



# A CFD based thermo-hydraulic performance analysis of an artificially roughened solar air heater having equilateral triangular sectioned rib roughness on the absorber plate



Anil Singh Yadav<sup>a,b,\*</sup>, J.L. Bhagoria<sup>b</sup>

<sup>a</sup> Mechanical Engineering Department, Technocrats Institute of Technology – Excellence, Bhopal, MP 462021, India

<sup>b</sup> Mechanical Engineering Department, Maulana Azad National Institute of Technology, Bhopal, MP 462051, India

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## ABSTRACT

In this article, a numerical investigation is conducted to analyze the two-dimensional incompressible Navier–Stokes flows through the artificially roughened solar air heater for relevant Reynolds number ranges from 3800 to 18,000. Twelve different configurations of equilateral triangular sectioned rib ( $P/e = 7.14\text{--}35.71$  and  $e/d = 0.021\text{--}0.042$ ) have been used as roughness element. The governing equations are solved with a finite-volume-based numerical method. The commercial finite-volume based CFD code ANSYS FLUENT is used to simulate turbulent airflow through artificially roughened solar air heater. The RNG  $k\text{--}\epsilon$  turbulence model is used to solve the transport equations for turbulent flow energy and dissipation rate. A total numbers of 432,187 quad grid intervals with a near wall elements spacing of  $y^+ \approx 2$  are used. Detailed results about average heat transfer and fluid friction in an artificially roughened solar air heater are presented and discussed. The effects of grid distributions on the numerical predictions are also discussed. It has been observed that for a given constant value of heat flux ( $1000\text{ W/m}^2$ ), the performance of the artificially roughened solar air heater is strong function of the Reynolds number, relative roughness pitch and relative roughness height. Optimum configuration of the roughness element for artificially roughened solar air heater is evaluated.

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## 1. Introduction

Solar energy, radiant light and heat from the sun, has been harnessed by humans since ancient times using a range of ever-evolving technologies. Before 1970, some research and development was carried out in a few countries to exploit solar energy more efficiently, but most of this work remained mainly theoretical and academic. After the dramatic rise in oil prices in the 1970s, several countries began to formulate extensive research and development programs to exploit solar energy. Solar air heater is an effective device to harness solar energy and used for heating purposes i.e., drying of crops, seasoning of timber, space heating etc. A simple solar air heater consists of an absorber plate to capture solar radiation and transfers this solar (thermal) energy to air via conduction heat transfer. This heated air is then ducted to the building space or to the process area where the heated air is used for space heating or process heating needs [1].

\* Corresponding author at: Mechanical Engineering Department, Technocrats Institute of Technology – Excellence, Bhopal, MP 462021, India. Tel.: +91 9229220126.

E-mail address: [anilsinghyadav@gmail.com](mailto:anilsinghyadav@gmail.com) (A.S. Yadav).

Artificial roughness is a well-known method to increase the heat transfer from a surface to roughen the surface either randomly with a sand grain or by use of regular geometric roughness elements on the surface. However, the increase in heat transfer is accompanied by an increase in the resistance to fluid flow. Several investigators have attempted to design an artificially roughened rectangular duct which can enhance the heat transfer with minimum pumping losses. Many investigators have studied this problem in an attempt to develop accurate predictions of the behavior of a given roughness geometry and to define a geometry which gives the best transfer performance for a given flow friction. A lot of studies have been reported in the literature on artificially roughened surfaces for heat transfer enhancement but most of the studies were carried out with two opposite or all the four walls roughened. An early study of the effect of roughness on friction factor and velocity distribution was performed by Nikuradse [2], who conducted a series of experiments with pipes roughened by sand grains and since then many experimental investigations were carried out on the application of artificial roughness in the areas of gas turbine airfoil cooling system, gas cooled nuclear reactors, cooling of electronic equipment, shipping machineries, combustion chamber liners, missiles, re-entry vehicles, ship hulls and piping networks etc.

**Nomenclature**

$C_p$	specific heat of air, J/kg k
$D$	equivalent or hydraulic diameter of duct, mm
$e$	rib height, mm
$H$	depth of duct, mm
$h$	heat transfer coefficient, W/m <sup>2</sup> k
$I$	intensity of solar radiation, W/m <sup>2</sup>
$k$	thermal conductivity of air, W/m k
$L$	length of duct, mm
$L_1$	inlet length of duct, mm
$L_2$	test length of duct, mm
$L_3$	outlet length of duct, mm
$m$	mass flow rate, kg/s
$P$	pitch, mm
$q$	heat flux, W/m <sup>2</sup>
$T$	air temperature, K
$T_0$	ambient temperature, K
$T_{am}$	mean air temperature, K
$T_i$	air inlet temperature, K
$T_o$	air outlet temperature, K
$T_{pm}$	mean plate temperature, K
$T_w$	wall temperature, K
$u$	air flow velocity in the $x$ direction, m/s
$U_0$	mean air flow velocity in the duct, m/s
$u_\tau$	friction velocity, m/s
$v$	air flow velocity in the $y$ direction, m/s
$W$	width of duct, mm
$\Delta P$	pressure drop, Pa

*Dimensionless parameters*

$B/S$	relative roughness length
$d/w$	relative gap position
$e/D$	relative roughness height
$e/H$	rib to channel height ratio
$f$	friction factor
$f_r$	friction factor for rough surface
$f_s$	friction factor for smooth surface
$g/e$	relative gap width
$g/P$	relative groove position
$G_d/L_v$	relative gap distance
$L/D$	test length to hydraulic diameter ratio of duct

$l/e$	relative logway length of mesh
$l/s$	relative length of grit
$Nu$	Nusselt number
$Nu_r$	Nusselt number for rough duct
$Nu_s$	Nusselt number for smooth duct
$P/e$	relative roughness pitch
$Pr$	Prandtl number
$Re$	Reynolds number
$S/e$	relative short way length of mesh
$St$	Stanton number
$W/H$	duct aspect ratio
$W/w$	relative roughness width
$y^+$	non dimensional wall coordinate

*Greek symbols*

$\alpha$	angle of attack, degree
$\Gamma$	molecular thermal diffusivity, m <sup>2</sup> /s
$\Gamma_t$	turbulent thermal diffusivity, m <sup>2</sup> /s
$\delta$	transition sub-layer thickness, mm
$\varepsilon$	dissipation rate, m <sup>2</sup> /s <sup>3</sup>
$\kappa$	turbulent kinetic energy, m <sup>2</sup> /s <sup>2</sup>
$\mu$	dynamic viscosity, Ns/m <sup>2</sup>
$\mu_t$	turbulent viscosity, Ns/m <sup>2</sup>
$\rho$	density of air, kg/m <sup>3</sup>
$\omega$	specific dissipation rate, 1/sec

*Subscripts*

a	ambient
am	air mean
f	fluid (air)
i	inlet
m	mean
o	outlet
pm	plate mean
r	roughened
s	smooth
t	turbulent
w	wall

In the case of solar air heater, roughness elements have to be considered only on one wall, which is the only heated wall comprising the absorber plate. These applications make the fluid flow and heat-transfer characteristics distinctly different from those found in case of two roughened walls and four heated wall duct. In the case of solar air heater, only one wall of the rectangular air passage is subjected to uniform heat flux while the remaining three walls are insulated. It is well known that the heat transfer coefficient between the absorber plate and air of solar air heater is generally poor and this result in lower efficiency. The effectiveness of solar air heater can be improved by using artificial roughness in the form of different types of repeated ribs on the absorber plate. It has been found that the artificial roughness applied to the absorber plate of a solar air heater, penetrates the viscous sub-layer to promote turbulence that, in turn, increases the heat transfer from the surface as compared to smooth solar air heater. This increase in heat transfer is accompanied by a rise in frictional loss and hence greater pumping power requirements for air through the duct. In order to keep the friction losses at a low level, the turbulence must

be created only in the region very close to the duct surface, i.e., in the laminar sub-layer.

Artificially roughened solar air heater has been the topic of research for last thirty years. Several designs for artificially roughened solar air heaters have been proposed and discussed in the literature [3–30]. Several investigators have attempted to optimize a roughness element, which can enhance convective heat transfer with minimum pumping power requirement by adopting experimental and numerical approaches. Most of the experiments are also conducted to specifically understand the influence of pitch-to-rib height ratio ( $P/e$ ) and/or rib height-to-hydraulic diameter ratio ( $e/D$ ) on average heat transfer and flow friction characteristics, and distributions of the mean velocities, pressure and turbulent statistics in the flows through the duct of an artificially roughened solar air heater. Literature search in this areas revealed that the heat transfer enhancement is strongly dependent on the relative roughness pitch ( $P/e$ ) and relative roughness height ( $e/D$ ) of roughness elements together with the flow Reynolds number ( $Re$ ). There are lot of experiments have been done and so many experiments are going on right now to optimize roughness parameters for heat

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