Improvement Of Thermal Conductivity Of Grout Mixture For Geothermal Heat Pump Systems

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ABSTRACT

A vertical geothermal probe consists of two or four polyethylene tubes U-shaped, used for circulating the coolant between the heat pump and the ground. It is installed in a deep borehole and sealed in a special grout, a kind of liquid cement, used to seal the borehole, and avoid the presence of air bags between the probe and the ground. Moreover, the grout provides a heat transfer medium between the geothermal probe and surrounding.

The main cost in a geothermal installation is drilling itself. Reducing the heat exchanger length, and thus reducing the depth of the borehole is an interesting solution to reduce the cost of the installation. The conventional cement grout has low thermal conductivity varying between 0.8 and 1 W/m.K, which leads to high heat exchanger length. Increasing this thermal conductivity, permit the improvement the heat transfer between the soil and the probe, thus reducing the heat exchanger length.

Laboratory studies were undertaken to determine the thermal conductivity of various grout mixture. Such as cementitious grout with bentonite, silica sand and graphite. A thermal modeling of the soil, the grout and the heat exchanger was conducted.

Experimental results shows that thermal conductivity of the grout can be increased up to 4 W/m.K. The simulation results shows that the reduction in required borehole length was predicted theoretically for an example heat pump system and found to reach 20%, depending on the soil thermal conductivity and borehole diameter.

1. INTRODUCTION

Geothermal energy is the heat energy contained in the Earth, specifically in the part accessible by current technology ie the entire basement area up to about 10 km depth.

Geothermal energy is a free source of energy that can be exploited in different forms depending on its temperature level. We can recognize three technology categories: Heating and cooling buildings via geothermal heat pumps that utilize shallow sources; Heating structures with direct-use applications; and Generating electricity through indirect use.

A geothermal heat pump system is made up of several key components including: the ground loop; the heat pump and the heat delivery system. The ground loop is a system of pipes that is buried in the shallow ground. A fluid circulates through the ground loop to absorb or release heat within the ground.

Most probes drilled are installed at a depth between 50 and 200 meters to operate a heat between 10 to 20 ° C. Generally, it would be better to drill down to reach higher temperatures, but the chosen depth is usually a compromise between the cost of drilling and probe, and the amount of electricity needed to run the pump which transfers the heat of from the basement to the building.

For a well-insulated family home, a single drill between 120 and 150 m is usually sufficient, where a vertical geothermal probe is sealed in a double pipe that descends and goes up. The working fluid, usually water, is the heat transfer medium between the soil and the building. If the heat recovered is not sufficient, in this case 2 probes are installed. The material used for the realization of a geothermal probe is simple; it is composed of polyethylene pipes coated in a sealing grout called bentonite.

The bentonite provides a heat transfer medium between the geothermal probe and surrounding. The conventional cement grout has low thermal conductivity varying between 0.8 and 1 W/m.K, which leads to high heat exchanger
length. Increasing this thermal conductivity, permit the improvement the heat transfer between the soil and the probe, thus reducing the heat exchanger length.

In this paper, an experimental study was performed to measure the thermal conductivity of various grout mixture. Such as cementitious grout, with silica sand, Axilat and graphite. Experimental results shows that thermal conductivity of the grout can be increased up to 4 W/m.K.

A thermal modeling of the soil, the grout and the heat exchanger was conducted. The simulation results shows that the reduction in required borehole length was predicted theoretically for an example heat pump system and found to reach 20%, depending on the soil thermal conductivity and borehole diameter.

2. EXPERIMENTAL APPARATUS

Several standards exist for measuring the thermal conductivity of materials, such as; IEEE Standard 442-1981, ASTM Standard D5334-08 and others. Based on these standards, an experimental apparatus was built in order to measure the thermal conductivity of various composition of grout mixture. The objective of this experimental study is to improve the thermal conductivity of the sealing cement in order to enhance the heat flux exchanged between soil and geothermal probes.

2.1 Description of the test bench

Figure 1 shows the scheme of an experimental apparatus developed to measure the heat conducting properties of different grout mixture. Test samples were placed in a cylindrical container insulated on the lateral surface. The sample is placed on a heat source delivering Q the quantity of heat, flowing through the cross section S.

![Figure 1: Scheme of the test bench](image)

The heat flux can be measured directly by measuring the electrical power supplied to the heater. The voltage supplied to the heater is varied in order to vary the heat flux. The heat flux flowing through the lateral surface of the sample is neglected, to consider that the heat flux delivered by the heater is axial. It propagates in the sample and is evacuated at the atmosphere by natural convection.

Four thermocouples are placed in the middle of the sample, where the temperature is measured. Thermal conductivity of the sample is measured at steady state, when the temperature measured at different points become constant. When the steady state is reached, thermal conductivity is calculated as following:

$$\lambda = \frac{Q \cdot \Delta x}{S \cdot \Delta T}$$  

(1)

Where; Q is the heat flux (W), S is the cross section (m2), Δx is the distance between two thermocouples, ΔT is the temperature gradient between two thermocouples.

2.2 Experimental results
Prior to the measurement of the thermal conductivity of the samples, we calibrated the different probes and the heat loss of the device. The thermal conductivity of different composition of bentonite was measured in the experimental device. Starting with cement as a product of base bentonite, we added a variety of components in cement such as silica sand, axilat and graphite to study their effect on the thermal conductivity of the mixture (M Jobmann, G Buntebarth (2009), A.M Tang, Y.J Cui, T.T Le (2008)). The effect of water content was evaluated and discussed as well.

2.2.1 Effect of Axilat on thermal conductivity of bentonite mixture: First dry bentonite composed of 40% of cement, 52% of Silica sand was tested. Then we added 0.5% of Axilat to the mixture, both tested without any water addition. After we measured the thermal conductivity of the composition were we added 5, 10 and 15 % of water. The wet mixture was dried and the thermal conductivity was tested 28 days after. By that time, the mechanical properties of the bentonite reaches there limit. Results are presented in figure 2.

![Figure 2: Thermal conductivity of bentonite](image)

Figure 2 shows the thermal conductivity of several test conducted by varying the heat source capacity between 10 and 100 W. The figure shows that the addition of axilat has improved the thermal conductivity of the bentonite from 1 W/m.K to 4 W/m.K. While water addition has reduced this property. In conventional applications, water content in the mixture should be around 12% in order to keep high viscosity of the bentonite, in order to pump it in the borehole without breaking the pump. Table 1 shows the average values of the measured thermal conductivity of the samples.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Sample composition</th>
<th>Thermal Conductivity (W/m.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Bentonite (or Cement and Silica sand)</td>
<td>1.09</td>
</tr>
<tr>
<td>B</td>
<td>Bentonite + 0.5% Axilat + 0 % water</td>
<td>4.00</td>
</tr>
<tr>
<td>C</td>
<td>Bentonite + 0.5% Axilat + 5 % water</td>
<td>3.42</td>
</tr>
<tr>
<td>D</td>
<td>Bentonite + 0.5% Axilat + 10 % water</td>
<td>3.28</td>
</tr>
<tr>
<td>E</td>
<td>Bentonite + 0.5% Axilat + 15 % water</td>
<td>2.63</td>
</tr>
</tbody>
</table>

2.2.2 Effect of graphite on thermal conductivity of bentonite mixture: Several types of graphite shaping are possible. A.M Tang and Y.J Cui, T.T Le (2008) have studied the effect of two forms of graphite: the glitz and expanded natural graphite (ENG). They tested the performance of several sizes of graphite flakes, were they found that the best results were reached with 5% of ENG having a density of 100 kg/m3. M. Jobmann et al (2009) have studied the effect of graphite doping on the thermal conductivity of bentonite, and they developed a correlation between the thermal conductivity of the composite and the amount of dopant such as:

$$\lambda = \frac{c_1}{1 + \exp[-c_2 \cdot (q - c_3)]}$$  \hspace{1cm} (2)

Where; $c_1 = 11.74$ ; $c_2 = 0.079$ et $c_3 = 30.74$, and q is the percentage of graphite in the grout.
In this study, we wanted to evaluate the impact of graphite doping on the grout composition number “D”. Tests were conducted using different amounts of ENG100. Results are shown in figure 3, they are compared to the correlation developed by M. Jobmann et al. The figure shows that graphite has positive effect on the grout thermal conductivity, increasing it three times when the doping amount reaches 20%. However, the comparison between the experimental results and the correlation shows that the effect of doping the grout with graphite has the same trend developed by the correlation. The addition of graphite to the grout increases its viscosity, thus the amount of grout in the mixture should be limited.

![Figure 3: Effect of ENG100 doping on the thermal conductivity of the grout](image)

3. THERMAL MODELING OF THE GEOTHERMAL PROBE

3.1 Description of the geothermal probe installation
A thermal model of the ground was developed. A geothermal probe composed of a polyethylene tube of 40 mm in diameter and 4 mm thick, is installed in a borehole of 30 cm in diameter. The tube is fixed by the grout. The vertical probe depth is 100 m. For a double probe we consider two boreholes of 30 cm in diameter each. Figure 4 shows a schematic representation of the geothermal probe.

![Figure 4: Schematic representation of the ground](image)

3.2 Modeling of the ground temperature variation
3.2.1 Modeling of the ambient air temperature: The evaluation of the potential of the use of appropriate probe length for geothermal energy and technology for its operation requires the determination of variations of the ground temperature at different depths all over the year. These variations are obtained by applying a simple model and using the soil properties and ambient temperatures. Daily ambient temperatures during a typical year were considered. To facilitate the use of these data, in the calculations, we adequately represented the temperature changes as a function of time (days) by a cosine function (Figure 5):

\[ T(t) = T_{av} + A \cos(\omega(t - t_0)) \]  

(3)

Where:
\( \omega \): angular frequency equal to 0.0172 rad / day, which corresponds to a period of 365 days.
\( T_{av} \): Average annual temperature
\( A \): Amplitude of the temperature variation
\( t_0 \): Day of the year when the maximum temperature is reached
These three parameters are obtained by smoothing the temperature data. Values are obtained from Meteonorm for the city of Beirut – Lebanon. These functions will be used below as boundary conditions in determining spatial -temporal distributions of ground temperature.

![Figure 5: Daily variation of ambient temperature](image)

3.2.2 Modeling of the soil temperature: In the case of vertical geothermal probe, we are interested to the first 100 meters below the ground surface. The soil is considered a semi-infinite medium and the supposed one-dimensional problem (Benhammoul et Draoui (2011)). The heat transfer is conduction dominant fashion. Assuming a homogeneous medium, the unsteady heat equation in this case is written as:

\[ \frac{\partial^2 T}{\partial z^2} = \frac{1}{a} \frac{\partial T}{\partial t} \]  \hspace{1cm} (4)

With;

- T: Temperature of the soil, a function of t and z (° C)
- t: Time (s)
- z: Depth below ground surface (m)
- a: Thermal diffusivity (m² / s)

To solve this differential equation, we need to prescribe initial and boundary conditions. We consider on the surface a cosine function for ambient temperature variation. The solution of the heat equation (4) with initial and boundary conditions introduced above provides the following spatial and temporal distribution of soil temperature:

\[ T(z, t) = T_{av} + A \exp \left( -\frac{z}{d} \right) \cos \left( \omega (t - t_0) - \frac{z}{d} \right) \]  \hspace{1cm} (5)

Where; d is the penetration depth (m) of the wave of heat in the soil. It is given by:

\[ d = \sqrt{\frac{2a}{\omega}} \]

The diffusivity depends on the nature of the soil. The National Geothermal Resource Assessment for Lebanon has discussed the different compositions of the outer layer of the Lebanese basement, taking into account their possible water content. 25 rock samples of the representative geological formations have been collected in Lebanon. The measured thermal conductivity of the rock samples varies between 1 and 6 W/m.K with a thermal diffusivity varying between 0.26 x 10⁻⁶ and 3 x 10⁻⁶ m²/s.

Figure 6 shows the temperature variation along the year, at different depth. These results are obtained by solving equation (5). As it can be seen, the soil temperature depends on the ambient temperature in the first layers and become constant, close to the annual average temperature of ambient air at 10 m depth.
3.2.3 Modeling of the borehole thermal behavior: The heat flux exchanged between the soil and the water glycol flowing in the tube is expressed in equation (6) as function of the temperature difference between the soil and the water and the thermal resistance of the borehole R.

\[ Q = \frac{(T_{r4} - T_0)}{R} \]  \hspace{1cm} (6)

The thermal resistance of the borehole is equal to the sum of the thermal resistances of the polyethylene tube, the grout and the soil. Figure 7 shows the temperature profile obtained between the flowing water in the tube and the soil. The origin of the graph corresponds to the centre of the tube. We can see that the most important thermal gradient is in the grout, which has a thermal conductivity between 1.5 and 2 W.m⁻¹.K⁻¹. Grout is a kind of cement, enhancing its thermal conductivity seems to be a solution to increase the heat transfer.

We have increased the thermal conductivity of the grout to see its effect on the heat transfer between the soil and the water flux. These results are shown in figure 8. For a conventional conductivity value, the thermal gradient observed in the grout is of the order of 7 °C, and then decreases sharply to 2.5 °C at 4W/m.K, and then stabilized to 1 °C for \( \lambda = 10 \) W/m.K. For this value of conductivity, the limiting factor is not the grout but the soil itself.

We find this trend in figure 9, the overall thermal resistance of a conventional geothermal borehole of 160 mm diameter decrease when the conductivity of grout increases to stabilize for a value of \( \lambda \) between 4 to 5W/m.K. At this value, it is very clear that the grout is no longer the main thermal resistance of borehole and will allow as shown in figure 9, a significant gain of linear power extracted.
Increasing the thermal conductivity of the grout from its initial value around 1 W/m.K to a value of 6 W/m.K, allows a power gain of about 50%. So we can set as a goal to study the target value of $\lambda$ to reach is 6 W/m.K. This value seems to be a good compromise.

Figure 9: Thermal behavior of the borehole

3.3.4 Improvement of the heat pump (HP) performance: We studied the impact of the linear power extraction increase from the soil for a constant probe depth of 100 m, on the performance of the heat pump. We developed a simple model for a HP on Refprop and we calculated the improvement of COP with the increase of the water temperature exiting the geothermal probe. Figure 10 shows that the COP increases 3.5% when $\lambda$ reaches 6 W/m.K. For greater values of $\lambda$ around 10 W/m.K, the HP performance is improved for about 1%. This proves that the optimal thermal conductivity of grout is around 6 W/m.K. However, if we decide to keep constant the COP of the pump, we can decrease the probe depth by 33% with a thermal conductivity value of 6 W/m.K, and thus reduce the cost of the drilling and the probe installation.

Figure 10: HP performance improvement as a function of the grout thermal conductivity
6. CONCLUSIONS
In this paper we investigated the importance of increasing the thermal conductivity of the grout to improve the heat transfer between the soil and the geothermal probe. Laboratory studies were undertaken to determine the thermal conductivity of various grout mixture. The experimental results have shown that the thermal conductivity can reach almost 4 W/m.K without graphite doping. Graphite doping improves further the thermal conductivity of grout. A thermal modeling of the soil, the grout and the geothermal probe was conducted. A thermal conductivity of the grout close to 6 W/m.K seems to be a good compromise, where we found that at higher values, the thermal properties of the soil become the limiting factor. This conductivity value of grout, increases of 50% linear power extracted from the soil and reduce the length of the geothermal probe around 33%, thus reducing the investment costs of a geothermal installation.

NOMENCLATURE

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Greek letters

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<tr>
<td>λ</td>
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Subscript

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