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Numerical Modelling of GHE Configurations and Geometry for Direct Geothermal Applications

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ABSTRACT

Direct geothermal heat pump systems use concrete piles or boreholes as ground heat exchangers (GHEs) to extract heat from or reject heat to the ground. The thermal process in the ground, the GHEs and the carrier fluid circulating within are modelled using state-of-the-art finite element methods in order to understand and enhance cost-effectiveness and energy efficiency of the system. Pipe geometry and GHE configuration are two of the design parameters which may significantly affect system efficiency. Therefore, GHEs with different pipe configurations have been modelled to investigate the thermal interference that occurs between the pipes within the GHEs as well as the effect of pipe diameter on the heat extraction rate. In this work, the pipe configurations studied include U-pipe, double U-pipe and double cross U-pipes with various diameters. Water is the carrier fluid circulating through the pipes and exchanging heat with the ground. Water inlet temperatures and ground far-field temperatures have been chosen as being typical for Melbourne conditions. U-pipes were located vertically in concrete piles or boreholes surrounded by the ground. The efficiency of the GHEs was investigated in heating mode. The results presented confirm the importance of GHE geometry in the design of ground loops and the significant effect of pipe geometry and configurations on performance.

1. INTRODUCTION

Geothermal energy is the energy derived from the interior layers of the Earth. It has become an attractive alternative energy source with great environmental and economical benefits in comparison to unsustainable and inefficient greenhouse gas emission fossil fuel sources. The geothermal sources range from shallow depth to hot water and hot rocks within a few kilometres below the ground surface. In addition to this from-the-core energy, the Sun also adds energy to the ground surface. In general, this defines the two basic forms of geothermal energy: direct and indirect (Johnston et al. 2011). Direct geothermal energy sources are mostly used for heating and cooling

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industrial, residential and commercial buildings by extracting/rejecting heat 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 foundations to form the Ground Heat Exchanger (GHE), ii) a heat pump that exchanges heat between the primary circuit and the secondary circuit with the addition of electrical or mechanical work, and iii) a secondary circuit which circulates heat within the building (Brandl 2006). The ground temperature within a few meters below the ground surface (0 to ~10 m) is greatly influenced by the air temperature. Below this relatively thin layer, ground temperature is considered constant and close to the mean atmospheric temperature, with a temperature gradient approximately equal to 25°C to 30°C per kilometre. Therefore, the ground is warmer than the atmosphere in winter and cooler 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. GSHP systems require less energy consumption, maintenance and operating costs than conventional systems. Vertical GSHP systems with single and multiple U-pipes placed within boreholes are a common form of GHE. These vertical systems provide the best use of land due to their reduced footprint and show higher energy performance than horizontal systems due to the narrower temperature fluctuation 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 different flow rates. To investigate the effect of pipe diameter on heat extraction rate, a parametric analysis involving variations of pipe diameter was performed at constant flow rate, for the most efficient GHE configuration of those three. 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 consist of concrete or grout piles or grouted boreholes located vertically in the ground. Water is circulating within pipes embedded in these GHEs. In this system, heat conduction occurs in the ground (soil), concrete or grout, pipe wall, and partially in the carrier fluid. Heat convection dominates in the water circulating in the pipe. It is assumed that there is no groundwater flow. The Navier-Stokes (NS) equations for Reynolds numbers ≤ 2,300, Reynolds Averaged Navier-Stokes (RANS) equations for Reynolds numbers ≥ 2,300 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 Navier-Stokes equations. For an incompressible flow, these equations can be written as follows:

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

$$\rho\frac{\partial \mathrm{u}}{\partial \mathrm{t}} + \rho(u.\nabla)u = \nabla.(-PI + \mu(\nabla u) + (\nabla u)^T) + F \tag{2}$$

where ρ represents fluid density in kg/m^3, u is the local fluid velocity vector in m/s, P is pressure in Pa, μ is the dynamic fluid viscosity in Pa.s, and F is a volume force field of various origins, such as gravity, in N/m^3.

In a turbulent flow, all quantities in Eq. (2) fluctuate in time and space. The averaged representation of turbulent flow divides the flow quantities into an averaged value and a fluctuating part. The decomposition of the flow field into an average part and a fluctuating part, followed by insertion into the NS equations and then averaging, gives the RANS equations, which allows a less expensive computational modelling of fluid flow in the turbulent regime (Wesseling 2010):

$$\rho\frac{\partial u}{\partial \mathrm{t}} + \rho u + \nabla u + \nabla.\overline{(\rho\boldsymbol{u}'\otimes\boldsymbol{u}')} = -\nabla P + \nabla.\mu(\nabla u + (\nabla u)^T) + F \tag{3}$$

$$\rho\nabla.u = 0 \tag{4}$$

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

$$\rho_m C_{p,m}\frac{\partial T}{\partial t} + \rho_m C_{p,m}u.\nabla T = \nabla.(k_m\nabla T) + Q \tag{5}$$

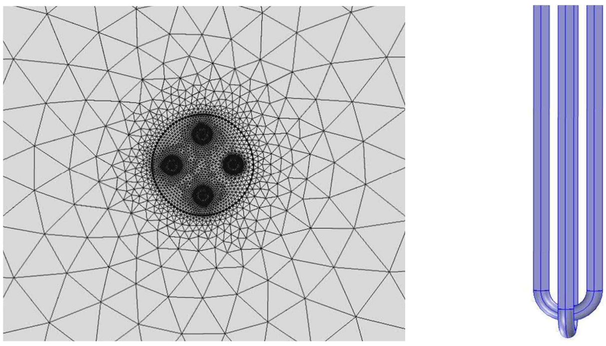
where ρ_m is the density of the medium (i.e., fluid or solid) in kg/m^3, u is the fluid velocity field in m/s, k_m represents the thermal conductivity of the medium (i.e., fluid or solid) in W/(m°K), $C_{p,m}$ is the heat capacity of the medium (i.e., fluid or solid) in J/(kg°K), Q can represent an external 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. (5) in full. Here the fluid velocity field u is coupled to either Eqs. (1) and (2) or Eqs. (3) and (4). In other words, the velocity field $\boldsymbol{u}$, found by solving the governing Eqs .(1) and (2) in laminar regime, or (3) and (4) in turbulent regime, is used in Eq. (5) 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. (5) but the second term of the left hand side vanishes as the velocity field is null (i.e., no fluid flow), and so Eq. (5) reduces to a conduction only equation. 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 the detailed simulation of heat transfer and fluid flow in the GHEs. Fig. 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)

Fig. 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 borefield 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, whilst 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 is varied within the laminar and turbulent regimes. 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. NUMERICAL SIMULATIONS, RESULTS AND DISCUSSIONS

The numerical model is validated against some analytical solutions. Subsequently, GHEs with single U-pipe, double U-pipe and double cross U-pipe configurations are examined. Results are discussed in this section.

3.1. Model validation

Heat extraction rate and water temperature at the outlet of a single U-pipe GHE, modelled in steady-state, were validated against well-known analytical solutions (Infinite line source model (ILSM), cylindrical source model (CSM) and Finite line source model (FLSM)). Details of these analytical solutions can be found elsewhere (Bernier 2001; Deerman 1990; Jun et al. 2009; Lamarche and Beauchamp 2007; Marcotte and Pasquier 2008).

The total heat flux calculation is based on the temperature difference between the inlet and outlet of the pipe and can be calculated as:

$$q^* = \dot{m} C_{p,water} \Delta T \qquad (6)$$

where $\dot{m}$ is the fluid mass density in kg/s, $C_{p,water}$ is the heat capacity of the water in J/kg°K and ΔT is the temperature difference between the inlet and outlet pipe average fluid temperatures in °K or °C.

Numerical results obtained from the simulation of a 30 m long single U-pipe GHE with a 0.025 m pipe diameter, prescribed average inlet water temperature of 5°C and water flow rate of 8.25 litres/min, are compared to results from analytical solutions. Table 1 shows that the numerically obtained values of the heat extraction rate (q) and the average water outlet temperature (T_{out}) are in good agreement with the analytical results.

Table 1. Comparison between analytical and numerical results

Parameter	ILSM	CSM	FLSM	This work
T_{out} (°C)	6.10	6.54	6.93	7.10
q (W/m)	21.16	29.64	37.22	40.5

3.2. Numerical simulations and results

GHEs with single U-pipe, double U-pipe, and double cross U-pipe configurations were examined. The cross sections of all generic cases studied herein are shown in Fig. 2. Note that the cross sections of double cross U-pipe (Fig. 2-b) and double U-pipe (Fig. 2-c) configurations are identical, which implies both have the same pipe cover, C (i.e., same cover to GHE diameter ratio, C/D), but different pipe separation, S (S in the double U-pipe is slightly smaller than in the double cross U-pipe). Parametric analyses involving variations of average water velocity (or water flow rate) and centre to centre separation, S, between inlet and outlet pipes (or pair of pipes) were conducted for all cases. To investigate the effect of pipe diameter on heat extraction rate, a parametric analysis was conducted on the most efficient GHE configuration of the three explored here. For easy comparison and discussion, heat extraction rates have been normalised.

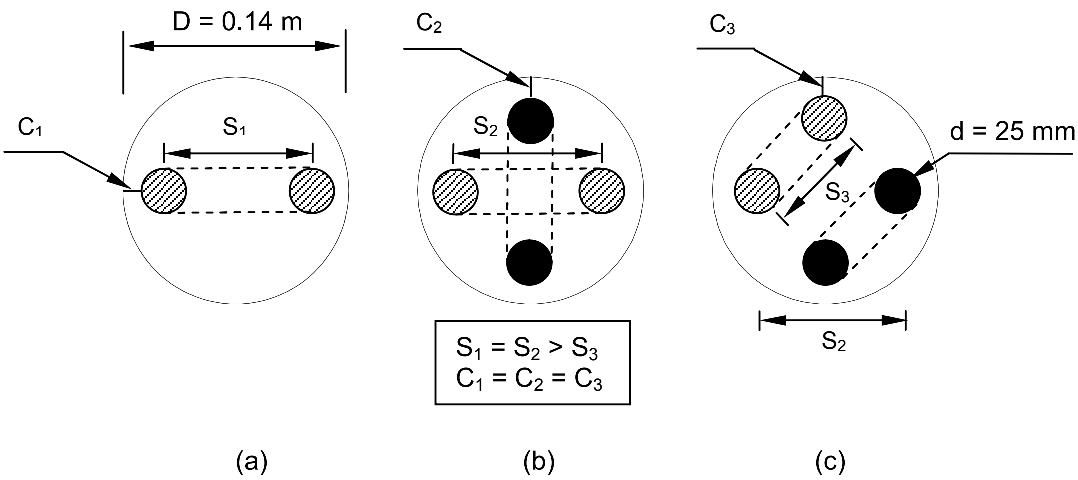


Fig. 2 Pipe configurations of GHEs: (a) single U-pipe, (b) double cross U-pipe, (c) double U-pipe. The GHE diameter is given by D, and the pipe diameter, by d.

Fig. 3 shows the effects of velocity and pipe separations on the heat extraction rate. The heat extraction rate is normalised with respect to the lowest thermal performance base case given by the GHE with a single U-pipe and with the smallest pipe separation that can be accommodated in all three configurations shown in Fig. 2.

The results show that as the average water velocity increases in the pipe, heat extraction rate first tends to increase at a high rate for all different GHE configurations considered here (double, double cross and single U-pipes) regardless of the pipe separation. However, from approximately u = 0.1 m/s (2.95 liters/min), heat extraction rate does not increase as sharply as it did in the laminar regime. Moreover, from about u = 0.2 m/s (5.89 litres/min) no significant increase was observed in the heat extraction rate.

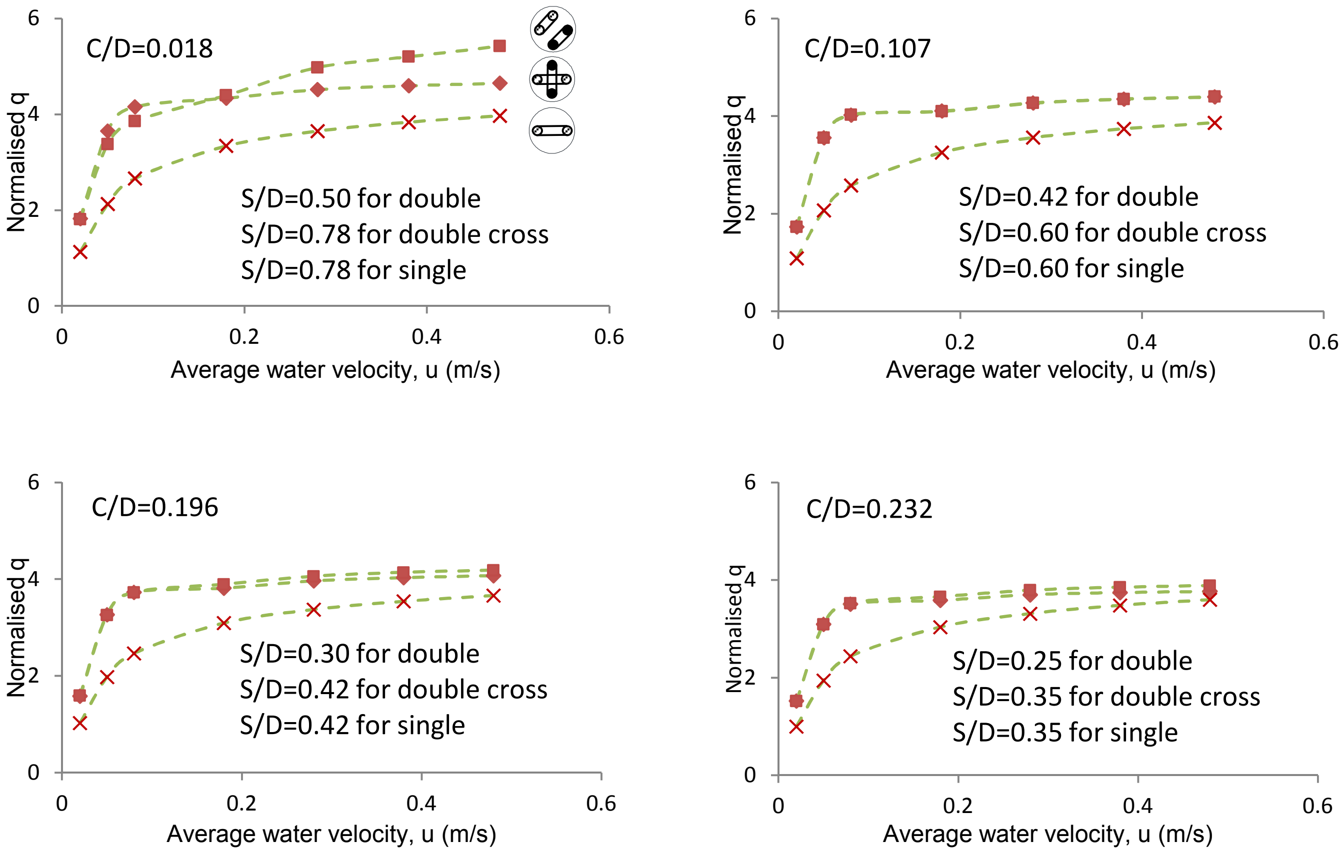


Fig. 3 Heat extraction normalised with respect to the lowest heat extraction rate configuration, versus average water velocity (i.e., flow rate), for different separations.

It can also be seen that at lower velocities (Re ≤ 2,300), the addition of a second U-pipe does not double the thermal performance, but achieves an increase in thermal performance of between approximately 44% and 72%. This represents a significant reduction in the total number of GHEs that would need to be drilled in a geothermal energy project. However, as the velocity increases and the flow becomes more turbulent (Re ≥ 2,300), the addition of a second U-pipe only improves the thermal performance between approximately 5% and 37%. Note that the high 37% increase was only observed for C/D=0.018 and in double U-pipe GHE.

The comparison of double U-pipe and double cross U-pipe configurations is not as straightforward as shown in Fig. 3. Although double U-pipe and double cross U-pipe configurations seem to perform equivalently for a fixed C/D ratio (representing that the cross sections of both GHEs look exactly the same), the two GHE configurations will have different spacing, S. Results show that for C/D = 0.018 and u = 0.48 m/s (14.14 litres/min), the double U-pipe configuration shows 17% better performance in comparison to the double cross U-pipe configuration, despite having a smaller separation. In fact, for a given S/D, the double U-pipe setting is then expected to perform even better. Numerical results show 7% to 11% better performance in a GHE with double U-pipe configuration than in the double cross U-pipe configuration for a fixed S/D=0.42. The difference between heat extraction rates obtained from GHEs with double U-pipe and double cross U-pipe configurations increases as the pipe separation increases, and reaches its highest value at about S/D = 0.5 in turbulent regime in this study. For S/D=0.5, the double U-pipe configuration performs about 30% better (at *u* = 0.48 m/s).

Finally, a parametric analysis on pipe diameter ranging from 0.02 to 0.035 m was conducted on GHEs with double U-pipe configurations, with C/D=0.018 at a constant flow rate of 8.25 litres/min, to investigate the effect of different pipe diameters on heat extraction rate. The average water velocity has been varied to maintain a constant flow rate for all cases. Varying the average water velocity and pipe diameter resulted in varying Reynolds numbers, ranging from about 5,000 to 8,750 for the different cases analysed here, thus, all in the turbulent regime.

Fig. 4 summarises such a parametric analysis, where changes with respect to the previously studied case of a double U-pipe configuration with a pipe diameter of 0.025 m are displayed. Slight changes of the C/D ratio are necessarily introduced as the pipe diameter is changed, however the trends observed in Fig. 3 still hold for the varying average flow velocity, although with a more pronounced variation here. The figure shows that as the pipe diameter increases, heat extraction rate decreases to about 13% with respect to the 25 mm pipe diameter case. This is valid when flow rate is kept constant, resulting in lower velocity for larger diameter pipes. Note that the change in average outlet water temperature is much smaller. However, increasing the pipe diameter and flow rate at the same time will result in around a 30% to 87% increase in heat extraction rate, for a flow rate of 1.47 litres/min (in the transition laminar-turbulent regime).

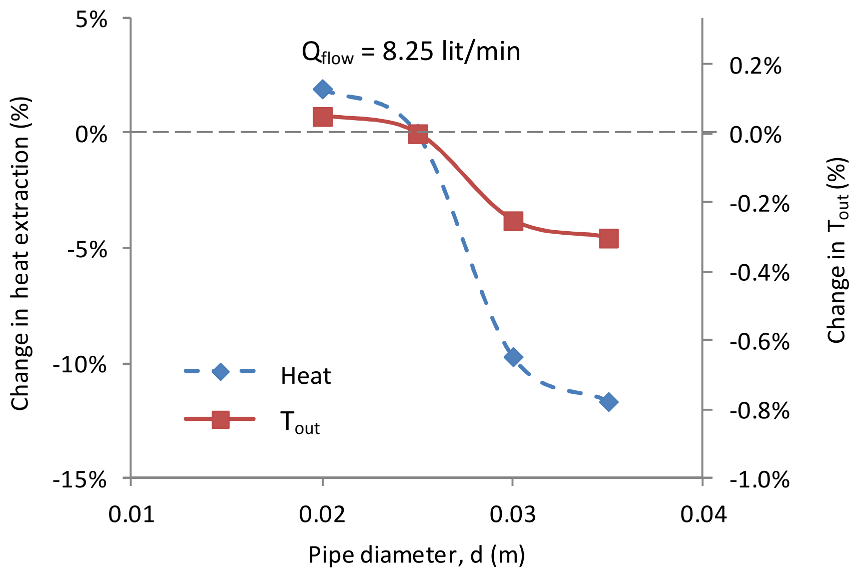


Fig. 4. Decrease in heat extraction rate and outlet temperature for different pipe diameters.

CONCLUSIONS

GHEs with different pipe configurations have been modelled in detail with state-of-the-art numerical tools in order to investigate their thermal performance. In this work, the circulating water inlet temperatures and ground far-field temperatures were chosen as being typical for Melbourne conditions, in heating mode. The outcomes of the simulations show that pipe geometry and GHE configuration may significantly affect system efficiency. Three cases were analysed, namely single U-pipe, double U-pipe, and double cross U-pipe configurations in vertical GHEs. The addition of a second U-pipe may achieve significant additional thermal performance, and while it does not double the performance, important savings may be achieved in terms of drillings costs, given the reduction in the total number of single U-pipe GHEs that would otherwise be needed. Heat extraction rates tend to increase rapidly as Reynolds number increases, particularly in the laminar regime; however, the rate of increase reduces with Reynolds numbers beyond a certain threshold. Finally, a double U-pipe configuration tends to deliver better thermal performance than that of a double cross U-pipe configuration, particularly as the pipe separation increases. This contributes to further reduce drilling and installation costs of vertical GHEs in a direct geothermal energy project.

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