Energy and Buildings 104 (2015) 323–335

Contents lists available at ScienceDirect

Energy and Buildings

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

Improving the performance of Ground Coupled Heat Exchangers in unsaturated soils

Arnold B. Platts*, Don A. Cameron, James Ward

Barbara Hardy Institute, University of South Australia, Australia

ARTICLE INFO

Article history:
Received 13 November 2014
Received in revised form 27 April 2015
Accepted 28 April 2015
Available online 3 July 2015

Keywords:
Dry soils
Ground wave
Passive cooling
Soil thermal conductivity
ANSYS 14.5-CFX

ABSTRACT

Ground heat exchangers (GHE) have serious limitations imposed upon them when installed in soils having low thermal conductivity and diffusivity. The restrictions to heat flow are: pipe surface area, the formation low thermal diffusivity and unsaturated soils moisture migration due to elevated temperatures. A comparative theoretical analysis has been conducted to ascertain the feasibility of a 'Membrane Conduction Augmentation System' (MCAS) to improve performance relative to a conventional Horizontal Ground Coupled Heat Exchanger (HGCHE). Results show that significant reductions in HGCHE length for equivalent cooling could be obtained in analyses both cyclic (simulating intermittent air-conditioning usage) and 10 day constant heat transfer stress test. Most significantly, the lower the soil's thermal conductivity and diffusivity the higher the efficiency of the proposed system. The MCAS simulated in the same size trench (300 mm) as that of a conventionally constructed 'direct burial' HGCHE yielded efficiency 46% higher for the 10 day stress test, while the 1200 mm MCAS improved by 150%. Both simulations used soil thermal conductivity of 0.54 W/m·K. Reductions in interface soil temperatures for the MCAS corresponded inversely to the size of the MCAS.

1. Introduction

Ground heat exchangers (GHEs) utilise the vast integrative heat capacity of the Earth's crust and exist in many forms to undertake a variety of duties involving the heat exchange with the ground. When cooling the air in summer within a building, generally a hydronic radiant cooling or a split system air conditioner is used with the heat expelled to the ambient air adjacent to the building. An alternative is to discard the heat underground at a depth of approximately two metres, offering the advantage of a lower and more stable ambient soil temperature than the air above.

Although ground temperatures are advantageous, a significant problem highlighted by Tarnawski [1] for GHEs constructed in unsaturated soils is the high thermal resistance (or low thermal conductivity), which impedes heat injection into the surrounding main soil body (or formation). An early understanding of the parameters for gauging the thermal behaviour of soils was given by Salomone et al. [2], whose research highlighted the significance of the soil type, density and moisture content with experimental data on silty clay. Similarly, Macaulay et al. [3] demonstrated the importance of density and water content, but also soil structure and the influence of increasing mineral content (mainly quartz) on heat transfer in a geothermal environment. Macaulay et al.'s study was on six soils encountered in Australia; the structure of the soils ranged from cohesive to granular. These studies all showed that increasing the moisture content in unsaturated soil is beneficial for heat transfer [4,5].

A serious problem encountered when attempting to dispose of heat in unsaturated soils is the moisture migration away from the heat source. This physical phenomenon was first reported by Gurr et al. [6] in a laboratory experiment, and later, Martin et al. [7] reported increased thermal resistance of the soil adjacent to a buried electrical power cable. It was reported in experiments with either sand or clay that soils adjacent to the cable dried out when exposed to elevated ampacity[1] in unsaturated soils. The reduction in heat transfer resulting from local drying of the soil has required cable ampere operating regimes to be incorporated to prevent overheating.

The current practice for horizontal ground heat exchangers (HGHEs) is to bed pipes in unsaturated sand as outlined by the

---

* Corresponding authorat: Mawson Lakes Campus, Mawson Lakes Boulevard, Mawson Lakes, 5095, Australia. Tel.: +61 432 084 434.
E-mail addresses: arnold.platts@mymail.unisa.edu.au, arnoldplatts1978@gmail.com (A.B. Platts), Donald.Cameron@unisa.edu.au (D.A. Cameron), James.Ward@unisa.edu.au (J. Ward).

[1] Ampacity is a cable electrical power capacity at a prescribed moment in time conditional on the soils ability to dissipate the heat generated within the cable.

http://dx.doi.org/10.1016/j.enbuild.2015.04.050
0378-7788/

Nomenclature

A	area (m^2)
C_p	specific heat at constant pressure (J/kg·K)
d	diameter (m)
k	thermal conductivity (W/m·K)
h	convective heat transfer coefficient ($W/m^2·K$)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
Nu_d	Nusselt number for forced convection (dimensionless)
P_r	Prandtl number (dimensionless)
q	heat flow (W)
r	radius (m)
R	resistance (m·K/W)
R_e	Reynolds number (dimensionless)
T	temperature (°C)
ΔT	temperature difference (K)
Δx	material thickness (m)
U_t	overall heat transfer coefficient (for whole heat exchanger) (W/K)
T_{in}	temperature inlet water (°C)
$T_{-y,t}$	temperature outlet water at distance '$-y$' along GHE pipe (°C)

Ground Source Heat Pump Association (UK) [8]. However, washed sand has low water holding capacity and relatively low levels of suction over the normal range of moisture content. When sand is placed alongside either silt or clay, the sand will surrender its moisture to any soil with higher suction until equilibrium is achieved between the sand and the adjacent soil [9]. Furthermore, moisture migration from both the bedding and backfill, will occur away from the heat source under a temperature gradient, namely the GHE pipe [1,10]. Moisture migration can be either by liquid or vapour.

Past attempts to improve subterranean soil heat transfer in partly saturated soils have focused on either improving the thermal conductivity of the backfill around the heat source, or on methods to maintain high moisture content. One such attempt was undertaken by Jackson [11] whereby it was proposed the buried heat source be encased either in sand mixed with an acrylic latex resin, or in sand and paraffin wax. Experimentally, the native soil (control) with a thermal conductivity of 1.19 W/m·K proved marginally superior to the acrylic latex resin (thermal conductivity of 1.05 W/m·K). In an assessment of Jackson's proposal by Couvillion and Cotton [12], merit was given to the fact that moisture migration was not detected close to the heat source. However, it should be noted that the thermal conductivity in those cases remained relatively low.

Another investigation by Remund et al. [13] involved modelling the replacement of moisture depleted from around the heat source. The recommendation from this study was to maintain water content in the soil adjacent to the pipe by irrigation, both in high and low thermal conductivity soils. It should be noted that the practicality of adding water was not discussed, though it may be impractical in free draining soil (sand), and dry environments where water is both scarce and a valuable commodity.

This paper investigates the impact of a hypothetical Horizontal Ground Coupled Heat Exchanger (HGCHE) with water-saturated quartz sand enveloping the GHE pipe and a polyethylene membrane enveloping both the pipe and the saturated sand. This novel arrangement is termed the "Membrane Conduction Augmentation System" (MCAS) and it is proposed as a solution to the problem of moisture migration close to a buried heat source. Using a numerical modelling approach, the theoretical benefit of the MCAS is quantified relative to a conventional HGCHE buried in dry soil. In particular, the numerical analysis considers the influence of the size of the MCAS on the potential benefit it provides.

2. Modelled scenario

The paper applies the cooling demand of a 7.5 star rated dwelling (NatHERS, 2009) [14]. A peak cooling load of 7.44 kW, which occurred on a very hot summer day on the 28th January 2009, was chosen for this study, based on the study of a South Australian dwelling in Lochiel Park, by Saman and Halawa [15]. This cooling load will be used as a test case for HGCHEs installed in both low and high thermally conductive soils.

A search for dry unsaturated soil not influenced by sub-surface groundwater for an associated experiment led to the choice of a field site in a semi-arid northern region of Adelaide, South Australia. The soil data from that experiment were extracted for this paper. The township is close to the Roseworthy Automatic Weather Station (AWS)[16]; Roseworthy is located 45 km from Lochiel Park and Wasleys lies approximately 7 km north–west of Roseworthy. Although the trials of the MCAS at this site are not discussed in this paper, the thermal properties of the clayey soils are used in the numerical analyses. The soils were not influenced by a shallow water table and were not saturated. In addition, historical weather data from Roseworthy AWS were used to establish temperatures at the boundaries of the model.

Fig. 1 shows a schematic of a HGCHE and cooling system; the orange box illustrates the boundary of the conceptual model used in the present analysis. In the interests of practicality, and in order to focus on the behaviour of the HGCHE, the model domain has been established with the upper boundary 0.5 m below ground level. This avoids unnecessary complexity and computing associated with highly variable ground precipitation, convection and surface irr/radiation effects.

Shown in Fig. 1, the HGCHE is installed in an excavated trench; a polyethylene membrane of substantial thickness (modelled as 1 mm) will readily conform to the walls [17], thereby presenting intimate contact with the main soil body. Sand or other granular material is then compacted to the appropriate depth with the pipe or heat source placed at its centre. Granular material is preferred as backfill because of ease of compaction and its high thermal conductivity when saturated [3].

3. Parametric study on a membrane conduction augmentation system

The MCAS was studied to determine whether the construction would improve the utility of HGCHEs in meeting a plausible house cooling demand. A parametric study was undertaken to investigate the influence of the size of the MCAS on the benefit it can potentially provide over a conventional HGCHE. The investigation primarily considered partially saturated, low thermally conductive soils, as these are problematic for GHEs [1,13].

The MCAS was evaluated for three trench widths (based on standard backhoe excavator bucket sizes): 300, 600 and 1200 mm. Comparisons were made with the conventional direct pipe burial method, termed "Direct Burial" (DB), which was assumed to have a single trench width of 300 mm.

3.1. Boundary conditions

A finite element method approach utilising ANSYS CFX 14.5 [18] software was chosen to explore the theoretical potential for heat transfer improvement. A 58 h period was used for transient conditions, and ten days for the constant operation modelling. A conceptual sketch of the model is provided in Fig. 2. Owing to