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A simplified ground thermal response model for analyzing solar-assisted ground source heat pump systems

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ABSTRACT

Ground source heat pump systems that are installed in areas with heating or cooling dominant seasons, or in buildings with utilization characteristics that lead to a disparity in demand, often encounter challenges related to ground thermal imbalance. This imbalance can lead to long-term ground temperature changes and may cause premature system failure. This paper focuses on combining a ground source heat pump system with a solar thermal array, with the goal of eliminating the effect of ground thermal imbalance, and minimizing system lifetime cost. A thermal mass ground heat transfer model is combined with a time-stepping model to analyze the system for a variety of solar array sizes. The details associated with this modelling technique are presented, and case studies are provided to illustrate the results of the calculations for three different buildings. It is shown that increasing the solar array size can offset ground thermal imbalances, but increasing the array size also results in a larger initial system cost. An economic analysis is then carried out to determine the system lifetime cost as a function of this solar array size, and an optimal array size from an economic perspective was found. The result of the study shows that hybridizing a ground source heat pump system with a solar array produces a viable system from a technical and economic standpoint, can be used to avoid premature system failure, and can reduce system lifetime cost.

1. Introduction

1.1. Research motivation

As global concerns with respect to climate change increase, there is growing pressure on building system designers to reduce energy consumption by improving system efficiency. There are a wide variety of efficiency improvements that can be implemented, ranging from new system hardware to sophisticated building control, but the target is typically to reduce building energy demand, and therefore energy cost. This reduction in energy demand often results in a decrease of greenhouse gas emissions from burning fossil fuels for heating a building, which is also being more heavily mandated by new emission laws in many jurisdictions. Ground source heat pump (GSHP) systems are being implemented as one of these efficiency measures since they can be designed to operate without on-site fossil fuel use, and can offer stable system efficiency year-round when compared to air source heat pumps [1].

The design of GSHP systems in heating or cooling dominant climate-zones, or for buildings with utilization characteristics that lead to a disparity in demand, often encounter challenges due to annual building load imbalances. These imbalances can cause long-term ground temperature changes from heat accumulation or depletion in the ground, which can lead to premature system failure [2]. To offset these imbalances, a geo-exchange system can be hybridized with conventional heating or cooling systems, such as natural gas boilers, such that the annual net ground heat exchange does not cause premature system failure [3,4]. However, using fossil fuels for hybridization still results in direct CO_2 emissions from the system, and may not be sustainable for long-term use. Therefore, there is now focus on using renewable energy for GSHP hybridization, and much of this focus is on the use of solar thermal panels since they can provide efficiencies of approximately 60% and emission-free heat at temperatures ranging from approximately 5–60 °C depending on weather conditions and panel selection [5]. In these systems, the interactions between the ground, heat pump, and solar array are critical to determine system performance, but these interactions are not well understood.

This paper focuses on the techno-economic analysis of a GSHP system that is hybridized with a solar thermal array, such that ground thermal-imbalance can be mitigated, and the lifetime cost of the system can be minimized. Unlike other studies in the literature, this analysis utilizes a conduction heat transfer finite element ground model to

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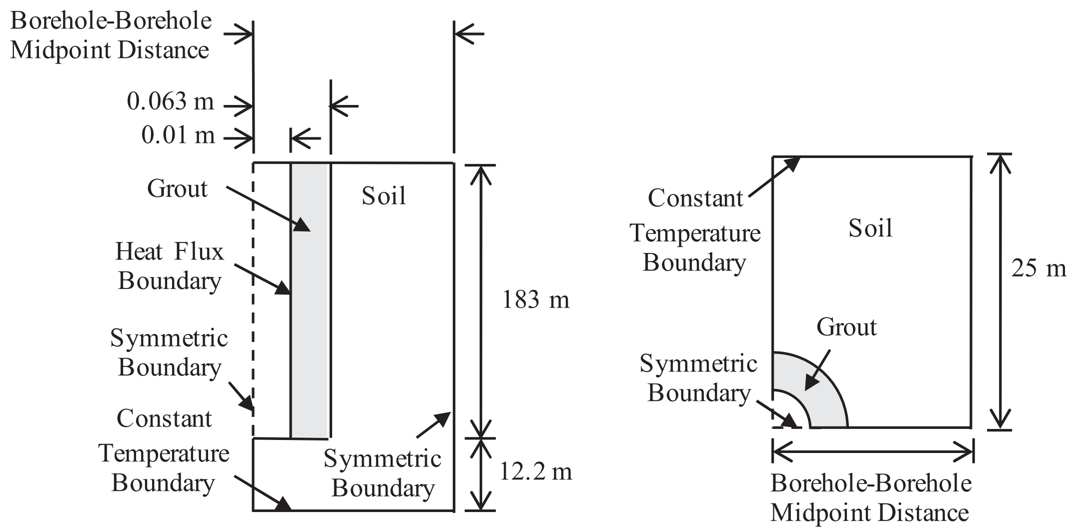

Fig. 1. Schematic of COMSOL ground model geometry with boundary conditions. Cross-sectional side view (left), top view (right).

determine the effect of thermal loads on the ground. A finite element model simplification technique based on a thermal mass model is also presented, which allows for a reduction in computation times, while still delivering results within 5% of those from a detailed finite element model. Manufacturer heat pump performance data, along with a semi-empirical solar energy analysis, are used alongside this simplified model to predict overall system performance.

1.2. Existing solar-assisted ground source heat pump systems, and modelling methodologies

The use of solar energy as a replacement for conventional heat sources is increasing in popularity due to concerns over fossil fuel usage and greenhouse gas (GHG) emissions [6,7]. Some systems use the solar thermal array as a refrigerant evaporator [8,9], while others circulate water or a water-antifreeze mixture through the solar panel to extract sensible heat [10,11]. Systems may also implement a thermal energy storage (TES) tank, which is used to store heated water before circulating the water to the ground or the building [7,12]. A statistical analysis of these studies has found that the addition of solar energy to the GSHP system can improve overall system efficiency by 10–20% in balanced systems, which will be used for comparison with the results of this study to ensure the reliability of the findings.

In this study, while improved system efficiency is a valuable result of using solar energy, the primary motivation for adding a solar array to the GSHP system is to replenish the thermal energy removed from the ground during winter months. The use of solar energy for this reason in an air-based thermosiphon system, coupled with a GSHP, has been shown to negate the effects of imbalanced thermal loads [13]. A flat-plate liquid solar panel system with TES was investigated for use in cold-climates, to reduce ground thermal imbalance, and the long-term efficiency of the system was shown to be stable [14]. Another study investigated the effect of adding a solar array to a three-year-old GSHP system, and it was shown that initial ground temperature decreases of 0.2 °C per year can be reversed by the solar thermal energy [15]. However, these studies did not implement a detailed ground temperature model to predict long-term ground temperature changes.

Ground thermal models in the literature are typically categorized as either analytical or numerical, and are often used to predict long-term temperature changes of the ground [16]. Analytical models include the infinite line-source model, along with the cylindrical source model, and both of these models neglect vertical heat transfer [17,18]. The resistance-capacitance approach to ground modelling is based upon an electrical circuit analogy, and can account for the interaction between the U-tube, grout, and the ground [19]. Finite element models have also been developed, and a two-dimensional model that accounts for one plane along the borehole depth has been shown to estimate borehole heat transfer within 8% of experimental values [20]. Finite element modelling has also been carried out using three-dimensional models, which allow for prediction of variable fluid temperatures along the borehole, and can also account for fluid flow dynamics in the borehole pipe [16,21]. However, in an on-off flowrate GSHP system, calculation of the fluid flow characteristics is not necessary and a three-dimensional numerical model that uses a heat flux term to represent the thermal load of the fluid on the ground has been validated against experimental data [22].

The work in this paper builds upon the previous solar-assisted GSHP studies by using a finite element ground model to predict the thermal response of the ground as a function of the solar-assisted GSHP system loads, and uses this response to determine system performance.

1.3. Detailed finite element ground model

In this study, a conduction heat transfer finite element model was used to determine ground temperatures in the GSHP system, as a function of the ground loads over time. This model was based upon the work completed by Law and Dworkin [22], with the modelling done using COMSOL [23]. The geometry shown in Fig. 1 illustrates the dimensions and boundary conditions that were applied when using this technique.

A single borehole from a multiple borehole GSHP system is included in the model, and symmetry conditions along mesh boundaries are used to replicate the effects of additional boreholes. Heat transfer in/out of the ground is included using a heat flux, which is applied along the boundary that represented the outside of the fluid-carrying pipe that is encased within a grout layer (i.e., the borehole). This heat flux is determined from building loads, which are generated using a building energy simulation, along with the performance of the heat pump in the system.

This COMSOL heat conduction model uses approximately 11,000 three-dimensional triangular prism domain elements, and 4,000 three-dimensional triangular prism boundary elements. The element starting size at the internal surface of the grout is 0.06 m, and an element growth rate of 1.3 was used through the domain resulting in a maximum element size of 1.3 m. The model has a wall-clock runtime of approximately 5–7 h per year of simulation time on a standard desktop personal computer. The other input parameters to the simulation are dependent on the soil and grout properties, and the parameters used in