Validation and Evaluation of a Modelica-based Ground Heat Exchanger (GHE) Model

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Abstract

This paper presents a simulation-based study focusing on evaluations of the performance of a Modelica-based ground heat exchanger (GHE) model. A performance analysis was conducted on two GHE models: (1) a Pre-calculated g-function model used in EnergyPlus and (2) a Modelica-based thermal resistance and capacity (TRC) model. A data set from an in-situ thermal response test (TRT) of the GHE was used to validate and evaluate these two models. The performance comparison of two GHE models with measurements are discussed in terms of the inlet/outlet temperature of the circulating fluid and the heat transfer rate to the ground. The results indicate that the Modelica-based TRC model performs better in predicting the fluid temperatures than the g-function based GHE model in EnergyPlus, especially during the transient heat transfer process.

Keywords: ground heat exchanger, thermal response test, g-function model, thermal resistance and capacity model, Modelica

1 Introduction

As one of the most efficient Heating, Ventilation and Air-conditioning (HVAC) system on the market, the ground source heat pump (GSHP) system has been proven to be the most efficient system, which helps to reduce the energy use in the building (DOE 2009). However, the high initial cost of the GSHP system is a major barrier limiting a wider adoption of the GSHP system in the United States. To be exact, the installation cost of the GHE eliminates the adoption of the GSHP system. Kavanaugh performed a survey-based study which collected the feedback from 23 building owners. The result indicated that the cost of ground loop portion was roughly 26% of the total GSHP project cost (Kavanaugh et al. 2012). Properly sized ground loop helps to reduce the installation cost of the GHE, which pushes the adoption of the GSHP system.

The ground heat exchanger model currently available in EnergyPlus, a whole building simulation program, is based on pre-calculated g-function data, which was originally developed by Eskilson and Claesson (Eskilson and Claesson 1988) and later was expanded by Spitler (Spitler 2016). Since the g-function data (both for short- and long-term simulation) is proprietary and need to be generated with another commercial GHE design software, the usage of this GHE model is severely limited. Furthermore, the current GHE model uses an empirical correlation to calculate the steady state borehole thermal resistance and thus neglects the thermal capacity of the fluid, pipe, and grout in the borehole. As a result, the transient heat transfer performance of a GHE during a typical operation of a GHSP system cannot be accurately simulated.

A new GHE model has been implemented in Modelica, which is a non-proprietary, object-oriented, equation-based simulation platform to model complex physical system. The new GHE model of Modelica uses equivalent thermal resistance and capacity (TRC) to model the transient heat transfer of a GHE (Bauer et al. 2011). It does not rely on the pre-calculated g-functions and thus could be used to simulate a GHE with any given design parameters. This new model can enable auto-sizing of a GHE based on heat transfer loads and desired fluid temperature delivered by the GHE.

In this study, computer simulations of a vertical bore closed-loop GHE were performed with the two GHE models, respectively; and the simulation results were compared against the measured data from an in-situ thermal response test (TRT) of the GHE. The methodology, results, and conclusion of this validation and evaluation exercise are presented below.

1.1 Ground Source Heat Pump (GSHP)

Compared to the conventional air-source heat pump, the GSHP utilizes the earth (i.e., soil or ground water) as the heat source/sink. By utilizing the relative constant ground temperature over the year, the GSHP system is about 45% more efficient than conventional air-source heat pumps (EPA 2019).

In general, open-loop system, closed-loop system, and semi-open-loop system are three most common designs for the GSHP system. According to Huttrer (Huttrer 1997), an open-loop system uses the groundwater directly. The groundwater passes through the heat pump unit and is discharged back to the source. In a closed-loop system, the water or the water-antifreeze solution circulates in a continuous buried pipe, which acts as a ground heat exchanger between the ground source and the circulating fluid. Compared to the closed-loop system, an open-loop system is inexpensive and efficient; however, additional maintenance is required to prevent fouling of loops by organic matter, etc. In addition, discharge of water from an open loop system to a surface waterbody may require a permit. In the U.S., Environmental Protection Agency requires reporting any injection of the water to a return well for groundwater heat pump systems. The vertical bore GHE is categorized into the closed-loop design, and it is the focus of this study.

1.2 Modeling of GHE with Modelica

As the mathematical modeling and simulation became the key factors in engineering, computational tools were developed to satisfy the needs of efficient engineering. Modelica-based models (Modelica 2018) complied with Dymola (DYMOLA 2019) are used in this study. Modelica is an equation-based and object-oriented modeling language for complex multi-physics systems. The use of Modelica for the built environment is promising as buildings involve multiple physical phenomena (e.g., heat transfer, fluid dynamics, electricity, etc.) and are complex in terms of their dynamics (e.g., the coupling of continuous time physics with discrete time and discrete event control). In addition, the problem size can be varied from equipment to buildings and communities with electrical distribution grids. An advantage of Modelica is the modularity of the language that allows modification of the code according to the specific needs of the application. The object-orientation enables extension and reuse of components, and the use of standardized interfaces enables collaboration across physical domains and disparate developer groups. Modelica has been used to model the complex physical system, e.g., mechanical, electrical, electronic, hydraulic, thermal, control, electric power systems or process-oriented subcomponents (Modelica 2018).

The Modelica-based GHE model uses the equivalent thermal resistance and capacity (TRC) to model the transient heat transfer of a GHE (Bauer et al. 2011). The borehole model was vertically discretized into n-segment, and each segment contains a sub-model for the heat transfer between the borehole itself, surrounding soil, and far-field boundary condition. In the TRC model, parameters include the heat transfer between two pipes, fluid velocity, heat resistance between the pipes, and borehole size are taking into account when calculating the convective heat transfer coefficient. In addition, the heat capacity of the fluid and grouting material are be considered in the TRC model (Wetter et al. 2014).

2 Methodology

2.1 Thermal Response Test (TRT)

A formation thermal conductivity test was performed at Webber State University in Ogden, Utah. The vertical borehole was completed in November 2013, and the test was performed in December 2013. The in-situ data was used to validate both g-function model and TRC model in this study. Figure 1 shows the schematic diagram of the TRT, and the simulation models will follow the same design of the TRT.

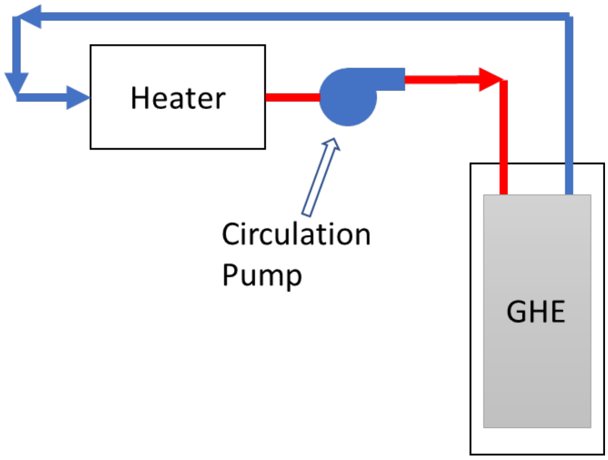

Figure 1. Schematic diagram of the TRT

2.2 Modelcia Simulation

The vertical bore closed-loop GHE was modeled with both the g-function based model in EnergyPlus) and the Modelica-based TRC model. The parameters needed to model the GHE are slightly different between the two models, as shown in Table 1. Some of these parameters are obtained from the TRT report, and the rest are from two sources: (1) manufacturer's specifications of a particular component (e.g., pipe and grout); and (2) typical values of certain parameters, such as the density of the soil in a given region. Figure 2 shows the TRT system model with the vertical bore closed-loop GHE in Dymola.

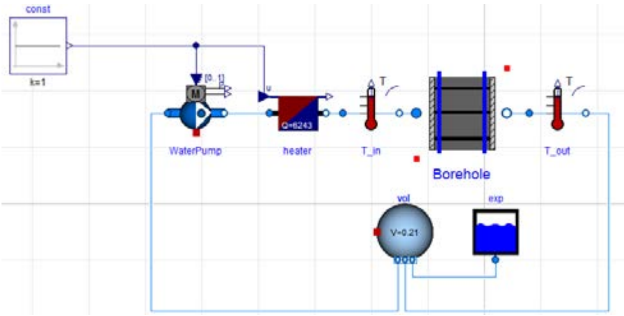

Figure 2. The TRT system model with GHE in Dymoloa

The accuracy of the simulation results, including inlet/outlet fluid temperature and the heat transfer rate of the GHE, is evaluated with the relative error (RE) between the simulation results and the measured data, as expressed in Equation 1:

$$RE\ (\%) = \frac{R_{model} - R_{actual}}{R_{actual}} \times 100\% \qquad (1)$$

Where, R_{model} is the model predicted result, R_{actual} is the measured in-situ TRT result.

The heat transfer rate to the ground ($\dot{q}_{GHX}$) is calculated as follows:

$$\dot{q}_{GHX} = \dot{m}_{fluid} \times C_{p_{fluid}} \times (T_{out} - T_{in}) \qquad (2)$$

Where $\dot{m}_{fluid}$ is the mass flow rate of the fluid; $C_{p_{fluid}}$ is the specific heat of the fluid; T_{out} and T_{in} are the leaving and entering fluid temperature of the GHE.

3 Result and Discussions

Figure 3 and 4 compares the measured data and simulation results of the two models for entering and leaving fluid temperature, as well as the heat transfer rate of the GHE. The relative differences between the measured data and that predicted by the Modelica model are -0.3~-0.1% for T_{in}; 0.9% for T_{out}; and 10~12% for $\dot{q}_{GHX}$. However, the relative differences of the simulation results of the g-function model overpredict T_{in} and T_{out} by 10~12%, but the relative error of $\dot{q}_{GHX}$ is smaller (7%) than that of the Modelica-based TRC model. These figures clearly show that the transient heat transfer performance during the first 10-15 hours of the TRT from the Modelica-based TRC model closely matches the measured data. In a contract, the transient heat transfer is predicted by the g-function model in EnergyPlus as a nearly step change.

A further investigation was performed to find out why the heat transfer rate to the ground predicted by the Modelica model is about 10% less than the heat input, which was measured at the electric heater of the test rig of the TRT. A sensitivity analysis was conducted by adjusting the flow rate of the heat carrier fluid in the GHE by +/-10% of the reported value. Then, resulting relative errors of the predicted heat transfer rate were compared. As shown in Figure 5, while the reported flow rate results in approximately 10% relative error, a 10% reduced flow rate almost completely eliminate the error, but a 10% increased flow rate results bigger error. It indicates that the difference between the Modelica-based TRC model predicted heat transfer rate to the ground and the measured heat input is very sensitive to the flow rate. In the transient heat transfer process of a TRT, the heat transfer rate to the ground is not exactly the heat input from the electric heater. Some of the heat input is absorbed by the heat carrier fluid to raise its temperature. At a lower flow rate, less heat is needed to raise the fluid temperature and thus the heat transfer rate to the ground is closer to the heat input.

4 Conclusions

The results of this validation indicate that the Modelica-based TRC model performs better in predicting the fluid temperatures than the g-function based GHE model in EnergyPlus, especially during the transient heat transfer process. Although the heat transfer rate predicted by the EnergyPlus model appears to be closer to the measured heat input than that predicted by the Modelica-based TRC model, it is believed that the heat transfer rate predicted by the Modelica-based TRC model is more accurate since it accounts for the heat absorbed by the heat carrier fluid in the GHE during the transient heat transfer process, which results in the difference between the heat input and the heat transfer rate to the ground.

The more accurate prediction of the transient heat transfer performance of a GHE is desirable because it can result in more accurate prediction of the energy consumption of a ground source heat pump system, which is often turned on and off in for short time periods on a daily basis to meet the fluctuating thermal loads.

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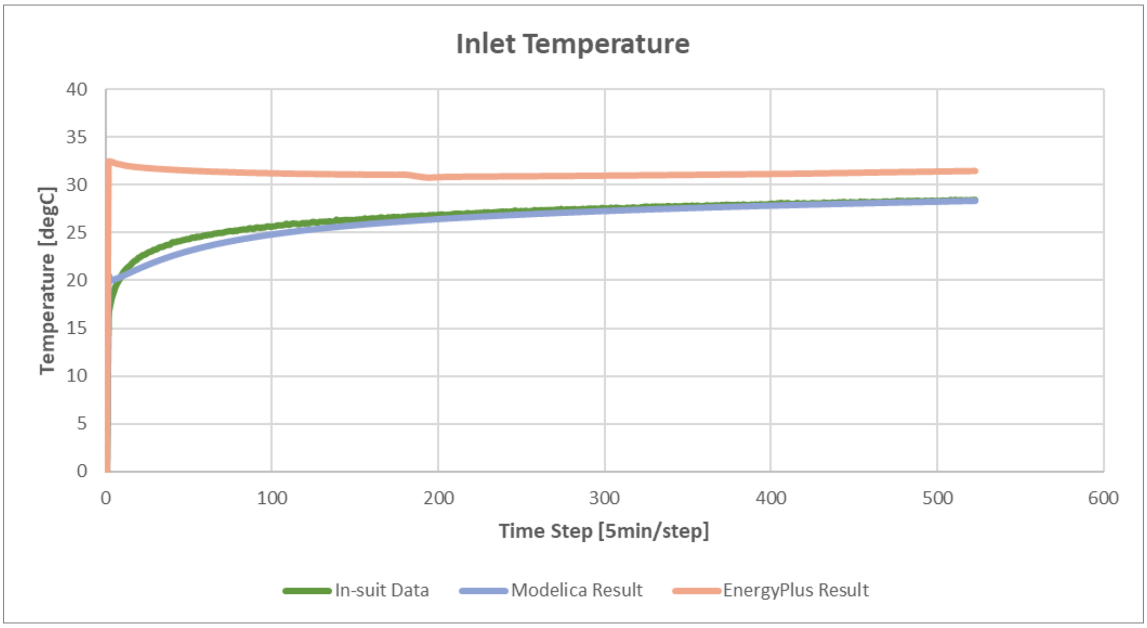
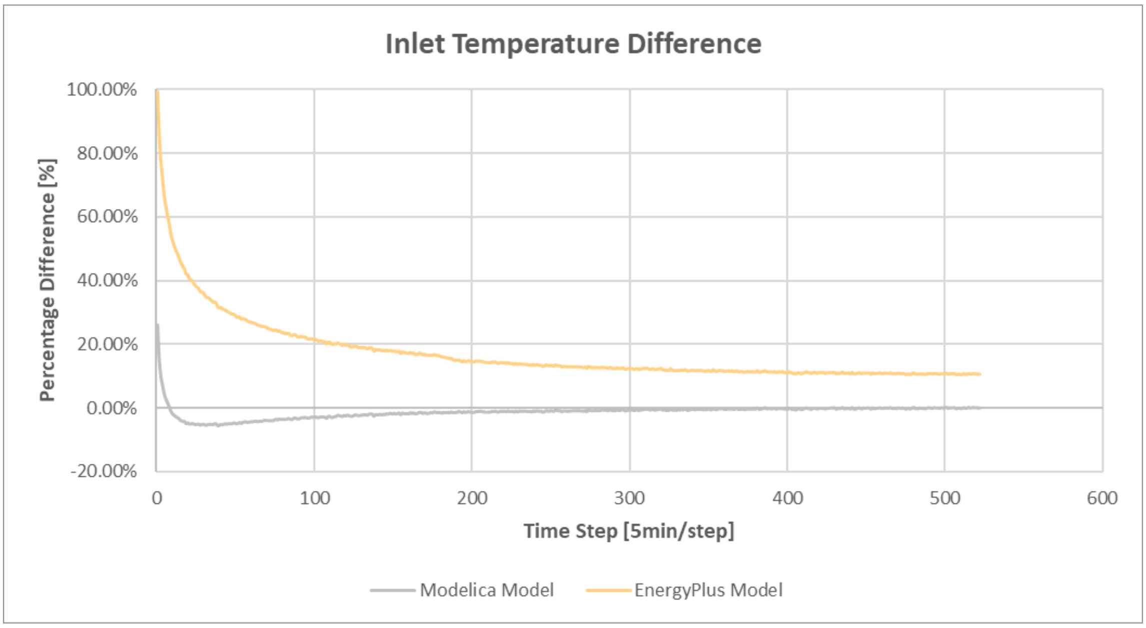
Table 1. Parameters of the simulated GHE

GHE Parameters				
Sources	*Parameter*	*Measured*	*TRC Model*	*g-function Model*
In-situ thermal response test report	Number of Boreholes	1	1	1
	Borehole length [m]	103.022	103.022	103.022
	Borehole diameter [m]	0.13335	0.13335	0.13335
	mdot_fluid [kg/s]	0.6372	0.6372	/
	Vdot_fluid [m^3/s]	/*	/	0.000637211
	Q_input [kW]	6243	6243	6243**
	Duration	43.5 hr	43.5 hr	43.5 hr
	Ground Temperature [degC]	13.33	13.33	~13
Manufacturer's specifications	U-Bend - Thinkness [m]	/	0.0038354	0.0038354
	U-Bend - I.D. [m]	/	0.034036	0.034036
	U-Bend - thermal heat capacity [J/m^3-K]	/	/	1823600
	k_U-Bend [W/m-K]	/	0.26	0.26
Typical values	k_grout [W/m-K]	/	1.2	1.2
	c_grout [J/kg-K]	/	840	/
	rho_grout [g/cm3]	/	2	/
	Grout thermal heat capacity [J/m^3-K]	/	/	1680000
	k_soil [W/m-K]	2.96	2.96	2.96
	c_soil [J/kg-K]	/	840	840
	rho_soil [g/cm^3]	/	2	2
	Shank space [m]	/	0.042	0.042
	Fluid Volume [m^3]	/	0.21	0.21

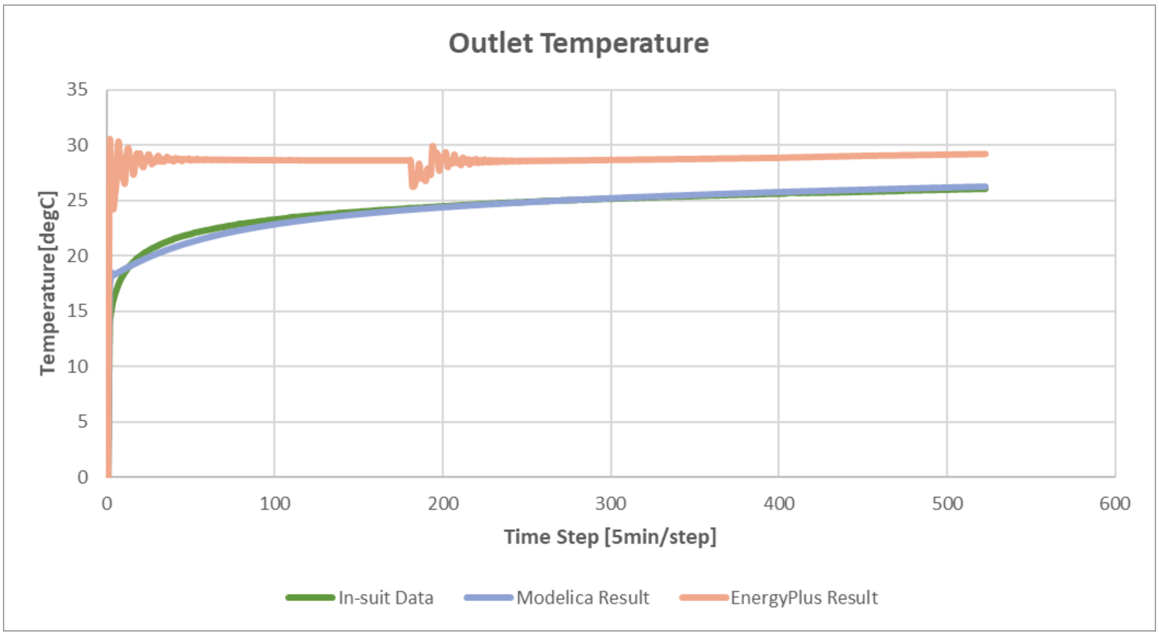
* "/" indicates a parameter that either not in the TRT report, or not required by the model
** It is the condensing heat of a water-air heat pump connected with the GHE



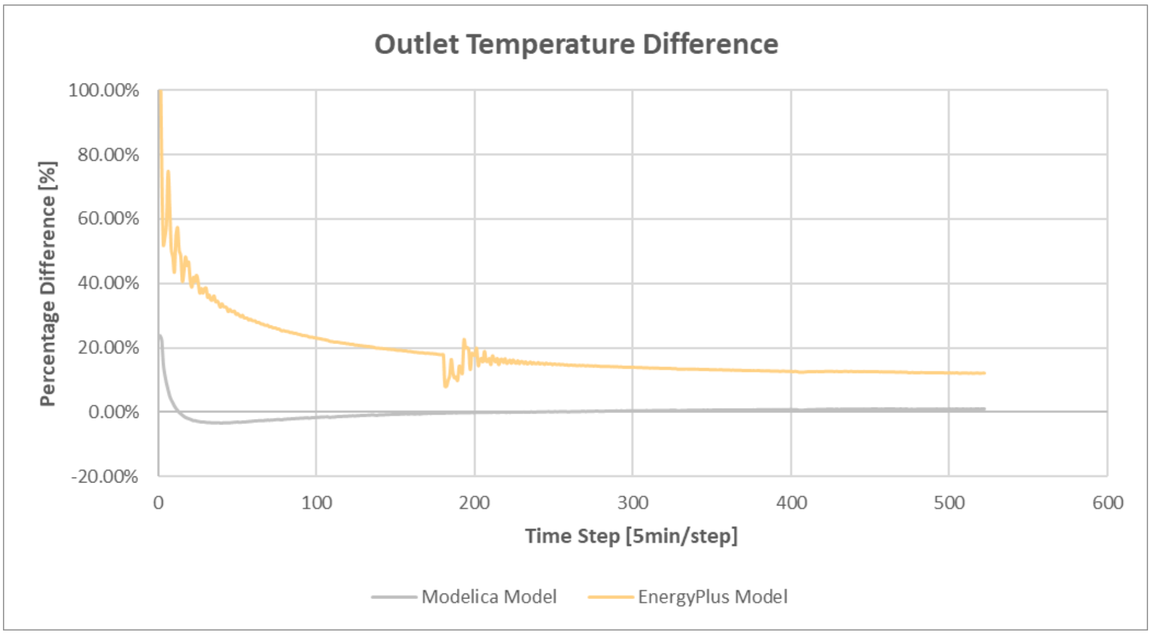
(a)


Inlet Temperature Difference
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-20.00%
Percentage Difference [%]
0
100
200
300
400
500
600
Time Step [5min/step]
Modelica Model
EnergyPlus Model

(b)

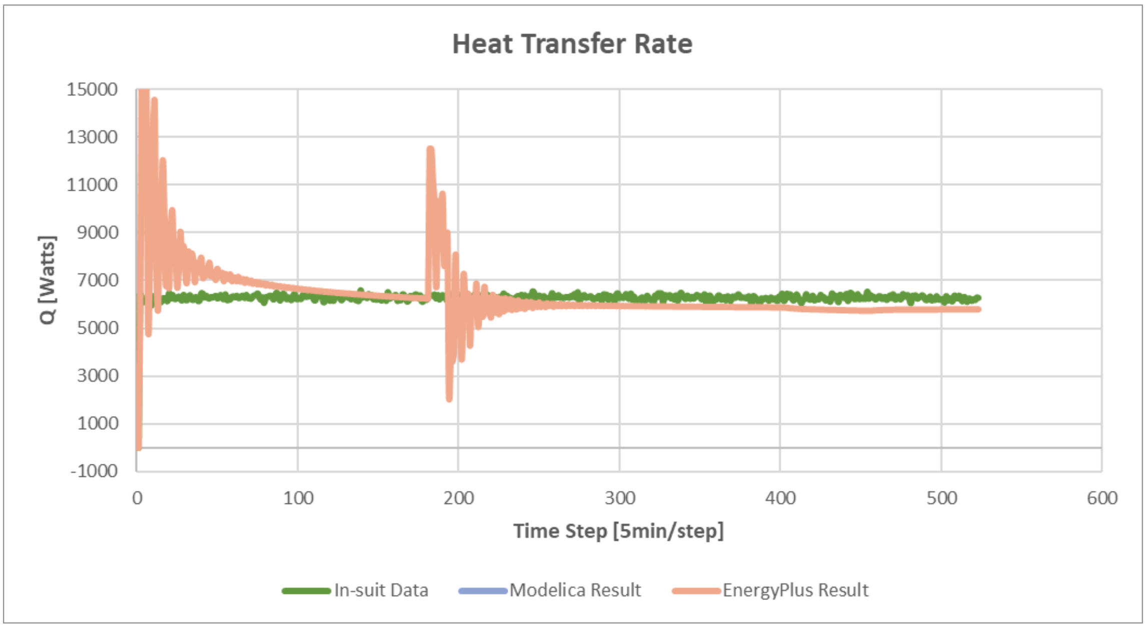

Outlet Temperature
35
30
25
20
15
10
5
0
Temperature[degC]
0
100
200
300
400
500
600
Time Step [5min/step]
In-suit Data
Modelica Result
EnergyPlus Result

(c)

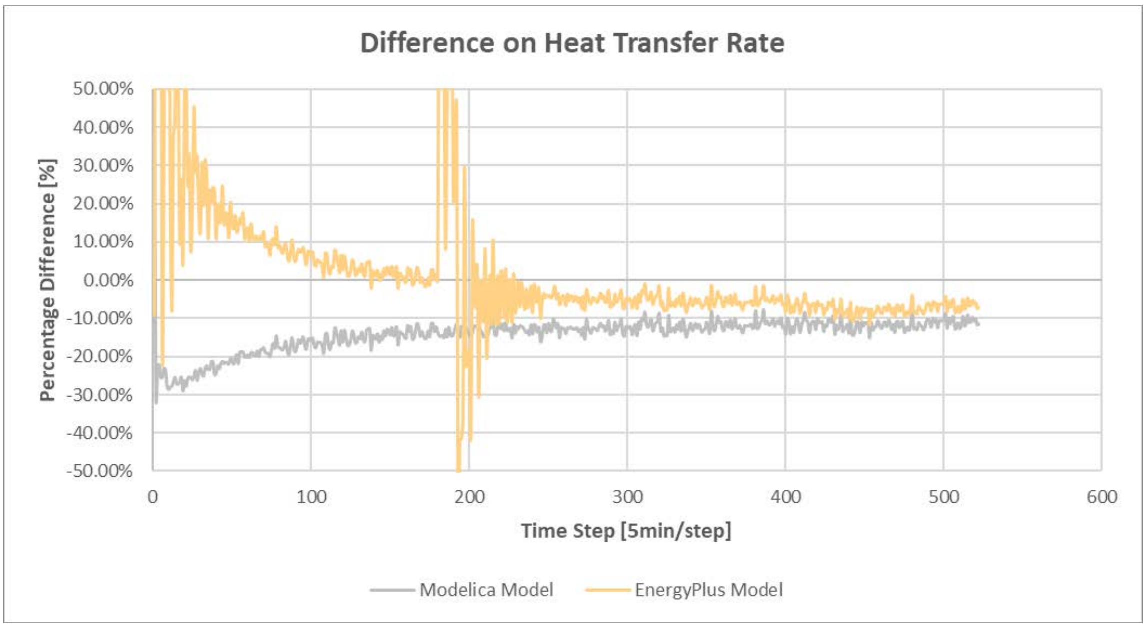


(d)

Figure 3. Comparisons of fluid temperatures of the GHE: (a) Inlet temperatures; (b) Percentage difference of inlet temperatures; (c) Outlet temperatures; (d) Percentage difference of outlet temperatures



(a)



(b)

Figure 4. Comparisons of heat transfer rate of the GHE: (a) Heat transfer rate; (b) Percentage difference of heat transfer rate

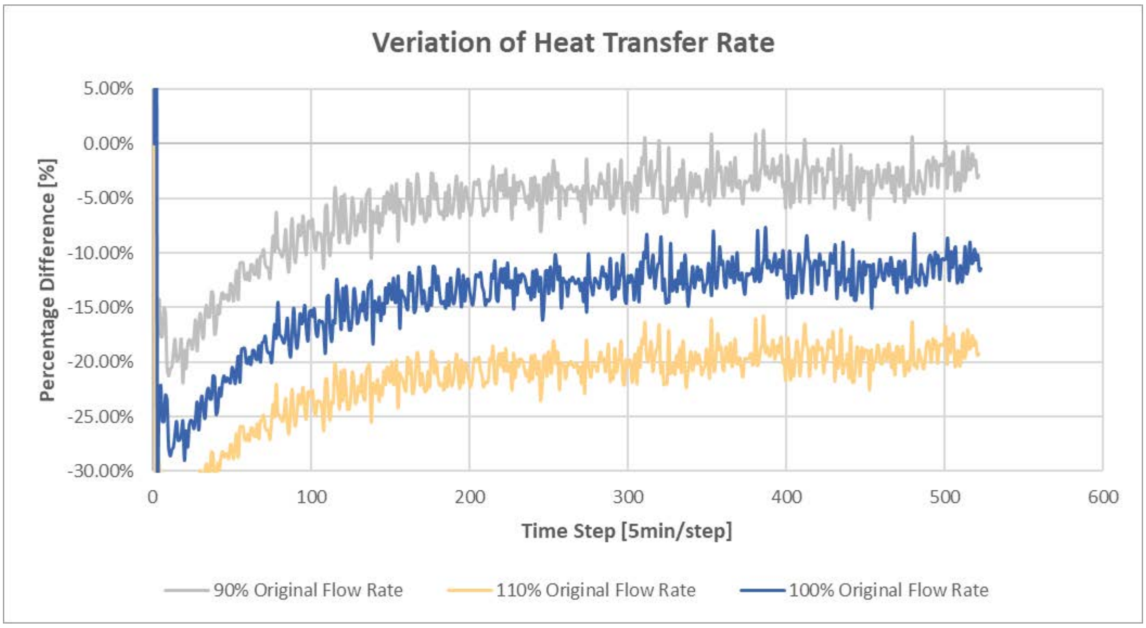


Figure 5. Relative errors of the heat transfer rate predicted by Modelica-based GHE model resulting from three different flow rates of the heat carrier fluid in the GHE