Renewable Energy 74 (2015) 357–368

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Energy and exergy analysis of different solar air collector systems with natural convection

D. Bahrehmand [a, b], M. Ameri [a, b, *]

[a] Department of Mechanical Engineering, Faculty of Engineering, Shahid Bahonar University, Kerman, Iran
[b] Energy and Environmental Engineering Research Center, Shahid Bahonar University, Kerman, Iran

ARTICLE INFO

Article history:
Received 13 January 2014
Accepted 9 August 2014
Available online 1 September 2014

Keywords:
Solar air collector
Energy efficiency
Exergy efficiency
Natural convection
Fin

ABSTRACT

In this research work, mathematical models are presented for single and two-glass cover solar air collector systems with natural convection flow. These models are based on an analytical solution of energy balance equations for various elements of collectors. The results obtained from the present work and the experimental results of other researchers are in good agreement. The effects of a tin metal sheet suspended in the middle of the air channel, longitudinal fins with rectangular and triangular shapes, and depth and length variations of the channel on energy and exergy efficiencies of solar air collectors are also investigated. The results show that the collector with two-glass covers has a better performance than a single-glass collector, and it is analytically preferred by the first and second laws of thermodynamics. The results also illustrate that the collectors with triangular fins are more efficient in terms of energy than those with rectangular fins.

1. Introduction

Solar air collector systems are simple devices in which the energy from the sun (solar insulation) is captured by an absorbing plate and used to heat air. Solar air heating is a renewable energy heating technology employed to heat or condition air for buildings or process heat applications. Solar air heaters can also be used for industrial purposes. To minimize heat escape in solar air heaters, the plate is located between a glazing (glass pane or transparent material) and an insulating panel. The glazing is chosen so that a maximum amount of sunlight can pass through and reach the absorber. The thermal performance of flat plate solar air collectors is greatly dependent on the number of the transparent covers and plates of the collector. To increase the efficiency of solar air collectors, the heat transfer between the absorber plate and flowing air should be improved. One of the most common ways to increase the heat transfer in solar air collectors is increasing the heat transfer coefficient using the turbulence promoters in the form of artificial roughness on the absorber surface. The artificial roughness on the absorber plate also increases the pressure drop due to the increased friction. Therefore, the design of solar air collectors is executed with the objectives of high heat transfer rates and low friction losses.

With the importance of the use of renewable energy sources in mind, solar air heaters, as a type of flat plate solar collectors have been attractive ideas for ventilation and natural heating and cooling of buildings and have been investigated by many researchers theoretically and experimentally [1–4]. Zho et al. [5] proposed a computer model derived from basic laws governing thermal energy exchanges between surfaces for the transient simulation of flat plate collectors. Gupta et al. [6] studied the thermohydraulic performance of solar air heaters with roughened absorber plates. They, for a given duct roughness geometry, computed the proper efficiency for different conditions. They concluded that with flow-rate variation, the proper efficiency has a maximum value. Akhtar and Mullick [7] developed an improved equation for computing the glass cover temperature of the flat plate solar collectors with single glazing. In that work also, a semi-analytical correlation for the factor "*f*" (the ratio of inner to outer heat transfer coefficients) as a function of collector parameter and atmospheric variables has been obtained by a regression analysis. Hirunlabh et al. [8] discussed the performance of a construction element, the Roof Solar Collector (RSC), with regard to maximizing the rate of induced natural ventilation, which contributes to the improvement of indoor thermal comfort of houses. In their research, the effect of RSC parameters, mainly tilt angle and length, was analyzed numerically. A test set-up was developed for determining the internal convective heat

* Corresponding author. Department of Mechanical Engineering, Faculty of Engineering, Shahid Bahonar University, Kerman, Iran. Tel.: +98 3412111763; fax: +98 3412120964.
E-mail addresses: ameri_mm@uk.ac.ir, ameri_mm@yahoo.com (M. Ameri).

http://dx.doi.org/10.1016/j.renene.2014.08.028
0960-1481/

transfer coefficient and the induced air flow-rate of a roof solar collector by Khedari et al. [9]. The set-up was composed of an open-ended inclined rectangular channel. Data analyses were made to develop Nusselt and Reynolds number correlations as a function of Rayleigh number and aspect ratio (gap = length). Forson et al. [10] described a mathematical model of a single pass, double duct solar air heater. They showed that significant improvement in the single pass, double duct solar air heater performance can be obtained with an appropriate choice of the collector parameters and the top-to-bottom channel depth ratio of the two ducts. Two kinds of roof solar collectors (RSCs), namely the single pass RSC and the double pass RSC, were analyzed and compared by Zhai et al. [11]. In that study, they found that the instantaneous efficiency of solar heat collecting for the double pass RSC is higher than that of the single pass one by 10% on average, and natural ventilation air mass flow-rate contributed by natural ventilation for the double pass RSC can be improved to a great extent for most cases, indicating that double pass RSC is superior to the single pass one from the points of view of both space heating and natural ventilation. Zhai et al. [12] also carried out experimental studies on a solar air collector (SAC). In that experiment, the uniform heat flux along the air channel was affected by three electric heating plates, which act as solar radiation. In their research, they found that the temperature distribution of air and the induced natural air flow-rate are highly dependent on heat input, inclination angle, channel gap, etc. Natural convection heat transfer in a vertical flat-plate solar air heater of 2.5 m height and 1 m width, with one and two-glass covers was studied experimentally by Hatami and Bahadorinejad [13]. In that study, six cases of air flow (two for air heater with one glass cover and four for air heater with two-glass covers) were considered. These cases included states in which air could flow within the space between the absorber plate and glass covers or was enclosed in such space. The absorber plate temperature, back-plate temperature, glass cover temperatures, mass flow rates of air within channels, and the solar radiation were measured, and relations were suggested for Nusselt number for these cases. Farahat et al. [14] developed an exergetic optimization of flat plate solar collectors to determine the optimal performance and design parameters of these solar to-thermal energy conversion systems. They carried out a detailed energy and exergy analysis for evaluating the thermal and optical performance, exergy flows and losses, as well as exergetic efficiency for a typical flat plate solar collector under given operating conditions. Bassiouny and Korah [15] investigated the effect of chimney inclination angle on air change per hour and indoor flow pattern numerically and analytically. Their analytical result showed that an optimum air flow-rate value is achieved when the chimney inclination is between 45° and 70° for a latitude of 28.4°. In the design of solar air heaters, channel depth is a principal variable to be fixed. The effect of the channel depth on the energy gain of solar air heaters has been investigated by computational fluid dynamics (CFD) simulations by Sun et al. [16]. Their study showed that the heat transfer corresponding to the temperature distribution across the channel in solar air heaters varies greatly with the change of channel depth. An experimental investigation to evaluate different thermal characteristics of a natural convection flat-plate solar air heater with longitudinal rectangular fin array was carried out by Fakoor Pakdaman et al. [17]. Having determined the thermal performance of the system, they presented a Nusselt number correlation for such finned duct devices. Amori and Mohamed [18] investigated heat transfer process and fluid flow in a solar chimney used for natural ventilation numerically and experimentally. Their experimental results show that a solar chimney with side entrance gives better thermal performance.

In this work, mathematical models are presented for single and two-glass cover solar air collector systems with natural convection flow. The aim of this work is to investigate the effects of tin metal sheet suspended in the middle of the air channel, longitudinal fins with rectangular and triangular shapes, channel depth, channel length, solar radiation intensity, and ambient temperature on energy and exergy efficiencies. In other words, the performance of different solar air collector systems using the first and second laws of thermodynamics is investigated.

2. Mathematical modeling

In this study, different solar air collectors (single and two-glass cover systems) with free convection flow are investigated. The structures of the investigated smooth flat plate solar air collectors with and without tin metal sheet suspended in the middle of the air channel (TMS) are illustrated by the schematic diagram of Fig. 1. Fig. 2 shows the schematic diagram of single-glass solar air collectors with rectangular and triangular fins. In every shape, the distance between TMS and glass cover and the distance between the two glass covers are equal. To investigate the effects of each parameter on the performance of the system, other parameters are considered constants (for example, to investigate the effects of channel depth change on the solar air heater performance, this parameter is considered changeable and other parameters constants).

3. Formulation of the mathematical model

The equations governing the performance of the solar air collector systems are formulated using the energy balance equations of the solar air collector components making the following assumptions:

(1) The systems operate under steady state conditions.
(2) The air temperature changes only in the direction of the flow.
(3) The inlet air temperature is equal to the ambient temperature.
(4) Heat transfer through the glass covers, absorber plate, and insulation plate is 1-D and in the direction of perpendicular to the air flow.
(5) The lateral walls heat loss are neglected due to their small amount.
(6) The fins thickness is negligible compared to their length.

Fig. 3 shows the schematic diagram of the smooth solar air collector with TMS and single glazing. In this shape, different parts of the system and the heat transfer coefficients are shown.

To write the energy balance equations, a differential element with a length of dx, a width of dz, and a distance of x from inlet is considered. For the studied systems, the energy balance equations are written as below:

3.1. Single-glass cover system with TMS and without fin

For the single-glass cover system with TMS and without fin, the energy balance equations for various components in natural convection mode are given below:

Glass cover

$$\alpha_g I W dx + (h_{r,g-p} + h'_c)(T_p - T_g) W dx = (h_w + h_{r,g-a})(T_g - T_a) W dx \quad (1)$$

Absorber plate