Experimental and numerical investigation of a thermal storage medium for ground source heat pump applications

A Mwesigye1, H V Nguyen1, D Salt2, Reza Daneshazarian1 and S B Dworkin1,*

1 Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, Canada
2 Capture Technologies, McMaster Innovation Park, 175 Longwood Road, Hamilton, Ontario, Canada
* seth.dworkin@ryerson.ca

Abstract. As a means of improving performance and alleviating thermal imbalance issues associated with ground source heat pump systems, ground thermal energy storage is becoming increasingly appealing. Moreover, an efficient means of transferring energy from the borehole to the surroundings is crucial. In this paper, an experimental and numerical investigation of the performance of a thermal storage medium for ground source heat pump applications is presented. A thermal storage tank of 1 m diameter and 1.5 m height equipped with temperature sensors at different radial positions and depths was used. It incorporates a 150 mm-diameter steel pipe in which a 25.4 mm u-shaped pipe is placed to emulate a borehole. A numerical model was developed using a finite element-based approach and validated with the obtained experimental data. Different bentonite-sand mixtures with varying thermal conductivities were considered inside and around the emulated borehole. A reduction in the tank temperature difference of about 57% was achieved by using bentonite-sand mixtures inside the borehole and around the borehole (in the tank) compared to using only bentonite inside the borehole and sand around the borehole. Results further show that the heat transfer performance increases by about 320% with the use of the bentonite-sand mixtures compared to the separated bentonite and sand arrangement. Moreover, the potential for energy storage with phase change material around the emulated borehole has been demonstrated.

1. Introduction

Buildings and buildings construction are said to account for about 36% of the global total energy consumption and 40% of the total direct and indirect CO2 emissions [1]. As such, there are several efforts to reduce the energy consumption and emissions from the buildings sector. Ground source heat pumps (GSHPs) are among the technologies with the potential to provide significant energy savings and CO2 reductions. They rely on the stable ground temperatures to supply the required heating and cooling throughout the year with minimum energy consumption. As the temperature remains stable, GSHPs do not suffer from low performance when the ambient temperatures reduce to very low values or increase to very high values during the summer. However, despite these benefits, GSHPs are not widely used owing to the high capital costs, primarily the expense of the required drilling. The other challenge further inhibiting the wide adoption of GSHPs include poorly balanced heating and cooling demands that result in ground thermal imbalance, which leads to reduced performance over time and could also lead to failure of these systems. In addition, lack of space in densely populated areas [2] is another issue hindering the use of GSHPs. Significant research and development efforts are underway to address these challenges and increase the use of GSHPs.

Ground thermal conductivity plays an important role in the performance of a ground source heat pump system. As such, site specific thermal conductivity measurements become essential in the design of these systems. Several studies on the determination of ground thermal conductivities can be found in the literature [3,4]. The performance of GSHPs is limited by the thermal properties of the soil surrounding the borehole and the grouting material used. To improve performance, several studies have
considered improving the thermal conductivities of backfill materials. Among these, sand-bentonite mixtures have been widely considered given their low cost and better thermal properties. Wang et al. [5] considered the potential of sand-bentonite backfill material to improve the performance of a borehole heat exchanger. Heat extraction and injection rates were enhanced by 22.2% and 31.2%, respectively using the optimal sand-bentonite mixture of 10-12% bentonite by dry mass in sand. Erol and François [6] considered different grouting materials and further investigated the potential enhancement with the use of graphite powder in the grouts. Fabien et al. [7] considered the enhancement of the thermal conductivity of bentonite grouts using graphite. Significant improvement in performance was obtained.

In other studies, use of phase change material to improve thermal performance, reduce heat transfer fluid volume and decrease pumping costs has been considered. Kong et al. [8] considered the use of phase change material slurry as the heat transfer fluid in the ground heat exchanger. However, the coefficient of performance was enhanced by only 4.9%. It has also been shown that in addition to improving the thermal performance, using phase change material leads to better ground temperature thermal balance [9–11].

In most studies, only the influence of backfill material properties on the performance of GSHPs is investigated. Moreover, the influence of the combination of high thermal conductivity materials with phase change material on the performance of GSHPs has not been widely investigated. In this study, the performance of a thermal storage medium was investigated with different combinations of sand-bentonite mixtures as backfill material and as material in the domain around the borehole. Furthermore, the potential for energy storage using phase change material was considered.

2. Experimental setup and procedure
The experimental setup used in this study consists of a steel tank 1.5 m high and 1 m in diameter as shown in Fig. 1(a). At the centre of the tank is a 150 mm diameter steel pipe closed at the bottom end to emulate a borehole. Inside the steel pipe is a 2.54 cm-diameter u-loop heat exchanger made from cross-linked polyethylene (SDR 9 PEX) and grouting material. The steel tube contains bentonite or a bentonite-sand mixture and is surrounded by sand. The tank was instrumented with temperature sensors as shown in Fig. 1(a) and (b). Sensors for determining tank temperature distribution are located at 0.254 m (upper layer), 0.508 m (middle layer) and 1.16 m (bottom layer) from the top of the tank at angular positions of 0°, 120° and 240° as shown in Figs. 1(a) and (b). At each height and angular position, three temperature sensors are used except for the upper layer at 240° where nine temperature sensors were used. In addition, two temperature sensors were also to measure the temperature inside the borehole and on the outer surface of the borehole. Inlet water at controlled inlet temperatures from a hot water tank was circulated through the u-loop heat exchanger. Inlet and outlet temperatures from the u-loop heat exchanger were measured.
were also measured and used in the determination of the energy transfer to and from the tank. Readings of the temperature sensors were recorded by the data acquisition system at intervals of 30 seconds over a 10-day period. The temperature sensors are accurate to within ±0.2°C.

Figure 1(c) shows the actual tank after instrumentation and loading of the materials. The tank’s outer surface was insulated with low thermal conductivity material - Styrofoam. Before the tank was loaded with sand, a layer of insulation was placed at the bottom and another layer was applied at the top after filling it with sand. The base materials used in the experiment are shown in Table 1. The properties of the different sand-bentonite mixtures used are provided in the product datasheet of the supplier [12].

The tank allows for laboratory scale testing of different materials in order to characterize heat transfer performance and the potential for energy storage with phase change material. Moreover, experimental results obtained are useful as a first step in validating numerical models for large scale GSHP systems.

| Material           | Density (kg/m³) | Thermal conductivity (W m⁻¹K⁻¹) | Specific heat capacity (J kg⁻¹K⁻¹) |
|--------------------|----------------|---------------------------------|-----------------------------------|
| Sand               | 2623           | 0.15                            | 827                               |
| Bentonite powder   | 1210           | 0.695                           | 1724                              |
| U-loop pipe        | 1009           | 0.41                            | 1958                              |
| Styrofoam          | 30             | 0.026                           | 1131                              |
| Water              | 1000           | 0.631                           | 4180                              |

3. Numerical model development
To study the performance with different materials, a numerical model was developed and validated using the obtained experimental results. The governing equations, the boundary conditions, solution procedure for the numerical model are described in this section.

3.1 Governing equations
The numerical model is based on the finite element method and was implemented in COMSOL Multiphysics® [13]. In developing the numerical model, the following assumptions were made: (i) The fluid flowing through the u-tube heat exchanger is Newtonian and incompressible, (ii) the effect of gravity on flow is negligible, and (iii) the flow is turbulent and one dimensional.

Heat transfer in solids and heat transfer in pipes were solved in this multiphysics problem. The conservation of energy equation representing heat conduction in an isotropic and continuous medium is

\[ \rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \]  

(1)

In which, \( \rho \) is the density, \( C_p \) is the specific heat capacity, \( T \) is the temperature, \( k \) is the thermal conductivity, and \( t \) is time. Equation (1) represents the energy conservation for a material with a constant specific heat capacity.

Fluid flow in the u-loop was modelled using the heat transfer in pipes model [13]. With this approach, the cross-section of the pipe, the thermal conductivity and the Nusselt number are specified. The Nusselt number for turbulent flow is given as a function of the Prandtl number and the Reynolds number as

\[ Nu = 0.027 \text{ Re}^{0.8} \text{ Pr}^{0.4} \]  

(2)

3.2 Boundary conditions
The boundary conditions used were: (i) At the inlet of the u-loop heat exchanger, an inlet boundary condition was used. An inlet velocity and inlet temperature were specified. (ii) A pressure outlet boundary condition was used together with an outflow boundary condition for the fully developed flow at the outlet of the u-loop heat exchanger. (iii) The walls of the tank are insulated; this insulation has been modelled by subjecting the outer wall of the tank to a very small convective heat flux (1.5 W m⁻²K⁻¹) and taking the upstream temperature to be the same as the ambient temperature.

3.3 Solution procedure
The numerical solution was obtained using COMSOL Multiphysics® [13]. The geometry of the tank as well as the mesh were built in COMSOL model builder. To ensure a solution that is mesh independent,
several mesh configurations were considered. Coarse, fine, extra fine and extremely fine grids were considered. The fine, extra fine and extremely fine meshes gave almost the same temperature distribution and energy transfer rates, to within less than 1%. Therefore, in the study, the extra fine mesh was considered sufficiently accurate. Both the stationary and time dependent solvers were considered. A fully coupled solver was adopted for the solution. The phase change material was implemented using the phase change model in COMSOL [13] by specifying the latent heat, melting temperature and the material properties.

4. Results and discussion

4.1 Validation of the numerical model

Figure 2(a) shows experimental and numerical results of the temperature distribution in the tank indicated by top level sensors at 240°. As shown, the experimental and numerical results are in excellent agreement – the numerical results are within ±0.5% of the experimental values. To validate the transient model, the inlet temperature to the tank was set in such a way that it fluctuates about a mean value by ±4°C. This was to ensure that the model can predict performance of actual GSHPs where the inlet temperatures to the ground vary with the building loads. The developed model predicts this transient performance excellently as Fig. 2(b) shows. In the transient simulation, actual inlet temperatures obtained experimentally were used with the inlet boundary condition.

![Figure 2. Validation of the developed numerical model with, \(k_b = 1.19\) W m\(^{-1}\)K\(^{-1}\) and \(k_s = 0.15\) W m\(^{-1}\)K\(^{-1}\) (a) Temperature distribution for the upper level sensor at 240° with \(T_{amb} = 296.77\) K, and (b) transient performance.](image)

4.2 Tank temperature distribution

In the investigation of the performance of ground source heat pump systems, it is always important to understand how the rejection and extraction of heat from the ground affects the ground temperature distribution. With this, it is possible to determine whether thermal imbalance exists with rejection and extraction of heat. In this study, the different sensors at different heights and different radial positions in the tank give the temperature distribution. As Fig. 2(a) and (3) show, the temperature is higher in the vicinity of the borehole, reducing to near ambient values as the radial position of the sensor increases.

![Figure 3. Temperature distribution with different materials.](image)
4.3 Influence of material properties

Figure 3 shows the influence of different materials on the temperature distribution (subscript $s$ represents the volume around the borehole and $b$, inside the borehole). In this study, the materials considered are different mixtures of bentonite, sand and water [12]. An additional combination with tank material thermal conductivity, $k_s = 4.02 \text{ W m}^{-1}\text{K}^{-1}$ and borehole material thermal conductivity, $k_b = 1.19 \text{ W m}^{-1}\text{K}^{-1}$ is added. Higher thermal conductivities greater than those of bentonite-sand mixtures are possible with the use of nanoparticles or carbon nanofibers as considered in studies by collaborating researchers [14]. As depicted in Fig. 3, increasing the thermal conductivity of the materials used improves the heat transfer performance. The temperature difference between the inlet temperature and the minimum tank temperature is shown to reduce as the heat transfer performance rises with increasing thermal conductivities. This is expected since the temperature difference and the thermal conductivity are inversely proportional.

The transient energy transfer rate has been determined by running the experiment and the numerical model for about 10 days. The obtained data was used to validate the developed transient model. Figure 4 shows the variation of the energy transfer rate for the different materials considered between 65 and 75 hours obtained numerically. The same variation was obtained at the other time intervals.

As expected, the energy transfer rate increases as the thermal conductivity increases. The material combination having borehole material with $k_b = 1.19 \text{ W m}^{-1}\text{K}^{-1}$ and tank material with $k_s = 4.02 \text{ W m}^{-1}\text{K}^{-1}$ showed the highest performance. The energy transfer rate increases by about 320% as the material arrangements change from the base materials with $k_b = 1.19 \text{ W m}^{-1}\text{K}^{-1}$ and $k_s = 0.15 \text{ W m}^{-1}\text{K}^{-1}$ to $k_b = 1.19 \text{ W m}^{-1}\text{K}^{-1}$ and $k_s = 4.02 \text{ W m}^{-1}\text{K}^{-1}$. The increase in the energy transfer rate with $k_s = 4.02 \text{ W m}^{-1}\text{K}^{-1}$ is about 50% more than that when a thermal conductivity of sand, $k_s = 1.52 \text{ W m}^{-1}\text{K}^{-1}$ is considered. For the same loads, higher thermal conductivities would translate into reduced borehole depths and thus cost savings.

4.4 Energy storage using phase change material

The potential for thermal energy storage was investigated both experimentally and numerically. A paraffin wax, PCM24 with a melting temperature of 24°C was used in the experimental investigations. This melting temperature was selected based on the prevailing ambient temperatures, lower melting temperatures could be used in field applications depending on the heating and cooling loads. Nine 5.08 cm pipes, filled with phase change material were installed in the test tank at 5.08 cm from the steel pipe that emulates the borehole. The density of the phase change material is 790 kg/m$^3$, the thermal conductivity is 0.25 W m$^{-1}$K$^{-1}$ and the specific heat capacity is 2200 J kg$^{-1}$K$^{-1}$. A comparison of the developed numerical model and the obtained experimental results showed good agreement. A further comparison of the performance with and without phase change material indicates that energy is stored during the charging phase and released during the discharging phase as Fig. 5 shows. When fully melted, the energy stored and later discharged by the phase change material is about 136 500 kJ per m$^3$ of the phase change material used. For the 5.56×10$^{-3}$ m$^3$ of phase change material used in the tank, the energy stored is about 760 kJ. It is this ability to store energy that makes the use of phase change material appealing in GSHPs to alleviate ground thermal imbalance issues, especially when heating and cooling loads vary.
5. Conclusion

In this study, the performance of a thermal energy storage medium consisting of a laboratory scale tank with a u-loop heat exchanger that emulates a single borehole for GSHP applications has been investigated experimentally and numerically. Different combinations of materials with varying thermal physical properties have been examined for use inside and around the emulated borehole. Moreover, the potential improvement in performance with phase change material has also been explored. As the thermal conductivity of the materials used increases, the heat transfer rate is shown to increase and the temperature difference between the borehole and the surroundings decreases. The heat transfer rate increases by about 320% as the thermal conductivities change from $k_s = 0.15 \text{ W m}^{-1}\text{K}^{-1}$ and $k_b = 0.69 \text{ W m}^{-1}\text{K}^{-1}$ to $k_s = 4.02 \text{ W m}^{-1}\text{K}^{-1}$ and $k_b =1.19 \text{ W m}^{-1}\text{K}^{-1}$. In addition, using phase change material, the energy extraction rate increases as it is absorbed and stored when the phase change material melts. The stored energy is discharged as the phase change material becomes solid again. This potential for energy storage is thought to reduce the thermal imbalance in the ground when the heating and cooling loads vary. The potential improvement in performance and the resulting reduction in thermal imbalance is a subject of further investigations that are considering coupling building loads to the ground heat exchanger.

Acknowledgement

The authors acknowledge funding from the Canadian Research Chairs Program and the Natural Sciences and Engineering Research Council (NSERC). The financial support received from McClymont and Rak Engineers, Inc. is also duly acknowledged and appreciated.

References

[1] IEA 2019 Energy Efficiency: Buildings The global exchange for energy efficiency policies, data and analysis. https://www.iea.org/topics/energyefficiency/buildings [accessed 14.02.2019].
[2] Law Y L E and Dwarkin S B 2016 Characterization of the effects of borehole configuration and interference with long term ground temperature modelling of ground source heat pumps Appl. Energy 179 1032–47.
[3] Spiteri J D and Gehlin S E A 2015 Thermal response testing for ground source heat pump systems—An historical review Renew. Sustain. Energy Rev. 50 1125–37.
[4] Fuji H, Okubo H, Nishi K, Ito R, Ohyama K and Shibata K 2009 An improved thermal response test for U-tube ground heat exchanger based on optical fiber thermometers Geothermics 38 399–406.
[5] Wang H, Cui Y and Qi C 2013 Effects of Sand–Bentonite Backfill Materials on the Thermal Performance of Borehole Heat Exchangers Heat Transf. Eng. 34 37–44.
[6] Erol S and François B 2014 Efficiency of various grouting materials for borehole heat exchangers Appl. Therm. Eng. 70 788–99.
[7] Delaleux F, Py X, Olives R and Dominguez A 2012 Enhancement of geothermal borehole heat exchangers performances by improvement of bentonite grouts conductivity Appl. Therm. Eng. 33–34 92–9.
[8] Kong M, Alvarado J L, Thies C, Morefield S and Marsh C P 2017 Field evaluation of microencapsulated phase change material slurry in ground source heat pump systems Energy 122 691–700.
[9] Bottarelli M, Bortoloni M, Su Y, Yousif C, Aydn A A and Georgiev A 2015 Numerical analysis of a novel ground heat exchanger coupled with phase change materials Spec. Issue Int. Heat Transf. Symp. 2014 88 369–75.
[10] Qi D, Pu L, Sun F and Li Y 2016 Numerical investigation on thermal performance of ground heat exchangers using phase change materials as grout for ground source heat pump system Appl. Therm. Eng. 106 1023–32.
[11] Chen F, Mao J, Chen S, Li C, Hou P and Liao L 2018 Efficiency analysis of utilizing phase change materials as grout for a vertical U-tube heat exchanger coupled ground source heat pump system Appl. Therm. Eng. 130 698–709.
[12] Baroid Industrial Drilling Products 2011 BAROTHERM® GOLD-Two part thermally conductive grout, Product Service Line, Houston, Texas.
[13] COMSOL Multiphysics® v. 5.3. www.comsol.com, COMSOL AB, Stockholm, Sweden.
[14] Eric T and Peijun G 2014 Thermal Conductivity of Bentonite Grout Containing Graphite or Chopped Carbon Fibers J. Mater. Civ. Eng. 26 6014013.