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Numerical modelling of ground loop configurations for direct geothermal applications

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ABSTRACT

The rigorous design of direct geothermal heat pump systems that use concrete piles or boreholes as heat exchangers to extract or reject heat with the ground needs a model for the thermal process in the ground, the ground heat exchanger (GHE) and the carrier fluid circulating within. Thermal interference between pipes in the GHE is an important factor which may significantly affect system efficiency. Different pipe configurations including single U-Pipe, double U-Pipe and double cross U-Pipe, are modelled using finite element methods to investigate the thermal interference that occurs between the pipes within the GHEs. In this work, water is the carrier fluid circulating through the pipes and exchanging heat with the ground. Water inlet temperatures and ground far-field temperatures were chosen as being typical for Melbourne conditions. U-Pipes are located vertically in concrete piles or grouted boreholes surrounded by the ground. The efficiency of the GHEs is investigated in heating mode. The results presented confirm the importance of geometry in design and the significant variations in performance that can be obtained using different pipe configurations.

Keywords: direct geothermal energy, ground source heat pump systems, vertical ground heat exchangers, ground loop configurations, numerical modelling

1 INTRODUCTION

Due to increasing concerns about greenhouse gas emissions and the un-sustainability of traditional fossil fuel sources, geothermal energy has become an alternative energy source with great environmental and economical benefits. Geothermal energy resources range from the shallow ground to hot water and hot rocks within a few kilometres below the ground surface. In addition to this from-the-core flow of energy, the sun also adds energy to the ground surface. In general terms, this defines the two basic forms of geothermal energy: direct and indirect (Johnston et al. 2011). The direct use of geothermal energy is in fact the most common form, and it is typically used to heat and cool buildings or to provide heating and cooling for certain industrial processes. It relates to relatively shallow (ground) sources which can be at normal or close-to-ambient temperatures, and where heat is extracted or rejected from/to the ground via a Ground Source Heat Pump (GSHP). GSHP systems typically consist of i) a primary circuit which exchanges heat with the ground via pipes installed in boreholes or in foundations to form the Ground Heat Exchanger (GHE), ii) a heat pump that exchanges heat between the primary circuit and the secondary circuit and enhances the geothermal energy with electrical or mechanical work, and iii) a secondary circuit which circulates heat within the building (Brandl 2006).

The functioning principles of direct geothermal energy are relatively simple. The ground temperature is relatively constant at approximately 5 to 10 m below the ground surface and is initially close to the mean atmospheric temperature. Therefore, the ground is warmer than the atmosphere in winter and colder during summer. GSHP technology takes advantage of this nearly constant temperature and uses the ground as a source or a sink of heat. GSHP systems extract heat in winter for heating and reject heat in summer for cooling residential, industrial and commercial buildings with lower energy consumption, maintenance and operating cost than conventional systems. Vertical GSHP systems with single and multiple U-pipes placed within boreholes are a common form of GHEs. These vertical systems provide the best use of land due to their reduced footprint and have significantly higher energy performance characteristics than horizontal systems due to smaller temperature fluctuations in the ground at depth.

The performance of GSHP systems depends on the amount of the heat transferred between the ground and the carrier fluid which circulates within the pipes. Around the world, there are a relatively limited number of numerical, analytical and experimental studies that have been conducted to allow the different design parameters to be optimised. Pipe loop configuration is one of these parameters which affect system efficiency. In this short paper, vertical GHEs with different pipe configurations including single U-pipe, double U-pipe and double cross U-pipe have been modelled using finite element methods to investigate the thermal interference between the pipes in these different configurations, at low flow rates. Heat transfer and fluid flow are the two main physical processes combined in the numerical model. Heat exchange rates, which arise from temperature distributions in the ground, at the borehole wall and in the carrier fluid in different ground loop configurations, are discussed.

2 DESCRIPTION OF THE NUMERICAL MODEL

In this model, the GHEs are formed by concrete or grout piles or grouted boreholes located vertically in the ground and water is circulated within pipes embedded in these GHEs. Heat transfer around and in the vertical GHE occurs primarily by conduction and convection. In this system, heat conduction occurs in the ground (soil), concrete or grout and pipe wall, and partially in the carrier fluid; while heat convection dominates in the water circulating in the pipe. It is assumed that there is no groundwater flow in the ground. The Navier-Stokes (NS) and the Conduction and Convection (CC) equations are coupled numerically within the finite element package COMSOL Multiphysics to produce a model to evaluate the performance of the GHEs.

2.1 Governing equations

The motion of the carrier fluid in the pipes is described by the well-known Navier-Stokes equations. These equations are the formulation of the continuity law for an incompressible flow which represents the conservation of mass, and the formulation for conservation of momentum described in Eqs (1) and (2) respectively:

$$\rho\nabla.\boldsymbol{u} = 0 \tag{1}$$

$$\rho\frac{\partial\mathbf{u}}{\partial \mathrm{t}} + \rho(\boldsymbol{u}.\nabla)\boldsymbol{u} = \nabla.\left(-P\boldsymbol{I} + \mu(\nabla\boldsymbol{u}) + (\nabla\boldsymbol{u}^T)\right) + F \tag{2}$$

where ρ = fluid density in kg/m^3, $\boldsymbol{u}$ = velocity field in m/s, P = pressure in Pa, $\boldsymbol{I}$ = identity, μ = dynamic fluid viscosity in Pa.s, T = absolute temperature in °K and F = volume force field of various origins in N/m^3.

Heat transfer from the ground to the heat exchanger and the carrier fluid can be modelled using conduction and convection equations. This process is the result of the flow of energy due to temperature differences. The generalized governing equation for heat transfer can be expressed as:

$$\rho_m C_{p,m}\frac{\partial T}{\partial t} + \rho_m C_{p,m}\boldsymbol{u}.\nabla T = \nabla.(k_m\nabla T) + Q \tag{3}$$

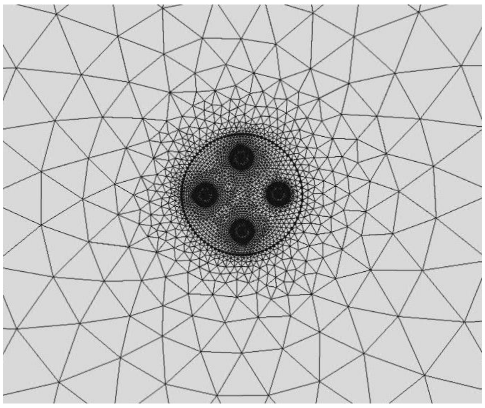
Where ρ_m = density of the medium (i.e., fluid or solid) in kg/m^3, $\boldsymbol{u}$ = velocity field in m/s, k_m = thermal conductivity of the medium (i.e., fluid or solid) in W/(m°K), $C_{p,m}$ = heat capacity of the medium (i.e., fluid or solid) in J/(kg°K), Q = external heat source in W/m^3. Note that “solid” can refer to soil, concrete, grout, steel or any other solid.

Heat transfer in the carrier fluid circulating in the pipes is a combination of heat conduction and convection and can be modelled using Eq (3) in full. Here the fluid velocity field $\boldsymbol{u}$ is coupled to Eqs (1) and (2). In other words, the velocity field $\boldsymbol{u}$, found by solving the governing Eqs (1) and (2), is used in Eq (3) when modelling the heat transfer by conduction and convection within the pipes.

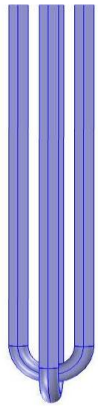
On the other hand, heat transfer in solids, which occurs in the ground, in the heat exchanger and in the pipe wall, also uses Eq (3) but the second term of the left hand side vanishes as the velocity field is null (i.e., no fluid flow), so Eq (3) reduces to a conduction only phenomenon. This is valid in the absence of groundwater flow.

2.2 3D finite element model

The numerical model consists of a 30 m long cylindrical vertical GHE, 0.14 m in diameter, comprising pipes embedded in grout, with assumed constant thermal properties of k_{grout}= 2 W/(m°K) and $C_{p,grout}$ = 840 J/(kg°K). A single, double or double cross U-pipe with a pipe diameter of 0.025 m is sequentially modelled (more details in Section 3) to assess the thermal response of these different pipe configurations, and thus investigate and quantify the effects of the thermal interference that occurs between the pipes of the GHEs. A soil cylinder with a diameter of 1 m surrounding the GHE completes the FEM model. Representative constant soil thermal parameters of k_{soil} = 1.4 W/(m°K) and $C_{p,soil}$= 1,300 J/(kg°K) are used. For simplicity, constant physical parameters are also selected for the (incompressible) circulating water, with ρ = 1,000 kg/m^3, μ = 0.001 Pa.s, k_{water} = 0.6 W/(m°K) and $C_{p,water}$ = 4,200 J/(kg°K). COMSOL Multiphysics is used for detail simulation of heat transfer and fluid flow in the GHEs. Figure 1 shows an example of a 3D model configuration and FEM mesh for the double cross U-pipe case. Whenever planes of symmetry are identified, the 3D models are halved in size to save computational time.



(a)



(b)

Figure 1. Example of a 3D FEM model: (a) FEM mesh of a double U pipe model (Top view), (b) detail of a double cross U-pipe configuration (GHE bottom part shown, side view).

2.3 Initial and boundary conditions

A uniform initial temperature equal to the undisturbed ground temperature, typically 18ºC (or ~291ºK) in the Melbourne area, is applied over the entire model (the GHEs and the ground). The boundary condition at the symmetry plane (whenever applicable) and at the ground surface and bottom of the model is prescribed to a zero heat flux condition. A constant far-field temperature of 18ºC (or ~291ºK) is applied on the outer surface of the ground domain. To account for the thermal interaction between conductive and convective heat transfer, the inlet temperature and fluid flow rate are specified as boundary conditions. The simulations are run in heating mode, that is, extracting heat from the ground. For simplicity, a typical inlet temperature of 5ºC (or ~278ºK) is prescribed in the inlet pipe(s) of the modelled GHE. The fluid flow rate was varied within the laminar regime only. A no slip boundary condition is applied on the pipe walls, i.e., the water velocity on the pipe walls is zero, and a reference atmospheric pressure is set in the outlet pipe(s) for the purpose of forced convection.

3 RESULTS AND DISCUSSIONS

In this section a brief summary of the model validation is presented together with the results of the numerical simulations, which are also discussed.

3.1 Model validation

Numerical results obtained from modelling the steady state thermal response of a GHE with a single U-pipe were validated against analytical solutions that are based on Infinite Line Source Model (ILSM), Finite Line Source Model (FLSM) and Cylindrical Source Model (CSM). Details of these analytical models can be found elsewhere (e.g., Bernier 2001; Deerman 1990; Jun et al. 2009; Lamarche and Beauchamp 2007; Marcotte and Pasquier 2008). The total heat flux $q*$ that can be extracted from a GHE can be computed as:

$$q^* = \dot{m}C_{p,water}\Delta T \quad (4)$$

where $\dot{m}$ is the fluid mass density in kg/s, $C_{p,water}$ is the heat capacity of the water in J/(kgºK) and ΔT is the difference in the average inlet and outlet temperature of the water in ºK.

As an example, Table 1 shows the comparison between the analytical and numerical solutions, for the case of a 30 m long GHE, with 0.025 m diameter pipes and a water flow rate of 1.47 litres/min (or average velocity $\boldsymbol{u}$ = 0.05 m/s). Once the model is solved numerically, the heat extraction is computed using Eq (4), and normalised with the total length of the GHE to obtain the heat extraction rate. The heat extraction rate q and average water outlet temperature T_{out} calculated analytically show good agreement with values obtained with the numerical model. These results are also within the range of measurements reported for full scale experiments (Banks 2008; Gao et al. 2008; Hamada et al. 2007; Miyara et al. 2011), recognising that the thermal performance in a turbulent flow regime is about 60% to 80% higher than the laminar flow regime which is the case herein.

Table 1: Comparison between analytical and numerical solutions

Parameter	ILSM	FLSM	CSM	Field data	This work
q [W/m]	20.5	29.7	21.7	10-60	23.7
T_{out} [°C]	11.0	13.6	11.3	-	11.9

The temperature gradients near and in the pipes are generally the steepest. Therefore, mesh elements are denser in this area. The temperature gradient between the outside pipe surface and far-field boundary in the ground undergo a gradual change, from very large gradients near the pipe walls, to very small ones in the ground far-field. Therefore, to save time and computational memory, the size of mesh elements in this area should also undergo a similar course of gradual change. A mesh size analysis was conducted so that reasonable accuracy could be achieved without excessive computational expense. A typical mesh pattern is shown in Figure 1(a), with very fine elements in the U-pipe, becoming coarser in the radial direction.

3.2 Numerical simulations and results

With the numerical model validated for the single U-pipe case, two more GHE pipe configurations were examined; these being the double U-pipe and double cross U-pipe configurations. Cross sections of all GHEs cases are shown in Figure 2 (with Figure 1(b) showing the base detail of the double cross U-pipe). These more complex configurations cannot be readily explored with analytical models, and as far as the authors are aware, have not been investigated with this level of detail to date.

Parametric analyses involving variations of water flow rate (or average velocity) and centre-to-centre separation between inlet and outlet pipes (or pair of pipes) were performed for these configurations. For easy comparison and discussion, heat extraction rates have been normalised with respect to a single U-pipe base case which is explained below.

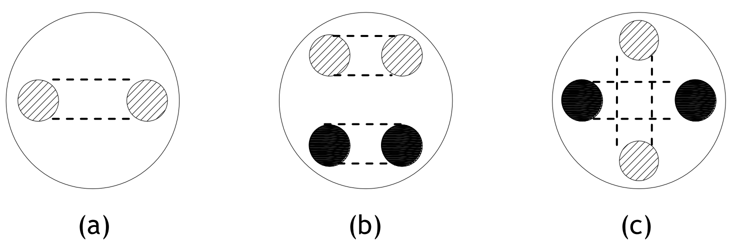


Figure 2. GHE pipe configurations: (a) single U-pipe, (b) double U-pipe, (c) double cross U-pipe.

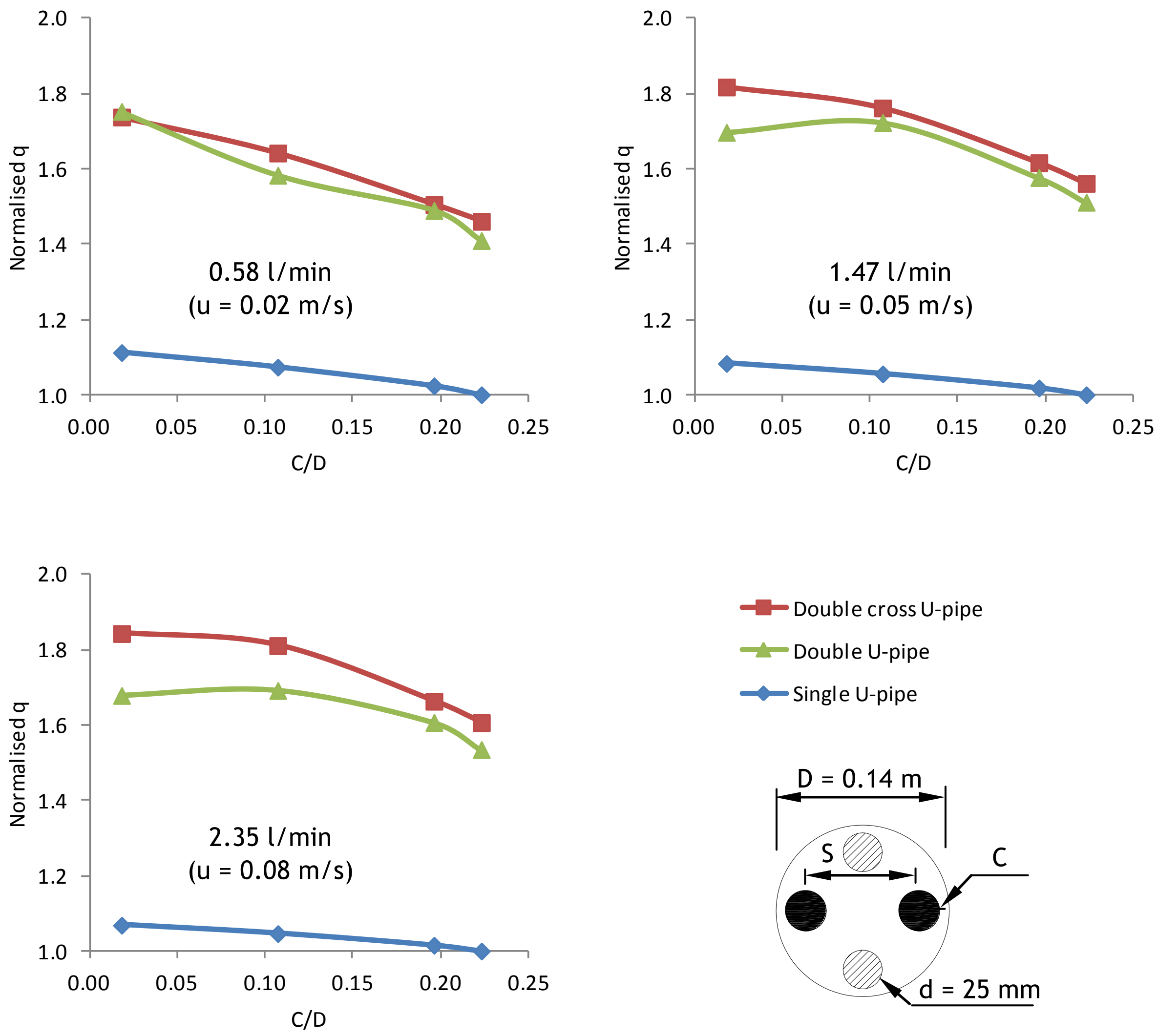


Figure 3. Normalised heat extraction as a function of normalised pipe cover for various flow rates.

Figure 3 shows a summary of the numerical results. These have been normalised for each flow rate to the lowest thermal performance base case given by the GHE with a single U-pipe with the largest pipe cover C (i.e., the closest separation S between the inlet and outlet pipes) that can be accommodated in all three cases shown in Figure 2. This corresponds to a separation of 50mm determined by the double cross U-pipe configuration leading to a minimum C/D of 0.23. Note that while the single U-pipe case can achieve a larger pipe cover (or smaller pipe separation), this is physically impossible to achieve when two pair of pipes are located within the borehole and the same separation is maintained for both pairs. Figure 3 shows that as the pipe cover increases, the heat extraction tends to decrease for all fluid flow rates considered here. Moreover, the addition of a second U-pipe to a single U-pipe GHE does not duplicate the thermal performance but achieves between about 40% and 83% additional thermal performance. This represents a significant reduction in the total number of GHEs that would need to be drilled in a geothermal energy project, and given that the cost of pipe is much smaller than that of drilling, important savings could be attained.

The comparison of double U-pipe and double cross U-pipe configurations is not as straightforward as Figure 3 appears to suggest. Although for the same C/D ratio, double cross U-pipe configurations seem to perform better; this only represents a situation where the cross sections of both GHEs look exactly the same. Borehole geometry requires that the separation between inlet and outlet pipes of each pair would be different and a little smaller. In fact, for a given same normalised separation S/D, the numerical results showed a modest 2 to 6% better performance in the double U-pipe configuration than in the double cross U-pipe configuration.

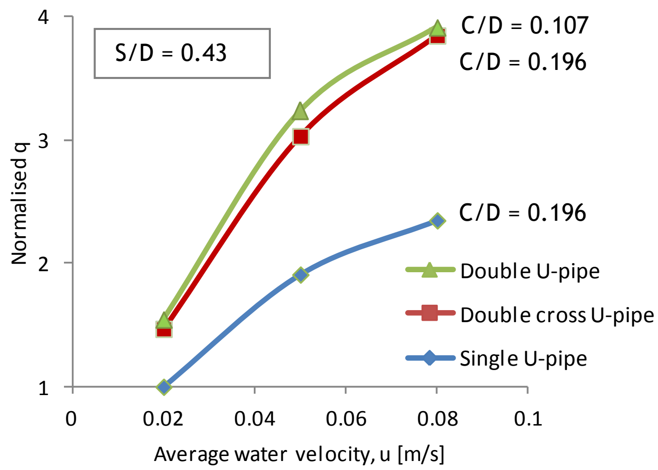


Figure 4. Heat extraction normalised with respect to the slowest single U-pipe heat extraction versus water average velocity (i.e., flow rate) for a fixed inlet-outlet pipe separation S =0.06 m.

Finally, Figure 4 confirms the significant effect of fluid flow rate on thermal performance of GHEs, and confirms the important advantage that can be obtained by introducing an additional U-pipe in a borehole. The figure shows the modest improved performance of double U-pipe over double cross U-pipe configurations, for the limiting inlet-outlet separation of the pairs of pipes in a fixed diameter borehole (see the change in C/D).

4 CONCLUSIONS

Using a state of the art numerical simulation tool, a detailed numerical model has been developed to model a single vertical borehole GHE of a direct geothermal system. This model appears to reasonably reproduce the extracted heat flux which has been suggested by various analytical models and limited field data using single U-pipe loops in the borehole. Further simulations show that the inclusion of second loop of pipe in the same borehole can significantly increase performance, suggesting important economic advantages can be obtained. The increase of flow rate contributes even more to enhance GHE thermal performance. Note that these findings correspond to the cases studied here and may not necessarily hold in the same terms at higher flow rates (turbulent regime).

5 ACKNOWLEDGEMENTS

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