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Soil Profile and Ground Properties Influence on Vertical Ground Heat Exchanger Efficiency

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Abstract. Soil properties have a significant impact on the performance of ground heat exchangers. Exchangers cooperating with heat pumps are a reliable and efficient source of renewable energy. In the article concentric vertical ground heat exchanger is analysed, which is a common application cooperating with heat pumps. Soil and ground properties have great importance during sizing the system, i.e.: determining the length, configuration and deployment of ground heat exchangers. With the depth the soil/ground type and its properties can change significantly. In addition, occurrence of a ground water can influence physical and thermal properties. Determination of soil type present at different depths in a specific location is possible by performing a soil profile. The article presents an analysis of the impact of two soil profiles on the efficiency of the vertical ground heat exchanger. The analysis was performed based on the model of a single heat exchanger made using CFD (Computational Fluid Dynamics) program. The model is divided into two parts: model of heat exchanger together with grout filling the borehole, second: axis-symmetric model of the ground surrounding the exchanger. Both models are coupled by first-type boundary condition. Simulations of ground heat exchanger work are made for a part of heating season period. The calculation results were compared to reference one with uniform ground profiles. Difference in heat rejected form ground in two analysed does not show high influence of ground layers on ground heat exchanger performance. On the other hand, results strongly depends on analysed soil profile.

Keywords: Vertical Ground Heat Exchangers, Heat Pumps, Ground heat transfer modelling, CFD.

Conference topic: Energy for buildings.

Introduction

Ground heat exchangers (GHE) are typical elements of ground heat pump installation. Ground is used as a renewable energy source during heating season. Heat pump efficiency depends on ground temperature and efficiency of transferring heat form ground to working fluid (Rusowicz *et al.* 2014). Natural processes of heat transfer in ground allows it to return to an undisturbed state before next heating season. Such situation take place only if system is designed properly and natural relaxation process occur long enough (Chwieduk 2012). Design of a system includes choosing type, size and configuration of GHE. Nowadays design of a heat pump installation with GHE is done with use of simulation programs. Simulations allows to take into consideration local ground parameters and analyse different system configuration that will provide efficient work and reasonable costs of installation. Introducing more detailed models of GHE work is important for its proper design. In the paper only vertical ground heat exchangers (VGHE) are analysed. This type of GHE is most common applied in Poland and most of European countries for ground source heat pump (GSHP).

Ground is a source of energy and its properties determine the efficiency of the system. Properties such as density, specific heat and thermal conductivity have direct impact on heat transfer process that occur in ground during heat removal and relaxation process. Ground properties depends on soil type and water mass content. Both can change with depth of VGHE. Soil profile determines the soil/ground type and water content existing on a different depth, ground layers with possible groundwater flow are identified. Typical soil profile gives additional information on water table and on saturation of ground layers with water. This information is crucial for obtaining reliable data of ground properties. Specific heat, thermal conductivity and thermal diffusivity change with water mass content (Kowalik 2007). Soil profile is performed by well drilling. Properties of different type of ground can be taken from literature (Diao *et al.* 2004) or measured in situ (Walker *et al.* 2015). In situ measurement gives most accurate data but because of costs and time needed to perform they are less popular. In most of cases soil profile is not performed and installation is sized by using typical values of thermal and physical properties of ground. Omitting details in ground properties may cause inaccuracies in simulations result, which are important for system sizing.

In this paper model of GHE with surrounding ground is purposed. Model is used to carry out simulation for two different soil profile. One assume uniform soil properties in all surrounding ground, it represents situation in which precise data are not available. Second one is based on real soil profile, which was measured near city of Warsaw in Poland (Data bank HYDRO).

Example of GHE model build to analyse influence of multiple layer with different properties and its impact on results of thermal response test (TRT), is model purposed by Lee (Lee 2011). Three dimensional model showed small difference between simulations conducted for multiple layer ground and uniform one, which was seen as a slight difference in accuracy of TRT. Different model was proposed by Sutton *et al.* (Sutton *et al.* 2002), model is based on cylindrical source model modified to allow definition of separate layers of soil with different properties.

Model proposed in paper was developed for ground heat storage (Chwieduk 2013), but with a few modifications it has universal application.

Ground properties and soil profile

Simulation of GHE work requires knowledge of thermal and physical properties of soil. Typical parameters such as: thermal conductivity (λ), specific heat (c_w) and density (ρ) of soil has to be specified. Data used in simulations presented in the paper are based on Diao *et al.* (Diao *et al.* 2004). All parameters used in simulations referring to ground properties are given in Table 1. Data used for simulations with uniform properties of ground (data assumed if data from soil profile was not available) are shown separately from data for different layers of ground specified in soil profile (nonuniform).

Table 1. Typical values of thermal and physical properties of soil, data used for simulation
(*Source*: Diao *et al.* 2004; Lavoue, Tourancheau 2010)

Type of soil:	λ [W/mK]	ρ [kg/m^3]	c_w [kJ/kgK]
Uniform ground			
Uniform ground (average values)	1	1950	1.7
Nonuniform ground			
Sand (fine) – low moisture content	0.8	1650	0.85
Sand (fine) – high moisture content	2	1900	1.53
Loam	1	1950	1.7
Clay	1	2100	1.57

Soil profile defines type of soil occurring on different depth. Layers of soil with a different water saturation are also specified during measurement. Locally defined soil profile in accurate only for small area around given location. It is impossible to describe average soil profile for a specific site. If soil profile was not performed on the location of planed GHE system, parameters of soil type known as possible to occur on the location are assumed for simulations. Values for thermal and physical properties of soil given as uniform ground in Table 1 are assumed as equal to values for loam, which has largest share in measured soil profile.

Borehole made for GHE is larger than dimensions of a pipe. Space between edge of borehole and GHE is filled with material with improved thermal properties especially higher thermal conductivity than typical soil. Usually material used for filling is a type of grout. Example of grout material used in VGHE systems is bentonite. Thermal conductivity of bentonite that is used nowadays overcomes 3 W/mK, specific heat is equal to 1500 J/kgK and density 2500 kg/m^3 (Delaleuxa *et al.* 2012).

Very important aspect of a heat transfer in ground is underground water flow. In case of GSHP underground water flow increases heat transfer coefficient and accelerates ground relaxation process. Taking into account underground water flow in GHE model requires adding flow equations and excludes use of two dimensional axis-symmetry model. Presented in paper model omits underground water flow, it is assumed worst scenario in which there is no underground water flow.

Properties of ground can change during the operation of GSHP, very important aspect of modelling GHE system is freezing of ground which directly influence its thermal properties. In presented simulations freezing of a ground does not occur and properties of soil during system operation remain constant (Ruciński *et al.* 2014).

Ground heat exchanger model

GHE and surrounding ground model proposed in paper is composed of two separate parts combined with boundary condition of the first type. Proposed model was developed with ANSYS Fluent program. Model of heat transfer in ground is build and realised in ANSYS Fluent. Model of GHE is built separately as a User Defined Function. GHE model is one dimensional model of fluid flow in concentric pipe. Fluid flow in GHE is forced convection model, discretised by upwind volume control method. Usually forced convection in pipe is modelled with 3D model which requires small mesh and short time step to achieve convergence. In case of GHE systems considered large volume of ground surrounding exchanger and simulation time exceeding more than one year, model of fluid flow has to be simplified. Proposed 1D model allows to shorten calculation time while maintaining required accuracy. Numerically solved equation of heat transfer in GHE allows to determine fluid outlet temperature and its distribution in GHE. Fluid velocity distribution in the heat exchanger is not considered. Numerically solved equation is as follows:

$$\rho_f c_f \frac{\partial T_f}{\partial t} + \rho_f c_f u \frac{\partial T_f}{\partial z} = \rho_f \frac{\partial}{\partial z} k \frac{\partial T_f}{\partial z} + \dot{q}_1 + \dot{q}_2, \tag{1}$$

where: ρ_f – fluid density, c_f – fluid specific heat, T_f – fluid temperature, t – time, u – fluid velocity, z – length, k – heat transfer coefficient, $\dot{q}_1$ – heat flux between fluid and external wall of concentric pipe, $\dot{q}_2$ – heat flux between fluid in inner and outer part of concentric GHE.

Equation (1) is discretised by upwind volume control method and solved by TDMA algorithm (tridiagonal matrix algorithm). In Eqn (1) value of heat flux between fluid in inner and outer part of concentric GHE is unknown, it depends on temperature of fluid for time step that is calculated. To achieve convergence of analytical and numerical solution, equations are solved iteratively. Eqn (2) represents discretised form of Eqn (1). Indexes used in equation are presented on Figure 1.

$$\begin{aligned}&\frac{\rho_f c_f dz}{dt} \cdot A \cdot T_p - \frac{\rho_f c_p dz}{dt} \cdot A \cdot T_p^0 + F_e c_f T_p - F_w c_f T_w = \\ &D_e T_e - D_e T_p - D_w T_p - D_w T_w + k \cdot A \cdot \left(T_p - T_{\text{wall}}\right) + \frac{1}{R_c} \cdot A \cdot \left(T_p - T_p^*\right),\end{aligned} \tag{2}$$

where: A – cross area of concentric pipe of GHE, T_p^0 – fluid temperature in specific control volume at previous time step, F – convective mass flow of fluid through the volume control, D – conductive heat flow through the volume control, T_p^* – fluid temperature of control volume with which heat is transferred, R_c – thermal resistance between fluids flowing in opposite directions, *indexes:* e – next control volume, p – specified control volume, w – previous control volume.

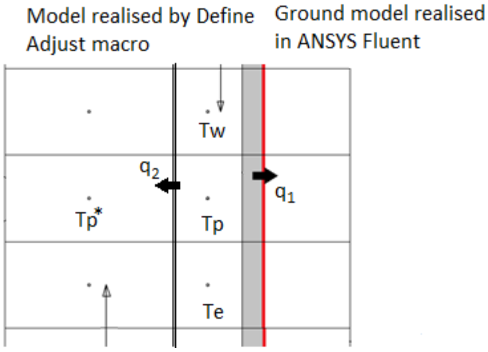

Fig. 1. Scheme of GHE model – upwind volume control method

Properties of fluid and properties of material used as a GHE in simulation are given in Table 2. Heat capacity of GHE material is omitted, only thermal conductivity is taken into account.

Table 2. Properties of GHE material and working fluid (*Source*: Gogół 1976)

Fluid density	998	kg/m^3
Fluid thermal conductivity	0.6	W/mK
Fluid specific heat	4183	J/kgK
Fluid kinematic viscosity	0.000001	m^2/s
Fluid dynamic viscosity	0.00001	Ns/m^2
GHE thermal conductivity	2	W/mK

Model of heat transfer in ground is built in ANSYS Fluent. Proposed model is 2D axis-symmetry model of heat conduction in ground. Mesh defined in ANSYS Fluent corresponds with discretisation of GHE, its regular mesh with dimensions 0.2×0.03 m. Because whole model is axis-symmetry – volume of a single control volume rises with a distance from axis. Such mesh ensures high density near GHE. Upper, bottom and external boundary conditions are defined as Define Profile macro, and are based on Eqn (3) proposed by Bags (Bags 1983). Bags formula describe ground temperature change with depth and during the year, it is as follows:

$$T\left(z,t_d\right)=T_m\pm\Delta T_m+1,07k_vT_0exp\left(-0,000316\cdot z\cdot\left(1\big/a\right)^{1/2}\right)\cdot cos\left[\left(2\pi\big/365\right)\left(t_d-t_{d0}-0,01834\cdot z\cdot\left(1\big/a\right)^{1/2}\right)\right],\quad(3)$$

where: t_d – number of the day of the year, T_m – annual average temperature of ambient air, T_0 – annual temperature amplitude, ΔT_m – temperature correction due to geothermal anomalies, k_v – dimensionless ratio of vegetation growth, z – depth, a – thermal diffusivity of ground, t_{d0} – phase shift amplitude of air temperature, number of the day in the year with the highest average temperature of ambient air.

Below GHE axis-symmetry boundary condition is defined. On the edge of GHE first type boundary condition is defined, GHE temperature is given by 1D model of fluid flow. Convergence is achieved by iterations determining temperature on the border of two models. Time step for all calculations is one hour. Parameters of soils and soil profile used in simulation are described on Figures 1 and 2. GHE defined in model is concentric pipe, which is directly surrounded by bentonite material.

Model of fluid flow through GHE was validated with analytical solution. Whole model was not validated, it was tested with different mesh and boundary conditions to obtain proper undisturbed temperature distribution in ground.

Presented model, build by connection of local and global part, allows to describe precisely geometry of GHE and take it into account during simulations. On the other hand, geometry of GHE does not influence calculations time and its accuracy. Modifying ground soil profile and results processing in ANSYS Fluent can be done in a simple way. Distinguishing feature of this model is combination of 2D axis-symmetry model and 1D GHE model which ensures accurate calculations without 3D time consuming simulations and enables investigation of ground profile influence of GHE efficiency.

Simulation and results

Two simulations were conducted for GHE with identical geometry, with the same boundary conditions and with the same load conditions. GHE length is 35 m and its outer diameter is 6 cm. Dimensions of GHE are selected as for small single family house with low energy demand for heating. Whole installation typically is made of 4 or more GHE, in this article only one GHE is analysed. Inner diameter of concentric GHE is equal to 1.95 cm. GHE is surrounded by 3 cm of bentonite material which properties are described in previous chapter. Soil properties are defined based on values given in Table 1 and soil type given on Figure 2 and Figure 3. Identical dimensions and boundary conditions allows comparison of two situations in which soil profile was unknown or it was measured before system sizing. Simulations where performed for 10 days of system operation.

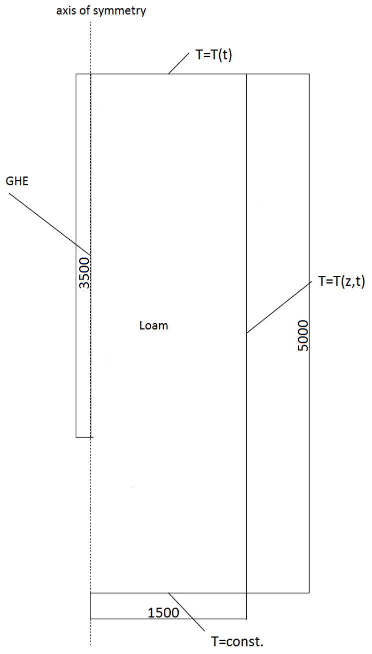

Fig. 2. Simulation variant 1 – dimensions in cm, type of soil, boundary condition types

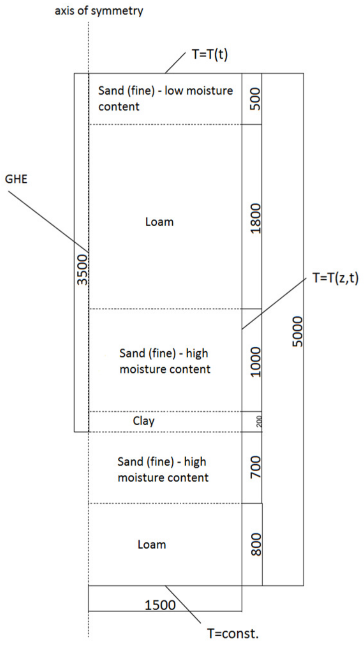

Fig. 3. Simulation variant 2 – dimensions in cm, type of soil, boundary condition types

Time of simulation (10 days) was selected after performing longer and shorter simulations. Because of very simple assumptions concerning receiving heat from ground, for a long period simulations differences in results for different soil profile decreases. Boundary conditions where assumed for Warsaw climate conditions. Simulations started on the 1 January. Load conditions where defined by fluid mass flow and fluid temperature on the inlet of GHE. For 8 hours of the day GSHP system was working and fluid mass flow equal to 0.1 kg/s and temperature of 0°C were assumed. Rest of the day ground is recovering, there is no fluid flow through GHE.

Results

Results that can be obtained from model are: temperature field in ground surrounding GHE, temperature distribution in GHE and value of heat received form ground during specified time of simulation. For simulation variant I (uniform ground) energy received form ground after 10 days is equal to 363.07 MJ. At the beginning of simulation fluid temperature rise in GHE was 4.04 °C, at the end temperature raise is equal to 3.29 °C. In simulation variant II energy received from ground after 10 days is equal to 355.24 MJ. At the beginning of simulation fluid temperature rise in GHE is 3.92 °C, at the end temperature raise is equal to 3.27 °C. On Figure 4 and 5 temperature distribution in ground at the end of simulation is shown. Because of small area of influence only 3 m of ground around GHE are shown on the figures. GHE is placed in the middle of figures. On Figure 5 slower ground cooling is observed, it is especially visible in the lower part of GHE.

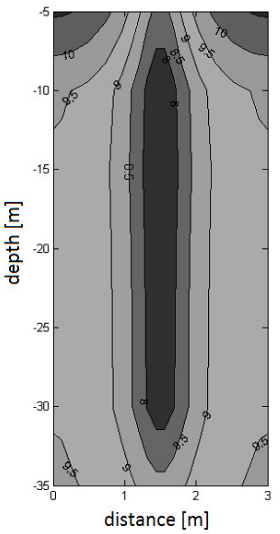

Fig. 4. Simulation variant 1 – temperature distribution in ground around GHE

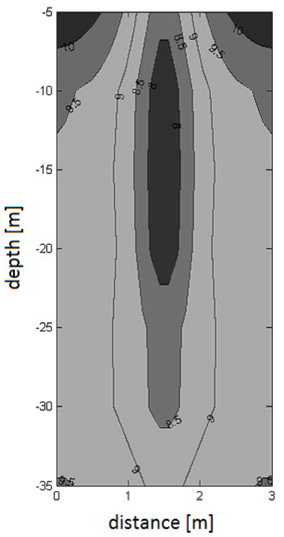

Fig. 5. Simulation variant 2 – temperature distribution in ground around GHE

Conclusions

Presented in the paper results show difference in work of two VGHE for different soil profile. Variant 1 shows simplified situation in which all soil surrounding GHE is the same type and has the same properties. Simulation variant 2 presents situation close to real conditions in which real soil profile is taken into account. Identical boundary and load conditions gives possibility to show only influence of soil profile on GHE work. Difference in received heat form ground in two variants is 7.17 MJ, simulation covered 10 days of GSHP system work. Energy received from ground calculated for real soil profile (variant 2) is only 2% lower than for uniform ground properties. Also values of outlet temperature of fluid in GHE calculated in simulations differs slightly. Results obtained from performed simulations are consistent with results obtained by Lee (Lee 2011). Effective work of GHE depends on many factors, soil profile is one of them. It is important to notice that obtained results strongly depends on structure of soil profile and types of soil occurring in specified location.

Presented in paper model allows to simulate GHE work with different soil profile. Simplified 1D model of fluid flow in GHE combined with 2D axis-symmetry ground heat transfer model ensures acceptable time of calculations with proper accuracy. On the other hand, model is limited to only one GHE, which is strong limitation for simulation of whole GSHP system. Model differs from the typical approach in modeling of the heat exchangers, which allows a good representation of its geometry with high simplicity.

Model need to be validated for whole season simulation. It also requires precise input data for simulations, which author of the paper was not able to obtain. Development of presented model will also include adding part that represents work of heat pump unit.

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