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Research paper

Data, exergy, and energy analyses of a vertical-bore, ground-source heat pump for domestic water heating under simulated occupancy conditions☆

Moonis R. Ally*, Jeffrey D. Munk, Van D. Baxter, Anthony C. Gehl

Oak Ridge National Laboratory, Oak Ridge, TN, USA

HIGHLIGHTS

- Exergy and energy analysis of a vertical-bore ground source heat pump for water heating over a 12-month period is presented.
- The ground provided 68%–76% of the energy to produce domestic hot water.
- Performance metrics are presented.
- Sources of systemic inefficiency are identified and prioritized using exergy analysis.
- Performance metrics suggests the value of using the ground as a renewable energy resource to mitigate climate change.

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ABSTRACT

Evidence is provided to support the view that 68%–76% of the energy required to produce domestic hot water may be extracted from the ground which serves as a renewable energy resource. The case refers to a 345 m^2 research house located in Oak Ridge, Tennessee, 36.01°N 84.26°W in a mixed-humid climate with HDD of 2218 °C-days (3993 °F-days) and CDD of 723 °C-days (1301 °F-days). The house is operated under simulated occupancy conditions in which the hot water use protocol is based on the Building America Research Benchmark Definition which captures the water consumption lifestyles of the average family in the United States. The 5.3 kW (1.5-ton) water-to-water ground source heat pump (WW-GSHP) shared the same vertical bore with a separate 7.56 KW water-to-air ground source heat pump for space conditioning the same house. Energy and exergy analysis of data collected continuously over a twelve month period provide performance metrics and sources of inherent systemic inefficiencies. Data and analyses are vital to better understand how WW-GSHPs may be further improved to enable the ground to be used as a practical renewable energy resource.

1. Introduction

A rigorous examination of using a vertical-bore ground source heat pump for domestic water heating is described in this paper. Although energy from the ground is freely available, its practical extraction from the ground for residential use is not yet widespread. The projected 2015 U.S. buildings sector energy end-use splits indicates that water heating alone would consume 7.47×10^{11} kWh of energy, accounting for 12.7% of total building energy consumption [1]. Carbon dioxide emission due to water heating in buildings is 2.041×10^{11} kg, of which 9.85×10^{10} kg is from electric water heating [2]. The total residential sector site energy consumption for water heating in 2015 is projected at 5.626×10^{11} kWh of which natural gas is the dominant fuel,

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* Corresponding author. Tel.: +1 865 576 8003; fax: +1 865 574 8884.
E-mail address: allymr@ornl.gov (M.R. Ally).

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Nomenclature

Quantities

ACH	air changes per hour measured at differential pressure of 50 Pa
CDD	cooling degree days
C.V.	coefficient of variance (dimensionless); a measure of dispersion
COP	coefficient of performance (dimensionless)
DOE	United States Department of Energy
DHW	domestic hot water
EWT	entering water temperature (K)
GL	ground loop
GSHP	ground source heat pump
GWP	global warming potential
HDD	heating degree days
HX	heat exchanger
g	gravitational acceleration ($m\ s^{-2}$)
h	enthalpy ($kJ\ kg^{-1}$)
$\dot{I}$	rate of thermodynamic irreversibility (W)
LWT	leaving water temperature (K)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
Mtoe	million tons of oil equivalent
OEM	original equipment manufacturer
P	pressure (kPa)
$\dot{Q}$	thermal energy flow (W)
QSSSF	quasi-steady-state-steady flow
R_{SI}	R-value, a measure of thermal resistance ($m^2\ K\ W^{-1}$)
R_{US}	R-value, a measure of thermal resistance ($ft^2\ °F\ h\ Btu^{-1}$)
S.D.	standard deviation, a statistical measure of dispersion
s	entropy ($kJ\ kg^{-1}\ K^{-1}$)
T	temperature (K)
U	internal energy in control volume (kJ)
V	velocity ($m\ s^{-1}$)
$\dot{W}$	rate of work (W)
WA-GSHP	water-to-air ground source heat pump
WW-GSHP	water-to-water ground source heat pump
%Δ	percent deviation
η	efficiency (dimensionless)
$\dot{\sigma}$	rate of entropy generation ($W\ K^{-1}$)

Subscripts

b	brine
Brine-HX	brine heat exchanger
comp.	pertaining to the compressor
comp. meas.	compressor quantity measured (actual)
CV	control volume
EWT	entering water temperature
i	inlet location
e	exit location or electrical energy
j	thermal reservoir other than the dead state or surroundings
o	dead state or surroundings
map	pertaining to the compressor map
Ref-Air HX	refrigerant-to-air heat exchanger

accounting for 3.84×10^{11} kWh (68.2% of total) followed by electricity, 1.407×10^{11} kWh (25% of total), and the remainder being fuel oil, liquefied petroleum gas, and renewables. The 1.407×10^{11} kWh on site electricity consumption translates to 4.2×10^{11} kWh of source energy consumption. In terms of source energy consumption, water heating and space heating represent 13.7% and 27.9%, respectively of total residential energy use [3]. For the January–October 2014 period, residential gas storage water heater and residential electric storage water heater sales increased 3.6% and 5.7%, respectively, compared to shipments in the same period in the previous year reflecting a growing trend in recent years, following the 2009 recession.

The abundant energy available in the ground represents a potentially huge opportunity to satisfy present and future energy demands. Within Europe, 7100 TWh or 610 Mtoe annually is available from accessible depths of which 260 Mtoe per year lie under the surface of the EU27 [4]. In an effort to combat climate change, the EU Commissioners want a binding target to reduce carbon dioxide emissions by 40% from 1990 levels by year 2030. To attain this target, approximately 27% of the EU's energy will need to come from renewable resources [5].

Similar emphasis is noted from other countries. Estimates of energy and CO_2 savings with ground source heat pumps (GSHPs) in 10 states in India are summarized by Sivasakthivel et al. [6]. Studies to investigate both space conditioning and water heating using ground source heat pumps with an emphasis on energy consumption in poorly and in well-insulated houses in the UK has been reported by Bagdanavicius and Jenkins [7]. An experimental study of GSHPs for space heating in a cold climate in Turkey by Ozyurt and Ekinci [8] yielded a COP between 2.43 and 3.55. A status review and comparison of GSHPs with other heating options is reported by Stuart et al. [9]. Performance of an experimental GSHP rig connected to a 120 m deep, 150 mm diameter vertical bore installed at Hebei University, China was investigated by Man et al. [10]. Energy and exergy analysis of combined GSHP whose evaporator component works as a photovoltaic-thermal collector has been investigated by Ozturk [11]. Hybridized variations of GSHPs for space conditioning and for water heating have been investigated by researchers in recent years with a focus on increasing the performance using solar energy in conjunction with the ground [12–15].

The use of various refrigerants such as a ternary mixture of R124/R142b/R600a (named HTR01), carbon dioxide, R410a, R134a and propane in water-to-water ground source heat pumps (WW-GSHPs) for domestic hot water production has been intensively investigated by several researchers [10,16–20]. *Prima facie* it seems that greater emphasis is being placed on carbon dioxide relative to the other refrigerants presumably because of its low global warming potential (GWP), low cost, ease of handling, and ability to produce domestic hot water (DHW) up to 80 °C, an indispensable level for certain commercial markets. The choice of refrigerants presents its own peculiar technical issues. For example, with carbon dioxide, water stratification in a tank is essential to attain high COP, and the overall COP is significantly higher for heating a tank full of cold water than it is for heating the same volume of warm water, a characteristic of refrigerants (like carbon dioxide) that must operate beyond their critical pressure.

A review of various models and systems of vertical bore GSHPs showing significant energy savings and applicability in cold and hot climates is discussed by Yang et al. [21]. Based on extensive experimental data as well as exergy and energy analyses of horizontal loop ground source heat pumps for space conditioning and for domestic water heating, Ally et al., [22,23] point out the