Experimental Validation of a Thermal Resistance and Capacity Model for Geothermal Boreholes

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ABSTRACT

Thermal Resistance Capacity (TRC) models are used to account for thermal capacity when simulating geothermal boreholes. One such model is presented in this paper. In the proposed model, the borehole is discretized in the axial direction with a limited number of segments of equal height. The grout capacity at any given cross-section is lumped together in various nodes each with its own temperature. The fluid capacity is also included with two nodes, one for each U-tube leg. Finally, the borehole wall temperature is obtained from a ground heat transfer model based on the classic cylindrical heat source analytical solution. Experimental data from two tests performed at the Canadian Centre for Housing Technology (Ottawa, Canada) are used to validate the TRC model presented here. The first data set is taken from a thermal response test (TRT) performed on a 76 m borehole. This test is used to obtain the ground thermal conductivity but also to calibrate the ground model to estimate the ground thermal diffusivity. The second set is taken from the actual operation of two parallel boreholes linked to two 3.52 kW (1 ton) heat pumps used to heat a house. Measurements were taken every 5 minutes over a period of 47 days and include periods of intermittent operation. Results show that there is excellent agreement between the outlet temperatures and the grout temperatures predicted by the TRC model and the corresponding experimental temperatures.

INTRODUCTION

Most geothermal borehole models do not account for borehole thermal capacity and assume steady-state heat transfer from the fluid to the borehole wall. Recently, a number of models that account for borehole thermal capacity have been presented. One such model, based on a Thermal Resistance Capacitance (TRC) network (Godefroy 2014 and Godefroy and Bernier 2014), is presented here. The model is validated using a 47 days test performed on two boreholes at the Canadian Center for Housing Technology in Ottawa, a Canadian government test facility (CCHT 2015).

LITERATURE REVIEW

Thermal capacity (fluid and grout) in boreholes can be modeled accurately using three-dimensional heat transfer models such as the ones presented by Rees and He (2013), He et al. (2011), and Bauer et al. (2011a). However, these models are not convenient for yearly simulations because of the relatively long computational times. He et al. (2010) proposed a two-dimensional model with additional inlet and outlet pipes to account for fluid thermal capacity. Results given by this improved 2-D model are in close agreement with 3-D models. Pärisch et al. (2015) also used an inlet pipe to account for fluid and grout thermal capacity. This virtual pipe can be used upstream of borehole models that do not

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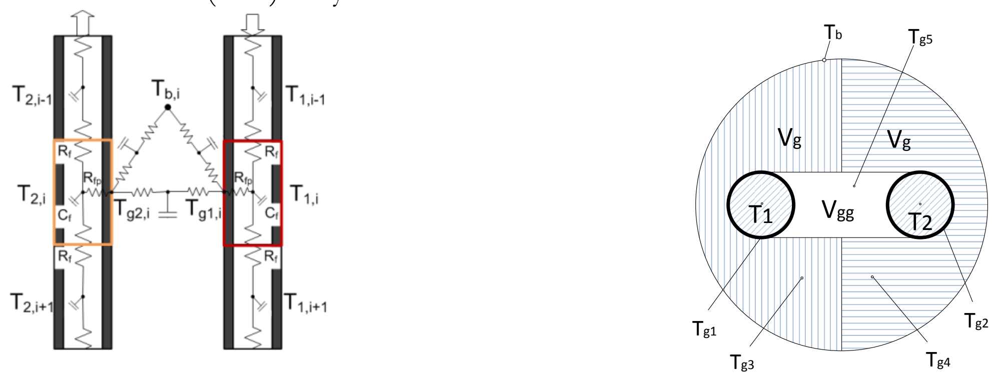
take into account borehole thermal capacity such as the Duct ground heat STorage (DST) model (Hellström et al. 1996). They successfully validated their approach using a two-hour test sequence. They also showed that the EWS model (Wetter and Huber 1997) is giving accurate results despite its simplicity but that the DST model is inaccurate in transient conditions. Shirazi and Bernier (2013) modeled the borehole capacity by using an equivalent hollow cylinder geometry which permitted the use of a simple and relatively fast 1-D axisymmetric numerical model.

One popular approach to simplify the calculations is to discretize the calculation domain and assign thermal (T) resistances (R) and capacitances (C) to a limited number of nodes. TRC models can be regarded as coarse representations of more detailed finite difference or finite element models. Zarella et al. (2011) and De Carli et al. (2010) used a so-called CaRM to model ground heat exchangers for short time steps. In their approach, the borehole as well as the ground are discretized in the axial and radial directions. Pasquier and Marcotte (2012) and Bauer et al. (2011b) used a similar approach in their TRC models. Pasquier and Marcotte (2012) validated their model using the results of a thermal response test (TRT) from a laboratory sand box (Beier et al. 2011). De Rosa (2015) proposed a similar model but with a different number of nodes. Borehole thermal capacity is accounted for in the EWS model (Wetter and Huber 1997). However, it can only be applied to a four-pipe borehole. Moreover, the discretization of the domain is crude with only one node representing the four pipes and another to describe the grout.

PROPOSED TRC MODEL

Domain Discretization

The model used in this paper (Godefroy 2014 and Godefroy and Bernier 2014) differs from the CaRM and TRC models presented above in that the TRC approach is only used inside the borehole while ground heat transfer is modeled using the cylindrical heat source (CHS) analytical solution.



a) b)

Figure 1 Axial and radial representation of the various nodes in the TRC model proposed by Godefroy (2014)

The analysis is limited here to a two-pipe borehole (one U-tube). Interested readers can consult the work of Godefroy (2014) who also developed a four-pipe model. Figure 1 presents the axial and radial node discretization. Pipe 1 is the downward pipe while the fluid flows upward in pipe 2. The borehole is divided into n_b vertical sub-regions (three are shown on Figure 1a) of equal height. For each of these sub-regions, there is an equivalent circuit of thermal resistance and capacitance which is shown in Figure 1b. These cross-sections are sub-divided into seven regions each with its own temperature: T_1 and T_2 are the fluid temperatures in pipes 1 and 2, respectively; T_{g1} and T_{g2} are the temperatures of pipes 1 and 2, respectively. The grout region is sub-divided into three volumes, two half circles each with a volume V_g and a quasi-rectangular volume between the pipes, V_{gg} .The corresponding temperatures are T_{g3}, T_{g4} and T_{g5}, respectively. Finally, the borehole wall temperature is T_b.

Governing Equations

Based on the nomenclature presented in Figure 1, the governing equations for the nodal temperatures can be derived based on simple energy balances:

$$\frac{T_{1,i}-T_{g1,i}}{R_{fp}}+\frac{T_{g3,i}-T_{g1,i}}{R_g}+\frac{T_{g5,i}-T_{g1,i}}{R_{gg}}=0 \quad (1)$$

$$\frac{T_{2,i}-T_{g2,i}}{R_{fp}}+\frac{T_{g4,i}-T_{g2,i}}{R_g}+\frac{T_{g5,i}-T_{g2,i}}{R_{gg}}=0 \quad (2)$$

$$\frac{T_{g1,i}-T_{g3,i}}{R_g}+\frac{T_{b,i}-T_{g3,i}}{R_g}= C_g\frac{T_{g3,i}-T_{g3,i}^0}{\Delta t} \quad (3)$$

$$\frac{T_{g2,i}-T_{g4,i}}{R_g}+\frac{T_{b,i}-T_{g4,i}}{R_g}= C_g\frac{T_{g4,i}-T_{g4,i}^0}{\Delta t} \quad (4)$$

$$\frac{T_{g1,i}-T_{g5,i}}{R_{gg}}+\frac{T_{g2,i}-T_{g5,i}}{R_{gg}}= C_{gg}\frac{T_{g5,i}-T_{g5,i}^0}{\Delta t} \quad (5)$$

In these equations, R_{fp} is the combined thermal resistance of the fluid and of the pipe wall; R_g and R_{gg} follow the model of the delta-circuit presented by Eskilson and Claesson (1988) with $R_g = R_1/2$ and $R_{gg} = R_{12}/2$. The thermal capacitance terms are $C_{gg} = V_{gg}(\varrho Cp)_g$, $C_g = V_g(\varrho Cp)_g$ where $(\varrho C_p)_g$ is the product of the density times the specific heat of the grout. Finally, superscript "0" refers to the value at the previous time step and Δt is the simulation time step.

An energy balance on the fluid segments in each pipe for each vertical region i leads to:

Pipe 1: $$\frac{\dot m\, c_{p_f}}{dH}\left(T_{in-1,i}-T_{out-1,i}\right)-Q_{1\to g1,i}=\pi r_i^2\rho_f c_{p_f}\frac{T_{1,i}-T_{1,i}^0}{\Delta t} \quad \text{with} \quad Q_{1\to g1,i}=\frac{T_{1,i}-T_{g1,i}}{R_{fp}} \quad (6)$$

Pipe 2: $$\frac{\dot m\, c_{p_f}}{dH}\left(T_{in-2,i}-T_{out-2,i}\right)-Q_{2\to g2,i}=\pi r_i^2\rho_f c_{p_f}\frac{T_{2,i}-T_{2,i}^0}{\Delta t} \quad \text{with} \quad Q_{2\to g2,i}=\frac{T_{2,i}-T_{g2,i}}{R_{fp}} \quad (7)$$

Where dH is the height of the fluid segments and r_i is the pipe internal radius. The heat injection rate at the borehole wall for each fluid segment height, Q_i, is given by:

$$Q_i=\frac{(T_{g3,i}-T_{b,i})+(T_{g4,i}-T_{b,i})}{R_g} \quad (8)$$

The borehole wall temperature is obtained at each time step using the CHS solution to radial heat transfer from a cylinder (Ingersoll et al. 1954). For a constant heat transfer rate per unit length, the use of the CHS leads to (Bernier, 2001):

$$T_g-T_{b,i}=\frac{Q_i}{k}\,G(Fo) \quad (9)$$

where T_g is the undisturbed ground temperature, k is the ground thermal conductivity, G is the CHS solution and Fo is the Fourier number defined as $\alpha t/r_b^2$. Since Q_i varies with time, temporal superposition (Bernier 2001) has to be used with a proper load aggregation scheme (Liu 2005). Equations 1-9 constitute a set of 9 equations with 9 unknowns at each cross-section. Thus, over the borehole height, there is a total of $9n_b$ equations with $9n_b$ unknowns. This linear set of equations has been implemented in a TRNSYS type and is solved with a simple matrix inversion. Godefroy and Bernier (2014) have used this model in annual simulations. They showed that neglecting borehole thermal capacity in annual simulations of ground-source heat pump systems can lead to an overestimation of up to 3.6% of the heat pump energy consumption when the heat pump is operating intermittently.

EXPERIMENTAL VALIDATION

Experimental Set-Up

Experiments took place at the Canadian Centre for Housing Technology (CCHT) in 2006. The CCHT is a Canadian government lab located on the campus of the National Research Council in Ottawa, Ontario, Canada. It consists of two detached, single-family houses that have the capacity to assess energy and building technologies with daily simulated occupancy effects. The experiments reported here were part of a larger study on residential total energy systems performed on one of the two houses (Yang et al. 2007).

A schematic of the installation related to the present work is presented in Figure 2. It consists of two boreholes piped in parallel and connected to two 1-ton (3.52 kW) water-to-air heat pumps. As shown in Figure 2, each borehole has a diameter of 15 cm (6 in.) and includes two 25.4 mm (1 in.) HDPE pipes (one U-tube) that are grouted with a sodium-based bentonite. Plastic spacers are installed at different depths to maintain a distance between the two legs of the U-tube. Borehole inlets are located 1.5 m below the ground surface. Boreholes #1 and #2 are 51.8 and 50.3 m deep, respectively. Thermocouples are installed inside each borehole at depths of 5, 10, 25 and 50 m (from the ground surface) to measure grout temperatures. The borehole cross-section in Figure 2 indicates the approximate position of these thermocouples inside the borehole.

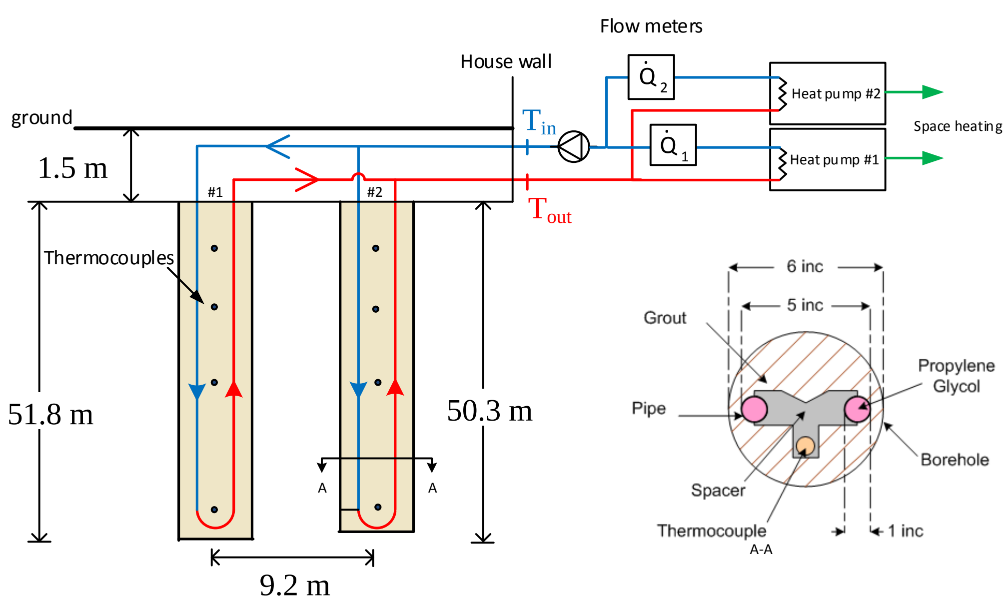


Figure 2 Schematic representation of the experimental set-up

The circulating pump delivers a nominal flowrate of 0.38 L/s (6 gpm) and it is activated if at least one heat pump is in operation; otherwise it is off. A 50% propylene-glycol mixture is used as the heat transfer fluid. Balancing valves are installed in the circuit such that the total flow rate is divided equally in each heat pump and in each borehole. The volumetric flow rates, $\dot{Q}_1$ and $\dot{Q}_2$, are measured using positive displacement water meters. The uncertainty is estimated to be ±1.5% based on manufacturer's data. Volumetric flow rates are then converted to mass flow rates, $\dot{m}_1$ and $\dot{m}_2$, using the appropriate fluid density. Fluid temperatures in and out of the two boreholes, T_{in} and T_{out}, are measured with type-T thermocouples with an uncertainty of ±0.5 °C. These thermocouples are installed inside the house about 5 m (16 ft.) from the borehole inlets. Whenever the heat pumps are not in operation T_{in} and T_{out} will tend to reach the house temperature.

The system shown on Figure 2 supplied the space heating needs for 47 consecutive days from November 4th to December 20th, 2006. During that period, parameters related to the system energy performance and characteristics were measured and recorded by a data acquisition system. Measurements were scanned every ten seconds and averaged over 5 minute periods. Based on these measurements and on the knowledge of the specific heat of the propylene glycol (Cp_{pg}), the rate of energy extraction from the ground for each 5 minute time period, Q_{ground}, is calculated with Equation 10.

$$Q_{ground} = (\dot{m}_1 + \dot{m}_2) Cp_{pg} (T_{out} - T_{in}) \qquad (10)$$

Thermal Response Test

A thermal response test (TRT) was conducted on a third borehole, 76 m deep, located in-between the two boreholes shown on Figure 2. The TRT was conducted over a 48 hour period about a month prior to the 47 day test. A study of the TRT results by Yang et al. (2007) establishes that the ground thermal conductivity is equal to 2.5 W/m-K (1.45 BTU/hr.ft.°F). The TRT was also used to calibrate the ground portion of the TRC model to obtain the ground thermal diffusivity. For this purpose, the TRT was simulated using the TRC model with various ground thermal diffusivities. A thermal diffusivity of 0.086 m^2/day yielded the best fit with a corresponding ground thermal capacitance of 2510 kJ/m^3-K (37.4 BTU/ft^3-°F). As shown in Figure 3 the agreement between the TRT test results and the proposed TRC model are excellent with this value of ground thermal diffusivity.

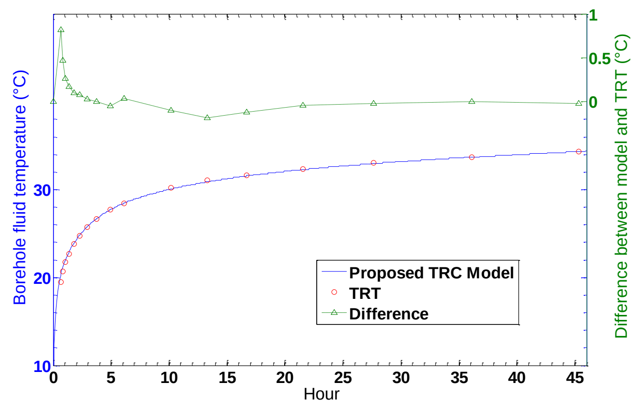


Figure 3 Results of the TRT and of the simulation with the proposed TRC model

Validation

The proposed TRC model had previously been validated using the numerical results of He et al. (2012) and the sand box experimental data of Beier et al. (2011). The validation exercise presented here consists of comparing the outlet temperature predicted by the TRC model with the ones obtained during the operation of a real system. In addition, a qualitative comparison is made between grout temperature measurements inside the borehole and model predictions at a particular borehole depth. Table 1 lists the borehole and ground characteristics used as inputs in the TRC model. Furthermore, the measurements of Q_{ground} (Equation 10) and total mass flow rates, taken every five minutes, are used as inlet conditions to the proposed model. The undisturbed ground temperature used in the model is the average of 8 temperature measurements taken at depth of 5, 10, 25, and 50 m in boreholes #1 and #2 prior to the start of the test. A one-minute time step is used in the simulations and the number of vertical segments, n_b, is set to 20.

Two single boreholes are simulated with the assumption that there is no thermal interference between them. Hellström (1991) established that borehole thermal interference could be neglected provided that the distance B between boreholes is greater than $3\sqrt{\alpha_g t}$. In the present case, $3\sqrt{\alpha_g t} = 6.5\ m$ which is less than the distance of 9.2 m between the two boreholes. The full set of data over 47 days is presented in Figure 4. The bottom portion of the figure presents the value of Q_{ground}. When no heat pump is operating, $Q_{ground} = 0$, while values of $Q_{ground} \approx 1700$ and ≈ 3400 W indicate the operation of one and two heat pumps, respectively. The figure shows that the rate of energy extraction varies frequently, between 0 and the full-load of the two heat pumps.

Table 1. Borehole and ground characteristics

Parameter	Value	Unit
Buried depth	1.5 (5)	m (ft)
Borehole #1 depth	51.8 (170)	m (ft)
Borehole #2 depth	50.3 (165)	m (ft)
Borehole spacing	9.2 (30)	m (ft)
Borehole diameter	150 (6)	mm (in.)
Shank spacing	50.8 (2)	mm (in.)
Pipe outer diameter	25.4 (1)	mm (in.)
Pipe inner diameter	20.4 (0.8)	mm (in.)
Pipe conductivity	0.4 (0.23)	W/mK (BTU/hr.ft.°F)
Grout conductivity	0.8 (0.46)	W/mK (BTU/hr.ft.°F)
Ground conductivity	2.5 (1.45)	W/mK (BTU/hr.ft.°F)
Grout capacitance	3900 (58.1)	$kJ/m^3.K(BTU/ft^3.°F)$
Ground capacitance	2510 (37.4)	$kJ/m^3.K(BTU/ft^3.°F)$
Fluid composition	50% Propylene-Glycol	-
Fluid density	1050 (65.5)	kg/m^3 (lbm/ft^3)
Fluid mass capacitance	3470 (0.83)	kJ/kg.K (BTU/lbm.°F)
Ground temperature	10.95 (51.7)	°C (°F)
Number sections n_h	20	-

The middle portion of Figure 4 shows the experimental outlet temperature as well as the one predicted by the model. It should be noted that this middle graph only shows data points when at least one heat pump is operating as the experimental measurements of T_{in} and T_{out}, taken inside the house away from the boreholes, are meaningless when both heat pumps are inactive. Finally, the top portion of Figure 4 compares the values of Tg_3 and Tg_4 obtained by the model with grout temperature measurements in borehole #2 at a distance of 10 m below the ground surface. The results show an excellent agreement between the model predictions and the experimental data. The Root Mean Square Error (RMSE) on the value of T_{out} is 0.28°C (0.5°F) over the test period when at least one heat pump is operating, whereas it is 0.63°C(1.1°F) when borehole thermal capacity is neglected. A zoomed portion of Figure 4 (represented by the dotted rectangle) is presented in Figure 5. It represents the behavior of the system over an 18 hour period starting at 3pm on day 19. During that period, the system experiences different levels of operation: a long off period starting at 15:00 and lasting about an hour; frequent heat pump cycling from ≈ 19:00 to ≈ 21:00; a four-hour long period of continuous operation starting at ≈ 0:00. During this first period, there is excellent agreement between the values of T_{out} predicted with and without thermal capacity. This is to be expected as conditions do not change (Q_{ground} = 0 for a long period) and both values of T_{out} will tend to reach the same value, i.e, the neighboring ground temperature. The results that starts at 19:00 show that there is better agreement between the model and the experiments when borehole thermal capacity is accounted for. For the third period starting at ≈ 0:00, the model predictions without thermal capacity underestimate the value of T_{out} by ≈ 1K. Then, as the conditions remain stable (Q_{ground} ≈ constant) both values tend towards the same value. However, both values differ by about ≈ 0.3 K with the experimental results at the end of this continuous heat pump operation at ≈ 4:00.

As shown in the top portion of Figure 5, the fluctuations of the grout temperatures are less pronounced than the ones observed for T_{out}. This was to be expected as fluid and grout capacities tend to dampen rapid fluctuations in operating conditions. The agreement between the predicted and measured grout temperatures is good considering that the final position of the thermocouple measuring the grout temperature is unknown and that T_{g3} and T_{g4} are average temperatures of a relatively large volume of grout as shown in Figure 1b.

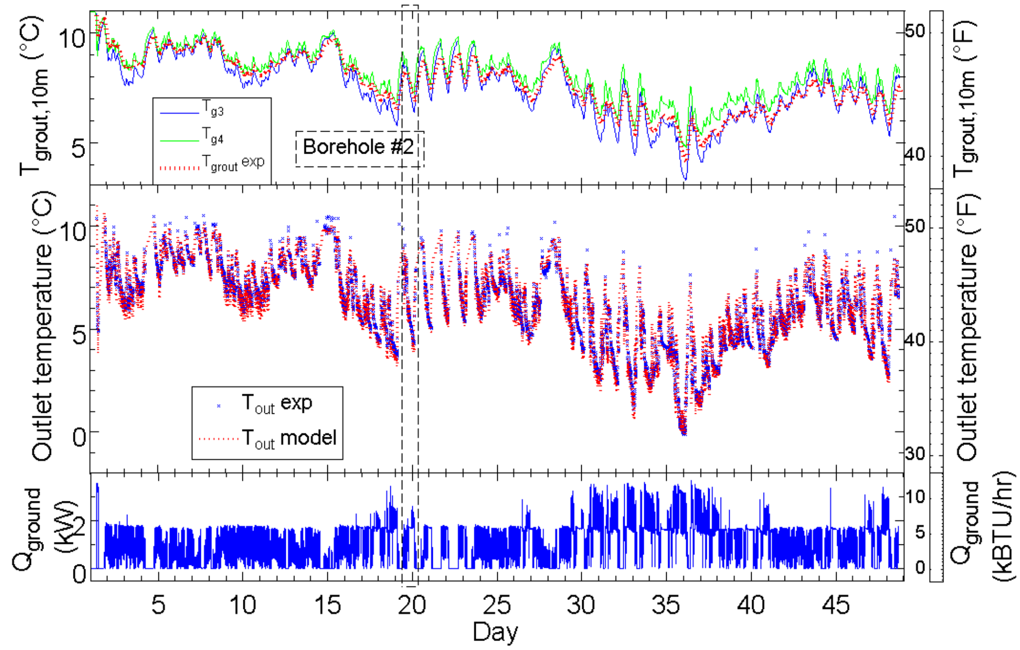


Figure 4 Comparison between the model and CCHT data

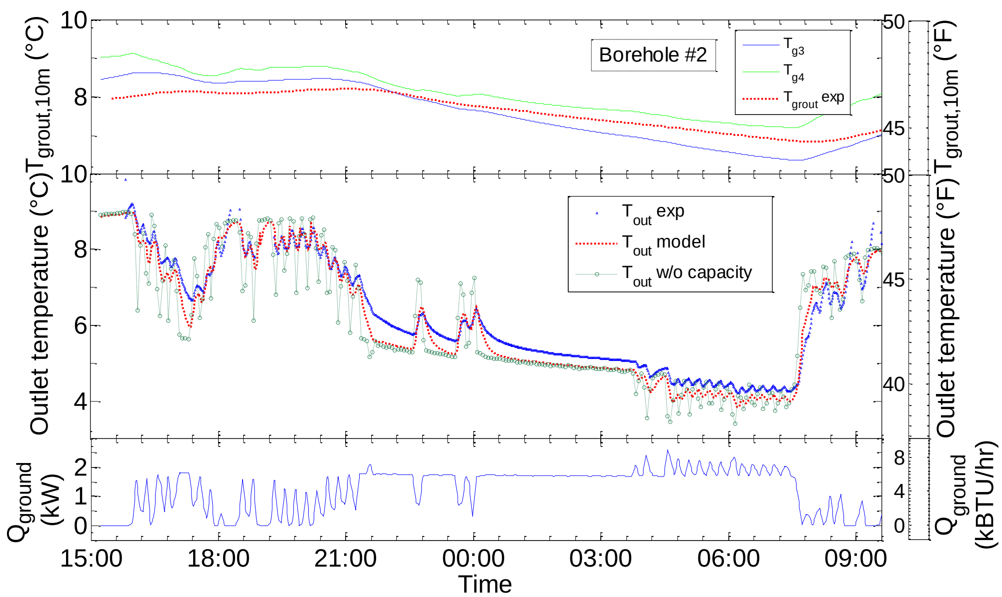


Figure 5 Evaluation of the model on a 18-hour time period.

CONCLUSION

The objective of this study is to validate a borehole model, based on the thermal resistance and capacity (TRC) approach, with experimental data obtained at the Canadian Center for Housing Technology (CCHT) in Ottawa, Canada. Experimental data from two sets of tests are used. The first data set is taken from a thermal response test (TRT) and is used to obtain the ground thermal conductivity and calibrate the ground model against the TRT results to obtain the ground thermal diffusivity. The second data set is taken from the actual operation, over 47 days, of two parallel boreholes linked to two 3.52 kW (1 ton) heat pumps used to heat a house. Results show that there is excellent agreement between the outlet temperatures predicted by the TRC model and the corresponding experimental temperatures with a RMSE difference of 0.28°C (0.5°F). Results also show that the prediction of the borehole outlet temperature is in better agreement with the experimental data when borehole thermal capacity is included. Finally, grout temperature measurements made inside the boreholes are in relatively good agreement with the model predictions.

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