Renewable Energy 127 (2018) 182–194

Contents lists available at ScienceDirect

Renewable Energy

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

# Simple index for onsite operation management of ground source heat pump systems in cooling-dominant regions

Sayaka Kindaichi*, Daisaku Nishina

*Graduate School of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, 739-8527, Japan*

ARTICLE INFO

*Article history:*
Received 23 October 2017
Received in revised form
17 April 2018
Accepted 19 April 2018
Available online 21 April 2018

*Keywords:*
Ground source heat pump systems
Cooling-dominant regions
Borehole-type ground heat exchangers
Operational management
Variable temperature penalty

ABSTRACT

In ground source heat pump (GSHP) systems, large imbalances between cooling and heating loads cause a rise or decline in ground temperature because of thermal interference between multiple ground heat exchangers (GHEs). To evaluate annual changes in ground temperature, we applied a variable temperature penalty, which was simply obtained using measured data without computer simulation. First, we examined measured data for 3 years after completion of a hybrid GSHP system that had 70 borehole-type GHEs, combined with an air source heat pump unit. In the hybrid system, the GSHP showed high efficiency (coefficient of performance > 5.0) throughout the year and had a variable contribution between years with regard to cooling/heating output and time of operation. The amount of heat rejected to the ground by cooling reached ~4.8 times that of heat extracted from the ground by heating after 3 years of operation. This imbalance produced ground temperature increases of ~3 °C in an internal borehole. The variable temperature penalty reproduced the measured temperature increase, suggesting that the index is appropriate for assessing long-term ground temperature changes in the operation phase. This simple index allows operational improvement onsite and will aid the sustainable operation of GSHP systems in cooling-dominant regions.



## 1. Introduction

Ground source heat pump (GSHP) systems have been used in many countries, particularly in North America, Europe, and recently China [1]. Although Japan has only a few percent of the world market share, the number of GSHP installations has been increasing recently [2]. The application of GSHPs varies on cooling/heating load characteristics. GSHPs were originally used for heating applications as an alternative to conventional boiler systems using fossil fuel in cold climate regions. Europe, Sweden and Switzerland have especially large GSHP shares for residential heating demand [3], but few projects using both cooling and heating have been reported for warm-climate regions [4,5]. Even though the United States and China have wide distributions of cooling/heating load [6], most areas have warm and humid climates in summer and require cooling functions [7–9]. A large portion of Japan also has high temperatures, where the seasonal energy demand is dominated by cooling for commercial buildings, rather than for residential ones. In such situations, it is not realistic to meet full cooling loads by only GSHP capacity, because of space and cost restrictions. Instead, design engineers tend to adopt hybrid GSHP systems, in which cooling towers or air source heat pumps (ASHPs) are used in tandem with GSHPs [10–12]. Other hybrid systems have been proposed in heating load-dominant regions [13,14].

Extreme imbalances between cooling and heating loads raise or reduce ground temperature in the long term (over several decades), because thermal interference between multiple GHEs limits heat flow and thereby causes thermal storage in the ground for large systems. Thus, the prediction of annual changes in ground thermal characteristics is useful for design study. Theoretical analyses based on a finite line source or cylindrical source heat conduction models are commonly used e.g. Refs. [15–20] in several types of software on the market [21–24]. The moving finite line source model has been used to account for groundwater flow [25,26]. Numerical analysis allows detailed customization of GSHP systems and provides distributions of heat and flow, although it generally needs more calculation time than theoretical analyses. A few studies have investigated GSHP system performance by numerical methods [27–29] and validated accuracy using measured data [30–33]. System simulation tools such as TRNSYS allow evaluation of full

* Corresponding author.
*E-mail address:* kindaichi@hiroshima-u.ac.jp (S. Kindaichi).

https://doi.org/10.1016/j.renene.2018.04.065
0960-1481/© 2018 Published by Elsevier Ltd.

**Abbreviations**

| | |
|---|---|
| ASHP | air source heat pump |
| BEMS | building energy management system |
| CHW | chilled and hot water |
| COP | coefficient of performance |
| GHE | ground heat exchanger |
| GSHP | ground source heat pump |

*Nomenclature*

| | |
|---|---|
| $C_{bottom}$ | Correction coefficient of heat release on the bottom side [−] |
| $COP_c$ | Rated COP for cooling [−] |
| $COP_h$ | Rated COP for heating [−] |
| $c_p$ | Specific heat of the ground [kJ/(kg K)] |
| $E_{ASHP\_sys}$ | Electric power consumption for an ASHP system [kWh] |
| $E_{GSHP}$ | Electric power consumption for a GSHP without transfer power [kWh] |
| $E_{GSHP\_sys}$ | Electric power consumption for a GSHP system including transfer power [kWh] |
| $E_p$ | Electric power consumption for circulation pumps in a GSHP system [kWh] |
| $E_{p\_grd}$ | Electric power consumption for circulation pumps on the ground side of a GSHP system [kWh] |
| $E_{p\_load}$ | Electric power consumption for circulation pumps on the load side of a GSHP system [kWh] |
| $f$ | Correction coefficient [−] |
| $k_g$ | Heat conductivity of the ground [W/(m K)] |
| $L_{GHE}$ | Total length of GHEs [m] |
| $N_{GHE}$ | Number of GHEs [−] |
| $N_{cor}$ | Number of corner GHEs [−] |
| $N_{in}$ | Number of internal GHEs [−] |
| $N_{peri}$ | Number of perimeter GHEs [−] |
| $Q_{gr}(i)$ | Seasonal thermal imbalance in the ground in $i^{th}$ year [GJ] |
| $Q_{ex}$ | Amount of heat extracted from the ground by heating operation [GJ] |
| $Q_{rej}$ | Amount of heat rejected to the ground by cooling operation [GJ] |
| $Q_{stored}$ | Heat stored in the ground surrounding a GHE [GJ] |
| $q_a(i)$ | Net annual average heat transfer to the ground in $i^{th}$ year [W] |
| $q_{ASHP}$ | ASHP cooling/heating output on the load side [W] |
| $q_{GSHP}$ | GSHP cooling/heating output on the load side [W] |
| $\overline{q_{GSHP\_c}}$ | Average GSHP cooling output [W] |
| $\overline{q_{GSHP\_h}}$ | Average GSHP heating output [W] |
| $q_{total}$ | Total cooling/heating output of GSHP and ASHP [W] |
| $r(i)$ | Radius at $i$th segment [m] |
| $S_{GHE}$ | Average separation length between GHEs [m] |
| $T_{air}$ | Air temperature [°C] |
| $\overline{T_{ave}}$ | Average ground temperature [°C] |
| $\overline{T_{cor}}$ | Average ground temperature of corner GHEs [°C] |
| $T_{g\_100m}$ | Ground temperature at 100-m depth [°C] |
| $\overline{T_{in}}$ | Average ground temperature of inner GHEs [°C] |
| $T_{inlet}$ | Ground source water temperature at GSHP inlet [°C] |
| $T_{outlet}$ | Ground source water temperature at GSHP outlet [°C] |
| $\overline{T_{peri}}$ | Average ground temperature of perimeter GHEs [°C] |
| $T_{supply}$ | Supply water temperature from heat pump [°C] |
| $t_{p0}$ | Temperature penalty (annual ground temperature change because of a seasonal thermal imbalance) for internal GHE [K] |
| $t_p$ | Temperature penalty adjusted to actual GHE field [K] |
| $t_{p0}^*$ | Variable temperature penalty for internal GHE [K] |
| $t_p^*$ | Variable temperature penalty adjusted to actual GHE field [K] |
| $\alpha$ | Thermal diffusivity of the ground [m$^2$/day] |
| $\Delta T$ | $(i)$ Temperature change at $i$th segment [K] |
| $\Delta t_{op}$ | Time of operation [hr] |
| $\Delta t_{op\_c}$ | Time of operation for cooling [hr] |
| $\Delta t_{op\_h}$ | Time of operation for heating [hr] |
| $\rho$ | Density of the ground [kg/m$^3$] |

heat-source or air conditioning systems in addition to GSHP systems [10,34].

Such computer simulation approaches are mainly used in the design phase. For instance, the total required length of ground heat exchangers (GHEs) has been determined using calculated results [35]. Differences of system performance under various operation modes were also evaluated [36–39] based on the assumption of a certain cooling or heating load on the building side. However, those loads change yearly depending on weather or user behavior in actual situations. This may lead to different amounts of heat extracted from and rejected to the ground, and therefore variable energy performance from prediction of the design phase. Additionally, cooling/heating loads tend to be much smaller than the total capacity of heat source machines for many hours. When all of the heat source machines are not required to operate under small loads in hybrid systems, the time of operation for each machine would be different from assumptions in the design phase. Inappropriate GSHP operations in preference to immediate economic benefits may decrease the coefficient of performance (COP) or cause excessive change in ground temperature after many years of operation. Therefore, processes in which actual performance is evaluated and problems are overcome (as in the commissioning process [40]) are needed in the operational phase. Although computer simulation as in the design phase above enables the determination of suitable operation, it is not necessarily reasonable onsite with regard to temporal and physical loads. For onsite management, easier methods to determine adequate cooling/heating operation would be useful, e.g., through a building energy management system (BEMS). With regard to sustainable operation for the long term (>20 years), management of annual thermal imbalances on the ground side, i.e., management of the seasonal time of cooling operation, is one of the most important problems in cooling load-dominant regions. Further studies are needed to establish a method for predicting influences of annual thermal imbalances on ground temperature, with easy consideration of use onsite over past years.

Herein we develop a simple index, one obtained without complicated computer simulation, for GSHP systems installed in warm-climate regions with excessive cooling loads. This is done by application of the concept of “temperature penalty” ($t_p$), which is defined in an ASHRAE guideline for use in the design phase [41]. The index called variable temperature penalty (symbolized $t_p$*) has features that vary annually depending on measured thermal imbalances, different from the original $t_p$. The use of $t_p$* may allow easy operational management of GSHPs onsite by inputting measured values automatically through BEMS. First, we analyzed actual operation based on measured data for 3 years after completion of a hybrid GSHP system with 70 borehole-type GHEs,