An Innovative Co-Axial Spiral Borehole Heat Exchanger Dynamic Model

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ABSTRACT

A dynamic model of a ground source heat pump (GSHP) system is a very useful tool in order to optimize its operation. It might reproduce the thermal behaviour of each component of the system both on a short-term and a long-term basis, as well as the effect that the borehole heat exchanger (BHE) has in the surrounding ground. Hence, it is possible to use this model to develop proper control strategies in order to increase the global system's efficiency as much as possible.

In this work, the approach used for the recently developed B2G dynamic model has been extended to a different configuration than the standard U-tube BHE. The new configuration is a novel co-axial spiral BHE designed in the framework of the GEOT€CH project (Geothermal Technology for €conomic Cooling and Heating), a HORIZON 2020 European project.

The model has been validated against experimental data from a real borehole located in Houten, Netherlands. The results show that the B2G approach applied to this specific configuration produces a model that can accurately predict the short-term behaviour of the BHE.

1. INTRODUCTION

Ground Source Heat Pump (GSHP) systems are well known as one of the most efficient technologies for heating and cooling in buildings (Mustafa Omer 2008). They contribute to energy savings in comparison with air-to-water heat pumps (Urchueguía et al. 2008), since the ground temperature is more constant than the air temperature during the year and, in most cases, it is more favourable than the air as a source.

This advantage should not be spoiled with a low efficiency of the system components and the operation. Thus, it is important to optimize them in order to achieve the highest possible efficiency of the entire system.

Amongst all of the components of the GSHP systems, the Ground Source Heat Exchanger (GSHE) is the most important and relatively expensive component. Hence, the design of this heat exchanger must be optimized in order to obtain a good efficiency, at a reasonable cost, in the heat transfer with the ground. In practice this trade-off between efficiency and cost means that the borehole heat exchanger should not be under-sized (low efficiency) or over-sized (high cost).

There exist different GSHE configurations (Florides and Kalogirou 2007), but the most common is the vertical heat exchanger, also known as Borehole Heat Exchanger (BHE). In this configuration, a vertical heat exchanger is drilled into the soil. There are several types of BHEs: single U-pipe, double U-pipe, simple coaxial, complex coaxial, etc. The most widely spread is the single U-pipe, but it is not the most efficient from a heat transfer point of view. Other configurations of BHEs have been studied in order to obtain a low thermal resistance and thus, improve the heat transfer between the transfer fluid and the ground.

Within the framework of the European project GEOT€CH, Geothermal Technology for €conomic Cooling and Heating, an innovative heat exchanger (developed by Geothex BV, http://geothex.nl) with a co-axial configuration and spiral fluid flow pathways will be further developed and optimized. The aim of this new configuration is to achieve high levels of thermal performance with low pressure losses (European Commision 2015). Preliminary investigations showed a significant increase of efficiency compared to conventional heat exchanger designs, especially at low Reynolds numbers (Witte 2012).

Furthermore, in order to optimize the operation of these GSHP systems, dynamic models are a very useful tool, as they are able to predict the behaviour of the whole system. Since the most important component in GSHP systems is the GSHE, an accurate dynamic model of this component is necessary, especially in an ON/OFF operation GSHP system. In addition, a GSHE model must consider the long-term response of the surrounding ground. Most available models are not able to accurately predict the short term dynamical behaviour of the heat exchanger, or have a very high computational cost – making them less attractive for systems simulations.

In this context, the B2G dynamic model (De Rosa et al. 2015) was developed for a U-tube BHE configuration and implemented in TRNSYS environment. This model consists of a thermal resistance and capacity model and has been validated against experimental data. It is able to predict with high accuracy the short-term behaviour of a U-tube BHE and also the long-term response of the ground when it is coupled with the g-function model (Ruiz-Calvo et al. 2016). In addition, the B2G model can be coupled with other long-term models (for example, the DST model) with an accurate prediction of the borehole behaviour (Cazorla-Marín et al. 2016).

This B2G dynamic model has been adapted to the novel co-axial configuration with spiral flow as a part of one of the work packages in the GEOT€CH project. The new dynamic model has been validated against experimental data, using a Thermal Response Test (Witte et al 2002) carried out in a real borehole located at the Geothex BV facilities in Houten, Netherlands.

This work presents a description of the B2G dynamic model as well as its adaptation to the new co-axial BHE with spiral flow path. The validation of this model is presented: the Thermal Response Test (TRT) used is described and it is carried out a comparison between the results calculated by the dynamic model and the results obtained experimentally. The main conclusion of this contribution is that the B2G model adapted to this novel configuration predicts with high accuracy the behaviour of the real borehole heat exchanger.

2. B2G MODEL

The B2G (Borehole-to-Ground) model is based on a 2D thermal network with different nodes in order to model the heat transfer between one borehole and the surrounding ground. The borehole is discretised vertically and in each borehole depth, the 2D thermal network represents the heat transfer between temperature nodes. Each node of this thermal network represents one of the parts of the borehole heat exchanger: the fluid inside the tubes, the borehole backfilling or the ground. These nodes are connected with thermal resistances, taking into account the conduction and convection processes. The thermal capacitance of each node is also considered in order to represent the inertia of each part.

This model is focussed on the short-term prediction of the borehole behaviour, with a typical time of 10 – 15 hours, for this reason, it takes into account the BHE and the surrounding ground that is affected by the injection/extraction of heat during the considered period of time.

2.1 Model description (single U-tube configuration)

The B2G model was developed for a single U-tube configuration. The 2D and 3D thermal network is shown in Figure 1. This model has been presented previously in (Ruiz-Calvo et al. 2015) and (De Rosa et al. 2015), where a detailed explanation of the model and the detailed equations of the heat transfer can be found.

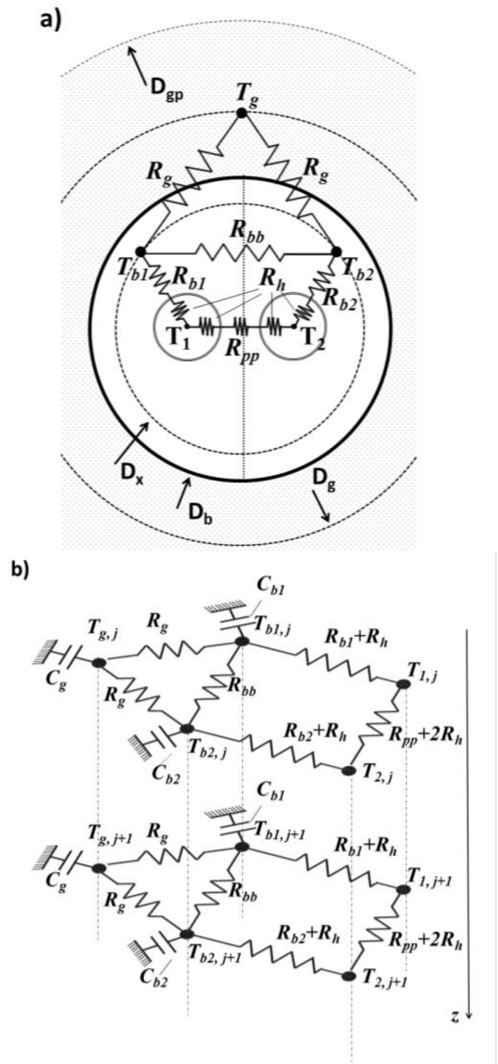

Figure 1: Thermal network of the B2G model: a) borehole layout; b) 3D model (De Rosa et al. 2015)**.**

Each node of the thermal network represents one part of the BHE: the nodes T_1 and T_2 represents the upward and downward water inside the pipe, the nodes T_{b1} and T_{b2} represent the borehole backfilling (the grout inside the borehole is divided in two regions, each node represents one of the regions), and the node T_g represents the surrounding ground affected by the heat injected/extracted in a period of 10-15 hours.

Vertical conduction (axial transport) is neglected, but the advection in vertical direction for the fluid nodes is considered in the transient energy balance equation.

The entire model consists of *n* thermal networks (with *n* the number of vertical divisions of the BHE) with 5 thermal capacitances and 6 thermal resistances at each depth in each thermal network (a 5C6R-n model). It can be solved by numerical procedures, solving the system of ordinary differential equations as described in (Ruiz-Calvo et al. 2015)

This model has been validated against experimental data from two real boreholes, one located in Stockholm, Sweden (Ruiz-Calvo et al. 2015), and another located in *Universitat Politècnica de Valéncia,* Spain (De Rosa et al. 2015). Furthermore, it has been validated against real data from a GSHP facility operation located at *Universitat Politècnica de València*, Spain (Ruiz-Calvo 2015).

2.2 Adaptation of the model to the novel co-axial spiral configuration

2.2.1 Model description

The B2G model has been adapted to the new co-axial configuration with spiral flow. For this purpose, the thermal network has been adapted to the co-axial configuration, obtaining a simpler thermal network. This thermal network is shown in Figure 2.

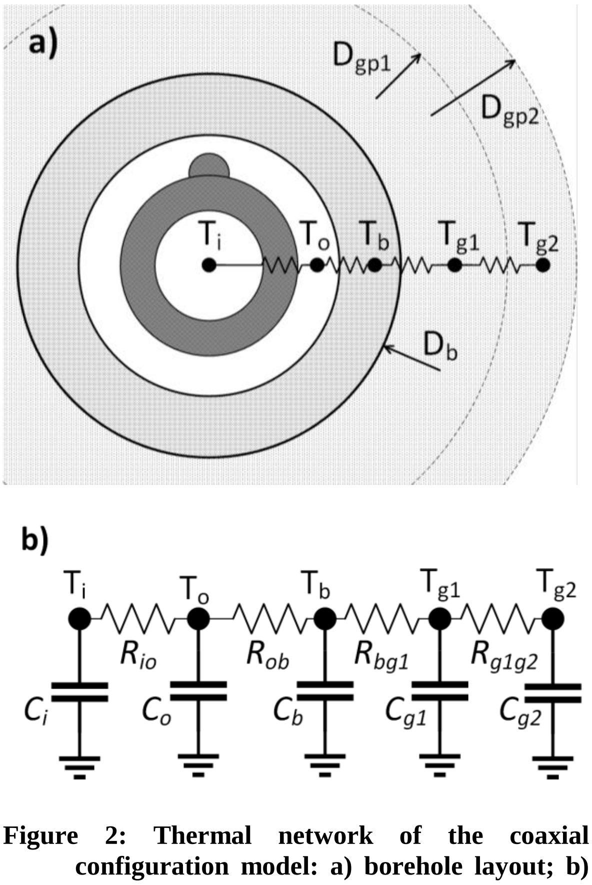

Figure 2: Thermal network of the coaxial configuration model: a) borehole layout; b) 2D model.

The node T_i represents the fluid in the inlet pipe, the node T_o represents the fluid in the outer pipe, the node T_b represents the borehole backfilling, and the nodes T_{g1} and T_{g2} represent the surrounding ground. In this model, two ground nodes are considered, the first node (T_{g1}) takes into account the surrounding ground affected by the heat injection/extraction during a short period of time (for example 1 hour), while the second node (T_{g2}) takes into account the ground affected during a larger period of time (for example 15 hours), in this way, the model predicts with a higher accuracy the short-term and the mid-term behaviour of the BHE than with only one node for the surrounding ground.

The position of each ground node is represented by the penetration diameter, considering the period of time of heat injection/extraction. This penetration diameter is calculated according to the equation for a region bounded internally by a circular cylinder and constant heat flux in its surface, found in (Carslaw and Jaeger 1959).

The BHE is discretised vertically from the top to the bottom in *n* 2D thermal networks (Figure 2). The energy balance equations for the different nodes are described in the equations [1]-[5].

$$\frac{\partial T_i(z)}{\partial t} = v_i \frac{\partial T_i(z)}{\partial z} - \frac{1}{C_i}\left(\frac{T_i(z) - T_o(z)}{R_{bi}}\right) \qquad [1]$$

$$\frac{\partial T_o(z)}{\partial t} = -v_o \frac{\partial T_o(z)}{\partial z} - \frac{1}{C_o}\left(\frac{T_o(z) - T_i(z)}{R_{io}} + \frac{T_o(z) - T_b(z)}{R_{ob}}\right) \qquad [2]$$

$$C_b \frac{\partial T_b(z)}{\partial t} = \frac{T_o(z) - T_b(z)}{R_{ob}} + \frac{T_{g1}(z) - T_b(z)}{R_{bg1}} \qquad [3]$$

$$C_{g1} \frac{\partial T_{g1}(z)}{\partial t} = \frac{T_b(z) - T_{g1}(z)}{R_{bg1}} + \frac{T_{g2}(z) - T_{g1}(z)}{R_{g1g2}} \qquad [4]$$

$$C_{g2} \frac{\partial T_{g2}(z)}{\partial t} = \frac{T_{g1}(z) - T_{g2}(z)}{R_{g1g2}} \qquad [5]$$

Vertical conduction is neglected, but the vertical advection in the fluid nodes is taken into account. Normally, the fluid is flowing downwards in the outer pipe and upwards in the inner pipe, this is the reason why the velocity of the fluid is added in the equation [1] and subtracted in the equation [2]. However, it can also be considered the fluid flow in the other sense.

In order to consider the spiral flow path inside the outer pipe, an equivalent section and the equivalent hydraulic diameter is considered in the calculation of the hydraulic and thermodynamic properties.

The entire model consists in *n* thermal networks, each one with five thermal capacitances and four thermal resistances (a 5C4R-n model). The numerical resolution of this co-axial model is analogous to the resolution for the single U-tube model.

2.2.2 Parameter calculation

The parameters of the B2G model adapted to the new co-axial configuration can be determined taking into account the thermo-physical properties and the geometrical characteristics of the borehole, similarly to the single U-tube B2G model (Ruiz-Calvo et al. 2015). The main parameters are the thermal resistances and the thermal capacitances of the different nodes of the thermal network.

2.2.2.1 Nodes capacitances

The thermal capacitances are calculated considering the volumetric thermal capacitance (c) and the volume of each zone in each vertical division (dz).

In the case of the ground nodes, the capacitances are calculated according to the equations [6] and [7].

$$C_{g1} = \frac{\pi}{4}\left(D_{gp1}^2 - D_b^2\right) c_{g1} dz \qquad [6]$$

$$C_{g2} = \frac{\pi}{4}\left(D_{gp2}^2 - D_{gp1}^2\right) c_{g2} dz \qquad [7]$$

In the case of the grout node, the heat capacity (C_b) can be calculated using the equation [8].

$$C_b = \frac{\pi}{4}\left(D_b^2 - D_{eo}^2\right) c_b\, dz \qquad [8]$$

In these equations, D_{gp1} and D_{gp2} are the penetration diameters of the short term ground node and the mid-term ground node, respectively, D_b is the borehole diameter, D_{eo} is the outer diameter of the outer pipe.

In the case of the fluid nodes, the thermal capacitance is calculated using the heat capacity (C_p) and the density of the fluid in the pipe (ρ), according to the equations [9] and [10].

$$C_i = \frac{\pi}{4} D_{ci}^2\, C_{p,i}\, \rho_i dz \qquad [9]$$

$$C_o = \frac{\pi}{4}(D_{ei}^2 - D_{co}^2)\, C_{p,o}\, \rho_o dz \qquad [10]$$

In these equations, D_{ci} is the inner diameter of the inner pipe, D_{ei} is the inner diameter of the outer pipe and D_{co} is the outer diameter of the inner pipe.

2.2.2.2 Thermal resistances

The thermal resistances between the nodes are calculated as an addition of conductive and convective cylindrical thermal resistances. For the calculation of the conductive thermal resistances, the nodes are located at an equivalent diameter. The position of the borehole node (D_x) is situated at the mean diameter between the borehole and the outer pipe. The short term ground node (D_{g1}) is placed at the mean diameter between the short term penetration diameter and the borehole diameter. The mid-term ground node (D_{g2}) is situated at the mean diameter between the mid-term penetration diameter and the short term penetration diameter.

$$D_x = \frac{D_b + D_{eo}}{2} \qquad [11]$$

$$D_{g1} = \frac{D_{gp1} + D_b}{2} \qquad [12]$$

$$D_{g2} = \frac{D_{gp2} + D_{gp1}}{2} \qquad [13]$$

In order to calculate the convective thermal resistance, the mean convective heat transfer coefficient of the fluid in the inner pipe (h_i) and in the outer pipe (h_o) is considered. The mean convective heat transfer coefficient (h) is calculated according to the equation [14]

$$h = \frac{Nu\, k}{D} \qquad [14]$$

The Nusselt number (Nu) is calculated depending on the flow regime (e.g. (VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen 2010)). The conductivity of the fluid inside the pipes (k) is calculated at the mean temperature inside each pipe. For the inner pipe, the internal diameter of the inner pipe is considered, for the outer pipe, an equivalent hydraulic diameter is calculated, considering the spiral flow path.

The same mean convective heat transfer coefficient for the outer pipe (h_o) is considered in the thermal resistance with the inner pipe and in the thermal resistance with the grout.

On the other hand, to calculate the conductive thermal resistance, the conductivity of the inner pipe (k_{ip}), the conductivity of the outer pipe (k_{op}), the conductivity of the grout (k_b) and the conductivity of the ground (k_g) is considered.

The thermal resistances between the nodes are calculated according to the equations [15]-[18].

$$R_{io} = \frac{1}{\pi\, D_{ci}\, dz\, h_i} + \frac{\ln\left(\frac{D_{co}}{D_{ci}}\right)}{2\,\pi\, k_{ip}\, dz} + \frac{1}{\pi\, D_{co}\, dz\, h_o} \qquad [15]$$

$$R_{ob} = \frac{1}{\pi\, D_{ei}\, dz\, h_o} + \frac{\ln\left(\frac{D_{eo}}{D_{ei}}\right)}{2\,\pi\, k_{op}\, dz} + \frac{\ln\left(\frac{D_x}{D_{eo}}\right)}{2\,\pi\, k_b\, dz} \qquad [16]$$

$$R_{bg1} = \frac{\ln\left(\frac{D_b}{D_x}\right)}{2\,\pi\, k_b\, dz} + \frac{\ln\left(\frac{D_{g1}}{D_b}\right)}{2\,\pi\, k_g\, dz} \qquad [17]$$

$$R_{g1g2} = \frac{\ln\left(\frac{D_{g2}}{D_{g1}}\right)}{2\,\pi\, k_g\, dz} \qquad [18]$$

3. EXPERIMENTAL VALIDATION

3.1 Thermal Response Test: experimental results

The main innovations of the Geothex® heat exchanger are an insulated inner pipe to minimize heat loss between the inner and outer flow channel and spiralling vanes in the annular space to enhance heat transfer, especially at low Reynolds numbers. As can be seen in figures 2a and 3, the edge of the vane and the inner wall of the outer pipe are not in full contact. In fact, there is a gap of about 3.25 mm on average. Although the vanes will touch the inner wall of the outer pipe at different places, the spiral flow path is not completely closed.

The reason for the existence of this gap is twofold. First of all, manufacturing tolerances of the special inner pipe material are not as high as in conventional extruded pipes. Secondly, and perhaps more importantly, if the fit would be very tight it would be very difficult to insert the inner pipe in the outer pipe due to friction, especially when the length of the heat exchanger increases.

Fluid flowing through the gap may generate a local higher turbulence and hence an increase in the heat transfer coefficient from the fluid in the outer pipe to the grout/ground.

In the following two scenario's, one without gap flow and one with gap flow, will be considered.

3.2 Validation of the model

In order to validate the model, the B2G model has been implemented as a TRNSYS type, creating a new type where the geometrical characteristics and the thermal properties are set as parameters.

The results calculated by the co-axial model have been compared with the TRT results described in the previous section. The length of the experiment used for the comparison is 15 hours, as it is a dynamic model and 15 hours is a common operation time for an ON/OFF GSHP system during a day.

The penetration diameter of each ground node is also introduced as an input, in this case the first ground node is set at a penetration diameter of 0.3 m, and the second at 0.7 m, according to the heat extraction time of 1 hour and 15 hours, respectively.

In the simulation, one BHE is modelled, the inlet temperature and inlet mass flow rate is introduced in intervals of 1 minute. Using this data, the model calculates the outlet temperature and it calculates the amount of heat transferred to the surrounding ground according to the equation [19].

$$Q\ (J) = \int \dot{m}\, C_p (T_{out} - T_{in}) dt \qquad [19]$$

The time step used in the simulation is 1 minute. The outlet temperature is compared with the experimental outlet temperature and the root mean square error (RMSE) is calculated according to the equation [20]. In addition, the amount of heat transferred from the BHE to the ground is also compared.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n} \left(T_{B2G,t} - T_{experimental,t}\right)^2}{n}} \qquad [20]$$

Regarding the spiral flow path inside the outer pipe of the BHE, two cases have been studied:

1. The fluid flows in its totality following the spiral path
2. Part of the fluid flows through the gap between the helical rib and the outer pipe wall, so the convective heat transfer from the outer pipe fluid to the grout is increased due to the turbulence generated by this rib.

   In order to take into account this phenomenon, an enhancement factor in the convective heat transfer coefficient between the outer pipe and the grout is considered, while the convective heat transfer coefficient between the outer pipe and the inner pipe is not modified.

   The enhancement factor has been considered in order to obtain a good fitting between the experimental results and the results calculated by the model. This factor is set to 1.5 (an increase of 50% in this coefficient).

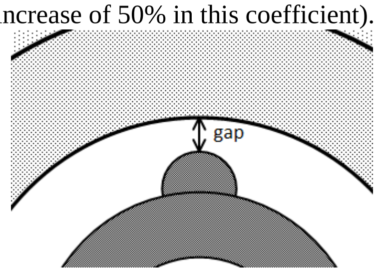

Figure 3: Gap between the spiral rib and the pipe wall.

The model parameters considered in the present work are shown in Table 1.

Table 1: Main parameters adopted

Thermophysical properties	
Ground thermal conductivity	2.13 W/m·K
Grout thermal conductivity	1.56 W/m·K
Ground volumetric thermal capacitance	2410 kJ/m^3·K
Grout volumetric thermal capacitance	3500 kJ/m^3·K
Percentage of propylene-glycol in the fluid	20 % (vol.)
Geometrical characteristics	
Length	44.43 m
Borehole diameter	0.088 m
Inner diameter of the inner pipe	0.0285 m
Outer diameter of the inner pipe	0.0445 m
Inner diameter of the outer pipe	0.057 m
Outer diameter of the outer pipe	0.063 m
Number of spiral ribs	1
Angle of the spiral rib	85.7 °
Model parameters	
Number of vertical divisions	150
Inner pipe conductivity	0.2 W/m·K
Outer pipe conductivity	0.42 W/m·K

4. RESULTS AND DISCUSSION

4.1 Case 1: fluid following the spiral path

In the first case, it is considered that the totality of the fluid flows along the spiral path. Figure 4 shows the simulation results for the TRT during 15 hours of heat extraction and the comparison between these results and the experimental data. The difference between the outlet temperature calculated by the model and the experimental is also represented. The main parameters adopted by the model are shown in Table 1.

The figure shows that the outlet temperature simulated by the model is similar to the experimental outlet temperature, although there is a higher difference during the first two hours of TRT. The highest temperature difference is 0.308 K and it occurs during the first hour. The root mean square error is 0.095 K.

Regarding the heat transferred, Table 2 shows the difference between the heat calculated by the model and the experimental, the heat calculated by the model is 3.52% lower than the experimental.

Table 2: Difference between the heat transferred during the 15 hours of the TRT in case 1.

Experimental	B2G model	Percentage difference
43022.6 kJ	41506.4 kJ	-3.52%

4.2 Case 2: Part of the fluid through the gap

In the second case, it is considered that the fluid through the outer pipe is following the spiral path, but a small part of the fluid flows through the gap between the spiral rib and the pipe wall. In order to model the turbulence created and the increase in the convection from the fluid to the grout, an enhancement factor in the convective heat transfer coefficient is assumed. It is set to 1.5 in order to get a good fitting between the experimental results and the results calculated by the model.

Figure 5 shows the outlet temperature calculated by the model and the experimental outlet temperature, as well as the difference between them in each time step. The main parameters adopted by the model are shown in Table 1.

The simulated temperature is very similar to the experimental, the highest difference between them is 0.212 K and it occurs during the first hour. The RMSE calculated is 0.049 K.

Regarding the heat transferred, Table 3 shows the difference between the heat calculated by the model and the experimental, the heat calculated by the model is 0.22% higher than the experimental.

Table 3: Difference between the heat transferred during the 15 hours of the TRT in case 2.

Experimental	B2G model	Percentage difference
43022.6 kJ	43116.0 kJ	0.22 %

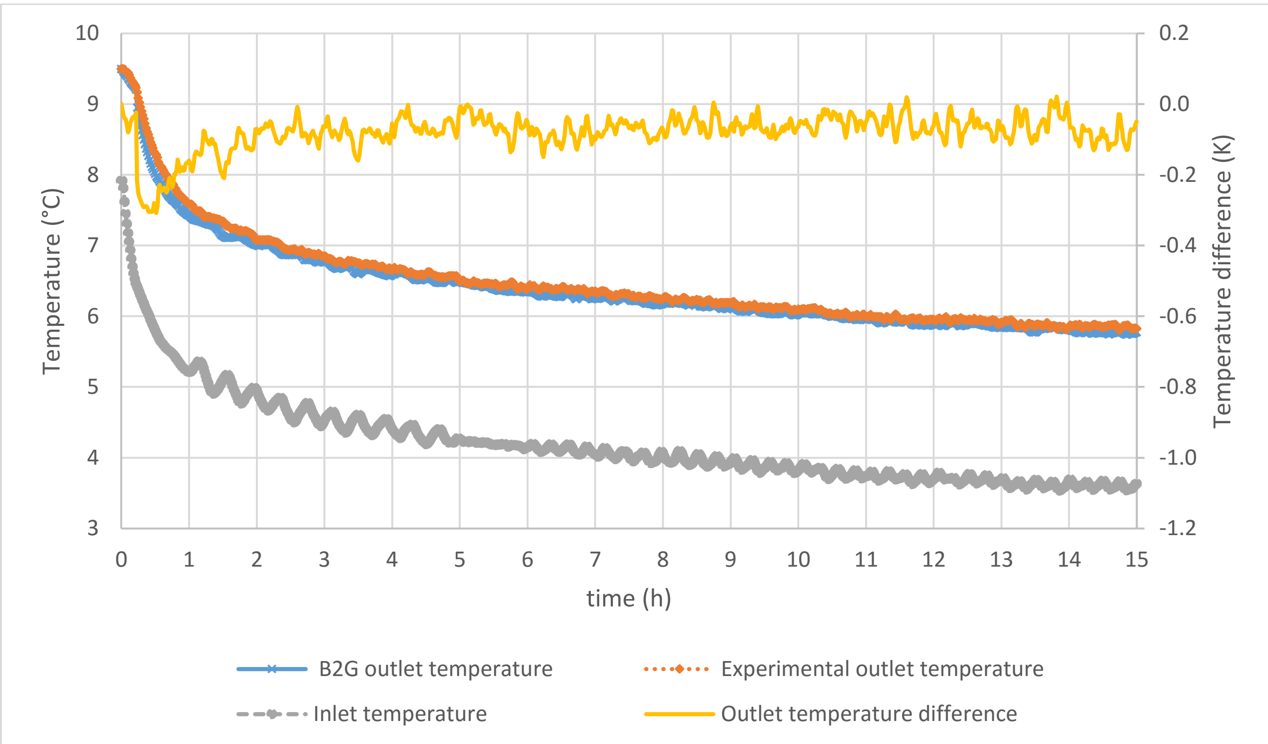

Figure 4: Comparison between the experimental outlet temperature and the outlet temperature calculated by the B2G model for a TRT test (Case 1: fluid following the spiral path)

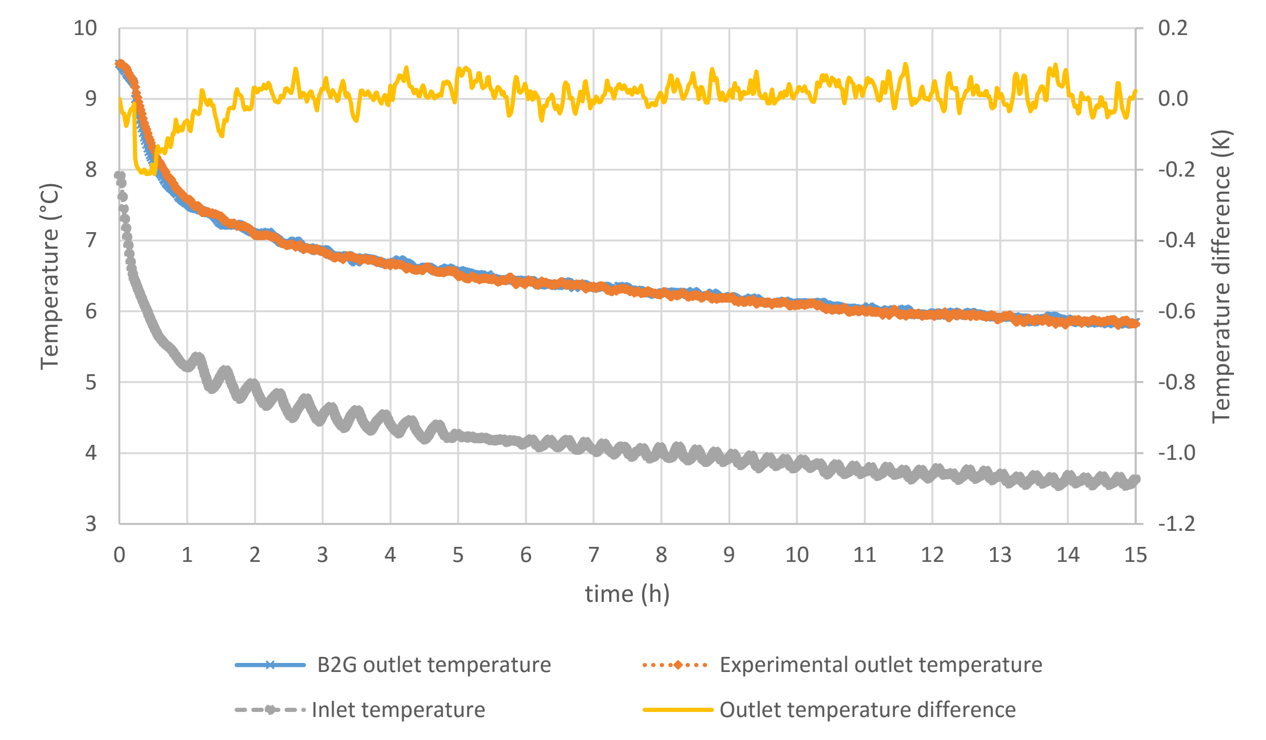

Figure 5: Comparison between the experimental outlet temperature and the outlet temperature calculated by the B2G model for a TRT test (Case 2: Part of the fluid through the gap, enhancement factor=1.5)

5. CONCLUSIONS

The B2G dynamic model has been adapted to the novel co-axial configuration with spiral flow path. The new thermal network and the equations of the model have been presented.

The model has been validated against experimental data using a TRT carried out at the Geothex BV facility. Two simulation cases have been considered: the first case considers that the totality of the fluid flows along the helical path through the outer pipe and the second case considers that a small part of this fluid flows through the gap between the spiral rib and the pipe wall, generating a higher turbulence and enhancing the convective heat transfer.

In the first case, the results calculated by the model are similar to the experimental results, the RMSE is lower than 0.1 K and the difference in the heat transferred is 3.52 %.

In the second case, an enhancement factor of 1.5 in the convective heat transfer coefficient between the outer pipe and the grout has been assumed in order that the results calculated by the model are more adjusted to the experimental results. The RMSE is lower than 0.05 K and the difference in the heat transferred is 0.22 %. With this enhancement factor, an increase of 50 % in the convective heat transfer between the fluid inside the outer pipe and the grout is considered, taking into account the turbulence generated by the fluid flowing through the gap.

In conclusion, the B2G model adapted to the new co-axial configuration produces accurate results, especially if it is considered that the totality of the fluid does not follow the helical path, but a small part of it flows through the gap between the rib and the pipe wall, enhancing the convective heat transfer.

REFERENCES

Carslaw, H. S., and Jaeger, J. C.: Conduction of heat in solids, Second edition, *Oxford University Press*, New York, NY, USA, (1959).

Cazorla-Marín, A., Ruiz-Calvo, F., Montagud, C., and Corberán, J. M.: Nuevo modelo dinámico de un intercambiador enterrado en TRNSYS: adaptación del modelo B2G a largos periodos de simulación, *CYTEF2016 - PROCEEDINGS. Advances in Refrigeration Sciences and Technologies - VIII*, Coimbra, Portugal, (2016).

European Commision: Geothermal Technology for €conomic Cooling and Heating (H2020-LCE-2014-2, GEOTeCH-656889), (2015), http://www.geotech-project.eu/.

Florides, G., and Kalogirou, S.: Ground heat exchangers—A review of systems, models and applications, *Renewable Energy*, 32, (2007), 2461–2478.

Mustafa Omer, A.: Ground-source heat pumps systems and applications, *Renewable and Sustainable Energy Reviews*, 12, (2008), 344–371.

De Rosa, M., Ruiz-Calvo, F., Corberán, J. M., Montagud, C., and Tagliafico, L. A.: A novel TRNSYS type for short-term borehole heat exchanger simulation: B2G model, *Energy Conversion and Management*, 100, (2015), 347–357.

Ruiz-Calvo, F., De Rosa, M., Acuña, J., Corberán, J. M., and Montagud, C.: Experimental validation of a short-term Borehole-to-Ground (B2G) dynamic model, *Applied Energy*, 140, (2015), 210–223.

Ruiz-Calvo, F., De Rosa, M., Monzó, P., Montagud, C., and Corberán, J. M.: Coupling short-term (B2G model) and long-term (g-function) models for ground source heat exchanger simulation in TRNSYS. Application in a real installation, *Applied Thermal Engineering*, 102, (2016), 720–732.

Ruiz-Calvo, F.: Análisis y modelado de una instalación geotérmica para climatización de un conjunto de oficinas, PhD Thesis, Universitat Politècnica de València, (2015).

Urchueguía, J. F., Zacarés, M., Corberán, J. M., Montero, Á., Martos, J., and Witte, H.: Comparison between the energy performance of a ground coupled water to water heat pump system and an air to water heat pump system for heating and cooling in typical conditions of the European Mediterranean coast, *Energy Conversion and Management*, 49, (2008), 2917–2923.

Gnielinski, V.: G1 Heat Transfer in Pipe Flow, in VDI Heat Atlas, VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen (Second Edition) *Springer-Verlag Berlin Heidelberg*, Düsseldorf, (2010).

Witte, H.J.L., Gelder, A.J, van, Spitler, J.D.: In-situ measurement of ground thermal conductivity: The Dutch perspective. ASHRAE Transactions, Volume 108, (2002), No. 1.

Witte, H.J.L.: The GEOTHEX geothermal heat exchanger, characterisation of a novel high efficiency heat exchanger design. *The 12th International conference on Energy Storage (INNOSTOCK, Lleida)*. INNO-U32, (2012).

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NOMENCLATURE

BHE	borehole heat exchanger
c	volumetric thermal capacity (J/m^3·K)
C	thermal capacitance (J/K)
C_p	Heat capacity (J/kg·K)
D	diameter (m)
GSHE	ground source heat exchanger
GSHP	ground source heat pump
k	conductivity (W/m·K)
h	convective heat transfer coefficient (W/m^2·K)
$\dot{m}$	mass flow rate (kg/s)
n	number of nodes (-)
R	thermal resistance (K/W)
RMSE	root mean square error
ρ	density (kg/m^3)
t	time (s)
T	temperature (C)
TRT	Thermal Response Test
v	velocity (m/s)
z	borehole depth coordinate (m)

Subscripts

1	downward pipe zone
2	upward pipe zone
b	borehole
bb	borehole node to borehole node
bg1	borehole node to short term ground node
c	conduction
ci	inner diameter of the inner pipe
co	outer diameter of the inner pipe
ei	inner diameter of the outer pipe
eo	outer diameter of the outer pipe
g	ground
g1	ground node (short term)
g2	ground node (mid-term)
g1g2	short term to mid-term ground nodes
gp	ground penetration
gp1	ground penetration for short term ground node
gp2	ground penetration for mid-term ground node
h	convection
i	inner pipe zone
ip	inner pipe
in	inlet
io	inner pipe node to outer pipe node
j	j-node
o	outer pipe zone
op	outer pipe
out	outlet
ob	outer pipe zone to borehole backfilling node
x	borehole node position