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Thermal performance analysis of semicircular and triangular cross-sectioned duct solar air heaters under external recycle

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ABSTRACT

The present work is focused on the analytical and numerical investigations related to thermal and thermo-hydraulic efficiencies of a solar air heater (SAH) with semicircular (Model-I) and triangular (Model-II) cross-sectioned ducts. V-down rib roughness is considered on the bottom side of the absorber plate under the external recycle operation and effect on the thermal performance is analyzed using the analytical investigation. It is observed that the employment of recycle operation substantially improves the thermal performance of these two SAH models as compared to the single-pass operation (without recycle). The external recycle of the air exiting from the SAH outlet increases the heat extraction rate and strengthen the heat transfer coefficient for the air flowing through the roughened SAH duct and further increases the thermal performance. Moreover, SAH models are operated for different hydraulic diameters. Whereas, the best results of thermal performance are obtained at the least value of the hydraulic diameter. It is predicted from the analytical investigation that the Model-I of the semicircular duct with recycle is 3% and 17% efficient in thermal efficiency as compared to Model-II of the triangular duct with and without recycle, respectively, at a hydraulic diameter of 0.06 m. While, the maximum value of the thermal and thermohydraulic efficiencies obtained for Model-I with recycle operation is found to be 75% and 72%, respectively. Although, the numerical investigation is carried out using Ansys-Fluent software to clearly present the associated air heating and pressure drop reduction abilities of both the solar air heater ducts.

1. Introduction

In practice, it is important to use heat exchangers of high heat transfer area in many thermal applications. In this study, a comparison of the semi-circular and triangular duct heat exchangers is made to analyze their compactness as well as effectiveness compared with the heat exchanger of the rectangular duct. As the thermal performance of solar air heaters (SAHs) is low, therefore, it is necessary to increase more heat transfer area using some techniques on the available collector area and the residential time of air. One of the effective techniques is to use artificial roughness on the absorber plate to increase the heat transfer area. Artificial roughness can be provided by protrusions, machining, fixing ribs and dimples, etc. [1–5]. Whereas, ribs as a roughness element on the absorber plate break the laminar sublayer, creates turbulence in the flow and increase the thermal performance of the SAH.

Several investigations are carried out to investigate the effect of providing artificial roughness in compact heat exchangers on the heat transfer and the fluid flow characteristics [6–12]. Leung et al. [13] studied the effect of corner geometry and surface roughness on heat transfer inside the horizontal isosceles duct with sharp corners experimentally. Five different apex angles and three roughness surfaces were considered. The horizontal duct with apex angle of 60° is obtained suitable for high thermal performance. Pimsarn et al. [14] considered the Z shaped rib roughness to increase the heat transfer in a rectangular duct. The ribs were set at 30°, 45° and 60° relative to the direction of flow. The maximum thermal performance was reported at 45° Z shaped ribs. Luo et al. [15] considered a fully developed turbulent air flow in horizontal equilateral triangular duct with internally ribbed surfaces and experimentally investigated the forced convection. The maximum average Nusselt number is reported at a rib size of 7.9 mm. However, increase in the pressure drop is observed linearly with increasing rib size due to increasing fluid friction. A roughened SAH is experimentally studied by Gupta et al. [16] and results present the effect of relative roughness height (e/D), Reynolds number and inclination of ribs in the flow direction on the effective efficiency.

However, another technique that can increase the thermal performance of SAHs is to increase the residential time of air in SAH ducts

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Nomenclature

A_p	surface area of absorber plate (m^2)
C	conversion factor
C_P	specific heat of air (J/kg K)
DH	hydraulic diameter (m)
d	gap position from the upstream side of the rib (m)
e	rib height (m)
e/DH	relative roughness height
F_r	collector heat removal factor
F'	plate efficiency factor
F	friction factor for roughened duct
G	gap width for rib (m)
H	height of duct (m)
h	convective heat transfer coefficient (W/m^2-K)
h_w	convective heat transfer coefficient due to wind (W/m^2-K)
I	Intensity of solar radiations (W/m^2)
K	thermal conductivity (W/m-K)
K_a	Thermal conductivity of air (W/m-K)
L	length of test section in the duct (m)
L_g	thickness of glass cover (m)
$\dot{m}$.	mass flow rate of air (kg/s)
Nu	Nusselt number
P	rib pitch (m)
P/e	relative roughness pitch
ΔP_d	pressure drop across duct, N/m^2
P_m	pumping power, W
Q_u	useful heat gain, W
Re	Reynolds number
t_e	thickness of edge (m)
t_i	thickness of edge insulation (m)
T_a	ambient temperature (K)
T_o	air outlet temperature (K)
$T_{f,i}^{o}$	mixing temperature (K)
$T_{f,0}$	outlet temperature (K)
$T_{f,i}$	inlet temperature (K)
T_i	air inlet temperature (K)
T_{sun}	sun temperature (K)
T_p	temperature of absorber plate (K)
T_{pm}	mean temperature of absorber plate (K)
T_f	average temperature of air (K)
ΔT	air temperature rise across the duct, °C
ΔT/I	temperature rise parameter, K. m^2/W
U_L	overall heat loss coefficient, W/m^2K
U_T	top loss coefficient, W/m^2K
U_B	bottom loss coefficient, W/m^2K
U_E	edge side loss coefficient, W/m^2K
V	mean flow velocity in the duct (m/s)
W	width of the duct (m)
W/H	aspect ratio (duct)

Greek Symbols

α	flow angle of attack (°)
δ_i	thickness of insulation, m
ε_p	emissivity of the absorber plate
ε_g	emissivity of the glass cover
η_c	Carnot efficiency
η_{th}	thermal efficiency of the solar air heater
τα	transmissivity-absorptivity product of glass cover

that can be achieved by employing the recycle of exiting air (recycle operation) [17,18]. Recently reported designs of SAHs under recycle operation present the significant improvement in the thermal performance. The use of wire mesh as a porous packed bed material [19–23], fins [24,25] and fins plus baffles [26,27] under recycle operations are some of them. Moreover, theoretical investigations [28,18–29] utilizing internal and external recycle operations exploring the geometrical aspects of SAHs reported the increased fluid velocity employing recycle operation corresponding to a fixed mass flow rate. Moreover, results present the substantial improvement in the thermal performance of SAHs. However, such solar air heaters are frequently used in many thermal applications such as space heating and drying agricultural products [17,18–29].

A detailed literature review in the proposed research area revealed the scarcity of the reported research on thermal performance investigation of SAHs consist of semicircular and triangular ducts under the external recycle operation. However, the present theoretical study is carried out in two ways, i.e., analytical and numerical (CFD). The analytical investigation aimed to: (1) investigate the thermal performance of these two different models of artificially rib roughened SAH under external recycle, (2) develop mathematical models that make use of an iterative solution procedure capable of predicting the thermal performance of both SAH models with respect to different input parameters and (3) study the effect of recycle ratio, hydraulic diameter, and the temperature rise parameter on the thermal and thermohydraulic efficiencies in order to get their optimum value for these air heating devices. While the numerical investigation is aimed to explore the physics to give the clarity about the heating and pressure drop reduction abilities associated with both semicircular and triangular cross-sectioned ducts in comparison with the conventional rectangular cross-sectioned duct.

2. Mathematical formulation

Schematic diagrams of proposed SAH models employing recycle operation are presented in Fig. 1. The designed SAH models consist of the single glass cover and an absorber plate. Artificial rib roughness is considered on the lower side of the absorber plate. The flow of air is considered between the absorber plate and well-insulated duct surfaces. In case of recycle, before entering the SAH, the inlet air mixes with the air exiting from the outlet. A centrifugal blower situated at the end of the roughened SAH duct regulates the flow rate of the exiting air and recycle the exiting air through an external passage to the inlet, while another blower situated at the inlet of the roughened SAH duct provides the inlet mass flow rate [20,21]. It is assumed that the thermal behavior of conventional flat plate SAH is similar to roughened SAH. The method for calculating absorbed irradiation and heat losses for the conventional flat-plate SAH, following assumptions are made; (a) Steady-state conditions (b) Negligible heat conduction in the flow direction (c) Minor edge effects (d) no air is flowing between the absorber plate and the glass cover. Fig. 2 presents the energy balance of both the semicircular and rectangular duct SAHs. However, details of the roughness geometry considered for the present theoretical investigation is shown in Fig. 3 [30].

The experimentally developed correlations for the Nusselt number and the friction factor for V-shaped roughened duct reported in [30] are used in the present study. The results for the optimum design of SAHs is required to present in terms of two design parameters, the, i.e., temperature rise parameter (ΔT/I) and recycle ratio (G). The overall heat loss coefficient involves the heat loss from the top (U_T) and the back (U_B) plates. The thermal and thermohydraulic efficiencies have been determined by the procedure given below:

Step 1: First select the solar air heater and operating parameters (Table 1).