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Modeling and performance evaluation of ground source (geothermal) heat pump systems

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Abstract

This study deals with the energetic and exergetic modeling of ground source heat pump (GSHP) systems for the system analysis and performance assessment. The analysis covers two various GSHPs, namely a solar assisted vertical GSHP and horizontal GSHP. The performances of both GSHP systems are evaluated using energy and exergy analysis method based on the experimental data. Energy and exergy specifications are also presented in tables. Some thermodynamic parameters, such as fuel depletion ratio, relative irreversibility, productivity lack and exergetic factor, are investigated for both systems. The results obtained are discussed in terms of energetic and exergetic aspects. The values for COP_{HP} ranged from 3.12 to 3.64, while those for COP_{sys} varied between 2.72 and 3.43. The exergy efficiency peak values for both whole systems on a product/fuel basis were in the range of 80.7% and 86.13%. It is expected that the model presented here would be beneficial to everyone dealing with the design, simulation and testing of GSHP systems.

Keywords: Building; Energy; Exergy; Exergy analysis; Geothermal energy; Ground source heat pump; Renewable energy

1. Introduction

Ground-coupled heat pump systems are increasingly deployed for heating and air-conditioning in commercial and institutional buildings as well as in residential ones. These systems consist of a sealed loop of pipe, buried in the ground and connected to a heat pump through which water/antifreeze is circulated. For the ground-loop heat exchangers, vertical borehole configuration is usually preferred over horizontal trench systems because less ground areas are required. The vertical ground heat exchanger consists of a number of boreholes, each containing a U-tube pipe. The depth of the borehole ranges usually between 40 and 150 m, and the diameter 0.075–0.15 m. The borehole annulus should be grouted with materials that provide thermal contact between the pipe and the surrounding soil/rock and to protect groundwater from possible contamination. The efficiency of GSHP systems are inherently higher than that of air source heat pumps because the ground maintains a relatively stable source/sink temperature [1,2].

The use of ground source heat pumps (GSHPs) in commercial and residential buildings is a tremendous example. A GSHP utilizes the ground as a heat source in heating and a heat sink in cooling mode operation. In the heating mode, a GSHP absorbs heat from the ground and uses it to heat the house or building. In the cooling mode, heat is absorbed from the conditioned space and transferred to the earth through its ground heat exchanger. GSHPs are an efficient alternative to conventional methods of conditioning homes because they utilize the ground as an energy source or sink instead of using the ambient air. The ground is a thermally more stable heat exchange medium than air, essentially unlimited and always available. The GSHPs exchange heat with the ground, and maintain a high level of performance even in colder climates. The ground heat exchanger used in conjunction with a closed-loop GSHP system consists of a system of long plastic pipes buried vertically or horizontally in the ground [1–4].

In a comprehensive study performed by Lund et al. [5], it is reported that GSHPs have the largest energy use and installed capacity according to the 2005 data, accounting for 54.4% and

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Nomenclature

C	specific heat (kJ/kg K)
COP	heating coefficient of performance (dimensionless)
$\dot{E}$	energy rate (kW)
$\dot{\mathrm{E}}\mathrm{x}$	exergy rate (kW)
f	exergetic factor (%)
F	exergy rate of fuel (kW)
h	specific enthalpy (kJ/kg)
$\dot{I}$	irreversibility (exergy destruction) rate (kW)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{P}$	exergy rate of the product (kW)
$\dot{Q}$	heat rejection rate (kW)
R	ideal gas constant (kJ/kg K)
s	specific entropy (kJ/kg K)
$\dot{S}$	entropy rate (kJ/K)
T	temperature (K or °C)
$\dot{V}$	volumetric flow rate (m^3/s)
$\dot{W}$	rate of work or power (kW)

Greek letters

δ	fuel depletion rate (dimensionless)
ε	exergy (second law) efficiency (dimensionless)
φ	humidity (dimensionless)
ξ	productivity lack (dimensionless)
ρ	density (kg/m^3)
χ	relative irreversibility (dimensionless)
ψ	specific exergy (kJ/kg)
ω	specific humidity ratio (kg_{water}/kg_{air})

Indices

0	reference (dead) state
a, air	air
col	collector
comp	compressor
cond	condenser
dest	destroyed
evap	evaporator
fc	fan-coil
gen	generation
grh	ground-heat exchanger
HP	heat pump
i	isentropic
in	input, inlet
m	mechanical
out	output
p	constant pressure
pump	pump
r	resident
re	relative
ref	refrigerant (R-22)
s	isentropic process, surface
sl	space heating load
sys	system
Tot	total
u	useful
v	water vapor
valve	expansion valve
wa	water–antifreeze solution

32.0% of the worldwide capacity and use. The installed capacity is 15,384 MW_t and the annual energy use is 87,503 TJ/year, with a capacity factor of 0.18 (in the heating mode). Almost all of the installations occur in North America and Europe, increasing from 26 countries in 2000 to the present 33 countries. The equivalent number of installed 12 kW units (typical of US and Western European homes) is approximately 1.3 million, over double the number of units reported for 2000. The size of individual units, however, ranges from 5.5 kW for residential use to large units of over 150 kW for commercial and institutional installations.

During the last decade, a number of investigations have been conducted by some researchers (e.g. [4,6–13]) in the design, modelling and testing of GSHPs and solar assisted heat pump systems. The study reported here includes: (i) The performance experimental evaluation of a vertical solar assisted ground source heat pump system with R-22 as the refrigerant in the heating mode. A flat-type solar collector was directly installed into the ground-coupled loop, is constructed and tested for the first time on the basis of a university study performed in the country [8–10]. (ii) The theoretical performance evaluation of a horizontal GSHP with R-22 designed. Although many installations of GSHP systems worldwide have been realized, the exergetic evaluation studies of these systems are very limited (e.g. [8,11]). This study also describes an easy-to-follow procedure for exergy analysis of solar assisted vertical and horizontal GSHP systems and how to apply this procedure to assess the heating system performance by calculating the exergy destructions.

2. Description of the systems studied

The university studies on GSHPs at the Turkish universities can be classified into two categories: theoretically and experimentally. These studies have been reviewed by the authors in more detail elsewhere [12].

2.1. Ground source heat pump system I

A schematic diagram of the constructed experimental system is illustrated in Fig. 1. This system mainly consists of three separate circuits as follows: (i) the ground coupling circuit with solar collector (brine circuit or water–antifreeze solution circuit), (ii) the refrigerant circuit (or a reversible vapour compression cycle) and (iii) the fan-coil circuit for heating (water circuit). The main characteristics of the elements of the solar assisted ground source heat pump system are given in Table 1, where the numbers in parentheses correspond to these elements as depicted in Fig. 1. Conversion from the heating cycle to the cooling cycle is obtained by means of a four-way valve. To avoid freezing the water under the working condition and during the winter, a 10%