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Low exergy modelling and performance analysis of greenhouses coupled to closed earth-to-air heat exchangers (EAHEs)

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ABSTRACT

The present study deals with modelling, analyzing and assessing the performance of greenhouse heating systems with earth–pipe–air heat exchangers (EAHEs) in closed loop mode. In this regard, an EAHE system is considered as an illustrative example. This system starts with the power plant, through the production of heat (EAHE), via a distribution system, to the heating system and from there, via the greenhouse air, across the greenhouse envelope to the outside environment. Exergy analysis method (the so-called low exergy or LowEx approach) has been and still being successfully used to design and evaluate sustainable buildings. It is applied to all components of this EAHE system for the first time to the best of the author's knowledge in this study. The overall energy efficiency value for the EAHE system studied is determined to be 72.10% while the overall exergy efficiency value is calculated to be 19.18% at a reference state temperature of 0 °C. The exergy efficiency of the whole EAHE system decreases from 19.18% to 0.77% with the increase in the reference environment temperature from 0 to 18 °C. The sustainability index values for the whole EAHE system decrease from 1.24 to 1.01 as the reference state temperature increases.

1. Introduction

Due to the efforts made towards reducing the energy demand of new office buildings, the interest in heating and cooling systems based on renewable sources of energy has recently significantly increased. Air conditioning has been widely used not only for industrial productions, but also for the comfort of occupants while it can be efficiently achieved by vapor compression machines. However, due to depletion of the ozone layer and global warming by chlorofluorocarbons (CFCs) as well as the need for reducing high grade energy consumption, numerous alternative techniques have been explored. One such method is earth-to-air heat exchangers (EAHEs). Since the thermal inertia of the soil is high, the temperature fluctuations at the ground surface are attenuated deeper in the ground. A time lag also occurs between the temperature fluctuations at the surface and in the ground. For this reason, at a sufficient depth, the ground temperature is lower than the outside temperature in summer and higher in winter. [1,2]. EAHE is a subterranean cooling/heating system with pipes buried below ground surface, through which ventilation air is circulated. Temperature difference between air and soil can be utilized to precool or pre-heat ventilation air supply using an EAHE in summer and winter, respectively [3].

The amount of energy used in agricultural production, processing and distribution is significantly high. Sufficient supplying the right amount of energy along with its effective and efficient utilization is necessary for improving agricultural production. It has also been reported that crop yields and food supplies are directly linked to energy [4]. In this regard, various types of heating systems, such as steam or hot water radiation systems, ground source heat pumps systems [5], have been applied to greenhouses for meeting the heating and cooling requirements.

As far as exergetic and exergoeconomic analyses of greenhouse based-EAHE systems are concerned, various assessments [i.e., 6–9] of a greenhouse installed in Solar Energy Institute, Ege University, Izmir, Turkey have been made. The analyses were based on different operational data obtained from the measurements since June 2009. The exergy efficiency values for the underground air tunnel on a product/fuel basis were determined to vary from 57.8% to 63.2% while the highest irreversibility occurred in an underground air tunnel unit [6]. An EAHE applied to the greenhouse heating system was also exergoeconomically investigated to provide useful insights into the relations between thermodynamics and economics for the system considered. The values for average COP and exergetic efficiency were reported to be 10.51% and 89.25%, respectively [7]. The exergetic efficiency of this EAHE system was evaluated in the cooling mode over a successive season of 3 years.

Abbreviations: COP, coefficient of performance; EAHE, earth-to-air (or earth-to-air) heat exchanger; ECBCS, energy conservation in buildings and community systems programme; IEA, international energy agency; LowEx, low exergy.

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Nomenclature

A	area (m^2)
C	specific heat (kJ/kg K)
COP	coefficient of performance
$\dot{E}$	energy rate (W)
$\dot{E}''$	energy rate per unit area or volume (W/m^2 or W/m^3)
$\dot{E}x$	exergy rate (W)
$\dot{E}x''$	exergy rate per unit area or volume (W/m^2 or W/m^3)
f	factor
F	factor
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (kW)
R	renewability ratio, thermal resistance (m^2 K/W), ratio
SI	sustainability index
T	temperature (°C or K)
V	volume (m^3)
$\dot{W}$	work rate or power (kW)

Greek letters

η	energy efficiency
ψ	exergy efficiency

Subscripts

air	air
aux	auxiliary energy requirement
b	boundary
c	construction type
dest	destroyed
dis	distribution system
en	energetic
ex	exergetic
elec	electricity
env	environment
flex	flexibility
Ge	generation
HS	heating system
h	heat
in	input, inlet
l	lighting
N	net
out	output, outlet
p	primary energy, constant pressure
pa	per area
pv	per volume
q	quality
R	renewability
rew	renewable
S	solar
s	source, system
sp	specific
sys	system
tot	total
usf	useful
V	ventilation
w	wind
0	reference (dead) state

Superscripts

over dot rate (quantity per unit time)

Mean cooling exergetic efficiency value was 24% for this period while maximum yearly mean exergetic efficiency was 29% in the cooling season of 2009. The maximum cooling capacity rate of the system was 15.09 kW, with a required pipe length of 3.11 m/kW of cooling capacity [8,9]. In another study conducted by the author [10], a solar assisted vertical ground-source heat pump greenhouse heating system was analyzed using low-exergy (the so-called LowEx) approach. The overall exergy efficiency values decreased from 3.33% to 0.83% at varying reference state temperatures of 0–15 °C.

The LowEx approach is one of these approaches, which may be successfully used in sustainable buildings design [11]. Its main objective is to constitute a sustainable built environment while future buildings should be planned to use sustainable energy sources for HVAC applications [12]. The author has [13] also comprehensively reviewed various studies on LowEx heating and cooling systems for sustainable buildings.

Based on the literature survey, it may be concluded that EAHE systems have been energetically, exergetically and exergoeconomically investigated by various investigators while there is only one study on LowEx applied to a ground source heat pump greenhouse system by the author [10]. No studies on modelling and evaluating the performance of EAHE systems from the power plant to the greenhouse envelope using LowEx approach have appeared in the open literature to the best of the author's knowledge. This provided the main motivation in doing the present contribution. In this context, the LowEx approach is applied to a winter greenhouse coupled to an EAHE based on some experimental values obtained from Ref. [9]. The performance assessment is made through energy and exergy efficiencies. The energetic and exergetic renewability ratios are also utilized here along with sustainability index.

2. System description of the illustrative example

Fig. 1 illustrates a schematic of the EAHE system for greenhouse heating. The greenhouse with a floor area of 11.5 m^2 was first utilized in some studies [i.e., 5,14]. An EAHE system was then connected to the greenhouse [6] and finally its floor area was extended to 18.4 m^2. An PV-system (consisting of a converter, PV cells of 0.9 kW and an inverter) was also added to the system to assist in meeting the electricity consumption of the fan. The analysis here included a system consisting of three main separate circuits, namely: (i) an EAHE (underground air tunnel), (ii) the fan (blower) circuit for greenhouse heating, and (iii) greenhouse. Table 1 lists the technical specification of the system and a summary of its main operational data over a period of four years from 2009 to 2012. The system was constructed and installed at the Solar Energy Institute, Ege University (latitude 38°24″ N and longitude 27°50″ E), Izmir, Turkey. The solar greenhouse was positioned towards the south along south–north axis.

Fig. 2 shows the energy flows in forms of primary and electricity for a greenhouse from primary energy transformation through the heat production system and a distribution system to a heating system, and from there, via the indoor air, across the greenhouse envelope to the surrounding air.

3. Analysis

In this study, the methodology and relations used are based on a pre-design analysis tool. This tool was produced during the ongoing work for the IEA-ECBCS Annex 37. Its main objectives were to better understand exergy flows in buildings and find possible energy utilization improvements in buildings [13,15,16]. The methodology has been developed for buildings, while the LowEx network [16],