Effects of Surface Air Temperature on Thermal Performance of Vertical Ground Heat Exchangers

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Introduction

Ground source heat pump (GSHP) systems efficiently heat and cool buildings using geothermal energy accessed via ground heat exchangers (GHEs). In closed loop systems, GHEs comprise high density polyethylene (HDPE) pipes embedded in specifically drilled boreholes or trenches or even built into foundations, all within a few tens of metres from the surface. GSHP systems operate at a coefficient of performance of about four throughout the year, basically delivering four kilowatts of thermal heating or cooling for every kilowatt input into the heat pumps, thus reducing energy demand with respect to other conventional systems of conditioning. The thermal performance of GHEs is usually studied with equivalent (groups of) linear heat sinks/sources or with more advanced numerical models. In most cases, the farfield ground temperature is assumed constant with depth, a simplification that is reasonable for typically long GHEs. However, the increasing use of piles (and other geostructures) as GHEs, whose length (depth) can be substantially shorter (shallower) than traditional borehole heat exchangers, requires a re-assessment of the thermal effects of the changing air temperature (weather) on GHEs. This work introduces and addresses such issues using state-of-the-art 3D detailed numerical models of GHEs and highlights its significant influence on thermal performance.

Detailed Numerical Model: an Overview

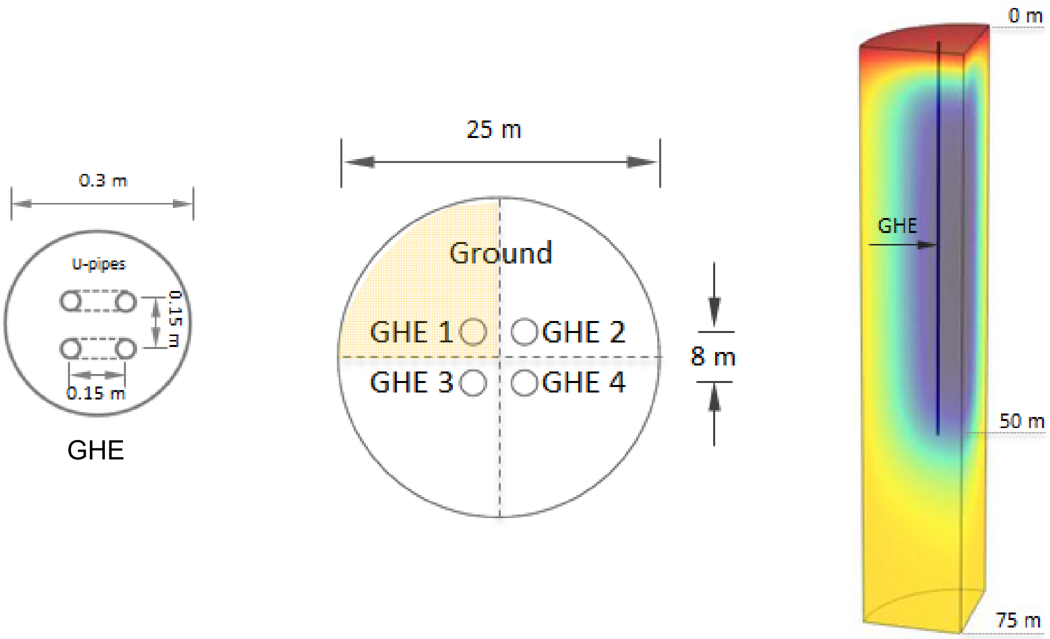
A 3D numerical model based on first principles has been developed and implemented using finite element methods [1, 2]. The model can account for the local geology, depth varying ground temperature and the local weather for a more realistic representation of GHEs. The governing equations for fluid flow and heat transfer are coupled numerically within the finite element package COMSOL Multiphysics to evaluate the thermal performance of GHEs.

The fluid flow in the pipes embedded in the GHEs is modelled by the Navier-Stokes equations in the laminar regime and by the Reynolds-Averaged-Navier-Stokes equations (RANS) in the turbulent regime (a k-ε turbulent type model), to save computational time. The velocity field u, found by solving these governing equations is coupled with a generalized Fourier governing equation for heat transfer. Heat transfer around and in the GHEs is modelled primarily by conduction and convection with this generalised Fourier equation. Heat conduction occurs in the soil, pile concrete and HDPE pipe wall, and partially in the carrier fluid circulating in the pipe; while heat convection dominates in the carrier fluid, in the absence of groundwater flow in the soil.

The Effects of Air Temperature Fluctuations

The seasonal and daily air temperature fluctuations greatly influence ground temperature variations with time and depth. These are typically neglected in much of the related literature [3-5]. While these variations only occur in the upper 5-10 m of the ground (up to 10 m in Melbourne, Australia), the axial heat transfer from the ground surface may affect the overall GHE thermal response.

In order to investigate to what extent air temperature fluctuations and surface thermal recharge/discharge influence thermal performance of GSHP systems, a GHE-field consisting of four 50 m deep, 0.3 m in diameter GHEs, located in a square pattern and 8 m apart is modelled. Each GHE contains two HDPE U-pipes of 0.025 m outside diameter, SDR 13.6, with 0.15 m spacing between the inlet and outlet pipes as well as between the two U-pipes (Figure 1). A soil cylinder of 25 m diameter and 75 m depth surrounding the GHEs completes the finite element model. The annual GHE thermal load shown in Figure 2 (which refers to a given year of operation) is applied to the model. The key model input parameters correspond to typically measured thermal values of Melbourne Mudstones, concrete, and HDPE pipes.



(a) (b) (c)

Figure 1. Base FE model used in this work: (a) schematic top view of the GHE and the pipes, (b) top view of GHE-field and (c) perspective view of one quarter of the modelled ground

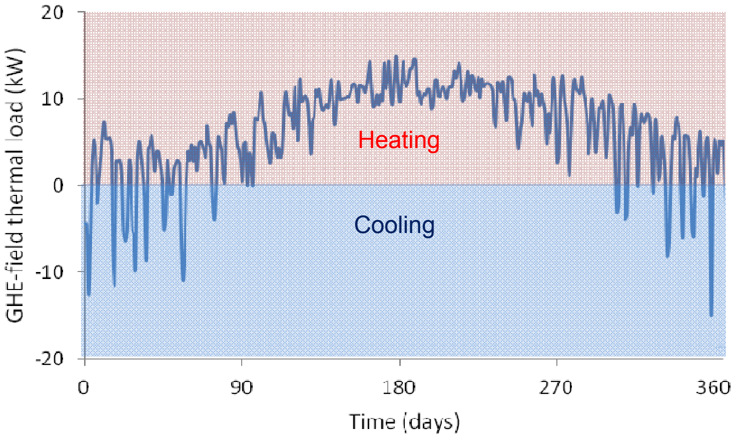


Figure 2. GHE-field annual thermal load for Melbourne conditions

A time and depth ground temperature equation, modified for Australian conditions by Baggs and co-workers [6], was applied as initial and boundary conditions, together with the annual thermal loads and U-loop fluid flow rates (~13 litres/min/U-loop). Results are compared with a model where no ground temperature variations are considered.

The temperatures at the GHE wall 25 m below the ground surface are compared for GHEs with and without surface thermal recharge (Figure 3). It is observed that when no thermal recharge is allowed from the surface of the ground and therefore no heat is transferred axially between the ground surface and the ground, the minimum temperature of the GHE wall is about 1.2°C lower than in the case when thermal recharge from the surface is accounted for.

Thermal recharge from the ground surface occurs naturally and seems to enhance the performance of the GHEs in the case analysed here. Neglecting this effect in the design process may result in the selection of longer (deeper) GHEs to compensate for the lower temperatures in the GHEs and in the ground that are estimated with current models, especially when sub-zero temperatures are reached in the ground or in the concrete. In the case above, the GHE wall temperature reaches 0.04°C, which may be increased to 1.25°C if the surface thermal recharge is accounted for in the model. This means that for a building with a slightly higher heating demand, an unrealistic prediction of occurrence of freezing in the grout may lead to an incorrect selection of a longer GHE that would not be required. This may be a costly result of a sometimes incorrect assumption in the models currently used for design. Moreover, these results also suggest that the length of the GHEs in this small 2 x 2 GHE arrangement could be reduced, as a significant thermal energy deriving from the additional ~1.2°C is underused. It is expected that under the same conditions, the effects of considering air temperature fluctuations in GHE modelling would be even more pronounced in larger GHE-fields and in GHEs that are shorter than the 50 m used here, since the 5-10 metres of ground temperature being affected would represent a much larger proportion of the length of the GHEs.

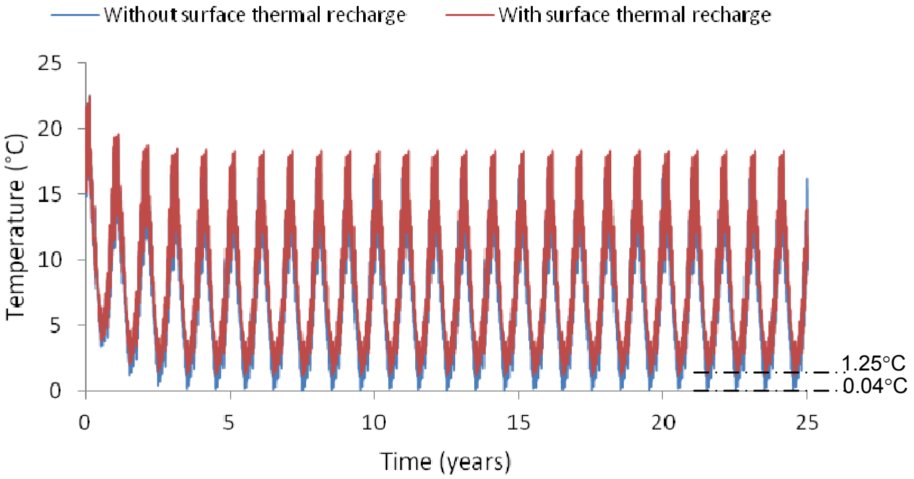


Figure 3. GHE wall temperature 25 m below the ground surface for models with and without surface thermal recharge

Conclusions

This paper studies the effect of air (and thus ground) temperature fluctuations in an example GHE-field. This effect is implemented in the numerical model using a time and depth dependent temperature for the natural ground as initial and boundary conditions.

The effect of thermal recharge and discharge from the ground surface seems to have considerable influence on thermal performance of the systems (in Melbourne) and should be implemented for a more accurate prediction of the GSHP system's thermal performance.

Ignoring the surface thermal recharge (in heating dominant cases) may lead to the false prediction of freezing in the ground, the GHE and the fluid and to overdesign systems with either more or deeper GHEs than actually required. Therefore, considering surface air temperature effects may lead to the closer-to-reality prediction of higher temperatures in the fluid, the GHEs and the ground, and more economically efficient GHEs.

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