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Modelling of the thermal performance of a borehole field containing a large buried tank

P. Kandiah, M.F. Lightstone*

Department of Mechanical Engineering, McMaster University, Hamilton, ON, Canada L8S 4L7

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ABSTRACT

Seasonal storage of solar thermal energy for space heating of multiple dwellings in cold climates can be accomplished through the use of borehole fields in conjunction with large buffer tanks. The buffer tank is used to account for the difference between the time over which solar energy can be collected and the time required to deposit the collected energy into the borehole field. There is motivation to bury the tanks in order to save space on ground level, as well as to improve the overall efficiency of the system by reducing heat losses from the tank. The current paper uses computational fluid dynamics (CFD) to explore the impact of a buried tank on the performance of a borehole thermal energy storage (BTES), as well as the thermal interactions between the tank and boreholes.

The long-term performance was assessed in detail by simulating a 20-year period. The first 5 years of performance were then compared to results for a series of other cases including: a typical BTES layout, a tank with the bottom wall insulated as well as tanks with varying aspect ratios. It was found that the presence of the tank did not significantly reduce the BTES performance. Moreover, performance was relatively insensitive to the tank aspect ratio. Insulating the bottom of the tank also had negligible difference.

1. Introduction

In cold northern climates such as Canada's, nearly two-thirds of the energy use of an average home goes towards space heating (Natural Resources Canada, 2012). The use of solar energy for space heating applications provides an opportunity to reduce the reliance on fossil fuels and decrease greenhouse gas emissions (Dincer, 2006).

There is, however, a seasonal mismatch between when the solar radiation is highest and when demand for space heating occurs (Ucar and Inalli, 2005). Consequently, there is a need for seasonal storage that stores the excess energy from the summer for use in the winter months when the heating load peaks (Wong et al., 2006).

The mediums most commonly used for thermal energy storage are water, gravel and soil. Water is advantageous due to its high heat capacity. It can be used for seasonal energy storage by employing very large tanks, from 100 to 12,000 m^3 (AEE Institute for Sustainable Technologies, 2008), or through natural aquifers such that employed for the German parliament buildings in Berlin (Sanner et al., 2005). Gravel-water pits have also been used but require a large lined pit. Thermal energy is injected and extracted either by means of directly exchanging water, or through the installation of pipes, which act as a heat exchanger. Due to the presence of gravel, there is no need to build load bearing walls. However, the drawback to using a gravel-water store is that they need to be up to 50% larger than a water only store since gravel has a lower specific heat than water (Schmidt et al., 2004).

Soil, or ground based systems, use vertical boreholes containing heat exchangers to deposit or extract thermal energy. Vertical boreholes depths are typically comprised between 30 and 100 m (Schmidt et al., 2004) and contain pipes through which a heat transfer fluid flows. The piping material is typically HDPE, PVC or other types of plastic and grout is placed between the outer pipe wall and the soil to enhance the heat transfer from the pipe to the soil. The fluid exchanges heat with the ground as it runs through the tubes; typically injecting heat in the summer and extracting it in the winter (Wong et al., 2006). The vertical pipes are usually arranged in a grid pattern and can be connected in series or parallel arrangements. There is often a layer of insulation at the surface of the borehole field to reduce the heat loss to the ambient (Schmidt et al., 2004). Careful design on the borehole field arrangement and depth is required to account for the local soil thermal properties (ρ, k, C_p). Economies of scale can be achieved by applying these systems at the community level rather than for a single dwelling

* Corresponding author.
E-mail address: lightsm@mcmaster.ca (M.F. Lightstone).

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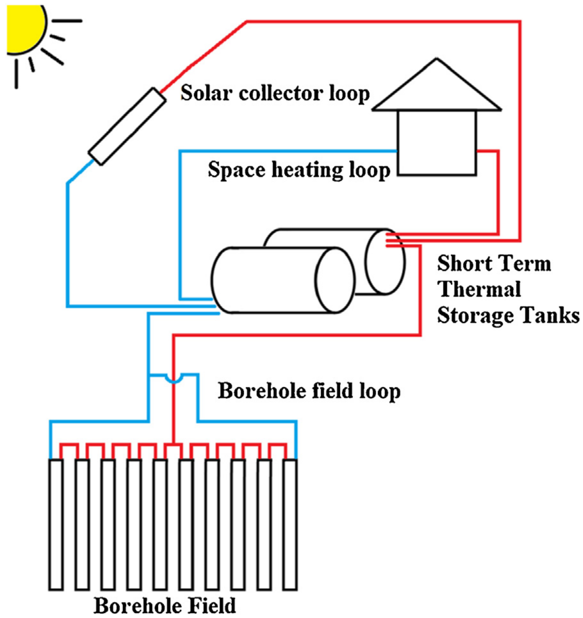

Fig. 1. Schematic of Drake Landing Solar Community.

(Ucar and Inalli, 2007). Additional discussion of methodologies for seasonal thermal energy storage are described in Pinel et al. (2011).

There are benefits, both economically and technically, from combining thermal energy storage mediums such as liquid water and soil for seasonal thermal energy storage (Schmidt et al., 2004; Natural Resources Canada, 2012; Reuss et al., 2006). Reuss et al. (2006) describe a case study in Germany in which the solar energy thermal storage system utilizes borehole field with a large water tank buried in the centre of the field. Heat pumps are also available to discharge the boreholes at night when electricity prices are reduced. The system was designed to provide space heating and domestic hot water for 30 houses as well as an indoor tennis court. Despite numerous challenges in the construction and control of the system, as high as 74% of the community energy needs have been supplied by solar energy.

The Drake Landing Solar Community (DLSC) located in Alberta, Canada also utilizes liquid water and a borehole field to attain seasonal storage of solar thermal energy at the community level. The water is stored in two large above ground tanks which are located in the energy centre building on the site. Additional information on the DLSC is provided in Section 2 below. The DLSC has attained very high solar fractions (defined as the fraction of space heating needs supplied by solar) and as a result there is an interest in developing new solar communities in Canada based on the DLSC concept. For the new communities, however, there is a desire to reduce the footprint of the energy centre building by placing the water stores into a single large buried tank within the borehole field. The thermal interactions between a large buried tank and the surrounding borehole field have not, to the authors' knowledge, been previously studied. The goal of the current paper is thus to explore this interaction.

2. Background

2.1. Drake Landing Solar Community

The Drake Landing Solar Community (DLSC) consists of 52 houses and is located in Okotoks, Alberta, Canada. It was built in 2007, and has reached a solar fraction of nearly 97% (Sibbitt et al., 2012). The system at DLSC consists of three major components and is shown schematically in Fig. 1. The three components are the solar collectors, which are mounted onto the roofs of the detached garages, two short term thermal storage (STTS) tanks, and a borehole thermal energy storage (BTES), otherwise referred to as a borehole field.

The 800 solar collectors are solar-thermal units tilted at 45°, with dimensions of 2.45 m by 1.18 m mounted on south facing garages. They circulate a 50% water, 50% propylene glycol antifreeze solution and the system operates without the need for a heat pump. The water–glycol mixture circulates through the collectors, gains heat from solar radiation, and returns the fluid to the STTS tanks.

The borehole field consists of 144 boreholes, which are 150 mm in diameter and 35 m deep. The boreholes have a spacing of 2.25 m in a square grid pattern as shown in Sibbitt et al. (2012). These boreholes are plumbed with six boreholes in series, called strings, and the entire field is made up of 24 of these strings. Water is injected from the centre outwards when storing heat, and in reverse when removing heat in order to radially stratify the field and reduce losses to the surrounding soil (Wong et al., 2006; Sibbitt et al., 2012). Radial stratification is the radial temperature gradient that arises by having the field hot in the centre and cooler on the outer edge. This results in decreased losses to the uncharged ground beyond the boreholes (Kandiah, 2014). In the summer, energy is stored within the borehole field, and in the winter, the energy is extracted and used for space heating purposes. The efficiency of the borehole field, defined as the energy extracted divided by the energy injected over a period of 1 year, was about 20% in the first year of operation. This efficiency was low during the first year because the ground temperature needed to be raised from the uncharged condition. Subsequent years had efficiencies that varied between 35% and 54% (Sibbitt et al., 2012).

The two STTS tanks have a volume of 120 m^3 each, which is roughly the size of a railway car. They are currently housed in the energy centre, and occupy about 70% of the floor space. The STTS acts as a buffer between the collector loop, the space heating loop and the borehole field loop. A control system is employed to control the flows in the various loops, thus delivering energy where required. In the summer, when space heating is not required, the energy from the solar collectors is sent to the STTS. The borehole field loop is run continuously to extract energy from the STTS and deposit it into the soil.

The STTS tanks are required because the heat transfer rate to the borehole field is much smaller than the rate at which the collector loop gains energy (Wong et al., 2006) and the BTES cannot store or extract enough energy during peak hours. Based on the volume and flow rates entering the STTS tanks, it is determined that the tank turnover time is around 6 h, whereas it takes a full 24 h to transfer this energy to the borehole field. Without the buffer tanks, the fluid would not be able to exchange heat quickly enough with the ground, and would result in hotter fluid returning to the collectors, which would reduce collector efficiency. Due to the STTS tanks' sizeable footprint, there is an interest in exploring the implications of burying the tank within the borehole field.

2.2. Mathematical modelling of single boreholes and borehole fields

Methods for modelling the heat transfer from boreholes to the adjacent soil vary in complexity from simple one-dimensional models, such as infinite line source (ILS) and cylindrical heat source (CHS), two-dimensional models such as finite line source (FLS), and three-dimensional methods such as g-functions (Eskilson, 1987; Cimmino and Bernier, 2014). These methods are based on solution of the transient heat conduction equation and as such inherently neglect the impact of moisture transfer on the soil heat transfer. Both the ILS and CHS methods require relatively small timesteps in order to give accurate predictions (Koohi-Fayegh and Rosen, 2013).