Simulation of Ground Heat Exchanger for Cryogenic Applications

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Abstract: Ground freezing techniques using liquid nitrogen are commonly used in order to increase the mechanical properties of the soil. This article presents a new ground heat exchanger using aluminum to increase the effective radius of the heat exchanger. Simulation results indicate that the current design generates a significant thermal short-circuit between the circulation pipes that must be diminished before its commercial use.

Keywords: Ground heat exchanger, ground freezing system, lens ice, ground consolidation with liquid nitrogen.

1. Introduction

Liquid nitrogen and brine have been used for several decades to freeze the interstitial water contained in the pores of unconsolidated soils or within the fractures of rock matrix (Stross and Valk, 1979; Veranneman and Rebhan, 1979). The groundwater freezing is achieved by circulating a cooling fluid in a ground heat exchanger (GHE) usually made of a loop of copper pipe lowered in a borehole filled with mineral slurry (Pimentel et al., 2011; Ziegler et al., 2009; Frivik and Thorbergsen, 1981) (see Figure 1). The technique is used to consolidate soils and create a solid wall, allowing reparation of damaged tunnels or infrastructures located under roads and railways without interrupting the service. The technique is also used to create impervious ice curtain in aquifers to reduce the migration of contaminated groundwater.

To reduce the time required to freeze the groundwater, but also to reduce the construction and operation costs of these systems, new GHE designs are currently under study. In this work, a new GHE made of two copper pipes embedded in an aluminum extrusion is studied. The objective of this study is to numerically quantify the efficiency of a new GHE design and understand its thermal behavior.

2. Use of COMSOL Multiphysics

2.1 Geometry

The GHE modeled in this work is illustrated in Figures 1a) and 2. The model includes a pair of copper pipes in which liquid nitrogen is circulating. These pipes are embedded in an aluminum structure whose voids are filled with polystyrene to reduce thermal short circuiting. The role of the aluminum structure is to increase the effective radius of the borehole and to improve the heat transfer with the surrounding ground.

The studied GHE is 20 m long and is embedded inside a borehole of 152 mm in diameter. The latter is filled with a bentonite slurry and is surrounded by a geological domain whose outer radius is 5 m. The aluminum mold has a diameter of 92.5 mm with a wall thickness of 1.78 mm. To prevent oxidation of the copper pipes and reduce the contact resistance between the copper and the aluminum, the pipes are coated with conductive grease. Figures 1a) and 2 show a close view of the heat exchanger.

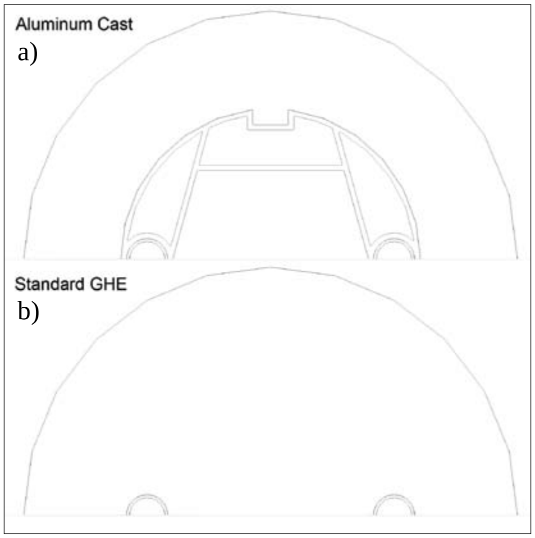

Figure 1. Ground heat exchanger made of an aluminum cast (a) and copper pipes (b).

2.2 Application Modes

Several techniques are used to model the freezing of groundwater taking into account its energy of phase change (Zhu and Michalowski, 2013; Li et al., 2011). In this work, three different application modes of COMSOL Multiphysics were used to simulate the problem. First, the heat transfer with phase change application mode was used to model the freezing ground. Then, the heat transfer in solid module was used to simulate the heat transfer in the grout filling the borehole, in the aluminum extrusion, in the polystyrene as well as in the copper pipes. Finally, to model the advection of the liquid nitrogen within the copper pipes, the heat transfer in fluids application mode was used.

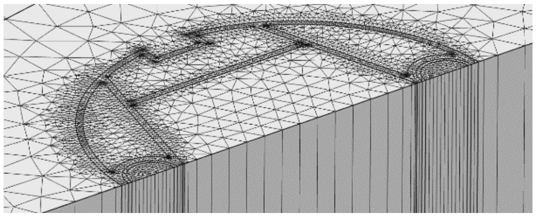

Figure 2. Geometry and mesh of the ground heat exchanger used for the simulation.

2.3 Material Properties

In order to quantify the thermal efficiency of the GHE, a simulation has been conducted with the thermal properties presented in Table 1. Since some parameters are temperature dependent, some thermal properties were represented by interpolation functions in the model. Table 1 shows, if available, the range of values used for the simulation. The experimental data used to construct these functions are coming from the National Institute of Standards and Technology (2013), the Cryogenic Data Handbook (2013) and the Copper Development Association (2013).

Note that to reduce the problem size, the thin layer of conductive grease covering the copper pipes has not been directly modeled. Instead, its thermal properties were mixed together with the corresponding properties of the copper to obtain an equivalent property.

The thermal conductivity of the fluid was increased in the horizontal plane to account for a turbulent flow in the pipes. The phase change of the nitrogen and the groundwater flow are not taken into account in this simulation.

2.4 Initial and Boundary Conditions

The initial temperature within the domains is set to 10°C (283.15K). The far field temperature is represented by a Dirichlet boundary condition of 10°C along the outer boundaries (r=5 m).

To model the vertical advection of the liquid nitrogen, upward or downward velocity field is used. The supply of liquid nitrogen at the top of the downward pipe is model by a Dirichlet boundary condition of -196.15 °C (77 K).

The U-loop at the base of the GHE is modeled by an outflow boundary condition for the downward pipe while the base of the upward pipe is modeled by a Dirichlet boundary condition. A probe is used to link the previous two boundary conditions.

The surface boundary at z=0 m and the symmetry plane are considered perfectly insulated. Finally, the geothermal heat flux is integrated at the bottom of the domain (z=20 m) with a heat flow of 60 mW/m^2.

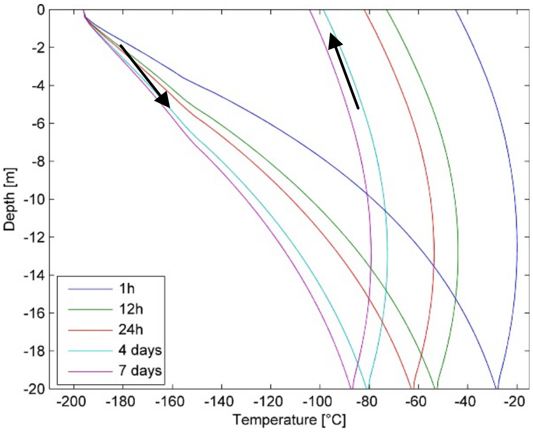

Figure 3. Temperature of the liquid nitrogen.

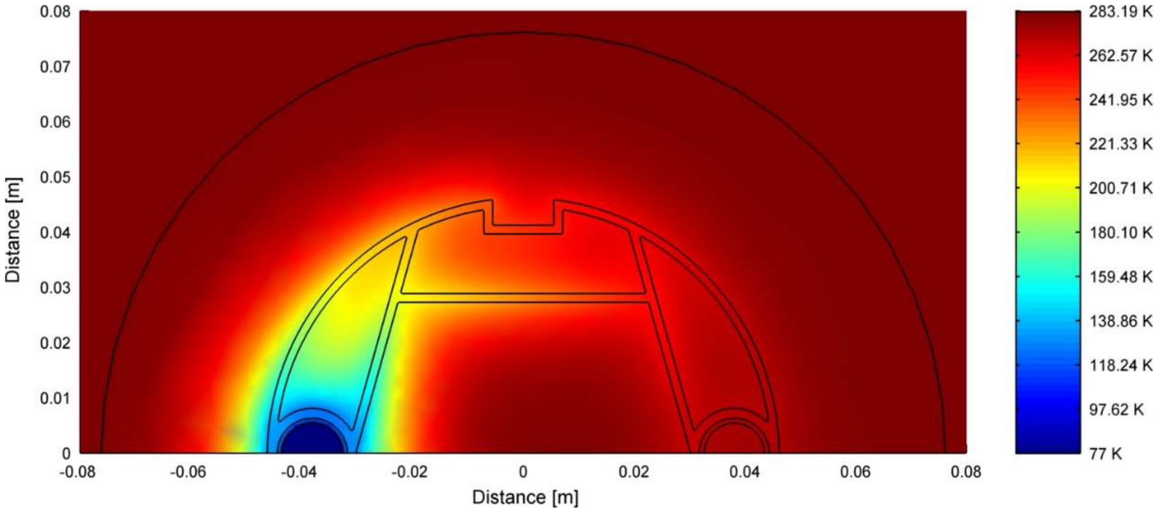

Figure 4. Thermal short-circuit in the aluminum (z=0m) after 60 seconds.

Table 1. Properties of materials.

Material	Properties	Value	Unit
Unfrozen Soil	Thermal conductivity	1.366 - 1.446	W/mK
	Heat capacity	1965.3 - 1964.8	J/kgK
	Density	1699.9 - 1687.5	kg/m^3
Frozen Soil	Thermal conductivity	4.595 - 2.029	W/mK
	Heat capacity	751 - 1333	J/kgK
	Density	1680.2 - 1675.0	kg/m^3
Grout	Thermal conductivity	2	W/mK
	Heat capacity	1000	J/kgK
	Density	2000	kg/m^3
Copper	Thermal conductivity	1.97466 - 1.97124	W/mK
	Heat capacity	0.099 - 389.4	J/kgK
	Density	9021 - 8934	kg/m^3
Aluminum	Thermal conductivity	34.36 - 201.27	W/mK
	Heat capacity	0.261 - 481	J/kgK
	Density	2700	kg/m^3
Polystyrene	Thermal conductivity	0.03271	W/mK
	Heat capacity	1130	J/kgK
	Density	36.7	kg/m^3
Liquid nitrogen	Ratio of specific heats	1.47	-
	Thermal conductivity	0.152 - 0.124	W/mK
	Heat capacity	1996.6 - 2809.6	J/kgK
	Density	868 - 407	kg/m^3

3. Results

Figure 3 shows the temperature in the downward (↓) and upward (↑) pipes as a function of depth for several simulation times. One can notice that the liquid nitrogen is supplied at -196.15°C (z=0 m) and is rapidly heated by the soil. The important curvature of the lines near the surface (z=0 m) indicates that, even with the use of polystyrene embedded in the aluminum structure, the energy transferred between the pipes is significant. This thermal short-circuit between the pipes reduces the ability of the GHE to cool down rapidly the ground. Not surprisingly, Figure 4 clearly shows that the aluminum structure represents the preferential path for heat conduction between the two pipes.

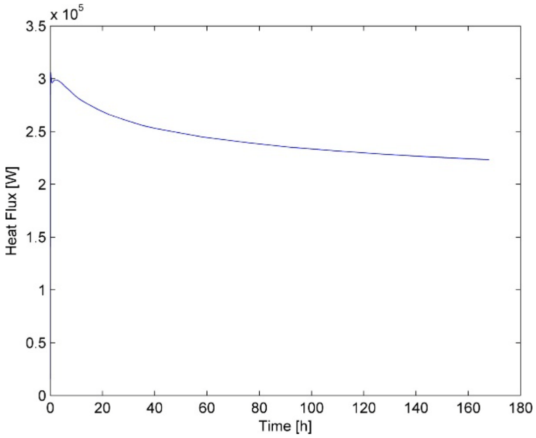

Figure 5. Heat flux across the outer boundary of the aluminum cast.

As the time progresses, the heat exchanged between the GHE and the surrounding soil tends to stabilize around a value of 2.25 X 10^5 W as shown in Figure 5.

The growth of the ice within the ground is usually not symmetric around the GHE. Also, since the formation of ice increases the equivalent thermal conductivity of the soil, it usually speeds up the ice growth in a specific direction. As a consequence of the short-circuit between the pipes, our results shown in Figures 6a) and 6b) indicate that the ice lens is only slightly asymmetric after an operation of only 20 minutes. A similar result is observed at all depths along the GHE.

Since the creation of ice in the ground increases its mechanical properties, the temporal evolution of ice creation is of practical interest. Figure 7 shows the freezing rate for a period of 7 days. The latter tends to slow down over time. At the end of the simulation, the borehole was surrounded by 5.8 m^3 of frozen ground.

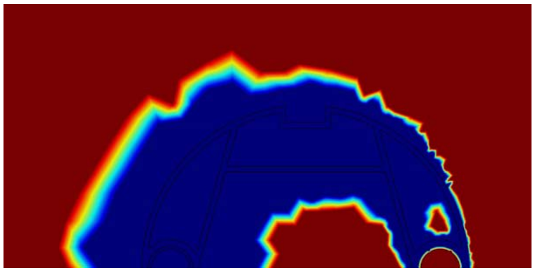
Figure 6a). Frozen (blue) and unfrozen soil (red) at z=0 m after 60 sec.

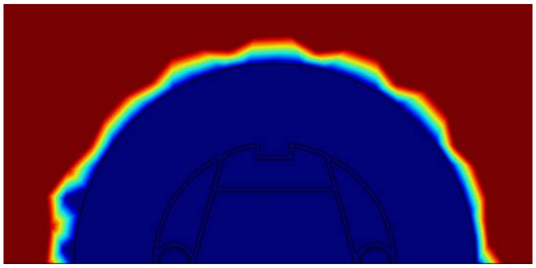
Figure 6b). Frozen (blue) and unfrozen soil (red) at z=0 m after 20 min.

4. Conclusion

A new ground heat exchanger using aluminum to increase the effective radius of the heat exchanger was simulated by means of Comsol Multiphysics. Simulation results indicate that the current design generates a significant thermal short-circuit between the downward and upward circulation pipes. Another design is currently under development that should increase the performance of the GHE for ground freezing applications.

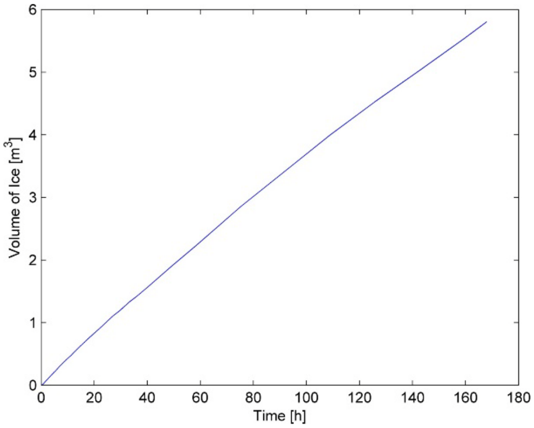

Figure 7. Volume of ground as a function of time.

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