Geothermics 53 (2015) 171–182

Contents lists available at ScienceDirect

Geothermics

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

Effects of coolant flow rate, groundwater table fluctuations and infiltration of rainwater on the efficiency of heat recovery from near surface soil layers

Mostafa Mohamed[a,*], Omar El Kezza[a,c], Mohamad Abdel-Aal[a], Alma Schellart[b], Simon Tait[b]

[a] School of Engineering and Informatics, University of Bradford, Bradford, West Yorkshire, BD7 1DP, United Kingdom
[b] Department of Civil and Structural Engineering, University of Sheffield, Sheffield, S1 3JD, United Kingdom
[c] Formerly postgraduate student

ARTICLE INFO

Article history:
Received 14 August 2013
Accepted 29 May 2014
Available online 19 June 2014

Keywords:
Ground source heat pump
Groundwater table fluctuation
Thermal properties of soils
Drainage
Heat transfer in soils
Heat recovery

ABSTRACT

This paper aims to investigate experimentally the effects of circulating coolant flow rate, groundwater table fluctuations, infiltration of rainwater, on the amount of thermal energy that can be recovered from the near surface soil layers. A comprehensive experimental investigation was carried out on a fully equipped tank filled with sand. A heat collector panel was embedded horizontally at the mid-height of the tank. Measurements of the temperature at various points on the heat collector panel, adjacent soil, inlet and outlet were continuously monitored and recorded. After reaching a steady state, it was observed that increasing water saturation in the adjacent soil leads to a substantial increase on the amount of heat recovered. A model was proposed for the estimation of temperature along the heat collector panel based on steady state conditions. It accounted for thermal resistance between pipes and the variability of water saturation in the adjacent soils. This model showed good agreement with the data. Whilst increasing the flow rate of the circulating fluid within the panel did not cause noticeable improvement on the amount of heat energy that can be harnessed within the laminar flow regime commonly found in ground source heat panels. Infiltration of rainwater would cause a temporary enhancement on the amount of extracted heat. Measurement of the sand thermal conductivity during a cycle of drying and wetting indicates that the thermal conductivity is primarily dependent upon the degree of water saturation and secondary on the flow path.

1. Introduction and background

Increasing utilisation of renewable energy is inevitable to reduce reliance on fossil fuels and so as to address the potential adverse effects of climate change. In many parts of the EU and the UK, climate change is predicted to cause more extreme severe weather conditions over the next few decades, e.g. higher volumes of rainfall and longer and more intense periods of rainfall, see for example, Ekstrom et al. (2005), Kay et al. (2006) and Mueller and Pfister (2011). In the UK a report by Jenkins et al. (2009) indicates that the UK is likely to experience wetter winters, both in terms of volume and intensity and slightly drier summers, but that there will be noticeable regional variations. The authors propose that these effects may have significant impacts on the extraction of thermal energy from the near surface soil layers due to the variability of degree of water saturation in the unsaturated zone and significant temporal fluctuations of the groundwater table, see for example, Pinault et al. (2005) and Ahmet (2010). The temperature of the near surface soil layers is warmer than the ambient air temperature in the winter and cooler in the summer. The ground temperature becomes relatively stable below a particular depth over the entire duration of the year. Heat pumps (HPs) coupled with heat collector panels (HCPs)/heat exchangers (HEs) in the form of shallow ground heat collectors could utilise the low temperature that can be harnessed from the ground. The recovered heat energy is then used to provide heating for residential houses and for the supply of domestic hot water. The efficiency of systems to extract heat from the ground is dependent on a number of key parameters including the

* Corresponding author. Tel.: +44 1274233856; fax: +44 1274234111.
E-mail address: m.h.a.mohamed@bradford.ac.uk (M. Mohamed).

http://dx.doi.org/10.1016/j.geothermics.2014.05.013
0375-6505/

Nomenclature

B	spacing between pipes (m)
C_p	thermal capacity ($J\,kg^{-1}\,K^{-1}$)
D	pipe diameter (m)
h_w	heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
k_{glycol}	glycol (circulating fluid) thermal conductivity ($W\,m^{-1}\,K^{-1}$)
k_p	pipe thermal conductivity ($W\,m^{-1}\,K^{-1}$)
k_s	soil thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	pipe length (m)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
Nu	Nusselt number
Pr	Prandtl's number
q	Thermal energy flux (W) or ($J\,s^{-1}$)
R_{total}	thermal resistivity ($m\,K\,W^{-1}$)
Re	Reynolds number
T	temperature (°C)
T_{inlet}	pipe inlet temperature (°C)
T_{outlet}	pipe outlet temperature (°C)
T_s	soil temperature (°C)
t_{soil}	soil thickness
Z	depth of pipes (m)
Q	thermal energy flux (W) or ($J\,s^{-1}$)
∇L	longitudinal mesh size for pipe (m)

Subscripts

s	soil
p	pipe
w	circulating fluid
$cond$	conduction
$conv$	convection

Greek letters

μ	dynamic viscosity
ν	kinematic viscosity
ρ	density ($kg\,m^{-3}$)

thermal properties of soils adjacent to the HCP, existence of groundwater table and characteristics of the HCP, e.g. length and diameter of pipes and hydrodynamics, e.g. glycol flow rate and Reynolds number.

Over the last two decades, several field and numerical studies have been conducted to investigate and to model the performance of different ground source heat pump systems (GSHPs) under various conditions, see for example, Piechowski (1998), Leong et al. (1998), İnallı and Esen (2004), Diao et al. (2004), Esen et al. (2007), Demir et al. (2009), Koyun et al. (2009), Ngo and Lai (2009), Pulat et al. (2009), Wu et al. (2010), Fontaine et al. (2011) and Abdel-Aal et al. (2012). Piechowski (1998) developed a model that is capable of estimating the heat recovery from HCP based on an implicit Finite Difference Method that was found to reduce the simulation time considerably. Esen et al. (2007) carried out simulations based on the Finite Difference (FD) method. They proved that there was a good correlation between the numerical results and those achieved from physical experiments provided that ground properties are kept uniform and constant throughout the tests. Maximum temperature difference between modelled and measured data was 1.2 °C which is equivalent to a difference of 8% of the measured temperature. Of note, Esen et al. (2007) did not consider moisture content and water migration within soil mass adjacent to the ground pipes which could have a substantial effect on the thermal conductivity.

Transient models were also proposed by some authors such as Esen et al. (2007), Ngo and Lai (2009), Demir et al. (2009) and Wu et al. (2010). Demir et al. (2009) validated their transient numerical model using experimental measurements of ground temperature in the vicinity of 3 m × 40 m parallel GSHP loops that were installed at a depth of 1.8 m and a spacing of 3 m. The proposed model by Demir et al. (2009) was based on FD Alternating Direct Implicit (ADI) method and showed a maximum soil temperature variation between modelled and measured of 10%. However, the variation of moisture content in soil was neglected. Esen et al. (2007) and Demir et al. (2009) have also neglected the pipe wall thickness of the HCP when modelling heat transfer between the circulating glycol and surrounding soils. Hence, only conduction was assumed to be transferring the heat between the soil and coolant. None of the above authors have numerically modelled temperature of coolant along the pipe profile. A maximum difference between experimental and computed outlet temperatures of around 3 °C which is equivalent to 8% of measured values can be attained using proposed models by Piechowski (1998) and Koyun et al. (2009). It was noticed that most ground temperature variation occurs close to the pipe (i.e. 150 mm from the pipe wall) in case of the heat pump loop as proven by Piechowski (1998). The range of soil thermal conductivity values, which is a key parameter in understanding heat transfer in soil, varied from 0.25 to 2.5 $W\,m^{-1}\,K^{-1}$ and may differ from calculated ones by ±25%, as stated by Piechowski (1998). In addition, implementation of the effects of thermal resistivity between buried parallel pipes was rarely found in literature (e.g. Claesson and Dunand, 1983) and not often considered when modelling temperature variation along HCP profile. However many authors studied the impact of thermal resistivity between borehole pipes such as Bennet et al. (1987), Hellstrom (1991), Zeng et al. (2003), Sharqawy et al. (2009) and Lamarche et al. (2010).

Based on the critically reviewed technical literature, it is reasonable to conclude that the dynamic effects of changing the level of water table and water saturation due to percolation of rainwater within the near surface soil layers on the efficiency of heat recovery have not been examined systematically. It is important for future enhancement of the ground source heat pumps efficiency that these issues are investigated in a controlled laboratory environment as well as implemented in analytical models. The key objectives of this work are then to investigate and evaluate the effects of groundwater table fluctuation, infiltration of rainwater and flow rate of the circulating glycol or coolant on the recovery of heat from soils. The assessment of these variables has been accomplished using a ground heat collector panel that is made of 8 mm diameter nylon tubes and buried in a relatively large scale 1 m^3 tank filled with sand. Temperature sensors were installed at predetermined locations for taking simultaneous measurements.

2. Methodology

2.1. Experimental approach

A fully instrumented tank with internal dimensions of 1 m × 1 m × 1 m was manufactured. Fig. 1 shows a schematic diagram of the tank. The sides of the tank were stiffened and fully insulated to minimise interaction with the ambient air temperature. A drainage system was designed and installed at the base of the tank to uniformly introduce/drain groundwater over the whole cross-section of the tank. The drainage system includes: perforated pipes, manifold, gravel bed, filter sheet and a well. The perforated pipes and manifold were embedded in a gravel bed that was wrapped by a synthetic filter sheet to prevent clogging of the drainage system. The manifold was connected with an external