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Experimental performance analysis of a solar assisted ground-source heat pump greenhouse heating system

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Abstract

Ground-source heat pumps (GSHPs), also known as geothermal heat pumps (GHPs), are recognized to be outstanding heating, cooling and water heating systems, and have been used since 1998 in the Turkish market. Greenhouses also have important economical potential in Turkey's agricultural sector. In addition to solar energy gain, greenhouses should be heated during nights and cold days. In order to establish optimum growth conditions in greenhouses, renewable energy sources should be utilized as much as possible. It is expected that effective use of heat pumps with a suitable technology in the modern greenhouses will play a leading role in Turkey in the foreseeable future.

The main objective of the present study is to investigate to the performance characteristics of a solar assisted ground-source heat pump greenhouse heating system (SAGSHPGHS) with a 50 m vertical 1 × 1/4 in. nominal diameter U-bend ground heat exchanger using exergy analysis method. This system was designed and constructed in 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. Exergetic efficiencies of the system components are determined in an attempt to assess their individual performances and the potential for improvements is also presented. The heating coefficient of performances of the ground-source heat pump unit and the overall system are obtained to be 2.64 and 2.38, respectively, while the exergetic efficiency of the overall system is found to be 67.7%.

Keywords: Ground-source heat pump; Geothermal energy; Greenhouse; Exergy; Heat pump; Renewable energy; Solar energy; Sustainable development

1. Introduction

The climatic conditions of the region are the prime factor, which effect the development of the plant and the economics of the greenhouse production. It becomes necessary to take measures to heat the greenhouses when the temperature goes below 12 °C in order to obtain high quality and high yield crop, that is especially important for export purpose [1].

Greenhouses also have important economical potential in Turkey's agricultural sector. In addition to solar energy gain, greenhouses should be heated during nights and cold days. In order to establish optimum growth conditions in greenhouses, renewable energy sources should be utilized as much as possible [2]. Heating applications in the greenhouses have an important effect on yield as well as on quality and the cultivation time of products [3–7].

Effective use of heat pumps with a suitable technology in the modern greenhouses plays a leading role in Turkey in the foreseeable future. Although in greenhouses not only the possibility of heating, but also the ability of cooling and dehumidification has been recognized, only a restricted number of practical applications have been realized [2]. The use of solar energy is considerable interest for two reasons. First, it leads to diminution of fossil fuels consumption. Second, solar energy is a non-polluting source of energy [8]. In this regard, investigations conducted on solar assisted heat pumps are getting more and more importance [9–14].

An exergy analysis has proven to be a powerful tool in the thermodynamic analyses of energy systems [15–20]. 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

Abbreviations: GSHP, ground-source heat pump; GHP, geothermal heat pump; GRP, glass reinforced plastics; SAGSHPGHS, solar assisted ground-source heat pump greenhouse heating system

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Nomenclature

A	area (m^2)
C	specific heat (kJ/kg K)
COP	heating coefficient of performance of heat pump (dimensionless)
E	energy rate (kW)
$\mathring{E}x$	exergy rate (kW)
f	exergetic factor (dimensionless)
F	collector heat removal factor (dimensionless)
$\mathring{F}$	exergy rate of the fuel (kW)
h	specific enthalpy (kJ/kg)
I	instantaneous total radiation on a horizontal surface (MJ/m^2)
$\mathring{I}$	rate of irreversibility (exergy destroyed) (kW)
IP	rate of improvement potential (kW)
$\mathring{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\mathring{P}$	exergy rate of the product (kW)
$\mathring{Q}$	heat transfer rate (kW)
s	entropy (kJ/kg K)
$\mathring{S}$	entropy rate (kW/K)
T	temperature (°C)
U	overall loss coefficient of the collector (W m^2/K)
$\mathring{W}$	work rate or power (kW)

Greek letters

α	absorbance (dimensionless)
δ	fuel depletion rate (dimensionless)
ε	exergy (second law) efficiency (dimensionless)
η	energy efficiency (dimensionless)
ξ	productivity lack (dimensionless)
τ	transmittance (dimensionless)
χ	relative irreversibility (dimensionless)
ψ	specific exergy (kJ/kg)

Subscripts

0	restricted dead state
a	ambient
act	actual
C	collector
Co	condenser
Comp	compressor
dest	destroyed, destruction
evp	evaporator
gen	generation
grh	greenhouse
H	high
HP	heat pump
i	component
in	inlet
k	location
L	loss, low
out	outlet
R	removal, rational
ref	refrigerant
s	surface
sr	solar radiation
SYS	system
Tot	total
u	useful
wa	water

Superscripts

°	quantity per unit time (except those denoted in the text)
CH	chemical
ex	specific exergy (kJ/kg)
KN	kinetic
p	plate
PH	physical
PT	potential

be used for the above-mentioned 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.

The impact of energy resource utilization on the environment and achievement of increased resource utilization efficiency are best addressed by considering exergy. The exergy of an energy form or a substance is a measure of its usefulness or quality or potential to cause change. The latter point suggests that exergy may be, or provide the basis for, an effective measure of the potential of a substance or energy form to impact the environment [21]. Exergy analysis can also indicate the possibilities of thermodynamic improvement of the process under consideration, but only an economic analysis can decide the expediency of a possible improvement [18].

Various studies have been undertaken by many investigators on exergy analysis of solar assisted heat pumps [8,22–25]. However, to the best of authors' knowledge, no studies on the performance testing of a SAGSHPGHS with a 50 m vertical 1 × 1/4 in. nominal diameter U-bend ground heat exchanger using 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 installed into the