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Heat dissipation effect on a borehole heat exchanger coupled with a heat pump

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HIGHLIGHTS

- Theoretical and experimental fluid differential temperatures were in good agreement.
- Theoretical results were obtained as 2.5 °C/4 °C for January/July.
- Experimental results were 2.9 °C–3 °C/3.87 °C–4.2 °C for January/July.
- Mean annual energy dissipated was 4.5 times more than the amount extracted.
- There was not enough evidence to support creeping soil degradation in the borehole.

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ABSTRACT

Thermal performance evaluation of a ground-coupled heat exchanger has been undertaken to assess the extent of heat dissipation into the ground and its long term effect on the cooling performance of a heat pump system. Simulation results were compared with operational data over a 3-year period and found to be in good agreement. However the annual average energy being dissipated into the borehole was found to be about 4.5 times more than the amount being extracted thus raising concern about long term effectiveness of the borehole as a heat sink. Even though, there was a slight decline in the energy dissipation rate during the third year, the result does not provide adequate evidence to support creeping soil degradation process in the borehole over such a relatively short period. Since the performance of each ground-coupled heat exchanger appears to be influenced by its location, more research is needed to acquire better and wider understanding of the effect of heat dissipation and soil degradation processes in borehole systems.

1. Introduction

One of the energy and environmental issues dominating most global policies is how to reduce energy consumption in buildings since the sector is responsible for about 40% of total global energy consumption and carbon emissions [1].

The potential of ground source heat pumps (GSHPs) are widely recognised as efficient technologies that could play an important role in providing heating and cooling for buildings [2–7]. GSHPs may be coupled with either vertical U-tubes or horizontal heat exchangers in order to dissipate or extract heat from the earth. The overall thermal performance of a GSHP is therefore dependent on factors such as the geometric configuration of the heat exchanger and thermophysical properties of the surrounding soil. To this end a number of theoretical and experimental studies have been carried out towards determining the main factors affecting the performances of ground heat exchangers (GHEs). For instance, Seong-Kyun et al. [8] developed a dynamic model for borehole heat exchangers. The model was validated on a number of installations and found to be fairly predictable in the assessment of the performance of GHEs. Yang et al. [9] investigated the effect of fluid temperature variation and heat transfer rates between two adjacent legs of a U-tube heat exchanger and obtained a validation error of less than 6%. Oppelt et al. [10] developed a model for the simulation of borehole filling (grout) of double U-pipe heat exchangers in relation to location of pipe shanks and achieved an error of 6% and 9% for a minimal and maximal shank spacing respectively. Georgios et al. [11] developed models for evaluating complex temperature variation around GHEs. Other theoretical approaches for evaluating the performance of heat exchangers have also been investigated [12–14] but they all have limitations in terms of the ground and GHE conditions at different locations.

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Nomenclature

$C_{1\varepsilon}$,C_2	constants
c_p	specific heat (J/kg K)
d	pipe diameter (m)
E	total energy (J/kg)
G_b	generation of turbulence kinetic energy due to buoyancy (J/s m^3)
G_k	generation of turbulence kinetic energy due to the mean velocity gradients (J/s m^3)
g_i	component of the gravitational vector in the *i*th direction
h	specific sensible enthalpy (J/kg)
h_s	specific sensible enthalpy for solid component (J/kg)
h_j	specific sensible enthalpy of species *j* (J/kg)
k	thermal conductivity (W/m K)
k_{eff}	effective thermal conductivity (W/m K)
$\dot{m}$	mass flow rate of fluid (kg/s)
n_p	number of pipes in boreholes
p	pressure (Pa)
P_{rt}	turbulent Prandtl number for energy
σ_k, σ_ε	turbulent Prandtl numbers for k and ε models
Q_c	maximum cooling load (kW)
Q_h	maximum heating load (kW)
R_e	Reynolds number
S	modulus of the mean rate-of-strain tensor
S_k, S_ε, S_{ij}	user-defined source terms
T	temperature (K)
t	time (s)
V	velocity (m/s)
v	component of the flow velocity parallel to the gravitational vector (m/s)
u	component of the flow velocity perpendicular to the gravitational vector
u_i,u_j,u_k	velocity for different direction (m/s)
x	length (m)
x_i,x_j,x_k	length in different direction (m)
Y_j	mass fraction of species *j*

Greek letter

β	thermal expansion coefficient
ε	dissipation rate
μ	dynamic viscosity (Pa s)
μ_t	turbulent viscosity (Pa s)
ρ	density (kg/m^3)
τ	deviatoric stress tensor

Subscripts

o	outside
s_u	summer
w_i	winter

Regarding experimental studies, Jun et al. [15] identified soil type and associated thermal resistance as the dominant factors affecting thermal performance of a ground heat exchanger. Pahud et al. [16] showed that thermal resistance on a double-U-pipe heat exchanger could be reduced by about 30% when quartz sand is used instead of bentonite. Aristodimos et al. [17] also revealed that de-bonding at the interface between borehole pipes and grouting material do have significant impact on ground heat exchangers. As a result they recommended a grouting material with low shrinkage properties for overcoming the de-bonding phenomenon. Studies carried out by Jun et al. [15] further showed that ground heat exchangers with wider shank spacing have better thermal performance than closely spaced shanks. Diao et al. [18] also established that the performance of ground heat exchangers could significantly be affected by groundwater.

There have however been growing concerns about the long term effectiveness of GHEs due to the relatively higher rates of heat dissipation into the ground as compared with the extraction rates in cooling dominated situations. This is due to the fact that as heat is added to or removed from the ground, the surrounding soil temperature changes. If the total annual heating load does not balance the total annual cooling load, then there will be a net change in the ground temperature after each year of operation. After many years of operation, the ground will become a poorer source of heat sink in an unbalanced system, and therefore, the overall cooling performance of a GSHP system would be affected.

These concerns have led to recent guidelines for tests procedures as reported in ASHRAE 2007 [19] and by Sanner et al. [20] in an effort to establish effective tests methods necessary for designing and sizing of ground-coupled heat pump systems. Meanwhile some heat mitigation techniques have been proposed and evaluated. For example, Li et al. [21] investigated a novel multi-function ground source heat pump system for mitigating the excessive heat in the soil and achieved a reasonable level of heat reduction. Wei et al. [22] evaluated an integrated solar-earth source heat pump system with a heat storage water tank and achieved a reduction of about 14.5% in the heat rejection rate as compared with conventional ground source heat pump. Sagia et al. [23] also showed that a cooling tower could be used to mitigate the excessive heat load in a Hybrid Ground Source Heat Pump system. However in all these test and evaluation cases, the results were influenced by factors such as geological condition, geographical location and the end use of the heat recovered from the systems thus making each case a unique system. For the benefit of achieving further understanding and contributing to wider knowledge of heat mitigation concepts in borehole designs, this study evaluates the thermal performance of a typical cooling dominated ground-coupled heat pump system.

2. Ground-coupled heat exchanger system

Fig. 1 shows the schematic diagram of a reversible heat pump coupled with the vertical U-bend close loop pipe heat exchangers. The system was fully commissioned in 2008 in the Centre for Sustainable Energy Technologies (CSET) building at the University of Nottingham Ningbo China. The installation is also part of an integrated ground source heat pump (GSHP) system for providing water supply to a radiant panel circuit in the building at 15 °C in summer and 45 °C in the winter period. The basic specifications for the system are:

- Heating capacity = 65 kW.
- Cooling capacity = 55 kW.
- Electrical power input during cooling = 10.5 kW.
- Electrical power input during heating = 15 kW.
- Heating coefficient of performance (COP) = 4.3.
- Cooling COP = 5.2.
- Depth of each borehole: 70 m.
- Specific heat factor (winter) for each borehole: 30 W/m.
- Specific heat factor (summer) for each borehole: 50 W/m.
- Total number of boreholes: 20.
- Distance between boreholes: 4.3 m.
- Heat transfer fluid in borehole pipes: water.