Applied Energy 179 (2016) 1032–1047

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Characterization of the effects of borehole configuration and interference with long term ground temperature modelling of ground source heat pumps

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HIGHLIGHTS

- Long term ground temperature response is explored using finite element methods.
- Simulation method is validated against experimental and analytical data.
- Temperature changes at a fast rate in the first few years and slows down gradually.
- ASHRAE recommended separation distances are not always sufficient.
- Thermal accumulation occurs at the centre of borehole field.

ARTICLE INFO

Article history:
Received 19 March 2016
Received in revised form 6 July 2016
Accepted 14 July 2016

Keywords:
Ground source heat pumps
Thermal imbalance
Temperature
Borehole configurations

ABSTRACT

Ground source heat pumps (GSHPs) are an environmentally friendly alternative to conventional heating and cooling systems because of their high efficiency and low greenhouse gas emissions. The ground acts as a heat sink/source for the excess/required heat inside a building for cooling and heating modes, respectively. However, imbalance in heating and cooling needs can change ground temperature over the operating duration. This increase/decrease in ground temperature lowers system efficiency and causes the ground to foul—failing to accept or provide more heat. In order to ensure that GSHPs can operate to their designed conditions, thermal modelling is required to simulate the ground temperature during system operation. In addition, the borehole field layout can have a major impact on ground temperature. In this study, four buildings were studied—a hospital, fast-food restaurant, residence, and school, each with varying borehole configurations. Boreholes were modelled in a soil volume using finite-element methods and heating and cooling fluxes were applied to the borehole walls to simulate the GSHP operation. 20 years of operation were modelled for each building for 2×2, 4×4, and 2×8 borehole configurations. Results indicate that the borehole separation distance of 6 m, recommended by ASHRAE, is not always sufficient to prevent borehole thermal interactions. Benefits of using a 2×8 configuration as opposed to a 4×4 configuration, which can be observed because of the larger perimeter it provides for heat to dissipate to surrounding soil were quantified. This study indicates that it is important to carefully consider ground temperature during the operation of a GSHP. Borehole separation distances, layout, and hybridization should be studied to alleviate ground fouling problems.

1. Introduction

Ground source heat pumps (GSHPs) are an environmentally friendly alternative to conventional heating and cooling systems because of their high efficiency and low greenhouse gas emissions [1,2]. GSHPs use the ground as a stable heat transfer medium to provide both heating and cooling for a building.

During the operation of a GSHP, the ground acts as a heat source and heat sink in heating and cooling modes, respectively [3]. An important aspect for a well-designed GSHP system is to balance the heat extraction and injection from and into the ground throughout the year. Long-term heat extraction of the ground (heating season), to heat the building, would cause the ground temperature to gradually decrease – lowering the heating efficiency of the system (vice versa for the cooling season). Ideally, when the heating and cooling demands of a building are well

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http://dx.doi.org/10.1016/j.apenergy.2016.07.048
0306-2619/

balanced, the ground temperature fluctuates within a stable, desirable range. However, when the heating and cooling demands are poorly balanced, the ground temperature may migrate up or down over time, and as a result, system performance diminishes, and in extreme cases the ground may fail to accept/provide more heat from/to the building. This phenomenon is referred to as 'ground fouling' and many systems in the past have had to stop their operation due to the resulting low coefficient of performance (COP) [4]. To ensure that a design is feasible, it is important to model and project the changes in ground temperature over many years of operation. Furthermore, a deeper understanding of factors that can affect and mitigate ground fouling is sought.

GSHP systems are often designed to meet the full heating and cooling demands of buildings. When the building's heating and cooling loads are balanced, the system can operate for the designed duration. However, when there is a large imbalance of loads, the system could foul shortly after operation begins due to the change in ground temperature. This ground fouling can lead to system shut down, which causes economic loss, extended payback period, and occupant discomfort. Increase in ground temperature can lead to an inefficient GSHP because of low COPs as a result of inadequate heat transfer temperatures [5]. In addition, the increase in ground temperature can lead to ecological problems of species in the soil [6]. The study of ground temperature is important in GSHP designs.

Studies have shown that during the operation of a GSHP, if the cooling loads are not fully compensated by the heating loads (or vice versa), changes can be observed in ground temperature [6–8]. The change in ground temperature was most significant in the region within 0.5 m of the borehole [8]. It was also observed that the change in ground temperature occurs in the first few years of operation and asymptotes after the first ten years [6–8].

For most buildings, balanced weather results in balanced heating and cooling demands. For example, in locations such as the Yangtze River, in China, studies have shown that the balance of hot summers and cold winters allowed the ground to be relatively balanced [5]. Slight imbalances in ground temperature are recovered during spring and autumn seasons, when heating and cooling demands are low [9]. Other specialized buildings, such as restaurants or skating rinks with high cooling needs, or processing plants with high heating needs, may have severely unbalanced loads. Studies of regions with very hot/very cold climate indicate that ground temperature would increase/decrease throughout the operation of the GSHP if necessary precautions are not taken [10,11]. There are two main concerns for operating GSHPs in cold climate regions: soil temperature is too low to obtain high COPs and soil temperature cannot be maintained over time due to high load imbalances [11]. An objective of the present study is to analyze the quantification of these imbalances so that engineers can better understand how to design accordingly.

According to ASHRAE, to achieve a balanced GSHP system, the heat pump heating-to-cooling ratio has to be 1.6–1.8:1; for every hour of cooling at full capacity, 1.6–1.8 h of heating at full capacity is required [12]. There is a need to understand the severity and implications for buildings with load ratios outside this range.

Aside from the building function and location, it is important to assess the effects of borehole arrangements on the thermal imbalance problems. The ASHRAE handbook of design recommends that boreholes should be separated by a distance of 6 m when they are placed in a grid pattern [12]. It also indicated that this distance may be decreased when the boreholes are placed in a line or when the annual loads are well balanced [12]. However, no formalized method of determining such a spacing reduction currently exists in the literature.

Studies show that in an array of boreholes, the centre boreholes have the greatest temperature change compared to their surrounding boreholes [13]. To mitigate ground thermal imbalance, the centre boreholes can be removed to provide more space for surrounding boreholes to dissipate heat to and from – improving heat transfer [13]. This tactic may not always be possible due to space limitations. The present work seeks to quantify the ground temperature changes and to determine whether changing the arrangement of the boreholes can reduce the effect.

In [14], the effects of ground temperature during the operation of a single borehole (single line) and an array of boreholes was studied. The study was done by modelling a single borehole in an infinite field of soil, a line of boreholes, and an array of boreholes in a grid. Each of these configurations were used to supply heating for a building. Zero, partial, and full supply cooling loads of were applied to each configuration to determine which configuration has the greatest change in ground temperature. Results indicated that for a single borehole in an infinite field of soil, no heat balance is required to ensure that the GSHP continues to be operable. However, the line configuration requires at least partial balance of heating and cooling loads and the grid configuration requires full balance of loads. This study indicates that there is a need to evaluate the grid configuration of boreholes to mitigate the effects of thermal imbalance. Studies in borehole configurations are important because large numbers of GSHP installations are in grid configurations due to space limitations. A study in [15] indicated that there is interaction between boreholes, and separation distances between boreholes can be calculated to prevent thermal imbalance.

In [16] the authors used eQuest/DOE-2.2 to simulate ground temperature response to geo-exchange. The eQuest/DOE-2.2 program used complicated g-functions to simulate temperatures at the borehole wall [16]. The development of these g-functions are based on cylindrical models developed by Eskilson [16,17]. The g-functions used the step responses of the boreholes to determine the temperature distribution of the borehole field. It was concluded that the use of g-functions was effective in reducing computation time for temperature distributions in a borehole field. The g-functions use the superposition of a single cylindrical model to model the behaviour of a borehole field. The effects of ground water filtration and surface convection were studied in [17] and were shown to have a negligible effect on modelling. G-functions are commonly adopted by ground heat exchanger programs, such as EED [18]. These works simplify multiple borehole simulations into a single borehole simulation through the use of a g-function. A thesis in 2013 [19], added to Eskilson's work by comparing the g-functions generated by Earth Energy Design (EED) with those generated using numerical models and COMSOL Multiphysics. The finite line source results were well-validated with the results from EED. Upon validation of the line source model results, the author built numerical models using COMSOL Multiphysics to create models involving borehole fields that were closer to reality than other methods [19]. Further examining the results of the study, the results of the numerical model were well validated against the results from EED.

A model in [20] used hourly heat fluxes and g-functions in an EnergyPlus program to simulate the temperature changes [21]. The results of this model were validated against the analytical solution and the results were within 2 °C error [20]. This study indicates that g-functions are highly accurate in determining the borehole wall temperature for multiple borehole simulation.

In [22], experimental results were validated against simulated results and ASHRAE design method results. The authors proposed the use of g-functions to simulate ground temperature response. The results indicated that using g-functions under-predicted required borehole length by 4% while the ASHRAE design method over-predicted the required borehole length by more than 100% [22]. This study indicates that the methods proposed by ASHRAE