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Modelling of a borehole heat exchanger using a finite element with multiple degrees of freedom

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A B S T R A C T

An increasing number of installations with underground heat storage have determined the development of new, more accurate and quicker calculation techniques. Therefore, this article shows a numerical model for a single vertical borehole heat exchanger working with underground heat storage. Emphasis has been put on developing a finite element which describes the process of heat exchange. A one-dimensional element with multiple degrees of freedom was used in this work. The changes of grout temperature affect the temperature of the circulating fluid, thus it is necessary to apply a suitable model. The grout area has been divided into three zones, and each one corresponds to a different temperature. Such an attempt allows to determine a more accurate temperature of the fluid. The results obtained for temperature distribution were compared to a model created with the use of Ansys commercial numerical software.

1. Introduction

Renewable energy sources have become popular both worldwide and in Poland; this trend has been described in Zimny et al. (2011), Zimny (2009, 2007). It should be remembered that the most serious problem is the seasonal and random nature of these renewable energy sources. Therefore, energy storages have become an important issue which was widely described by Dincer and Rosen (2002). Geothermal systems and underground storage merit our attention.

In comparison to traditional solutions (HAVAC), systems with a ground-coupled heating pump (GCHP) constitute a very effective method for heating and cooling residential and commercial buildings. A typical GCHP system consists of a heat pump coupled with a ground heat exchanger (GHE). Usual GHE configurations include a horizontal loop, vertical loop or a loop placed at a certain angle to the surface of the ground. Currently, vertical U-tube exchangers are commonly used as their placement in the ground does not need much surface and, additionally, when considering minor seasonal temperature fluctuation they are more efficient in comparison to horizontal exchangers.

This work concerns a shallow closed vertical system supported by the underground seasonal storing of heat, commonly known as Borehole Thermal Energy Storage (BTES) systems.

Recent research has contributed to broad application of this technology. Still, modelling is an important area for research and has been a significant instrument for system optimisation, long-term efficiency testing and an instrument to determine the effective thermal conductivity of rocks. Some detailed simulations are also necessary in order to estimate the economic and ecological benefits of these systems. An oversized system or a system with an insufficient number of exchangers leads to an increase in costs and losses. That is why preparation of an effective, reliable and accurate calculation instrument is required.

At present there exist many models that help determine transient heat transfer in the U-tube heat exchanger. Also, in Poland a theoretical model of the borehole heat exchanger has been developed and introduced in the work of Śliwa and Gonet (2005). Many theoretical models have been based on the analytical solution provided by Ingersoll and Plass (1948), i.e. the so-called line source model, and the solution presented by Carslaw and Jaeger (1959), i.e. the so-called cylindrical source model. In the line source model, Ingersoll and Plass approximated the U-tube and grout to a line heat source with a neglected radial dimension. In the cylindrical source model, Carslaw and Jaeger treated a borehole as an infinite cylinder surrounded by a homogeneous material with stable properties. Heat flux was directly set onto the surface of the borehole cylinder, and this meant that the heat capacity of the U-tube and grout might be totally neglected. This model is known as "hollow". The line source model and cylindrical source model omit heat transfer along the exchanger. For this reason the models are inappropriate for long-term analyses of GCHP systems. Currently, the above-mentioned models, with certain modifications, have been applied to determine effective thermal conductivity during

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Nomenclature

A	area (m^2)
a	coefficient
b	heat transfer coefficient (W/m^2K)
c	specific heat (J/kg K)
d	diameter (m)
F	applied heat flows
h	characteristic length (m)
K	conductivity matrix
M	specific heat matrix
N	shape function
P, B	matrix
Q	heat flow (W)
R	residua or thermal resistance (m^2K/W)
r	radius (m)
S	surface or length of the edge (m)
t	time (s)
T	temperature (K)
u	fluid velocity (m/s)
V	volume (m^3)
W	weight function
w	shank spacing (m)
x, y, z	coordinates (m)

Greek letters

α	heat transfer coefficient (W/m^2K)
β	angle (rad)
δ, ε	deviations (%)
γ, ψ, ξ,	parameters
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)

Subscripts

adv	advection
bal	balance
con	conduction
f	fluid
fem	finite element method
g	grout
g1	grout part 1
g2	grout part 2
g3	grout part 3
i	inner, inlet
o	outer, outlet
p	pipe
s	rock mass

thermal response testing (TRT), which is adequately described in the work of Gehlin (2002).

Recent development of numerical calculation methods has contributed to the preparation of several models of this type. Eskilson (1987) determined the temperature of the ground around the borehole heat exchanger (BHE) using the explicit finite-difference method on a two-dimensional coordinate system. Eskilson also proposed a non-dimensional coefficient, named the g-function, to determine the efficiency of the borehole exchanger for different configurations. Hellström (1991) worked out a model for a vertical heat exchanger system and determined the efficiency of this system based on the global solution and a superposition of the local stable heat flux. Kavanaugh (1986) used the two-dimensional model of finite differences to test the efficiency of the concentric borehole heat exchanger. Lei (1993) applied the finite-difference method to determine the model of the U-tube heat exchanger. Lei (1993) also introduced the double two-dimensional (instead of three-dimensional) cylindrical coordinate system in order to simplify perception of the problem. Based on the explicit finite-difference method, Rottmayer et al. (1997) worked out a numerical model of the U-tube heat exchanger. Also, Lee and Lam (2008) worked out the numerical model of the borehole heat exchanger using the explicit three-dimensional finite-difference method. Oppelt et al. (2010) used the finite-difference method to analyse the grout for a double U-tube heat exchanger. Oppelt et al. (2010) proposed a new way of approximating grout by dividing it into three subareas. In his work Muraya et al. (1996) applied the finite-element method to test relations between tubes within a U-tube. Li and Zheng (2009) by the application of the finite-volume method, presented a three-dimensional model of a vertical U-tube heat exchanger.

Based either on the finite-element method or the finite-volume method, various design instruments for full discretisation of the BHE models have also been formed. These instruments are employed to solve transient effects and to determine accurate borehole geometry (He et al., 2009; Lamarche et al., 2010; Signorelli et al., 2007; Śliwa et al., 2012). In order to decrease the time of calculations, some of the models have been restricted to 2D models. The work by Yavuzurk et al. (1999) and Austin et al. (2000) may serve as an example. However, in order to provide a full description of the borehole's geometry, 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 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 particular, procedures for estimating parameters for a large amount of iteration may constitute a non-solvable task when fully discrete models are applied. Additionally, some effort put into implementation of the model would be significant. This is mainly due to the extreme values of the exchanger middle proportion (a small diameter in comparison to the length – the huge slenderness ratio), which subsequently requires more advanced and numerically effective calculation strategies. New techniques were proposed by Al-Khoury et al. (2005), Al-Khoury et al. (2010) and Al-Khoury and Bonnier (2006), who first used a one-dimensional (1D) finite element representing the exchanger borehole and a U-tube element. The so-called thermal resistance and capacity model (TRCM), worked out by Bauer et al. (2011), introduced an improvement to the method of approximation of borehole elements by placing some additional nodes to the grout area. Bauer showed that the approximation described in Al-Khoury's work is insufficient and less accurate for transient variables. In the works of Diersch et al. (2011a,b), Al-Khoury's model was improved by application of the approximation as proposed by Bauer et al. (2011).

The models discussed above do not take into account the fact that while receiving or supplying heat to a rock mass there is a huge temperature difference between the tubes of the exchanger, particularly at the initial step of the process. This was observed in the following works: Hellström (1998), Oppelt et al. (2010), and Śliwa et al. (2012). This article proposes a new, original model which constitutes an extension of the numerical model for the borehole heat exchanger on the basis of the finite-element method as proposed by Al-Khoury et al. (2005) and Diersch et al. (2011a). A model of a single U-tube has been worked out with approximation of the grout to three nodes, which divides this area into three parts (Fig. 2). This new model is called Multiple Degrees of Freedom (MDF).