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# Long-term study of vertical ground heat exchangers with varying seasonal heat fluxes

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ABSTRACT

A numerical finite volume method in a two-dimensional domain is used to determine the temperatures in the ground surrounding multiple borefields, each consisting of 16 boreholes. Such information can help examine potential negative impacts of installing geothermal heat pump systems on the surrounding environment. The effect of implementing ground heat exchangers is considered as is the temperature rise in the soil over a period of five years, while accounting for the seasonal variation of heat input to/removal from the ground. Bin data for a building in Belleville, IL are used to calculate the building heating/cooling loads and to analyze the ground heat flows with regards to varying heat pump performance.

## 1. Introduction

The use of geothermal energy systems is increasing significantly, having had a revival in the 1980s and again more recently. Due to its efficiency and other benefits, the use of geothermal energy is often advantageous. However, investigations of the movements of thermal plumes in the ground suggest the potential for geothermal systems to impact the local environment. The migration of thermal plumes from these systems and changes in ground temperatures caused by either closed or open loop systems, or due to changes in ground water flow patterns from open-loop systems, may cause undesirable temperature rises temperature-sensitive ecosystems that are nearby. For example, ground temperature disturbances caused by operating geothermal systems may disrupt life stages of sensitive aquatic organisms. Such environmental effects are observed for heat loop and waterline projects (Fisheries and Oceans Canada, 2009). Markle and Schincariol (2007) show that there is a narrow temperature range (e.g. 0–20 °C for some freshwater invertebrates) for spawning in cold water streams which need to be cooled in the summer and warmed in the winter by the groundwater flow. Once the groundwater temperature is affected due to the performance of ground heat exchangers, it can negatively affect the temperature of the cold water streams, making these sites unsuitable for spawning. A study on the effects of thermal fluctuation on microorganisms in the aquifers of a geothermal well field shows increases in total microbial number in aquifer samples, which correlate with the increase in temperature in the geothermal well field (York et al., 1998). Moreover, counts of cultured bacteria suggest that even when no significant differences in total bacterial number are observed, changes may occur in the types of microorganisms present in the aquifers of the geothermal well field.

To improve understanding of potential environmental impacts of geothermal heat exchangers, the temperature rise and heat flows surrounding borefields needs to be understood. Such understanding could help modify system operating parameters to avoid migration of thermal plumes in the ground surrounding the borefield which could raise temperatures detrimentally in temperature-sensitive areas. Numerous studies have focused on modelling single ground boreholes, mostly using analytical approaches (Jun et al., 2009; Eskilson, 1987; Hellström, 1991; Ingersoll and Plass, 1948; Hart and Couvillion, 1986; Lamarche and Beauchamp, 2007; Hikari et al., 2004; Zeng et al., 2002; Diao et al., 2004; Yang et al., 2009; Bernier et al., 2004; Kavanaugh, 1995; Bandyopadhyay et al., 2008) and/or numerical methods (Mei and Baxter, 1986; Yavuzturk et al., 1999; Yavuzturk and Spitler, 2001; Muraya, 1995; Rottmayer et al., 1997; Lee and Lam, 2008; Li and Zheng, 2009; He et al., 2009, Fang et al., 2002). The models vary in how heat conduction is modelled inside and outside the borehole, how the models are coupled, and in the numerical techniques utilized to accelerate the evaluation of the temperature rise and heat flows in these methods. However, either in development of methods or in analyses of results stemming from those methods, these studies do not focus on the heat flows in the ground surrounding a borefield for periods of time longer than a year. In this article, such time durations are referred as "long-term".

Some recent articles have focused on the long-term operation of borehole heat exchangers (Abdelaziz et al., 2015; Lazzari et al., 2010; Teza et al., 2012; Bidarmaghz et al., 2016). Lazzari et al. (2010)

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**Nomenclature**

| | |
|---|---|
| $c_p$ | Specific heat at constant pressure, J/kgK |
| $k$ | Ground thermal conductivity, W/mK |
| $T$ | Temperature, K |

*Greek letters*

| | |
|---|---|
| α | Thermal diffusivity, $m^2/s$ |
| ρ | Density, $kg/m^3$ |

*Superscripts*

| | |
|---|---|
| *CL* | Cooling load |
| *HL* | Heating load |
| o | Outside |

investigate the performance of boreholes in various borefield configuration using finite element simulations. They examine the long-term performance of double tube boreholes by evaluating the running fluid temperature inside the borehole. Teza et al. (2012) use a two-dimensional finite element approach to model a borefield consisting of 28 boreholes. They examine the performance of the overall system under various borehole shapes and heating and cooling loads (i.e., balanced versus unbalanced loads). They find that effects of unbalanced heating and cooling loads could become substantial in the long-term. Bidarmaghz et al. (2016) develop a three-dimensional detailed numerical model of GHEs to examine the effect of surface air temperature fluctuations on GHE long-term performance. Although these studies focus on the long-term simulation of borehole heat exchangers, they have different objectives from that of the current study and the heat flow patterns outside the boreholes and existence of thermal plumes outside the borefield is either not examined or not presented in adequate detail for making conclusions regarding environmental impacts of boreholes.

In the current article, the seasonal heat flow variation of multiple vertical ground heat exchangers is investigated over a period of five years to examine the migration of thermal plumes in the ground surrounding the borefield. A numerical finite volume method in a two-dimensional meshed domain is utilized to determine the temperature variations in the ground surrounding multiple borefields, each consisting of 16 boreholes. To find the heat flux from the borehole wall, most numerical simulations do not account for the variation in heat pump performance. They either use a sinusoidal function as an assumption based on no building load simulated data, or generate heating and cooling loads using software that are not linked to the heat interactions between the borehole and the ground. In the current study, the boundary condition on the borehole wall is represented by a sinusoidal function that is fitted to data from building load calculations for a typical building in Belleville, IL. The building load data is calculated based on the bin method and the monthly variation of the heat pump performance as the ground temperature varies is taken into account.

## 2. Approach and methods

In evaluating the ground temperature rise due to ground heat exchanger operation either as a single borehole installation or in a borefield, an important step is the definition of the heat flux to the soil from the heat exchanger surface. This can be complex due to the dynamic nature of the heat transfer to the borehole wall from the fluid in borehole U-tubes. The U-tube configuration in the borehole is not simulated in the model for simplicity, and the borehole wall boundary condition is set to the heat flux. This is done because the inner dynamic heat exchange can be a second priority, when examining ground heat flows and temperature rises surrounding the borefield over long periods. The transient nature of geothermal systems responding to building needs is described elsewhere by the present authors (Koohi-Fayegh and Rosen, 2014), through a case study which correlates seasonal periodic weather variations with borehole wall heat flux. The following three sections focus on the modelling steps used for single boreholes, as part of a borefield. These steps are necessary in the borefield modelling in this article.

### 2.1. Building and weather data

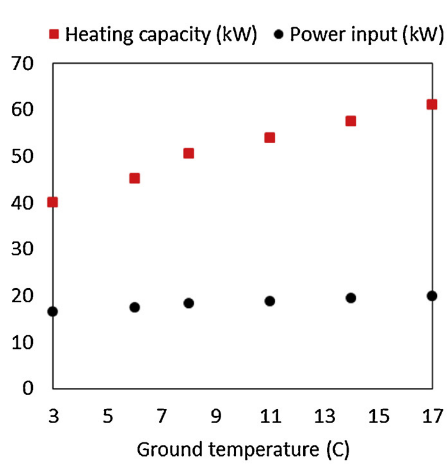
To model transient heat exchange between the ground and boreholes (as part of a borefield) corresponding to transient building loads, building loads are evaluated using a simplified load profile. Koohi-Fayegh and Rosen (2014) consider a building in Belleville, IL, with the following simplified load profiles:

$$\text{Heating load:}\quad \dot{q}_{HL} = 32.7 - 2.7T_o \tag{1}$$

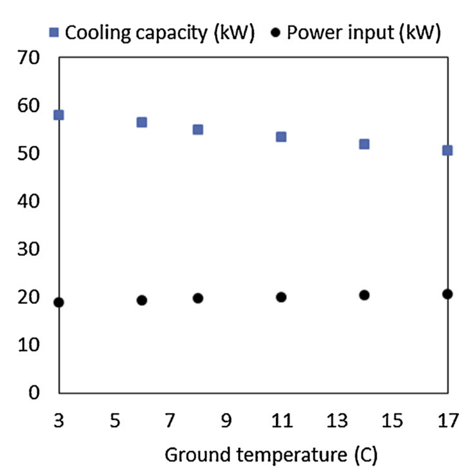
$$\text{Cooling load:}\quad \dot{q}_{CL} = 2.7T_o - 52.3 \tag{2}$$

This correlation yields building loads (in kW) using the ambient air temperature (in °C). Note that the heating and cooling loads are assumed to vary linearly with ambient air temperature.

The building is assumed to have no shift breakdowns, i.e. the




(a)




(b)

**Fig. 1.** Heating and cooling capacities for a typical heat pump at an air flow rate of 6000 CFM (2.8 $m^3/s$).