Energy Conversion and Management 90 (2015) 53–61

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Borehole thermal energy storage system for heating applications: Thermodynamic performance assessment

Onder Kizilkan [a,*], Ibrahim Dincer [b,1]

[a] Süleyman Demirel University, Faculty of Technology, Department of Energy Systems Engineering, 32200 Isparta, Turkey
[b] Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario L1H 7K4, Canada

ARTICLE INFO

Article history:
Received 6 March 2014
Accepted 19 October 2014
Available online 21 November 2014

Keywords:
Borehole thermal energy storage
Energy
Exergy
Efficiency
Heat pump

ABSTRACT

A comprehensive thermodynamic assessment of a borehole thermal energy storage system (BTES), which helps in meeting the heating and cooling demands of campus buildings of University of Ontario Institute of Technology (UOIT), is presented for the heating case. The BTES located on UOIT campus in Oshawa, Canada is recognized as the world's second largest BTES system. Energy and exergy analyses of the heating system are performed through the balance equations, and exergy destruction rates are determined for each system component and the overall BTES. In addition, a comparative system performance assessment is carried out. Based on the conducted research for the studied system, COP_{HP} is calculated to be 2.65 for heating applications. Energy and exergy efficiencies of the boilers are determined to be 83.2% and 35.83%, respectively. The results of the exergy analysis show that the boilers are the major contributor to exergy destruction, followed by condenser and evaporator. The effects of condenser and evaporator temperatures of the heat pump systems on energy and exergy efficiencies are also investigated. The overall exergy efficiency of the whole system is calculated to be 41.35%.

1. Introduction

Humankind has been facing great energetic and environmental challenges which urge us to develop potential solutions for every sector of economic activities. As known, one-third of the world's total primary energy is consumed by residential and commercial buildings [1]. Heating and cooling applications represent a major contributor to energy consumption in buildings. For such applications, energy storage systems can contribute substantially to meeting society's demands for more efficient energy usage. Besides, energy storage ensures environmentally-benign energy utilization. The use of energy storage systems includes significant advantages, such as reduced energy costs, reduced energy consumption, better indoor air quality, increased flexibility of operation and reduced pollutant emissions [2] and [3]. It is expected that energy consumption will continue increasing due to the drastic increase in population, industrialization of developing countries, increased use of technologies, etc. The focus has recently been placed on renewables and earth energy options [4].

The use of ground source heat pusmps (GSHPs) in residential and commercial buildings and facilities is considered a remarkable application, since the ground temperature becomes almost constant during the years, after the first upper 5–10 m. The ground is essentially boundless and always existent and as a heat exchange medium it is thermally more consistent than air. This results in a more efficient use of energy for heating applications, and it has been employed as the heat resource in heating, ventilation and air conditioning (HVAC) systems and preparing domestic hot water for both residential and commercial facilities [5] and [6]. GSHP systems are well known systems and have been widely utilized in various countries, including Europe and North America, as one of the important sustainable technologies. Also these systems have become very attractive in some Asian and some other developing countries during the 1990s, since it is substantially treated as advantageous for better energy economy and reduced environmental impacts [7].

In the GSHP, heat absorption is done by circulating the working fluid in borehole heat exchanger (BHE). The working fluid can be water/anti-freeze mixture, or brine that usually circulates in the high density polyethylene pipes installed vertically in boreholes or horizontally in grooves [8]. In numerous applications, it is widespread to fill the gap between borehole wall and pipes with grouting material, while groundwater is frequently used for this aim in some Scandinavian countries. The benefit of using water

---

[*] Corresponding author. Working at UOIT as Visiting Associate Professor during the study. Tel.: +90 246 2111409; fax: +90 246 2371283.

E-mail addresses: onderkizilkan@sdu.edu.tr (O. Kizilkan), Ibrahim.Dincer@uoit.ca (I. Dincer).

[1] Department of Mechanical Engineering, KFUPM, Dhahran 31261, Saudi Arabia.

http://dx.doi.org/10.1016/j.enconman.2014.10.043
0196-8904/

Nomenclature

ex	specific exergy (kJ/kg)
$\dot{E}x$	exergy (kW)
$\dot{F}$	fuel energy rate (kW)
h	specific enthalpy (kJ/kg)
$\bar{h}$	specific enthalpy (kJ/kmol)
$\bar{h}^{\circ}$	specific enthalpy at reference state (kJ/kmol)
$\bar{h}_f^{\circ}$	specific enthalpy of formation (kJ/kmol)
HHV	higher heating value (kJ/kg)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
M	molar mass (kg/kmol)
N	number of moles
$\dot{Q}$	heat (kW)
$\dot{P}$	product (kW)
s	specific entropy (kJ/kg K)
$\bar{s}$	specific entropy (kJ/kmol K)
$\bar{s}^{\circ}$	specific entropy at reference state (kJ/kmol)
$\dot{S}$	entropy (kW/K)
T	temperature (°C)
$\dot{W}_C$	compressor power (kW)
$\dot{W}_p$	circulating pump power (kW)
η	efficiency

Subscripts

0	reference state
B	Boiler
BHE	borehole heat exchanger
BW	BHE side glycol-water solution
ch	chemical
C	condenser
d	destruction
elec	electric
E	evaporator
EV	expansion valve
FC	fan-coil system
GEN	generation
HP	heat pump
HW	heating water
mech	mechanic
P	product
R	reactant
sys	system

is cheaper mountings and if needed more easy attainment to the collector. On the other hand, grouting is used in many counties in order to strengthen the borehole wall [9].

Recently, various analytical and numerical studies have been conducted by some researchers about BTES systems, mostly concerning with modelling of pipe configurations, investigation of heat transfer characteristics, thermal response tests of different boreholes types, performance tests of ground, etc. A number of them have dealt with thermodynamic analysis of BTES systems for residential and commercial applications. Ozgener et al. [10] carried out energetic and exergetic analysis of the Salihli geothermal district heating system with the actual thermal data. They analyzed the system performance through energy and exergy aspects for determining improvement potentials of the system. The major exergy destruction rates were found in the pumps and heat exchangers. The systems energy efficiency was found to be 55.5% while the exergy efficiency was 59.4%. Esen et al. [6] conducted energy and exergy analysis of a GCHP system using two different horizontal ground heat exchangers (GHE). They analyzed experimentally the effects of the buried depth of the ground coupled heat exchanger on the efficiencies. They found that the energy efficiencies of the system were 2.5 for the first GHE and 2.8 for the second, while the exergetic efficiencies of the system were found to be 53.1% and 56.3%, respectively. Sakulpipatsin et al. [11] presented a method for exergy analysis HVAC systems situated in the Netherlands. They exemplified an office building which was equipped with heating and cooling systems. In their results, the overall exergy efficiencies were found to be 17.15% for heating and 6.81% for cooling. They also noted that there was a big potential to be improved. Zhai and Yang [12] investigated a ground source heat pump system which was constructed in Shanghai. The system consists of two heat pumps with the rated cooling capacity of 500 kW for each and 280 boreholes with 80 m in depth. They reported that operating cost of the GSHP system was lowered by 55.8% when compared with a traditional air source heat pump system. Additionally they analyzed the implementations of GSHP systems for different climatic zones of China. Urchueguía et al. [13] investigated the ground source heat pump systems in terms of technical and economic feasibility for mixed climate applications. For this aim, they implemented an experimental heat pump system with ground source heat exchanger. The air conditioned area of the experimental system was 250 m^2 and heating and cooling loads were 15 kW and 17 kW, respectively. The ground heat exchangers (2×3) were 50 m in depth. They found that, ground coupled heat pump system had an energy savings of 43% for heating and 37% for cooling, respectively. Sharqawy et al. [14] investigated a vertical U-shaped GHE with 80 m depth and 20 cm borehole diameter which was installed at KFUPM, Dhahran, Saudi Arabia. They constructed a mobile thermal response test apparatus to the system in order to measure the performance of the GHE. They found the GHE's energy efficiency to be 46.6% and the second law efficiency to be 51.1%. Wu et al., [15] simulated ground source absorption heat pumps coupled with borehole for three different cities. They carried out dynamic simulations obtaining soil and water temperatures of the borehole for long-term operation. They found high COP and heating capacity of their proposed systems.

In present study, thermodynamic analysis of the BTES system located in UOIT in Ontario, Canada, is conducted for thermodynamic performance assessment for winter season. In this regard, energy and exergy flows of the system are determined through thermodynamic balance equations to layout the buildings' heat demand pattern. Parametric studies are also performed to determine the effects of various system parameters and operating conditions on energy and exergy efficiencies. Actual data accessed from the operating system in university campus is used for the calculations.

2. System description

The BTES system studied and assessed here is installed on the campus of University of Ontario Institute of Technology in Oshawa, Canada. A schematic representation of this system for heating season is shown in Fig. 1 [16]. The buildings were designed to be cooled and heated with GSHP system. During summer, the fluid circulating through tubing extended into the wells, collects heat from the buildings and carries it to the ground. In winter, the system reverses to take heat from the ground and transmits it into the buildings. For a long time operation the heat load is balanced using cooling towers in summer season. As mentioned earlier,