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Suggestion of a Load Sharing Ratio for the Design of Spiral Coil-type Horizontal Ground Heat Exchangers

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Abstract

As a primary component of the horizontal ground heat source pump (GSHP) system, spiral coil-type horizontal ground heat exchangers (HGHEs) have been widely used because of their superior heat transfer performance. To evaluate the ground temperature rise, many analytical solutions for spiral coil-type horizontal ground heat exchangers have been proposed. This study suggests a load sharing ratio, which is essential to consider the presence of an outlet pipe in the analytical solution to achieve more accurate prediction of ground temperature rise. This ratio enables the determination of the spiral coil heat exchange rate. Thus, a three-dimensional numerical model of the spiral coil-type ground heat exchanger was developed. Then, the effects of the factors influencing the load sharing ratio were investigated through a parametric study. Finally, the linear regression method was used to develop a load sharing ratio model. The load sharing ratio model may provide a more accurate prediction of ground temperature rise and help us design spiral coil-type HGHEs reliably.

Keywords: horizontal ground heat exchanger; Green's function; load sharing ratio

1. Introduction

As one source of renewable energy, ground source heat pumps (GSHP) systems have utilized geothermal energy for space heating and cooling for several decades. The ground source heat pump (GSHP) systems generally are divided into three components: the ground heat exchanger, heat pump unit and heat distribution system. The ground heat exchanger enables heat release to or absorption from the ground. Depending on the shape of the ground heat exchanger, various types of ground heat exchangers, such as straight line, slinky, spiral coil, etc., are widely used in the horizontal ground source heat pump systems. A number of research were conducted using numerical and experimental studies to investigate the heat transfer mechanisms for these heat exchangers [1, 2], and it was found that the spiral coil-type demonstrates higher heat transfer performance than the other types.

Recently, Wang et al. [3] have suggested a new analytical solution for the spiral coil-type horizontal ground heat exchanger (HGHE), with a similar concept proposed by Cui et al. [4], which simplified the spiral coil shape into

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several rings. Jeon et al. [5] also suggested a new analytical solution for a spiral coil-type HGHE, which enables the capture of the real geometry of spiral coil by modifying the analytical solution for a spiral coil-type vertical ground heat exchanger (VGHE) proposed by Park et al. [6]. However, the outlet pipe was not considered in these studies, and therefore, it is difficult to accurately predict the ground temperature rise. Accordingly, an investigation of the heat exchanger rate for the spiral coil should be performed to consider the outlet pipe.

This paper aims to provide a load sharing ratio that enables the determination of the spiral coil heat exchange rate. Based on a parametric study, the effects of the factors influencing the load sharing ratio were investigated. Consequently, a load sharing ratio model was proposed using the linear regression analysis.

Nomenclature

C_p	specific heat ($J/kg \cdot K$)
ρ	density (kg/m^3)
k	thermal conductivity ($W/m \cdot K$)
k_{wall}	thermal conductivity of the pipe wall ($W/m \cdot K$)
u	velocity field ($m/\sec$)
p	fluid pressure (Pa)
d_h	mean hydraulic diameter (m)
e	surface roughness (m)
F	volume force term
Q	general heat source
Q_{wall}	external heat exchange through the pipe wall
Re	Reynolds number
Pr	Prandtl number
e_t	unit tangent vector to the pipe axis
f_D	Darcy friction factor
h_{int}	heat transfer coefficient on the inside of pipe
p_c	pitch size of spiral coil (m)
r_c	radius of spiral coil (m)

2. Determination of the load sharing ratio

2.1. Numerical modelling

A commercial finite element code COMSOL Multiphysics was employed to construct the numerical modelling of heat transfer for the spiral coil-type horizontal ground heat exchanger. The generalized governing equations for a solid medium and an incompressible fluid flowing in a pipe are described as follows [7, 8]:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q \tag{1}$$

$$\frac{\partial A\rho_f}{\partial t} + \nabla_t \cdot \left(A\rho_t u e_t\right) = 0 \tag{2}$$

$$\rho_f \frac{\partial u}{\partial t} = -\nabla_t p \cdot e_t - \frac{1}{2} f_D \frac{\rho_f}{d_h} |u| u + F \cdot e_t \tag{3}$$

$$\rho_f A C_p \frac{\partial T}{\partial t} + \rho_f A C_p u e_t \cdot \nabla_t T = \nabla_t \cdot \left(Ak\nabla_t T\right) + \frac{1}{2} f_D \frac{\rho_f A}{d_h} |u| u^2 + Q + Q_{wall} \tag{4}$$

To calculate the external heat exchange through the pipe wall, the Darcy friction factor and Nusselt number were obtained using the empirical equations proposed by Churchill [9] and Gnielinski [10], respectively.

$$Q_{wall} = \left(hZ\right)_{eff}\left(T_{ext} - T\right) \tag{5}$$

$$f_D = 8\left[\left(\frac{8}{\mathrm{Re}}\right)^{12} + (c_A + c_B)^{-1.5}\right]^{1/12} \tag{6}$$

$$Nu = \max\left\{\begin{array}{c} Nu_{lam} = 3.66 \\ Nu_{turb} = \dfrac{\left(f_D/8\right)\left(\mathrm{Re}-1000\right)\mathrm{Pr}}{1+12.7\left(f_D/8\right)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)} \end{array}\right\} \tag{7}$$

Fig. 1 depicts a three-dimensional model of the spiral coil HGHE. The outlet pipe was assumed to be placed at the center of the spiral coil, and the ground heat exchanger was installed 2 m below the ground surface. The material of the spiral coil-type horizontal ground heat exchanger was assumed to be a polyethylene circular pipe, with an outer diameter of 0.02 m, a thickness of 0.002 m, thermal conductivity of 0.38 $W/m \cdot K$ and a surface roughness of 0.0015 mm. The mass flow of the inlet fluid was designated as a constant value of 0.1 kg/sec, which is enough to induce the turbulent flow in the pipe. The load sharing ratio for the spiral coil was defined as the ratio of the amount of heat released to the surrounding ground from the spiral coil part to the total heat released from whole ground heat exchanger. To reasonably investigate the load sharing ratio, various influencing factors were considered for the parametric study, as summarized in Table 1. The range of these factor values also covered typical real-life conditions observed in the field. A total of 729 cases were considered in this study.

Table 1. Input parameters for parametric study.

Parameters	Unit	Values
Volumetric heat capacity of the ground	$J/m^3 \cdot K$	1500000, 2750000*, 4000000
Thermal conductivity of the ground	$W/m \cdot K$	0.8, 1.1*, 1.4
Pitch size of the spiral coil	m	0.05, 0.2*, 0.5 (0.1, 0.4, 0.8)
Radius of the spiral coil	m	0.1, 0.2*, 0.3 (0.15, 0.25)
Length of the spiral coil	m	4, 8*, 12
Temperature difference	$°C$	5, 10*, 15

Superscript (*) represents the base case for the parametric study, and the values shown in bracket were used to investigate the effect of the spiral coil configuration in more details.

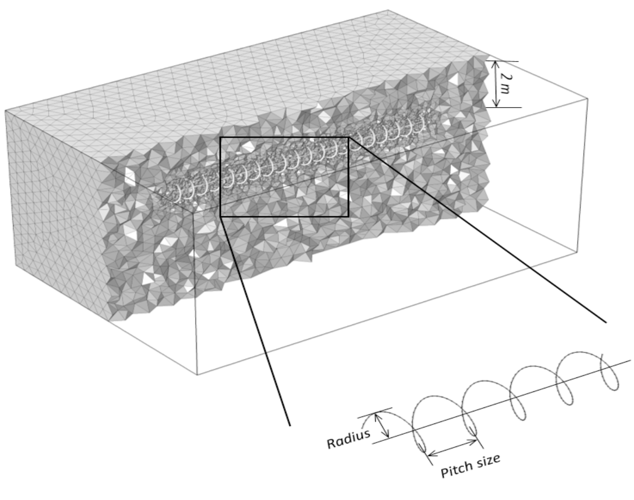

Fig. 1. A three-dimensional numerical model of the spiral coil-type HGHE.

2.2. Effects of injected heat and length

Fig. 2 plotted the change in the spiral coil load sharing ratio for nine cases (all part of the 729 cases) when the temperature difference was altered. The temperature difference between the circulating fluid in the ground heat exchanger and the surrounding soil represents the heat injected into the ground heat exchanger. The higher difference temperature indicates higher injected heat, which is transferred by the ground heat exchanger. Even when the injected heat was increased, the change in the sharing ratio of the spiral coil was extremely low in all cases, as shown by 0.0017 for the greatest change. Therefore, the effect of the injected heat on the load sharing ratio would be negligible. Similar to the effect of the injected heat, the length of the spiral coil-type HGHE also exerted a limited influence on the load sharing ratio (less than 0.045).

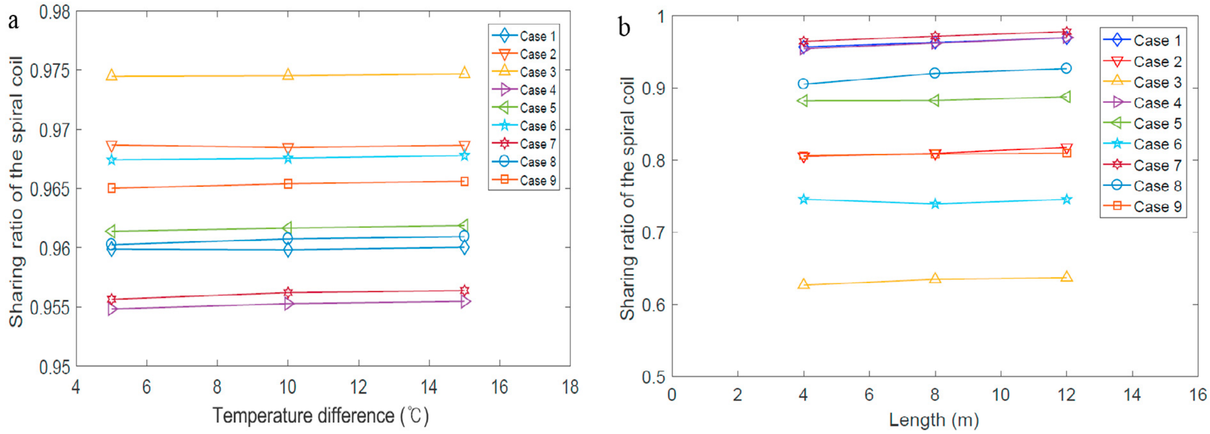

Fig. 2. Effects of (a) injected heat; (b) length.

Effect of thermal properties of the ground

Fig. 3 shows the effects of the ground thermal properties on the spiral coil load sharing ratio. The load sharing ratio increased as the thermal conductivity of the ground increased. Unlike the thermal conductivity, the trend of volumetric heat capacity was divided into two cases by the spiral coil configuration. When the ratio of the radius and pitch was low, the spiral coil load sharing ratio decreased, as the volumetric heat capacity increased. However, the opposite trend occurred when the ratio of the radius and pitch was high. Nevertheless, the effect of the thermal properties of the ground still demonstrated limited influence on the load sharing ratio (less than 0.021).

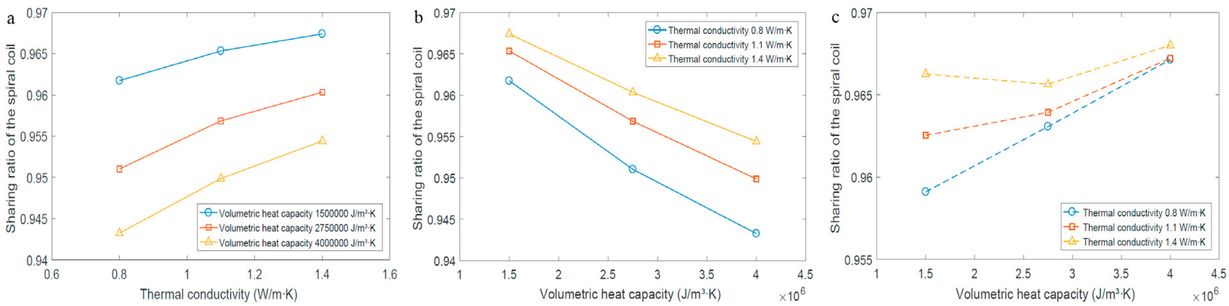

Fig. 3. Effects of (a) thermal conductivity; (b) volumetric heat capacity for low radius/pitch; (c) volumetric heat capacity for high radius/pitch.

2.3. Effect of spiral coil configuration

As shown in Fig. 4, the spiral coil sharing ratio was sensitive to the spiral coil configuration. The load sharing ratio decreased when the pitch size increased and the spiral coil radius decreased. The maximum change in the load sharing ratio of the spiral coil by pitch size reached approximately 39%.

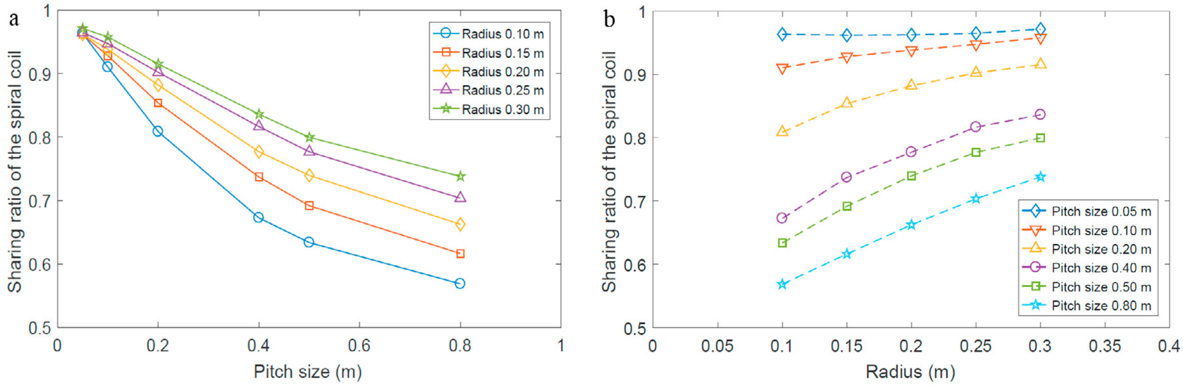

Fig. 4. Effect of the (a) pitch size; (b) radius.

3. Determination and validation of the load sharing ratio

Based on the parametric study results, the factors that most influenced the load sharing ratio were related to the configuration of the spiral coil-type ground heat exchanger, such as the radius of the coil and pitch size. As demonstrated by the bracketed values shown in Table 1, a total of 30 cases for the spiral coil load sharing ratio were obtained, with various radii and pitch sizes. Based on these results, a linear regression model for the load sharing ratio was proposed. Table 2 shows the linear regression results for the load sharing ratio. The coefficient of determination for the linear regression model was 0.986 (approximately 1.0).

Table 2. Linear regression analysis results.

Predictors	Estimated coefficients	p-value
Intercept	0.91959	3.5577E-22
Radius	-0.94862	3.0375E-16
Pitch size	0.71318	0.011378
Radius·pitch size	1.0803	1.0097E-7
Radius^2	0.37472	1.8255E-8
Pitch size^2	-1.3231	0.046972

Consequently, an equation for estimating the load sharing ratio of the spiral coil can be expressed as follows

$$\eta = 0.91959 - 0.94862 \cdot p_c + 0.71318 \cdot r_c + 1.0803 \cdot p_c \cdot r_c + 0.37472 \cdot p_c^2 - 1.3231 \cdot r_c^2 \quad (8)$$

To validate the applicability of the above equation, a spiral coil-type HGHE with a 0.15 m of radius and 0.25 m pitch size was considered. The load sharing ratio was calculated as 0.819, while the measured load sharing ratio from the numerical model was 0.824. Fig. 5 illustrates the ground temperature rises computed at the monitoring point by the numerical and analytical solutions. The monitoring point was located at 0.225 m (corresponding to 1.5 times the radius) from the central line of the spiral coil-type HGHE. Compared to the analytical solution without considering the load sharing ratio, the analytical solution considering the load sharing ratio more accurately predicted the ground temperature rise obtained from the numerical solution.

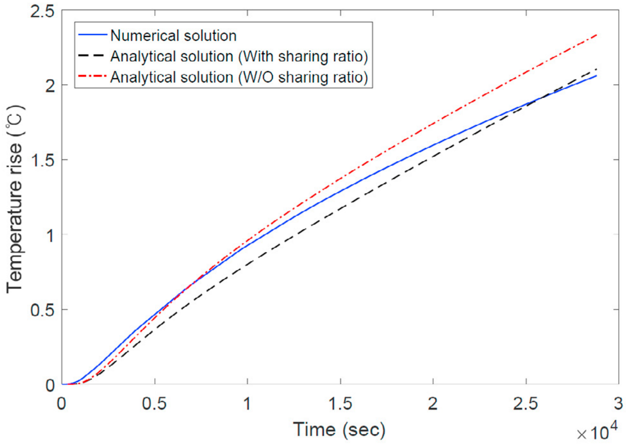

Fig. 5. Validation of the proposed equation considering the load sharing ratio.

4. Conclusions

This paper investigated the load sharing ratio for the spiral coil-type horizontal ground heat exchanger through a numerical parametric study. The load sharing ratio was defined as the ratio between the heat exchange rate for the spiral coil only and that for the whole spiral coil-type horizontal ground heat exchanger (including the outlet pipe). The following conclusions can be drawn from this study.

- The effect of the injected heat, length, thermal conductivity of ground, and volumetric heat capacity on the load sharing ratio were not significant because the maximum values of the load sharing ratio variation were 0.0017, 0.025, 0.017, and 0.021, respectively.
- Depending on the ratio of the radius to the pitch size, the effect of the volumetric heat capacity on the load sharing ratio exhibited different trend. When the ratio of the radius to the pitch size was high, the load sharing ratio increased in conjunction with increases in the volumetric heat capacity of the ground.
- The primary factors influencing the load sharing ratio were determined to be the radius and pitch size of the spiral coil.
- A load sharing ratio model with 0.986 as the determination coefficient was proposed through a linear regression analysis. The linear regression model result well aligned with the numerical solution.
- The load sharing ratio model may help us more accurately predict the ground temperature rise.

However, the on-site experimental results are still needed for validation. In addition, the load sharing ratio model developed using an artificial neural network could be considered for the more accurate prediction because of the non-linear effects of each factors [11].

Acknowledgements

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