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Single and double pass solar air heaters with partially perforated cover and packed mesh

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ABSTRACT

In this study, the thermal performance of the single and double pass solar air heaters with normal glazing and with quarter perforated cover was investigated experimentally. The solar air collector was tested with two different perforated covers in which the holes made on one cover had the center-to-center distance of 20*D* (6 cm) and on the other cover it was 10*D* (3 cm), where *D* (0.3 cm) was the hole diameter. The air mass flow rate was varied between 0.011 kg/s and 0.037 kg/s. The efficiency of the double pass was always greater than the single pass air heater by 5–22.7% for the same air mass flow rate. At mass flow rate of 0.037 kg/s, the average efficiency of single and double pass air heaters with normal glazing were 49.98% and 53.67%, respectively. It was found that, the efficiency of the air heater with 10*D* perforated cover is slightly higher than the one with 20*D* perforated cover for both single and counter flow collectors. The average efficiency of single and double pass solar air heaters with 10*D* perforated cover were 46.40% and 54.76%, respectively, at mass flow rate of 0.032 kg/s while at the same mass flow rate, the average efficiency of single and double pass air heaters with normal glazing were 49.36% and 51.70%, respectively.

1. Introduction

Among all different renewable energy resources, solar energy is one of the valuable heat sources with variety of applications such as space heating and cooling, industrial process heating and electricity generation. The solar air heater can be used in water desalination process especially in the places with hot climate and lack of potable water also; it can be used for drying applications (i.e. drying of fruits and vegetables).

Solar air collectors are simple devices that utilize solar energy to heat air. Panel, air duct and a glass cover are the main parts of a typical solar air heater. The active solar system has an air blower as well. The wooden or metallic air duct consists of an absorber plate. The thermal insulation covers the sides and bottom of the duct.

The efficiency of the solar air heater is affected by the length and bed height of collector, the type of the absorber plate, glass cover, wind speed and many other parameters. Among these factors, the cover and the absorber plate are the most effective ones in the design of solar collectors [1]. It is obvious that the major heat losses from a normal solar air collector are through the top cover which reduce the thermal efficiency of the system also, the low heat transfer coefficient between the air stream and the absorber plate is another reason of low thermal efficiency in solar air heaters. Different adjustments on the absorber part of the air heater were done by researchers to increase the thermal efficiency of the solar systems. Using fins between the wire mesh (as an absorber plate) to increase the path of the air flow inside the channel [2], adding porous material inside the collector [3], making a cross-corrugated absorber plate [4], and using counter flow solar air heater [5–8] are few examples of these modifications. Also the performance of air heaters with fin or v-corrugated absorber plates [9,10], with fins and baffles attached over the absorber plate [11] and absorber plates coated with various selective coating materials [12] were investigated experimentally or theoretically.

The performance of the single and double pass solar collectors with fins and wire mesh layers were investigated experimentally by Omojaro and Aldabbagh in 2010 [1]. They used seven steel wire mesh layers and the range of the air mass flow rate was between 0.012 kg/s and 0.038 kg/s. The distance between the glass and the bottom of the collector used in their study, was 7 cm. According to their study, the maximum efficiency for the single and double pass solar air heaters were 59.62% and 63.74%, respectively for mass flow

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rate ($\dot{m}$) of 0.038 kg/s. A novel solar air collector of pin-fin integrated absorber was designed by Donggen et al. [13] to achieve high thermal efficiency and reduce heat losses from the cover. In their design the gap between the glazing and the absorber plate was 5 cm. According to their experimental results, the average thermal efficiency of pin-fin arrays collector reaches 50–74% compared to the solar transmittance of 83% for the glazing, with the air volume flow rate of 19 m^3/h. The investigations on a packed bed solar air heater having its duct packed with blackened wire screen matrices of different geometrical parameters, wire diameter and pitch, were performed by Mittal and Varshney [14]. They indicated that the effective efficiency of packed bed solar air heater was relatively higher compared with flat plate collectors, even though the pressure drop across the packed bed duct increased significantly. A single-glazed solar matrix air collector was tested by Kolb et al. [15]. Their collector consists of two parallel sheets of black galvanized industrial woven, fine-meshed wire screens made of copper. Their results show that at the duct height of 4 cm and mass flow rate of 0.04 kg/s, the thermal efficiency of the solar air heater was around 70%. Ho-Ming Yeh et al. [16] have designed a solar air heater in which the absorber plate was constructed with fins on it and the baffles were attached to the fins to create turbulence and extend the heat transfer area. In their work, the distance between the glass and the absorber plate in the lower channel was 5.5 cm and it was indicated that the efficiency of baffled solar air heaters was greater than that of flat plate air heaters without fins and baffles. The thermal performance of cross-corrugated solar air collector was studied by Wenxian et al. [4]. The cross-corrugated collector consists of a wavelike absorbing plate and a wavelike bottom plate, which are crosswise positioned to form the air flow channel. In their study, the mass flow rate ($\dot{m}$) changes in the range of 0.001–0.25 kg/m^2 s. Their results show that the efficiency of collectors increases monotonically and dramatically with $\dot{m}$, therefore, to achieve a better thermal performance of the solar air collectors it is essential to maintain a higher air mass flow rate. Several configurations of copper screen meshes were investigated experimentally by Tian et al. [3]. They found that porosity and surface area are two key parameters controlling heat transfer.

Some researchers [17,18] suggested using double glazing on the solar collectors in order to minimize the heat losses through the top cover to improve the thermal efficiency. In other studies [5–8] the absorber plate was inserted into the panel to make a double pass channel where the air flows from above and then below the absorber plate. The same method was used by Yeh et al. [19], Ozgen et al. [20] and Esen [21], with this difference that, in their work the air was passing from above and below the absorber plate at the same time. A counter flow solar air heater was analyzed for cold climate by Qenawy and Mohammad [22]. Moreover, a double pass solar air heater with and without porous media in the lower channel was studied by Mohammad [23]. It was indicated that the efficiency of the mentioned solar air heater with porous media exceeded 75%.

An unglazed solar air pre-heater consisting of perforated corrugated siding was examined by Sebastien and Suzelle [24] and it was found that the efficiency of the unglazed solar air heater depends on the wind velocity, as the efficiency was found to be 65% for wind velocities under 2 m/s and dropped below 25% for wind velocities exceeding 7 m/s. Experimental study on the perforated baffles with various open area ratio in a rectangular duct, a system similar to a solar air heater, was shown that the baffles with 46.8% open area ratio give the best performance [25].

To best of our knowledge, no experimental investigation has been reported for the performance analysis of the single and double pass solar air collector with the perforated cover and porous media and with the duct height of 3 cm. The aim of this study is to investigate experimentally the performance of the single and double pass (counter flow) solar air heaters with porous media. There is no absorber plate in the proposed solar air heater. The steel wire mesh layers in the lower channel are acting as an absorber plate. The height of duct is fixed at 3 cm. The porous media are arranged in a way to give high porosity (around 0.83) and low pressure drop across the collector.

Another purpose of this study is to investigate experimentally the efficiency of the solar air heater with partially perforated cover. The collector was not examined with a fully perforated cover as it was believed that, the ambient air with lower temperature compared with the air streams coming from the top side of collector, enters to the collector through the holes at the bottom side of cover (close to outlet), and mixes with the air inside the collector and reduces the temperature of the outlet air and the thermal efficiency of collector. The air which enters to the collector through the holes close to outlet does not have enough time to get heat from the mesh layers; therefore it reduces the temperature of the outlet air. The solar air heater is tested with various quarter perforated covers which were made of plexiglas and had various distances between the hole centers.

2. Experimental set up and equipment

The experimental work on the single and double pass solar air heater was conducted at a geographic location of Cyprus in the city of Famagusta. The schematic view of the constructed solar air collector is shown in Fig. 1. The collector length and width were 150 cm and 100 cm, respectively. Normal window glass of 0.4 cm thickness was used as glazing. The distance between the second glass cover and the bottom of the collector, duct height, was 3 cm. The distance between the second glass and the first glass was 2 cm. The collector becomes a single pass air heater by removing the first glass. The frame of the solar collector was made from plywood of 1.8 cm in thickness and the whole frame was painted with black. To minimize the heat losses, the sides and bottom of the frame were insulated with 3 cm thick Styrofoam.

Fourteen steel wire mesh layers were fixed inside the collector's duct parallel to the glazing. The diameter of the wires and cross section openings of the meshes were 0.025 cm and 0.2 cm $\times$ 0.2 cm, respectively. The wire meshes used in this collector were similar to the ones which were used by Refs. [1,2–26].

The arrangement of the wire mesh layers is as follows: 6 wire mesh layers were attached to each other as one matrix and placed at the bottom of the collector, 5 more layers were attached with each other and placed at the middle and the last 3 meshes were connected to each other and located on top of the other layers.

The distance between the three sets of wire meshes were fixed to be 0.5 cm. Moreover, 0.5 cm spacing was left between the second glazing and the upper layers. In order to increase the absorptivity of the mesh layers, they were painted with black color with absorptivity of 0.96 and emissivity of 0.87. The absorber plate was omitted since the wire mesh layers were acting as an absorber plate and as a result the cost of the solar air heater was reduced significantly because the wire mesh was much cheaper compared with sheet metal absorber plate and was readily available in the market. In addition, the new arrangement of the wire mesh layers in the collector that gives high porosity, $\Phi = 0.83$, reduces the pressure drop through the collector.

In the second part of this work the concentration was on the cover, as it was known that the major heat loss from flat plate collectors is through the cover. Therefore, quarter of cover area was perforated to minimize the heat losses through the cover and to cool it. In this case the ambient air will have two functions, to cool the cover while penetrating through it as well as supplying air to