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Analytical investigation of solar air heater with jet impingement using energy and exergy analysis

M.M. Matheswaran[a,*], T.V. Arjunan[b], D. Somasundaram[a]

[a] Department of Mechanical Engineering, Jansons Institute of Technology, Coimbatore, Tamil Nadu 641659, India
[b] Department of Mechanical Engineering, Coimbatore Institute of Engineering and Technology, Coimbatore, Tamil Nadu 641109, India

A R T I C L E I N F O

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A B S T R A C T

In this present work an exergy efficiency of the single pass double duct jet plate solar air heater (SPDDJPSAH) is analytically investigated. The analysis is carried out for different mass flow rate m = 0.002–0.023 kg/s, stream wise pitch ratio X/D_h = 0.435–1.739, span wise pitch ratio Y/D_h = 0.435–0.869 and jet diameter ratio D_j/D_h = 0.043–0.109. The overall performance of solar air heaters is effectively evaluated by the exergy analysis by considering both the useful energy gain and subsequent pumping power requirement. Results show that SPDDJPSAH has been enhancing the effective efficiency by 21.2% and exergy efficiency by 22.4% when compared with Single Pass Single Duct Jet Plate Solar Air Heater (SPSDJPSAH). The effects of mass flow rate and jet plate design parameters on the exergy efficiency have been presented. The optimized values of stream wise pitch ratio X/D_h = 1.739, span wise pitch ratio Y/D_h = 0.869 and jet diameter ratio D_j/D_h = 0.065 are identified at the mass flow rate of 0.0035 kg/s and yields the maximum exergy efficiency of 4.36%. Design plots are also prepared in order to identify the optimum values of jet plate design parameters to achieve the desired temperature rise. Using the analytical results, the correlations have been developed for predicting the exergy efficiency in terms of Reynolds number and jet plate design variables.

1. Introduction

Flat plate solar air heaters (SAHs) are commonly used as heat exchangers that converts solar energy into heat which are widely used for low grade energy applications that requires temperature in the range of 60–100 °C like space heating, dehydrating of agriculture products and timbers etc. But the thermal performance of the SAHs is poor due to low density, small heat capacity and poor thermal conductivity of the air. To improve the performance of SAHs, a Single Pass Double Duct Solar Air Heater (SPDDSAH) configuration was adopted in which air is flowing on the both sides of the absorber plate (Pawar et al., 1994; Forson et al., 2003). Further the investigators focused on adding the artificial roughness on the absorber plate to improve the heat transfer coefficient between absorber plate and flowing air by breaking the viscous sub layer. Sahu and Prasad (2017) analytically evaluated that arc shaped wire roughed air heater have better thermal efficiency improvement factor when compared with other roughness geometries. In recent studies researchers identified that jet impingement technique in solar air heater was effective method to improve its performance.

Choudhury and Garg (1991) analytically investigated the Single Pass Single Duct Jet Plate Solar Air Heater (SPSDJPSAH) and revealed that the maximum thermal efficiency enhancement occurred at non cross flow conditions is up to 26.5% when compared with conventional parallel plate solar air heater. Belusko et al. (2008) presented the analytical and experimental results on thermal performance of unglazed jet plate solar air heater. Results show that increasing the jet spacing improves the flow distribution and progresses the thermal efficiency up to 21%. Chauhan and Thakur (2013) developed the correlation for calculating the Nusselt number and friction factor for inline jet plate solar air heater as a function of Reynolds number, stream wise, and span wise and jet diameter ratios. They also concluded that improvement in heat transfer rate by 2.6 times and friction factor by 3.5 times when associated with conventional design. Using the above correlations they theoretically evaluated the maximum thermo hydraulic performance and developed the design plots for obtaining the optimum jet plate parameters. They also used performance selection index approach for identifying the optimum design configuration of stream pitch ratio, span pitch ratio and jet diameter ratio of 0.435, 0.865 and 0.065 respectively. But they refined optimum values using Taguchi method as 1.304, 1.304 and 0.065 and the contribution of these parameters on thermo hydraulic performance was about 9.5%, 41.6% and 48.8% respectively (Chauhan and Thakur, 2014, 2016, 2017).

* Corresponding author.
E-mail addresses: madhume01@gmail.com (M.M. Matheswaran), arjun_niv@yahoo.com (T.V. Arjunan), soms.iitm@gmail.com (D. Somasundaram).

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Nomenclature

A	area of absorber plate (m^2)
A_e	effective heat transfer area of jet plate (m^2)
C_p	specific heat of air (J/kg K)
D_h	hydraulic diameter of air flow path (m)
D_j	jet hole diameter (m)
e/D_h	rib height-to-duct hydraulic diameter ratio
f	friction factor of duct
g	acceleration due to gravity (m^2/s)
h_c	convective heat transfer co efficient (W/m^2 K)
h_c	convective heat transfer coefficient due to
h_r	radiative heat transfer co efficient (W/m^2 K)
h_w	wind (W/m^2 K)
k	thermal conductivity (W/m K)
L	length of the duct (m)
$\dot{m}$	mass flow rate of air (kg/s)
N	total number of holes
Nu	Nusselt number
P	pitch distance (m)
P_m	pumping power (W)
Q_u	useful heat gain (W)
Re	Reynolds number
I	intensity of solar radiation (W/m^2)
S_1 to S_{14}	factors used in matrices
T	temperature (K)
U_b	bottom loss coefficient (W/m^2 K)
V_w	wind velocity (m/s)
W	width of the collector
X	stream wise pitch (m)
Y	span wise pitch (m)
Z	height of the duct (m)
ε	Emissivity
α	absorptivity
τ	transmissivity of glass cover
μ	viscosity (kg/m s)
ρ	density (kg/m^3)
σ	Stefan's Boltzmann constant (W/m^2 K^4)
η_I	thermal efficiency (%)
η_{eff}	effective (or) thermo hydraulic Efficiency
η_{II}	exergy efficiency
Φ	tilt angle (°)
ΔP	pressure drop (N/m^2)

Subscripts

1	flow path under jet plate
2	flow path above jet plate
3	flow path above absorber plate
a	air inside the flow path
am	ambient air
bp	back plate
c	glass cover
i	inlet
in	insulation
j	jet plate
o	outlet
p	absorber plate
s	sky

Zukowski (2013, 2015) experimentally studied the slot jet air heater and concluded that Nusselt number progresses with rising the Reynolds number, nozzle width and deteriorates with increasing spacing between nozzle and plate. Results also show that energy conversion efficiency is up to 90% at laboratory testing conditions.

Brideau and Collins (2014) developed the analytical model to evaluate the performance of jet impingement PV/T solar collector and validated the model by comparing with experimental results. Rajaseenivasan et al. (2017) experimentally concluded that the maximum thermal performance of 55.8% was attained at the angle of attack of 30°, nozzle diameter of 5 mm and the mass flow rate of 0.016 kg/s for impinging jet solar air heater. Nayak and Singh (2016) experimentally reported that when channel spacing ratio increases, there is a significant improvement in thermal performance of staggered jet plate solar air heater with cross flow conditions. Soni and Singh (2017) experimentally analysed the SPSDJPSAH with cross flow condition and reported that the negative impact of stagnant layer formulation on the thermal performance when the jet diameter ratio is greater than 0.07.

The exergy analysis is an effective tool for evaluating the overall performance optimization when compared with first law analysis. Singh et al. (2012), Yadav and Kaushal (2014) and Sahu and Prasad (2016) analytically evaluated the exergy efficiency of the system and optimized the absorber plate roughness geometry.

Based on the above cited literature it is observed that substantial analytical and experimental analyses on thermal performance improvement of SPDDSAH, artificially roughed SAHs and SPSDJPSAH were individually carried out. The results were reported in the form of first law, thermo hydraulic efficiencies and exergy efficiency. However a comprehensive theoretical investigation to find the loss based exergy performance including the optimization of jet plate design parameters for the combined design configuration of SPDDSAH with arc shaped wire attached on the top of the absorber plate with jet impingement air flow on the bottom has not been investigated. Proposed design configuration is named as Single Pass Double Duct Jet Plate Solar Air Heater (SPDDJPSAH). Main objective of present work is to study the loss based exergy performance of SPDDJPSAH by developing a detailed mathematical model. Effect of mass flow rate, stream wise pitch ratio, span wise ratio and jet diameter ratio on the exergy efficiency will be investigated. The effect of design parameters on the exergetic efficiency and their optimum values are presented in the form of design plots. Further a correlation is developed based on the jet plate design parameters and Reynolds number for predicting the exergy efficiency. Theoretical study of SPSDJPSAH is also carried out and its results are validated with experimental results available in the literature. A detailed comparison study with SPDDJPSAH is also carried out under identical conditions.

1.1. Description of the solar air heaters

The cross sectional view of SPDDJP and SPSDJP solar air heaters is shown in Fig. 1a and b. Air heaters consist of a glass cover, absorber plate, jet plate and back plate with insulation. In SPDDJP solar air heater, there are two air flow channels which are introduced at upper and lower sides of the absorber plate and in SPSDJP solar air heater, an air flow channel is introduced at the bottom of the absorber plate. As seen from Fig. 1a, air stream is supplied into the air heater by two equal parts and it flows simultaneously on both the sides of the absorber plate to absorb the heat. While the air passes through the lower duct, it is conceded through the jet plate and makes a jet impingement on the bottom of the absorber plate. Then the two hot streams of air are mixed together in a plenum. In SPSDSPSAH, the flow of air passes through the lower duct and induces convection heat transfer by jet impingement. Fig. 1c depicts the upper side of the absorber plate in which arc shaped wires are attached. These wires act as an artificial roughness and break the formulation of the laminar sub layer. A jet plate is attached at the lower channel of the air duct which is illustrated in the Fig. 1d.