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Thermoeconomic optimization of vertical ground-source heat pump systems through nonlinear integer programming

Waldemar Retkowski *, Jorg Thöming

University of Bremen, Centre of Environmental Research and Sustainable Technology, Leobenerstr. 1, 28359 Bremen, Germany

HIGHLIGHTS

- A new bi-criteria MINLP for an optimal peak-load design of GSHPSs is proposed.
- Efficient optimal results were provided by the GRG2, whereupon the EA was limited.
- We examined optimal model responses of crucial model variables.
- A detailed evaluation showed efficient provided estimates for optimization purposes.
- This new method was able to improve the TAC of about more than 10%.

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ABSTRACT

Vertical ground-source heat pump systems (GSHPSs) use the ground's undisturbed relative constant temperature as a source for space heating of residential and commercial buildings. The design of GSHPSs is focused in finding the optimal depth and amount of boreholes and also the connected power requirement like the amount and size of heat pumps. In this paper a mixed-integer nonlinear programming (MINLP) approach to solve the design problem of a vertical GSHPS is presented. The resulting mathematical model includes the calculation of the total annual costs (TAC) and the coefficient of performance to obtain estimates of both economic and ecological relevance to design an optimal equipment set-up. For desired constraints the numerically optimal values of the design parameters (borehole depth, mass flow rate, number of boreholes, type and number of the heat pumps) were calculated. Two numerical solution alternatives are investigated, namely Generalized Reduced Gradient (GRG2) and evolutionary algorithm. The GRG2 approach provides a more stable and faster optimal solution. Calculated results are presented through a validation example. The evaluation of the proposed objectives and studied sensitivity effects present the applicability of the model. This method was able to improve the TAC about more than 10%.

1. Introduction

One way to exploit sustainably produced electrical energy is in using a vertical ground-source heat pump system (GSHPS) to supply the heating equipment in residential and commercial buildings. The European number of these installed systems is rapidly growing. Extrapolating currently observed growth rates for Europe of 5.4 million heat pump units per year, let expect a number of 70 million installed units in Europe for 2020 [1]. Along with this increasing relevance and impact there is a rising demand for optimal designed vertical GSHPSs.

The research and developments of vertical GSHP technology based on various mathematical models and systems is described in detailed reviews [2–4]. Over the years different analytical [2,4], numerical [5–8] and hybrid [2,4] models have been developed especially to calculate the thermal behavior of ground-heat exchangers (GHEs). Therefore is the simulation of these systems an important tool for system design purposes. These approaches focus on the thermal ground behavior and are often time consuming techniques even for experienced users [9]. Furthermore is the optimal sizing of GHEs important because of the high drilling costs and the design challenge of sizing an optimal borehole thermal capacity with an optimal capacity of heat pumps [10]. To design competitive GSHPSs involves thorough technical also economic considerations. In these consequences arises the need to consider simultaneously the soil cycle, the heat pump cycle and their economic aspects for optimal design purposes.

As one early work Wall [11] analyzed heat pump systems and pointed out that a thermoeconomic optimization is an economic optimization in conjunction with thorough thermodynamic description of the system. In [12] they developed a method to

* Corresponding author. Permanent address: Robinsbalje 13, 28259 Bremen, Germany. Tel.: +49 (0) 176 233 74415.
E-mail address: wret@uni-bremen.de (W. Retkowski).

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Nomenclature

Abbreviations

MINLP	mixed-integer nonlinear programming
MILP	mixed-integer linear programming
GSHPS	ground-source heat pump system
GSHP	ground-source heat pump
EED	earth energy designer
GHE	ground-heat exchanger
Diff.	difference

Indices

f	fluid
m	half borehole length
g	grout
gr	ground
gs	ground surface
b	borehole
geo	geological
dwn	down
up	up
ln	natural logarithm
s	soil
$\sim$	dimensionless variable
–	mean value
max	maximal
min	minimal
eva	evaporator
M	manufacturer
i	different equipment sections
HC	heating circuit
HP	heat pump
SC	soil circuit
Q	heat
P	power
tot	total
α, β	heat coefficients
δ, ε	power coefficients
p	pipe
dem	demand
$load$	load
pi	inner pipe
po	outer pipe

Parameters

t_{hy}	yearly operating hours (h y^{-1})
T_{air}	air temperature (°C)
η_{el}	electrical efficiency (–)
φ_t	start-up cycles (h^{-1})
$\lambda_{1,2,3}$	geometrical expressions (–)
R	thermal resistance (m K W^{-1})
f	empirical based function
t_{ho}	full operating time period (h)
t_{hs}	heating season time period (h)
$t_{h\varphi}$	start-up time period (s)
A	ampere (A)
V	volt (V)
λ	thermal conductivity (W m^{-1} K^{-1})
Q_{load}	heat load (kW)
$\dot{q}$	heat flux (W m^{-1})
r	radius(m)
xc	half shank space (m)
c_p	heat capacity (J kg^{-1} K^{-1})
ρ	density (kg m^{-3})
v	viscosity (m^2 s^{-1})
C	costs (€)

Variables

$\dot{m}$	mass flow rate (kg s^{-1})
T	temperature (K)
TAC	total annual costs (€ y^{-1})
IC	investment costs (€)
OC	operating costs (€)
Q_1^{SC}	ground heat (kW)
L	length (m)
N	integer number (–)
Q_2^{SC}	evaporator heat (kW)
Q_3^{SC}	ground heat load (kW)
$P^{\Delta el}$	electrical power start-up (kW h)
P^{HP}	electrical power operating (kW h)
COP	coefficient of performance (–)
SPF	seasonal performance factor (–)
T_1	temperature out of SC (K)
T_2	temperature into the SC (K)
T^m	disturbed temperature (K)
$\dot{V}$	flow rate (m^3 h^{-1})

minimize the entropy generated in a heat exchanger, whereupon an optimum U-tube length and diameter was determined. Sayyaadi et al. [13] optimized a vertical GSHP for a given cooling load. Seven temperature differences and one pipe diameter for the ground heat exchanger were chosen as design variables. They minimized a thermodynamic-, a thermoeconomic- and a multi-objective and considered the sensitivities of the interest rate, operating hours and the cost of electricity. In [14] they optimized a vertical GSHP for given heating and cooling loads. They developed a nonlinear optimization model and applied for a thermoeconomic optimization eight temperature design parameters and one nominal pipe design parameter. Li and Lai [15] provided analytical expressions for optimizing flow velocity and borehole length by applying the entropy generation minimization method for GSHPs with a single U-tube. Their analyses indicated the existence of optimum parameters based on pure heat transfer and thermodynamics ground. In [16] they proposed an algorithm for optimization of cooling tower-assisted GSHPs applying 12 decision variables and additional constraints. Their sensitivity consideration of costs showed that the product cost of all regarded systems increased due to an increasing interest rate. Lee et al. [17] used for GSHP optimization an objective function representing the initial system costs divided by the annual energy production as a measure of cost effectiveness, which should be minimized. With an emphasis on building optimization [18] used three objective function criteria, the total cost of the system, the primary energy saving and the CO_2 emission costs. They applied different values for different penalty parameters and focused applying a mixed-integer linear program (MILP) on optimization robust building loads. Florides et al. [19] investigated the cost and efficiency impact of double U-tubes, single U-tubes and parallel or serial arrangements. They concluded that the building costs of double U-tubes are 22–29% higher than of single U-tubes. While their parallel configuration is more efficient by 26–29%, while the series configuration by 42–59%. The assumption of a maximization of heat pump performance due to a minimization of ground temperature changes was followed by [20]. They achieved a balanced ground cooling with the application of GHE distributed loads. A connection to heat pumps or modeled flow through GHEs had there not a special emphasis. A related work of [21] pointed out that an optimization