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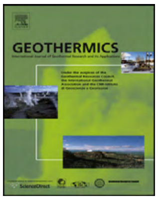

Modelling of the borehole filling of double U-pipe heat exchangers

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ABSTRACT

A new model MISOS is proposed for the simulation of the borehole filling (grout) of double U-pipe heat exchangers. When simulating ground-coupled heat pumps, a suitable model of the filling is necessary because the temperature of the filling effects the temperature of the heat carrier fluid. The filling is divided into three elements whose geometry corresponds to the different temperature zones. For each time step, the temperatures of the filling elements can be calculated from energy balances. MISOS is very fast compared to computational fluid dynamics (CFD) algorithms. CFD calculations were performed for different shank spacings, and results compared with those obtained from MISOS. If the pipe shanks are situated between the axis and the wall of the borehole, nearly the same difference of the fluid temperature between inlet and outlet is predicted by MISOS and CFD. For a minimal shank spacing, heating is overpredicted by about 6% for an extraction period of 3 h while an underprediction of about 9% is obtained for maximal shank spacing.

1. Introduction

Detailed simulations of ground-coupled heat pump systems are necessary in order to estimate the economical and ecological benefits of such installations, especially when the additional use of solar heat is considered. The heat pump efficiency depends on the heat transfer from the soil. Here, vertical double U-pipe heat exchangers are considered which are common especially in Europe. They are characterised by a complex geometry of the borehole filling which does not exhibit an axial symmetry. However, the filling needs to be modelled appropriately because it affects the fluid temperature. Computational Fluid Dynamics (CFD) calculations are possible, but these are very time-consuming and not practical.

In general, more information is available on simulations of single U-pipes than on double U-pipe heat exchangers. For example, Yavuzturk et al. (1999) presented a two-dimensional finite volume model which approximates the shanks of the single U-pipe as pie sectors. Yavuzturk and Spitler (1999) used this model to obtain short-time step response factors for U-pipes. In this way, the well-known response functions (Eskilson, 1987) were extended for short times. Xu and Spitler (2006) reported a numerical one-dimensional model which replaces the real geometry by a centred fluid with equivalent thermal mass. Lamarche and Beauchamp (2007) derived an analytical solution for concentric cylinders as an approximation of single U-pipes. An equivalent radius was employed in order to represent the actual geometry. Bandyopadhyay et al. (2008) obtained Laplace domain solutions for the equivalent core of single U-pipes. Li and Zheng (2009) described a 3D model based on the finite volume method in order to simulate single U-pipes. The actual geometry of pipe walls and filling was considered in order to simulate short-time effects.

A finite-difference model for double U-pipes called EWS was published by Huber and Schuler (1997) and improved by Huber and Pahud (1999). The latter model is used to calculate the temperature distribution within fluid, filling and soil close to the heat exchanger. The vertical direction is divided into slices without considering heat flow in the axial direction. The temperature distribution in the radial direction is calculated using an one-dimensional model for each slice. In general, this model proved to be suitable for short-time simulations although the filling within a slice is regarded as just one element. As the largest temperature gradient during heat pump operation is expected within the filling, it is useful to improve the accuracy of its representation. A new model MISOS is proposed in the following which allows a more detailed consideration of the filling. MISOS permits the fast simulation of 1 year or more of heat pump operation with a time step of about 1 h. Results with sufficient accuracy can be obtained using a standard PC and a short calculation time.

2. Calculation model MISOS

Fig. 1 shows a slice with a thickness ΔH of a double U-pipe within the borehole. When the heat flow in the vertical direction is neglected for such a slice and symmetry is assumed, the tem-

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Nomenclature

A	area (m^2)
c_p	heat capacity (J/(kg K))
d	diameter (m)
h	heat transfer coefficient (W/(m^2 K))
H	height (m)
k	thermal conductivity (W/(m K))
l	length (m)
Q	heat quantity (J)
$\dot{q}$	heat flux (W/m^2)
r	radius (m)
s	distance (m)
s_p	shank spacing (m)
w	velocity (m/s)

Greek symbols

β	angle
Δt	time step (s)
ϑ	temperature (°C)
ρ	density (kg/m^3)
ψ	a geometrical parameter

Subscripts

a	outer
an	half annulus
b	borehole
bal	balance
co	core
cs	core cross-section segment
dom	domain
e	soil
f	filling
fl	heat carrier fluid
geo	geothermal
i	inner
in	inlet
o	outlet
p	pipe
pi	inlet pipes
po	outlet pipes
ps	pipe cross-section segment
surf	surface

perature distribution in the soil (radial direction from the borehole centre) can be calculated using an one-dimensional model, e.g. by the finite-difference method (FDM) described by Huber and Schuler (1997). The temperature of the heat transfer fluid can be calculated using FDM in the vertical direction through all the slices. This calculation is based on a simple one-dimensional heat exchanger model which consists of two differential equations for the inflowing and the outflowing fluid. The fluid temperature depends on the temperature at the outer walls of the pipes, i.e. in the filling of the borehole. Thus, the modelling of the filling is of special importance.

As shown in Fig. 2, the geometry of the filling depends on the borehole diameter d_b, the outer pipe diameter $d_\mathrm{p,a}$ and the shank spacing s_p. The calculation model presented here is based on the assumption that both inlet pipes are next to each other, i.e. the pipes on the left-hand side in Fig. 2 are the inlet shanks and those on the right-hand side are the outlet shanks. For this case, the filling is divided into three computational elements for each slice as shown in Fig. 3.

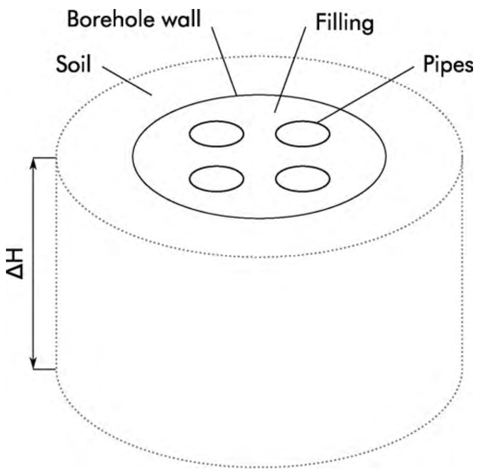

Fig. 1. Horizontal slice of a double U-pipe within the borehole.

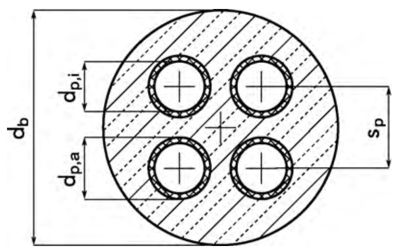

Fig. 2. Cross-section of a double U-pipe within the borehole.

- Core (co): The core element is defined such that it includes 1/4 of the circumference of each pipe.
- Semi-annulus around the inlet pipes (an,in): The element adjoins 3/4 of the circumference of both inlet pipes, the core and the soil with half of the borehole circumference as boundary.
- Semi-annulus around the outlet pipes (an,o): The element is defined like the one around the inlet pipes, but with the outlet pipes as neighbour elements.

The core is defined as a separate element because it has the lowest temperature when heat is extracted from the ground due to heat pump operation. The remaining annular filling space is divided into two parts in order to reproduce the temperature difference between the inlet and the outlet part. The half annulus around the outlet pipes has a higher temperature than around the inlet pipes because the fluid is heated by heat transfer from the earth as it flows upwards.

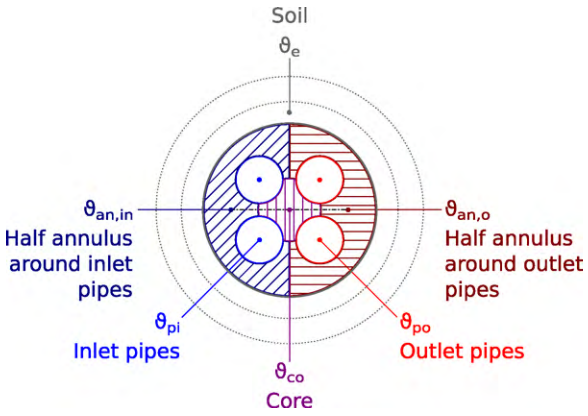

Fig. 3. Heat transfer elements within the borehole and their connection to the soil.