A Study of the Effect of Variation in Soil Thermal Conductivity on a Ground Source Heat Pump System

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Abstract

The impact of variation in the soil thermal conductivity on the performance of a ground source heat pump (GSHP) system is investigated using experimentally determined thermal conductivity data for three soil types: coarse sand, fine sandy loam, and loam. A transient system modelling software, TRNSYS, is used to model the GSHP system currently being utilized at the Kortright Centre in Vaughan, Ontario, Canada. The GSHP system is connected to a three-storey archetype sustainable house with a basement. The GSHP is connected to separate systems for cooling (via an air handling unit) and heating (via in-floor heating). The simulation is performed for one year (8760 hours), with soil thermal conductivity at three different moisture levels (complete dryness, field capacity and full saturation) for each soil type. The results show a reduction in heat pump electricity consumption with increasing soil thermal conductivity. In addition, a variation in the heat pump electricity consumption among the three soil types is observed, suggesting that the heat pump performance is dependent on soil type as well.

Keywords: soil thermal conductivity, ground source heat pump, TRNSYS

Résumé

On étudie les effets de la variation de conductivité thermique du sol sur les performances d’une thermopompe utilisant le sol comme source de chaleur (GSHP) au moyen de données expérimentales sur la conductivité thermique de trois types de sol : sable grossier, limon sableux fin et limon. Un logiciel de modélisation de système transitoire, TRNSYS, sert à modéliser le système de GSHP en cours d’utilisation au Kortright Centre à Vaughan, en Ontario, au Canada. Le système de GSHP est raccordé à une maison durable Typique de trois étages avec sous-sol. La GSHP est reliée à des systèmes séparés pour le refroidissement (par l’intermédiaire d’un appareil de ventilation) et le chauffage (plancher chauffant). La simulation se rapporte à une année (8 760 heures), la conductivité thermique de chaque type de sol étant considérée à trois niveaux d’humidité différents (dessiccation complète, capacité de rétention et saturation totale). Les résultats indiquent que la pompe à chaleur consomme de moins en moins d’électricité à mesure qu’augmente la conductivité thermique du sol. En outre, la consommation d’énergie électrique par la pompe à chaleur varie selon les trois types de sol, indiquant que les performances de la pompe dépendent également du type de sol.

Mots-clés : conductivité thermique du sol, thermopompe utilisant le sol comme source de chaleur, TRNSYS

1. Introduction

The thermal conductivities of three soil types were measured using a guarded hot plate apparatus (GHPA). The results were used to investigate their effect on an actual ground source heat pump (GSHP) system. Hence, a computer simulation model of the GSHP system was developed using TRNSYS. TRNSYS is a transient system simulation software which allows a heating, ventilating and air-conditioning (HVAC) system to be modelled together with a building model and simulated the dynamic interactions among all components in the system. The soil property investigated was soil thermal conductivity, which depends on soil water content and soil texture. The experimental data of soil thermal conductivity of a coarse sandy soil, a fine sandy loam soil, and a loam soil were implemented in the simulation to investigate the impact of variation in soil water content and soil type on the GSHP performance in terms of electricity consumption. The model was tested for one year (8760 hours) to be able to properly investigate the GSHP's performance throughout the year. The description and experimental procedure of the GHPA, as well as the GSHP system under investigation, are described in the following sections.

2. Description of the guarded hot plate apparatus

Figures 1 and 2 present the GHPA set-up [1] and a specimen container, respectively.

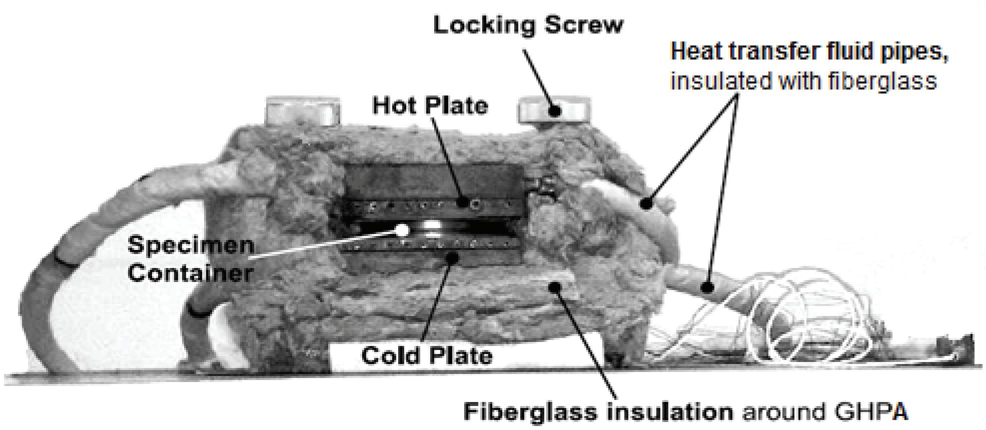
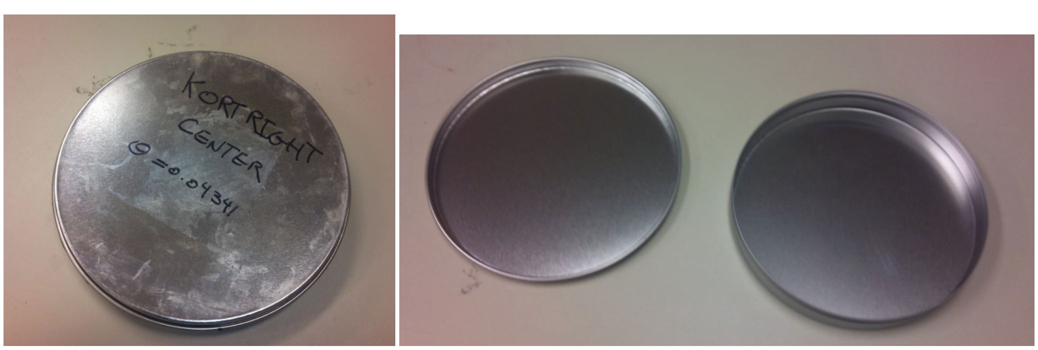


Figure 1. Guarded hot plate apparatus (GHPA) used to measure soil thermal conductivity [2].



(a) (b)

Figure 2. A specimen container: (a) closed and (b) open.

The hot and cold plates are 17.8 cm by 17.8 cm (7 in. by 7 in.) in dimensions. The hot plate is at the top and cold pate at the bottom, with a closed specimen container in between. The locking screws are used to move the hot plate up or down so that the specimen container can be removed easily or secured tightly between the hot and cold plates. The GHPA and heat transfer fluid pipes are insulated with fiberglass to minimize heat gain from or loss to the environment. Oil is used as the heat transfer fluid, since it does not evaporate easily at temperatures up to 100ºC.

3. Experimental procedure

First, soil samples with various water contents are prepared and packed into specimen containers according to the soil sample preparation techniques described in [2]. Then, a specimen container is placed inside the GHPA for measuring thermal conductivity of the soil sample. In between the specimen container and the hot/cold plate of the GHPA, a 0.5-mm thick silicon rubber pad (of known thermal conductivity) is inserted in order to provide better surface contact between the plates and the container. At the start of each test, the circulating baths are manually turned on and each bath's temperature is set to maintain a 4ºC temperature difference between the hot and cold plates. The baths are allowed approximately 30 minutes to warm up and stabilise. A data acquisition system and automation software are used at this point to observe temperature stabilization at both plates. Once the hot and cold plates' temperatures are stabilised, the data acquisition system is used to collect the data during the experiment. The automation software consists of two parts. First, the electrical power optimiser program is run to obtain the required electrical power supplied to the heater plate in order to equalize the temperature of the heater plate with the temperature of the guarded hot plate. Once the required electrical power is achieved, the second part of the program is run, which collects several data such as electrical power to the heater plate, hot and cold plate temperatures, and the heat-flux-sensor output. It was observed that in order to obtain enough data to cover the fluctuations in the system and ensure accurate results, the data collection time should be 1800 s, with a sampling rate of 1 Hz. In addition, data is collected three times for each temperature (from 5º°C to 92º°C with an increment of 10ºC) and averaged to increase the accuracy of the experimental data. The details of the experimental techniques and procedure can be obtained from [2,3].

4. Description of the GSHP under investigation

The HVAC system under investigation is installed at an experimental house, called the Archetype House B, which is located at the Kortright Centre in Vaughan, Ontario. The system is providing space heating and cooling for the three-storey residential house, with an attached guest suite. Since this is an experimental house, it is unoccupied throughout the year except at times when various researchers come to the house to work on the equipment. The house is equipped with all the appliances and includes all the internal loads of a normal house, such as washer/dryer, fully operational shower and lavatories, fully equipped kitchen with dish washer and fridge, as well as lighting system.

The HVAC system includes a GSHP which provides heating and cooling to the house, connected to a buffer tank in the basement and two horizontal-looped pipes buried in the yard area at 1.83 m (6 ft) under the ground. Heating is provided by in-floor heating at each floor and cooling is by a multi-zone air handling unit (AHU). The buffer tank is connected to both in-floor heating system and the AHU. During winter season, the GSHP provides hot water to the buffer tank, which is connected to the in-floor heating system, and during summer season the GSHP provides chilled water to the buffer tank, which is switched and connected to the AHU. An antifreeze solution is used as the heat transfer medium to allow the operation of the horizontal ground loops below 0ºC and extract heat from the freezing ground during winter season. Table 1 provides detailed specifications of this HVAC system.

Table 1. Detailed specifications of the HVAC equipment under investigation [4].

Equipment	**Technical Specification**
Buffer tank	270 liters (80 USG)
Ground source heat pump (GSHP)	a) Heating capacity : 13.3 kW[1] COP: 3.0 b) Cooling capacity: 12.66 kW[2] COP: 2.86 EER: 12.86 c) Number of horizontal ground loops: 2 d) Length of each loop: 152.4 m (500 ft) e) Depth of ground loops: 1.83 m (6 ft)
Air handling unit (AHU)	a) Maximum heating capacity: 28 kW (95 MBH)[3] b) Cooling capacity: 5.27-12.3 kW (1.5-3.5 tons) c) Nominal air flow rate: 660 L/s (1400 CFM)

Sensors have been installed throughout the house and within the HVAC system to monitor relevant loads and system performance throughout the year. To validate the developed model, results from the model have been compared to the actual data collected from the house. The collected data are from December 1 to 19, 2010 for heating and August 23 to September 14, 2010 for cooling.

5. Simulation details

In order to investigate the impact of soil thermal conductivity on the performance of the GSHP system, a transient simulation software, called TRNSYS, was used to model the house and its HVAC system described in section 4. Since the GSHP is connected to two different systems for

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1 At 0ºC (32°F) EWT, and flow rate of 1.04 L/s (16.5 GPM).
2 At 25ºC (77°F) EWT, and flow rate of 1.04 L/s (16.5 GPM).
3 At 82ºC (180°F) EWT.

house cooling (air handling unit) and heating (in-floor heating), two separate computer models were first developed, one for cooling and one for heating. Once calibrated, the two models were combined to develop one complete model to simulate the actual HVAC system, with simulation time step of one hour for one year (8760 hours). Figure 3 shows the complete HVAC model with all the components used in the TRNSYS model. Since the program screen was small, the overall screen was very dense; as the result, three relevant sections have been snipped and enlarged as presented in Figure 4. Table 2 provides the descriptions of the major components in Figure 4.

To ensure an accurate model, actual data collected from the GSHP, such as heating and cooling performance curves [5], are used to develop the computer model. Results from computer simulation are compared to the actual data and the model is calibrated. Also, to ensure simulated results are as realistic as possible, the ground temperature component (Table 2) is used within the model to obtain the average ground temperature, at a depth of 1.83 m (6 ft) and over 8760 hours, and the soil thermal conductivity data of the three soil types closest to the average ground temperature are used for three levels of soil water content (complete dryness, field capacity, and full saturation).

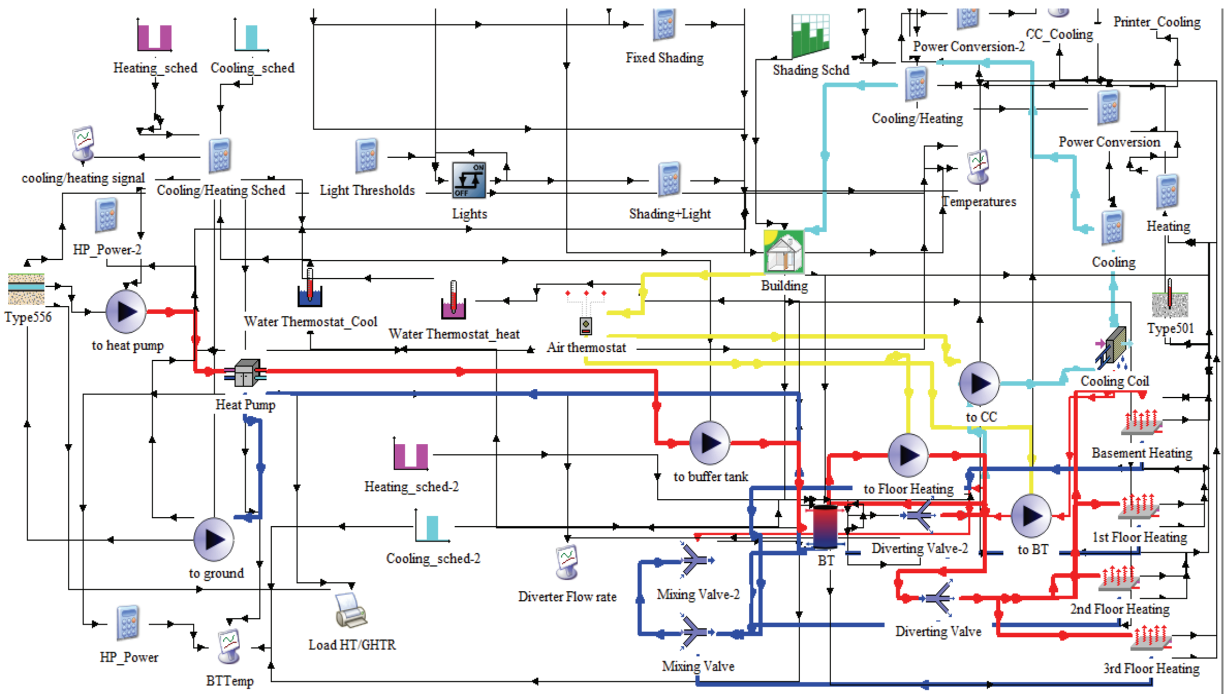
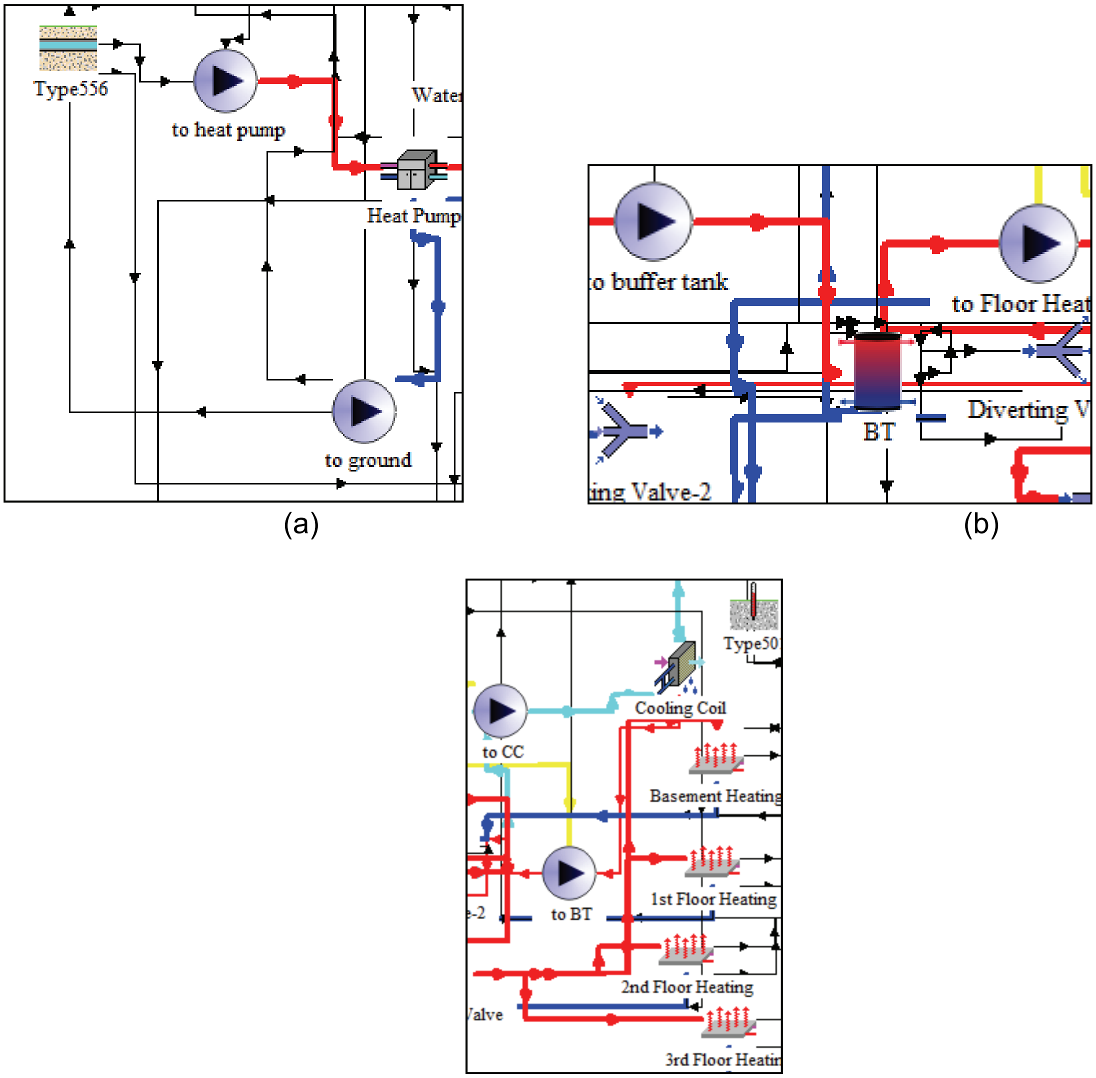


Figure 3. An overview of the TRNSYS model of the HVAC system.



(C)

Figure 4. Three major sections of the HVAC system as modeled in TRNSYS. a) Heat pump-to-ground, b) Heat pump-to-buffer tank, and c) Buffer tank-to-AHU/in-floor heating.

The parameters that affect the soil thermal conductivity are soil type and water content. Since the buried horizontal pipe component (Type556) does not currently consider soil water content and soil type in its calculations, the soil thermal conductivity was changed within the component to account for these two parameters in the analysis. Hence, the simulation was performed nine times, i.e., at three different soil types and three different soil moisture levels, as presented in Tables 3 through 5 for a coarse sandy, a fine sandy loam and a loam soil, respectively.

Table 2. TRNSYS component description.

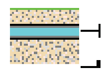
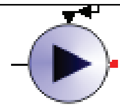
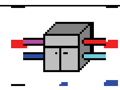
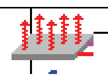
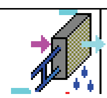
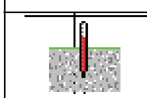
Component	Description
 Type556	Buried horizontal pipe component
	Circulation pump component
	Ground source heat pump (GSHP) component
	Buffer tank component
	In-floor heating component
	Air handling unit (AHU) component
 Type501	Ground temperature component

Table 3. Simulated data for a coarse sandy soil [2].

Volumetric Water content, *θ* [m^3/m^3]	**Thermal Conductivity [W/m·K] (% change w.r.t. dry state)**
0	0.338
0.183 (FC)[4]	1.806 (434)
0.366 (FS)[5]	3.329 (885)

Table 4. Simulated data for a fine sandy loam soil [2].

Volumetric Water content, *θ* [m^3/m^3]	**Thermal Conductivity [W/m·K] (% change w.r.t. dry state)**
0	0.223
0.2684 (FC)	0.665 (198)
0.571 (FS)	1.318 (491)

[4] Field Capacity
[5] Full Saturation

Table 5. Simulated data for a loam soil [3].

Volumetric Water content, θ [m^3/m^3]	Thermal Conductivity [W/m·K] (% change w.r.t. dry state)
0	0.253
0.260 (FC)	0.883 (249)
0.520 (FS)	1.495 (491)

For comparison purposes, cooling degree day (CDD) and heating degree day (HDD) from the same periods were extracted from the weather data of the typical meteorological year (TMY) in TRNSYS as well as the actual data from Environment Canada [6]. The base temperature is selected as 18ºC for CDD and HDD, based on Environment Canada [6]. Table 6 shows the percent differences between the two data sets.

Table 6. Total CDD and HDD for the actual and simulated data.

Total	Environment Canada Data	TMY Data	Difference [%]
CDD	58.9	36.7	38%
HDD	436.4	372.5	15%

As shown in Table 6, there are 38-percent and 15-percent differences between the actual and TMY CDD and HDD data sets respectively. The operation of a heat pump is directly related to the outdoor temperature; the lower the outdoor temperature, the higher the heating load and vice versa. Hence, the heat pump must come on more often to meet the required heating or cooling demand. As the result, based on the data provided in Table 6, it would be expected for the GSHP system modeled in TRNSYS to operate less frequently and consume less electricity by 38 percent, compared to actual performance during summer season. Similarly, it would be expected for the GSHP system to operate less frequently and consume less electricity by about 15 percent, during the winter season.

6. TRNSYS simulation results and discussion

Figures 5 and 6 present the comparison between the actual heat pump electricity consumption, obtained from the Archetype House B [5], and the simulated results from TRNSYS based on loam soil at field capacity conditions, for cooling and heating seasons, respectively. The loam soil sample from the yard of the Archetype House B was used to obtain the experimental thermal conductivity data [3].

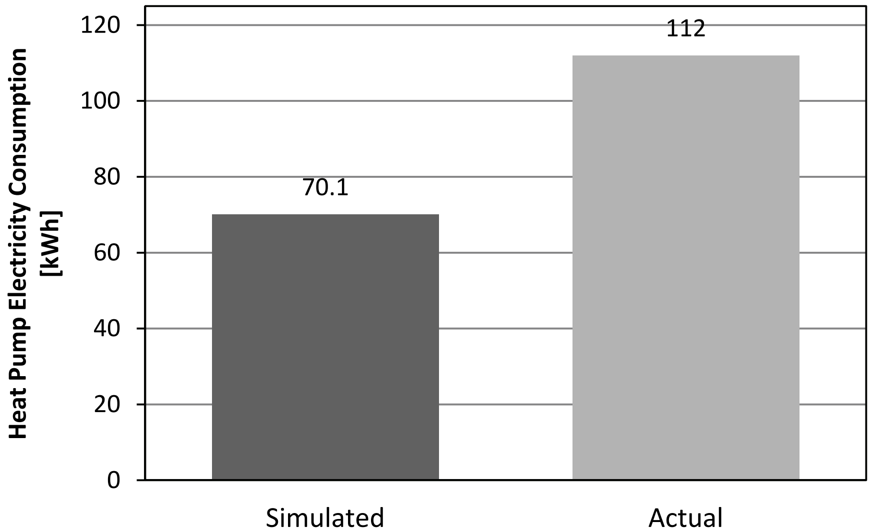


Figure 5. Comparison between actual and simulated heat pump electricity consumption for the cooling period from August 23rd to September 14th, 2010.

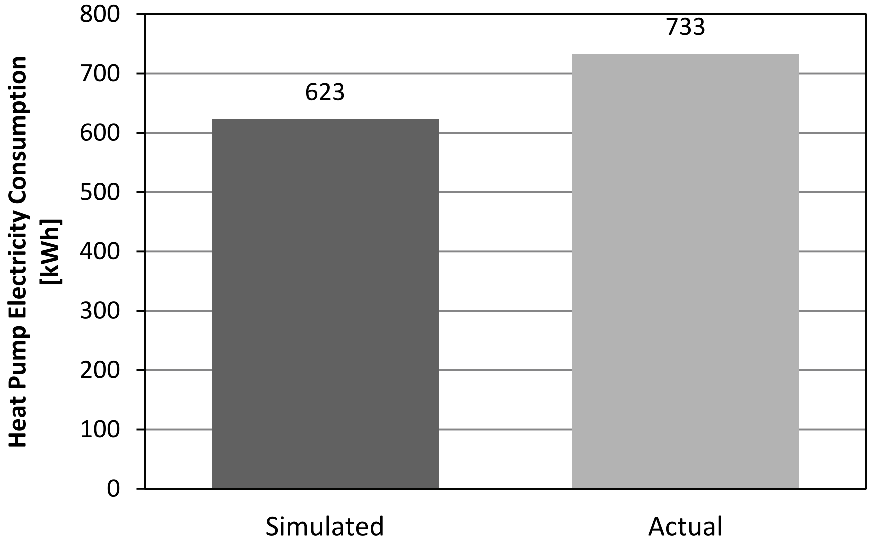


Figure 6. Comparison between actual and simulated heat pump electricity consumption for the heating period from December 1st to December 19th, 2010.

The comparison between the actual and simulated heat pump electricity consumption shows a difference of 37 percent and 15 percent for the cooling and heating results, respectively. This shows that the cooling and heating seasons were simulated accurately as the actual electricity consumptions are very close to the percent differences of the CDD and HDD indicated in Table 6.

The simulation was performed for all three soil types (coarse sand, fine sandy loam, and loam). The heat pump electricity consumptions have been presented in Figure 7 for each soil water content level and soil type.

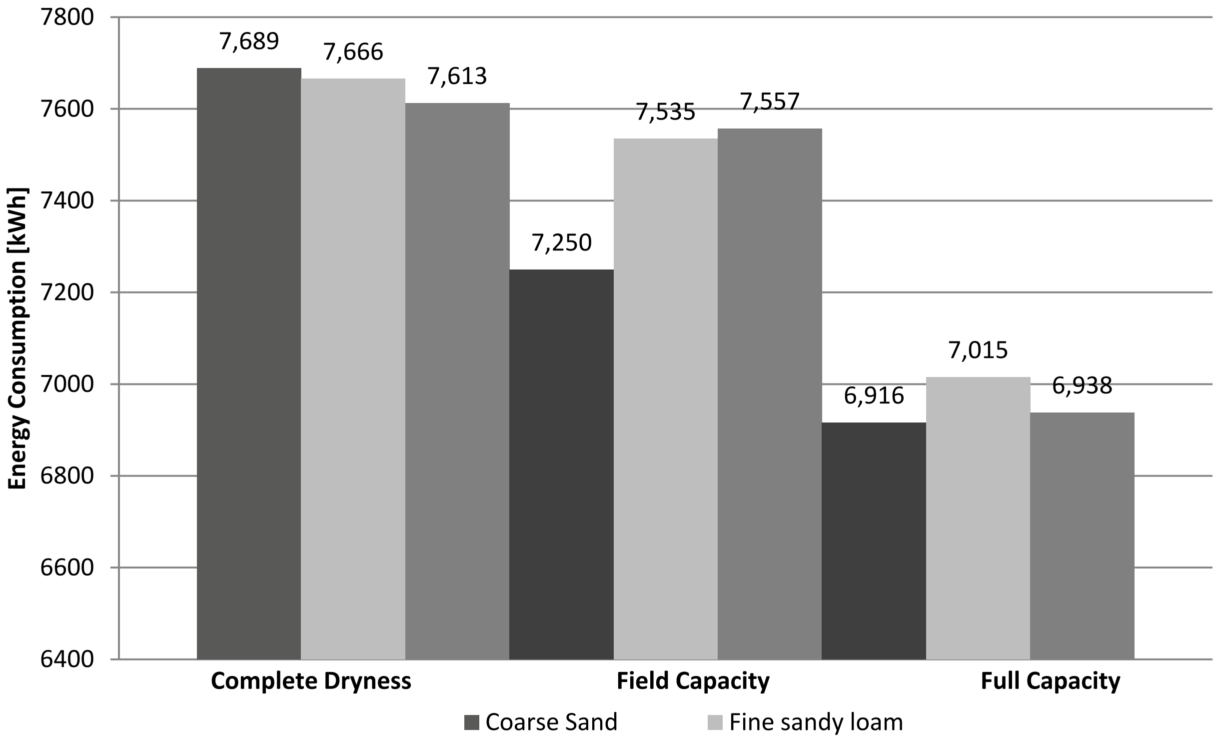


Figure 7. Variation in heat pump electricity consumption at three different water contents for all three soil types under investigation.

Figure 7 shows a decrease in heat pump electricity consumption as the soil thermal conductivity increases due to increase in the soil water content. The increase in soil thermal conductivity results in better heat transfer between the buried pipes and the surrounding soil. Hence, the GSHP can be operated more efficiently because it is easier to reject heat to the ground (resulting lower entrance fluid temperature to the heat pump) during summer and extract heat from the ground (resulting higher entrance fluid temperature to the heat pump) in winter season, thereby resulting in a reduction of heat pump electricity consumption.

The decrease in electricity consumption obtained from the TRNSYS model suggests that the impact of variation in soil thermal conductivity becomes significant with a significant change in soil water content. Hence, the impact of variation in soil thermal conductivity, due to soil water content, on the heat pump performance and electricity consumption becomes significant in regions with significant changes in their weather patterns. For cities that have several months of complete dryness and several months of significant rainfall, soil water content will play a significant role in designing underground thermal energy storage (UTES) systems. Figure 8 presents the monthly rainfall in Toronto from January 2009 to December 2011[6]. As evident in this graph, there is a large variation in rainfall in Toronto from January to December. As the

[6] Data was not available for September and October 2011.

result, for a project in Toronto involving UTES, the impact of variation in soil water content on such system's performance may need to be investigated.

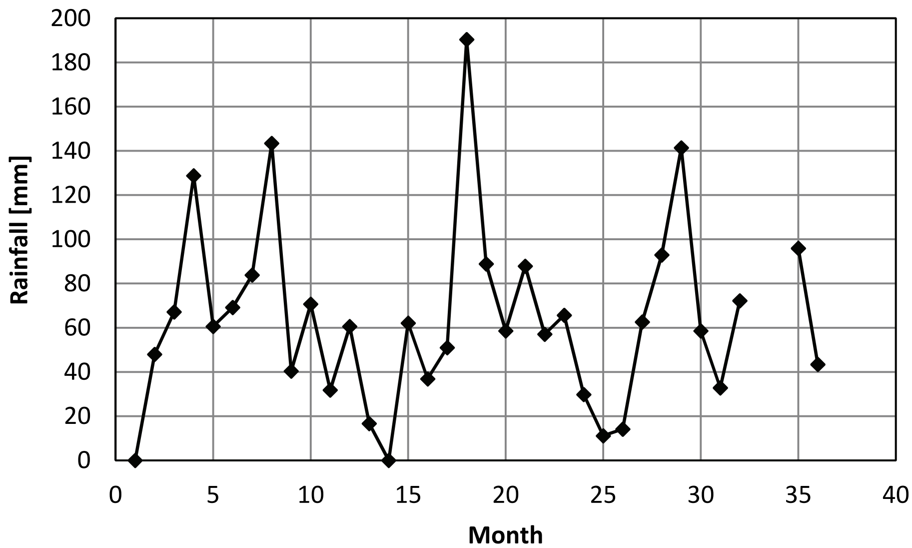


Figure 8. Monthly variation in amount of rainfall for the city of Toronto from 2009 to 2011 [7].

5. Conclusions

Based on an actual archetype house with a GSHP system located at Kortright Centre in Vaughan, Ontario, a computer simulation model was developed using TRNSYS. The GSHP system with two horizontal ground loops was modelled as built. The impact of variation in soil thermal conductivity, due to soil types (coarse sand, fine sandy loam, and loam) and soil water contents (complete dryness, field capacity, and full saturation), on the performance of the GSHP system was investigated. A summary of the findings follows:

- The GSHP electricity consumption decreases more prominently (up to 10% decrease with respect to dry-soil conditions) from complete dryness to full saturation of each soil, for all three soil types.
- A change in GSHP electricity consumption was observed with variation in soil texture as well; however, it is less prominent. The finer textured soils cause higher GSHP electricity consumption (up to 4.2% increase with respect to sand).
- These results suggest that for regions with significant rainfall variation throughout the year, soil water content may become an important factor to consider, when designing an underground thermal energy storage system.

6. References

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[7] Monthly Data Report. Environment Canada Nathional Climate Data and Information Archive. [Online] 2011. http://www.climate.weatheroffice.gc.ca/climateData/monthlydata_e.html?Prov=ON&StatonID=5097&Year=2011&Month=6&Day=30&timeframe=3.

7. Acknowledgements

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8. Biography

Mr. Behnam Jowkar has recently graduated from Ryerson University with a MASc degree in Mechanical Engineering, with specialization in Management Sciences. He is an Associate of Enermodal Engineering, working as a specialist in building design for LEED certification and sustainability.

Dr. Wey H. Leong is an Associate Professor of Mechanical Engineering at Ryerson University. He specializes in thermofluids science and engineering. He has researched in the areas of natural convection, computational fluid dynamics, thermal conductivity of soils, modelling and simulation of thermal systems, especially ground source heat pump (GSHP) systems. His recent research is in high-temperature ground thermal energy storages for hybrid GSHP systems with solar energy or waste heat utilization.

Dr. Marc A. Rosen is a Professor of Engineering at the University of Ontario Institute of Technology, where he served as founding Dean of the Faculty of Engineering and Applied Science. He is a Director of Oshawa Power and Utilities Corporation, and has been

President of the Engineering Institute of Canada and the Canadian Society for Mechanical Engineering. He is Editor-in-Chief of the journal Sustainability and Editor of Energy Conversion and Management.