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Exergy, exergoenvironmental and exergoeconomic evaluation of a heat pump-integrated wall heating system

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ABSTRACT

In this study, a vertical ground source heat pump wall heating system belonging to the Yıldız Renewable Energy House on the Davutpaşa Campus of Yıldız Technical University was experimentally and theoretically studied. The examination included energy, exergy, exergoenvironmental and exergoeconomic analyses from 1 January 2013 to 30 March 2013 (i.e., the "Winter Session"). Data were collected and uploaded to a MySQL database. "The moments when the heat pump is activated" was detected and "Monthly Average Values" were analysed. Theoretical analyses were conducted for the Winter Session and correlated with the experimental results. This study includes exergetically, exergoeconomically, and exergoenvironmental evaluate a building and its heating system from the generation stage to the envelope of the building. The findings are based on applying a low exergy, exergoenvironmental and exergoeconomic analysis to investigate the system performance. The energy and exergy efficiencies of the entire system were 67.36% and 27.40%, respectively, and the energy and exergy efficiencies of the wall heating system panels were 86.61% and 82.90%, respectively. The monthly average exergy-based environmental impact value was 0.212 mPts/s. The exergoeconomic factors changed from 74.97% to 75.77%.

1. Introduction

Declining tendency of fossil fuels and greenhouse emissions are the driving forces of renewable energy technologies research. Solar energy and other renewable energy technologies are being evaluated as primary energy sources for the future. While research regarding new and renewable energy resources is vital, improvements to current heat pump systems can provide similar benefits as those derived from pursuing new energy resources. The building sector is one of the leading sectors in energy consumption. For this reason, the utilisation of renewable energy sources in building heating and air conditioning systems is of significant importance. By using heat pump systems integrated with renewable energy-sourced heating and air conditioning systems, the benefits of cyclic renewable sources, such as soil, geothermal, and solar energy, may be exploited for longer periods of time. Using such an approach, increasing the solar fraction and decreasing the dependence on fossil fuels in heating systems will be possible. However, the environmental impacts of these technologies must also be minimised. To this end, alternative technologies, such as HPs (heat pumps) technologies, must be developed, and further work must be performed to implement these systems, especially in the residential sector [1,2]. Currently, with reduced energy sources, increased energy prices and increased environmental awareness in society, interests in residential and industrial uses of VGSHP (Vertical Ground Source Heat Pump) technologies in European, American and Asian markets continue to increase.

In the literature, many studies have examined the design, performance, and testing of VGSHPs and have also conducted economic analyses and other tests. Sarbu and Sebarchievici [3] performed a detailed literature review of VGSHP technology, concentrating on ground-coupled heat pump systems. Montagud et al. [4] presented energy performance measurements of a GCHP (GeoCool Heat Pump) system during five years of operation and also examined the evolution of the return water temperature from the ground. Urchueguía et al. compared the energy performances of air-sourced HPs and Ground Source Heat Pumps (GSHPs) in typical Mediterranean climate regions [5]. The technical and economic

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Nomenclature

A	Area [m^2]
B_F	Environmental impact depent on exergy [mPts/s]
b_F	Environmental impact per unit of exergy ratio [mPts/kJ]
c_p	Specific heat [kJ/kg°C]
CRF	First investment improvement factor
CELF	Constant escalation levelling factor
D	Diameter [m]
E	Energy [kJ]
$\dot{E}$	Energy ratio [kW]
Ex	Exergy [kJ]
$\dot{E}x$	Exergy ratio [kW]
$f_{B,k}$	Exergoenvironmental factor
f_c	Exergoeconomic factor
g	Acceleration of gravity [m^2/s]
h	Convective heat transfer coefficient [W/m^2.K], Enthalpy [kJ/kg]
m	Mass [kg]
$\dot{m}$	Mass flow [kg/s]
Q	Heat energy [kJ]
$\dot{Q}$	Heat ratio [kW]
P	Pressure [kPa, Bar]
R	Thermal resistance [W/m^2.K]
r_i	Interest rate
S	Entropy [kJ/K]
s	Entropy for per mass [kJ/kg.K]
T,t	Temperature [K, °C]
U	Conduction heat transfer coefficient [W/m^2K], Internal energy [kJ]
u	Internal energy, for per mass [kJ/kg]
V	Volume [m^3]
W	Work [kJ]
$\dot{W}$	Power [kW]
$\dot{Y}_k$	Environmental impact based on part [mPts/s]
Z	Total cost [€/h]
$\dot{Z}^{IC}$	Investment cost [€/h]
$\dot{Z}^{OM}$	Operation cost [€/h]

Subscripts

0	References state
aveAverageC	AverageCCooling
c	Component
comp	Compressor
cond	Condenser
dest	Destruction
e	Electricity
eva	Evaporator
k	Each system part
L	Land
in	Input
j	Process flow point/each flow
p	Pipe/Pump
p_1	Pump 1
p_2	Pump 2
p_3	Pump 3
sys	System
th	Thermal
tr	Reversibility
out	Output
W	Wall

Superscripts

IC	Investment cost
n	Specified lifetime of systems or components (year)
ope	Operation
OC	Operation cost
prod	Production
wst	Waste
sys	System

Greeks

Δ	Differences
η	Efficiency [%]
ρ	Density [kg/m^3]
υ	Specific volume [m^3/kg]
ϕ	Exergy change for per mass at closed system [kW]
ψ	Exergy change for per mass at open system [kW]

Abbreviation

ACU	Accumulator
ANU	Annual working hour
CV	Control volume
CExC	Cumulative exergy consumption
COP	Coefficient of performance
COMP	Compressor
COND	Condenser
ELEC	Electricity
EVA	Evaporator
FIC	First investment cost
GSHP	Ground source heat pumps
HP	Heat pump
HHV	High heating value
KE	Kinetic energy
LHV	Low heating value
MC	Maintenance cost
MTEP	Million tons equivalents petroleum
PE	Potential energy
TV	Throttling valve
SL	System life
UGC	Underground circuit
UHE	Underground heat exchanger
WHS	Wall heating systems
WHSP	Wall heating system panels

feasibility of GSHP (ground source heat pump) systems were evaluated for the regions with climates requiring the GSHP cooling properties. Hepbaşlı et al. [6] determined the COP (Coefficient of performance) and performed an exergy analysis of a GSHP system at a vertical depth of 50 m for a 65 m^2 classroom with passive heating and air conditioning at the Solar Energy Institute. The other study, mathematical model produced to describe the operation of a water to water heat pump system for steady-state condition. The proposed mathematical models of heat exchangers were described by coupled differential equations, while the models of the compressor and the expansion valve are of lumped parameters. The RungeeKutta and the AdamseMoulton predictor-corrector methods were applied for the numerical solution of differential equations, i.e. the equation systems. The developed mathematical model is validated with 118 tests using R134a as a working fluid. The results show that an average difference between the modelled and