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Optimization method for multiple heat source operation including ground source heat pump considering dynamic variation in ground temperature

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HIGHLIGHTS

- An optimization method εDE-RJ is proposed for optimal operations of GSHP system.
- The method can find an optimal solution without approximating non-linear behavior.
- Operating costs reduced by 3.78–12.56% compared to empirical operations.
- Proposed method can be utilized for practical problems due to fast calculation.

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ABSTRACT

Recent years have witnessed the widespread use of highly efficient energy systems as an important measure to reduce not only energy consumption but also operating costs. A ground source heat pump system has been attracting considerable attention because of its high efficiency. Although many studies have been conducted to investigate and evaluate the ground source heat pump's performance, they have not sufficiently studied its optimal operation considering dynamic ground temperature variation caused by the high thermal capacity of the ground. Calculations considering both thermal history of the ground and optimal load dispatch are complicated and thus entail high computation costs. In this paper, an efficient optimization method is proposed to determine optimal operations of a hybrid ground source heat pump system that is used to handle the cooling load and hot water demand. The proposed method, namely epsilon-constrained differential evolution with random jumping, can solve nearly all possible configurations and is a suitable method for the nonlinear configuration used herein because the ground source heat pump has highly nonlinear characteristics and the ground temperature calculation cannot be simplified to a linear formulation. The optimal operations achieved by the proposed method can reduce operating costs by at least 3.78% and at most 12.56% compared to empirical operations. In addition, the proposed method derives the solution rapidly while maintaining high computation accuracy. Therefore, it can be used in practical situations to determine an optimal operating schedule as a day-ahead optimization.

1. Introduction

In recent years, efficient utilization of energy sources has emerged as an important target owing to ever-increasing energy consumption and CO_2 emissions. Toward this end, it is necessary to achieve energy saving and efficient operation of energy systems in a building section. Moreover, minimization of the operating cost and life cycle cost is an important issue in a building section. Thus, many studies have focused on optimizing the operation and planning of energy systems [1–4]. In terms of renewable energy source technology, a ground source heat pump (GSHP) has recently emerged as a promising heat source/sink for reducing energy consumption and carbon dioxide emissions [5,6]. Although many studies have been conducted with the aim of investigating and evaluating GSHP [7–12], when and how much heat should be generated from GSHP considering ground temperature variation has

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Nomenclature

Glossary

C	volumetric heat capacity [J/m^3 K]
c_e, c_g	amount of electricity and gas consumption, respectively [kW h], [m^3]
F	mutation rate
g	generation
h_i	convective heat transfer coefficient of pipe inner surface [W/(m^2 K)]
Lr	machine load rate
Nu	Nusselt number
Pr	Prandtl number
P	decision variable
P^*	temporary decision variable
p_e, p_g	unit price of electricity [yen/kW h] and gas [yen/m^3], respectively
$\mathbb{P}$	population vector
q	heat rate per unit length of BHE [W/m]
r	radius, radial direction [m]
R	thermal resistance [m K/W]
Re	Reynolds number
t	time, time step used for GSHP [s]
t_k	time step used for BHE calculation [–]
t_s	time step used for system optimization [–]
T	temperature [°C]
T_0	initial ground temperature [°C]
T_b	BHE wall temperature [°C]
T_{bf}	average borefiled wall temperature [°C]
$\overline{T}_f$	average fluid temperature [°C]
v	velocity [m/s]
$\overline{v}$	averaged velocity [m/s]
V_f	volumetric flow rate [m^3/s]
x_s	half of the shank spacing [m]

Subscripts

AB	auxiliary boiler
b	borehole
bhe	borehole heat exchanger
c	convective, cooling
chw	chilled water
f	circulating fluid
g	grout
gas	gas
h	heating
hw	hot water
HP	heat pump
i	inner
in	inlet
j	dimension
k	time step
m	machine number
o	outer
out	outlet
p	pipe
s	soil
tot	total

Greek letters

α	exponent of power law
λ	thermal conductivity [W/(m K)]
μ	dynamic viscosity [kg/(m s)]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
$\mathcal{U}$	uniformly distributed random number

Acronyms, abbreviations

AB	auxiliary boiler
ASHP	air source heat pump
BHEs	borehole heat exchangers
COP	coefficient of performance
DE	differential evolution
GAs	genetic algorithms
GSHP	ground source heat pump
GSHPc	ground source heat pump for cooling
GSHPh	ground source heat pump for heating
GXP	pump for ground heat exchanger loop
HSP	heat source machine pump
ILS	infinite line source
m-PSO	mutation particle swarm optimization
PSO	particle swarm optimization
εDE-RJ	epsilon-constrained differential evolution with random jumping

not been studied thus far. Some studies have been conducted to optimize borefield configurations [13,14] and several machine parameters, such as the capacity and set-point temperature of GSHP [15–19]. Pardo et al. [15] optimized an energy system component that included GSHP and thermal energy storage throughout a long-term calculation. Cui et al. [16] and Sayyaadi et al. [17] adopted a multi-objective evolutionary algorithm to find a pareto-front curve in terms of two objective functions: thermodynamic and economic. They set a fixed temperature difference between inlet and outlet temperatures of ground fluid loop and thus, dynamic variation of a GSHP performance corresponds to the inlet fluid temperature of heat pump was not considered. Sanaye and Niroomand [18] used a hybrid method of the Nelder–Mead simplex algorithm and a genetic algorithm to optimize some parameters that were used in modeling GSHP. Retkowski and Thöming [19] considered nonlinear characteristics of GSHP and calculated dynamic variation of entering fluid temperature of GSHP in detail.

However, previous studies have not optimized the operating schedule. Instead of optimizing the operation, previous studies have only compared some operating scenarios to reduce the computation costs, because the calculation of ground temperature variation under multiple boreholes generally involves complicated calculations and high computation costs. Furthermore, some studies that have proposed optimal operating strategies have only compared limited scenarios [20–23]. Liu et al. [20] compared some scenario-based strategies on an actual energy system including GSHP to propose an optimal strategy. Zhou et al. [21] investigated the energy efficiency of a GSHP system over a 10-year simulation using TRNSYS. They considered the variation in fluid temperature of ground loop. However, the operating scenarios were of only two patterns: with and without a free-cooling system included. Thus, it was not enough to optimize the operation. Yavuzturk and Spitler [22] compared 10 different operating strategies under an energy system consisting of GSHP and a cooling tower. Gang et al. [23] proposed suitable operating strategies to control a hybrid energy system consisted of GSHP and a cooling tower. An artificial neural network was used to predict the dynamic variation in fluid temperature of ground loop. However, no optimization of thermal output combinations was conducted.

In terms of optimizing the operating schedule, although Edwards and Finn [24] proposed a decision-making strategy for