Importance of Proper Design of Vertical Ground Heat Exchangers according to Weather Conditions

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Abstract

This study demonstrates the importance of proper design of a vertical ground heat exchanger according to weather conditions. The geographical change in weather should be considered while designing for ground source heat pump systems. Therefore comparisons of a house utilizing a ground source heat pump with a vertical ground heat exchanger were made to a house located in the Town of Milton in Ontario with simple weather data, as well as with comprehensive weather data. Models were created using the transient energy system simulation tool TRNSYS to simulate the different scenarios.

Keywords: Heat Pump, Vertical U-tube Ground Loop Heat Exchanger, TRNSYS, GHEADS, Weather Data

Résumé

Cette étude démontre l'importance de la bonne conception d'un échangeur de chaleur vertical du sol en fonction des conditions météorologiques. Le changement géographique par temps devrait être considérée lors de la conception des systèmes de pompe géothermique. Par conséquent comparaisons d'une maison en utilisant une pompe à chaleur géothermique avec un échangeur de chaleur vertical du sol ont été apportées à une maison située dans la ville de Milton en Ontario avec des données météorologiques simples, ainsi que des données météorologiques globales. Les modèles ont été créés en utilisant les transitoires d'énergie TRNSYS système de simulation d'outils pour simuler les différents scénarios.

1. Introduction

Ground source heat pump (GSHP) systems use the ground as a heat source or heat sink to provide space heating and cooling as well as domestic hot water. The GSHP system can offer higher energy efficiency for air conditioning compared to conventional air conditioning systems because the underground environment provides lower temperature for cooling and higher temperature for heating with less temperature fluctuation than ambient air.

The ground heat exchanger (GHE) is a major component of the GSHP system by which the thermal energy is extracted from and injected to the ground. The GHE operation induces a simultaneous heat and moisture flow in its surrounding soil. The transfer of heat between the GHE and adjoining soil is primarily by heat conduction and to a certain degree by moisture migration. The entire process of heat injection and extraction is transient in nature, due to the weather-dependent ground surface boundary conditions and heating/cooling load. The soil thermal conductivity varies greatly with the soil type (texture, mineralogical composition), moisture content, dry bulk density and temperature. The soil moisture content in close vicinity to the GHE can be influenced by numerous factors, such as: soil structure, temperature gradient, moisture gradient, irrigation, and gravity effects. In particular, the temperature gradient in the soil surrounding the GHE plays an important role in the combined heat and moisture flow. When the soil temperature near the GHE is well above 40°C, the effect of the moisture gradient is limited as compared to the temperature gradient, which may lead to a dry-soil belt around the GHE behaving like an annular zone of insulation [1]. Moreover, depending on the moisture content and temperature, structural and textural properties of the same soil sample can vary considerably with seasonal climatic conditions. Therefore, thorough understanding of the intricate nature of soils and transport phenomena related to coupled heat and moisture flow in the ground is essential to both the design and the operation of ground heat pump systems. Due to the very complex characteristics of the ground, the actual design of the GHE should be based on a detailed mathematical model of simultaneous heat and moisture flow in soils, plus an integrated heat pump model and reliable ground hydro-geological data.

A number of design tools for vertical ground heat exchanger (VGHE) based on some typical heat transfer models have been developed in the last two decades. A good design program for VGHE should have high computational efficiency, which allows for a quick simulation of the transient effects over long period of time. There are numerous factors, which affect to some extent the final sizing of a VGHE, should be considered in the mathematical methodology or heat transfer model as a crucial part of a design program.

2. House load and system configuration

2.1 House load

The house selected for this study is located in the Town of Milton, Ontario. The house was one of two energy efficient demonstration houses built by a local builder, in 2005. It is a detached two storey building having 498 m^2 (5,360 ft^2) of heated area including the basement.

TRNBuild [2], a component of the TRNSYS simulation software was used to generate the house load profile. TRNBuild was developed as a part of TRNSYS for simulating multi-zone building. It works under Type 56 (house model) in the TRNSYS studio (system generating module). This component models the thermal behavior of a building divided into different thermal zones. In order to use it, a separate pre-processing program must be first executed. The TRNBuild program reads in and processes a file containing the building description, and then generates two files used by the TYPE 56 component during TRNSYS simulation. TRNBuild generates an information file describing the outputs and required inputs of TYPE 56.

In TRNbuild the house was separated in three zones: 1- Basement, 2- First floor 3- Second floor. The maximum heating and cooling demand is 11.5 kW and 9.5 kW respectively. The annual space heating demand for the house was estimated to be 95 GJ, with an annual space cooling demand of 19 GJ.

The heating season was set from 1st of October (6552 hr) to 30th of April (2880 hr), and the cooling season from 1st of May (2881 hr) to 31st of September (6553 hr).

2.2 System configuration

The system selected for this study is from previously studied system by Rad et al. [3]. It is a solar assisted ground source heat pump (SAGSHP) system. The vertical ground heat exchanger (VGHE) system consists of four vertical U-tube closed loop circuits, joined in parallel. Each borehole has 0.25 m (10 in) diameter and 55 m (180 ft) length. They are located 3.6 m (12 ft) apart from each other in the backyard and merged at 1.8 m (6 ft) below grade. Figure 1 shows this arrangement.

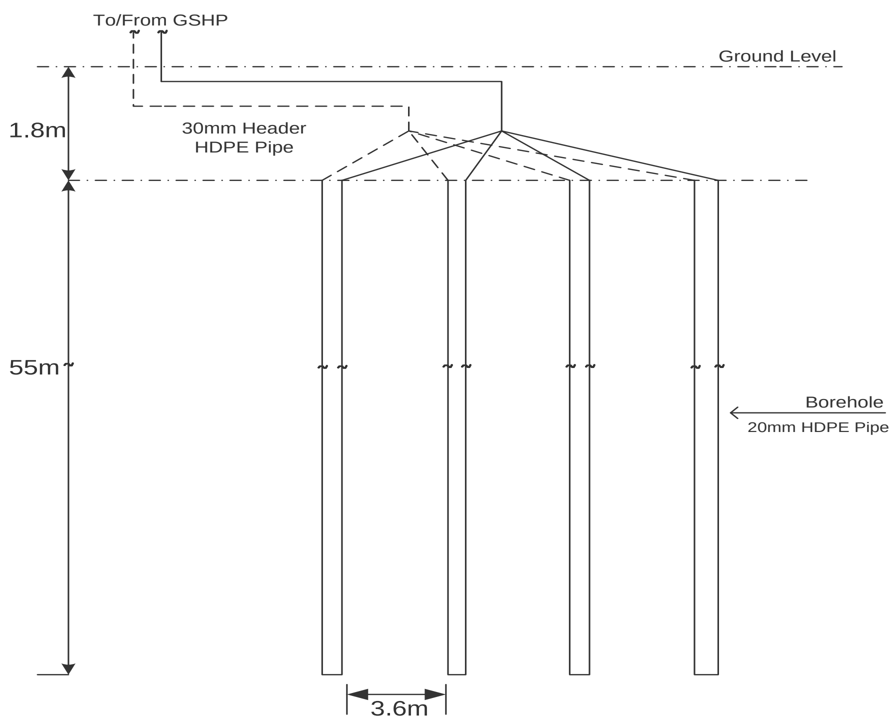

Figure 1- Ground loop borehole layout.

The VGHE is connected in parallel to the solar thermal collectors. The solar collectors receive a percentage of the total flow from the VGHE. Two circulation pumps are located upstream and down-stream of the VGHE flow. A solenoid valve and a control valve control the flow rate to the solar collectors.

The heat pump is selected to suit the space heating requirements of the house for both radiant floor heating for the basement and forced air heating for the first and second floors. The same heat pump provides cooling via forced air in the summer. The heat pump has a dedicated domestic hot water generation through its desuperheater with an internally mounted loop and pump. The hot water from the desuperheater loop flows into a hot water tank. Both the hot water tank and heat pump are equipped with auxiliary electric heaters.

Cold main water is directed to a grey water heat recovery equipment and then sent to the hot water tank and/or desuperheater. Basement in-floor radiant heating is directly fed from the hot water tank by a dedicated pump.

3. System model- TRNSYS

Figure 2 shows the system equipment configuration modeled in TRNSYS 16. The main systems components are as follows:

1. House Model- Type 56
2. Heat Pump Model- Type 505
3. Ground Loop Heat Exchanger Model- Type 557
4. Solar Collector Model- Type 1
5. Water tank Model- Type 4
6. In-floor Radiant Heating Model- Type 653
7. Grey Water Heat Recovery Model- Type 91
8. Ventilation Model- Type 667b
9. Pump Component and Flow Control Model- Type 114
10. Control Flow Mixer- Type 11h and 11d
11. Control Model for Heat Pump- Type 698, 14e and 14k
12. Cold Main Water and Domestic Hot Water draw Model- Type 14b
13. Weather model- Type 109

In this study, three main system components, which are more focused on, are: 1) heat pump, 2) weather data, and 3) VGHE. Solar collectors are bypassed as they are not part of this study. This also helps to reduce the simulation time.

3.1 Heat pump

This component models a single-stage liquid source heat pump with desuperheater for hot water heating. The heat pump conditions a moist air stream by rejecting energy to (cooling mode) or absorbing energy from (heating mode) a liquid stream. The desuperheater is attached to a secondary fluid stream. In cooling mode, the desuperheater relieves the liquid stream from some of the burden of rejecting energy. However, in heating mode, the desuperheater requires the liquid stream to absorb more energy than would be required for space heating only. This heat pump model is intended for residential ground source heat pump (GSHP) application [4]. This model is based on user-supplied data files containing catalogue data for the capacity (total in heating mode and both total and sensible in cooling mode) and power, based on the water temperature entering the heat pump, the entering water flow rate and the air flow rate. The model is also equipped with a two-stage auxiliary heater. The Atlas AT060 model of GSHP with a desuperheater [5] is a good match with Type 505. Table 1 shows the parameters from the technical manual of the chosen heat pump needed for simulation.

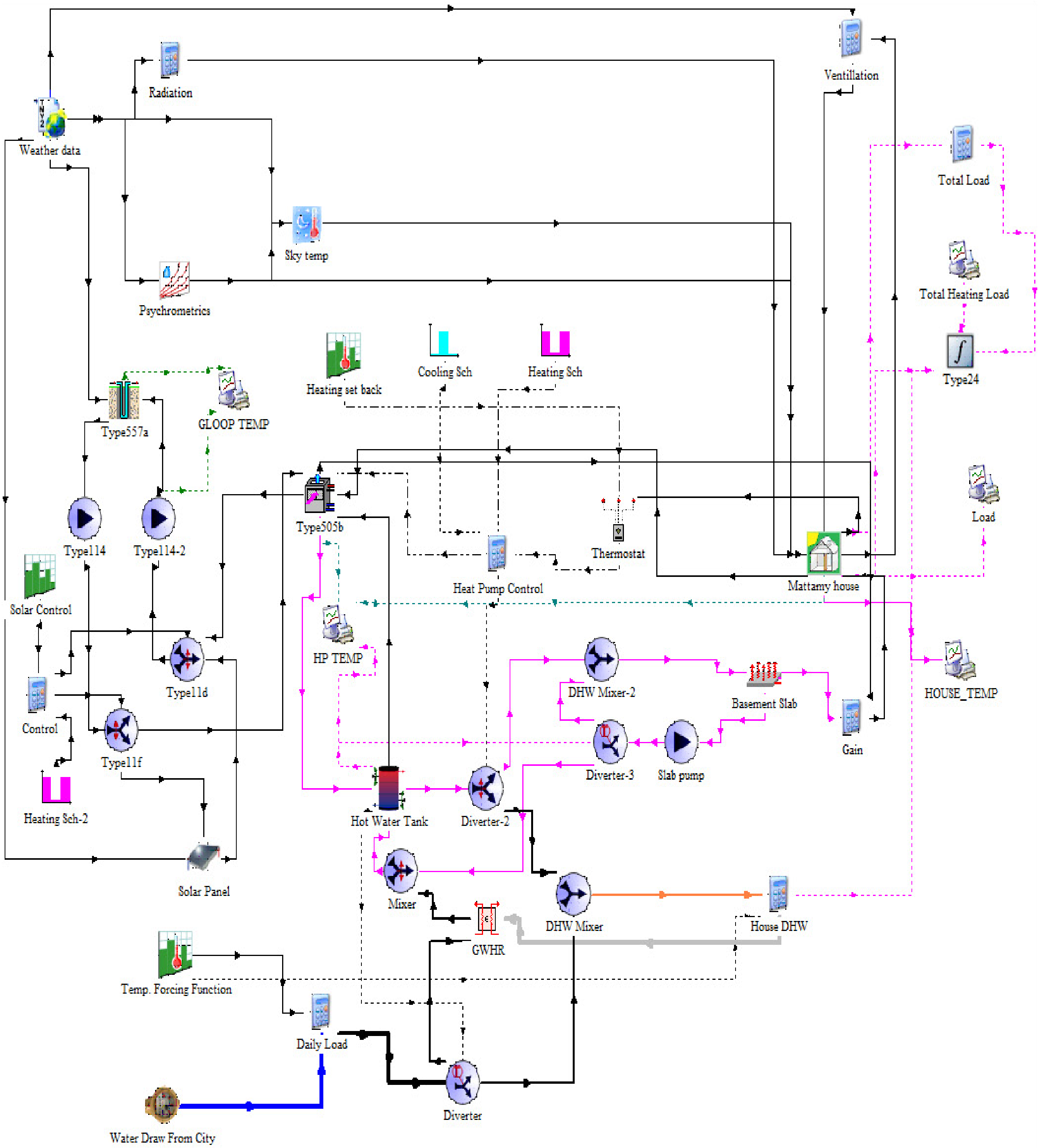

Figure 2- TRNSYS model layout

Table 1- Ground source heat pump parameters

Density of liquid stream	1036	kg/m^3
Specific heat of the liquid stream	3.6	kJ/kg·K
Specific heat of DHW fluid	4.18	kJ/kg·K
Blower Power	0.19	kW
Controller power	0.01	kW
Capacity of stage-1 auxiliary heater	5	kW
Capacity of stage-2 auxiliary heater	5	kW
Total air flow rate	944	l/s

3.2 Vertical ground heat exchanger (VGHE)

3.2.1 TRNSYS 16 Default Component, Type 557

Type 557 models the VGHE that interacts thermally with the ground. GSHP applications commonly use this VGHE model. This component models vertical U-tube or vertical tube-in-tube heat exchangers. A heat carrier fluid is circulated through the VGHE and either rejects heat to or absorbs heat from the ground depending on the temperatures of the heat carrier fluid and the ground. In typical U-tube or tube-in-tube applications, a vertical borehole is drilled into the ground. A U-tube or tube-in-tube heat exchanger is then pushed into the borehole. The top of the VGHE is typically several feet below the ground surface. Finally, the borehole is filled with a backfill material, either virgin soil or a grout of some type. The model assumes that the boreholes are placed uniformly within a cylindrical storage volume of ground. There is convective heat transfer within the pipes and conductive heat transfer to the ground storage volume. The temperature of the surrounding ground is calculated from three parts: a global temperature, a local solution, and a steady-flux solution. The global and local problems are solved with the use of an explicit finite-difference method. The steady-flux solution is obtained analytically. The resulting temperature is then calculated using superposition methods. This component was developed by the Department of Mathematical Physics at the University of Lund, Sweden [7].

3.2.2 GHEADS Component, Type 201a

Vertical Ground Heat Exchanger Analysis, Design and Simulation (VGHEADS) [8] is based on computer simulation of the performance of an entire GSHP system. A detailed numerical solution incorporates the following:

1. Equations describing simultaneous heat and moisture transfer in ground heat storage solved by the finite element method.
2. A steady-state model of heat pump units.
3. The heating and cooling loads of the house.
4. Average daily climatological data.
5. An initial soil temperature and moisture content profile.

Temperature variation of circulating fluid along the closed-loop VGHE is calculated upon the energy balance and heat transfer between the circulating fluid and surrounding soil. It is assumed that the ground heat storage around the borehole has axisymmetric conditions; thus, soil temperature and moisture profiles in ground heat storage are calculated only in the axial and radial directions, reducing the problem to a two-dimensional one [8]. The developed computer program takes into account a large number of obstacles which are normally disregarded for a simpler analysis. Major processes which have been addressed in this program, could be highlighted as follow:

1. coupled heat and moisture flow in ground heat storage.
2. soil freezing-thawing and drying-rewetting due to heat extraction and heat deposition.
3. different soil types and layers, as well as the presence of the ground water table.
4. dynamic ground-surface effects (radiation, convection, advection, evapotranspiration, snow cover, etc.).

The soil moisture transport properties are obtained from the Philip-de Vries model [9] and field experimental data provided by Clapp and Hornberger [10] and Campbell [11]. The site topography and comprehensive climatological data, such as ambient temperature, solar radiation, wind speed, rainfall, snow cover, snow density, and water vapor pressure, are used to simulate the boundary conditions at the ground surface.

The program can simulate a multiple full-year operation of a ground heat pump system in the heating and cooling mode. The entire computer program is written in FORTRAN 77 and can be run on a wide range of computers.

The program has been modified and ported to TRNSYS 16 as component Type 201a in 2009.

3.3 Weather data

The default weather data, used for the North American cities in the TRNSYS 16, is a typical meteorological year 2 (TMY2) data sets derived from the 1961-1990. Data are from National Solar Radiation Data Base (NSRDB) which was completed in March 1994 by the National Renewable Energy Laboratory (NREL) [6]. TRNSYS 16 database does not contain all the weather data components by default, The output parameters of the Type 109-TMY2 are used as an input for the house simulation module (Type 56) and ground heat exchanger (Type 557). This TMY2 data has enough information required for the Type 557.

In order to run VGHEADS's module (Type 201a) in TRNSYS, a more detailed weather file is required. Table 2 shows the output parameters required in addition to the default parameters in Type 109-TMY2 for using the Type 201a module. These parameters are extracted from Environment Canada and defined in a supplementary data file read by Type 300b. Figures 3, 4, 5 and 6 show the yearly mentioned parameters for the city of Toronto. It can be seen that these parameter values are relatively large. Therefore they should be taken into the consideration for accurate heat transfer calculations.

Table 2- Supplementary weather data file, output parameters

Output of supplementary weather data file	Units
Ground surface albedo	-
Cloudiness	-
Rainfall	mm
Snow cover depth	m
Snow cover density	kg/m^3

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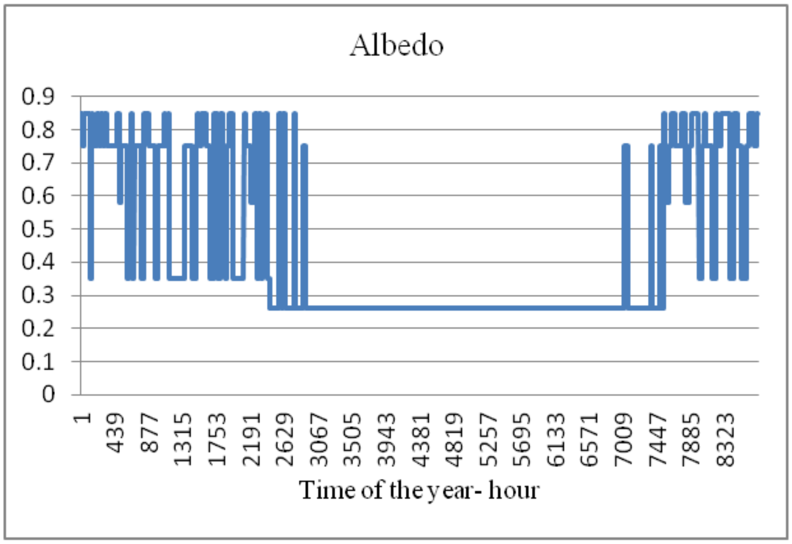

Figure 3- City of Toronto albedo yearly data, starting January 1st

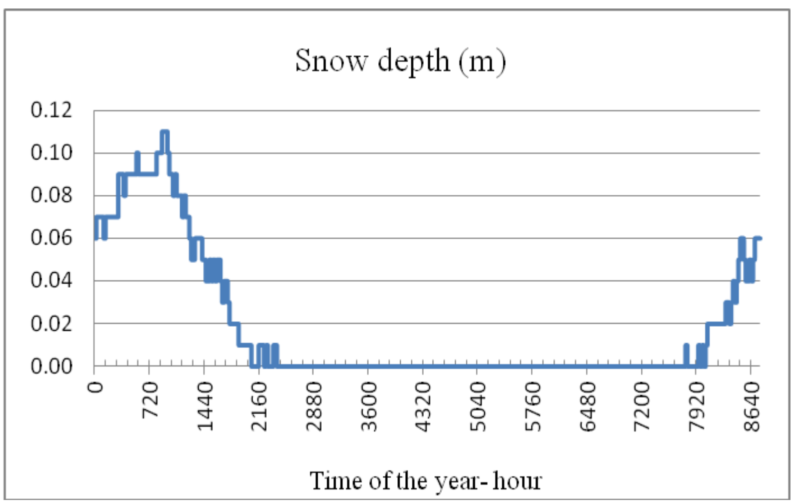

Figure 4- City of Toronto snow depth yearly data, starting January 1st

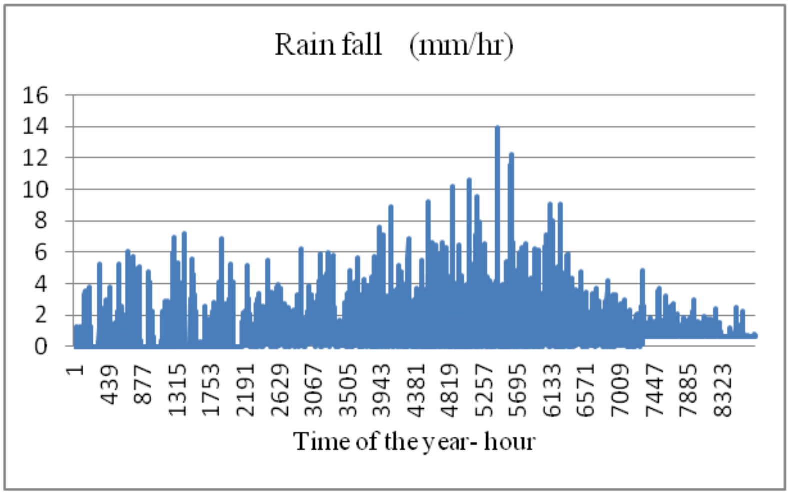

Figure 5- City of Toronto rain fall yearly data, starting January 1st

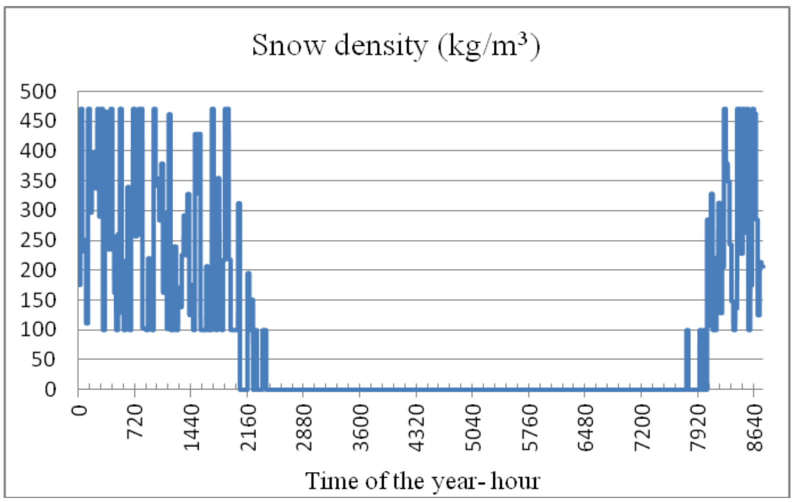

Figure 6- City of Toronto snow density yearly data, starting January 1st

4. Sensitivity analysis - different borehole lengths, Type 201a vs. Type 557

The effect of the different borehole arrangements and depths for the default TRNSYS VGHE (Type 557) vs. VGHEADS VGHE (Type 201a) are investigated. The borehole arrangements and depths were selected as follows (the total borehole lengths are 220 m for the all cases) :

1. 4 boreholes at 55-m depth each as shown in Figure 1 (55m×4) which is considered as the base case.
2. 8 boreholes at 27.5-m depth each (27m×8).
3. 12 boreholes at 18.33-m depth each (19m×12).
4. 16 boreholes at 13.75-m depth each (14m×16).

The performance of the systems for the two different modules, Type 201a and Type 557, were investigated. Figures 7 and 8 show the averages of differences in temperatures IN and OUT of the heat pump (ΔIOT) for Types 201a and 557 in the heating and cooling modes, respectively. The average ΔIOTs are shown for different borehole arrangements and depths.

In heating mode the average ΔIOT for the Type 201a is higher than the Type 557 by 21.6% for the base case and by 23% for the 14m×16 case. In cooling mode the average ΔIOT for the Type 201a is higher than the Type 557 by 19% for the base case and by 18% for the 14m×16 case. Figures 9 and 10 show the average annual coefficient of performance (COP) of heat pump for Types 201a and Type 557 in the heating and cooling modes, respectively. The average COPs are also shown for different borehole arrangements and depths.

In the heating mode the average heat pump COP for the Type 201a is almost the same as the Type 557. For the base case the average heat pump COP for the Type 557 is 2% higher than the Type 201a. In the cooling mode the average heat pump COP for the Type 201a is higher than the Type 557 by 3.9% for the base case and by 3.8% for the 14m×16 case.

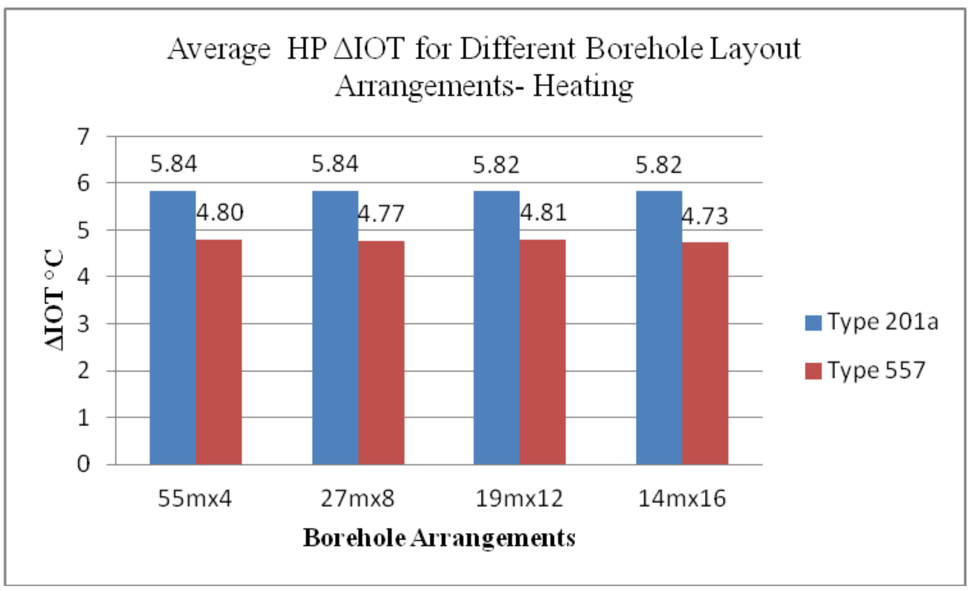

Figure 7- Average heat pump differential IN and OUT fluid temperature (HP ΔIOT) for different borehole layout arrangements in heating mode.

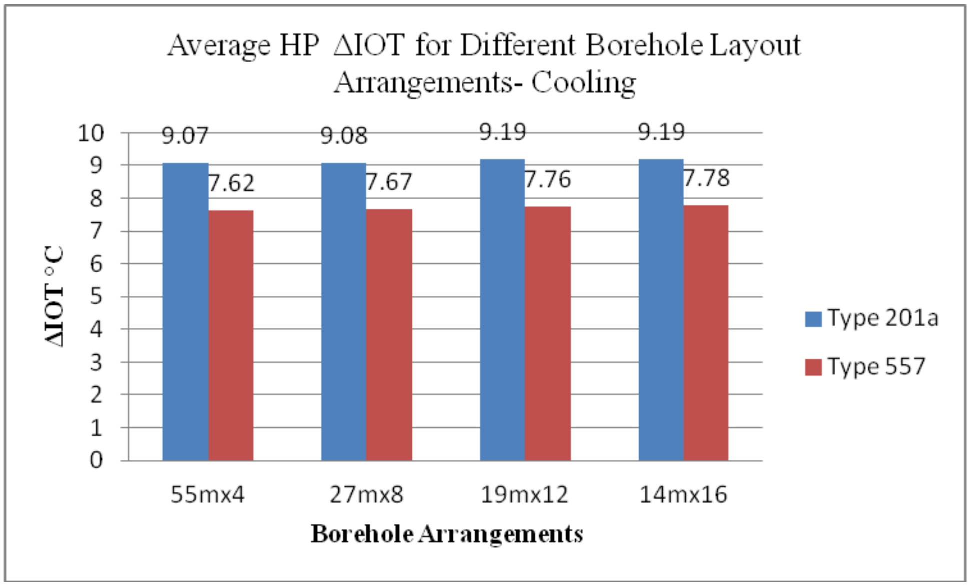

Figure 8- Average heat pump differential IN and OUT fluid temperature (HP ΔIOT) for different borehole layout arrangements in cooling mode.

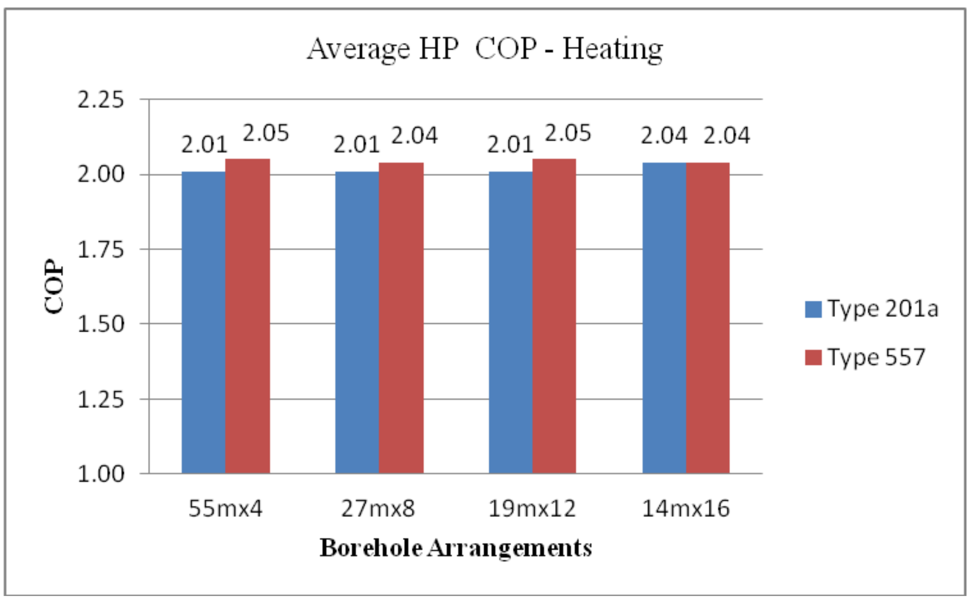

Figure 9- Average heat pump Coefficient of Performances (COPs) for different borehole layout arrangements in heating mode.

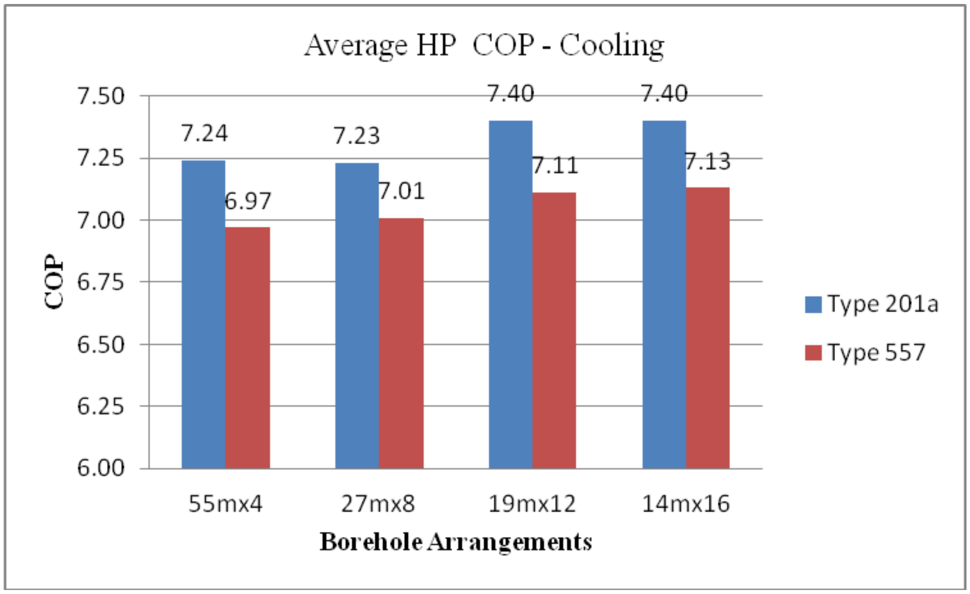

Figure 10- Average heat pump Coefficient of Performances (COPs) for different borehole layout arrangements in cooling mode.

5. Result discussions and conclusions

Sensitivity analysis for the Type 201a for heat pump entrance fluid temperatures (EFTs) and the different borehole arrangements and depths gives the following results:

1. Heat pump EFT increases with the decrease of the borehole depths in the heating mode.
2. Heat pump EFT decreases with the decrease of the borehole depths in the cooling mode.

The above results show, by decreasing the borehole depth, the heat pump EFTs are in favor of the system performance in both heating and cooling modes. The increases of the performance are quantified by the heat pump COPs in the heating and cooling modes by 1.5% and 2.2% respectively. The performance increases correspond to 75% borehole depth reduction from 55 m to 14 m.

The results for the effect of borehole depth reduction on the heat pump EFTs for the Type 557 are as follows:

1. The heat pump EFTs decreases with decreasing of borehole depths in the heating mode.
2. The heat pump EFTs decreases with decreasing of borehole depths in the cooling mode.

In the cooling mode, the two simulation results for Type 557 and Type 201a are in agreement with each other whereas in heating mode the effect of borehole depth reduction in two systems are opposite.

For the Type 201a which considers the effects of all climatic data, such as rainfall and snow cover, it can be concluded that, in the heating mode, the shallower boreholes perform better than the Type 557 which does not consider such parameters. In the cooling mode, both Type 201a and 557 have the same results because the rainfall has less effects in heat transfer calculations.

Table 3 shows the summary of the sensitivity analysis results for the system performance with different borehole arrangements and depths.

Table 3- Summary of sensitivity analysis results between Type 201a (VGHEADS) and Type 557 (TRNSYS default Geo-exchange modules)

	Borehole layouts			
	55m×4	27m×8	19m×12	14m×16
Type 201a - VGHEADS, Geo-exchange Module				
Average HP, ΔIOT (IN & OUT ΔT) - Heating (°C)	5.84	5.84	5.82	5.82
Average HP, ΔIOT (IN & OUT ΔT) - Cooling (°C)	-9.07	-9.08	-9.19	-9.19
Average HP COP - Heating	2.01	2.01	2.04	2.04
Average HP COP - Cooling	7.24	7.23	7.40	7.40
Type 557 - TRNSYS, Geo-exchange Module				
Average HP ΔIOT (IN & OUT ΔT) - Heating (°C)	4.80	4.77	4.81	4.73
Average HP ΔIOT (IN & OUT ΔT) - Cooling (°C)	-7.62	-7.67	-7.76	-7.78
Average HP COP - Heating	2.05	2.04	2.05	2.04
Average HP COP - Cooling	6.97	7.01	7.11	7.13

Note: HP = Heat Pump, ΔIOT (IN & OUT ΔT) = the average heat pump IN and OUT fluid temperature differences (ΔIOT), COP = Coefficient of Performance of the Heat Pump.

From Table 3 and Figures 7, 8, 9 and 10 the following conclusions can be made from the results:

1. In the heating and cooling modes, the average heat pump IN and OUT fluid temperature differences (ΔIOT), in the system with Type 201a (VGHEADS) are higher than in the system with Type 557 (TRNSYS default). It can be concluded that the Type 201a module calculates more heat transfer to/from the ground. The average heat pump ΔIOTs for the Type 201a in the cooling mode are higher than in the heating mode. In the heating mode the average heat pump ΔIOTs of Type 201a are 21.6% and 23% higher than those of Type 557 for the base case and the 14m×16 case, respectively. In the cooling mode the average heat pump ΔIOTs of Type 201a are 19% and 18% higher than those of Type 557 for the base case and the 14m×16 case, respectively.

2. In the heating mode, the average heat pump COPs for the system with Type 201a and Type 557 for the shallower borehole arrangements (14m×16) are the same (2.04). In the base case borehole arrangements (55m×4), the average heat pump COP for the system with Type 557 is slightly (2%) higher than the system with Type 201a. This is not what was expected to see based on the above ΔIOT conclusions. This could be due to the average taking approach for data comparison for the heat pump COPs which might not be an appropriate approach for this case. Further detail investigation for this part is required.

3. In the cooling mode the average COP for the Type 201a is higher than the Type 557 by 3.9% for the base case and by 3.8% for the 14m×16 case.

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7. Biography

Farzin Rad is holding a Master of Applied Science degree in Mechanical Engineering from Ryerson University in Toronto and is currently PhD candidate in the same program. He is a professional engineer, licensed in province of Ontario, Alberta and BC. He is also a Certified Energy Manager (CEM) from American society of Energy Engineer (AEE) and active member of ASHRAE. He has been involved in extensive research in renewable hybrid energy systems.

M. Ebrahim Poulad received his Bachelor of Science degree in Materials Sciences Engineering (honour) from Shiraz University in Iran. He graduated as a Master's in Mechanical Engineering from Ryerson University in Toronto, Ontario, Canada, where he is a PhD candidate in the same program now. Professionally, he successfully passed the Quality Management System (QMS) Lead Auditing qualification exams from London, UK in 2000. He is an active member of CSME, ASME, ASHRAE, IBPSA, and CaGBC.

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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 fluiddynamics, thermal conductivity of soils, modeling 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.