Energy and Buildings 119 (2016) 242–255

Contents lists available at ScienceDirect

Energy and Buildings

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

Development and validation of a custom-built ground heat exchanger model for a case study building

Sung Lok Do[a,*], Jeff Haberl[b]

[a] Department of Building and Plant Engineering, Hanbat National University, Daejeon, South Korea
[b] Department of Architecture, Texas A&M University, College Station, TX, United States

ARTICLE INFO

Article history:
Received 8 August 2015
Received in revised form
23 December 2015
Accepted 19 March 2016
Available online 19 March 2016

Keywords:
Ground source heat pump
Custom-built ground heat exchanger
Simulation model
Field measurement
Entering water temperature

ABSTRACT

Use of a ground-source heat pump (GSHP) system is becoming widespread in energy savings applications. A typical GSHP system is equipped with one of three ground heat exchanger (GHX) configurations: vertical, horizontal, or surface-water. Due to site characteristics/limitations, however, some residential/commercial buildings utilize a combination of different GHX configurations for their GSHP systems; in this research, we will refer to such a system as a custom-built GHX. A residential building utilizing a custom-built GHX combining two different GHX types (horizontal and surface-water) was selected to be the case study for this research. This research developed a custom-built GHX model to calculate the entering water temperatures (EWTs) circulated from the custom-built GHX to the GSHP system. In order to validate the developed model, the measured EWTs from the case-study house were referenced and compared to the calculated EWTs. The comparison showed that the average EWT differences resulted in about 1.2 °C (2.1 °F) and 1.6 °C (2.8 °F) for the full heating and cooling seasons, respectively.

1. Introduction

The global increase in energy use has greatly contributed to atmospheric climate change, most noticeably by the increase in carbon dioxide levels [1–3]. Increased worldwide energy use also has led to higher energy prices, which is of major concern to the world's economy [4–6]. Climate change and higher energy prices have served to focus attention on improving the efficiency of heating and cooling systems in buildings in order to reduce building energy use.

One of the more efficient systems that is currently in wide use is a ground source heat pump (GSHP). A GSHP system is a general term that includes ground-coupled heat pumps (GCHPs), ground-water heat pumps (GWHPs), and surface-water heat pumps (SWHPs) [7]. A GSHP system utilizes relatively constant ground temperatures instead of ambient temperatures for its residential and commercial heat pump system applications, taking advantage of the fact that the ground is warmer than the ambient air in the winter and cooler than the ambient air in the summer, and thus leading to higher level of efficiency. This is attributable to the increase in temperature difference between the heat source/sink and the condenser, which allows the heat pump compressor to operate at a lower discharge pressure and results in reduced power consumption [8].

The most common application of the GSHP system is a conventional water-source heat pump system connected with ground heat exchanger (GHX) pipes. The GHX unit is where the heat transfer occurs between the heat pump and heat source/sink, by circulating fluid through the GHX pipe. Depending upon the heat source/sink type used in the GHX unit, the GHX can be categorized as one of three types [7]: a vertical GHX using annually constant ground temperatures at a deep underground, a horizontal GHX using ground temperatures at a shallow ground depth, and a surface-water GHX using shallow ground water (such as a pond).

The different source/sink temperatures significantly impact the entering water temperatures (EWTs) flowing into the heat pump unit (i.e., the temperatures after the fluid passes through the GHX pipes). In addition, the EWTs are influenced by the GHX thermal properties, GHX depth, GHX length, ground thermal properties, and building thermal loads. The EWTs play an important role in the GSHP system's thermal performance; lower EWTs typically provide better system performance for cooling, and vice versa. Thus, in general, a GHX configuration is selected and designed to achieve the desired EWTs for a building's heating and cooling system. The selection of the best GHX type largely is dependent upon the local, geological, thermal, and economic characteristics of the soil at the site [8]. Due to the site characteristics and/or limitations, some

---

[*] Corresponding author. Tel.: +82 042 821 1184; fax: +82 042 821 1175.
E-mail address: sunglokdo@hanbat.ac.kr (S.L. Do).

http://dx.doi.org/10.1016/j.enbuild.2016.03.049

Nomenclature

A_{pond}	Surface area of the pond (m^2)
C_p	Specific heat of the fluid (J/kg °C)
$d_{constant}$	Distance between the pipe's surface and the undisturbed ground (m), assumed to be the external radius of the pipe
d_g	Ground depth at a constant ground temperature (m)
d_{pond}	Pond's depth (m)
$D_{in,pipe}$	Pipe's inner diameter (m)
$D_{out,pipe}$	Pipe's outer diameter (m)
h	Convection coefficient of the airflow (W/m^2 °C)
h_{conv}	Convective heat transfer coefficient by wind (W/m^2 °C)
I	Incident solar radiation on the pond's surface (W/m^2)
k_{fluid}	Thermal conductivity of the fluid (W/m °C)
k_{ground}	Thermal conductivity of the ground (W/m °C)
l	Length of the ground heat exchanger pipe (m)
l_{pond}	Perimeter length of the pond (m)
$\dot{m}$	Rate of fluid flow through the pipe (kg/hour)
Nu_D	Nusselt number (non-dimensional)
P_{pond}	Saturation vapor pressure at the pond's surface (kPa)
Q_{conv}	Convection at the pond's surface (W)
Q_{evap}	Evaporation at the pond's surface (W)
Q_{fluid}	Heat transfer between the fluid in the pipe and the pond (W)
Q_{ground}	Heat transfer to/from the ground contact with the pond (W)
Q_{rad}	Thermal radiation from water to sky (W)
Q_{solar}	Solar radiation absorbed by the pond water (W)
R_{cond}	Thermal conductive resistance of the pipe wall (m °C/W)
R_{conv}	Thermal convective resistance between the circulation fluid and the inner pipe surface (m °C/W)
R_{ground}	Thermal resistance between the outer pipe surface and the ground (m °C/W)
R_{pond}	Convective resistance between the outer pipe surface and the pond water (m K/W)
R_{total}	Total thermal pipe resistance (m °C/W)
t	Time of year (hour)
t_{phase}	Phase angle (hour), accounting for the time when the lowest ground temperature occurs
T_{amp}	Amplitude of the ground surface temperature variation (°C)
T_{ground}	Ground temperature (°C)
T_{in}	Leaving fluid temperature (LWT) from the heat pump (°C) (i.e., the inlet fluid temperature into the pipe)
T_{mean}	Mean ground surface temperature for the year (°C)
T_{oa}	Outdoor air temperature (°C)
T_{out}	Entering fluid temperature (EWT) into the heat pump (°C) (i.e., the outlet fluid temperature from the pipe)
T_{pond}	Pond water temperature (K)
$T_{pre,pond}$	Pond water temperature for the previous hour (°C)
T_{sky}	Sky temperature (K)
v	Wind speed (m/s)
V	Pond volume (m^3)
Z_{depth}	Depth of ground (m)
α_{ground}	Thermal diffusivity of the ground (m^2/hour)
ε	Emissivity of the pond water (non-dimensional)
γ	Reflectance of solar radiation (non-dimensional)
ρ	Density of the pond water (kg/m^3)
σ	Stefan-Boltzmann constant, 5.670373×10^{-8} ($W/m^2 K^4$)
$\frac{dT}{dt}$	Pond water temperature change at the current hour (°C)

residential/commercial buildings utilize custom-built GHXs, which use a combination of different GHX configurations. The GHX combination may provide a system designer/engineer more flexibility to design a GHX unit.

This study evaluates the EWTs resulting from a custom-built GHX. A residential building in Texas was selected to serve as the case-study; in this building, a GSHP system was installed that was equipped with a custom-built GHX (a combination of the horizontal and surface-water GHXs). To calculate the EWTs for this residential building, this study developed a custom-built GHX model. To validate the developed model, this research measured the EWTs from the residential building; the measured EWTs were then compared to the calculated EWTs. Fig. 1 presents the overall research process conducted for this study to analyze the EWTs using a custom-built GHX.

2. Residential building with a custom-built GHX

The case-study house used for this study is located in College Station, Texas. It is a two-story residential house built in 1997 (see Fig. 2). The total floor area is 286 m^2, including 202 m^2 for the first floor and 84 m^2 for the second floor. The HVAC system consists of a water-source heat pump (WSHP) system (12.3 kW) for the entire house and a solar energy domestic hot water system.

The WSHP system utilizes a custom-built GHX. The GHX uses a combination of two horizontal GHX units (see Fig. 3(a)) and one surface-water GHX unit (see Fig. 3(b)). The WSHP system is connected to the first horizontal GHX, the surface-water GHX, and the second horizontal GHX, in sequence (see Fig. 4). The first GHX is of the horizontal type; it is 137 m in length and 1.5 m in depth. The second GHX is of the surface-water type; it is 317 m in length and 1.8 m in depth. The third GHX is of the horizontal type; it is 280 m in length and 1.8 m in depth. The total length of all the GHXs is 735 m. The GHXs use polyethylene (PE) throughout the GHX units. The PE pipe is two inches in diameter. A single pump is used to circulate water from the WSHP to the GHXs. The pump has a single speed, 124 W (1/6HP) motor (about 16.2 L/min); this estimate was based on the manufacturer's specifications [9].

In order to measure the temperatures of the supply air, return air, entering water, and leaving water for the case-study house, ten T-type thermocouple sensors were used. Fig. 5 presents a conceptual diagram of the installation of the sensors used to measure the air and water temperatures. Five thermocouple sensors were installed to measure the supply air temperature, three to measure the return air temperature, one to measure the EWT, and one to measure the Leaving Water Temperature (LWT). The data from the case-study house were collected from the middle of December 2012 to the end of July 2013. This period included both the heating and cooling seasons. Table 1 is a summary table illustrating the thermocouple sensors used to measure the air and water temperatures.

The supply air and return air temperatures were measured using multiple thermocouples (i.e., a thermocouple grid) to account for air temperature variations that can occur in the supply/return duct. The thermocouple grid for the return air consisted of three thermocouples; the thermocouple grid for the supply air consisted of more thermocouples (i.e., five) because the location of the thermocouples sensors to measure supply air temperatures was close to the cool-