numerical models, steady-state and transient analysis, one-dimensional (1-D), two-dimensional (2-D) and three-dimensional (3-D) simulation, have been done to model the operation and efficiency of GHE in a GSHP system. The use of different numerical techniques in engineering environmental applications is becoming more and more popular [5, 6]. Analytical models for GHE utilize mainly two theories, line heat source [7, 8] and cylinder heat source theory [9, 10] to predict the heat exchange between the soil and the heat carrier fluid in the GHE. Numerical models [11] calculate finite differences to simulate the temperature distribution profile around the GHE. Steady-state analysis [12] is used to estimate average heat transfer rates between the circulating fluid and the ground for given working conditions whereas, transient simulation [13] calculates heat transfer rates taking into consideration the changeable working conditions of the GSHP system during a long working period. In the 1-D simulation [14] borehole is regarded as an infinite line source or sink of heat in an infinite medium, the soil, whereas in the 2-D simulation [15] calculations are performed in a cross-sectional area of GHE to the working fluid flow. These attempts are based on two significant observations. Firstly, the GHEs diameters are very small comparing with their lengths and secondly, the temperature of the ground can be assumed as constant under certain depth, what is called undisturbed ground temperature, ignoring that temperature increases 1-3 ^{o}C every 100 m of depth of the earth surface [16]. The 3-D simulation attempts to model the full geometry of GHE during its operation so as to achieve more precise results of heat transfer calculations but this is not always achievable.

A number of physical phenomena are taking place during the operation of GHE such as heat conduction, heat convection, working fluid flow, groundwater movement and others with minor significance to GSHP system efficient operation. The heat conduction between the soil and the heat carrier fluid in the GHE plays a major role in the operation of GSHP engineering applications, thus it is a common topic for researchers in the field of geothermal energy. The physical and thermodynamic properties of the circulating fluid, pipe material, filling material between the pipes and the ground, and

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the Prandtl number for water at 70 °F (21 °C). An approximate value of pipe resistance for a HDPE pipe, with thermal conductivity of 0.23 Btu/(hr ft °F) (0.40 W/m K), is calculated using the expression for the hollow cylinder by Incropera and DeWitt [25]. It is worth mentioning that, in GLD, the close together configuration assumes an 1/8 in. (3 mm) average distance between the pipes and not touching one the other, an assumption which represents actual configurations in practice. Several calculations have been made for the pipe configurations, SDRs of the pipes, borehole diameters and grouts (see Table **2**) which have been mentioned above.

2.4. Numerical Simulation

A 2-D steady-state finite element simulation is built up through Heat Transfer Module of COMSOL Multiphysics [26] in order to calculate borehole thermal resistances so as to be compared with those of Remund correlation [21] and to calculate total conductive heat fluxes. A square field, of 5.5 m edge, of four Borehole Heat Exchangers (BHEs), BHE1, BHE2, BHE3, BHE4 centered at its vertices, with a vertical U-tube GHE in each borehole has been placed at the infinite ground (see Fig. (**2**)). The square field selection is made so as to simulate a part of a real borehole field. The 5.5 m edge is also selected in order to ensure the absence of thermal interference between neighboring boreholes. An extra increase in edge size would not lead to significantly decrease in borehole thermal resistance while a decrease in edge size, especially below 5 m, would lead to a portionally increase in borehole thermal resistance value in the region of 3% in the current work. It is also worth mentioning that in an actual borehole installation at which there are many vertical and horizontal series of boreholes, the 5.5 m distance between two successive boreholes does not eliminate thermal interference among them. In this case, longer distances are proposed if there is no space limit. A single U-tube GHE is placed in each borehole so as to be in accordance with the analytical and GLD analyses which are mentioned in sections 2.2 and 2.3.

The infinite ground is simulated as a circle with a radius of 20 m, centered at the centre of the square field, with its circumference to be set to undisturbed ground temperature (T_{gr}). Each bore has a diameter of 110 mm, which is roughly in the middle of 90-190 mm range mentioned in section 2.1, and the pipes are sized according to SDR9, SDR11 and SDR17 with nominal diameter of 1 in (25.4 mm). It is obvious that the 20-meter radius is by far greater than the 55-milimeter borehole radius so as the first can be characterized as satisfactory far away distance at which ground temperature is not affected by boreholes' presence. Only the circle's circumference is set to T_{gr}, enabling the temperature evolution to be developed during the simulation time from the boreholes' wall to thermally unaffected ground.

The GHE is modelled using a 2-D cross sectional area to its length at an average depth at which the ground temperature and the fluid temperatures in both the upward (T_u) and

Table 4. COMSOL Modeling Parameters

Parameter and Symbol	Value
Infinite ground	
Thermal conductivity k_{gr}	2.42 W/m K
Specific heat capacity $c_{p,gr}$	840 J/kg K
Density ρ_{gr}	2800 kg/m^3
Grout	
Thermal conductivity k_g	0.78 W/m K
Specific heat capacity $c_{p,g}$	1600 J/kg K
Density ρ_g	1000 kg/m^3
HDPE	
Thermal conductivity k_p	0.4 W/m K
Specific heat capacity $c_{p,p}$	2300 J/kg K
Density ρ_p	940 kg/m^3
Operating conditions	
Undisturbed ground temperature T_{gr}	18 °C
Temperature of upward flow in heating mode $T_{u,h}$	17 °C
Temperature of downward flow in heating mode $T_{d,h}$	14 °C
Temperature of upward flow in cooling mode $T_{u,c}$	30 °C
Temperature of downward flow in cooling mode $T_{d,c}$	33 °C

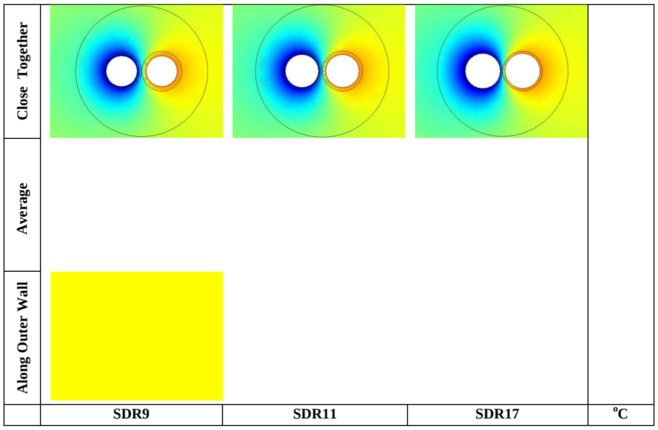

Fig. (5). Temperature distribution around a borehole for winter working conditions.

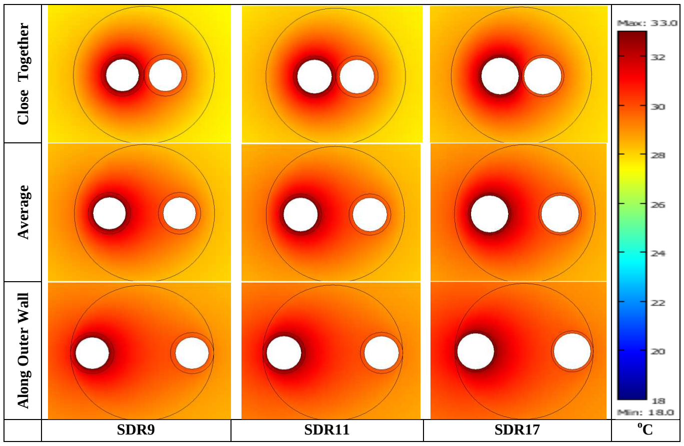

Fig. (6). Temperature distribution around a borehole for summer working conditions.

Table 5. Total Conductive Heat Flux for Summer Working Conditions

Pipes' Dimensions and Configuration	Total conductive heat flux (W/m)
SDR9	
Close Together	16.14
Average	17.17
Along Outer Wall	18.24
SDR11	
Close Together	16.41
Average	17.45
Along Outer Wall	18.53
SDR17	
Close Together	16.81
Average	17.85
Along Outer Wall	18.99

meaning a high heat transfer rate. Based on this remark the thermally enhanced grouts tend to replace the common ones. The exact value of borehole resistance can be derived from experimental data of a specific GHE, although the existing correlation methods and software result at satisfactory estimations.

The current study is limited to steady-state analytical approaches and a 2-D steady-state numerical one. The use of

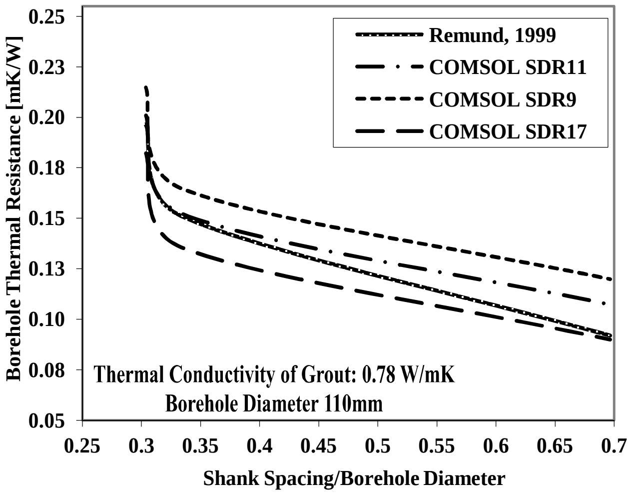

Fig. (7). Borehole thermal resistance as a function of Shank Spacing to Borehole Diameter for a grout of 0.78W/m K thermal conductivity.

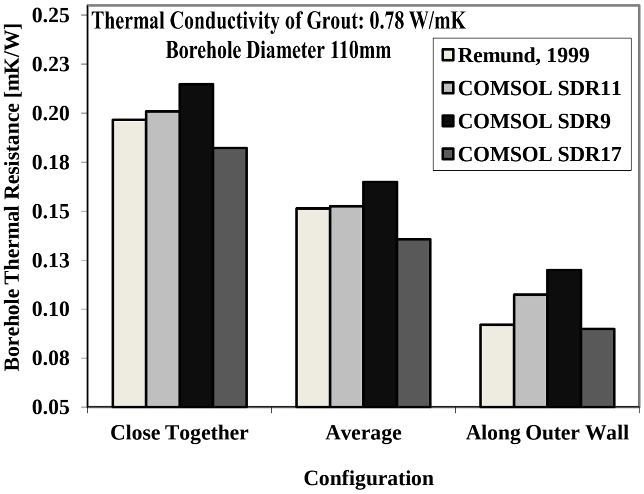

Fig. (8). Borehole thermal resistance for a grout of 0.78W/m K thermal conductivity for three configurations.

transient analytical correlations in borehole thermal resistance calculations and the comparative study between transient and steady-state analysis with the use of the same dimensionless ratios (borehole diameter to outside pipe diameter, shank spacing to borehole diameter and SDR) are proposed for future research. What is more, 3-D steady-state or transient simulations can be attempted to calculate borehole thermal resistance values so as to be compared with the present study's results.

CONFLICT OF INTEREST

None declared.

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NOMENCLATURE

d_b = Borehole diameter (mm)

d_i, d_o = Pipe inner, outer diameter (mm)

n = Number of pipes in the borehole

Q = Heat sink or source (W/m K)

q = Algebraic sum of total heat flow of pipes (W/m)

q_s = Production or absorption coefficient (W/m^3 K)

R_b = Borehole thermal resistance (m K/W)

s = Shank spacing (mm)

s_p = Pipe wall thickness (mm)

T_b = Borehole wall temperature (^{o}C)

T_d, = Downward

T_u = Upward flow stream temperature (^{o}C)

T_{gr} = Undisturbed ground temperature (^{o}C)

β_o, β_i = Coefficient of Eq. (4)

ABBREVIATIONS

GSHP = Ground Source Heat Pump

GHE = Ground Heat Exchanger

1,2,3-D = One, Two, Three-Dimensional

SDR = Standard Dimension Ratio

HDPE = High Density Polyethylene

GLD = Ground Loop Design

BHEs = Borehole Heat Exchangers

REFERENCES

[1] Ozgener, L.; Hepbasli, A.; Dincer, I.; Rosen, A.M. Exergoeconomic analysis of geothermal district heating systems: A case study. *Appl. Thermal Eng.*, **2007**, *27*, 1303-1310.

[2] Akella, K.A.; Saini, P.R.; Sharma, P.M. Social, economical and environmental impacts of renewable energy systems. *Renewable Energy*, **2009**, *34*, 390-396.

[3] Chua, K.J.; Chou, S.K.; Yang, W.M. Advances in heat pump systems: A review. *Appl. Energy*, **2010**, *87*, 3611-3624.

[4] Connolly, D.; Lund, H.; Mathiesen, B.V.; Leahy, M. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Appl. Energy*, **2010**, *87*, 1059-1082.

[5] Cheng, C.T.; Ou, C.P.; Chau, K.W. Combining a fuzzy optimal model with a genetic algorithm to solve multi-objective rainfall-runoff model calibration. *J. Hydrol.*, **2002**, *268*, 72-86.

[6] Muttil, N.; Chau, K.W. Neural network and genetic programming for modelling coastal algal blooms. *Int. J. Environ. Pollut.*, **2006**, *28*, 223-238.

[7] Ingersoll, L.R.; Zobel, O.J.; Ingersoll, A.C. *Heat Conduction with Engineering and Geological Application*; McGraw Hill: New York, **1948**.

[8] Carslaw, H.S.; Jaeger, J.C. *Conduction of Heat in Solids*, 2nd ed.; Oxford University Press: London, **1959**.

[9] Ingersoll, L.R.; Zobel, O.J.; Ingersoll, A.C. *Heat Conduction with Engineering, Geological and Other Applications*, revised edition; University of Wisconsin Press: Madison, **1954**.

[10] Deerman, J. D.; Kavanaugh, S.P. Simulation of vertical U-tube ground coupled heat pump systems using the cylindrical heat source solution. *ASHRAE Trans.,* **1991**, *97*, 287-295.

[11] Rottmayer, S.P. M.Sc. Thesis, University of Wisconsin, **1997**.

[12] Florides, G.; Kalogirou, S. Ground heat exchangers - a review of systems, models and applications. *Renewable Energy*, **2007**, *32*, 2461-2478.

[13] Signorelli, S.; Kohl, T.; Rybach, L. *Sustainability of Production from Borehole Heat Exchanger Fields*, Proceedings of World Geothermal Congress 2005, Antalya, Turkey, April 24-29, **2005**.

[14] Shonder, J.A.; Beck, J.V. Determining effective soil formation thermal properties from field data using a parameter estimation technique. *ASHRAE Trans.* **1999**, *105*, 458-466.

[15] Yavuzturk, C.; Spitler, J.D.; Rees, S.J. A transient two-dimensional finite volume model for the simulation of vertical U-tube ground heat exchangers. *ASHRAE Trans*. **1999**, *105*, 465-474.

[16] Banks, D. *An Introduction to Thermogeology: Ground Source Heating and Cooling*, Blackwell Publishing, **2008**.

[17] Engineering Toolbox. http://www.engineeringtoolbox.com (accessed November 8, 2010).

[18] Gaia Geothermal. Ground Loop Design Software, GLD **2009**.

[19] Shonder, J.A.; Beck, J.V. Field test of a new method for determining soil formation thermal conductivity and borehole resistance. *ASHRAE Trans*. **2000**, *106*, 843-850.

[20] Gu, Y.; O'Neal, D.L. Development of an equivalent diameter expression for vertical U-tubes used in ground-coupled heat pumps. *ASHRAE Trans*, **1998**, *104*, 347-355.

[21] Remund, C.P. Borehole thermal resistance: laboratory and field studies. *ASHRAE Trans*. **1999**, 105, 439-445.

[22] Bose, J.E.; Parker, J.D.; McQuiston, F.C. *Design/Data Manual for Closed-Loop Ground-Coupled Heat Pump Systems*; American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE): Atlanta, **1985**.

[23] Remund, C.P.; Paul, N.D. *A Nationally Acceptable Grouting Manual for GSHP Boreholes*, Draft; Electric Power Research Institute, RP-3881-1: Palo Alto, **1996**.

[24] Holman, J.P. *Heat Transfer*, 9th ed; McGraw Hill Companies Inc.: New York, **2002**.

[25] Incropera, F.P.; Dewitt, D.P. *Fundamentals of Heat and Mass Transfer*, 5th ed.; John Wiley & Sons Inc.: New York, **2002**.

[26] COMSOL Multiphysics, v. 4.0; Heat Transfer Module, **2010**.

[27] Rakopoulos, C.D. *Heat & Mass Transfer II*; Frame Publishing Co.: Athens, **1985**.

[28] Katsoyiannis, I.A.; Hug, S.J.; Ammann, A.; Zikoudi, A; Hatziliontos, C. Arsenic speciation and uranium concentrations in drinking water supply wells in Northern Greece: Correlations with redox indicative parameters and implications for groundwater treatment. *Sci Total Environ*. **2007**, *383*, 128-140.

[29] Kavanaugh, S.P.; Rafferty, K. *Design of Geothermal Systems for Commercial and Institutional Buildings*; American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), **1997**.

[30] Esen, H.; Inalli, M.; Esen, Y. Temperature distributions in boreholes of a vertical ground-coupled heat pump system. *Renewable Energy*, **2009**, *34*, 2672-2679.

[31] Eskilson, P.; Claesson, J. Simulation model for thermally interacting heat extraction boreholes. *Numer. Heat Transfer*, **1988**, *13*, 149–165.

[32] Acuña, J.; Palm, B. *Local Conduction Heat Transfer in U-pipe Borehole Heat Exchangers*, Excerpt from the Proceedings of the COMSOL Conference 2009, Milan, Italy, October 14-16, **-**.

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