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Energy and exergy analysis of a new flat-plate solar air heater having different obstacles on absorber plates

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ABSTRACT

This study experimentally investigates performance analysis of a new flat-plate solar air heater (SAH) with several obstacles (Type I, Type II, Type III) and without obstacles (Type IV). Experiments were performed for two air mass flow rates of 0.0074 and 0.0052 kg/s. The first and second laws of efficiencies were determined for SAHs and comparisons were made among them. The values of first law efficiency varied between 20% and 82%. The values of second law efficiency changed from 8.32% to 44.00%. The highest efficiency were determined for the SAH with Type II absorbent plate in flow channel duct for all operating conditions, whereas the lowest values were obtained for the SAH without obstacles (Type IV). The results showed that the efficiency of the solar air collectors depends significantly on the solar radiation, surface geometry of the collectors and extension of the air flow line. The largest irreversibility was occurring at the SAH without obstacles (Type IV) collector in which collector efficiency is smallest. At the end of this study, the energy and exergy relationships are delivered for different SAHs.

1. Introduction

Energy in various forms has played an increasingly important role in world wide economic progress and industrialization. In view of the world's depleting fossil fuel reserves, which provide the major source of energy, the development of non-conventional renewable energy sources has received an impetus. Sunlight available freely as a direct and perennial source of energy provides a non-polluting reservoir of fuel. The simplest and the most efficient way to utilize solar energy is to convert it into thermal energy for heating applications by using solar collectors. Solar air heaters, because of their inherent simplicity are cheap and most widely used collection devices. The main applications of SAHs are space heating; seasoning of timber, curing of industrial products, and these can also be effectively used for curing/drying of concrete/clay building components. The SAH occupies an important place among solar heating system because of minimal use of materials and cost [1,2].

Thermal performance of the solar air collectors depends on the material, shape, dimension and layout of the collector. Performance improvement can be achieved using diverse materials, various shapes and different dimensions and layouts. The modifications to improve the heat-transfer coefficient between the absorber plate and air include the use of an absorber with fins attached, corrugated absorber, matrix type absorber, with packed bed, with baffles and different configurations are given in the literature [3–16]. For high solar gains, an efficient thermal coupling between absorber and fluid is required, while the electrical power for the fan operation ought to be as small as possible. There are different factors affecting the SAH efficiency, e.g. collector length, collector depth, type of absorber plate, glass cover plate, wind speed, etc. Increasing the absorber area or fluid flow heat-transfer area will increase the heat transfer to the flowing air, on the other hand, will increase the pressure drop in the collector, thereby increasing the required power consumption to pump the air flow crossing the collector [14,17]. Performance improvement can be achieved using diversematerials, various shapes and different dimensions and layouts. The modifications to improve the heat-transfer coefficient between the absorber plate and air include the use of an absorber with fins attached, corrugated absorber, matrix type absorber, with packed bed, with baffles and different configurations are given in the literature [3–16].

Thermodynamic analysis is an effective means to obtain precise and valuable information about energy efficiency and losses due to irreversibility in a real situation [18]. The first law is widely used in engineering practice and is the basis of the heat balance method of analysis that is commonly used in engineering systems performance analysis. The second law involves the reversibility or irreversibility of processes and is a very important aspect of the exergy method of energy systems analysis [19]. The energy analysis has some deficiencies. Fundamentally, the energy concept is not sensitive to the assumed direction of the process, e.g. energy analysis does not object if heat is considered to be transferred

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Nomenclature

A_C	surface area of the collector (m^2)
C_P	specific heat of air at constant pressure (kJ/kg K)
$\dot{E}$	energy rate (kW)
$\dot{E}x$	exergy rate (kW)
Ex_D	dimensionless exergy loss (dimensionless)
$\dot{E}x_{dest}$	rate of irreversibility (kW)
h	enthalpy (kJ/kg)
I	solar radiation (W/m^2)
$I\dot{P}$	rate of improvement potential (kW)
$\dot{m}$	mass flow rate (kg/s)
M	mass (kg)
P	fluid pressure (Pa)
R	universal gas constant (J/kg K)
R	regression coefficients
$\dot{Q}_c$	useful heat rate (kW)
$\dot{Q}_s$	incident energy in the collector area (kW)
s	entropy (kJ/kg K)
$\dot{S}$	entropy generation rate (kW/kg K)
t	time (s, min)
T	temperature (°C)
U	heat loss coefficient (W/m^2 C)
$\dot{W}$	work rate or power (kW)
W	uncertainty in the measurement (%)

Greek letters

α	absorptivity (dimensionless)
η_I	thermal efficiency (dimensionless)
η_{II}	exergetic efficiency (dimensionless)
η_o	optical yield (dimensionless)
$\tau\alpha$	effective transmission (dimensionless)
ψ	specific exergy (kJ/kg)

Subscripts

a	air
ave	average
C	collector
c	convection
e	environment
f	fluid
in	inlet
m	mean
out	outlet
gen	generation
p	plate
r	radiation
s	sun

spontaneously in the direction of the increasing temperature. It also does not distinguish the quality of the energy, e.g., 1 W of heat equals 1 W of work or electricity. Energy analyses on their own incorrectly interpret some processes, e.g., environmental air, when isothermally compressed, maintains its energy (e.g. enthalpy) equal to zero, whereas the exergy of the compressed air is larger than zero. However, exergy data are more practical and realistic in comparison to the respective energy values. Thus, the exergy analysis provides a more realistic view of process, sometimes dramatically different in comparison to standard energy analyses [20,21]. Exergy analysis establishes the theoretical limits of ideal operations, very convenient to determine the best collector for a specific application [22].

Recently, several researchers have undertaken many studies covering the thermodynamic analysis of SAHs. Karsli [17] determined the first and second laws of efficiencies of four types of air heating flat-plate solar collectors. Altfeld et al. [23,24] performed an optimization analysis on the net flow of exergy in flat plate collectors for air heating. They found that the collection surface characteristics, especially those of the extended surface, diminished the air flow, thus increasing the net flow of exergy and the thermal efficiency of the device. Gupta and Kaushik [25] established the optimal performance parameters for the maximum exergy delivery during the collection of solar energy in a flat-plate SAH. They stated that based on the output energy evaluation, the SAH should have high aspect ratio, low duct depth, and low inlet temperature of air. They have observed and proved that if the inlet temperature of air is low, then maximum exergy output is achieved at low value of mass flow rate. Comaklı and Yuksel [26] presented the experimental results of four types of SAHs. Only the exergetic efficiencies of the collectors were calculated and comparisons were made among them on the basis of the exergetic efficiencies. Öztürk and Demirel [27] presented an experimental investigation of the thermal performance of a SAH having its flow channel packed with Raschig rings. They observed that the energy and exergy efficiencies of the packed-bed SAH increased as the outlet temperature of heat transfer fluid increased. Öztürk [28] described an experimental evaluation of energy and exergy efficiency of a seasonal latent heat storage system for greenhouse heating with the SAH. Kurtbas and Durmus [29] investigated five types of SAHs, which had different front absorption surfaces. They concluded that there was a reverse relationship between dimensionless exergy loss and heat transfer, as well as pressure loss. The more important parameters in order to decrease the exergy loss were found to be the collector efficiency, temperature difference of the air and the pressure loss. Torres-Reyes et al. [22] performed thermodynamic optimization based on first and second law to determine the optimal performance parameters and to design a solar thermal energy conversion system. They produced graphs of exergy flow rate as a function of mass flow rate for different collector configurations. Torres-Reyes et al. [30] established a generalized methodology to determine the optimum path flow length of the working fluid by means of a thermohydraulic model developed from the first and the second law points of view. Ajam et al. [31] derived the equations to study the exergetic efficiency of SAHs and used MATLAB to optimize the system. Layek et al. [32] presented the mathematical model for predicting the entropy generation of a SAH having chamfered rib – groove roughened absorber plate. They found that the entropy generation decreases with increase in relative roughness height. Esen [33] reported an experimental study to evaluate the energetic and exergetic efficiencies of four types of double-flow SAHs with several obstacles and without obstacles under a wide range of operating conditions. He showed that the use of obstacles in the air duct of the double flow collector is an efficient method of adapting air exchanger according to user needs.

This paper presents the performance analysis of a novel SAH. Four different absorbing plates have been used in this study. An experimental set-up, described in the next section, is constructed and tested. The analysis includes both the first law and second law of thermodynamics. The collector efficiencies were determined for four types of SAHs and comparisons were made among them. The method used by Esen [33] was employed to analysis the sample solar installation data. All sources of irreversibility were considered to minimize the irreversibility by optimizing the air flow rate.