Parametric study and thermal performance evaluation of a sub-slab horizontal ground heat exchanger coupled with a heat pump

Luminita Dumitrascu[1], Ian Beausoleil-Morrison[1]
[1] Carleton University, Ottawa, Canada

Abstract

The research investigates the thermal performance of a sub-slab ground heat exchanger (GHE), coupled to a heat pump, and the ability of the system to provide space conditioning and domestic hot water (DHW) heating for a low-rise multi-unit residential building. The thermal performance of the horizontal GHE directly influences the performance of the heat pump. Therefore, this paper presents the results of a parametric study conducted via TRNSYS simulation, investigating the main factors affecting the thermal performance of a sub-slab GHE. Among these factors are the design properties (number of pipes/layers, distance between pipes/layers), the thermal characteristics of the backfilling materials, fluid properties, as well as various configurations for the insulation layer. Each design of the GHE will be used to evaluate the performance of the ground coupled heat pump system, for a multi-unit residential building (MURB) in Ottawa.

Introduction

One of the largest contributors of global warming, widely recognized, is the increasing atmospheric concentration of carbon dioxide. In Canada, buildings represent 28% of the secondary energy use and they have a significant contribution towards the emission of greenhouse gases (Natural Resources Canada 2019). In order to meet the carbon dioxide emissions reduction targets, and move towards a low-carbon society, the use of renewable and/or low-carbon technologies, such as ground coupled heat pump systems (GCHPS) is increasingly important (Yuanlong, et al. 2019). A GCHPS is characterized by a compact system structure, low electrical consumption, low maintenance requirements (Garber, Choudhary and Soga 2013) and limited environmental impacts through the installation of the ground heat exchanger (GHE). Moreover, compared with an air source heat pump, soil can provide higher evaporation temperatures and lower condensation temperatures, gaining more energy efficiency and higher reliability (Gao, et al. 2016).

The ground is warmer than the ambient air in the winter and cooler in the summer, resulting in a thermal energy potential that can be harnessed for heating or cooling buildings. Moreover, due to its high heat storage capacity, the ground can store some of the energy rejected by the cooling system during the summer, and this energy can be effectively used in the winter for space and DHW heating.

Lately, the application of geothermal energy to meet the thermal energy demand of buildings completely or partially has been expanded (Tian and Xinhua 2018). In recent decades, GHEs have gained increasing popularity in building heating and cooling systems due to long-term durability, high efficiency, and environmental friendliness (Soni, Pandey and Bartaria 2015). Generally, air, water or an antifreeze-water mixture is taken as the heat transfer medium that flows inside the GHE to transport the thermal energy.

Traditionally, the GHE can be vertical, consisting of drilled boreholes, or horizontal, consisting of shallow trenches placed in a near field, or around the foundation of the building (Florides and Kalogirou 2007). However, one of the barriers to the uptake of GCHPSs is the relatively high-capital cost of drilling boreholes for vertical heat exchangers or, in many residential systems, excavating trenches in the soil for horizontal heat exchangers (Yuanlong, et al. 2019).

Another type of GHE, that has not been investigated as extensively, is a horizontal GHE placed directly beneath the slab floor of a house. This loop design attempts to use the ground beneath the slab as a seasonal thermal storage system, and to reduce the installation cost of the ground loop heat exchange portion of the system by containing this loop within the excavated location below the slab.

Among the limitations of such heat exchangers is the proximity to the building. This has the potential for significant interaction between the GHE and the building. Careful consideration should be provided to the design of such a GHE, to avoid the increasing of the heating load (by excessively cooling the soil) or of the cooling load (by injecting too much heat into the soil).

The literature points to the potential of a sub-slab horizontal GHE, coupled to a water-to water heat pump, to fully meet the loads for space heating and cooling of a single detached house. However, such systems are not extensively investigated, and there is a lack of detailed operational data from full-scale systems, especially for those employing a multi-source water-to-water heat pump.

The objective of the research is to contribute to the knowledge base by predicting the performance of a sub-slab thermal storage system coupled with a multi-source heat pump, and to evaluate the ability of the system to provide not just space heating and cooling, but DHW heating and chilled water for dehumidification as well, for a low-rise multi-unit residential building (MURB). Figure 1 presents a simplified schematic (floor loop for one dwelling unit only, no diverting valves for the individual zones, and dehumidification loop for one dwelling unit only) of the integrated system. As this figure illustrates, the system contains a multi-source heat pump (MSHP), a horizontal GHE, a domestic hot water tank, radiant floors for space heating and sensible cooling, coupled with a buffer tank for regulating the flow rate to the heat pump, two heat recovery ventilators (HRV 1 and HRV 2) and a cooling coil for latent cooling, all coupled with a chilled water tank and multiple valves and circulation pumps. The horizontal GHE is used to store the energy rejected during cooling and to extract thermal energy from the ground when space or DHW heating is required.

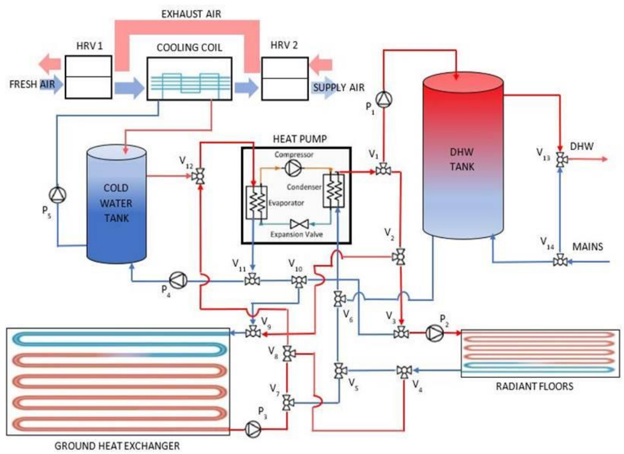

Figure 1. System configuration

Factors affecting the thermal performance of a GHE

The performance of a horizontal GHE is strongly correlated with technical factors such as: pipe configuration, length, loop diameter, spacing of pipes, fluid flow rate, thermal loads of the buildings, or quality of building envelope, as well as with the local geological and environmental conditions (Chong, et al. 2013), (Benazza, et al. 2011), and (Demir, Koyun and Temir 2009).

To ensure a good thermal exchange with the subsoil, the horizontal loops can assume different lengths and configurations (linear, helical, slinky) according to local characteristics and building conditioning requirements (Wu, et al. 2010). Congedo et al. (2012) made a comparative analysis of three types of horizontal GHEs, to be coupled with water-to-water heat pumps. The GHEs analyzed were linear, helical and slinky.

For each type, different geometrical variables such as diameter, pitch, and depth or functional variables as water velocity and ground thermal conductivity were varied in order to investigate the most important parameters to be considered in the evaluation of their performance. The main parameters having an influence on the performance of GHEs have been analyzed by CFD simulations for different working conditions (winter and summer) and varying:

- burying depth of the heat exchanger inside the ground (from 1.5 to 2.5 m);
- heat transfer fluid velocities (from 0.25 to 1 m/s);
- thermal conductivities of the ground around the heat exchangers (from 1 to 3 W/m·K).

According to the results, the most important parameter for the heat transfer performance of the system was the thermal conductivity of the ground surrounding the GHE, and the optimal ground type was the one with the highest thermal conductivity (3 W/m·K). For all configurations, the velocity of the heat transfer fluid inside the tubes was a key factor for heat transfer performance. For all the geometrical arrangements considered, the GHE depth of installation did not play an important role on the system performance. Comparing the geometric arrangements, it was concluded that helical GHEs, known as helix systems, provide the best thermal performance compared to common horizontal loop systems, even if they need more tube length (Congedo, Colangelo and Starace 2012).

Another study conducted by Di Sipio and Bertermann (2017) investigated five helix GHEs installed horizontally, at 1 m depth. The GHEs were surrounded by five different backfilling materials, under the same meteorological conditions, and they were tested under different operation modes. Measurements of climatic data, soil thermal properties and temperatures of the ground have been performed for 1 year.

The trenches were filled in with five thermally enhanced backfilling materials (TEBM), as follow: (1) fine sand 0 – 1 mm (fs); (2) fine sand 0 – 1 mm with 15% bentonite (fs15B); (3) a commercial product (GeoSolid 240HS) in direct contact with the helix, in turn surrounded by sand 0 – 5 mm (s); (4) sand 0 – 5 mm + 15% bentonite (s15B); (5) loamy sand (SC). The long-term investigation of soil temperatures, environmental parameters and soil characterizations provided information about the effects of meteorological parameters on the five different soil bodies.

Due to the low burial depth of installation (0.60 – 1.0 m depth) the helix performance was still affected by daily and monthly temperature amplitude fluctuations, but this effect was limited compared to thermal conductivity variations induced by different soil moisture content. The thermal properties of the soil mixtures measured in situ, together with the soil moisture content showed the following pattern: Loamy sand conductivity > Bentonite mixtures conductivity > Pure sand conductivity. A decrease of water content with depth was observed (no groundwater flow was present), followed as expected, by a reduction of thermal conductivity. It was noticed that in coarse sand, a gradual decrease of moisture content implies a rapid decrease of thermal conductivity, while on bentonite mixtures or loamy sands, the reduction is more gradual. All analyzed materials were promising for a better performance of the helix if initial adequate moisture conditions (>12.5%) are provided and maintained over time. According to the authors, to increase and renew the soil moisture content, in order to enhance the performance of the system and simultaneously improve the recovery time of ground temperature after the heat pump shutdown, a practical solution could be to bypass with pipes the roof precipitation drainage into the ground (Di Sipio and Bertermann 2017).

Another study (Gao, et al. 2016) found also that the variation in soil moisture content was the major factor influencing the thermal conductivity of soil. The thermal conductivity was noticed to increase with the moisture content, and this was beneficial for the thermal performance of the GHE. Integrating a horizontal GHE with a rainwater management system, was beneficial for the groundwater recharge by rainwater and increased soil moisture content, providing favorable conditions for GHE.

Sandy soil container experiment results showed that water migration in soil was possible under the thermal action of a horizontal GHE. The major driving force was the temperature gradient. During the winter, when the heat pump extracts heat from the soil, water transfer could be neglected, because of relatively small temperature differences between the fluid and adjacent soil. During the summer, when the heat pump rejects heat to the soil (for storage), the heat and water transfer was coupled and a drying region appeared adjacent to the tube wall because of relatively large temperature differences between the fluid and adjacent soil (Gao, et al. 2016).

Methodology

The thermal performance of a sub-slab GHE coupled with a multi-source heat pump is examined via simulation, by focusing on a MURB in Ottawa, and using the typical meteorological year for this location. Both, the MURB and the GCHPS were modelled using TRNSYS 17. A short description of the TRNSYS types used to model the main components of the system, and the parametric analysis conducted for the GHE are provided further.

MURB description and modelling

The building has a footprint of 612 m^2 and two above-grade stories. There are 10 two-bedroom dwelling units and two one-bedroom ones. The mechanical room and the attic space were assumed to be unconditioned.

The nominal steady-state U-value for the above-grade walls is 0.090 $W/m^2{\cdot}K$; the slab of the ground floor has a nominal U-value of 0.092 $W/m^2{\cdot}K$; and the attic insulation has a nominal U-value of 0.05 $W/m^2{\cdot}K$. The interior vertical partition walls have a nominal U-value of 0.500 $W/m^2{\cdot}K$, and the slab of the second floor has a nominal U-value of 0.600 $W/m^2{\cdot}K$. Type 932 (the Sherman - Grimsrud model) was used to predict the infiltration, based on the provided effective leakage area, stack and a wind coefficient, as well as a shelter class (TRNSYS 2014). The effective leakage area was calculated from the assumed airtightness rating of 0.6 Ach at 50 Pa depressurization.

The window-to-wall ratio (WWR) was assumed to be 10% for the North facade, and 30% for the South. There are no windows on the East and West façades. The windows are triple glazed, with low-e coating and the thermal properties are the following: standard U-value 0.700 $W/m^2{\cdot}K$, solar heat gain coefficient (SHGC) 0.518, solar transmittance 0.521 and solar reflectance 0.355. The properties of the overhangs installed for the South façade windows are: projection 1.1 m, the distance between the window and overhang 0.2 m, the right and left extension 0.5 m. Type 34 was used to compute the solar radiation incident on the window shaded by the overhang.

Ventilation rates were determined using ASHRAE Standard 62.2 (ASHRAE 2019). This resulted in a continuous ventilation rate of 26 L/s for a two-bedroom dwelling unit, and 21 L/s for a one-bedroom unit. The setpoint temperature for the conditioned zones was selected to be 20ºC for heating, and 25ºC for cooling, and the setpoint for relative humidity was selected to be 55%. Annual DHW draw profiles at a time-resolution of 5 min have been created based on the work of Edwards, Beausoleil-Morrison, and Laperriere (2015). The sensible heat gains from appliances and lighting were considered following a 5 min resolution as well. The patterns were configured using the internal heat gains due to domestic appliances presented in ASHRAE – Handbook of fundamentals (2017), and Wills et all. (2018). The amount of moisture released by the various sources was calculated according to Straube (2002).

The MURB was modelled using the TRNBuild application of TRNSYS. The radiant floors providing both heating and cooling, were represented by using the so-called "active layer" model of TRNBuild.

GHE modelling

The sub-slab GHE was modelled using Type 1267. This component can model a buried heat exchanger with one or more layers of pipes that interact thermally with the ground. The subroutine can model also multiple distinct soil layers, under different boundary conditions (conditioned zone above or insulating layer above or buried to the sides) and requires a user provided file with the noding map of the soil domain and the pattern of the pipes (the pipes must be placed along one of the x, y or z direction). Heat transfer occurs by convection within the pipes, and by conduction through the pipe walls and the soil; heat transfer from the soil surface to the surroundings (either directly to the environment or through insulation to a conditioned zone) occurs by radiation and convection. The soil that thermally interacts with the heat exchanger pipes is divided into a 3-D mesh; the different boundary conditions are applied to simultaneously solve for the soil temperature gradient along with heat transfer rates, energy storage rates, and fluid outlet temperatures.

The far-field and deep-earth distances were assumed to be 10 m. The deep edge boundary conditions were specified as a time-dependent temperature profile (Kusuda model) for the far-field and deep-earth boundaries (Kusuda and Achenbach 1965). For the near-field boundary (above GHE) the time-dependent temperature profile was an output of Type 56 (the multi-zone building).

Other important components and controls

The overall model of the system was developed using available TRNSYS components. Type 534, the stratified tank model, was used for representing the buffer tank, the DHW tank and the chilled water tank. The HRVs were represented using Type 667 that models an air-to-air heat recovery device and Type 752g was used to model the cooling coil. Types 647 and 649 were used to model various diverting and mixing valves. The circulations pumps were modelled using Type 114, and the water-to-water heat pump using Type 927.

A set of equations combining logical operators were used to achieve the desired functionality of the controller. This monitors the temperature and relative humidity of the zones, the temperature at the top and at the bottom of the DHW tank, and the temperature at the bottom of the cold tank. Based on these signals, the controller regulates the heat pump, the circulation pumps, and the diverting valves accordingly. Due to the high thermal inertia of the radiant floors, it was assumed that the DHW heating can take precedence over space conditioning.

GHE parametric analysis

As was previously mentioned, the thermal performance of a GHE is strongly correlated with technical factors such as: pipe configuration, length, pipe spacing, thermal loads of the buildings, or quality of building envelope, as well as with the local geological and environmental conditions. Type 1267 allows the modelling of linear configurations only (no helical or slinky). The sub-slab GHE has four individual loops, one consisting of a single pipe, placed around the perimeter of the foundation, and three others consisting of a linear serpentine (for distance between pipes 0.8 m, and 1.0 m respectively). When the distance between pipes is 1.2 m, the GHE has three individual loops only, one consisting of a single pipe, placed around the perimeter of the foundation, and two others consisting of a linear serpentine. According to the simulation results, there is no difference between the thermal performance of the GHE with one inlet/outlet and multiple inlets/outlets. However, for safety reasons, having multiple loops might be an advantage in case of failure. If one loop is compromised, it can be isolated, preventing the failure of the whole GHE.

Multiple simulations were performed changing the design parameters of the GHE (such as depth of the pipe layer, distance between pipes, insulation layer configuration), as well as the thermal properties of the soil (soil thermal conductivity, density). The mathematical model of Type 1267 does not take into account the moisture migration due to the temperature gradient. However, the literature points to a direct correlation between the soil moisture content and the thermal conductivity (Gao, et al. 2016). The moisture content increases the density of the soil as well. To account for a higher moisture content of the soil, both the thermal conductivity and the density of the soil were slightly increased compared with the values recorded for dry soil. However, a study investigating a sub-slab horizontal ground heat exchanger in a cold climate (Mittereder, N.; Poerschke, A. 2013) noticed a low variability in the moisture transport properties of the soil during the calendar year. The low and constant moisture levels were the result of a well-installed French drain around the structural footing. As such, the density of the soil was assumed to have slightly higher values due to compaction of the soil rather than moisture content.

Table 2 presents the GHE design parameters. For conciseness, as variable parameters were selected the ones having the biggest impact on the thermal performance of the horizontal ground heat exchanger, as well as on the energy consumption of the heat pump. The technical factors such as: depth, distance between pipes, or pipe diameter were assumed based on typical values from literature. The soil thermal conductivity values were assumed according to the ASHRAE Handbook – Fundamentals (SI Edition) (2017).

Table 2: Ground heat exchanger design parameters.

Fixed parameters	
Parameter	**Value**
Number of pipe layers	1
Pipe inside diameter	0.0254 m
Pipe outside diameter	0.0320 m
Pipe thermal conductivity	0.420 W/m·K
Fluid specific heat	4.19 kJ/kg·K
Fluid density	1020 kg/m^3
Insulation thickness	0.1 m
Far field distance	10 m
Deep earth distance	10 m
Soil density	2100 kg/m^3
Soil specific heat	0.85 kJ/kg·K
Variable parameters	
Pipe layer depth	0.5; 1.0; 1.5 m
Pipe distance	0.8; 1.0; 1.2 m
Soil thermal conductivity	Low (1.65 W/m·K) Average (1.95 W/m·K) High (2.25 W/m·K)
Insulation placement	All sides+Top+Bottom All sides+Top No insulation

A five-year simulation (with a seven-month pre-conditioning period) was performed for a time-step of 5-min, using the Canadian Weather for Energy Calculations (CWEC) typical meteorological year weather file for Ottawa (Environment Canada 2019). The pre-conditioning period was assumed to be from June to December, such as the ground would be charged for the first heating season.

The initial soil temperature is calculated by using the Kusuda's correlation (Kusuda and Achenbach 1965). A steady periodic solution was achieved after two years, so all the results reported in this article are obtained from the 3rd year of the multi-year simulations. The thermal performance of the GHE was evaluated by quantifying the annual heat extraction/injection. To account for the impact of the distance between pipes (that leads to different lengths of the loop) the annual heat extraction/injection per unit length was also calculated. The electricity consumption of the heat pump, for the whole MURB, as well as per dwelling unit was also calculated on a yearly basis.

A final simulation was run using the configuration of the GHE providing the best performance of the overall system (lowest electricity consumption of the heat pump), to quantify the ability of the system to fully meet the loads. The space conditioning and DHW heating requirements of the MURB were evaluated by examining the predicted air temperatures and the relative humidity of the zones, as well as the temperature of the DHW, both at the top and bottom of the storage tank, as well as at the outlet fixtures.

Results

Multiple scenarios, considering the GHE configuration, environmental factors (soil thermal properties), and technical factors (fluid properties) were investigated. Table 3 presents the scenarios having as working fluid water.

Table 3: Ground heat exchanger design parameters.

Scenario	Description
Scenario I	Pipe distance 0.8 m; Depth 0.5 m; Low soil properties; Insulation all sides +Top+Bottom
Scenario II	Pipe distance 0.8 m; Depth 1.0 m; Low soil properties; Insulation all sides +Top+Bottom
Scenario III	Pipe distance 0.8 m; Depth 1.5 m; Low soil properties; Insulation all sides +Top+Bottom
Scenario IV	Pipe distance 1 m; Depth 0.5 m; Low soil properties; Insulation all sides +Top+Bottom
Scenario V	Pipe distance 1 m; Depth 1.0 m; Low soil properties; Insulation all sides +Top+Bottom
Scenario VI	Pipe distance 1 m; Depth 1.5 m; Low soil properties; Insulation all sides +Top+Bottom
Scenario VII	Pipe distance 1.2 m; Depth 0.5 m; Low soil properties; Insulation all sides +Top+Bottom
Scenario VIII	Pipe distance 1.2 m; Depth 1.0 m; Low soil properties; Insulation all sides +Top+Bottom
Scenario IX	Pipe distance 1.2 m; Depth 1.5 m; Low soil properties; Insulation all sides +Top+Bottom
Scenario X	Pipe distance 0.8 m; Depth 1 m; Average soil properties; Insulation all sides +Top+Bottom
Scenario XI	Pipe distance 0.8 m; Depth 1 m; High soil properties; Insulation all sides +Top+Bottom
Scenario XII	Pipe distance 0.8 m; Depth 1.0 m; Low soil properties; Insulation all sides+Top
Scenario XIII	Pipe distance 0.8 m; Depth 1 m; Low soil properties; No insulation

According to the results, Scenario XII (pipe distance 0.8 m; depth 1.0 m; low soil properties; insulation placed along all sides and between the slab of the house and soil domain) resulted in the lowest heat pump energy consumption.

A propylene glycol-water solution (15%) was also considered. As per the manufacturer recommendations, a correction factor must be applied to the heating/cooling capacity of the heat pump (the heating/cooling capacity of the heat pump decreases as the concentration of the anti-freeze solution increases). Since the energy consumption of the heat pump was noticeable higher when an anti-freeze solution was used, and the soil temperature was above the freezing point when water is used as working fluid (see Figure 5), Table 3 presents only the scenarios using as working fluid water.

As previously mentioned, there is a direct correlation between the performance of the GHE and the performance of the heat pump. Moreover, this type of GHE, placed directly under the slab of the building, can significantly increase the thermal interaction between the building and the soil (potentially increasing the heating or cooling load). Considering these factors, one of the metrics used to assess the suitability of the GHE design is the energy consumption of the heat pump. Figure 2 presents the energy consumption of the heat pump for each type of load (space heating, DHW heating, space cooling, and chilled water for dehumification), and for each dwelling unit, for all scenarios presented in Table 3.

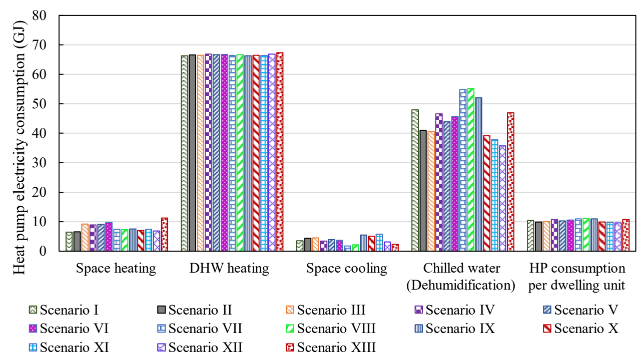

Figure 2. Heat pump electricity consumption

The amount of heat extracted or rejected by the GHE is also important. Figure 3 presents the annual amount of heat extracted, as well as the annual amount of heat rejected to the ground, for all scenarios presented in Table 3.

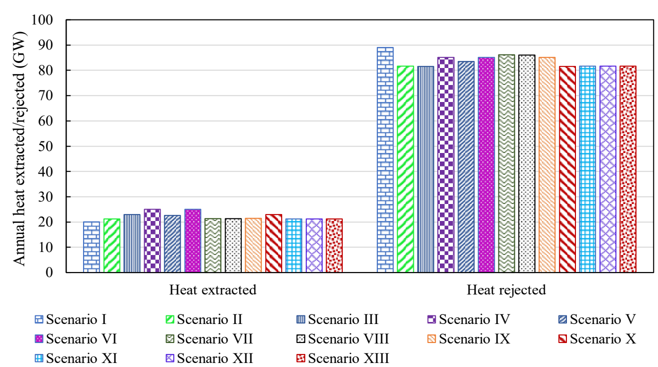

Figure 3. Annual heat extracted/rejected by the GHE

There is a direct correlation between the amount of heat extracted or rejected by a GHE and its length. Keeping the volume of the soil domain constant and increasing the distance between the pipes results in a decrease of the overall length of the horizontal GHE. To be able to quantify the impact of the distance between pipes on the thermal performance of the GHE, the annual heat extraction and rejection was also assessed per unit length. Figure 4 presents the annual heat extracted/rejected by the GHE placed at 1 m depth and three pipe distances: 1.2 m, 1.0 m, and 0.8 m.

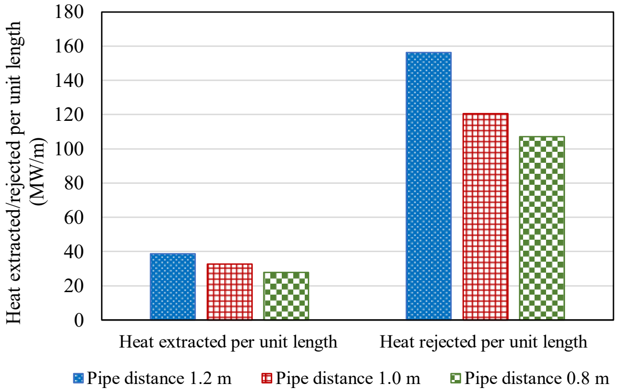

Figure 4. Annual heat extracted/rejected by the GHE per unit length (1 m depth)

The temperatures at the inlet and outlet of the ground heat exchanger were also predicted via simulation. Figure 5 presents the annual variation of the working fluid temperatures at the inlet/outlet of the GHE.

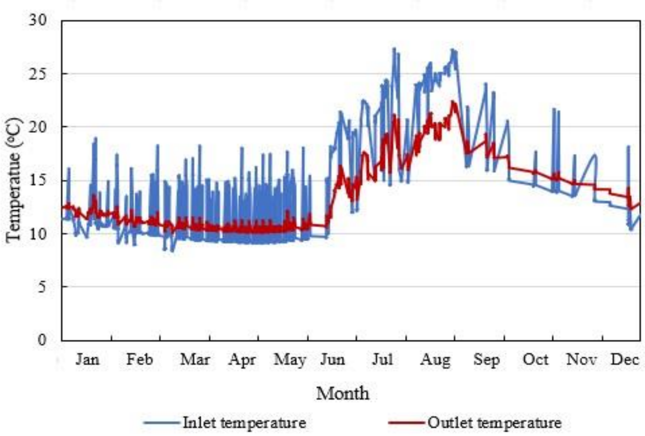

Figure 5. Annual variation of the GHE inlet and outlet temperature

The temperature of the soil containing the GHE is also of interest when assessing various design scenarios. Extracting too much heat for example, can result in freezing the soil under the slab of the house. Since the soil domain is in thermal contact with six zones (one zone per dwelling unit), with different temperature profiles, the soil temperature was initially recorded for six distinct points (each point was assumed to be under the centre of the slab of each respective zone). For each point, the temperature of the soil was predicted for three distinct depths: 0.5 m; 1.0 m, and 1.5 m. The analysis of the results led to the conclusion that the two end zones of the MURB (Zone 1 and Zone 6) have an identical soil temperature profile. Soil temperature profiles almost identical were also noticed for the four middle zones of the MURB (Zone 2 to Zone 5).

Figure 6 presents the soil temperature profile under one end zone (Zone 1) and one middle zone (Zone 2), for all three depths: 0.5 m, 1.0 m, and 1.5 m.

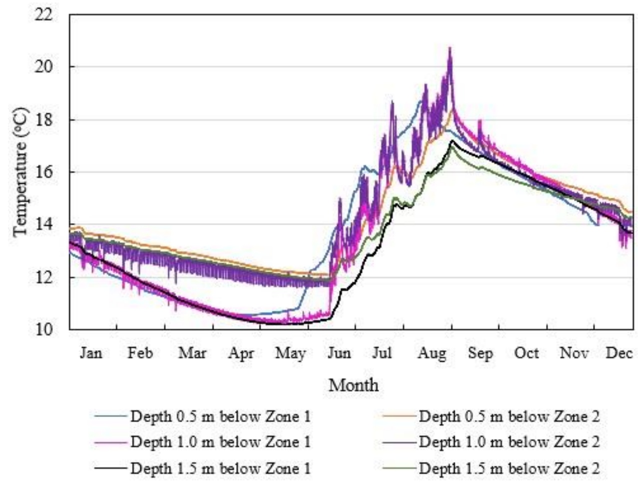

Figure 6. Annual variation of soil temperature under Zone 1 (end zone) and Zone 2 (middle zone)

The ability of the system to meet the space conditioning requirements of the MURB was assessed by predicting the air temperature of the zones, as well as the relative humidity.

Discussion

As Figure 2 illustrates, there are noticeable differences between scenarios for the space heating and cooling energy consumption, as well as for the chilled water (loads impacted by the MURB heat losses to the ground). A small variation between scenarios was noticed for the DHW heating as well. Depending on the scenario, the number of hours for which the heat is extracted from one source (ground, cold floor, or cold tank) varies. The heat pump coefficient of performance varies as well, depending on the source (1.8 when heat is extracted from the cold tank, and 2.1 when extracted from the floor), resulting is a small difference between scenarios for the energy required by the DHW heating. However, according to the results, there is a 15% difference only between the best and the worst scenario, when quantifying the energy consumption of the heat pump per one dwelling unit. According to the results presented in the previous section, Scenario XII provided the best performance of the system. The annual electricity consumption of the heat pump for each dwelling unit was 9.6 GJ, resulting in 115.2 GJ for the whole MURB.

According to Figure 3, there is a noticeable difference in the amount of heat extracted/rejected by the GHE, between some of the different scenarios. The distance between the pipes is one of the factors having visible impact on the performance of the GHE. Even though the heat extraction/rejection per unit length is the highest for the pipe distance of 1.2 m, overall, the GHE with the distance between pipes of 0.8 m resulted in the highest heat extraction/rejection rate due to its additional length (550.6 m versus 762.4 m).

The depth of the pipe layer was noticed to have an impact for the distance between pipes of 0.8 m only. According to the results, placing the GHE at 1.0 m depth resulted in the best performance of the heat pump, while placing it at 0.5 m in the worst performance of the heat pump. When the GHE is placed at 0.5 m under the slab it was noticed to increase both, the heating and cooling loads of the building. The heat extraction resulted in lower temperature for the soil in the immediate proximity of the slab, increasing the heat losses to the ground, and implicitly the heating load. When the heat was rejected to the ground, the proximity of the GHE to the slab of the house resulted in a higher heat flux being send back to the house, increasing this way the cooling load of the building.

Generally, the soil thermal conductivity has significant impact on the performance of a GHE placed in a field adjacent to the building, leading to higher outlet fluid temperatures, and higher coefficient of performance for the heat pump. However, in the present case, the best results were provided when the soil thermal conductivity was assumed to have lower values. This can be due to the contrary effects the higher soil thermal conductivity can have on the overall system. On the one hand the thermal exchange between the pipes and the soil is increasing, but at the same time, the storage ability of the soil is decreasing, leading this way to lower soil temperatures. As Figure 5 illustrates, the soil temperature in the proximity of the foundation was noticed to have temperatures lower during the winter and higher during the summer, due to the influence of the ambient temperatures. However, this influence was noticed to decrease with the increase of the depth. The soil temperature has also a more noticeable variation in the proximity of the pipe layer. Figure 5 presents the soil temperature for a GHE with the pipe layer placed at 1.0 m depth. It can be noticed that there is no significant difference in the soil temperature at the pipe layer depth depending on the position of the zone.

The configuration of the insulation layer was another factor noticed to have an impact on the performance of the GHE, and of the overall system. The best scenario was the one assuming that the insulation is placed around the foundation of the building (10 cm of extruded polystyrene, up to 2 m depth) and between the slab of the building and the soil, leaving the bottom open to the far field domain. This was most probably due to the influence of deep soil temperature on the temperature of the soil in the proximity of the slab. During the heating season, when heat was extracted from the ground, the open bottom allowed the migration of the heat from the deep earth closer to the surface, while during the cooling season, when heating was injected into the ground, the open bottom allowed the migration of the heat away from the slab to the far field.

The system was also able to meet the comfort requirements for the occupants even for the worst weather conditions. During the space heating, the air temperature of the zones was below 19.5ºC between 2 and 19 hours, depending on zone (the end zones have more surface exposed to the environment, resulting in higher transmission losses), but never lower than 19.3ºC. During the space cooling, the air temperature of the zones exceeded 25.5ºC between 11 and 26 hours, depending on zone, but was never higher than 26.1ºC. The relative humidity of all zones was above 55% between 2 and 39 hours, depending on the latent heat gains profile of the zone. However, the relative humidity was never higher than 61.8% on the ground floor, and 61.2% on the second floor. The temperature of the DHW tank was kept always between the limits of the dead band, and the temperature at the outlet fixtures at 45ºC. The temperature variation at the bottom of the chilled water tank was also between the limits of the dead band.

Conclusion

The performance of a sub-slab horizontal GHE coupled with a multi-source heat pump was predicted by a simulation model developed in TRNSYS 17. The ground temperature and the electricity consumption for space conditioning and DHW heating were simulated for a five-year period, analysed, and discussed. According to the results, Scenario XII (pipe distance 0.8 m; depth 1.0 m; low soil properties; insulation placed along all sides and between the slab of the house and the soil domain) provided the lowest annual energy consumption of the heat pump (115.2 GJ, resulting in 9.6 GJ per dwelling unit).

Among the parameters having a significant influence on the energy consumption of the heat pump were the distance between pipes, the depth of the GHE, as well as the presence of insulation. The system was able to provide space conditioning and DHW heating for a 12 dwelling units MURB. However, the results pointed to the high energy consumption of the heat pump when operating to provide the chilled water for dehumidification. Further investigation will be conducted for identifying dehumidification solutions less energy intensive.

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