GEO
ST. JOHN'S
2019
UNDER LAND & SEA

# Performance of ground-source heat pump systems in cold regions: a case study

Ali Fatolahzadeh, Hartmut Holländer & Pooneh Maghoul
*Department of Civil Engineering – University of Manitoba, Winnipeg, Manitoba, Canada*
Rob Sinclair
*KGS Group, Winnipeg, Manitoba, Canada*

## ABSTRACT

Ground-source heat pump (GSHP) systems are known to be environmentally-friendly technology for heat and air conditioning purposes. The thermal capacity of GSHPs depends on site conditions and are specific to the system parameters. Numerical simulations, e.g., finite element analysis can be used to predict the performance of such systems, by taking most of these parameters into account. In this study, the ground heat exchangers of a closed-loop GSHP system in Winnipeg Smart Park at the University of Manitoba were simulated in 3D, using COMSOL. Two operational scenarios were studied. The simulations calculated the maximum heat extraction and injection powers of 1.8 kW and 1.2 kW per exchanger, respectively. The results indicate that the performance of exchangers varies throughout the year, and such simulations can be a useful tool for calculation of system capacity for different configurations.

## RÉSUMÉ

Les systèmes de pompes à chaleur géothermiques sont connus comme des technologies écoresponsables pour la climatisation. La capacité thermique des systèmes géothermiques dépend des conditions du site et, spécifiquement, aux paramètres de tels systèmes. Des simulations numériques peuvent être utilisées pour prédire leur performance en prenant en compte la plupart de leurs paramètres. Dans cette étude, les échangeurs de chaleur utilisés dans un système GSH en boucle fermée, au Smart Park de Winnipeg à l'Université du Manitoba, ont été modélisés en 3D à l'aide du logiciel de calcul COMSOL. Deux scénarios opérationnels ont été étudiés. Les simulations ont calculé que les puissances maximales d'extraction et d'injection de chaleur atteignent 1,8 kW et 1,2 kW par échangeur, respectivement. Les résultats indiquent que la performance des échangeurs varie tout au long de l'année et de telles simulations peuvent être un outil utile pour calculer la capacité du système dans différentes configurations.

## 1 INTRODUCTION

Global energy consumption is rising every year. With growing concerns about climate change and other environmental issues, substituting fossil fuels with cheap, clean and sustainable sources is now a must. It is estimated that almost 50% of energy consumption in buildings and 20% of total consumption in North America is used for heat, ventilation and air conditioning (HVAC) purpose (Pérez-Lombard, Ortiz, & Pout, 2008). Therefore, developing sustainable HVAC systems can significantly reduce the carbon footprint.

Below a depth of a few meters, the ground temperature remains almost constant throughout the year. Sub-surface layers are usually warmer than the ambient weather during winters but cooler during summers. Even small temperature differences hold considerable energy due to the specific heat of groundwater and soil particles. This energy can be collected by implementing a series of pipes in the ground, which are known as ground heat exchangers (GHEs). A cold fluid, usually water or air, is pumped in pipes. The temperature of the fluid then increases as it absorbs heat from the ground due to conduction. The fluid is then directed to a heat pump, to extract its energy and provide heat at the desired temperature.

A heat pump is a device that transfers heat against the natural direction of heat flow, i.e., from a low-temperature medium to a warmer one. A heat pump system that extracts heat from the ground and transfers it to the building is called a ground-source heat pump (GSHP), or geo-exchange. GSHP systems can work in the opposite direction too. In other words, a reverse approach can cool buildings during summer, since the ground is usually colder than the ambient air.

GSHP systems have been used commercially for decades. They come in various designs. Where the ground is permeable and groundwater level is high, an open-loop system may be used in which groundwater is pumped from a well and re-injected somewhere else after its heat is extracted. In a closed-loop, on the other hand, a liquid is passed through heat exchanger pipes that are buried in the ground. The exchangers can be implemented horizontally or vertically, and in parallel or serial arrangements. Choosing between such designs depend on many factors, such as land availability, ground temperature profile, and excavation costs, etc. (Omer, 2008) Cost analysis of systems working in Europe has shown investment payback periods between 2 and 10 years (Brandl, 2006). The payback period can be longer in cold climates, as there is more heat demand in those regions.

One of the challenges in designing a GSHP system is to predict how they perform. It is a complex process since there are many affecting parameters. For example, the ground temperature profile has a delay in reflecting the surface conditions. Also, soil structure and groundwater have different heat capacities. Every site has a unique climate condition, sub-surface material profile, and groundwater level. Numerical simulations are useful for predicting the performance of a GSHP system, as they can take most of these parameters into account.

In this study, a closed-loop GSHP system was numerically simulated, to predict its performance under single-purpose (heating) and dual-purpose (heating and cooling) scenarios. A multi-physics approach was followed, which included seasonal temperature variations, heat transfer in the heat exchanger pipes, and its propagation in the multi-phase soil medium.

## 2 THEORY

The operation of a closed-loop GSHP system consists of several processes. Low-temperature fluid enters the buried heat exchanger pipes. It absorbs heat and its temperature increases. The fluid is then directed to a heat pump to extract its energy, which decreases its temperature. The cold fluid is pumped to the ground exchangers again, for another cycle. The transferred heat between two media can be written as:

$$Q = m\ c\ \Delta T \qquad [1]$$

in which:

Q: absorbed/released energy (heat) [J]
m: mass [kg]
c: specific heat capacity [J/kg.°C]
$\Delta T$: temperature gradient [°C]

Assuming a steady flow in the ground heat exchangers, the above equation can be re-written as:

$$Q = \rho\ q\ t\ c\ (T_o - T_i) \qquad [2]$$

where:

Q: total energy absorbed from/injected to the ground [J]
$\rho$: density of the fluid [kg/m$^3$]
q: flow rate in the exchanger(s) [m$^3$/sec]
t: duration of the flow [sec]
$T_i$: input flow temperature [°C]
$T_o$: output flow temperature [°C]

Equation 2 can be used to calculate how much energy is exchanged with the ground by exchangers. Assuming there is no heat loss while the fluid is being transferred to the heat pump, the formula can be used to calculate the capacity of the GSHP system.

Since power is defined as P=Q/t, Equation 2 can be written as:

$$P = \rho\ q\ c\ (T_o - T_i) \qquad [3]$$

Therefore, the heat extraction/injection power of a GHE is proportional to the difference between outflow and inflow temperatures. Assuming the system is 100% effective, the powers of GHEs can be added to estimate the capacity of the system.

## 3 PROBLEM DEFINITION AND SIMULATION

The system is located in the Winnipeg Smart Park in Manitoba. The ground heat exchangers (GHEs) are 100 m long, implemented by horizontal (directional) drilling method. The system is arranged in parallel since there are two main pipes laid down in two trenches and they are connected by 30 parallel HDPE pipes as heat exchangers, which carry water from one main pipe to the other. The outer and inner diameters of the GHEs are 37.5 mm and 30 mm, respectively. The GHEs are located at 3 levels below the ground surface. They all have the same depths at both ends, where they connect to the main pipes, but they have different maximum depths at their mid-span (4.5 m, 9 m, and 13.5 m). The three levels are not vertically aligned, i.e., there are two pipes at 4.5 m and 13.5 m in one row while the next row has one layer at 9 m. The horizontal distance between the rows is 5 m.

Borehole data near the site indicates that the soil consists mostly of silty clay, reaching down to at least 20 meters. The thermal properties of the soil were measured in another study on similar soil, close to the site (Saaly et al., 2019). The other parameters, such as hydraulic conductivity, were assumed within the usual range for silty clays (Table 1).

Table 1. Soil characteristics used in simulations

| Characteristics | |
|---|---|
| Thermal conductivity | 2.5 W/(m·°K) |
| Density | 1700 kg/m³ |
| Heat capacity (at constant pressure) | 867 J/(kg·°K) |
| Porosity | 0.3 |
| Permeability | 10e-8 m/s |

Soil temperature at the ground surface is not equal to the ambient temperature. The air temperature is measured under shade conditions, while the ground surface is subjected to sunshine and wind. Also, snow cover during winter acts as insulation since it has a comparatively low thermal conductivity. Therefore, applying only air temperature at the ground surface might be an inaccurate assumption. If the ground temperature data at the surface is available, it can be directly implemented in the model since it already includes all factors. Such data were previously recorded at Highway 210 near Winnipeg by KGS Group and were used in the simulations. Figure 1 shows daily mean ambient and ground temperatures during the study period (15 months). It can be seen that the surface temperatures are often higher than the ambient air, probably due to snow cover or exposure to sunshine.

The simulations were done by COMSOL Multiphysics, a commercial finite element (FE) simulation software. A thermal analysis calculates the heat transfer between the ground and the exchangers, and also the distribution of heat along them. Although there is no significant groundwater flow due to low hydraulic conductivity at the site, the groundwater module was used because it enables the utilization of the multi-phase soil-groundwater function in the model.

The ground exchanger array of the system has a repeating pattern. To save the calculation time, a repeating block of 8 exchangers were separated and modeled instead of the whole array. Most geometric parameters of the model were defined parametrically. Therefore, the model was automatically generated from the applied parameters, and there was no need to redefine the geometry after one or several parameters were changed. The pumping rate of the circulation pump was 5 $m^3$/h and assumed to be evenly distributed between the exchangers.

The soil domain was defined as a homogenous, isotropic porous material (Table 1). The side boundaries were set to thermal insulation (zero heat flux), to exclude the block of GHEs from the whole array. The top surface boundary was set to daily ground temperatures measured at Provincial Road 210, about 50 kilometers southwest of Winnipeg, which has the same climate as the site. The bottom surface at -20 m was fixed to 7°C, based on deep measurements in Winnipeg (Ferguson & Woodbury, 2004). The temperature profile of the soil at day 0 (January 1st) was applied as the initial condition. The properties of water were chosen from the built-in software libraries since they were already available as temperature-dependent functions.

For the ground heat exchangers, the inflow nodes of the pipes were set as Dirichlet boundaries and were linked to the injection temperature. Heat outflow boundaries were applied to their other end. To include the thermal interaction between soil and the exchanger pipes, wall heat transfer boundaries were applied along the pipes. The exchanger wall thickness was set to 3.75 mm, and the thermal conductivity of HDPE (0.3 W/m.°K) was chosen.

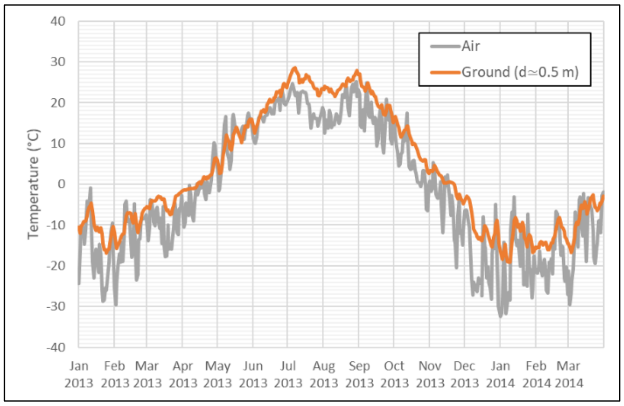

Figure 1. Daily mean ambient and ground temperature data at Highway 210 (courtesy of KGS Group)

The hydraulic boundaries were selected as no-flow at the bottom and the three sides due to the low hydraulic conductivity of silty clay. One side of the soil body was set as constant head to reflect hydrostatic head since at least one Dirichlet boundary is required for numerical stability.

The simulation period was 15 months in total, which included two successive winters. Three transient stages were defined (Table 2), to model the operation scenarios. In the first case (heat extraction only), the pump injects 1°C water to the exchangers, extracting heat from the ground. The system is turned off in the summer stage, and then re-activated during the next cold season. In Case 2 (dual purpose), the system is the same and works similarly during winters but instead of turning it off during summer, it extracts heat from the building and transfers it to the ground by pumping 10°C water to the buried exchangers. The time steps were set to one day. The water temperatures at the pipes (T) and the temperature in the soil (T2) were set as output variables to be recorded at each time step. Default solver settings were selected, which use the multifrontal massively parallel sparse direct solver (MUMPS) (Amestoy et al., 2000).

Table 2. Simulation stages

| Stage | Days | Pumping (Injection Temperature) | |
|---|---|---|---|
| | | Case 1 | Case 2 |
| 1 | 1-150 | Active (1°C) | Active (1°C) |
| 2 | 151-270 | Off | Active (10 C) |
| 3 | 271-455 | Active (1°C) | Active (1°C) |

A finite element mesh consisting of tetrahedral elements were used in the simulations (Figure 2). The maximum global element size was set to 4 m and the mesh was refined around the exchangers. The dimension was chosen from a preliminary sensitivity analysis, in which the mesh was refined until the element size had no noticeable effect on the results.

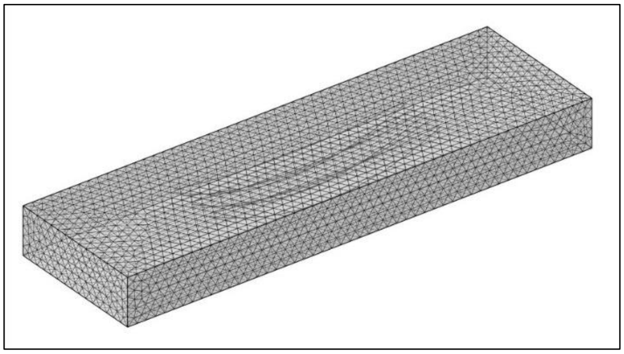

Figure 2. Tetrahedral meshed domain.

## 4 RESULTS AND DISCUSSIONS

Figures 3 and 4 show the temperature distribution in the soil body and the GHEs for the 400th day of the simulation period, respectively. These figures are consistent with the applied boundaries and demonstrate a smooth temperature transition, without any irregularities that might happen due to poor mesh selection. Such figures may provide insight about heat propagation, in case they are rendered at other time steps and presented as animations.

To verify the results, the measured and calculated ground temperature profiles can be compared at an arbitrary time step in the study period. Such comparison is shown in Figure 5, for the 60th day of the period. There is a conformity between the calculated and measured temperatures, which implies the validity of the results. It should be noted that the temperature profile at Highway 210 was measured up to 4 meters. Therefore, the deepest measurement (20 m) was taken from another study (Ferguson & Woodbury, 2004).

The nodal temperatures at the beginning and end of GHE pipes, i.e., inflow and outflow temperatures, are plotted for the two operation scenarios, as shown in Figure 6 and Figure 7. The temperatures between the 150th and 270th days are drawn as a straight line and grayed out in Figure 6 (scenario 1) because the circulation pump was off in that period. Both figures indicate different outflow temperatures for exchangers implemented at different depths. The highest fluctuations were observed at the top exchangers (the ones with a maximum depth of 4.5 m). This is because they were the closest to the ground surface, affected by surface temperature. Conversely, the deepest layer, i.e., the exchangers with a maximum depth of 15 m, had the most stable outflow temperature throughout the period.

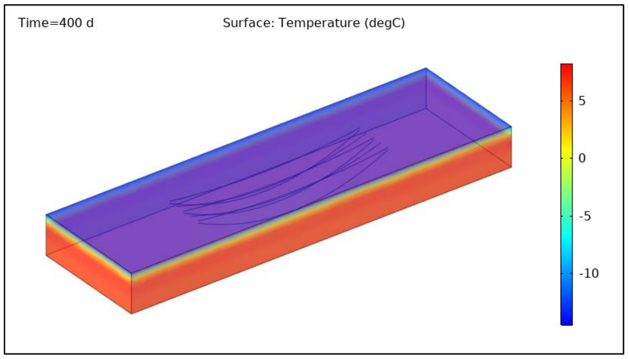

Figure 3. Temperature distribution in soil body (t=400 days)

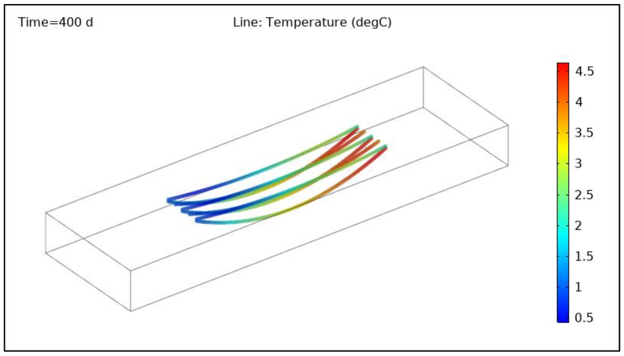

Figure 4. Temperature distribution at GHEs (t=400 days)

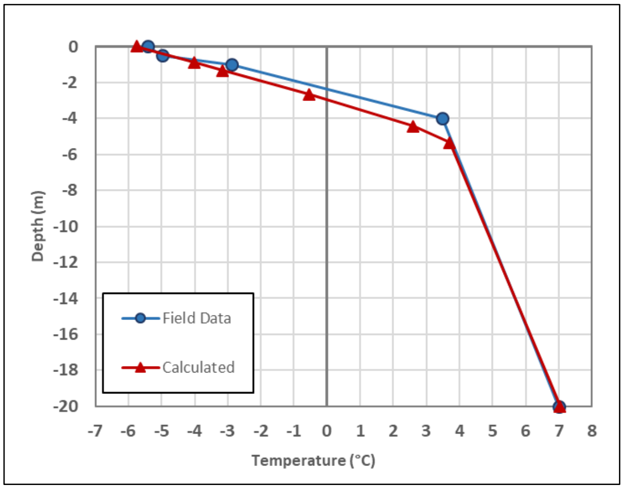

Figure 5. Verification of ground temperature profile (t=60 days)

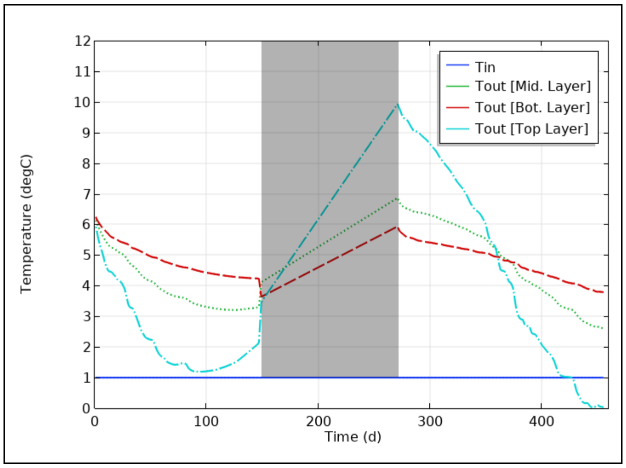

Figure 6. Inflow and outflow temperatures (Case 1)

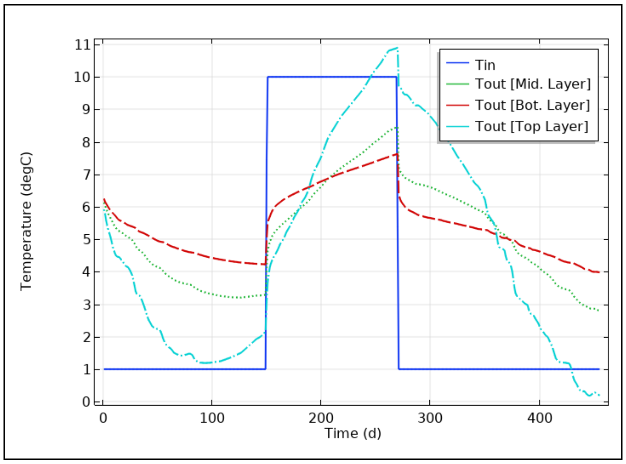

Figure 7. Inflow and outflow temperatures (Case 2)

The calculated heat extraction/injection powers of GHEs are shown in Figure 8 and Figure 9, for the two scenarios. The figures indicate that GHEs of different depths had different thermal responses. The results for Case 1 (Figure 8) show that in the 270th day (early October), the top layer (at 4.5 m) had the largest extraction power among the three layers. This is due to the fact that the shallow ground still stored heat from the previous summer. The extraction power of the top GHEs then decreased to the point that after the 365th day (early January), they produced less power than the bottom GHEs, and after 400 days (March), their extraction power dropped to zero. On the other hand, the bottom GHEs provided steadier power throughout the year.

The maximum heating power of 1800W was reached per GHE pipe. Although the average was noticeably lower, the total power of the system can be significant, considering the fact that the system consists of several GHEs (30, in this case). However, the efficiency of the system is not 100%, due to heat loss in the other parts of the system.

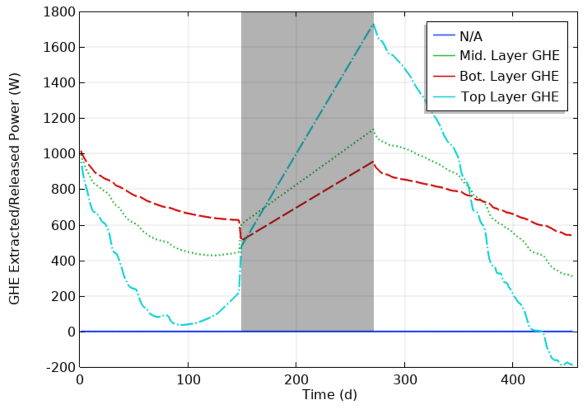

Figure 8. Thermal extraction/injection power per GHE (Case 1)

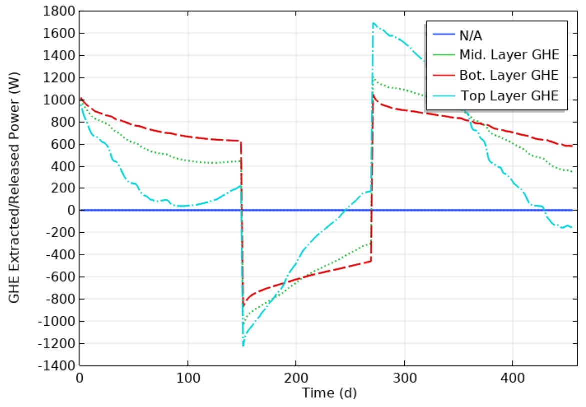

Figure 9. Thermal extraction/injection power per GHE (Case 2)

The results of the second operation scenario (Figure 9) show a similar response regarding the depth of exchangers. Therefore, deeper GHEs are preferred, as they are more stable. However, their implementation may not be feasible due to construction costs and site-specific conditions.

It also shows that a reversed cycle during summer can be used to extract heat from the building and inject it to the ground. Cooling powers up to 1200 W were reached, per exchanger.

## 5 CONCLUSION

The performance of a closed-loop GSHP system was investigated by conducting 3D finite element simulations. The verified results indicate that such simulations provide detailed predictions about the performance of GSHP systems throughout the year.

Comparing the two operation scenarios, it was also shown that GSHP systems can be used as an environmentally-friendly HVAC technology. By running the heat pump with the electricity from renewable sources such as hydroelectricity or solar, these systems will have zero carbon footprint.

As suggestions for future studies, long-term effects of heat extraction/injection should be studied by running the simulations for longer periods, since the performance of the system may change after using it for several years.

Moreover, this study was carried out by assuming the fluid flows equally in all GHEs. In reality, the flow rates vary due to different lengths of exchangers. A pipe flow analysis enables the calculation of flow rate in each pipe, resulting in more realistic outcomes.

The dimensions and arrangements of the system, e.g., the length of GHEs, can significantly affect the outcomes. Therefore, several models with different parameters should be simulated, to find how they affect the system capacity.

## REFERENCES

Amestoy, P. R., Duff, I. S., & L'excellent, J.-Y. 2000. Multifrontal parallel distributed symmetric and unsymmetric solvers. *Computer Methods in Applied Mechanics and Engineering*, *184*(2–4), 501–520.

Saaly M., Bobko K., Maghoul P., Kavgic M. 2019. Energy Performance of Below-Grade Envelope of an Institutional Building in Cold Regions. *International Journal of Building Engineering (Elsevier)*, Under Review.

Brandl, H. 2006. Energy foundations and other thermo-active ground structures. *Geotechnique*, *56*(2), 81–122.

Ferguson, G., & Woodbury, A. D. 2004. Subsurface heat flow in an urban environment. *Journal of Geophysical Research: Solid Earth*, *109*(B2).

Omer, A. M. 2008. Ground-source heat pumps systems and applications. *Renewable and Sustainable Energy Reviews*, *12*(2), 344–371.

Pérez-Lombard, L., Ortiz, J., & Pout, C. 2008. A review on buildings energy consumption information. *Energy and Buildings*, *40*(3), 394–398.