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Effect of Geological Formations on Thermal Performance Modelling of a Deep Borehole

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ABSTRACT

Deep borehole heat exchangers (DBHEs) are currently one of the hot research topics for geothermal heat pump (GHP) applications. There are several computational and experimental works on the topic. Because of the great depth, DBHEs are surrounded by vertically varying geological layers which have different thermal properties. A reliable prediction of time-dependent heat transfer rate (thermal performance) for a DBHE is an important issue for engineering design of a GHP application. Homogeneous or layered models can be established and used for predictions. The homogeneous model is based on the homogenization approach which considers all layers as a single layer having effective thermal properties. On the other hand, the layered model considers all layers separately and gives better accuracy in its predictions, but it is computationally more complicated and time consuming. In this study, thermal performance predictions are made by both the homogeneous and layered models and the results are compared to determine the difference between these two approaches. Furthermore, by considering the true geological formations, different thermal property profiles are used in these models to examine the dependency of thermal performance on formation characteristics. It is seen that the deviations of layered model from those of the homogenous one for energy predictions are proportional to the square of the coefficient of variation of thermal conductivity. The results help to understand the effect of geological formations on thermal performance modelling of a DBHE and as well as the necessity to use a layered model for performance predictions.

1. INTRODUCTION

Thermal energy related consumption is almost half of the total energy consumption of commercial and residential buildings, Vorsatz et.al., (2015), Serrano et.al., (2017). These quite high rates can be reduced by integrating energy efficient heating and cooling equipments during the building's design phase. Heat pump technologies provide both environmentally friendly and energy efficient choices for heating and cooling of buildings. In this technology, depending on seasonal periods, heat energy is extracted from the environment into the buildings or released into the environment. Environment can be air, water or ground depending on application type and location. Since the heat transfer between environment and heat pump occurs through the heat exchanger which is placed in the environment, heat pumps are named with emphasis on the environment such as air-coupled, water-coupled or ground-coupled. It is clear that, the thermal properties of environment directly affect the heat transfer rate and also changes the coefficient of performance value (COP) of heat pumps. Furthermore, it is thermodynamically well known that higher COP values can be achieved if the source and sink (environment and indoor air or vice versa) temperatures are close to each other, Rees, (2016). Therefore, because of its high heat capacity, stable thermal properties and relatively closer temperature to the indoor one, underground makes the ground-source heat pumps (GSHP) advantageous on COP.

GSHP's are scaled depending on thermal demands and requirements and widely coupled with horizontal or vertical heat exchanger systems (GSHE). Therefore, the number of GSHE's may vary from a single one for residential use to hundreds or even thousands for large scale commercial applications. Thermal performance of GSHE's strongly depends on the thermal properties of the ground structure. Hence, thermal properties of ground must be well defined for proper sizing of optimum GSHE's length. However, generally, instead of having detailed information about the ground, an effective thermal diffusivity definition is used. Effective thermal diffusivity can be obtained by using only inlet and outlet temperatures besides volumetric flow rates. This widely used and relatively simple technique is named as constant temperature thermal response test (TRT) [Mogensen, 1983; Eskilson,1987; Spitler and Gehlin, 2015]. By using the effective thermal diffusivity based on homogenized ground property assumption, thermal properties are considered unchanged with depth and direction. However, there are stratified structures in the underground due to its nature and thermophysical properties considerably change from one layer to another. Therefore, conventional TRT is inadequate to determine the optimal GSHE length and system cost. It is clear that, optimal design needs to know the vertical distribution of thermophysical properties of the ground. For this purpose, new TRT models have been developed by using optical fiber thermometers and more accurate results have been obtained about the surrounding formations, Fujii et.al., (2006), Fujii et.al., (2009), Acuna and Palm, (2013), Sakata et al., (2018). Also, there is an analytical TRT approach verified by synthetically generated data for multilayer structures to determine thermal properties at different depths, Raymond and Lamarche, (2013).

Even if the performance of a GSHE depends on many natural factors, the most dominant one is the thermal properties of underground structure. Thermal properties are important not only for reliable long term performance predictions of GSHEs but also for widely used multiple vertical shallow (approximately 100-200 m in depth) borehole applications due to thermal interactions (shortcuts) between the adjacent GSHEs, Kurevija et.al., (2012), Gultekin et.al., (2016), Lam and Dborkin, (2016). Also, groundwater may be the cause of these thermal shortcuts, Meng et.al., (2018), Mendez et.al., (2013), Zanchini et.al., (2012). In recent years, besides shallow wells, there is a considerable increment in studies of deep boreholes with coaxial pipes by both analytical Cai et.al. (2019), Morchio et.al. (2019) and numerical methods Renaud et.al., (2019), Lou et.al., (2019). Especially in deep borehole applications, GSHE pass through many geological layers of the ground and variations in heat transfer between GSHE and different layers become important, Abdelaziz et.al., (2014), Erol and François, (2018), Li et.al., (2019), Florides et.al., (2013), Lou et.al., (2014). The amounts of heat stored/extracted in different layers are different from each other. Besides, neighboring layers vertically exchange heat which may change thermal performance of GSHE. Therefore, thermal property profile of geological layers (thickness, volumetric heat capacity, thermal conductivity etc.) should be known for realistic modelling and optimization of deep GSHEs. The true modelling of heat exchange between borehole and the ground is quite complicated in general due to complex nature of geological formations. On the other hand, it also possible to consider underground structure as a homogenized (effective) single domain instead of complicated layered formations. This approach considerably simplifies the computer model and save both computational time and efforts during the modelling phase of a deep GSHE. However, because of this approach, the results of homogeneous model deviate from those of the true one which considers the layered structure of underground. In this work, the effect of geological formations on the results of thermal performance modelling for a deep GSHE is numerically investigated and the results are compared with those of the homogeneous model to understand the importance of the layered modelling.

2. NUMERICAL MODEL

GSHE is considered as a cylindrical borehole with radius of 0.1 m and constant surface temperature of 2 °C. It is in contact with a surrounding layered ground structure (geological formations), as shown in Fig.1. The initial temperature of the ground is assumed as 17°C. 2D (radial and axial) transient heat diffusion equation is solved in COMSOL environment by considering different thermal properties of each layer to obtain the time dependent temperature distribution in layered ground. During the calculations, vertical heat transfer between the layers is also considered. By integrating the normal conductive heat flux on borehole surface, total heat transfer rate is calculated. Total energy transfer between GSHE and surrounding ground is then determined by time integration of total heat transfer rate over the operation time of 2400 h.

The same calculations are made both for more realistic heterogeneous (multilayer) and simple homogenized (single layer) ground structures. Heterogeneous model assumes that each layer has homogenous thermal properties (thermal conductivity and volumetric heat capacity) within the layer. In homogeneous model, however, ground is considered as a single species structure. Thermal properties of each layer is weighted by using its thicknesses to find the averaged properties of ground for the homogeneous model. Four different deep borehole models consisting of different geological formations with total depth of 750 m (called case-A, B, C and D) are established in COMSOL environment based on real data, Ivanova, (2013). In each model, five different depths (150m, 300m, 450m, 600m and 750m) are considered to investigate the depth dependence of deviations of homogeneous model results from the heterogeneous ones. Geological units and their thicknesses are given in Table 1 for four different cases (A, B, C and D). All boreholes have a total depth of 750 m. The horizontal red lines indicate the units of 150 meters in depth to consider and compare the sub-cases with the same depth in different borehole models. Cases A and C contains 20 layers while cases B and D consist of 16 and 17 layers respectively. Thermal properties (k, thermal conductivity; ρ, density; c_p, specific heat; α, thermal diffusivity) of geological units are also given in Table 2.

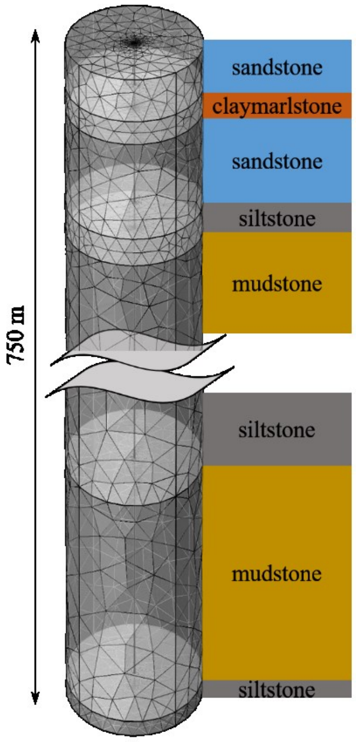

Figure 1: A sketch of a model in COMSOL environment for a deep GSHE passing through different geological layers.

Table 1: Geological layers and their thicknesses for four different cases of computational modelling. The horizontal red lines indicate the units of 150 meters in depth.

Case A		Case B		Case C		Case D	
Δz [m]	**Geological layers**	**Δz [m]**	**Geological layers**	**Δz [m]**	**Geological layers**	**Δz [m]**	**Geological layers**
11	sandstone	51	sandstone	18	sandstone	59	sandstone
6	claymarlstone	98	mudstone	7	claymarlstone	90	mudstone
25	sandstone	1	siltstone	28	sandstone	1	siltstone
7	siltstone	109	siltstone	85	mudstone	26	siltstone
94	mudstone	37	mudstone	12	siltstone	10	sandstone
7	sandstone	4	sandstone	17	siltstone	25	mudstone
31	sandstone	66	sandstone	9	sandstone	49	siltstone
28	siltstone	77	siltstone	22	mudstone	10	sandstone
76	mudstone	7	mudstone	48	siltstone	12	mudstone
15	siltstone	44	mudstone	11	sandstone	18	sandstone
26	siltstone	36	claymarlstone	19	mudstone	5	sandstone
31	sandstone	6	anhydrite	14	siltstone	10	siltstone
28	claymarlstone	31	claymarlstone	10	sandstone	53	sandstone
21	sandstone	15	mudstone	37	sandstone	25	mudstone
44	mudstone	13	claymarlstone	29	mudstone	20	sandstone
93	mudstone	5	sandstone	20	sandstone	23	siltstone
8	anhydrite	25	sandstone	34	siltstone	14	mudstone
30	mudstone	37	mudstone	30	mudstone	110	mudstone
19	claymarlstone	32	claymarlstone	71	mudstone	15	anhydrite
14	claymarlstone	56	anhydrite	14	anhydrite	25	mudstone
18	sandstone			65	mudstone	150	mudstone
52	siltstone			14	mudstone		
62	mudstone			23	sandstone		
4	siltstone			113	mudstone		

Table 2: Thermophysical properties of the layers Eppelbaum, (2014), Scharli, (2001), Fuchs, (2015), Labus, (2018).

Geological Layer	k [W/mK]	ρ [kg/m³]	c_p [J/kgK]	α [x10⁻⁶ m²/s]
SandStone	3.52	2300	845	1.811
SiltStone	2.22	2550	795	1.095
MudStone	3.34	2630	830	1.530
Claymarlstone	2.14	2500	858	0.997
Anhdyrite	4.85	2960	585	2.801

3. RESULTS

Because of the different thermal properties of layers, heat transfer rates are different in each layer and this causes differences in temperature field in each layer. Therefore, vertical heat transfer is developed in some regions of interfaces of the layers. As a result of time and space dependence of this vertical heat transfer, the effect of geological formation on total energy transfer between borehole and the layered ground becomes very complicated. On the other hand, fortunately, total contribution of vertical heat transfers through interface of these layers to total heat energy exchange of BHE is less than 0.1%. In other words, it is completely negligible in all the cases considered here. This is probably valid for almost all kind of lithology.

In Fig 2, the ratios of the predictions of heterogeneous and homogeneous models for total heat energy extracted from ground vs depth are given for different geological compositions. It is seen that the deviations from the homogeneous model results are nearly negligible and slightly smaller than the unity for different depths of all cases considered here. Therefore, as long as we accept the deviations less than 1%, homogeneous model can safely be used to make thermal performance predictions of deep boreholes. However, this is a consequence of the results obtained for the cases considered here. To make a more general statement and more reliable interpretation, it is necessary to investigate the relation between the statistical characteristics of geological formation and these deviations. If we neglect the vertical heat transfer, it is possible to show that there is a strong relation between the profiles in Figure 2 and the differences of the square of the coefficients of variation for thermal conductivity from unity, $1-\sigma_k^2/\bar{k}^2$, given in Fig 3.

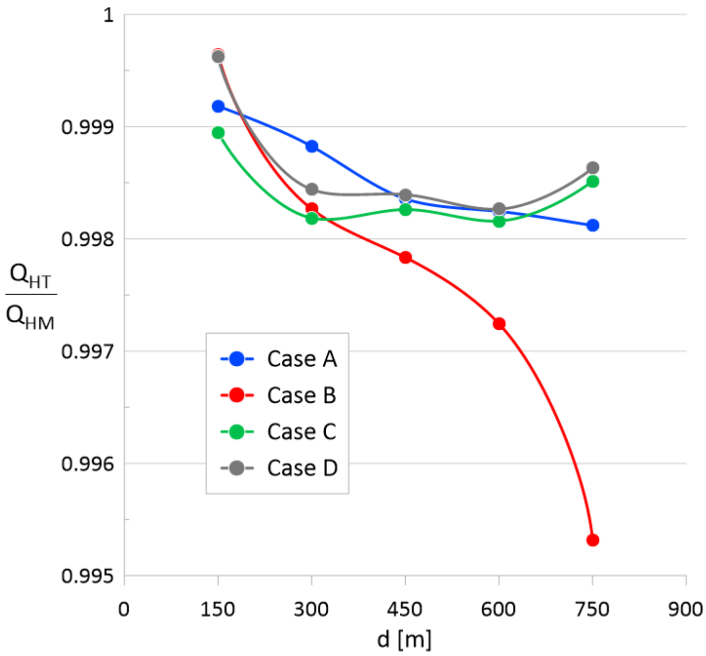

Figure 2: Ratios of the predictions of heterogeneous and homogeneous models for total heat energy extracted from ground vs depth for different geological compositions.

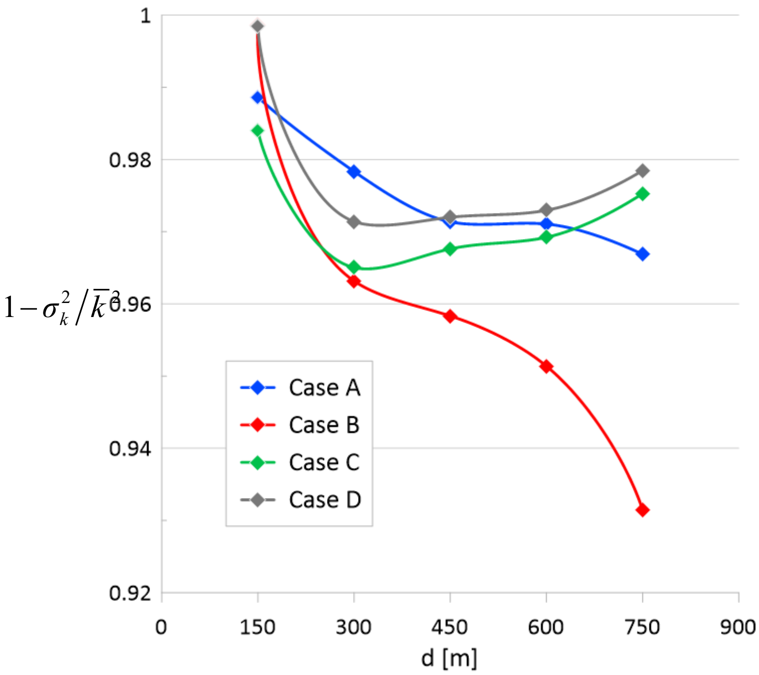

Figure 3: Difference of the square of the coefficient of variation for thermal conductivity from unity versus depth. $1-\sigma_k^2/\bar{k}^2$

Here,

$$\sigma_k^2 = \sum_{i=1}^{N} \frac{\Delta z_i}{z} \left(k_i - \bar{k}\right)^2 = \sum_{i=1}^{N} \frac{\Delta z_i}{z} \left(k_i^2 - 2k_i\bar{k} + \bar{k}^2\right) = \sum_{i=1}^{N} \frac{\Delta z_i}{z} \left(k_i^2 - \bar{k}^2\right) = \overline{k^2} - \bar{k}^2 \tag{1}$$

$$\bar{k} = \sum_{i=1}^{N} \frac{\Delta z_i}{z} k_i \tag{2}$$

where $z = \sum_{i=1}^{N} \Delta z_i$ is the total thickness (depth) of the considered part of DBHE, N is the total number of layers, $\bar{k}$ is the average thermal conductivity and σ_k^2 is the weighted variance of thermal conductivity.

Although the values in Fig 2 and Fig 3 are different, the profiles are nearly the same. In other words, deviations of layered model from the homogenous one depends on the magnitude of $1-\sigma_k^2/\bar{k}^2$. Therefore, as long as the square of the coefficients of variation for thermal conductivity is small enough, homogenous model can safely be used instead of complicated layered model.

4. CONCLUSION

Different geological formations consisting of different layers at different thicknesses are considered here and the numerical models showed that a homogenized medium approach gives quite accurate results. The true behavior (represented by layered model) deviates from the homogenous model predictions only in the order of less than 1%. These deviations are strongly related with $\sigma_k^2/\bar{k}^2$, which is usually very small. The relation between the statistical characteristics of formation's thermal profile and the deviations from the homogeneous model results can further be developed by considering the variance of volumetric heat capacity and covariance between heat conductivity and heat capacity. On the other hand, it seems that the dominant quantity for these deviations is $\sigma_k^2/\bar{k}^2$.

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