International Journal of Scientific Research in Computer Science, Engineering and Information Technology
ISSN : 2456-3307 (www.ijsrcseit.com)
doi : https://doi.org/10.32628/CSEIT206533

A Simplified Thermal Design Model for a Single Vertical U-Tube Borehole Utilized in Ground-Coupled Source Heat Pumps

Ali H. Tarrad
Professor, Ph.D. Mechanical Engineering, Université de Lorraine, CNRS, LEMTA, Nancy, France
Email: ali.tarrad@univ-lorraine.fr

ABSTRACT

Article Info
Volume 6, Issue 5
Page Number: 151-162
Publication Issue :
September-October-2020

The present work dealt with the thermal assessments of the ground-coupled heat pump heat exchangers utilized in the field of geothermal energy source. A model was performed to predict the overall thermal resistance of a single vertical heat exchanger embedded in the borehole. The philosophy of the U-tube replacement with a single equivalent tube size was implemented with new development. Four tube sizes were used to build several borehole geometry configurations, they were (9.53) mm, (12.7) mm, (15.88) mm, and (19.05) mm accommodated in borehole sizes of (65) mm, (75) mm, (90) mm, and (100) mm respectively. Twelve borehole geometry configurations were examined as DX condensers circulate R410A refrigerant. These geometry assemblies produced a range of (0.29-0.57) for tube spacing to borehole ratio tested at (0.73) W/m K to (1.9) W/m K filling thermal conductivity range. The results of the present correlation showed good agreement with previously published correlations in the open literature. A mean temperature difference between the condensed vapor refrigerant and soil was assumed to have existed as (14) °C. Increasing the tube spacing from (2) to (3) times the tube diameter exhibited an augmentation in the heat loading of the borehole. This rise in the heat loadings of the U-tube was (8-10) % and (13-17) % for the geometry configurations of (9.53) mm and (12.7) mm tube sizes respectively. The tube diameter has also shown its importance in the thermal process of the borehole. At (75) mm borehole size and tube spacing of (2) times tube outside diameter, the predicted borehole thermal resistance for (9.53) mm tube diameter was higher than that of (19.05) mm one by (78-80) % for the test range of grout thermal conductivity.

Keywords : Single U-tube, Borehole Thermal Resistance, Correlation, DX Heat Exchanger, R410A

Article History
Accepted : 01 Oct 2020
Published : 07 Oct 2020

I. INTRODUCTION

The geothermal energy source is conceived as one of the best sustainable energy sources because it is a clean, cheap, and inexhaustible. Manufacturers have focused on the utilization of ground-coupled heat pumps for heating and cooling in residential and commercial buildings. This is because of the fast payback of their installation cost and power consumption cost. The (GHE) plays a major role in the assessment of the performance of the ground-coupled heat pumps. Hence, qualitative and quantitative research was conducted to understand, optimize the (GHE) design and size to achieve the best thermal performance.

There is quite a good number of researches have been conducted to model the borehole design analytically. Zeng and Fang [1], Zeng et al. [2], and Zanchini et al. [3, 4] built 2-dimensional models for the ground heat exchangers to simulate the thermal aspects in the borehole. Li and Zheng [5], Bauera et al. [6], and Rees and He [7] presented a 3-dimensional numerical simulation model for U-tube borehole heat exchangers. Song et al. [8] developed a 3-dimensional steady-state numerical model for a U-tube geothermal heat exchanger. The influences of depth, porosity, and geological factors on the performance of heat exchanger were investigated.

Yavuzturk et al. [9] have proved that the approximation of the heat transfer in the borehole region being a steady-state process was suitable and described by a constant borehole thermal resistance, except for analysis dealing with dynamic responses within a few hours. The borehole depth is much larger than its diameter; hence, the heat transfer mechanism in the borehole and heat exchanger is usually formulated by a 1-dimensional line source, Ingersoll et al. [10]; Muttil and Chau [11]. It was also analyzed as cylindrical-source theory, Ingersoll et al. [12], Carslaw et al. [13]; Kavanaugh [14].

Most of the available correlations for the prediction of the thermal resistance of the vertical U-tube borehole depend on the replacement of the U-tube by single equivalent tube geometry. The equivalent diameter of the U-tube can be presented in the form of:

$$d_e = \phi\, d_o \tag{1}$$

Where (ϕ) is an equivalency coefficient greater than (1.0). A value of (ϕ) for equal tube leg diameters was found as ($\sqrt{2}$) for two buried horizontal pipes by Claesson and Dunand [15]. The same value was also suggested by Bose et al. [16]. A one-dimensional heat transfer model was built by Shonder and Beck [17] for the U-tube heat exchanger. They replaced the U-tube legs by an equivalent concentric tube at the borehole and arrived at the following expression for the filling thermal resistance:

$$R_{f=} \frac{\ln\left(\frac{D_B}{d_e}\right)}{2\,\pi\,k_g} \tag{2.a}$$

In which the equivalent diameter corresponds to:

$$d_e = \sqrt{n}\, d_o \tag{2.b}$$

Where (n) is equal to (2) for a single U-tube system. A steady-state heat transfer simulation for a cylindrical source was accomplished by Gu and O'Neal [18]. They arrived at a correlation for the grout resistance of a vertical U-tube ground heat exchanger in the form:

$$R_{f=} \frac{\ln\left(\frac{D_B}{d_o}\sqrt{\frac{d_o}{S_p}}\right)}{2\,\pi\,k_g} \tag{3.a}$$

This form of equation reveals that the equivalent diameter was expressed as:

$$d_e = \sqrt{S_p\, d_o} \tag{3.b}$$

Remund [19] has formulated the borehole thermal resistance for three different cases of the two tube legs spacing. These conditions were described according to the U-tube leg spacing as, close, average and along the outer wall of the borehole in the form:

$$R_f = \frac{1}{\beta_0\, k_g \left(\frac{D_B}{d_o}\right)^{\beta_1}} \tag{4}$$

The values of the coefficient (β_0) and the index (β_1) were (17.44) and (-0.6052) respectively for the average tube spacing case in the borehole. Sharqawy et al. [20] developed a correlation for the grout thermal resistance as:

$$R_f = \frac{\left(-1.49\frac{S_p}{D_B}+0.656\ ln\left(\frac{D_B}{d_o}\right)+0.436\right)}{2\,\pi\,k_g} \tag{5}$$

Koenig [21] has performed an analytical model for the heat transfer problem in a borehole with single and multi-vertical U-tube loops. He postulated a correlation for the borehole thermal resistance of a single U-tube heat exchanger is:

$$R_B = \frac{\beta\, R_p}{2} \tag{6.a}$$

$$\beta = \frac{R_f+R_p}{R_p} \tag{6.b}$$

Tarrad [22] has reported a simple correlation for the prediction of a borehole thermal resistance in a vertical single U-tube ground heat exchanger. It has incorporated the U-tube and borehole diameters, and tube spacing in the following expression for the concentric equivalent diameter:

$$d_e = \frac{D_B}{\left(x+\sqrt{x^2-1}\right)} \tag{7.a}$$

$$x = \frac{{D_B}^2+{d_o}^2-{S_p}^2}{2\,D_B\,d_o} \tag{7.b}$$

The correlation showed an acceptable agreement with previously published ones in the open literature. Tarrad [23] developed a correlation for the borehole thermal resistance based on the equivalent tube diameter technique. He has arrived at an expression for the equivalent concentric tube as:

$$d_e = \frac{\sqrt{2}\,d_o+2\,d_o}{2} \approx \sqrt{3}\,d_o \tag{8}$$

In this expression, the equivalency coefficient (ϕ) in eq. (1) is equal to ($\sqrt{3}$).

Tarrad [24] developed an analytical model for the prediction of the borehole thermal resistance of a single U-tube loop. It included the effect of an obstruction factor for the heat conduction flow in the borehole geometry in the following expression:

$$R_f = \frac{1}{\sigma}\,\frac{cosh^{-1}\left\{\frac{{D_B}^2+{d_o}^2-4\,{l_p}^2}{2\,D_B\,d_o}\right\}}{2\,\pi\,k_g} \tag{9}$$

The obstruction factor was expressed for the single loop by:

$$\sigma = 1-\frac{2\,(D_B+S_p)\,tan^{-1}\left(\frac{d_o}{2\sqrt{{S_p}^2-\left(\frac{d_o}{2}\right)^2}}\right)}{\pi\,D_B} \tag{10}$$

$$R_B = \frac{\beta\,R_p}{2\,\sigma} \tag{11}$$

$$\beta = \frac{R_f+R_p}{R_p} \tag{12}$$

The obstruction factor value lies in the range of ($0 < \sigma \leq 1$). It is equal to unity when there is no obstruction object.

In this study, the thermal resistance of the grout was coupled with the tube resistance to accomplish a model for the assessment of borehole effective thermal resistance in a single U-tube assembly. The tube spacing (S_p) corresponded to (2), (2.5), and (3) times the U-tube outside diameter. These tube spacing factors produced a geometry factor defined as the ratio of tube spacing to borehole diameter (D_B) in the range of (0.29-0.57) for different configurations.

II. MODEL PRESENTATION

2.1. Equivalent tube methodology

Consider a vertical U-tube ground heat exchanger as shown in Fig. 1 is to be transformed into an equivalent geometry configuration.

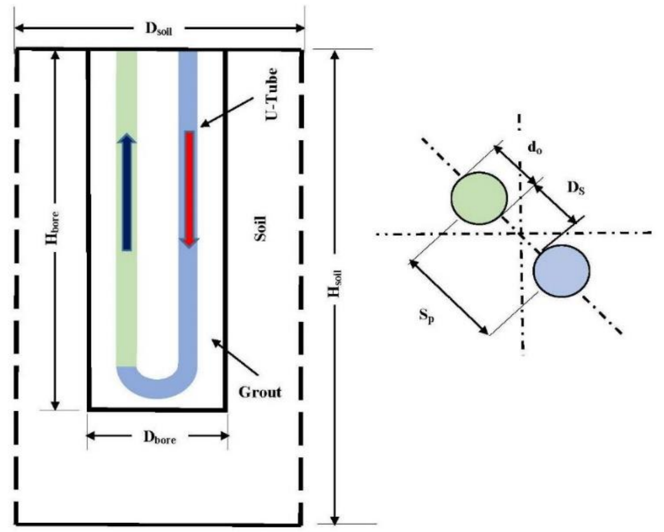

Figure 1: A schematic presentation of a single vertical U-tube heat exchanger

The replacement of the U-tube is sought to be in the form of keeping the same filling volume as that of the original geometry, Fig. 2. The mathematical presentation of this statement is expressed in the following relation:

$$\frac{\pi}{4}\{D_B{}^2 - 2\,d_o{}^2\}\,L = \frac{\pi}{4}\{D_B{}^2 - \,d_e{}^2\}\,L \qquad (13)$$

Solving this equation yields to:

$$d_e = \sqrt{2}\,d_o \qquad (14)$$

This result is similar to that stated by Claesson and Dunand [15] and Bose et al. [16].

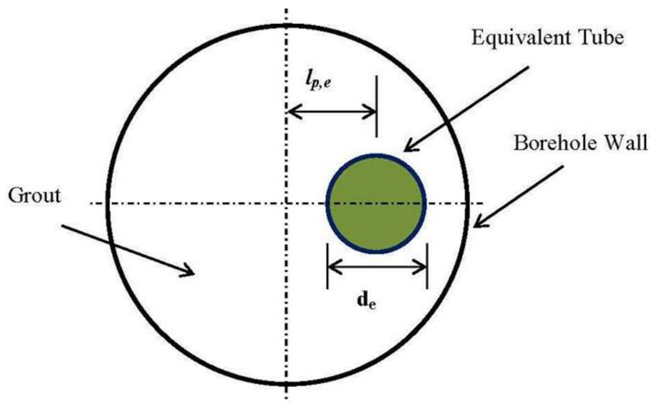

Figure 2: A representation for the equivalent borehole geometry

2.2. Equivalent tube eccentricity

The transaction of the equivalent diameter ($d_e = \sqrt{2}\,d_o$) to the offset position was achieved by keeping the shank diameter as a constant:

$$D_S = S_p - d_o = S_{p,e} - d_e \qquad (15)$$

This expression gives the eccentricity of the equivalent tube as:

$$l_{p,e} = \frac{1}{2}\left\{S_p + \left(\sqrt{2} - 1\right) d_o\right\} \qquad (16.a)$$

Hence

$$l_{p,e} \approx l_p + 0.207\,d_o \qquad (16.b)$$

2.3. U-tube and borehole sizes

The outer circle diameter of U-tube installation in a borehole for practical applications is controlled by the following expression, Koenig [21]:

$$D_s + 2\,d_o \leq 0.75\,D_B \qquad (17)$$

Rearranging this relation in terms of the tube spacing (S_p) gives:

$$S_p + \,d_o \leq 0.75\,D_B \qquad (18)$$

This expression shows that the maximum tube spacing inside the borehole is controlled by:

$$S_{p,max} = 0.75\,D_B - d_o \qquad (19)$$

The U-tube legs spacing in the borehole is usually designated in terms of the outside diameter of the tube as:

$$S_p = \,\alpha\,d_o \qquad (20)$$

Here, the coefficient (α) is defined as the tube spacing factor.

2.4. Thermal resistance

The filling thermal resistance per unit length is estimated with the aid of the expression cited in Holman [25] for an offset pipe having the equivalent geometry physical dimensions as:

$$R_f = \frac{cosh^{-1}\left\{\frac{D_B{}^2 + d_e{}^2 - 4\, l_{p,e}{}^2}{2\, D_B\, d_e}\right\}}{2\,\pi\, k_g} \qquad (21)$$

The pipe thermal resistance composes of the heating or cooling medium that flows inside the pipe and the conduction term of tube wall metal, it is estimated per unit length from:

$$R_p = \frac{1}{\pi\, d_i\, h} + \frac{ln\left(\frac{d_o}{d_i}\right)}{2\,\pi\, k_p} \qquad (22)$$

This term is in a series circuit heat transfer resistance analogy with that of the filling portion. Hence the borehole thermal resistance may be estimated from:

$$R_B = R_f + R_p \qquad (23)$$

2.5. Assessment Methodology

2.5.1. Case study

Table 1 illustrates the examined geometry configurations of the borehole in the present work.

Table 1: Examined geometry configurations

Conf.	d_o (mm)	WF (----)	α (--)	D_B (mm)	S_p/D_B (----)	$\frac{S_p + d_o}{D_B}$
G1	9.53	12.5	3	65	0.44	0.59
G2	9.53	12.5	2.5	65	0.37	0.51
G3	9.53	12.5	2	65	0.29	0.44
G4	12.7	14.29	3	75	0.51	0.68
G5	12.7	14.29	2.5	75	0.42	0.59
G6	12.7	14.29	2	75	0.34	0.51
G7	9.53	12.5	2	75	0.25	0.38
G8	15.88	15.63	2	75	0.42	0.64
G9	19.05	17.86	2	75	0.51	0.76
G10	9.53	12.5	3	75	0.38	0.51
G11	15.88	15.63	3	90	0.53	0.71
G12	19.05	17.86	3	100	0.57	0.76

2.5.2. Grout thermal conductivity

Sagia et al. [26] presented a tabulated list of the thermal conductivity of several grout mixtures as deduced from Gaia Geothermal [27].

Table 2. Thermal conductivity of grout mixtures, Gaia Geothermal [27]

Grouts	Thermal Conductivity (W/m K)
20% Bentonite	0.73
30% Bentonite	0.74
Cement Mortar	0.78
Concrete 2100 kg/m³	1.04
30% Bentonite - 30% Quartzite	1.3
30% Bentonite - 40% Quartzite	1.47
60% Quartzite- Flowable Fill (Cement+Fly Ash+Sand)	1.85
Concrete (50% Quartz Sand)	1.9

This range of filling thermal conductivity was implemented in the present model verification.

2.5.3. Operating conditions

The condensation heat transfer coefficient for R-410A refrigerant is fixed at (3000) W/m² °C as a typical reference value deduced from Huang et al. [28] and Kim and Shin [29]. Garbai and Méhes [30] found that the ground thermal resistance approaches a steady-state value after a one-year operation. They estimated the ground thermal resistance as (0.053) m.°C/W for a ground thermal conductivity of (2.42) W/m. °C. Hence, this magnitude was used to estimate the total borehole thermal resistance as:

$$R_t = R_B + R_{soil} \quad (24)$$

The heat loading of the borehole is estimated from:

$$q_l = \frac{\Delta T_m}{R_t} \quad (25)$$

A typical value of (14) °C for the mean temperature difference between the condensed refrigerant vapor and soil was assigned at the present work. This value was assumed for the cooling mode of the heat pump in which the ground heat exchanger acts as a condenser.

III. RESULTS AND DISCUSSION

3.1. Present work comparison

The present correlation is compared with the previously published work of other investigators in Fig. 3. The results showed that the predicted borehole thermal resistance by Bose et al. [16] and Koenig [21] was the higher and lower among other examined models regardless of borehole geometry configuration.

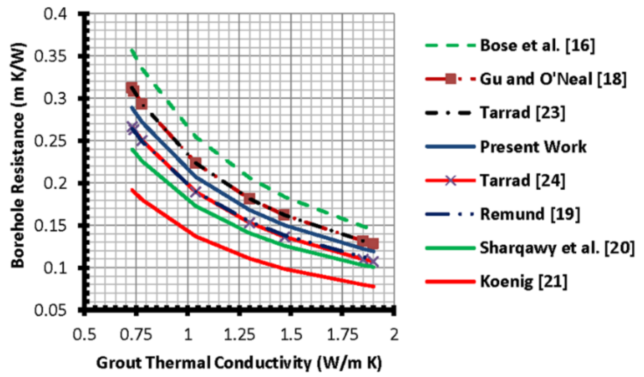

Figure 3.a: (G1) geometry configuration of (9.53) mm tube size, D_B=65 mm, Sp=3 d_o

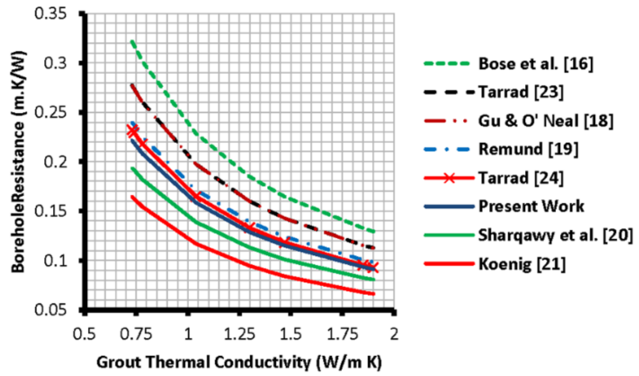

Figure 3.b: (G4) geometry configuration of (12.7) mm tube size, D_B=75 mm, and Sp=3 d_o

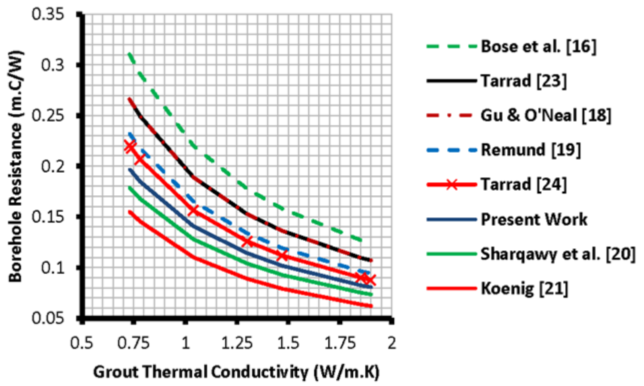

Figure 3.c: (G11) geometry configuration of (15.88) mm tube size, D_B=90 mm and Sp=3 d_o

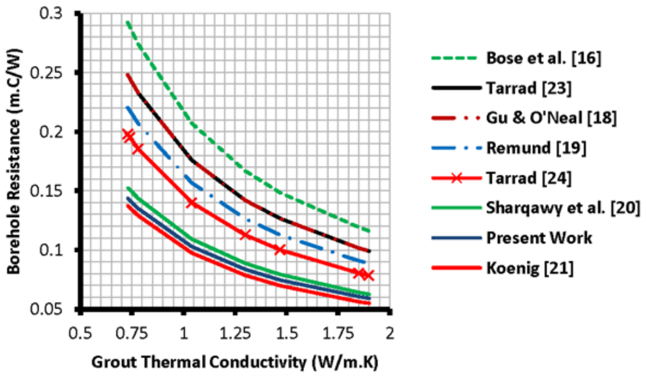

Figure 3.d: (G12) geometry configuration of (19.05) mm tube size, D_B=100 mm and Sp=3 d_o

Figure 3: Comparison of the present work borehole resistance with existing models

The Bose et al. [16] correlation is a conservative thermal design one, it predicted about twice as much as that of the Koenig [21] model. The predicted numerical values of the borehole thermal resistance by Bose et al. [16] fell in the range (0.29-0.36) m.°C/W and (0.12-0.15) m.°C/W estimated at grout thermal conductivity of (0.73) W/m. °C and (1.9) W/m. °C respectively. The respective values of the Koenig [21] predictions were within (0.14-0.19) m.°C/W and (0.06-0.08) m.°C/W estimated at grout thermal conductivity of (0.73) W/m. °C and (1.9) W/m. °C respectively. The present work predicted (R_B) in the range of (0.14-0.29) m.°C/W and (0.06-0.12) m.°C/W calculated at (k_g) of (0.73) W/m. °C and (1.9) W/m. °C respectively. The higher range value was usually obtained at the smaller tube size (9.53) mm whereas, the higher was assigned for the larger examined tube size of (19.05) mm. This is due to the greater grout layer in the borehole around the smaller tube than that of the bigger tube size and hence revealed a higher thermal resistance.

The predicted values of the borehole thermal resistance by Gu and O'Neal [18] and Tarrad [23] were identical for the test tube sizes when the tube spacing factor (α) is equal to (3). This condition leads to equal values of the equivalent tube diameters (d_e) as shown in equations (3.b) and (8). Hence, the same grout and borehole thermal resistances will be obtained for both correlations. Remund [19] and Tarrad [24] predicted close magnitudes of the borehole thermal resistance and the divergence between these correlations increases as the U-tube diameter increases.

The data revealed that the thermal resistance experiences a significant reduction as the grout thermal conductivity increases. All of the examined correlations exhibited a similar variation trend with grout thermal conductivity. In general, the estimated (R_B) at (1.9) W/m. °C by the tested correlations and models showed that their numerical magnitudes were about (40-42) % of those predicted at (0.73) W/m. °C. Hence, it is expected to have more heat loading of the U-tube heat exchanger at the higher tested grout thermal conductivity.

3.2. Effect of tube size

The role of the U-tube size is inferred from the comparison illustrated in Fig. 4.

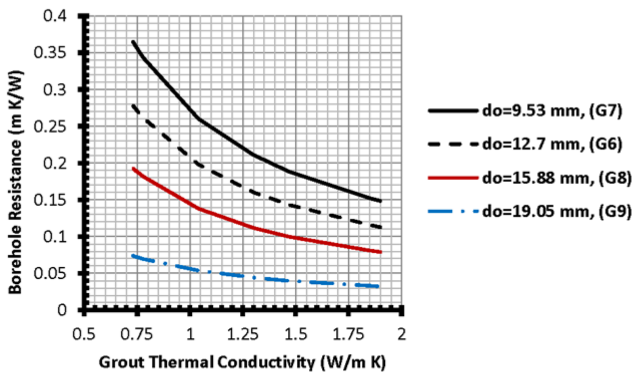

Figure 4: Comparison of borehole thermal resistance at fixed D_B=75 mm and Sp=2 d_o

A borehole diameter of (75) mm was selected to investigate this parameter with a variety of outside tube diameter as stated in (G6-G9). The thermal resistance of the borehole exhibits a reduction as the tube size increases. Hence, the (19.05) mm showed the lower (R_B) than the others due to the reduction of the grout layer around the tube. The bigger tube size showed a minor variation with the grout thermal conductivity because it is located closer to the borehole wall. This phenomenon was also confirmed by the previous work of Remund [19], Gu and O'Neal [18], and Tarrad [23]. The predicted (R_B) for the (9.53) mm was higher than that of the (19.05) mm tube size by about (70) % and (79) % estimated at (k_g) of (1.9) W/m. °C and (0.73) W/m. °C respectively. For the present operating conditions, the bigger U-tube is expected to transfer or absorbs more energy than that of the smaller ones.

The gradient of the borehole thermal resistance with grout thermal conductivity ($\Delta R_B/\Delta k_g$) was steeper as the tube size decreases. The bigger tested tube of (19.05) mm exhibited a flatter variation trend as the grout thermal conductivity increases. This is mainly because the tube boundary is closer to the borehole wall than other tube sizes.

3.3. Effect of tube spacing

Fig. 5 depicts a comparison for the borehole thermal resistance estimated at different U-tube legs spacing.

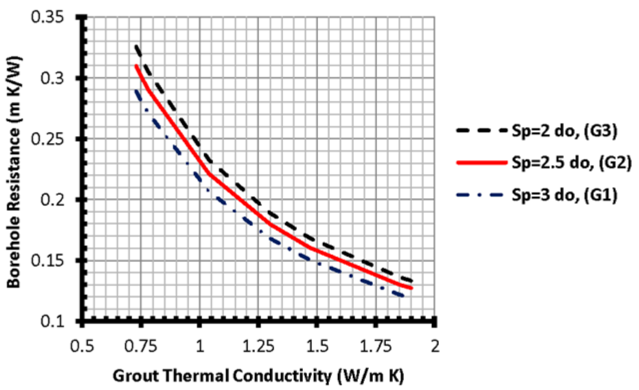

Figure 5.a: Geometry configuration of (9.53) mm tube size and D_B=65 mm

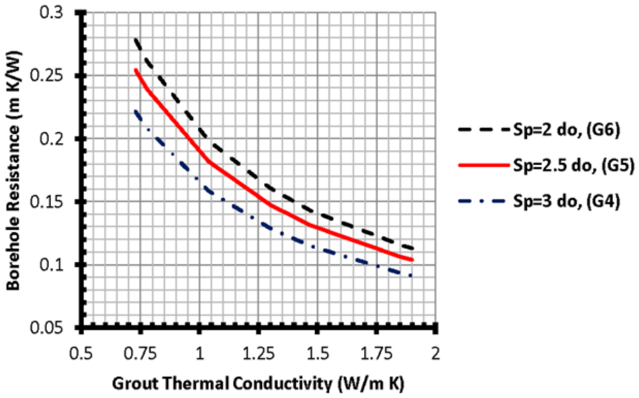

Figure 5.b: Geometry configuration of (12.7) mm tube size and D_B=75 mm

Figure 5: Comparison of borehole thermal resistance at various tube spacing

The results show that the borehole thermal resistance exhibits deterioration as the tube spacing increases for the same geometry configuration. The predicted (R_B) at tube spacing (Sp) of (2 d_o) were higher than those at (3 d_o) by (11) % for the (9.53) mm U-tube size and (65) mm borehole diameter. The corresponding value for the (12.7) mm tube size and (75) mm borehole size was within (20) %. It seems that the reduction percentage of the borehole thermal resistance is a function of the U-tube/borehole sizes combination.

The predicted heat loadings for these geometry configurations are shown in Fig. 6; it is constructed depending on the assumed operating conditions utilized in the present work

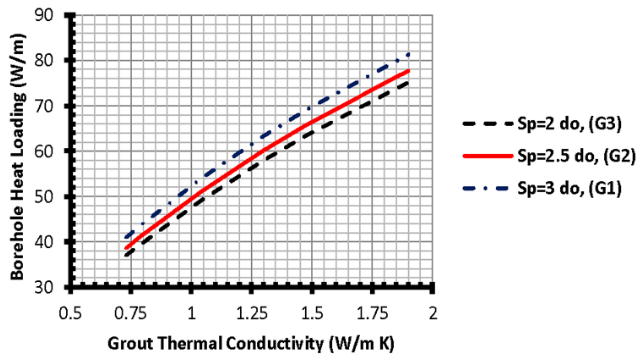

Figure 6.a: Geometry configuration of (9.53) mm tube size and D_B=65 mm

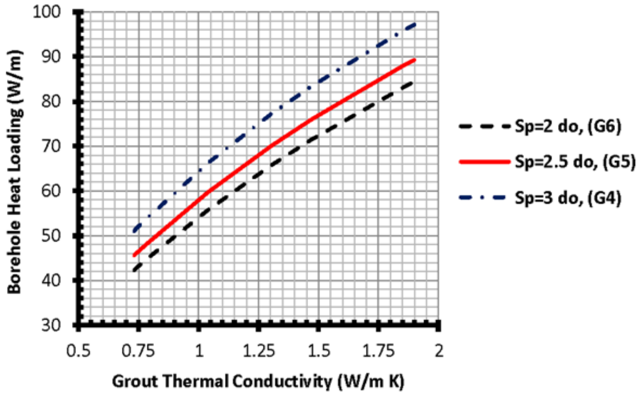

Figure 6.b: Geometry configuration of (12.7) mm tube size and D_B=75 mm

Figure 6: Comparison of borehole heat loading at various tube spacing

The heat loading pattern of the U-tube illustrates that it increases as the grout thermal conductivity and U-tube spacing increase. The predicted heat loadings at (k_g) of (1.9) W/m. °C was as much as twice those at (0.73) W/m. °C for both borehole geometry configurations at all of the examined tube spacing. Increasing the tube spacing revealed an augmentation in the heat loading for both test geometry configurations. The enhancement factor was ranged between (8) % (10) % for the small tube size of (9.53) mm and fell between (13) % and (17) % for the (12.7) mm tube size where the enhancement factor is defined as:

$$\eta = \frac{(q_l)_3 - (q_l)_2}{(q_l)_3} \tag{26}$$

The indices (3) and (2) indicate that the parameters were taken at (S_p) of (3 d_o) and (2 d_o) respectively.

3.4. Effect of borehole size

Fig. 7 was constructed to investigate the effect of the borehole size on the thermal performance of the U-tube heat exchanger.

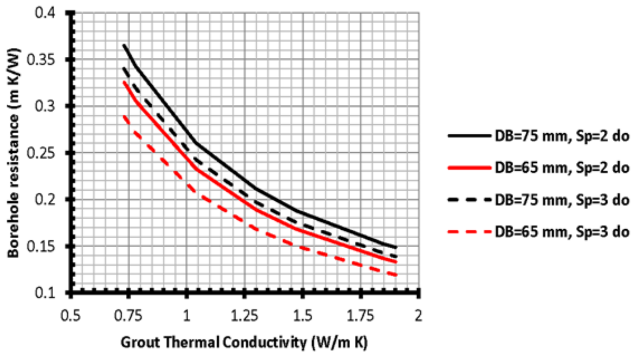

Figure 7: Comparison of borehole thermal resistance for (9.53) mm tube size at various borehole diameter and tube spacing

The results revealed that the borehole thermal resistance exhibited an increase as the borehole diameter increases and vice versa for fixed tube size. Increasing of the borehole size from (65) mm to (75) mm with (9.53) mm tube configurations causes an increase for (R_B) in the range of (10-11) % at (S_p) of (2 d_o). The increase percentage values for the case of tube spacing of (3 d_o) were higher, the estimated values were within (14-15) % for the whole examined range of grout thermal conductivity.

IV. CONCLUSION

A correlation for the prediction of the borehole thermal resistance was derived and verified with previously published ones. The results showed that the borehole thermal resistance depends on the geometry configuration and grout thermal conductivity. Increasing of the grout thermal conductivity from (0.73) W/m. °C to (1.9) W/m. °C has doubled the heat loading of the U-tube. The predicted (R_B) for the (9.53) mm was higher than that of the (19.05) mm tube size when are installed in a (75) mm borehole size by about (70) % and (79) % estimated at (k_g) of (1.9) W/m. °C and (0.73) W/m. °C respectively. The present work revealed that the estimated (R_B) at (1.9) W/m. °C was about (40-42) % of that at (0.73) W/m. °C for all examined geometry configurations. The heat loading of the borehole showed an increase as the U-tube legs spacing increases for fixed borehole size. The heat loading enhancement factor (η) was within (8-10) % for the tube size of (9.53) mm and (65) mm borehole geometry configuration. The corresponding value for the (12.7) mm and (75) mm borehole diameter geometry configuration fell in the range of (13-17) %. Borehole geometry configurations that have a fixed tube size with bigger borehole diameter gave a higher borehole thermal resistance and lower heat loading.

V. NOMENCLATURE

Parameter	**Definition**
d	Tube diameter, m
D	Diameter, m
GHE	Ground heat exchanger
h	Convection heat transfer coefficient, $W/m^2 K$
k	Thermal conductivity, W/m.K
L	Length, m
l_p	Tube offset distance, m
q_l	Heat loading, W/m
R	Thermal resistance per unit length, m.K/W
S	Geometry shape factor, m
S_p	Tube legs spacing, m
t	Thickness, m
ΔT	Mean temperature difference, K
WF	Wall factor=d_o/t

Subscribes

B	Borehole
cond	Condenser
e	Equivalent
f	Filling
g	Grout
i	Inside
m	Mean
max	Maximum value
o	Outside
p	Pipe
s	Shunt
t	Total
x	Parameter defined in eq. (7.b)

Greek Letters

α	Tube spacing factor
β	Factor defined in eq. (6.b)
β_0	Coefficient in eq. (4)
β_1	Index in eq. (4)
η	Enhancement factor defined in eq. (26), %
σ	Obstruction factor defined in eq. (10)
ϕ	Equivalency coefficient

VI. ACKNOWLEDGMENTS

The author would like to express his sincere thanks to the Laboratoire Énergies & Mécanique Théorique et Appliquée (LEMTA) of the University of Lorraine for their valuable support. Thanks are also extended to the administration of (PAUSE) program of Collège de France for allowing the author to pursue his research activities.

VII. REFERENCES

[1] Zeng H, Fang Z (2002) A fluid temperature model for vertical U-tube geothermal heat exchangers. Journal of Shandong Institute of Architecture and Engineering 17(1): 7-10.

[2] Zeng H, Diao N, Fang Z (2002) A finite line-source model for boreholes in geothermal heat exchangers. Heat Transfer – Asian Research 31(7): 558-567.

[3] Zanchini E, Lazzari S, Priarone A (2010) Effects of flow direction and thermal short-circuiting on the performance of small coaxial ground heat exchangers. Renewable Energy 35: 1255–1265.

[4] Zanchini E, Lazzari S, Priarone A (2010) Improving the thermal performance of coaxial borehole heat exchangers. Energy 35: 657–666.

[5] Li Z, Zheng M, (2009) Development of a numerical model for the simulation of vertical U-tube ground heat exchangers. Applied Thermal Engineering, 29(5): 920-924.

[6] Bauera D, Heidemann W, Diersch, H G (2011) Transient 3D analysis of borehole heat exchanger modeling. Geothermics 40: 250–260.

[7] Rees S J, He M (2013) A three-dimensional numerical model of borehole heat exchanger heat transfer and fluid flow. Geothermics 46: 1– 13.

[8] Song X, Lyu Z, Li G, Sheng M, Liu J, Li R, Shi Y (2017) Numerical analysis of characteristics of a single U-tube down hole heat exchanger in the geothermal reservoir. GRC Transactions 41.

[9] Yavuzturk C, Spitler J D, Rees S J (1999) A transient two-dimensional finite volume model for the simulation of vertical U-tube ground heat exchangers, ASHRAE Transactions 105(2): 465-474.

[10] Ingersoll L R, Zobel O J, Ingersoll A C (1948) Heat conduction with engineering and geological application, McGraw Hill, New York.

[11] Muttil N, Chau K W (2006) Neural network and genetic programming for modeling coastal Algal Blooms. Int. J. Environ. Pollut. 28: 223-238.

[12] Ingersoll L R, Zobel O J, Ingersoll A C (1954) Heat conduction with engineering, geological and other applications, revised edition; University of Wisconsin Press: Madison.

[13] Carslaw H S, Jaeger J C (1959) Conduction of heat in solids, 2nd ed.; Oxford University Press: London.

[14] Kavanaugh S P (1985) Simulation and experimental verification of vertical ground-coupled heat pump systems. International Journal of Energy Research, 21(8): 707-722.

[15] Claesson J, Dunand A (1983) Heat extraction from the ground by horizontal pipes- A mathematical analysis, Document D1, Swedish Council for Building Research, Stockholm.

[16] Bose J E, Parker J D, McQuiston F C (1985) Design/data manual for closed-loop ground-coupled heat pump systems. American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE): Atlanta.

[17] Shonder J A, Beck J V (1999) Determining effective soil formation thermal properties from field data using a parameter estimation technique. ASHRAE Transactions 105: 458-466.

[18] Gu Y, O'Neal D L (1998) Development of an equivalent diameter expression for vertical U-tubes used in ground-coupled heat pumps. ASHRAE Transaction 104(2), pt. (2)- 4214: 1-9.

[19] Remund C P (1999) Borehole thermal resistance: laboratory and field studies, ASHRAE Trans 105: 439–445

[20] Sharqawy M H, Mokheimer E M, Badr H M (2009) Effective pipe-to-borehole thermal resistance for vertical ground heat exchangers. Geothermics 38: 271–277.

[21] Koenig A A (2015) Thermal resistance of borehole heat exchangers composed of multiple loops and custom shapes. Geothermal Energy 3(10): 1-14.

[22] Tarrad A H (2019) A borehole thermal resistance correlation for a single vertical DX U-tube in geothermal energy application. American Journal of Environmental Science and Engineering 3(4): 75-83.

[23] Tarrad A H (2020) A perspective model for borehole thermal resistance prediction of a vertical U-tube in geothermal heat source, Athens Journal of Technology and Engineering 7(2): 73-92

[24] Tarrad A H (2020) Development of analytical model for a vertical DX single U-tube ground-coupled heat pump system. Global Journal of

Researches in Engineering, J: General Engineering 20(3):1-14.
[25] Holman, J. P, 2010. Heat Transfer, 10th edition, published by McGraw-Hill, chapter 3: 83-86.
[26] Sagia Z, Stegou A, Rakopoulos C (2012) Borehole resistance and heat conduction around vertical ground heat exchangers. The Open Chemical Engineering Journal 6: 32-40.
[27] Gaia Geothermal. Ground loop design software, GLD 2009.
[28] Huang X, Ding G, Hu H, Zhu Y, Gao Y, Deng B (2010) Condensation heat transfer characteristics of R410A–oil mixture in 5 mm and 4 mm outside diameter horizontal microfin tubes. Experimental Thermal and Fluid Science 34(7): 845-856.
[29] Kim M, Shin J (2005) Condensation heat transfer of R-22 and R410A in horizontal smooth and microfin tubes. International Journal of Refrigeration 28(6): 949-957.
[30] Garbai L, Méhes S (2008) Heat capacity of vertical ground heat exchangers with single U-tube installation in the function of time. WSEAS Transactions on Heat and Mass Transfer 3(3): 177-186.

Cite this article as :

Ali H. Tarrad, "A Simplified Thermal Design Model for a Single Vertical U-Tube Borehole Utilized in Ground-Coupled Source Heat Pumps", International Journal of Scientific Research in Computer Science, Engineering and Information Technology (IJSRCSEIT), ISSN : 2456-3307, Volume 6 Issue 5, pp. 151-162, September-October 2020. Available at doi : https://doi.org/10.32628/CSEIT206533
Journal URL : http://ijsrcseit.com/CSEIT206533