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Sensitivity analysis of efficiency thermal energy storage on selected rock mass and grout parameters using design of experiment method

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ABSTRACT

The aim of this study was to investigate the influence of selected parameters on the efficiency of underground thermal energy storage. In this paper, besides thermal conductivity, the effect of such parameters as specific heat, density of the rock mass, thermal conductivity and specific heat of grout material was investigated. Implementation of this objective requires the use of an efficient computational method. The aim of the research was achieved by using a new numerical model, Multi Degree of Freedom (MDF), as developed by the authors and Design of Experiment (DoE) techniques with a response surface. The presented methodology can significantly reduce the time that is needed for research and to determine the effect of various parameters on the efficiency of underground thermal energy storage. Preliminary results of the research confirmed that thermal conductivity of the rock mass has the greatest impact on the efficiency of underground thermal energy storage, and that other parameters also play quite significant role.

1. Introduction

Issues connected with energy saving, sustained development and reduction of CO_2 emission have recently resulted in the implementation of more efficient technologies of energy production from renewable sources [1]. One such technology are heat pumps that are installed with borehole heat exchangers. The first theoretical works on borehole heat exchangers appeared in the 1940s and 1950s. Ingersoll and Plass [2] presented theory of the ground pipe heat source for the heat pump the so-called line source model and Carslaw and Jaeger [3] presented the so-called cylindrical source model. Whereas the most important works on the Borehole Heat Exchanger (BHE) were written in the 1980s and 1990s. Eskilson [4] presented the so-called g-function which is the dimensionless temperature response at the borehole wall. Kavanaugh [5] used the two-dimensional model of finite differences to test the efficiency of the concentric borehole heat exchanger. Based on the theory of cylindrical source model Kavanaugh [6] presented a model to determine the temperature in the ground. Hellström [7] describes the transformation of the internal thermal resistance between two pipes and the borehole thermal resistance between pipes and the borehole wall into the thermal resistances of the Delta-circuit. Kujawa et al. [8] presented mathematical model of a geothermal field exchanger.

Recent research has contributed to broad application of this technology. For example paper [9] presents an innovative Borehole Heat Exchanger (BHE) configuration in which the U-tubes are immersed in an artificial fluid, contained in a case separated from the ground by the usual filling material. In work [10] author shown how spacing of adjacent boreholes and thermal interferences influence required borehole length for heat transfer. In work [11] a combined simulation–optimisation procedure is presented to regulate the operation of Borehole Heat Exchangers (BHEs) in a multiple BHE field when groundwater flow exists. A number of analyses and investigations of borehole heat exchangers were also performed in Poland. For example in the work [12] author presented theoretical model of borehole heat exchanger and [13] where author present possibility of adaptation existing wells to borehole heat exchanger.

Still, modelling is an important area of research, as it has been a significant instrument for system optimisation, long-term efficiency testing and for determining effective thermal conductivity of rocks. Some detailed simulations are also necessary to estimate the economic and ecological benefits of these systems. An oversized system or a system with an insufficient number of exchangers will lead to an increase in costs and losses. That is why the development of existing models and accurate calculation instruments is required, in order to reduce computation time while maintaining a high level of accuracy.

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Nomenclature

b	thickness of the pipe wall, m, heat transfer coefficient, $W/(m^2\,K)$
c	specific heat, J/(kg K)
D	diameter, m
E	energy, J
G	geothermal gradient, K/m
H, h	depth, m
k	distance between pipes, m
P	parameters
q	heat flux, W/m^2
R^2	determination coefficient
r	radius, m
S	sensitivity
T	temperature, K
t	time, s
u	fluid velocity, m/s
$\dot{V}$	volume flow, m^3/s
x, y, z	Cartesian coordinates, m
y	parameters value predicted from response surface or simulation
Greek symbols	
λ	thermal conductivity, W/(m K)
ρ	density, kg/m^3
μ	dynamic viscosity, Pa s
Subscripts	
f	fluid
g	grout
i, in	inner, inlet
o, out	outer, outlet
p	pipe
s	rock mass

At present there exist, many models that help determine transient heat transfer in the U-tube heat exchanger. Many theoretical models have been based on the analytical solution provided by Ingersoll and Plass [2] the so-called line source model, and a solution presented by Carslaw and Jaeger [3] the so-called cylindrical source model. Both the line source model and the cylindrical source model omit heat transfer along the exchanger. For this reason, the models are inappropriate for long-term analyses of Ground-Coupled Heat Pump Systems (GCHP). Currently, the above-mentioned models, with certain modifications, have been applied to determine effective thermal conductivity in Thermal Response Testing (TRT), which is adequately described in the work [14].

In work [15] in order to combine the advantages of fully discretised and analytical models, the authors developed two-dimensional thermal resistance and capacity models for different types of BHE. In paper [16] authors developed analytical model which can estimate the soil thermal conductivity and in work [17] borehole thermal resistance without the mean temperature approximation in TRT. In [18] authors investigates the thermal properties of U-shaped borehole heat exchangers using conformal–mapping method to calculate the thermal resistance of BHE. In work [19] a new method is proposed to calculate temperature excursions in rock during borehole creation. Work [20] presents a semi-analytical model that couples a model outside the borehole with one inside the borehole. In paper [21] a numerical model in MODFLOW/MT3DMS of a single U-pipe in a sandy aquifer is proposed. Above researches has confirmed that modelling is an important research area for underground thermal energy storages with borehole heat exchangers.

Based on the finite-element method or finite-volume method, various design instruments for full discretisation of (BHE) models have also been formed. These instruments are employed to solve transient effects and to determine accurate borehole geometry. For example, Signorelli [22] compared the results from a 3-D finite-element numerical model with those of a simple analytical line-source solution. In work [23] authors presented numerical model of borehole heat exchanger in ANSYS CFX software, and in work [24] authors presented a dynamic three-dimensional numerical model for borehole heat exchangers.

In order to decrease the time of calculations, some of the models have been restricted to 2D models. Yavuzurk et al. [25] presented a transient two-dimensional finite volume model for the simulation of vertical u-tube ground heat exchanger. Austin et al. [26] based on two-dimensional finite volume model develop an in situ system for measuring ground thermal properties. Raymond et al. [27] presented two-dimensional numerical simulations of the borehole temperature evolution during thermal response tests.

Al-Khoury et al. [28] based on finite element method presented an efficient finite element formulation for geothermal heating systems for steady-state and in work [29] for transient. A validation example comparing computed results with measured results were presented in [30]. Diersch et al. [31] improved Al-Khoury's model by application of the new approximation of grouting material. In [32] authors validate their model in FEFLOW–TRNSYS module.

However, in order to provide a full description of the geometry of the borehole, only 3D models give consideration to heat transfer inside and outside a borehole, the various layers of the ground, the geothermal gradient, transient heat transfer in a U-tube and accurate boundary conditions. Fully discrete BHE models allow for the reception of accurate results of the simulation, even with rapidly changing boundary conditions. In contrast, in spite of the application of modern computer hardware and the possibility of parallel data processing, fully discrete models lead to long-term analyses due to the multiple number of elements required for appropriate discretisation of the borehole. In the work [33] the authors of this paper presented a new numerical model called Multi Degrees of Freedom (MDF) which is fast and accurate.

This paper presents an application of this new numerical model (MDF) to research the influence of selected parameters on the efficiency of underground thermal energy storage. Authors measured the influence of thermal conductivity, specific heat, density of the rock mass and thermal conductivity as well as, specific heat of the grout material on the amount of energy that could be supplied and received. To solve this problem authors used design of experiment techniques. Conducting experiments for a given problem is very expensive and 3D numerical experiments are time-consuming, therefore authors decided to complete a short series of numerical experiments. This raises the question of proper planning of the experiment.

2. Object of research

The subject of the research was a borehole heat exchanger with underground thermal energy storage, which consisted of two basic elements: a geological medium guaranteeing thermal capacity of the storage, and a single U-tube borehole heat exchanger, which

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