# A Review on CFD Analysis of Turbulent Heat Transfer in Solar Air Heater by using Roughness Geometry

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*Abstract*— In mechanical industries or thermal power sector the most commonly using element is "AIR PRE HEATER", which is a form of Heat Exchanger and by this equipment we can increase the temperature of the air which has been to use in required purpose. By using the solar air heater we can increase the efficiency of organization. And the use of artificial roughness in the form of repeated ribs on a surface is an effective technique to enhance the rate of heat transfer. A numerical investigation on the heat transfer and fluid flow characteristics of fully developed turbulent flow in a rectangular duct having repeated transverse X shaped rib roughness on the absorber plate has been carried out. The commercial finite-volume CFD code ANSYS FLUENT is used to simulate turbulent airflow through artificially roughened solar air heater. The flow Reynolds number of the duct varied in the range of 3800 to 18,000, most suitable for solar air heater. Solar air heater is operating on the principle of forced convective heat transfer between the wall and a working fluid (air). But the efficiency of the air heater is naturally of low value due to the fact that air has inferior thermodynamics properties in terms of heat transfer but it can be increase by the changing the shape of duct inner area in terms of roughness of artificial roughness. The method used to increase the heat transfer coefficient between the working fluid (air) and absorber surface is to create the turbulence inside the solar air heater duct. The turbulence is used to break the viscous sub layer at the absorber surface and change into the turbulent air flow from the laminar. Yadav and Bhagoria have simulated the above geometries using ANSYS FLUENT code and RNG kε turbulence model. The results were presented in terms of Nusselt number versus Re, friction factor versus Re, Nusselt number ratio versus Re, friction factor ratio versus Re, and thermal enhancement factor versus Re. From the literature review cited above, it is revealed that both experimental and numerical analysis works are done using the Roughness geometries fitted on the flow side of absorber plate. Promvonge et al. have adopted a new concept to increase the heat transfer in solar air heater duct. Promvonge et al. used ribs as artificial roughness on the absorber plate and in addition to this delta winglet, as a swirl flow generator in inlet section to create the additional turbulence from inlet section. This concept results in increase of heat transfer rate.

***Key words:*** Artificial Roughness, Solar Air Heater, Roughness Geometry, Nusselt Number, Friction Factor, Thermo Hydraulic Performance, Reynolds Number

## I. Introduction

A solar air heater is a type of heat energy collector by which we can collect the solar heat by using a solar heat absorber. And this absorbed heat can be utilized to increase the temperature of air which is passing throw a rectangular duct. In this paper it is focused to present different surface roughness geometries used in various researches and the geometry arrangements.

| Nomenclature | |
|---|---|
| Ac | surface area of absorber plate (m2) |
| Cp | specific heat of air(J/kg/K) |
| D | equivalent or hydraulic diameter of duct(m) |
| E | rib height(m) |
| H | heat transfer coefficient(W/m2/K) |
| H | depth of duct(m) |
| I | turbulence intensity/intensity of solar radiation (W/m2) |
| K | thermal conductivity of air(W/m/K) |
| L | length of duct(m) |
| $L_1$ | inlet length of duct(m) |
| $L_2$ | test length of duct(m) |
| $L_3$ | outlet length of duct(m) m mass flow rate(kg/s) |
| $D_P$ | pressure drop(Pa) |
| P | pitch (m) $q_u$ useful heat flux(W/m2) |
| $Q_u$ | useful heat gain(W) |
| $Q_L$ | heat loss from collector(W) |
| $Q_t$ | heat loss from top of collector(W) |
| $T_o$ | fluid outlet temperature(K) |
| $T_i$ | fluid inlet temperature(K) |
| Ta | ambient temperature(K) |
| $T_{pm}$ | mean plate temperature(K) |
| $T_{am}$ | mean air temperature(K) |
| $T_w$ | wall temperature(K) |
| Tm | bulk mean temperature(K) |
| $U_L$ | overall heat loss coefficient(W/m2/K) |
| V | velocity of air in the duct(m/s) |
| W | width of duct(m) |
| Dimensionless parameters | |
| e/D | relative roughness height |
| F | friction factor |
| Nu | Nusselt number |
| Pr | Prandtl number |
| p/e | relative roughness pitch |
| R | roughness function |
| Re | Reynolds number |
| W/H | duct aspect ratio |

Solar air heaters, because of their simple in design, are cheap and most widely used collection devices of solar energy. It is one of the basic equipment through which solar energy is converted into thermal energy. The main applications of solar air heaters are space heating, seasoning of timber, curing of industrial products and these can also be effectively used for curing/drying of concrete/clay building components. A conventional solar air heater generally consists of an absorber plate, a rear plate, insulation below the rear plate, transparent cover on the exposed side, and the air flows between the absorbing plate and rear plate. A solar air heater is simple in design and requires little maintenance. However, the value of the heat transfer coefficient between the absorber plate and air is low and this results in a lower efficiency [1, 2]. CFD is a science that can be helpful for studying fluid flow, heat transfer, chemical reactions etc. by solving mathematical equations with the help of numerical analysis. It is equally helpful in designing a solar air heater system from scratch as well as in troubleshooting/optimization by suggesting design modifications. CFD employs a very simple principle of resolving the entire system in small cells or grids and applying governing equations on these discrete elements to find numerical solutions regarding pressure distribution, temperature gradients, flow parameters and the like in a shorter time at a lower cost because of reduced required experimental work [3-8].

### A. *Artificial Roughness on Upper Layer of Duct*

Artificial Roughness technique has been used by the researchers since long period of time for the enhancement of heat transfer from the absorber plate of the solar air heater. This type of heater has flat plate absorber with insulation to prevent the heat loss from the heater and the upper most part of the duct is roughened to create turbulence in the air which is passing throw.

For the analysis of the performance of the solar air heater with artificial roughness, some parameters are used e. g Relative roughness pitch, Relative roughness height, Angle of attack and aspect ratio. Various roughness geometries have been used by the researchers for heat transfer analysis some of the geometries are V shaped, Square shaped, wire rib, transverse rib grooved, metal grit rib and chamfered rib but we are using here X-shaped roughness on the upper layer of the duct or sun heat absorbing plate.

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 for high Reynolds number range in the area 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.

### B. *Application of Solar Air Heater*

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## II. PERFORMANCE OF SOLAR AIR HEATER

The performance of this air solar heater can represents the degree of utilization of input to the system. Thermal performance concerns with heat transfer process within the collector and hydraulic performance concerns with pressure drop in the duct. A conventional solar air heater is considered for brief analysis of thermal and hydraulic performance in the following sub-sections. Design and construction details of such type of conventional system are described by Garg and Prakash.

The thermal performance of flat plate solar air heater could be observed by considering the energy balance between solar energy absorbed by absorber plate and useful thermal energy output of the system accompanied by some losses.

### A. *Thermal Performance*

Thermal performance of a solar air heater can be computed with the help of Hottel–Whillier–Bliss equation reported by Duffie and Beckman [9,10].

The energy balance equation can be written as follows

$$Qa = Ap\,[IR(\tau\alpha)e] = Qu + Q1 \quad (1)$$

Where Qa is the energy absorbed by the absorber plate,
Ap is the area of the absorber plate,
I is the intensity of insulation,

R is the conversion factor to convert radiation on horizontal surface to that on the absorber plane, $(\tau\alpha)$ e is the effective transmittance absorptance product of the glass cover-absorber plate combination, Qu is the useful energy gain and Ql is energy loss from the collector.

The useful energy gain can be expressed in terms of inlet air temperature Ti and other system and operating parameters as:

$$Q_U = A_C\, F_R\, [I(\tau\alpha)_e - U_L(T_i\text{-}T_a)] \quad (2)$$

Where $F_R$ is given by:

$$F_R\text{=}Cp/APU_L[1\text{-}exp(\text{-}F'U_LAP/cp)] \quad (3)$$

Where $F_R$ is the collector heat removal factor which indicates the thermal resistance meet by the absorbed solar energy in reaching to the flowing air.

$U_L$is the overall loss coefficient and Ti and Ta are the inlet air and ambient temperatures respectively.

F' is termed as collector efficiency factor which provides the relative measurement of thermal resistance between absorber plate and ambient air to that of thermal resistance between the air flowing through collector and the ambient air.

Collector efficiency factor (F') is expressed as:

$$F' = 1 / (1+U_L / he) \quad (4)$$

Where he is the effective heat transfer coefficient

Between the absorber plate and flowing air. The thermal efficiency of the collector is the ratio of useful heat gain to the incident solar energy falling on the Collector.

$$\text{Therefore: } \eta th = Qu / IAp = F_R[(\tau\alpha)e - U_L(Ti\text{-}Ta) / I] \quad (5)$$

According to the above equation, the thermal efficiency of the solar collector could be improved by increasing the value of FR which depends on collector efficiency factor F'. By enhancing the heat transfer coefficient between absorber plate and air, higher values of F' could be achieved. Roughening of absorber surface has been found to be the convenient and effective technique to enhance the convective heat transfer rates from the absorber surface to air.

### B. *Hydraulic Performance*

Hydraulic performance of a solar air heater concerns with pressure drop (DP) in the duct. Pressure drop accounts for energy consumption by blower to propel air through the duct.

The pressure drop for fully developed turbulent flowt hrough duct with Re<50,000 is given as follows equation:

$$f = \frac{2\Delta pD}{\rho Lu^2} \quad (6)$$

Where

$$f = 0.079Re^{-0.25} \quad (7)$$

## III. APPLICATIONS OF CFD IN VARIOUS ASPECTS OF SOLAR AIR HEATERS

A lot of experimental and theoretical studies have been reported to evaluate performance of solar air heater. Kumar et al. [11] experimentally investigated heat transfer and friction characteristics of solar air heater by using discrete W-shaped roughness on one broad wall of solar air heater. The maximum enhancement of Nusselt number and friction factor as a result of providing artificial roughness was found to be 2.16 and 2.75 times that of smooth duct. Mittal et al. [12] presented a comparison of effective efficiency of solar air heater shaving different types of geometry of roughness elements on the absorber plate. The effective efficiency was computed by using the correlations for heat transfer and friction factor developed by various investigators within the investigated range of operating and system parameters. Prasad and Saini [13] developed various design curves for artificially roughened solar air heater that gave the optimal thermo-hydraulic performance. Prasadand Saini [14] investigated the effect of relative roughness pitch (P/e) and relative roughness height(e/D) on the heat transfer coefficient and friction factor for fully developed turbulent flow in a solar air heater duct with small diameter protrusion on wires on the absorber plate. It was found that for a given relative roughness pitch, both the Nusselt number and friction factor increased with increasing relative roughness height and for a given relative roughness height both the Nusselt number and friction factor decreased with increasing relative roughness pitch, but not in direct proportion. Aharwal et al. [14] carried out an experimental investigation of heat transfer and friction factor characteristics of a rectangular duct roughened with repeated square cross-section split-rib with a gap, on one broad wall arranged at an inclination with respect to the flow direction. The maximum enhancement in Nusselt number and friction factor was observed to be 2.59 and 2.87 times of that of the smooth duct respectively. The thermo-hydraulic performance parameter was found to be maximum for the relative gap width of 1.0 and the relative gap position of 0.25. Muluwork [16] carried out an experimental analysis of a solar air heater having V-shaped staggered discrete ribs on the absorber plate and reported that maximum heat transfer enhancement occurred at an angle of attack of $60^0$. Prasad and Mullick [17] utilized artificial roughness in a solar air heater duct in the form of small diameter wires to increase the heat transfer coefficient for relative roughness height and relative roughness pitch of 0.019 and12.7, respectively. Gupta [18] investigated the effect of relative roughness height, angle of attack and Reynolds number on heat transfer and friction factor in rectangular duct having circular wire ribs on the absorbe rplate. The maximum enhancement of Nusselt number and friction factor as a result of providing artificial roughness was found to be 1.8 and 2.7 times that of smooth duct. Vermaand Prasad [19] investigated the effect of geometrical parameters of circular wire ribs on heat transfer and friction factor. It was observed that the value of heat transfer enhancement factor varies from 1.25 to 2.08 within the range of parameters investigated. The value of optimal thermo-hydraulic performance was found to be about 71% corresponding to roughness Reynolds number of 24. Karwa [20] carried out a comparative experimental study of augmented heat transfer and friction in are ct angular duc to fa solar air heater with rectangular cross-section ribs arranged in V-continuous and V-discrete pattern. The performance of V-down ribs was observed to be better than that of V-up ribs. Sahuand Bhagoria [21] experimentally investigated the effect of $90^0$ broken ribs as roughness elements and found that thermal efficiency lies in the range of 51–83.5%. The maximum enhancement in heat transfer was reported at the pitch of 20mm. Guptaetal. Saini and Saini [22] studied the effect of arc shaped ribs on the heat transfer coefficient and friction factor of rectangular solar air heater ducts. Enhancement of heat transfer and friction factor was reported to be of order 3.6 and 1.75 times respectively over smooth solar air heater duct for relative arc angle value of 0.333 and relative roughness height value of 0.042. Saini and Verma [23] investigated the effect of roughness and operating parameters on heat transfer and friction factor in a roughened duct provided with dimple-shape roughness geometry for the range of Reynolds number from 2000 to 12,000, relative roughness height from 0.018 to 0.037 and relative roughness pitch from 8 to 12. The maximum value of the heat transfer was found to be corresponding to relative roughness height of 0.037 and relative roughness pitch of 10. Karmare and Tikekar [24] performed an experimental investigation of heat transfer to the airflow in the rectangular duct of an aspect ratio 10:1. The top wall surface was made rough with metal ribs of circular cross section in staggered manner to form defined grid. The roughened wall was uniformly heated and the other walls were insulated. The effect of relative roughness height of grit, relative roughness pitch of grit and relative length of grit on the heat transfer coefficient and friction factor were investigated by authors. Kumar et al. Kumar et al. [25] carried out an experimental investigation to determine the heat transfer distributions in solar air heater having its absorber plate roughened with discrete w-shaped ribs. It was reported that thermal performance of the roughened duct was found to be 1.2–1.8 times the smooth channel for range of parameters investigated. Jaurker et al. [26] investigated the effect of relative roughness pitch, relative roughness height and relative groove position on the heat transfer coefficient and friction factor of rib-grooved artificial roughness. The maximum heat transfer was obtained for a relative roughness pitch of about 6, and it was decreased on either side of the relative roughness pitch. The optimal condition for heat transfer was found at a groove position to pitch ratio of 0.4 as compared to the smooth duct. As compared to smooth surface, the presence of rib grooved artificial roughness increases the Nusselt number up to 2.7 times, while the friction factor raises up to 3.6 times in the range of parameters investigated. Layek et al. [27] investigated heat transfer and friction characteristics of repeated integral transverse chamfered rib-groove rough- ness. Authors reported that Nusselt number and friction factor was increased by 3.24 times and 3.78 times respectively as compare to smooth duct.

Maximum enhancement of Nusselt number and friction factor was obtained corresponding to relative groove position of 0.4.

### *A. Thermo-Hydraulic Performance*

It is necessary that while evaluating the performance of a solar air heater with respect to the enhancement of thermal gain, the energy spent in propelling air should also be taken into account. It is desirable that design of solar air heater should be made in such a way that it should transfer maximum heat energy to the flowing fluid with minimum consumption of blower energy. Therefore in order to analyze overall performance of a solar air heater, thermo-hydraulic performance should be evaluated by considering thermal and hydraulic characteristics of the collector simultaneously. Thermo-hydraulic performance of a solar air heater is given by the following index

$$\text{Thermo hydraulic performance} = \frac{Nu_r/Nu_s}{(f_r/f_s)^{1/3}} \quad (8)$$

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### *B. Discussion about Turbulence Models*

The literature survey reveals that the solar air heaters are thermo-hydraulically more efficient if system operates at Reynolds numbers ranges from 3000 to 19,000. Reynolds number inside the rectangular duct of solar air heater shows that the flow is turbulent. One of the great challenges in the

| Authors | Computational methodology | Difference between experimental and simulation results |
|---|---|---|
| Arulanandam et al. [28] | CFD code: TASC flow<br>Turbulence:-<br>Mesh: uniform | Close agreement observed |
| Ammari [29],<br>Chaube et al. [30] | CFD code: Fluent 6.1<br>Turbulence model: SST k– ω<br>Mesh: rectangular, non-uniform | Good agreement observed ,<br>Good agreement observed |
| Chaube et al. [31] | CFD code: Fluent 6.1<br>Turbulence model: SST k– ω<br>Mesh: rectangular, non-uniform | Good agreement observed |
| Wang et al. [32],<br>Varol and Oztop [33] | CFD Code: CFDRC ACE+<br>Turbulence model:-<br>Mesh: Non-uniform | Good agreement observed,<br>Good agreement observed |
| Kumar and Saini [34] | CFD Code: Fluent 6.3.26<br>Turbulence model: RNG k– ε<br>Mesh: non-uniform | Good agreement observed |
| Karmare and Tikekar [35] | CFD code: Fluent6.2.16<br>Turbulence model: RNG k– ε<br>Mesh: non-uniform | Good agreement observed |
| Soi et al. [36] | CFD code: Fluent<br>Turbulence model: RNG k– ε<br>Mesh: non-uniform | Nusselt number 715%<br>Friction factor 720% |
| Giri [37] | CFD code: Fluent<br>Turbulence Model: RNG k– ε<br>Mesh: Non-uniform | Good agreement observed |
| Rajput [38] | CFD code: Fluent<br>Turbulent model: RNG k– ε<br>Mesh: uniform | Good agreement observed |
| Sharma et al. [39] | CFD code: Fluent<br>Turbulence model: RNG k– ε<br>Mesh: non-uniform | Nusselt number 715%<br>Friction factor 715% |
| Sharma and Thakur [40] | CFD code: Fluent<br>Turbulent model: Realizable k–ε<br>Mesh: uniform | Nusselt number 73%<br>Friction factor 73% |
| Gandhi and Singh [41] | CFD code: Fluent<br>Turbulence model: k–ω<br>Mesh: Uniform | Good agreement observed except for the friction factor |

Table 1:

## IV. CONCLUSION

- This Paper reviews the investigation carried out by various investigators in order to enhance the heat transfer by use of artificial roughness.
- Use of artificially roughened surfaces with different type of roughness geometries of different shapes, sizes and orientation is found to be the most effective technique to enhance the heat transfer rate with little penalty of friction.
- Roughness in the form of ribs and wire matrix were mainly suggested by different investigators to achieve better thermal performance. Among all, rib roughness

was found the best performer as far as thermal performance is concerned.

- Correlations developed for heat transfer and friction factor for solar air heater ducts having artificial roughness of different geometries for different investigators are also shown in tabular form. These correlations can be used to predict the thermal efficiency, effective efficiency and then hydraulic performance of artificial roughened solar air heater ducts.

## V. SCOPE FOR FUTURE WORK

By using this type of heat exchanger we increase the efficiency of any machine and we'll also encourage the renewable energy sources. We know that there are limited sources of non-renewable energy sources.

Some of the important point future scopes of solar air heater are given below:

- Broken inclined rib roughness performed excessively well as compared to continuous inclined rib roughness and therefore the performance of multi V rib roughness shall be improved by introducing gap at suitable location.
- V ribs arranged in transverse direction which were tested recently showed outstanding performance and in future these V rib arrays could be arranged inclined to the direction of flow and subsequently arrays arranged in V type fashion could be tested in the quest of higher heat Transfer rates.
- It was observed that wedge shape rib roughness performed better than other rib shapes as far as heat transfer enhancement rate is concerned and therefore wedge shape ribs combined with grooves could be the better combination in order to get better enhancement rates in heat transfer.

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