Modeling Horizontal Ground Heat Exchangers in Geothermal Heat Pump Systems

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Abstract: Calculation of the design length of buried horizontal ground heat exchangers (GHXs) as used in geothermal heat pumps systems typically relies on the use of empirical data or quasi-analytical approximations. In the present work, COMSOL Multiphysics is used to simulate horizontal GHXs and preliminarily develop a computationally-efficient means of calculating design lengths of horizontal GHXs under the influence of transient weather and thermal loading conditions. The use of COMSOL also allows further understanding of the thermal behavior of these transient systems.

Keywords: transient heat transfer, geothermal, solar.

1. Introduction

Geothermal heat pumps use the earth as a heat source and sink via a ground heat exchanger (GHX) that consists of a network of buried heat exchange pipes that can either be installed in vertical boreholes or in shallow horizontal trenches or excavations. The main goal in GHX design is to determine the minimum length of pipe needed to provide adequate fluid temperatures to heat pumps over their life cycle.

A considerable amount of recent research has been devoted to simulation and design of vertical borehole GHXs, with much less focus on modeling of horizontal GHX systems due to complexities that arise from significant transients at the ground surface caused by weather. Consequently, design of horizontal GHX systems currently rely on the use of empirical data or quasi-analytical approximations.

In this paper, COMSOL Multiphysics is used to model horizontal GHXs in two-dimensional cross-section with hourly time-varying boundary conditions at the ground surface and at internal heat exchange pipe surfaces. Heat transfer processes at the ground surface include those due to variable wind speed, air temperature, solar radiation, and long-wave radiation. Hourly heat rejection and extraction loads due to heat pump operation are modeled as transient heat fluxes imposed on internal boundaries that represent the inside surface of buried heat exchange pipe.

The objectives of this work are twofold: (i) develop (if possible) a computationally-efficient means of determining design lengths of horizontal GHXs, and (ii) examine the long-term thermal performance of horizontal GHX systems.

2. Model Implementation in COMSOL

2.1 Physical System

Figure 1 is a sketch of a typical buried six-pipe GHX. The GHX typically consists of high-density polyethylene (HDPE) pipes, 19 mm (¾-in.) nominal diameter, buried at a typical depth of 1.5 to 2 m. The heat exchange fluid is either pure water or an aqueous antifreeze solution.

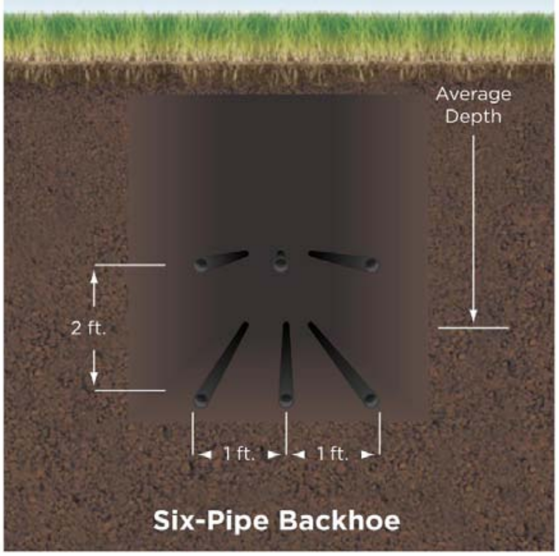

Figure 1. Sketch of a buried six-pipe ground heat exchanger (*Source: WaterFurnace*).

Numerous other horizontal GHX configurations exist (i.e., one-pipe, two-pipe, four-pipe, eight-pipe, slinky, mat-type), but this preliminary work is limited to six-pipe configuration as shown in Figure 1.

2.2 Finite Element Mesh

Figure 2 shows the finite element mesh that was discretized in COMSOL Multiphysics to represent a buried six-pipe GHX. The mesh was constructed in two-dimensional (2-D) cross-section to reduce computational time. The 2-D approach is reasonable if the cross-section is taken through the mid-section of the trench along the major direction of fluid flow in the pipe system.

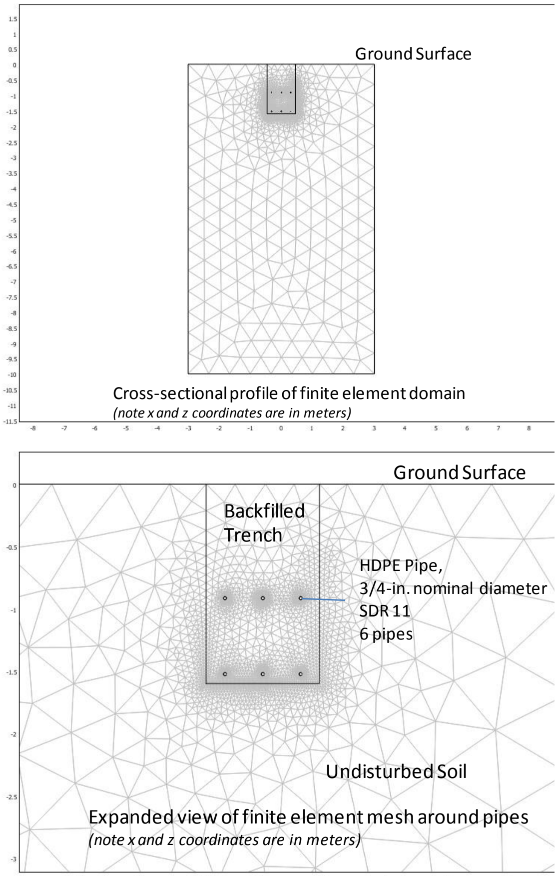

Figure 2. Finite element mesh representing a six-pipe GHX.

Note that due to symmetry conditions and small temperature differences between trenches, and neglecting end effects, only half of the domain shown in Figure 2 was modeled. The modeled half domain consisted of 8458 elements.

In the *z* direction, the domain corresponds to the ground surface and a depth of 10 m, where the temperature remains constant. In the x direction, the domain corresponds to a distance from the center-line of a trench to half the distance to the adjacent trench.

Material properties (thermal conductivity, density, and heat capacity) were specified for undisturbed soil, trench backfill, and HDPE pipe.

2.3 Governing Equations

The governing partial differential equation in the model is the 2-D transient heat diffusion equation in the Cartesian coordinate system:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{dT}{dt} \qquad (1)$$

where T is temperature (K), x and z are space coordinates (m), α is the thermal diffusivity ($m^2 \cdot s^{-1}$), and t is time (s).

2.4 Boundary and Initial Conditions

The left- and right-hand boundaries are adiabatic by definition of the symmetry condition. The bottom boundary is specified as a constant temperature (Dirichlet condition). The top boundary represents the ground surface where heat fluxes due to varying weather conditions are modeled as a Neumann condition:

$$\begin{aligned} n \cdot (k \nabla T) = q''_{solar} + h\left(T_{inf} - T\right) \\ + \varepsilon\sigma\left(T_{sky}^4 - T^4\right) \end{aligned} \qquad (2)$$

where k is the thermal conductivity of the soil ($W \cdot m^{-1} \cdot K^{-1}$), T is temperature (K), q''_{solar} is the solar heat flux on horizontal ($W \cdot m^{-2}$), h is the convection coefficient ($W \cdot m^{-2} \cdot K^{-1}$) due to wind (Duffie and Beckman, 2006), T_{inf} is the ambient air temperature (K), ε is the thermal emissivity of the ground surface (-), σ is the Stefan-Boltzmann Constant ($W \cdot m^{-2} \cdot K^{-4}$), and T_{sky} is the sky temperature (K). Typical hourly climatic data for Edmonton, AB, Dayton, OH, and Houston, TX were taken as representative of a cold, moderate, and hot climate, respectively.

The boundary condition at internal pipe surfaces was modeled as a Neumann condition, representing the heating and cooling loads on the GHX. Hourly building loads (Figure 3) were computed using ESim Software Tool (Kissock, 1997) with EnergyPlus climate data (US Department of Energy). Loads were computed for an actual 140 m^2 (1,500 ft^2) home, and were then converted to thermal loads on the GHX assuming a heat pump coefficient of performance (COP) of 4.0 for cooling mode and 3.0 for heating mode at design conditions.

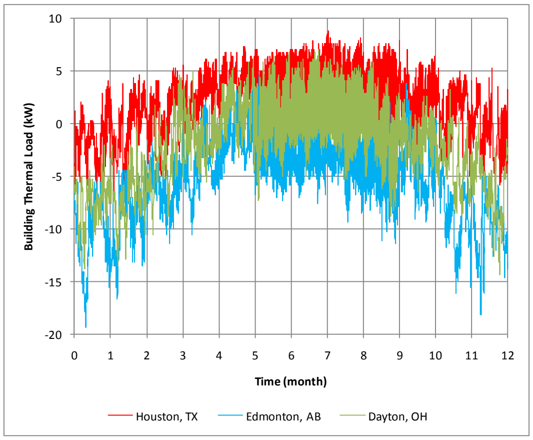

Figure 3. Hourly building loads for a house modeled in three climates. (Heating loads are negative, cooling loads are positive).

Transient boundary conditions were implemented in COMSOL by specifying them as time-varying functions with data stored in text files. For improvement of computational speed, weather data were averaged per month, and hourly building loads were averaged per month with the monthly peak load imposed for a six-hour time period. Parameters defined as time-varying functions included: ambient air temperature, wind speed, solar radiation on horizontal, sky temperature, and building thermal loads.

The initial condition for each model was the undisturbed earth temperature at each location: 13.0°C for Dayton, OH, 6.3°C for Edmonton, AB, and 21.7°C for Houston, TX.

2.5 COMSOL Model Simulations

As previously mentioned, one main goal of GHX design is to determine the minimum length that will supply adequate fluid temperatures to the geothermal heat pump over its life cycle (i.e., greater than -4°C to 0°C in heating mode and less than 32°C to 37°C in cooling mode). Thus, adequate GHX sizing is inherently an optimization problem.

COMSOL simulations were conducted for 20-year simulation times. The GHX was iteratively adjusted such that the calculated fluid temperature remained within typical design criteria. Output from COMSOL included the integral temperature over the internal surface of the heat exchange pipes. The average fluid temperature was determined from convection correlations due to internal flow in tubes (Incropera et al.2007). The fluid temperature exiting the GHX was then determined by an energy balance on the fluid.

3. Results and Discussion

Implementation of the methods described in Section 2 of this paper proved to be very computationally efficient. Twenty-year simulations were completed in less than one minute using an Intel(R) Core(TM)2 Duo CPU with 2.96 GB RAM.

The main results of the COMSOL simulations are shown in Figure 4, which summarizes the monthly peak fluid temperatures exiting the GHX for the three climates modeled. As intuitively expected, the GHX length in the Houston, TX climate is constrained by the cooling loads, with a maximum and minimum GHX exiting temperature of 34.4°C and 18.8°C, respectively. Conversely, the GHX length in the Edmonton, AB climate is constrained by the heating loads, with a maximum and minimum GHX exiting temperature of 18.1°C and -2.4°C, respectively. The GHX length in the Dayton, OH climate is heating constrained, but also experiences extreme temperature variations, with a maximum and minimum GHX exiting temperature of 31.7°C and -3.2°C, respectively.

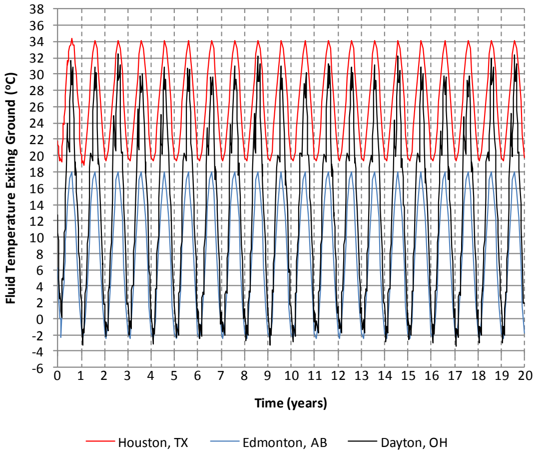

Figure 4. Peak monthly fluid temperatures exiting the horizontal GHX over a 20-year period for the three climates modeled.

The trench lengths required to produce the temperature profiles shown in Figure 4 were as follows:

- Dayton, OH: 7 trenches x 50 m length
- Edmonton, AB: 23 trenches x 50 m length
- Houston, TX: 15 trenches x 50 m length

An important result of the COMSOL simulations (Figure 4) is the recurring nature of the fluid temperatures exiting the GHX over the life cycle. This recurring nature is unlike those observed in vertical GHXs due to the seasonal effects at the ground surface. In vertical GHXs, long-term changes in the underground temperature are observed in situations where the building loads are unbalanced over the year. The recurring nature of temperatures in horizontal GHXs has implications in the design of hybrid GHX systems that rely on seasonal underground thermal energy storage.

Figures 5 through 8 show the subsurface temperature distribution for the GHX in Dayton, OH at the end of March, June, September, and December, respectively. A review of these figures clearly shows the large temperature variations experienced by the GHX.

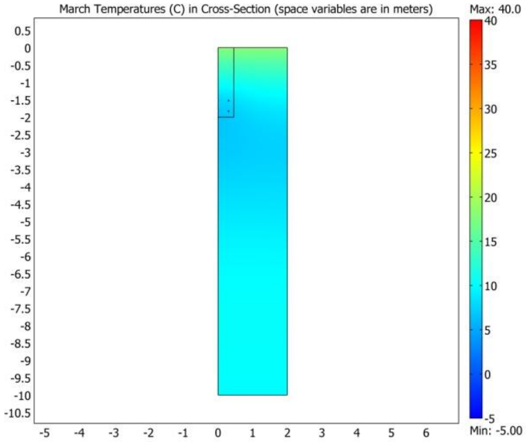

Figure 5. Subsurface temperature distribution around the six-pipe horizontal GHX at the end of **March** for the building in Dayton, OH.

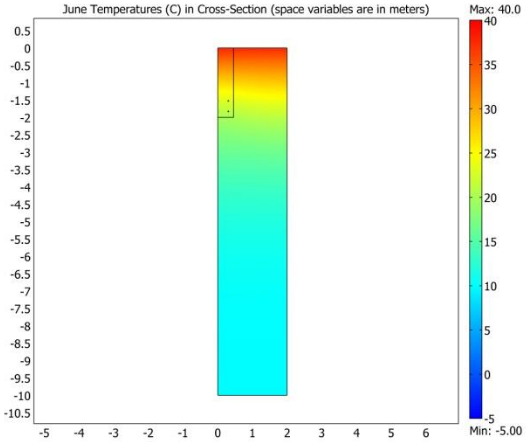

Figure 6. Subsurface temperature distribution around the six-pipe horizontal GHX at the end of **June** for the building in Dayton, OH.

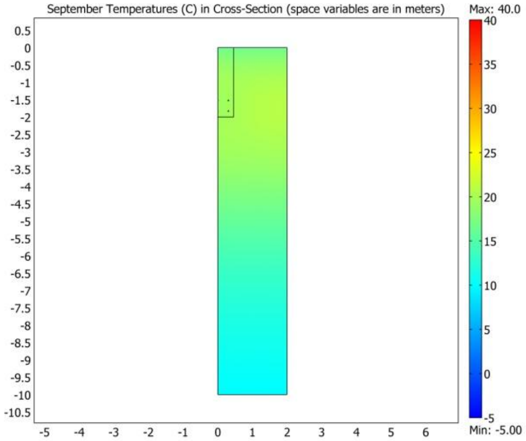

Figure 7. Subsurface temperature distribution around the six-pipe horizontal GHX at the end of **September** for the building in Dayton, OH.

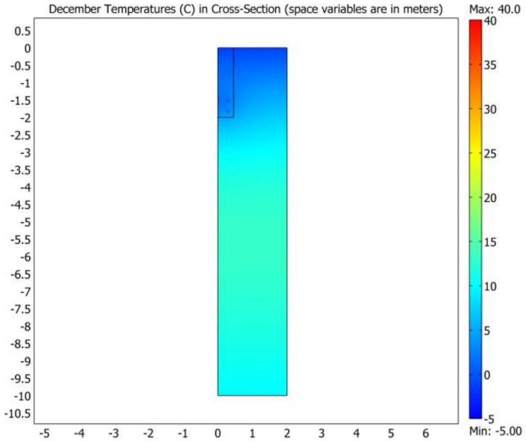

Figure 8. Subsurface temperature distribution around the six-pipe horizontal GHX at the end of **December** for the building in Dayton, OH.

4. Conclusions

This paper has examined the use of COMSOL Multiphysics for modeling horizontal GHXs under the influence of several weather parameters at the ground surface, including solar radiation, thermal radiation, and convective heat transfer. This study preliminarily examined a six-pipe GHX.

This work has demonstrated that COMSOL Multiphysics is a viable tool for horizontal GHX design. Multi-year simulations of simple 2-D cross-sectional models can be run is less than one minute on an Intel(R) Core(TM)2 Duo CPU with 2.96 GB RAM, and are therefore very computationally efficient.

This work has also shed light on the long-term thermal performance of horizontal GHXs in various climates. The annually-recurring temperatures of the fluid exiting the GHX is unlike that observed in vertical GHXs. The annually-recurring temperatures from horizontal GHXs has implications in the design of hybrid GHX systems that rely on seasonal underground thermal energy storage.

Recommended future work includes: multiphysics modeling of saturated and unsaturated soil moisture transport, multiphysics modeling of soil freezing and snow cover, and modeling of shallow solar energy storage in cold climates.

5. References

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