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Cooling tests, numerical modeling and economic analysis of semi-open loop ground source heat pump system

Hadi Farabi-Asl*, Hikari Fujii, Hiroyuki Kosukegawa

Graduate School of International Resource Sciences, Akita University, 1-1 Tegata-gakuencho, Akita, 010-8502, Japan

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ABSTRACT

Ground source heat pump (GSHP) systems are serving the heating and cooling demands of buildings worldwide. However, the widespread usage of these systems is limited because of their higher initial costs compared with conventional heating and cooling systems, especially in countries with high drilling costs like Japan. The semi-open loop GSHP system was introduced by authors and the results of heating tests and numerical modeling have been published. This system comprises two ungrouted vertical Ground heat exchangers (GHEs) in which groundwater is pumped from one well and injected to another using a water pump. The purpose of the water pumping and injection is to create an artificial groundwater flow around the GHEs to increase the heat advection between the GHEs and the surrounding environment.

In this study, cooling tests on the semi-open loop GSHP system were performed and the thermal performance of the system was measured in each test. The developed numerical model was validated using the results of the cooling tests. Then, a sensitivity analysis was performed to evaluate the system performance under different operational and geological conditions during cooling operation. The results showed that in comparison with conventional GSHP operation, cooling coefficient of performance (COP) and system coefficient of performance (COPsys) can be enhanced by 13.1% and 6.6%, respectively, under fast groundwater flow conditions, as expected at the experimental site. In the absence of groundwater flow, the semi-open loop system is estimated to boost the cooling COP and COPsys by 101% and 62%, respectively, for cooling operations. Finally, an economic analysis was performed, considering the capital and running costs of the system and also the additional equipment costs associated with semi-open loop systems. The results of the economic analysis showed that water pumping and injection can reduce GSHP system costs by 22–36%.

1. Introduction

Buildings and activities in buildings make up a major share of global environmental concerns (Gabrielli and Bottarelli, 2016). In 2010, the building sector used approximately 115 × 10^{18} J globally, accounting for 32% of global final energy demand (24% for residential and 8% for commercial; Ürge-Vorsatz et al., 2013) and 30% of energy-related CO_2 emissions (IEA, 2012).

Ground source heat pumps (GSHPs) are a rapidly growing use of geothermal energy (Soldo et al., 2016), accounting for 70% of the installed capacity and 55% of the total direct use of geothermal energy in 2015 (Lund and Boyd, 2015). GSHP systems are highly efficient technologies that meet the heating and cooling demands of houses and buildings while preserving fossil fuels and avoiding additional CO_2 emissions (Molina-Giraldo et al., 2011). The renewable energy production and carbon footprint of GSHP systems, as well as the geothermal potential of aquifers, have been intensively studied (e.g. Arola et al., 2014; Arola and Korkka-Niemi, 2014; Bayer et al., 2012; Laitinen et al., 2014; Mattinen et al., 2014).

The energy performance of GSHPs strongly depends on the heat transfer process between the Ground heat exchangers (GHEs) and the ground. The heat transfer occurs by conduction and advection mechanisms. Recently, some research efforts have included the effects of the presence of a groundwater flow in GHE modeling (Angelotti et al., 2014). In the presence of a groundwater flow, the heat is also transported by convection, i.e., advection in hydrogeology. In formations with fast groundwater flow, advective heat transfer increases the heat transfer rate between GHEs and the surrounding environment (Fujii et al., 2005; Huber and Arslan, 2015; Lim et al., 2007; Molina-Giraldo et al., 2011; Niibori et al., 2005; Wang et al., 2009; Wang et al., 2014; Zanchini et al., 2012). As a result, the necessary GHE length to meet the heating and cooling loads of a building decreases, resulting in a lower initial cost.

Diao et al. (2004) estimated the impact of groundwater flow on the

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* Corresponding author.
E-mail address: HadiFarabi@gmail.com (H. Farabi-Asl).

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Nomenclature

Q_{ROOM}	Room heat transfer rate (W)
Q_{GHE}	Ground heat exchanger heat transfer rate (W)
W_{TOT}	System power consumption (W)
W_{HP}	Heat pump power consumption (W)
W_{CP}	Working fluid circulation pump power consumption (W)
W_{WP}	Water pump power consumption (W)
T_{out}	Ground heat exchanger outlet temperature (°C)
λ	Soil thermal conductivity (W/m/K)
K	Soil hydraulic conductivity (m/s)
$Q_{heating}$	Room heating load (W/m^2)
$Q_{cooling}$	Room cooling load (W/m^2)
A_e	Building envelope area (m^2)
A_f	Building floor area (m^2)
T_i	Room temperature (°C)
T_o	Ambient temperature (°C)
I	Solar radiation (W/m^2)
U	Overall heat transfer coefficient ($W/m^2/K$)
η	Average solar heat acquisition rate ($W/W/m^2$)
g	Inflation rate (−)
n	Project life time (year)
i	Interest rate (−)
P	Present value of the investment (Japanese yen)
$W_{heating}$	Heat pump power consumptions for heating operation (W)
$W_{cooling}$	Heat pump power consumptions for cooling operation (W)

Acronyms

GSHP	Ground source heat pump
GHE	Ground heat exchanger
COP	Coefficient of performance
COP_{sys}	System coefficient of performance
TRT	Thermal response test
HVAC	Heating, ventilation and air conditioning
OD/ID	Outside diameter/interior diameter

Subscripts

xx	X direction, in horizontal plane
yy	Y direction, in horizontal plane
zz	Z direction, in vertical plane

performance of geothermal heat exchangers. Computations showed that water advection in the porous medium may significantly alter the conductive temperature distribution, resulting in smaller temperature changes and eventually leading to a steady condition.

Experimental studies of the effect of groundwater flow on the thermal performance of GHEs are limited in the literature. Wang et al. (2009) conducted a thermal performance experiment with a GHE under groundwater flow. They also presented a simplified theoretical model to estimate the characteristics of groundwater flow. The results showed that the heat injection and heat extraction of the BHE were enhanced by the groundwater flow by averages of 9.8% and 12.9%, respectively.

Huber and Arslan (2015) performed experimental investigations with a conduction and convection laboratory device and compiled an extensive database of groundwater-influenced geothermal systems. The results showed that in strongly aquiferous water-saturated sand (0.6–1.0 m/day), a 100% increase in the effective thermal conductivity can be expected.

Witte (2001) performed a thermal response test (TRT) in which groundwater flow was induced by pumping in an extraction well located 5 m from the thermal well. Clear indications of enhanced heat transfer due to the induced groundwater flow were observed.

Farabi Asl et al. (2015) studied the effect of water injection and pumping on the heat transfer rate in an ungrouted GHE by performing TRTs. They developed a numerical model and validated it with experimental data. The results of field tests and sensitivity analysis showed that water pumping and injection can increase the heat transfer rate of GHEs, especially in formations with slow natural groundwater flow.

In summary, the presently available results indicate that even relatively slow groundwater flows can strongly affect the heat transfer rate in GSHP systems. However, groundwater flow is a natural characteristic of GHE sites and cannot be artificially changed. Groundwater flow can be improved only by injecting or pumping water into ungrouted vertical GHEs. Injection requires a cheap water source, whereas pumping may cause long-term damage to the groundwater source or violate local regulations.

The semi-open loop GSHP system was introduced by Farabi Asl et al. (2017). This system comprises two ungrouted vertical GHEs and groundwater is pumped from one GHE and injected to the other using a water pump. The purpose of the water pumping and injection is to create an artificial groundwater flow around the GHEs to increase the heat advection between the GHEs and the surrounding environment. Field tests during heating operation were performed and the results showed that water pumping and injection could enhance the system thermal performance; however, the enhancement was limited due to the fast natural groundwater flow in the formation. A numerical model was developed and validated by the results of heating tests. Results of the numerical modeling and sensitivity analysis showed that the heating coefficient of performance (COP) and system coefficient of performance (COPsys) can be enhanced by 12% and 9%, respectively, under the same groundwater flow conditions as the experimental site, depending on the operational conditions. In the absence of groundwater flow, the semi-open loop system was estimated to increase the heating COP and COPsys by 40% and 20%, respectively.

In this study, cooling tests of a semi-open loop GSHP system were performed and the system thermal performance was measured in each test. The developed numerical model was presented and validated using the results of the cooling tests. Sensitivity analysis was then performed to evaluate the semi-open loop GSHP system performance under different operational and geological conditions. In the last part of this study, an economic analysis of the semi-open loop GSHP system was performed. The effect of water pumping and injection on the GSHP system capital and running costs was evaluated for different scenarios considering the costs of additional equipment in the semi-open loop GSHP system.

2. Semi-open loop GSHP system configuration

The ground heat exchanger part of the semi-open loop GSHP system comprises two vertical ungrouted GHEs (GHE1 and GHE2) with 5 m separation distance at the Akita University campus, Akita City, Japan. The upper part (surface to 60 m) of the formation is an alluvial deposit of the Quaternary System, comprising mainly silt, sand and gravel. The lower part comprises siltstone of the Tertiary System. The geological column and undisturbed ground temperature are shown in Fig. 1. Below 15 m, a clear geothermal gradient of 0.04 °C/m was observed. The system specifications are shown in Fig. 2 and Table 1.

Both GHEs are enclosed in a steel casing from the ground surface to the well bottom. Between −10 m and −60 m, the casing is slotted to allow groundwater flow across the GHEs. Double U-tubes are installed in both GHEs from the surface to −60 m. The GHE connecting piping is placed on ground, 10 cm higher than ground surface. In order to prevent the thermal interaction between ambient air and working fluid inside the piping, Styrofoam insulation with 3 cm of thickness was used