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Exergy analysis of borehole thermal energy storage system for building cooling applications

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ABSTRACT

In this study, exergy analysis of a borehole thermal energy storage system (BTES) for cooling season is carried out. A comprehensive case study is conducted based on the system at University of Ontario Institute of Technology in Oshawa, Canada, and actual thermal load data are employed for analysis. The exergy destruction rates of each system component and overall system are calculated and studied for comparison purposes. It is determined from the analysis that the exergy destructions in a system particularly take place in condensers of cooling systems. Also, it is found that condenser and evaporator temperatures have strong effects on the exergetic performance of the system. For system performance analysis and improvement, exergy efficiencies of the overall BTES are investigated and determined to be a maximum of 62%.

1. Introduction

The need for alternative low-cost energy sources has recently increased drastically. In this regard, the development of ground source heat pumps (GSHP) for residential and commercial heating and cooling applications has received attention from the community. These systems have been recognized to provide viable, environment-friendly alternatives to conventional unitary systems. They can make significant contributions to reductions in electrical energy usage, and allow for more effective demand-side management schemes [1].

The ground is an attractive heat source and heat sink, since its temperature retains near constant throughout the year except for the upper 5–10 m. It is a thermally more stable heat exchange medium than air, essentially unlimited and always available. Therefore, it has been utilized as the heat source or heat sink in HVAC systems for air conditioning, space heating, and water heating for both residential and commercial buildings [2]. GSHPs have been widely used in Europe and North America as one of the basic renewable technologies. As it is significantly beneficial to the energy saving and CO_2 emission reduction in the area of built environment, the geothermal heat pump technology has aroused great attention in China and some other developing countries since 1990s [3].

A GSHP with borehole heat exchanger (BHE) uses the ground as a heat source or sink for space conditioning in residential and commercial buildings. In Scandinavia groundwater is often used to fill the space between borehole wall and collector wall, while otherwise it is more common to backfill with some grouting material. The advantage of using water is cheaper installations and more easy access to the collector if needed. Grouting is on the other hand required in many counties by national legislation in order to prevent groundwater contamination or is used to stabilize the borehole wall [4].

Exergy analysis is important for all energy resource utilization, because exergy is the part of the energy analysis. The theory of exergy analysis is essentially that of available energy analysis. Exergy is also a measure of the maximum useful work that can be done by a system interacting with an environment which is at a constant pressure P_0 and a temperature T_0. The simplest case to consider is that of a reservoir with heat source of infinite capacity and invariable temperature T_0 [5].

Within the past decades, several studies have been carried out about BTES systems. Most of them were dealing with heat transfer characteristics of boreholes, modeling of boreholes, thermal response test, etc. [6–14]. A few of them deal with energy and exergy analysis of cooling systems using BTES. Hepbasli [15] carried out thermodynamic analysis of GSHP systems with a U-bend ground heat exchanger for district heating. He evaluated the performance characteristics of GSHP system in terms of energetic and exergetic aspects. He found that the heating coefficient of

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Nomenclature

ex	specific exergy (kJ/kg)
$\dot{Ex}$	exergy (kW)
gl (15%)	15% water/glycol solution
gl (30%)	30% water/glycol solution
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat (kW)
s	specific entropy (kJ/kgK)
$\dot{S}$	entropy (kW/K)
T	temperature
$\dot{W}$	work (kW)
η_{ex}	exergy efficiency

Subscripts

0	reference state
BHE	borehole heat exchanger
BW	BHE side water/glycol solution
Comp	compressor
Con	condenser
CW	cooling water
dest	destruction
ExpV	expansion valve
FanCoil	fan-coil system
GEN	generation

performance of the heat pump was about 2.85. Also in his study, it was reported that the exergy efficiencies for the heat pump and whole system found to be 66.8% and 66.6%, respectively. Sharqawy et al. [16] examined energy, exergy, and uncertainty analyses for the thermal response test of a ground heat exchanger. They used a vertical U-shaped ground heat exchanger with 80 m depth and 20 cm borehole diameter. They carried out thermal response test at different thermal loads. They analyzed the energy and exergy transports of these thermal response tests using the data obtained from experimental results. Ozgener et al. [17] performed energy and exergy analysis of geothermal district heating system in one of the cities of Turkey. In their analysis, they used an actual system data to determine the heating system performance, energy and exergy efficiencies, and exergy losses. They found that the exergy losses take place in the pumps and in the heat exchangers. In their results, they determined the overall energy and exergy efficiencies of the system to be 55.5% and 59.4%, respectively. Pinel et al. [18] presented a review about the principal methods available for seasonal storage of solar thermal energy. They investigated residential scale systems. Zhai and Yang [19] designed and constructed a GSHP system for determining the thermodynamic behavior of the system. They compared the system with an air source heat pump and found that the operating cost of the GSHP system was reduced by 55.8% and the payback time was found to be two years. They also analyzed the applications of GSHP systems corresponding to different climatic zones of China. Sakulpipatsin et al. [20] presented a method for exergy analysis of buildings and Heating Ventilation Air Conditioning systems. They illustrated an office building equipped with low-temperature heating and high temperature cooling systems situated in the Netherlands. They found the overall exergy efficiencies of the system to be 17.15% and 6.81%. They also noted that the thermal energy emission and control system and the energy conversion system were the main causes of the exergy inefficiencies in the heating and cooling cases, respectively.

In this study, an exergetic assessment of the BTES system to meet the cooling load of the university campus buildings is carried out. Some parametric studies are performed to investigate and examine the influences of different system parameters on exergetic efficiencies. The performance of a BTES system along with its each effect is evaluated by using exergy analysis, which targets a better identifying process efficiencies and losses. The data used are calculated from the actual cooling load data of the system, which is designed and installed in University of Ontario Institute of Technology, Ontario, Canada.

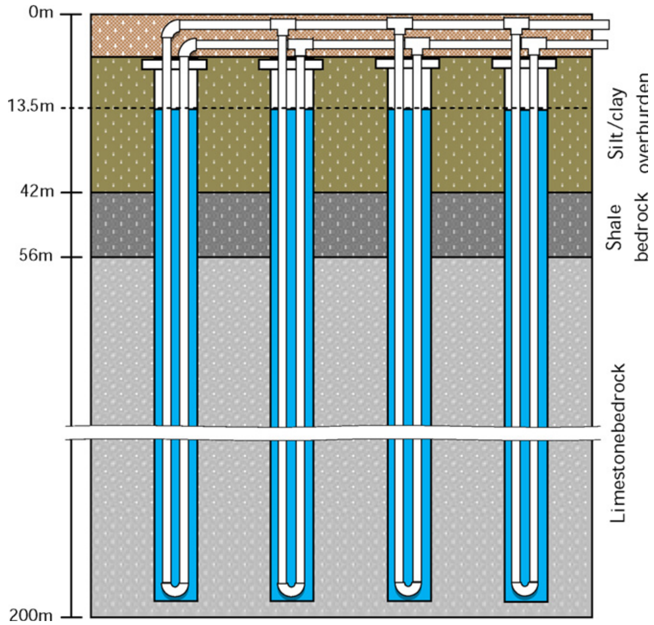

Fig. 1. Illustration and details of the UOIT BTES system. Modified from Ref. [21].

2. System description

The underground BTES considered in this article is installed at the UOIT. The UOIT campus includes seven buildings, most of which are designed to be heated and cooled using GSHPs in conjunction with the BTES, with the aim of reducing energy resource use, environmental emissions, and financial costs. However the analyses in this paper are carried out for ten buildings since the whole system was designed for ten buildings. Besides being a critical component of the university's heating and cooling system, the BTES is used for research and student education. The UOIT BTES field is the largest and deepest in Canada, and the geothermal well field is one of the largest in North America [21].

Test drilling programs were carried out to determine the feasibility of thermal storage in the overburden and bedrock formations at the UOIT site (Fig. 1). The total cooling load of the campus buildings is about 7000 kW. Using the thermal conductivity test results, it was determined that a field of 370 boreholes, each 200 m in depth, would be required to meet the energy demand. The Swedish practice of water-filled BHEs was utilized instead of the North American practice of grouted BHEs [22].

UOIT's central plant provides a cooling and heating system for the entire campus, utilizing the BTES. Chillers are used to pump energy from the buildings into the BTES. The chillers are run only in the cooling mode, their primary purpose of cooling. The other heat pump modules assist in this cooling load. Chilled water is supplied from two multi-stack chillers, each having seven modules, and two sets of heat pumps each with seven modules. Chillers are variable displacement centrifugal units with magnetic bearings that allow for excellent part-load performance. The condenser water goes into a large borehole field that has 370 holes, each 200 m deep. The field retains the heat from the condensers for use in the winter (when