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A parametric analysis of rectangular rib roughened triangular duct solar air heater using computational fluid dynamics

Rajneesh Kumar*, Anoop Kumar, Varun Goel

Department of Mechanical Engineering, NIT Hamirpur, 177005, India

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ABSTRACT

Solar air heater (SAH) absorbs thermal radiations from Sun and utilizes it to heat air. The thermal performance of SAH can be improved by using ribs on the absorber plate. In this paper, rectangular geometry of ribs is considered over the absorber plate. The fluid flow characteristics and heat transfer in ribbed triangular duct (with an apex angle of 60°) SAH is analyzed using computational fluid dynamics (*CFD*). The roughened side of duct is subjected to a constant heat flux of 1000 W m^{-2}, whereas, roughness elements are adiabatic in nature. The three-dimensional model of SAH is developed and numerical simulations are carried out by developing CFD code with the help of finite volume method. The numerical simulations are performed on commercial ANSYS Fluent 12.1 software. A new roughness parameter called rib aspect ratio (e/w) is introduced in this study and its effect on friction factor (f) and Nusselt number (Nu) is investigated along with relative roughness height (e/D) and relative roughness pitch (P/e) for the Reynolds number ranges from of 4000 to 18,000. The values of rib aspect ratio (e/w), roughness height (e/D) and relative roughness pitch (P/e) range from 0.25 to 4.0, 0.02 to 0.04 and 5 to 15, respectively. A considerable increase in friction factor (f) and Nusselt number (Nu) is observed due to rectangular rib in comparison to smooth one. The numerically predicted results are compared with the available results and a good agreement between them is observed with maximum error of ± 4.04%. A significant variation in friction factor (f) and Nusselt number (Nu) is observed by varying rib aspect ratio (e/w) values from 0.25 to 4.0. The maximum value of thermohydraulic performance parameter (TPP) is found 1.89 in case of relative roughness pitch (P/e), rib aspect ratio (e/w) and relative roughness height (e/D) value of 10, 4.0 and 0.04, respectively, at the Reynolds number (Re) of 15,000.

1. Introduction

Solar air heater (SAH) is a device which stores solar radiations for heating applications. The air acts as a working medium in SAH. But, due to its low coefficient of heat transfer value, SAH has poor performance (thermal). The different heat transfer augmentation techniques such as surface, fluid and combined were discussed by Balaras (1990) and Bergles (1988). Among them the heat transfer augmentation using surface methods is most effective and economic technique (Yadav and Thapak, 2014). In this technique, the artificial roughness is placed over the hot surface and because of these roughness elements, generation of local turbulence takes place which increases heat transfer along with pressure drop in the SAH (Iacovides and Raisee, 2001; Varun et al., 2007; Kumar et al., 2017a). For getting optimum thermal performance, the transition, sub-layer thickness should be smaller than the height of roughness element (Prasad and Saini, 1991).

The orientation and shape of duct are the two parameters which affects the flow characteristics and heat transfer through the duct (Kumar et al., 2016). The triangular cross-sectional duct has minimum friction factor value in comparison to other cross-sectional duct (square, circular, rectangular and semi-circular) and therefore, triangular shaped duct required low pumping power for fluid flow (Cebeci and Bradshaw, 1988). Due to advantage of low pumping power, the triangular duct is used in many engineering applications such as compact heat transfer (Zhang, 2005; Sunden, 2010; Nascimento and Gracia, 2016; Chennu, 2016), SAH (Bharadwaj et al., 2013, 2017), etc.

A lot of experimental and numerical studied are available on roughened rectangular duct in comparison to triangular duct SAH (Tsai et al., 2000; Gao and Sunden, 2001; Unalan et al., 2007; Liou et al., 2007; Ma et al., 2015; Raisee and Rokhzadi, 2009; Sethi et al., 2012; Singh et al., 2014, 2015; Yadav et al., 2014; Scholl et al., 2016; Jiang et al., 2016; Pandey et al., 2016; Kumar et al., 2017b). In case of triangular duct SAH only few studies are available in the area of heat transfer augmentation using artificial roughness. Chegini and Chaturvedi (1986) studied the effect of fin location on friction factor in duct and observed that placing of fins on same side of the duct results

* Corresponding author.
E-mail address: rajneesh127.nith@gmail.com (R. Kumar).

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Nomenclature

a	side length of the duct (m)
D	hydraulic diameter (m)
k	thermal conductivity (W m^{-1} K^{-1})
h	coefficient of heat transfer (air) (W m^{-2} K^{-1})
H	height of duct (m)
L	length (m)
n	number of ribs
P	pressure (Pascal)
P_{wetted}	wetted perimeter (m)
T	temperature (K)
u	axial velocity (m s^{-1})
W	width of duct (m)
w	width of rectangular rib roughness element (m)
x	distance in the flow direction (m)

Dimensionless

e/D	relative roughness height
f	friction factor
I	turbulence intensity
Nu	Nusselt number
P/e	relative roughness pitch
Pr	Prandtl number
Re	Reynolds number
e/w	rib aspect ratio
y^+	dimensionless wall distance

Greek symbols

μ	viscosity (N s m^{-2})
μ_t	thermal viscosity
ρ	density (kg m^{-3})
ε	dissipation rate
k	turbulent kinetic energy (m^2 s^{-3})
α	thermal conductively (W m^{-1} K^{-1})
Γ	molecular thermal diffusivity (=μ/Pr)
Γ_t	turbulent thermal diffusivity (=μ_t/Pr)

Subscripts

avg	average
eff	effective
enh	enhancement
L_0	start of test section
penalty	penalty
p	plate
r	ribbed
s	smooth
test	test
test,0	start of test section
test,*l*	end of test section
t	total

Abbreviations

ASHRAE	American Society of Heating, Refrigeration Air Conditioning Engineers
CFD	Computational Fluid Dynamics
ICEM	Integrated Computer-aided Engineering and Manufacturing
RNG	Renormalized group method.
SAH	Solar Air Heater
TPP	Thermohydraulic performance parameter

low friction factor in comparison to three side finned duct, under similar conditions. It is observed that fins can result in heat transfer improvement up to 200% under particular conditions but it increases pressure drop along the flow considerably. Similarly, Obot et al. (1987) analyzed the effect of roughness on pressure drop in round corner triangular duct. They found that pressure drop is higher in case of three side roughened duct in comparison to two sides. Due to presence of laminar as well as turbulent flow at the corner region, the turbulence is suppressed by flow distribution around corners (Daschiel et al., 2013; Karabulut et al., 2016) which results in low heat transfer in triangular duct (Sparrow and Haji-Sheikh, 1965). Even though, micro size roughness element can results a better heat transfer in the duct (Kang et al., 1998). Kang et al. (1998) has used rolling and shaping process to create micro sized roughness inside the duct. The maximum roughness size was of the order of 11.5 µm and they had observed maximum increase of Nusselt number (*Nu*) in the range of 15–30% in comparison to smooth duct. The roughness can be created by producing groove in the fluid flow region. Leung et al. (2000) had examined the effect of v-groove roughness. They had considered constant value of roughness pitch and groove depth which is 34 *mm* and 1 *mm*, respectively. But the groove angle varied from 0° to 150°. The maximum value of *Nu* is obtained in particular range of groove angle which is 15° to 18°. The effect of square ribs on performance of duct has been studied by Leung et al. (2001), Ahn and Son (2002) and Luo et al. (2004). Leung et al. (2001) had analyzed the effect of rib height (range from 6.35 to 12.7 mm) by considered fixed vale of roughness pitch i.e. 57.15 mm. The *Nu* increased by amount of 170% in roughened duct as compared to smooth. Ahn and Son (2002) had analyzed the effect of relative roughness pitch (range from 4 to 16) for constant rib height value i.e. 2 mm. They had concluded that the friction factor increases with decrease in gap between two successive ribs and best thermal performance is achieved for relative roughness pitch (P/e) value of 10. The combined effect of relative roughness (P/e) and relative rib height (H/D) has been studied by Luo et al. (2004). The P/e and e/D value range from 3.41 to 13.93 and 0.11 to 0.21, respectively. The maximum increase in *Nu* is observed for H/D and P/e value of 0.18 and 7.22. The flow and heat transfer through the duct also get affected by the rib inclination angle. The effect of rib inclined angle on flow and heat transfer in SAH is analyzed by Bharadwaj et al. (2013). The rib inclination angle, e/D and P/e was varied from 30° to 60°, 0.021 to 0.043 and 8 to 16, respectively. The maximum increase in *Nu* and friction factor (f) is observed for rib inclination angle of 60°. A non-dimensional correlation has been also developed for inclined ribbed SAH (Bharadwaj et al., 2017). The maximum increase in *Nu* and f is found for rib inclination angle, P/e and e/D value of 60°, 12 and 0.043, respectively. The heat transfer in semi-circular rib roughened triangular duct has been investigated by Kumar et al. (2017a). The commercial ANSYS software has been used for the numerical analysis. They found that k-ε model calculate *Nu* accurately as compared to other available turbulence models in Fluent. The best thermohydraulic performance is observed of the order of 1.7 for e/D and P/e value of 0.067 and 7.5. From discussed literature, it is concluded that rib roughness has significant effect on *Nu* and f. Different shaped rib elements (such as circular, square, V-grooved, semi-circular has been analyzed by different researchers and *Nu* and f value changes remarkable by varying the shape of rib elements. There is no such study which analyse the effect of rectangular ribs on thermal performance of triangular duct SAH. Therefore, in this article numerical study has been performed on rectangular ribbed SAH with the help of computational fluid dynamic (CFD) based software.

Computational fluid dynamics (CFD) is a powerful tool to analyze