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Optimal design of vertical ground heat exchangers by using entropy generation minimization method and genetic algorithms

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ABSTRACT

This paper presents the development and validation of an optimal design methodology for vertical U-tube ground heat exchangers (GHEs) used in HVAC systems. The dimensionless entropy generation number obtained by scaling the entropy generation due to heat transfer and pressure drop, on the ratio of the heat transfer rate to the average fluid temperature of vertical GHEs is employed as the objective function. Five design variables are first selected based on the global sensitivity analysis and then optimized by a genetic algorithm optimization technique. The entropy generation process combines the heat transfer and fluid mechanics with thermodynamic analysis. A case study shows that this optimal design approach can decrease the total system cost (i.e. the upfront cost and 10-year operation cost) by 5.5%, compared with the original design. The entropy generation number (EGN) of the optimal design case is 12.2% less than that of the base design case. From the thermo-economic aspect, decreasing the upfront cost is more important than decreasing the operational cost for the case studied. The results also demonstrate the effectiveness and feasibility of using the entropy generation minimization method for optimal design of vertical GHEs.

1. Introduction

The increasing demand on energy supply, in conjunction with global warming due to the greenhouse gas emissions from the use of fossil fuels, has led to the rapid development of low energy technologies for building heating and cooling applications [1–3]. Ground source heat pumps (GSHPs) with high energy efficiency and low greenhouse gas emissions have been recognized as one of the most sustainable and environmentally friendly solutions for heating and cooling of both residential and commercial buildings [4–6]. It is reported that reductions in energy consumption of 30–70% in the heating mode and 20–50% in the cooling mode can be achieved through proper use of GSHPs to replace conventional air-conditioning systems [7]. GSHPs are gaining market share with an annual increase rate of 10–30% in recent years [8]. In spite of their popularity, high installation cost, installation infrastructure limitations and system design are the main challenges preventing the wide application of GSHP systems in buildings [9]. In particular, the high installation cost makes the short-term economics unattractive [5,9].

Over the last two or more decades, significant efforts have been made on the development of GSHPs in building applications and various issues such as system design, component modeling, capacity control, load imbalance and thermal performance optimization have been addressed in various studies. For instance, Garber et al. [10] proposed a methodology to evaluate the financial risk due to the over-size of ground heat exchangers. Zogou and Stamatelos [11] presented the optimization of the thermal performance of buildings integrated with GSHPs using TRNSYS. It was concluded that detailed simulation can allow better assessment of the effects of control settings and system characteristics. Yu et al. [12] experimentally evaluated a constant temperature and humidity air-conditioning system driven by GSHPs in Shanghai, China. The suggested borehole distance is in the range of 4–5 m. Pertzborn et al. [13] investigated the impact of weather variations on the design of GSHP systems. A comprehensive review on the design of borehole heat exchangers for GSHPs can be found in [14]. Alavy et al. [15] proposed a new methodology for optimization of the capacity of GSHPs in hybrid systems in terms of the net present value. The results indicated that, in most cases, the GSHPs need to meet around 80% of the total design load of the hybrid system. Robert and Gosselin [16] developed a new design method to determine the optimal borehole number, borehole distance and depth, and the optimal size of heat pumps, based on the total cost minimization method. However, in above two new design studies, the optimization was performed based on the economic aspect, and the thermodynamic

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Nomenclature

GHE	ground heat exchanger
GSHP	ground source heat pump
EGM	entropy generation minimization
EGN	entropy generation number
GSA	global sensitivity analysis
TAC	total annual cost ($)
IC	upfront cost ($)
OC	operating cost ($)
C	cost ($)
Q	design load (W)
L	depth (m)
T	temperature (K)
ΔT	temperature difference (K)
N	borehole number
D	half shank space (m)
B	borehole distance (m)
S_{gen}	entropy generation rate (W/K)
N_s	dimensionless entropy number
R	thermal resistance (mK/W)
ΔP	pressure drop (Pa)
Nu	Nusselt number
Re	Reynolds number
τ	time (s)
q	heat transfer rate (W/m)
m_f	mass flow rate (kg/s)
r	radius (m)
ρ	density (kg/m^3)
k	thermal conductivity (W/mK)
f	friction number
h	convective heat transfer coefficients (W/m^2 K)
c	specific heat (J/kg K)
μ	dynamic viscosity (kg/m s)

Subscripts

b	borehole/borehole wall
p	U-tube pipe
f	fluid
s	soil
0	environmental condition
1	inlet of U-tube pipe
2	outlet of U-tube pipe
i	inner
o	outer
m	average
tot	total

performance of the ground heat exchangers (GHEs) was not the main design target.

There are some studies focusing on investigating the thermodynamic performance of GSHP systems in terms of exergy analysis. Hepbsali and Akdemir [17], for instance, performed a detailed energy and exergy analysis of a GSHP system. The result indicated that detailed exergy analysis is able to provide quantitative information for the proportion of the exergy input that is dissipated in various components, which was important for system optimization. The comprehensive exergy analysis performed by Bi et al. [18] showed that the GHEs normally have minimum exergy efficiency and thermodynamic perfection, indicating great potential of design optimization from the aspect of thermodynamic performance.

In order to facilitate better design of GSHP systems, efforts have also been made on the development of design optimization methods by taking into consideration of thermodynamic perfection. Sayyaadi et al. [19] carried out a multi-objective optimization of GSHP systems for reducing both the cost and exergy destruction associated with the use of GSHPs. Sayyadi and Nejatolahi [20] further performed a thermodynamic and thermo-economic optimization of a cooling tower-assisted GSHP system, in which a genetic algorithm was used as the optimization technique. Min and Lai [21] applied the entropy generation minimization (EGM) method for the design optimization of a vertical GHE. In their study, the analytical expressions were developed to determine both the optimal borehole depth and flow velocity.

The EGM, or thermodynamic optimization, is a method for modelling and optimization of thermodynamic cycles, which has been widely applied to the optimization design of heat exchangers [22,23]. Minimization of the entropy generation of a system is equivalent to the optimization of its thermodynamic performance. Usually, the application of EGM is referred as entropy generation number (EGN), which is defined by scaling the entropy generation rate on the heat capacity rate [22].

In this paper, the entropy generation minimization and genetic algorithms are used to formulate an optimal design methodology for vertical U-tube ground heat exchangers (GHEs). In this methodology, the entropy generation number (EGN) is defined as the objective function, and the infinite line source model is utilized for performance prediction. The global sensitivity analysis is used to determine the non-influential design parameters to reduce the number of decision variables. Genetic algorithm is used as the optimization technique to solve the optimization problem and search for optimal values of major design parameters. An illustrative example is used to validate the effectiveness of the proposed optimal design methodology.

2. Formulation and development of the optimal design methodology

2.1. Outline of the optimal design methodology

The aim of the thermodynamic modelling of vertical U-tube ground heat exchangers is to evaluate and compare the thermal performance of alternative design options. Fig. 1 illustrates the block diagram of the optimal design methodology. The overall optimization procedure consists of two steps. The first step is to use a global sensitivity analysis method to determine the major design parameters and their design constraints. The second step is to formulate the entropy generation minimization method (EGM)-based optimization strategy, including the development of the objective function, and selection of the performance model and optimization technique.

Genetic algorithm (GA) as an optimization tool can provide good solutions with random initialization and has been widely used to solve the optimization problems in engineering and science fields [24,25]. The algorithm is maintained by a population of parent individuals that represent the latent solutions of a real-world problem. After some generations, the algorithm converges to a best individual, which probably represents the best or nearly optimal solution of the given problem [24,25]. A GA optimizer is used in this study to search for optimal values of major design