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Exergy based performance evaluation of solar air heater with arc-shaped wire roughened absorber plate

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ABSTRACT

Exergy efficiency analysis is an useful method to evaluate overall performance of solar thermal systems as it takes into consideration of useful energy output and consequent pumping power requirement. In present work, an investigation on exergetic performance evaluation of solar air heater with arc-shaped wire rib roughened absorber plates has been made analytically by employing mathematical model and the results have been compared with a plane absorber plate solar air heater for similar operating conditions. The exergetic efficiency curves as a function of Reynolds number (Re) and temperature rise parameter ($\Delta T/I$) for different roughness parameters have been plotted. The maximum enhancement in exergetic efficiency of roughened solar air heater as compared to smooth absorber plate solar air heater has been found as 56% corresponding to relative roughness height (e/D) = 0.0422. The design plots, exhibiting the optimum combination of roughness parameters, can be used to design arc shaped wire rib roughened solar air heater.

1. Introduction

Solar energy is the most promising source of energy that can be employed in solar thermal energy utilization systems. A solar air heater is a simple device in which the air to be heated is passed through a rectangular cross-section duct below a metallic absorber plate with its sun-facing side blackened to facilitate absorption of solar radiation incident on it. This heated air is to be utilized for many applications such as space heating, drying for industrial and agricultural purposes [1]. Transparent covers are placed over the absorber plate to reduce the thermal losses from the heated absorber plate. The conventional solar air heater has the inherent disadvantage of its low thermal efficiency due to low heat transfer capability between absorber plate and fluid (air) flowing in the duct. To achieve improvement in collector thermal efficiency, several methods like use of ribs, an extended heat transfer surface area, porous media, corrugated plate surfaces, and artificial roughness on air flow side of the air heater duct have been adopted. They create turbulence in the flow that results in increase in fluid mixing and interrupt the development of thermal boundary layer which attributed to enhancement in heat transfer.

A number of experimental and theoretical investigations have been carried out by the researchers by employing artificial roughness geometries on the absorber plate of solar air heater duct. The artificial roughness were attached on single, double or three sided wall of the duct (absorber plate). Varun et al. [2] carried out experimental investigations, using the combination of inclined and transverse wire ribs on the principal wall i.e. on the absorber plate of the solar air heater. Kumar et al. [3] investigated the effect of gap in the multiple V-ribs by the experimental investigations and found 6.74 times enhancement in Nusselt number and 6.37 times enhancement in friction factor over the smooth plate solar air heater. Prasad et al. [4] analytically investigated the effect of transverse circular wire ribs as artificial roughness by employing it on the three-sides of the solar air heater duct, and found it better than the one sided transverse ribs. Gupta et al. [5] found that inclined continious ribs as roughness elements delivered higher thermal performance as compared to transverse and smooth plate solar air heater duct, they also evaluated the thermohydraulic (effective) efficiency criteria analytically. Effective and thermal efficiency factor of discrete V-down roughness ribs was investigated by Singh et al. [6] by employing mathematical model. Mittal et al. [7] studied numerically the effective efficiency of five different roughness geometries and compared with the conventional solar air heater. The second law based analysis and entropy generation number of chamfered rib-groove rib roughened absorber plate

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Nomenclature

A_C	surface area of absorber plate,m^2
C_p	specific heat of air, J/kg K
D	equivalent or hydraulic diameter of duct, m
e	rib height, m
E_n	net energy flow, W
E_S	exergy inflow, W
F_P	collector efficiency factor
G	mass velocity of air, kg/s m^2
h	heat transfer coefficient, W/m^2 K
h_w	convective heat transfer coefficient due to wind, W/m^2 K
H	depth of duct, m
I	intensity of solar radiation, W/m^2
K	thermal conductivity of air, W/m K
K_g	thermal conductivity of glass cover, W/m K
K_i	thermal conductivity of insulation, W/m K
L	length of duct, m
L_1	spacing between covers, m
L_g	thickness of glass cover, m
L_e	thickness of collector edge, m
M	number of glass cover
m	mass flow rate, kg/s
ΔP	pressure drop across the duct, Pa
ΔT	(T_o-T_i), air temperature rise across the duct, °C
ΔT/I	temperature rise parameter, °C m^2/W
T_g	temperature of glass cover, K
T_o	outlet air temperature, K
T_s	sky temperature, K
P	roughness pitch, m
P_m	pumping power, W
Qu	useful heat gain, W
T_i	fluid inlet temperature, K
T_a	ambient temperature, K
T_p	mean plate temperature, K
T_{am}	mean air temperature, K
T_f	bulk mean temperature of air in duct, K
T_{sun}	sun temperature, K
U_L	overall heat loss coefficient, W/m^2 K
U_t	top loss coefficient, W/m^2 K
U_b	bottom loss coefficient, W/m^2 K
U_s	side loss coefficient, W/m^2 K
V	velocity of air in the duct, m/s
V_w	wind velocity, m/s
W	width of duct, m

Dimensionless parameters

e/D	relative roughness height
e^+	roughness Reynolds number
f	friction factor for rough surface
f_s	friction factor for smooth surface
F_R	collector heat-removal factor
α/90	relative angle of attack
Nu_s	Nusselt number for smooth duct
Nu	Nusselt number for rough duct
W/H	duct aspect ratio
P/e	relative roughness pitch
Re	Reynolds number

Greek symbols

μ	dynamic viscosity of air, N s/m^2
$(\tau\alpha)_e$	effective transmittance-absorptance product
ρ_a	density of air, kg/m^3
α	angle of attack, degree
σ	Stefan-Boltzman's constant, W /m^2 K^4
δ_i	thickness of insulation, m
ε_p	emissivity of absorber plate
ε_g	emissivity of glass cover
β	tilt angle of collector surface, degree
η_C	Carnot efficiency
η_{th}	thermal efficiency
η_{eff}	effective efficiency
η_{EX}	exergetic or exergy efficiency
η_{II}	exergetic or exergy efficiency

solar air heaters has been reported by Layek et al. [8].

The studies [2–5] reveals that the dimensionless roughness parameters such as relative roughness height (e/D), relative roughness pitch (P/e), angle of attack (α), duct aspect ratio (W/H), etc. have significant impact on heat transfer and friction factor characteristics of roughened solar air heater duct. The artificially roughened absorber plates enhance the thermal performance of solar air heater but friction loss also increases substantially due to presence of roughness elements, which leads to more power consumption in propelling the air through the heater-duct. Therefore, it is imperative to perceive the roughness element geometry and its parameters combination which will deliver high thermal performance and low friction factor of a solar air heater. The undesirable power consumption requires to be minimized in order to improve the overall performance of the solar air heater. Thermal performance evaluation does not take the frictional power loss in the duct into consideration, hence the concept of effective efficiency that includes both the terms: useful thermal energy gain and pumping power expended is considered to evaluate the thermohydraulic performance. Exergetic performance analysis, derived from I^{st} and II^{nd} laws of thermodynamics, is an appropriate method that takes into account the useful energy output and pumping power requirement to evaluate the overall performance of solar thermal systems.

Gupta and Kaushik [9] studied numerically the energy, effective and exergy performance evaluation of solar air heater duct provided with different artificial roughness geometries. Gupta and Kaushik [10] carried out there analytical investigation by using expanded metal mesh as roughness geometry of solar air heater duct; they evaluated the energy, effective and exergy augmentation criteria of the roughened duct. Exergy based analysis, reported by Gupta and Kaushik [11] for smooth plate solar air heater, Öztürk and Demirel [12] for Packed bed solar air heater, Pandey et al. [13] for solar cookers, Petela [14] for Cylinder parabolic cooker, Sami et al. [15] for solar cabinet dryer provides useful information to evaluate performance of solar thermal systems.

The exergy is the maximum work potential that can be obtained from a form of energy [20]. Exergy analysis, derived from both the first and second laws of thermodynamics is a powerful tool for design, optimization, and performance evaluation of solar thermal utilization systems [16–20]. Experimental investigation was carried out by Saini and Saini [23] to enhance heat transfer and friction