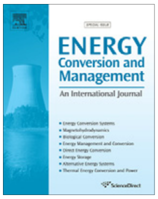
Energy Conversion and Management 51 (2010) 2600–2612

Contents lists available at ScienceDirect

Energy Conversion and Management

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



Horizontal ground coupled heat pump: Thermal-economic modeling and optimization

Sepehr Sanaye *, Behzad Niroomand

Energy Systems Improvement Laboratory (ESIL), Department of Mechanical Engineering, Iran University of Science and Technology (IUST), Iran

ARTICLE INFO

Article history:
Received 18 January 2009
Received in revised form 14 September 2009
Accepted 27 May 2010
Available online 25 June 2010

Keywords:
Thermal-economic modeling
Optimization
Ground coupled heat pump
Horizontal ground loop

ABSTRACT

The modeling and optimizing processes of a Ground Coupled Heat Pump (GCHP) with closed Horizontal Ground Heat eXchanger (HGHX) are presented in this paper. After thermal modeling of GCHP including HGHX, the optimum design parameters of the system were estimated by minimizing a defined objective function (total of investment and operation costs) subject to a list of constraints. This procedure was performed applying Genetic Algorithm technique.

For given heating/cooling loads and various climatic conditions, the optimum values of saturated temperature/pressure of condenser and evaporator as well as inlet and outlet temperatures of the water source in cooling and heating modes were predicted. Then, for our case study, the design parameters as well as the configuration of HGHX were obtained.

Furthermore, the sensitivity analysis of change in the total annual cost of the system and optimum design parameters with the climatic conditions, cooling/heating capacity, and soil type were discussed.

1. Introduction

The earth and ground water are energy sources or sinks with relatively constant temperature during the year. This approximately constant ground temperature is closer to the room temperature than the air temperature during a year. Due to the above, ground coupled heat pumps (GCHPs) consume less annual energy.

Healy et al. [1] modeled the effects of various system parameters on performance and energy efficiency of ground source heat pumps based on sensitivity studies conducted using a computer model. They also presented a comparative economic evaluation to assess the feasibility of using a GCHP in place of electric resistance and oil fired furnace heating/cooling systems and an air source heat pump based on the systems present worth. They analyzed the effects of area, depth, pipe size, horizontal pipe spacing, and fluid flow rate of ground heat exchanger, soil type, and heat pump size on energy consumption. Their study showed that although the GCHP is the least expensive heating/cooling system to operate, it is the most expensive to install. For their case study, this system is economically preferable to conventional systems. Their results also indicated that system parameters can have a significant effect on GCHP performance. Thus, it would be necessary to conduct a pre-design analysis to determine optimal system parameters that would ensure minimum energy consumption and favorable economics. With the help of GCHP simulation models such analysis can be conducted with ease.

The optimal design of GCHP system was not studied in [1].

Mustafa Inalli [2] presented an analysis of performance evaluation of a horizontal GCHP with R-22 as the refrigerant for a heating mode. An experimental set-up was constructed and tested on the basis of the study performed in Turkey. The influences of various system parameters, such as the buried depth of earth coupled heat exchanger, the mass flow rate of the water-anti-freeze solution and the sewer water, on the COP of the GCHP system were examined and the significant variables were identified.

Their experimental results showed that the average values of the system COP were very low due to a poor design of the system. The primary reason was oversizing some system parts. They also concluded that in the design of a GCHP system, all parts of the system should be checked in terms of energy efficiency. Thus, it is necessary to conduct a pre-design analysis to determine optimal system parameters that will ensure minimum energy consumption and favorable costs.

The optimal design of GCHP system was not investigated in [2].

Zhao et al. [3] presented an integrated optimal mathematical model by analyzing the operating characteristics of the groundwater heat pump and optimized the system according to technical and economic optimal principle with an objective function of the annual total costs. A computation program was also developed. They used the model to calculate and optimize some key operating parameters and components according to different temperature

---

* Corresponding author. Address: Energy Systems Improvement Laboratory, Mechanical Engineering Department, Iran University of Science and Technology, Narmak, Tehran 16488, Iran. Tel./fax: +98 21 77240192.

E-mail address: sepehr@iust.ac.ir (S. Sanaye).

0196-8904/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enconman.2010.05.026

Nomenclature

A	heat transfer surface area of exchanger, m^2
A_s	air temperature swing, °C
a_1–a_9	constants in computing the equipment cost
c_{AF}	cost of anti-freeze solution, \$/m^3
C_{El}	annual cost of power consumption, \$/y
C_{Inv}	initial or investment cost per operating years of the system, \$/y
c_{Pipe}	cost of polyethylene pipe, \$/m
c_p	specific heat, kJ/kg °C
COP	coefficient of performance
CRF	capital recovery factor
$D_{e,Eva}$	equivalent diameter of the evaporator annulus for estimating $h_{W,Eva,h}$, m
D_{GHX}	GHX nominal pipe diameter, in
$D_{i,GHX}$	GHX inner pipe diameter, m
$D_{o,GHX}$	GHX outer pipe diameter, m
$D_{I,i,Con}$	inner diameter of inner pipe of condenser, m
$D_{I,i,Eva}$	inner diameter of inner pipe of evaporator, m
$D_{I,o,Con}$	outer diameter of inner pipe of condenser, m
$D_{I,o,Eva}$	outer diameter of inner pipe of evaporator, m
E	annual power consumption, kWh/y
F	part-load factor
h	enthalpy, kJ/kg; convection heat transfer coefficient, kW/(m^2 K)
H_{pum}	pump head, Pa
i	interest rate, %
$k_{p,Con}$	thermal conductivity of inner pipe of condenser, kW/(m °C)
$k_{p,Eva}$	thermal conductivity of inner pipe of evaporator, kW/(m °C)
$k_{p,GHX}$	thermal conductivity of GHX pipe, kW/(m °C)
k_S	thermal conductivity of soil, kW/(m °C)
L	length of heat exchanger, m
$\dot{m}$	mass flow rate, kg/s
n	depreciation time, y
Nu	Nusselt number
Q	thermal load, kW
R	effective thermal resistance, m °C/kW
T	annual operating hours, h/y
T_{Con}	condensation temperature, °C
T_{Eva}	evaporation temperature, °C
t_{now}	current time (day of the year)
T_S	ground temperature, °C
$\bar{T}_S$	mean surface temperature (average air temperature), °C
t_{shift}	day of the year of the minimum surface temperature
T_{W1}	water temperature at the inlet of heat pump and outlet of the HGHX, °C
T_{W2}	water temperature at the inlet of the HGHX and outlet of heat pump, °C
T_{Wi1}	building circulating water temperature at the inlet of heat pump, °C
T_{Wi2}	building circulating water temperature at the outlet of heat pump, °C
TAC	total annual cost, \$/y
U	overall heat transfer coefficient, kW/m^2 K
$V_{pipe,in}$	pipe inside volume, m^3
VFA	volume fraction of the anti-freeze in the intermediate fluid, %
W	power consumption, kW
X	depth, ft

Subscripts

AF	anti-freeze
c	cooling mode
Con	condenser
Com	compressor
Eva	evaporator
GHX	ground heat exchanger
h	heating mode
HP	heat pump
i	inner
M	monthly
Min	minimum
Max	maximum
o	outer
Pum	circulating pump
R	refrigerant
S	soil
W	water

Greek abbreviations

α_S	thermal diffusivity of ground, ft^2/day
τ	equivalent annual full-load hours, h/y
η_M	efficiency of pump motor, %
η_{Pum}	electric efficiency of circulating pump, %
η_s	isentropic efficiency of compressor, %
η_{el}	electric efficiency of compressor, %
μ	dynamic viscosity, Pa s
Δp	pressure drop of water flow, Pa

English abbreviations

CEES	commercial earth energy systems
ESIL	energy systems improvement laboratory
GA	genetic algorithm
GCHP	ground-coupled heat pump
HGHX	horizontal ground heat exchanger
NM	Nelder–Mead
NPT	number of parallel pipes per trench

and depth of the groundwater. They concluded that it is feasible to use a computer for the optimization design of the groundwater source heat pump, because solving the set of equations in the mathematical model minimizes the cost, establishes the most cost-effective design parameters for the specific design configuration analyzed, and reduces the workload of design greatly.

Due to the fact that the studied GCHP was an open loop type, there was no need to consider the ground heat exchanger design parameters such as configuration and length of GHX in [3].

All the mentioned researches declared the benefits of conducting a pre-design analysis to determine optimal parameters of GCHP system. Developing a software program based on a proper model of GCHP with HGHX and defining the total annual cost of the system as the objective function facilitates the pre-design analysis of the system to obtain the most cost-effective design parameters.

In this paper, in order to optimal design of a GCHP including HGHX, the thermal and economic simulation and optimization of such a system were performed. To optimize the system, an objective function, the system total annual cost (including investment and operational costs), was defined. A software program was developed in Visual Basic 6 based on the presented model in order to optimize the system using genetic algorithm and Nelder–Mead optimization techniques. Two optimization methods were applied to ensure the validity of optimization results. For given heating/cooling loads, and various climatic conditions, the optimum values of heat pump design parameters (saturated temperature/pressure