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Thermal performance improvement of a horizontal ground-coupled heat exchanger by rainwater harvest

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ABSTRACT

Increased moisture content leads to increased thermal conductivity and is beneficial for heat exchange of ground-coupled heat exchangers (GCHE). In this study, a horizontal GCHE was combined with a rain garden, characterized by the beneficial supply of rainwater to groundwater, increased soil moisture content and favorable conditions for GCHE. Sandy soil container experiment results showed that water immigration was possible under thermal action of the horizontal GCHE. Compared with little water transfer under the heat evacuation condition, with a relatively small temperature difference between fluid and adjacent soils, heat and water transfer were coupled under the heat rejection condition and a drying region appeared at regions adjacent to the tube wall because of the relatively large temperature difference. Water immigration was more likely to occur when sandy soil had low moisture content, for example 0.1 m^3/m^3. The coupled heat and water transfer model was necessary for prediction of horizontal GCHE thermal performance. Under high moisture content conditions, the coupled model was dispensable but it was necessary to consider moisture-dependent variation in thermal conductivity.

1. Introduction

Promoting the use of renewable energy is important, especially in the current environment of depletion of fossil energy resources and rising energy prices. Specifically, low-grade renewable energy fits and matches low-grade need for space conditioning very well. Simultaneously, water is essential for life. Environmental degradation and global warming also raise concerns about water resource utilization, especially in water-deficient regions. The optimum conservation of rainfall resources is a focus for concern.

Geothermal energy, using the ground as a heat source or sink, is a renewable energy resource that can be used to provide heating and cooling for buildings. Ground water heat pumps might lead to loss of underground water resources, whereas the impact of ground-coupled heat pumps (GCHP) on the underground water is nearly zero. Compared with systems utilizing a carbon or gas boiler combined with a chiller, the GCHP system is characterized by a compact system structure, low electrical consumption, low maintenance requirements [1] and limited environmental impacts through the installation of the ground-coupled heat exchanger (GCHE). Moreover, compared with an air source heat pump, soil can provide higher evaporation temperatures and lower condensation temperatures, gaining more energy efficiency and higher reliability. If the necessary geological and site conditions are fulfilled, GCHP systems can make use of geothermal energy and take advantage of the relatively constant temperature of the earth. The outcome of the energy and exergy flow analysis revealed that the ground source heat pump heating system is better than air source heat pump or conventional heating system [2]. The advantages of the GCHP system have been recognized and these systems have been widely applied. The main disadvantage is the higher initial capital cost, being about 30–50% more expensive than air source units [3].

GCHPs can be grouped into two categories based on the type of GCHE (vertical or horizontal GCHE, installed in vertical boreholes or trenches, respectively). Vertical GCHE has the advantages that it requires a small land area and yields the most efficient system performance [4]. Heat exchange models and model solutions are the primary coverages that have been studied. The models include

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Nomenclature

D	diffusivity coefficient, m^2/s ($m^2/s\,K$)
E	water evaporation per unit surface area, $kg/s\,m^2$
J	infiltration rate per unit area, $kg/s\,m^2$
K	soil permeability (hydraulic conductivity), m/s
L	length, m
M	mass, kg
P	pressure, Pa
Q	heat flow, W/m^2
R	rainwater amount per unit surface area, $kg/s\,m^2$
T	temperature, K or °C
U	intrinsic energy, J/m^2
V	volume, m^3
c	volumetric thermal capacity, J/kg K
d	diameter, m
f	the scale of catchment areas and absorbing areas
h	enthalpy, J/kg
k	heat transfer coefficient, $W/m^2\,K$
q	heat flow rate of tube per unit long, W/m
ε	soil porosity
θ	volume fraction of constituent parts of soil, m^3/m^3
λ	thermal conductivity, W/m K
ρ	density, kg/m^3
τ	time variable, s
ψ	soil moisture potential, m

Subscript

d	dry
f	fluid
eq	equivalent
$inlet$	tube inlet
in	inner of tube wall
out	outer of tube wall
s	solid
sat	saturate
$surf$	ground surface
v	water vapor
w	water (moisture)
atm	molecular
kn	Knudsen

Coefficients

a, b, γ	coefficients depend on soil properties
f_0	tortuosity factor of soil
g	gravity acceleration, 9.8 m/s^2
M_v	molecular weight of water vapor, 18 g/mol
R_v	gas constant of water vapor 461.5 J/kg K
S_g	specific surface area of soil, m^2

Coordinate axis

x	horizontal radial direction
y	depth direction perpendicular to the tube axis

the classical analytical line source model [5,6], cylindrical source model [7–10], finite line source model [4,11] and numerical models [12,13]. The largest cost component of GCHE is bore drilling and the installation of the GCHE is costly. The horizontal ground-coupled source heat pump has become increasingly important as it can reduce installation costs compared with those of the vertical GCHE as no drilling is necessary.

The horizontal type of heat exchanger consists of straight or coiled tubes which are buried in a trench at a depth of approximately 1.6–2.0 m [14]. Horizontal GCHE is more affected by ambient temperature fluctuations because of its proximity to the ground surface, and the installation of horizontal systems requires larger ground area than for vertical systems. Mei [15] has developed a model inclusion of the effect of seasonal ground temperature variation and validated by field measurements, that would enable to simulate horizontal GCHE operation more realistically. Petit and Meyer indicated that the horizontal ground-source heat exchanger offers the maximum economic viability of the air source, horizontal and vertical GCHE systems in South Africa [16]. Inalli and Esen [17] carried out experimental measurements in Turkey of a GCHP system with horizontal GCHE at 1.0 and 2.0 m depths, and obtained average system coefficient of performance (COP) values of 2.66 and 2.81, respectively. Metz [18] monitored a horizontal GCHP system for one year and obtained average Seasonal Performance Factor (SPF) in heating and cooling of 2.46 and 1.91, respectively. Based on an experimental study in Bursa, Turkey, estimation of soil thermal conductivity was discussed, and preliminary numerical temperature distribution around GCHE pipes was obtained. The COP of the entire system and the heat pump unit ranged from 2.46 to 2.58 and from 4.03 to 4.18, respectively [19]. Apart from the conventional single tier ground loop, the average COP of a slinky ground loop (requiring horizontal trench lengths of 20–30% of those for a horizontal single pipe configuration) GCHP was 2.50 [20].

The performance of a ground heat pump system depends strongly on the moisture content and the type of soil [21]. The soil is usually unsaturated soils at the horizontal GCHE installation depth, in which heat transfer is coupled with water transfer, a very complex phenomenon. In the most recent studies, thermal models are always based on heat transfer, without consideration of the water effect [22–25]. Only few research works have been accomplished in soil moisture migration caused by GCHE heat pump operation, for example, a model designed to check the effect of soil moisture freezing around the coil was developed by Mei [26].

If water transfer is included, a more complicated mathematical model is necessary for accurate description and simulation. An inner heat source model has been developed for heat and water transfer in soil with implementation of the model using Autough2 software [27]. Thermal and moisture behaviors of dry and wet soils heated by buried capillary plaits were studied in a prototype agricultural tunnel greenhouse [28]. These studies did not yet analyzed detailed soil temperature and moisture fields around horizontal GCHEs. Mei [29] developed mathematical model with radially symmetrical temperature and moisture profiles in detail. But limited experiment data validation and adaption to heap pump operation conditions have been reported.

According to Piechowski [14], the initial estimation of soil moisture content is crucial for accurate design or simulation of GCHE. In laboratory studies using four soil types, an increase in moisture content at a given density increased thermal conductivity [30]. In other words, increasing soil moisture plays a role in the enhancement of heat transfer. Improved thermal conductivity will be beneficial for heat exchange. In some areas, rainwater could be used to improve ground thermal conductivity at no additional cost, especially in relatively dry areas, where rainfall is not abundant.

Traditionally, most rainwater management has focused on large end-of-pipe systems. Rainwater runoff is undesirable and must be removed from the site as quickly as possible to achieve good drainage. But rainwater drainage reduces water infiltration to soil, increases runoff pollution, reduces groundwater recharge and increases the chance of land subsidence. To solve these problems using methods that are different from conventional stormwater treatment, the Low-Impact Development (LID) concept was proposed [31], which is characterized by “natural” source control. Instead of rapidly and efficiently draining the site, LID relies on various planning tools and control practices to preserve the natural hydrologic functions of the site. LID techniques help to reduce