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Exergy Analysis of a Solar-Assisted Ground-Source (Geothermal) Heat Pump Greenhouse Heating System

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ABSTRACT

The main objective of the present study is to investigate the performance characteristics of a solar assisted ground-source heat pump greenhouse heating system (SAGSHPGHS) with a U-bend ground heat exchanger using the exergy analysis method. This system was installed in the Solar Energy Institute of Ege University, Izmir, Turkey. The exergy transports between the components and the destructions in each of the components of the SAGSHPGHS are determined for the average measured parameters obtained from the experimental results. The exergetic efficiencies of the system components are also calculated to assess their individual performance. The exergetic efficiency of the overall system is found to be 67.7%.

1. INTRODUCTION

Exergy analysis has proven to be a powerful tool in the thermodynamic analyses of energy systems, e.g., Moran (1982), Kotas (1985), Bejan (1998), Szargut et al. (1998), Hasan et al., (2002), Dincer (2002), Rosen and Dincer (2003), Petela (2003), In order to calculate exergy, the environment must be specified. Because of the lack of thermodynamic equilibrium in the surrounding nature, only its common components can be used for the abovementioned purpose. The ability of an energy carrier to do work expresses the general ability to be converted into other kinds of energy, and therefore exergy can be used not only to analyze the process of power plants and of other mechanical machines, but also to investigate technological process. An engineer designing a system is expected to aim for the highest possible technical efficiency at a minimum cost under the prevailing technical, economic and legal conditions, but also with regard to ethical, ecological and social consequences. Exergy is a concept that makes this work a great deal easier.

Various studies have been undertaken by many investigators on exergy analysis of solar assisted heat pumps and greenhouse heating, e.g., Bascetincelik et al. (1999), Singh et al. (2000), Reyes and Gortari (2001), Badescu (2002), Izquierdo et al. (2002), Ozturk and Bascetincelik (2003), Ghosal et al. (2004), Hepbasli and Akdemir (2004), and Ozgener and Hepbasli (2004, 2005). However, to the best of the authors' knowledge, only two studies (Ozgener and Hepbasli, 2004, 2005) on the performance testing of a SAGSHPGHS with a 50 m vertical 32 mm nominal diameter U-bend ground heat exchanger using the exergy analysis method have appeared in the open literature. The study reported here includes the performance analysis of a SAGSHPGHS with R-22 as the refrigerant in the heating mode by using exergy analysis. A flat-type solar collector is directly connected into the ground-coupled loop. An experimental set-up, described in the next section, is constructed and tested for the first time on the basis of a university study performed in the country. This study also describes an easy-to-follow procedure for exergy analysis of SAGSHPGHSs and how to apply this procedure to assess the heating system performance by calculating exergy destruction.

2. SYSTEM DESCRIPTION

A schematic diagram of the experimental set up is illustrated in Figure 1. This system mainly consists of three separate circuits: (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 greenhouse heating (water circuit). The working fluid is R-22. The SAGSHPGHS studied was installed at the Solar Energy Institute of Ege University (latitude 38^{o} 24' N, longitude 27^{o} 50' E), Izmir, Turkey. The solar greenhouse was positioned towards the south in the direction south-north.

3. MODELING

An accurate analysis can be realized by evaluating the exergy destroyed for every single component of the system. Table 1 lists the energy and exergy balance equations for the components of the SAGSHPGHS illustrated in Figure 1 (see Ozgener and Hepbasli (2004, 2005) for more detail). These exergy balance equations are employed to find the rate of exergy decrease, the rate of irreversibility and the exergy efficiencies.

4. RESULTS AND DISCUSSION

In this study, the restricted dead state was taken to be the state of environment at which the temperature and the atmospheric pressure are 10.93 °C and 101.325 kPa, respectively, which were the values measured at the time when the SAGSHPGHS data were obtained. The exergy rate results given in Table 2 indicate that the compressor produces an increase in exergy rate due to its work input, while all other components result in a decrease in exergy rate due to their irreversibilities.

The heating coefficients of performance of the ground source heat pump unit and the overall system are calcultated to be 2.64 and 2.38, respectively. The exergy efficiency value for the whole system is found to be 67.7%. The causes of exergy destruction in the system include the compressor, greenhouse, heat exchanger (ground heat exchanger, condenser and evaporator), circulating pumps and solar collector losses. It is obvious from Table 3 that the highest irreversibility occurs in sub-regions I and V for the GSHP unit and the whole system, respectively. The losses in the motor-compressor subassembly are due to the electrical, mechanical and isentropic efficiencies and emphasize the need for paying close attention to the selection of this type of equipment, since components of inferior performance can considerably reduce the overall performance of the system. The second largest irreversibility in the GSHP unit is due to the condenser. This is partly due to the large degree of superheat achieved at the end of the compression process, leading to large temperature differences associated with the initial phase of heat transfer. The third highest irreversibility is in the capillary tube due to the pressure drop of the refrigerant passing through it. Besides this, the evaporator has the lowest irreversibility on the basis of the heat pump cycle.

5. CONCLUSIONS

The main conclusions drawn from the present study are listed below:

a) The exergy efficiency values for the GSHP unit and the whole system are shown to be 71.8% and 67.7%, respectively.

b) The highest irreversibility on a system basis occurs in the greenhouse fan-coil unit, followed by the compressor, condenser, expansion valve and evaporator, sub-regions I and V for the GSHP unit and the whole system, respectively. Besides this, the remaining system components have a relatively low influence on the overall efficiency of the whole system.

c) Experimental results show that monovalent central heating operation (independent of any other heating system) cannot meet the overall heat loss of the greenhouse if the ambient temperature is very low. The bivalent operation (combined with another heating system) is suggested as the best solution in the Mediterranean and Aegean region in Turkey, if peak load heating can be easily controlled.

d) It is expected that the present study will help engineers and investigators in the design, operation and simulation of GSHP systems in terms of exergetic evaluations.

NOMENCLATURE

$\dot{E}x$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
s	entropy (kJ/kgK)
$\dot{Q}$	heat transfer rate (kW)
$\dot{W}$	work rate or power (kW)
T	temperature (°C)

Greek letters

ε	exergy efficiency (dimensionless)
ψ	specific exergy (kJ/kg)

Subscripts

0	restricted dead state
act	actual
col	collector
comp	compressor
cond	condenser
dest	destroyed, destruction
evap	evaporator
fc	fan coil
grh	greenhouse
HE	heat exchanger
HP	heat pump
in	inlet
out	outlet
R	removal, rational
ref	refrigerant
SYS	system
wa	water
u	useful

Abbreviations

GSHP	round source heat pump system
SAGSHPGHS	solar assisted ground-source heat pump greenhouse heating system

REFERENCES

Badescu, V.: First and Second Law Analysis of a Solar Assisted Heat Pump Based Heating System, *Energy Conversion and Management,* **43**, (2002), 2539-2552.

Bascetincelik, A., Ozturk, H.H., Paksoy, H.O., and Demirel, Y.: Energetic and exergetic efficiency of latent heat storage system for greenhouse heating, *Renewable Energy,* **16**, (1999), 691-694.

Bejan, A.: Advanced Engineering Thermodynamics, *John Wiley & Sons*, New York (1998).

Dincer, I.: The Role of Exergy in Energy Policy Making, *Energy Policy,* **30**, (2002), 137-149.

Ghosal, M.K., Tiwari, G.N., Srivastava, N.S.L., and Sodha, M.S.: Thermal Modeling and Experimental Validation of Ground Temperature Distribution in Greenhouse, *International Journal of Energy Research,* **28**, (2004), 45-63.

Hasan, A.A., Goswami, D.Y., and Vijayaraghavan, S.: First and Second Law Analysis of a New Power and Refrigeration Thermodynamic Cycle Using a Solar Heat Source, *Solar Energy,* **73(5)**, (2002), 385-393.

Hepbasli, A., and Akdemir, O.: Energy and Exergy Analysis of a Ground Source (Geothermal) Heat Pump System, *Energy Conversion and Management*, **45(5)**, (2004), 737-753.

Izquierdo, M., Vega, M.D., Lecuona, A., and Rodriguez, P.: Compressors Driven by Thermal Solar Energy: Entropy Generated, Exergy Destroyed and Exergetic Efficiency, *Solar Energy,* **72(4)**, (2002), 363-375.

Kotas, T.J.: The Exergy Method of Thermal Plant Analysis, Anchor Brendon Ltd, Tiptree, Essex. Great Britain (1985).

Moran, M.J.: Availability Analysis: a Guide to Efficiency Energy Use. Prentice-Hall, Englewood Cliffs, NJ (1982).

Ozgener, O., and Hepbasli, A.: Experimental Performance Analysis of a Solar Assisted Ground-source Heat Pump Greenhouse Heating System, *Energy and Buildings*, **37(1)**, (2005), 101-110.

Ozgener, O., and Hepbasli, A.: Experimental Investigation of Performance of a Solar Assisted Ground-source Heat Pump System for Greenhouse Heating, *International Journal of Energy Research,* (2004), in Press.

Ozturk, H.H., and Bascetincelik, A.: Energy and Exergy

Efficiency of a Packed-bed Heat Storage Unit for Greenhouse Heating, *Biosystems Engineering*, **86(2)**, (2003), 231-245.

Petela, R.: Exergy of Undiluted Thermal Radiation**,** *Solar Energy*, **74(6)**, (2003), 469-488.

Reyes, E.T., and Gortari, J.C.: Optimal Performance of an Irreversible Solar Assisted Heat Pump, *Exergy an International Journal*, **1(2)**, (2001), 107-111.

Rosen, M.A., and Dincer, I.: Exergy–cost–energy–mass analysis of thermal systems and processes, *Energy Conversion and Management*, **4(10)**, (2003), 1633-1651.

Singh, N., Kaushik, S.C., and Misra, R.D.: Exergetic Analysis of a Solar Thermal Power System, *Renewable Energy*, **19**, (2000), 135-143.

Szargut, J., Morris, D.R., and Stewart, F.R.: Exergy Analysis of Thermal, Chemical, and Metallurgical Processes, Edwards Brothers Inc. USA (1998).

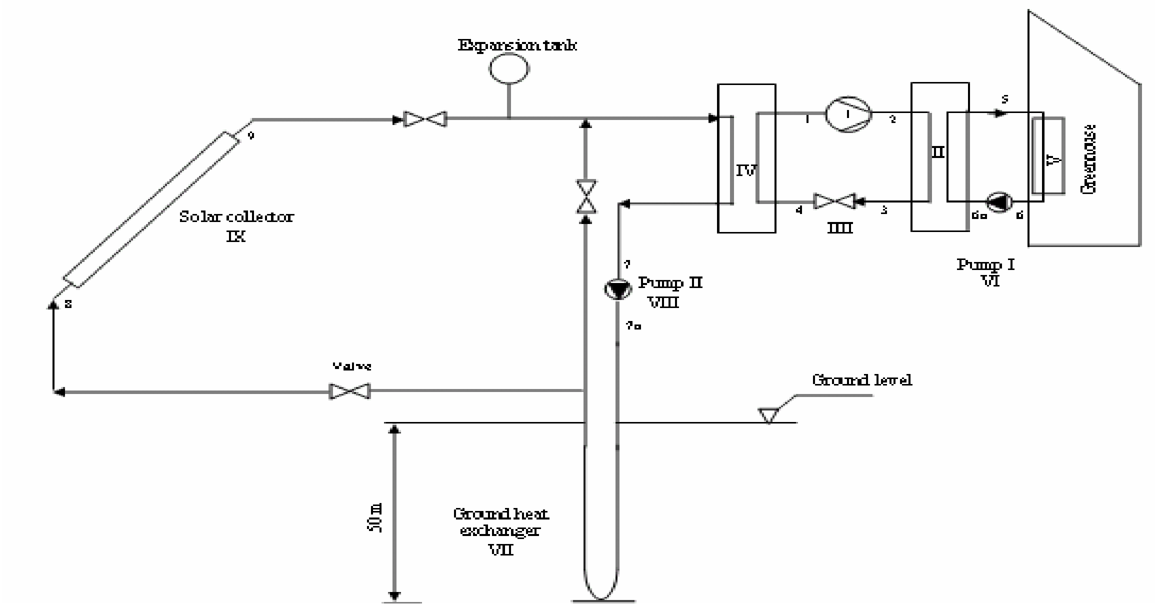

Figure 1: A schematic of the solar assisted ground-source heat pump greenhouse heating system (SAGSHPGHS).

Table 1: General exergy equations obtained for the SAGSHPGHS studied.

Equation no	Equation	Descriptions
(1)	$\dot{E}x_{dest,comp} = \dot{m}_{ref}(\psi_1 - \psi_2) + \dot{W}_{comp}$	Exergy destroyed (irreversibility) by compressor
(2)	$\dot{E}x_{dest,cond} = \dot{m}_{ref}(\psi_2 - \psi_3) + \dot{m}_{wa}(\psi_6 - \psi_5)$	Exergy destroyed by condenser
(3)	$\dot{E}x_{dest,valve} = \dot{m}_{ref}(\psi_3 - \psi_4)$	Exergy destroyed by expansion valve
(4)	$\dot{E}x_{dest,evap} = \dot{m}_{ref}(\psi_4 - \psi_1) + \dot{m}_{wa}(\psi_9 - \psi_7)$	Exergy destroyed by evaporator
(5)	$\dot{E}x_{dest,fc} = \dot{m}_{wa}(\psi_5 - \psi_6) - \dot{Q}_{cond}\left(1 - \frac{T_0}{T_{grh}}\right)$	Exergy destroyed by fan coil
(6)	$\dot{E}x_{dest,grh} = \dot{m}_{brine}(\psi_{7a} - \psi_8) + \dot{Q}_{grh}\left(1 - \frac{T_0}{T_{ground}}\right)$	Exergy destroyed by ground heat exchanger
(7)	$\dot{E}x_{dest,col} = \dot{m}_{brine}(\psi_8 - \psi_9) + \dot{Q}_u\left(1 - \frac{T_0}{T_s}\right)$	Exergy destroyed by solar collector
(8)	$\dot{E}x_{dest,pump_I} = \dot{W}_{pump_I} - \dot{m}_{wa,6}(\psi_{6a} - \psi_6)$	Exergy destroyed by pump I
(9)	$\dot{E}x_{dest,pump_{II}} = \dot{W}_{pump_{II}} - \dot{m}_{wa,7}(\psi_{7a} - \psi_7)$	Exergy destroyed by pump II
(10)	$\varepsilon_{comp} = \frac{\dot{E}x_{out} - \dot{E}x_{in}}{\dot{W}_{comp}}$	Exergy efficiency by compressor
(11)	$\varepsilon_{pump} = \frac{\dot{E}x_{out} - \dot{E}x_{in}}{\dot{W}_{pump}}$	Exergy efficiency by pump
(12)	$\varepsilon_{HE} = \frac{\dot{m}_{cold}(\psi_{cold,out} - \psi_{cold,in})}{\dot{m}_{hot}(\psi_{hot,in} - \psi_{hot,out})}$	Exergy efficiency by heat exchanger (condenser/evaporator)
(13)	$\varepsilon_{SYS} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}}$	Exergy efficiency by SAGSHPGHS
(14)	$\varepsilon_{R,HP} = \frac{\dot{E}x_{heat}}{\dot{W}_{act,in}} = \frac{\dot{E}x_{in,cond} - \dot{E}x_{out,cond}}{W_{act,in}}$	Exergy efficiency by GSHP

Table 2: Property data and exergy rates for the SAGSHPGHS studied.

Item no	Name of element	Fluid	Phase	Temp. T (°C)	Pressure P (kPa)	Specific enthalpy h (kJ/kg)	Specific entropy s (kJ/kgK)	Mass flow rate $\dot{m}$ (kg/s)	Specific exergy Ψ (kJ/kg)	Exergy rate $\dot{E}x = \dot{m}\psi$ (kW)
0	-	Refrig.	Dead state	10.93	101.325	420.31	1.9510	-	0	0
0'	-	Water	Dead state	10.93	101.325	46.55	0.1646	-	0	0
1	Evaporator outlet / Compressor inlet	Refrig.	Sat. vapor	7.4	425.5	412.12	1.7898	0.02	37.60	0.75
2	Condenser inlet /Compressor outlet	Refrig.	Sup. heated vapor	112.5	2837.1	466.58	1.7967	0.02	90.10	1.80
3	Condenser outlet	Refrig.	Liquid	52.8	2800	268.02	1.2208	0.02	55.14	1.10
4	Evaporator inlet	Refrig.	Mixture	-3.0	451.1	268.02	1.2522	0.02	46.22	0.92
5	Greenhouse supply water inlet	Water	Liquid	56	250	234.39	0.7798	0.095	13.07	1.24
6	Greenhouse return water pump inlet	Water	Liquid	45.7	250	191.42	0.6472	0.095	7.77	0.73
6a	Greenhouse return water pump outlet	Water	Liquid	46.0	350	192.76	0.6511	0.095	8.01	0.76
7	Ground heat exchanger water pump inlet	Brine	Liquid	8.8	250	37.83	0.1329	0.2	0.29	0.06
7a	Ground heat exchanger water pump outlet	Brine	Liquid	9.1	350	39.18	0.1374	0.2	0.36	0.07
8	Ground heat exchanger water outlet (Solar collector water inlet)	Brine	Liquid	12.36	300	52.7	0.1857	0.2	0.16	0.03
9	Solar Collector water outlet	Brine	Liquid	13.01	250	55.36	0.1953	0.2	0.09	0.02

Source: Ozgener and Hepbasli (2005)

Table 3: Exergy destruction rates and exergy efficiencies for the SAGSHPGHS.

Item no	Component	Exergy destruction rate (kW)	Utilized power (kW)	Exergy efficiency (%)
I	Compressor	0.450	1.500	70.0
II	Condenser	0.220	3.977	68.5
III	Expansion valve	0.180	-	83.6
IV	Evaporator	0.130	2.882	23.5
V	Fan coil unit in the greenhouse	0.480	3.977	61.3
VI	Circulating pump I	0.029	0.059	50.8
VII	Ground heat exchanger	0.040	2.974	42.8
VIII	Circulating pump II	0.049	0.059	16.9
IX	Solar collector	0.010	0.532	66.6
I-IV	GSHP unit	0.980	8.359	71.8
I-IX	Overall system	1.588	15.960	67.7