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Experimental investigation of heat transfer augmentation using multiple arcs with gap on absorber plate of solar air heater

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ABSTRACT

In this present article an experimental study has been carried out on heat transfer and friction factor in rectangular channel which is having multiple-arc shaped with gaps as roughness element. The investigation encompassed Reynolds number (*Re*) ranges from 2100 to 21,000 (7 values), relative roughness height (e/D) ranges from 0.016 to 0.044 (4 values), relative roughness pitch (p/e) ranges from 4 to 16 (4 values), arc angle (α) values are 30–75° (4 values), relative roughness width (W/w) ranges from 1 to 7 (5 values), relative gap distance (d/x) values are 0.25–0.85 (4 values) and relative gap width (g/e) ranges from 0.5 to 2.0 (4 values). The maximum increment in Nusselt number (*Nu*) and friction factor (*f*) is 5.85 and 4.96 times in comparison to the smooth duct. Utilizing these data, correlations were developed for *Nu* and *f*.

1. Introduction

Solar energy is indefatigable source of energy. The only known living planet the earth intercepts is 1.7×10^{14} kW of energy from sun approximately which is more than the consumption rate of all commercial non-renewable sources. The earth receives more energy from the Sun in just one hour than the world's population uses in a whole year. The greatest advantage of solar energy as compared with other forms of energy is that it is clean and can be supplied without any environmental pollution (Kalogirou, 2004). Solar collectors absorb incident radiations and transform them into heat. This heat is used for heating collector fluid such as water and air (Yadav et al., 2013). Solar air heaters (SAHs) are very simple and cheap that's why most widely used for the collection devices. The efficiency of smooth solar air heaters is low due to less heat transfer coefficient of air. The reason for low convective heat transfer coefficient is due to presence of viscous sub layer (laminar sub layer). To increase the heat transfer it is recommended to disturb this laminar sublayer in order to enhance heat transfer from the surface (Varun et al., 2009). Use of a turbulence promoter on the heated surface is considered to be an effective technique for augmenting convective heat transfer coefficient in SAH ducts (Kumar and Kim, 2014, 2015).

Artificial roughness can be provided in the form of sand blasting, wires of different geometry, dimples, protrusions, grooves, wedge shape etc. and it is used in heat augmentation studies. Prasad and Saini (1988) had experimentally studied the effect of e/D and p/e on Nusselt number (*Nu*) and friction factor (*f*) for transverse ribs shaped geometry. The maximum enhancement in *Nu* and *f* found to be 2.38 and 4.25 times respectively. Gupta et al. (1993) had experimentally investigated the effect of e/D and angle of attack on *Nu* and *f* factor using inclined ribs as a roughness element. Inclined wire enhance heat transfer more as compared with transverse wire due to generation of secondary flow in addition to breaking of laminar sub layer. Momin et al. (2002) had experimentally studied the effect of V-shaped ribs on heat transfer and fluid flow characteristics in rectangular duct of a SAH. Result shows that maximum enhancement of Nusselt number and friction factor as a result of providing roughness were found to be 2.30 and 2.83 times respectively over the smooth duct for an angle of attack (α) value of 60°. Correlations for Nusselt number (*Nu*) and friction factor (*f*) were developed using experimental data. Saini and Saini (2008) had experimentally investigated arc-shaped ribs in rectangular channel and reported an enhancement in *Nu* and *f* was of the order of 3.6 and 1.75 times respectively as compared to smooth one. Aharwal et al. (2009) has carried out an experimental investigation on heat transfer and friction characteristics using integral repeated discrete square ribs on plate of a solar air heater. Result shows that maximum increment in Nusselt number (*Nu*) is observed at a

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Nomenclature

a	chord length (mm, dependent on relative roughness width)
A	area (m^2)
C_P	specific heat of air (J/kg K)
C_d	coefficient of discharge
D	hydraulic diameter (m)
d/x	relative gap position
e	rib height (m)
e/D	relative roughness height
f	friction factor
g/e	relative gap width
Δh_o	head difference in manometer (m)
H	height of duct (m)
h	heat transfer co-efficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	test section length (m)
m	mass flow rate of air (kg/s)
Nu	Nusselt number
ΔP	pressure drop (Pa)
p	pitch (m)
p/e	relative roughness height
Pr	Prandtl number
Q_u	useful heat gain (W)
Re	Reynolds number
T_i	air inlet temperature (K)
T_o	air outlet temperature (K)
T	temperature (K)
v	mean flow velocity in duct (m/s)
W	width of duct (m)
W/w	relative roughness width
X	wooden cylinder diameter used for fabrication of angular ribs (mm)

Greek Symbols

α	arc angle (°)
ρ	density (kg/m^3)
β	ratio of orifice diameter to pipe diameter

Sub-scripts

D	duct
f	fluid
m	manometric
o	orifice
p	absorber plate
s	smooth

relative gap position of 0.25 for relative gap width of 1.0, p/e of 8.0, α of 60° and e/D of 0.037. Based upon collected data, correlations were developed for Nu and f. Varun et al. (2008) has carried out an experimental study on the combination of ribs that is inclined and transverse. Result shows that maximum thermal efficiency occurs at p/e of 8. Hans et al. (2010) used multiple v-shaped ribs on the heated plate having rectangular passage. The maximum enhancement in Nu and f factor were found in the order of 6 and 5 times respectively as compared with smooth one. Bhushan and Singh (2011) have experimentally investigated the effect of protrusion as roughness on heat transfer and friction in solar air heater. Singh et al. (2011) has carried out experimental study on discrete V-down ribs used as roughness elements. The maximum enhancement in Nusselt number (Nu) and friction factor (f) has been obtained to be 3.04 and 3.11 times as compared to smooth one. Correlations were also developed for Nu and f. Sethi et al. (2012a, b) has carried out experimental work to study the augmentation in heat transfer by using dimple shaped roughness element which was arranged in angular arc fashion. The maximum enhancement was found in Nu and f is 2.46 and 3.08 times respectively. Correlations were also developed for Nu and f. Singh et al. (2014b) has been experimentally investigated the heat transfer and friction characteristics of rectangular duct having multiple arc shaped roughness element on the absorber plate. The maximum enhancement is observed to be about 5.07 and 3.71 times for Nu and f respectively in comparison with flat one. Correlations were also developed for Nu and f. Shui-Lian et al. (2015) has carried out experimental study to investigate heat transfer and friction factor having hemispherical protrusions shaped roughness on the absorber plate. Correlations were also developed for Nu and f. Gawande et al. (2016) has studied forced convection heat transfer of air in a solar air heater using reverse L-shaped ribs. The maximum enhancement in Nu and f has been found to be 2.827 and 3.424 times over the smooth duct. Correlations for Nu and f were developed as a function of roughness and flow parameters. A number of review studies on heat transfer augmentation using artificial roughness have been performed over several years (Varun et al., 2007; Kumar et al., 2012; Alam et al., 2014). Yadav and Bhagoria (2014) has carried out numerical investigation to analyse flow through roughened rectangular duct of solar air heater. Twelve different configurations of equilateral triangular sectioned rib were used as roughness element for different p/e and e/D. The equations were solved using commercial software Ansys (Fluent) which is based on finite volume approach. Result shows that maximum enhancement in Nu has been found to be 3.073 times over smooth duct corresponds to e/D and p/e value of 0.042 and 7.14 respectively at Reynolds number of 15,000. It is evident from the literature that by providing roughness on the absorber plate increases the amount of heat transfer. A continuous type of roughness significantly improves the heat transfer coefficient but further making it discrete (by providing gaps) it will further enhance the amount of heat transfer. The objectives of the study are:

1. To investigate the effect of various roughness parameters along with Reynolds number on the heat transfer enhancement and flow friction characteristics using multiple-arc shaped with gap as an artificial roughness on the underside of an absorber plate of solar air heater by experimental analysis.
2. By using experimental data correlations for Nu and f have to be developed for this new type of roughened geometry.

1.1. Roughness parameters

The schematic view of multiple arcs having gap type geometry chosen for study is shown in Fig. 1(a and b). The roughness has been fabricated on plate by pasting aluminum wires in the desired fashion by creating arcs with the help of wooden cylinder of the specified dimension. The diameters of wooden cylinder were calculated using Eq. (1) given by Singh et al. (2014a).

$$X(\text{CylinderDiameter, mm}) = a/\cos(90 - \alpha) \quad (1)$$

To investigate the heat transfer and friction characteristics, 29 roughened plates were fabricated and tested. The roughness parameters were expressed as arc angle (α), relative roughness