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A High-Speed Portable Ground Heat Exchanger Model for Use in Various Energy Simulation Software

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A High-Speed Portable Ground Heat Exchanger Model for Use in Various Energy Simulation Software

Abstract

A portable component model (PCM) of a ground source heat pump system was developed and used as a test case in the creating of a PCM development framework. By developing this framework, new building energy simulation models will be able to be easily integrated into existing simulation software such as EnergyPlus and the Modelica Buildings Library. Our model uses a time responsive g-function and numerical methods to simulate ground source heat pumps for single time steps as well as long time scales. We validated our model against GHESim and GLHEPro and found that our model agrees with these two standards within acceptable ranges of error. This allows for development of the PCM framework to have a functional test case for trouble shooting errors during the development process. Future work on this model to include non-uniform time steps would allow it to be used independent on other software as a standalone system.

Keywords

Geothermal energy, building energy simulation, heatpump, ground heat pump, physical modeling, EnergyPlus, Modelica Buildings Library, Spawn of Energy Plus

Cover Page Footnote

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I. INTRODUCTION

Ground source heat pumps provide a low operational cost and high efficiency electric building climate control system that can be driven by 100% renewable electricity [1]. These systems are composed of two main parts: the heat pump (HP) and the ground heat exchanger (GHE). The HP exchanges heat between the interior air of a building and a fluid flowing through the GHE. The GHE is composed of a field of vertical boreholes containing a U-shaped tube through which that fluid exchanges heat with the ground. While heat pumps are well understood and can be relatively simple to model through quadratic approximations, GHE's require a much more thorough physical analysis to accurately replicate their behavior. Models must account for the long heat dissipation time of the ground and the boreholes' thermal interactions with one another, which causes a non-negligible annual impact on GHE operation. GHE's can be modeled both analytically and numerically, with the latter being favored for research applications [1].

The method used for the development of our model was derived from the work of Matt Mitchell [2, 3] and calculates GHE outlet temperatures numerically. The calculations will be discussed in more detail in following sections, but the general flow is as follows. The model is passed an inlet temperature and flow rate. It then calculates a GHE load, incorporating the inputs as well as the historical loads from the GHE's operation. That load is used to find the borehole temperature as well as the temperature rise the GHE has on neighboring GHE's. From the borehole temperature, the mean fluid temperature (MFT) of the U-tube inlet and outlet is calculated. The MFT is one common output that is used for the validation of GHE models. From the MFT the GHE outlet temperature is found and returned as the model's output. With this structure the model can be used as a component in a larger building energy simulation system; being passed an inlet temperature and returning an outlet temperature. In our work, we added a simple HP model as an optional component to the system. This component takes in a load (in Watts) and produces an output temperature that is passed to the GHE.

Our model was created as a test case for a portable component model (PCM) framework currently in development. Models of a new building climate control technology are currently produced in parallel. Multiple teams build similar models but all for different simulation engines. The PCM framework will streamline this development process, allowing a single model to be plugged into the different simulation engines. A physics model, once created, is wrapped in 'shells', which allow it to plug into software such as EnergyPlus or the Modelica Buildings Library while also being used as a standalone model. This work has been made especially relevant today with the passage of the 2022 Inflation Reduction Act, which will speed the adoption of new building technologies requiring new simulation models [4].

Two different GHE models have been used to validate our model. For handling loads on the GHE directly, we compared our model to the one used in Mitchell et. al, called GHESim [3, 5]. For handling inlet temperatures provided by the HP, we compared our model to GLHEPro [6]. By verifying our model against these accepted simulators, we can ensure that when it is used as a test case the results will be accurate. We will be able to trace errors that arise when it is coupled with the PCM framework to the framework itself, and thus we will be able to resolve those issues much faster.

II. MODEL

A. g-functions

The g-function is an essential tool for allowing our model to run on a personal computer. It encapsulates much of the time dependent thermodynamical properties of the GHE into a simple set of values. It was first proposed by Claesson and Eskilson in 1988 to decrease the computational time of GHE modeling [7]. It is a number that contains all the precomputed geometric and thermodynamical properties of a GHE. This includes borehole spacing, soil properties, grout properties, etc. The g-function is a function of the natural log of the non-dimensionalized time (LNTTS) prior to the current instance of GHE operation, where time is in seconds (Eq. 1), so small time values indicate g-values that are temporally close to the current operation. This allows the functions to be smoothly collected into a concise data set that maximizes short term resolution. A self g-function describes a single bore field while a cross g-function describes the interactions between bore fields. The cross g-function is the difference between a g-function of the entire system of bore fields and the g-function of a single bore field in that system. Further explanation of self and cross g-functions can be found in Mitchell [3]. The value of the g-function has little physical interpretation, but rather is a computational tool to decrease model runtime because the calculation of these functions can be quite computationally expensive.

Our standalone shell takes GHE formatted JSON files that contain data about the load, load period, GHE characteristics, and the GHE g-functions. The g-functions are linearly interpolated to fit the length of the runtime by a built-in function in the model, allowing easy indexing. The g-functions we used for testing the single borehole case were calculated using a built-in feature of GLHEPro. The self and cross g-functions used in the multi bore field simulation were extracted from Mitchell (Fig. 1) using the software WebPlotDigitizer [8]. While not precise, this method allowed us to have a dataset by which we could test our model without needing to calculate the g-functions ourselves.

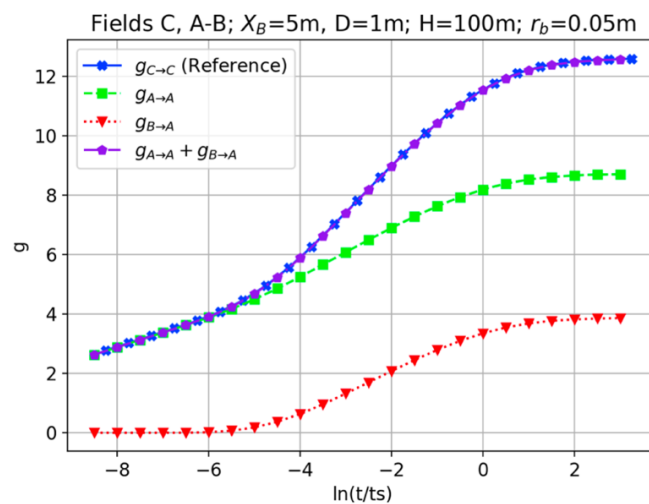


Figure 1. g-functions used for the multiple bore field simulations. g_A and g_B both represent a two borehole geometry. $g_{B \rightarrow A}$ is the cross g function for A and B. g_C represents a four borehole geometry which is a combination of A and B. Chart: Mitchell [3]

B. Model Structure

Our model emphasizes portability by defining the pump, HP, and GHE as three separate classes that communicate solely by passing fluid temperatures and flow rates. In this way, the model accurately mimics a real-world system. This allows for future development and testing with more complex components without the need to completely rewrite code. The pump class is simple and serves to provide a constant flow rate. The HP class contains more complexity. Using a quadratic function, it models the load on the HP and then calculates outlet temperature (Eq. 2a,b). This simple model is the same model as used in GLHEPro [6].

The bulk of the computation occurs in the GHE class, which is based off the work of Mitchell [2, 3, 5]. When given an inlet temperature and a flow rate, the model's first step is to calculate the GHE load using the HP. If the model is being run with GHE loads directly, this step is skipped (Eq. 3). Next, the model sums the g-function values and the load deltas from all previous loops of the model in the current execution (Eq. 4). This summation occurs with the g-functions being reversely indexed in comparison to the load deltas and is calculated each timestep of the loop. Using the summation value, the cross temperature and bore hole temperature rise are found and are used to find the MFT (Eq. 5,6,7). Lastly, the outlet temperature is calculated from the MFT (Eq. 8). These steps can be seen in Figure 2.

For simulating the effect of multiple bore fields in proximity an external cross temperature rise is added to the borehole temperature. The cross temperature rise is the same calculation as the summation except cross g-functions are used (Eq. 4). This value is multiplied by a scalar to produce the cross temperature rise. The model is constructed twice in the scenario with bore fields A and B, once for each bore field. When A is simulated, it will return the temperature rise of B because of A in addition to the outlet temperature of the A. This rise will be input into the simulation for B and be used to calculate the borehole temperature. This is convenient because the complex interactions with regards to field orientation, geometry, and thermal properties are contained in the g-functions. This allows the model to run quickly and without complications.

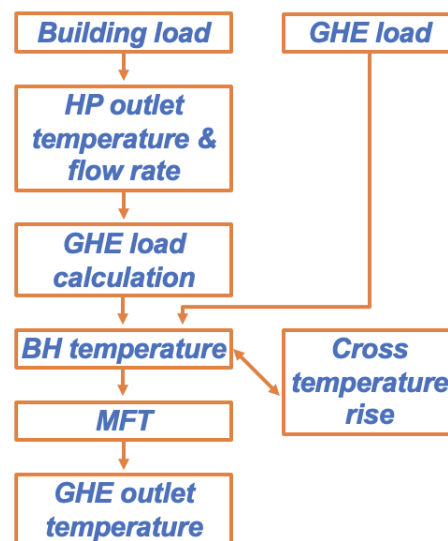


Figure 2. PCM operational flowchart for a single time step

Portability was inherent in the design of this model as it was created within the PCM framework. The HP, GHE, and pump as separate classes allows for the system to be easily integrated into different models that might contain separate versions of a HP or a fluid pump. The GHE can be simulated for a single time step or looped in an external function. Additionally, our model is written in C++, which allows for easy implementation into a variety of software running in different languages. All of these give the model it's portability. An added benefit is that the runtime is extremely fast. On a personal laptop, the multi bore field model simulated for 8760 time steps had a runtime of less than 2 seconds.

III. MODEL PERFORMANCE

Our model was compared against both GLHEPro and GHESim with a monthly oscillating square wave load of ± 1000 W (hourly resolution). We tested the model with this load in two ways. The load was passed as input into the HP for testing Tout calculations (HP Loaded). The load was also passed directly to the GHE for testing MFT calculations (GHE Loaded). In the GHE loaded case, this cut out Equation 2 and 3 from the process and allowed us to test the model without the added HP component. We compared the two load types for a single GHE configuration as well as a multiple GHE configuration, the latter of which accounted for cross effects between the two bore fields.

A. Single bore field (SBF)

We compared the GHE loaded SBF configuration directly to the GHESim MFT value. The load passed to our model was augmented by Eq. 10 to match internal manipulations by GHESim. This load was passed directly to the GHE bypassing the HP class. We found that for all time steps, our MFT values were within 1% error of GHESim, and the MFT profile over the simulated year was preserved (Fig. 3).

We found our HP loaded model matched within 1% error of the GLHEPro GHE outlet temperature (Tout) for 8348 time steps (Fig. 4). Additionally, our model retained the load profile of Tout over the entire simulated year. The time steps where the error was greater than 1% corresponded to the load switching from heating to cooling or vice versa (Fig. 5). We determined that this error was most likely due to the input g-function. These contained negative values on short time scales, which represents non-physical behavior and an error in the calculation of those g-functions. The HP loaded simulation uses information from previous iterations of the loop, causing the errors from g-functions to be magnified after many iterations. This is not a feature of the GHE directly loaded simulation, in which no information is passed from run to run.

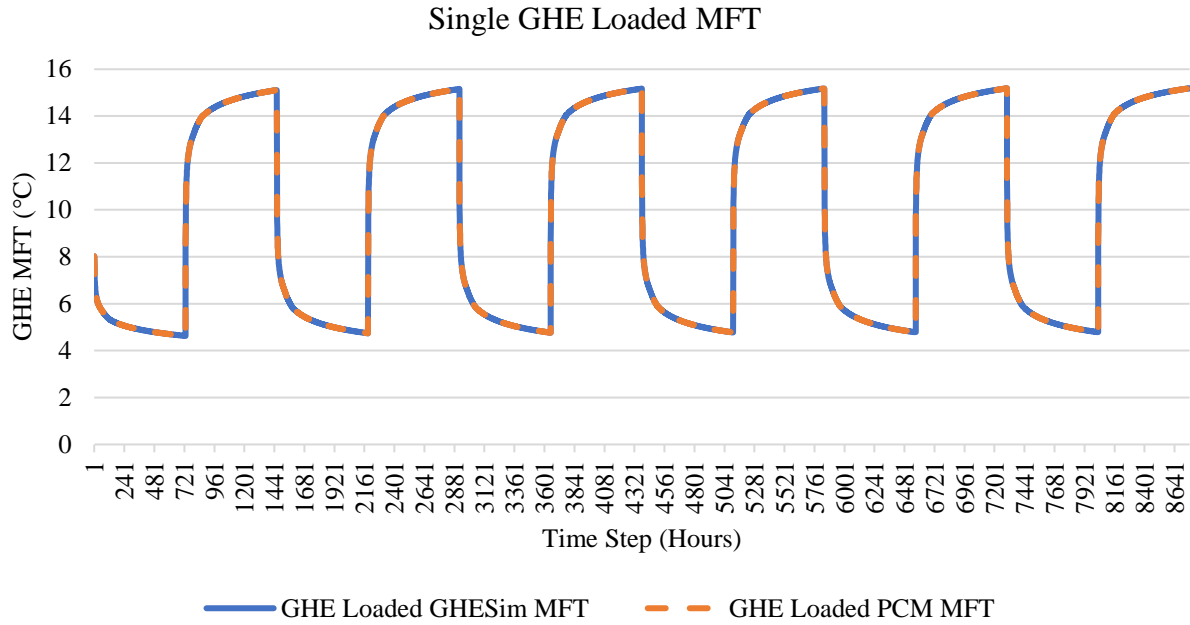


Figure 3. MFT comparison for a single bore hole with a directly loaded GHE

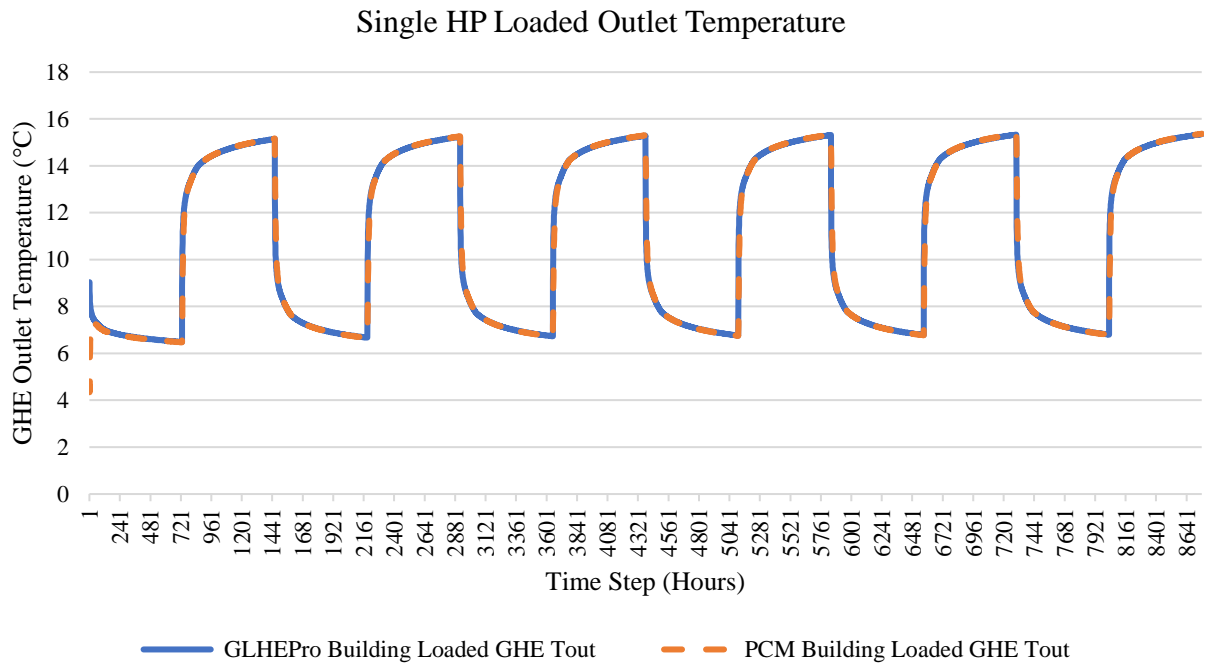


Figure 4. Tout comparison for a single bore hole with a load passed through the HP

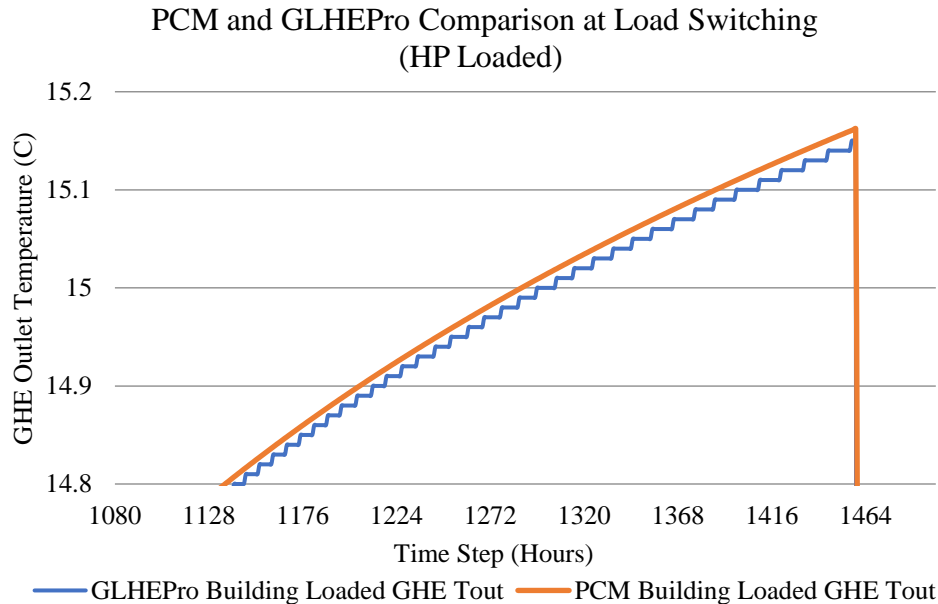


Figure 5. PCM and GLHEPro Tout at load switching demonstrating minor errors

B. Multiple Bore fields (MBF)

We tested the MBF HP loaded case by comparing to the already validated SBF HP model. GLHEPro was not used because the cross effects of multiple bore fields are not a current capability of the software. Instead, we used the g-functions from Mitchell [3] (Fig. 1). We created the dataset A-B, which contained the self and cross g functions for bore field A and bore field B. We extracted dataset C from Mitchell et. al, which was the combination of g-functions A and B [3]. A and B were simulated by the MBF model, while C was simulated by the SBF model. This allowed us to compare our multiple HP loaded bore fields to a simulation run with our PCM single configuration, which had already been verified.

We compared the A-B Tout to the Tout of C for the HP loaded case. We found that for all time steps, the A-B Tout values were within 1% error the C Tout. A-B preserved the load profile of C over the entire simulated year. Near the end of the simulation, the error between A-B and C began to grow. This discrepancy can be attributed to the approximate nature of our g-function data extraction method. Fig. 6 and Fig. 7 show that the curves are not completely smooth. This is due to the approximate nature of our g-function extraction. These errors over long time scales were amplified and led to the small increase in error near the end of the simulation (Fig. 7).

For the directly loaded GHE case, we compared our model to the MFT from GHESim because GHESim has MBF simulation capability. The load we provided the model was augmented by Eq. 10 and divided by two, to account for the fact that there were two simulated bore fields. Eq. 10 was used to match the internal load manipulation of GHESim. We found that for all time steps, our MFT values were within 1% error of GHESim values, and the MFT profile over the simulated year was preserved.

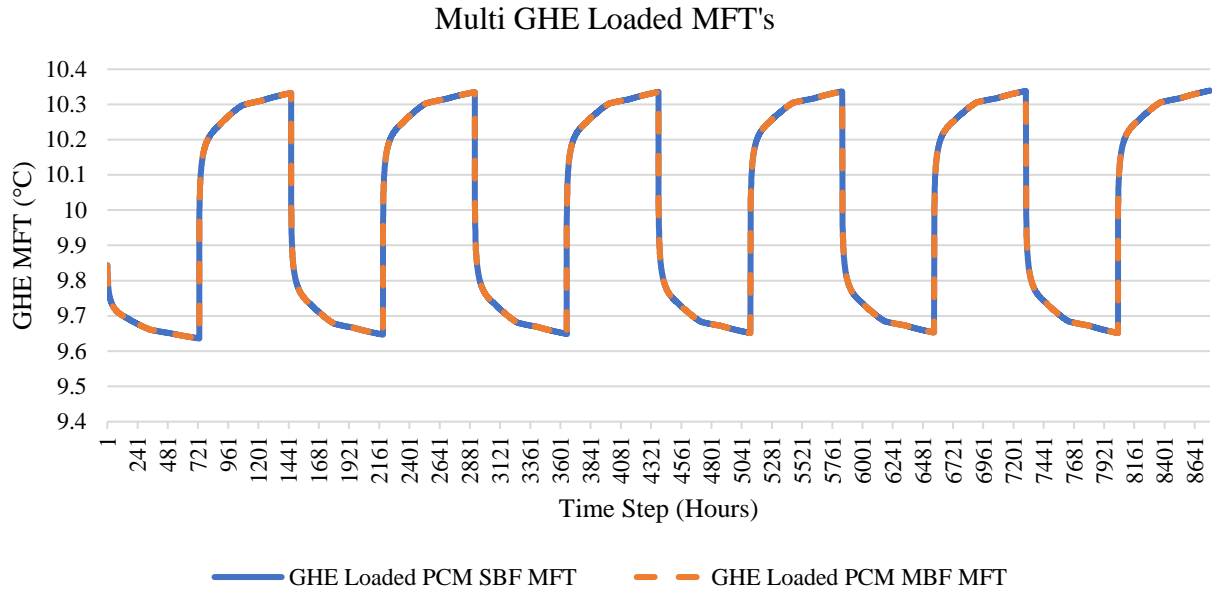


Figure 6. MFT comparison for a multiple bore hole system with a directly loaded GHE

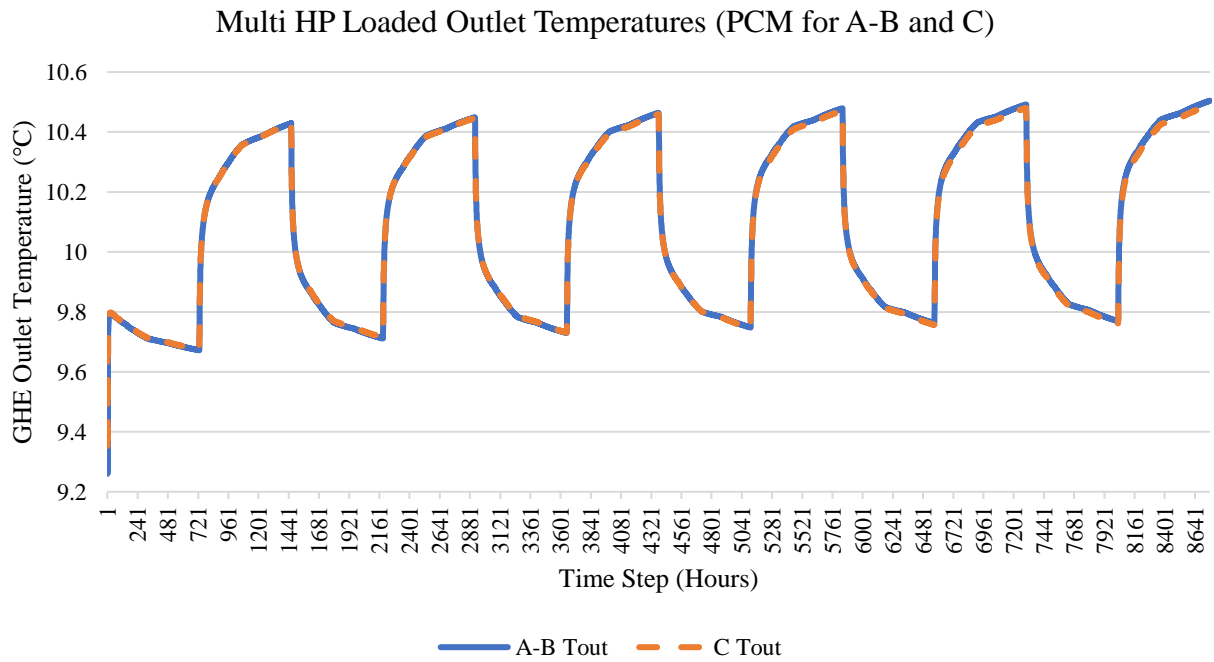


Figure 7. Tout comparison for a multiple bore hole system with a load passed through the HP

IV. CONCLUSION & FUTURE IMPROVEMENTS

A. Summary and Applications

Our model uses a time responsive g-function and numerical methods to simulate ground source heat pumps for single time steps. This functionality can be looped to simulate long time scales. The model can accommodate both single and multiple bore fields. We validated our model for the SBF configuration against GHESim and GLHEPro and found minimal and acceptable errors at load switching when compared to GLHEPro and no errors when compared to GHESim. For validation of the MBF configuration, we compared to GHESim and our already validated model. There was less than 1% error when compared to both GHESim and the SBF PCM configuration.

Our model will allow further development of the PCM framework by acting as a test case. Errors that do occur during the shell development process can be quickly resolved, ensuring that the framework is accurate once it is completed. Additionally, further development of this model would allow it to function as a high speed standalone model for research purposes.

B. Improvements

The next step for further development of this model is to add the capability to handle non-uniform time steps when run in an external loop. This capability would make the model like those in software such as EnergyPlus or the Modelica Buildings Library, where it is common for time steps to be non-uniform. Implementing this functionality would also add the ability to calculate g-functions, which would be a major requirement for non-uniform time step modeling. Including the ability to calculate g-functions would additionally alleviate the reliance on external software to pre-compute. This would reduce the overall error of the system, but it would come at the cost of computational resources.

V. APPENDICES

Appendix A: Nomenclature

GHE - Ground Heat Exchanger
HP – Heat Pump
MFT - Mean Fluid Temperature
PCM - Portable Component Model
LNTTS - Natural log of the non-dimensionalized time
SBF - Single bore field configuration
MBF - Multi bore field configuration
Tout - GHE outlet temperature

Appendix B: Equations

1) LNTTS

$$a. \quad t_s = \frac{H^2}{9 * \frac{k_s}{rho * cp}}$$

$$b. \quad lntts = \ln t/t_s$$

2) HP quadratic and outlet temperature

$$a. \quad q_{hp} = q_b * (x_1 + x_2 * T_{in, hp} + x_3 * T_{in, hp}^2)$$

$$b. \quad T_{out, hp} = T_{in, hp} - \frac{q_{hp}}{flowrate * cp}$$

3) GHE Load Calculation

$$q = \frac{T_{in, ghe} - T_s + c_0 * ((q_{n-1} * g_n) - c_1)}{\left(0.5 * \frac{H}{flowrate * cp}\right) + (g_n * c_0) + R_b}$$

4) GHE C₁ summation (indicate the reverse indexing of the two lists)

$$c_1 = \sum_{i=1}^{n-1} g_{n-1-i} * (q_i - q_{i-1})$$

5) Cross and self bore hole temperature rise and definition of c₀

$$a. \quad c_0 = \frac{1}{2 * \pi * k_s}$$

$$b. \quad T_r = c_0 * (c_1 + g_0 * q_n)$$

6) Bore hole temperature

$$T_{bh} = T_s + T_{r, self} + T_{r, cross}$$

7) GHE MFT

$$MFT = (q_n * R_b) + T_{bh}$$

8) GHE Tout

$$T_{out, ghe} = MFT - 0.5 * \left(\frac{q_n * H}{flowrate * cp}\right)$$

9) Load augmentation for matching GHESim load manipulation for MBF

$$q_{new} = - \frac{q_n}{H * \# \text{ of boreholes}}$$

VI. REFERENCES

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