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Thermal Performance of Three Sided Artificially Roughened Double Duct Parallel Flow Solar Air Heater

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Abstract **- A solar air heater is basically a heat exchanger, which intercepts the incident solar radiation, converts it into heat and finally transfers this heat to a working fluid for an end use system. The mode of air flowing in the ducts of a solar air heater is one of the most significant aspects concerned with solar air heater which dominantly affect. A double duct parallel flow artificially roughened solar air heater with three sides of the absorber plate is investigated in the current study. Unlike the conventional model of solar air heater with only one sided roughened absorber plate, a novel solar air heater with three artificially roughened absorber plate is used so that the surface area of the absorber plate is increased which ultimately increases the rate of heat transfer. Additionally, a double duct parallel flow arrangement through inner and outer duct of solar air heater is considered order to enhance the heat transfer rate. A numerical investigation of the heat transfer and friction factor characteristics of a double duct parallel flow three sided artificially roughened solar air heater has been carried out. A commercial finite volume CFD code ANSYS FLUENT is used to simulate turbulent air flow through artificial roughened solar air heater. Governing equations of the fluid flow and heat transfer i.e. Navier-Stokes equation and energy equation are solved with RNG k-ε turbulence model. Nine different configuration of square rib are studied with relative roughness pitch (P/e = 5-10) and relative roughness height (e/D = 0.03-0.06). The Reynold number of the flow is varied from 2500 to 16000.**

Keywords: Solar Heater, CFD, Navier-stokes equation, ANSYS FLUENT

I. INTRODUCTION

A. Solar air heater

A solar air heater is basically a heat exchanger, which intercepts the incident solar radiation, converts it into heat and finally transfers this heat to a working fluid for an end use system [2]. Solar air system is a type of system which collects solar energy and transforms it into heat. The general idea is that the air is flowing through solar collector and heat from sun naturally raises the temperature of the air. The collector has on first layer of glazing which is exposed to sun. Circulation of the air in the building can be by natural driving forces (buoyancy effect) or by fan which is more certain. Optionally the fan can be powered by solar cell mounted on collector. Solar air heaters of many types have been developed in India . The application of these air heaters are limited to a few demonstration projects for food dehydration, and space heating. Space heating by solar air heaters and their use for natural ventilation are also common applications of solar air heater. Few major applications of the solar air heater are listed below:

1. Solar drying [3]: In India solar drying is employed for drying few major crops.

a. Paddy drying: The most adopted drying method after parboiling is the traditional open sun drying. The moisture content is reduced up to 16%. Hot air drying with temperatures between 60°C and 80°C is useful and for that solar air heaters in standalone mode or in hybrid mode can be employed.

b. Timber drying: The solar kilns are employed to season timber for handicrafts, furniture, doors and windows. The feedback obtained was satisfactory and the economics are very attractive.

c. Drying of cash crops: Some of the cash crops like Tea, Coffee, Spices, Cardamom and Cashew are major foreign exchange earners. Use of solar air heaters for drying process in the production of these cash crops can provide an impulse to the solar energy programme in the country.

2. Space heating [3]: Space heating is required in high mountain regions in the North and North-Eastern Himalayas during the winter periods. Natural convection based solar air heaters, known as thermo-syphon air panels have been employed for space heating in Leh. Large scale experimentation with solar air heaters for space heating has not been undertaken in India so far.

B. Solar collectors

A solar collector is a special kind of heat exchanger that transforms solar radiant energy into heat. A solar collector differs in several respects from more conventional heat exchangers. The latter usually accomplish a fluid-to-fluid exchange with high heat transfer rates and with radiation as an unimportant factor. In the solar collector, energy transfer is from a distant source of radiant energy to a fluid. The flux of incident radiation is, at best, approximately 1100 W/m^2 (without optical concentration), and it is variable. The wavelength range is from 0.3 to 3 μ m, which is considerably shorter than that of the emitted radiation from

most energy-absorbing surfaces. Thus, the analysis of solar collectors presents unique problems of low and variable energy fluxes and the relatively large importance of radiation.
Broadly solar collector can be classified as:

1. Flat plate collectors.
2. Concentrating Collectors.

1. Flat plate collectors
Flat plate collectors are most widely used as solar collectors due to its easily manufacturing and low cost. They are mechanically simpler than concentrating collectors. They are in the application as early as in second world war times used by Germany. Flat-plate collectors can be designed for applications requiring energy delivery at moderate temperatures, up to perhaps $100^{o}C$ above ambient temperature. They use both beam and diffuse solar radiation, do not require tracking of the sun, and require little maintenance. The major applications of these units are in solar water heating, building heating, air conditioning, and industrial process heat. Passively heated buildings can be viewed as special cases of flat-plate collectors with the room or storage wall as the absorber.

2. Concentrating collectors
To deliver energy at temperatures higher than those possible with flat-plate collectors. Energy delivery temperatures can be increased by decreasing the area from which heat losses occur. This is done by interposing an optical device between the source of radiation and the energy-absorbing surface. The small absorber will have smaller heat losses compared to a flat-plate collector at the same absorber temperature. Many designs have been set forth for concentrating collectors. Concentrators can be reflectors or refractors, can be cylindrical or surfaces of revolution, and can be continuous or segmented. Receivers can be convex, flat, or concave and can be covered or uncovered. Many modes of tracking are possible.

II. LITERATURE REVIEW ON SOLAR AIR HEATERS

A comprehensive literature survey on solar air heaters has been given in this section. A summary of the findings in the history of solar air heater is presented.

A. Augmentation of heat transfer from the absorber plate

The performance of a flat plate collector either operated under single or double air pass has been found to depend strongly on the rate of incident solar radiation, the losses from the absorber surface and the rate of heat transfer from absorber plate to the air. The poor heat transfer rate from the absorber plate to air in the duct results in relatively higher absorber plate temperature leading to higher thermal losses to the environment. These losses can be reduced by lowering the absorber plate temperature by increasing the heat transfer coefficient between absorber and air. There are several way by which the temperature of the absorber can be reduced. This objective can be achieved by using:

1. extended surfaces on the absorber surfaces,
2. porus media air flow duct and
3. artificial roughness.

1. Extended surfaces

The extended surfaces in the form of fins , fins plus baffles or v-corrugations on the absorber plate help in two ways; firstly by increasing turbulence and secondly by increasing the area of heat transfer and hence more heat transfer occurs. In an experimental study by Bevil Brandt [4] on two square collectors with absorber plate having 96 parallel fins of aluminum 61 cm long 6.35 cm high and 0.635 cm apart , a gain in efficiency has been reported.

Kuzay et al. [5] investigated the performance of solar air heaters with straight and staggered fins. The staggered arrangement was fabricated from U-shaped aluminum fins, 2.5 cm high with the U-section tapered and the spacing ranging from 0.6 cm to 1.0 cm. The staggering was done after every 1.9 cm. Efficiencies of 74% and 49% respectively were reported with temperature rise of 26 °C and 73 °C.

Matrawy [6] showed that the efficiency of solar air heater can be enhanced by using the metal vanes, which are attached between the absorber and bottom plate of the collector. The comparison between the performance of a collector having box frame absorber and one having a finned plate absorber was carried out. The result show that a higher efficiency can be achieved with the use of metal vanes.

Ryan et al. [7] investigated the thermal performance of flat plate, v-corrugated and finned solar air collectors. It was found that the thermal performance of v-groove collector is 7–12% higher efficiency than flat-plate collectors. Moreover, study was carried out to determine the optimum conditions of the three collectors. Results show that the thermal efficiency of the v-groove collector is approximately 70% at a mass flow rate of 0.031 kg/m^2s. From many years, several studies using different corrugated absorber plate were reported in the literature.

Theoretical and experimental investigations were performed in order to investigate the thermal performance of solar air collector under single [8–19] or double air pass operations. Though, thermal performances of such solar collectors were compared with flat plate solar collectors. Many studies have depicted that use of corrugated absorber plate as an absorber is one of the best techniques to enhance thermal performance of the solar collectors by increasing the air turbulence and heat transfer area to the air. Hence the use of corrugated absorber plate is an effective way of enhancement of heat transfer in a solar air heater.

2. Porous absorber

The nature of solar energy is intermittent, thus storage is required for uninterrupted supply of heated air in order to match the needs. Packed beds are generally used for storage of thermal energy from solar air heaters. A packed bed is a volume of porous media obtained by packing particles of selected material into a duct. A number of studies carried out on packed beds for their performance analysis are reported in the literature. These studies included the design of packed beds, materials used for storage, heat transfer enhancement, flow phenomenon and pressure drop through packed beds. Solar collectors with porous absorbers packed beds have been found to be more efficient as compared to conventional collector because they have high heat transfer rates. In such an absorber the solar radiation penetrates to greater depths and is absorbed gradually depending on the density of the packing.

Heat losses associated with a higher absorber temperature are reduced resulting in an improvement in the thermal efficiency of the collectors. Use of porous beds for the enhancement of collector performance has been shown to have certain specific advantages over the other methods. Packed bed solar air heater having its bed packed with semi-transparent materials like glass beads, porcelain beads and glass tubes was investigated, theoretically and experimentally by Hasatani et al. [20]. The energy balance equations were solved numerically to obtain the collector performance. Based on the analysis and experimentation, it was reported that solar air heater having semi-transparent materials for the heat collector-cum-storage has 15–20% higher efficiency of the energy collection as compared to that of a smooth collector.

Bhagoria et al. [21] have used mild steel chips as a packed bed material and compared the performance of the packed bed solar collector with that of marble chips packed bed solar air collector. It was obtained that steel chips packed bed solar collector give better performance that marble chips packed bed solar air collector. Studies performed using these packed bed materials indicates that thermal performance of such solar air collectors is better than flat plate solar air collectors.

3. Artificial roughness on the surfaces

Efficiency of flat plate solar air heater is low because of low convective heat transfer coefficient between absorber plate and flowing air which in turn increases the absorber plate temperature, leading to higher heat losses to the environment. The low value of heat transfer coefficient is generally attributed to the presence of a viscous sub-layer adjacent to the wall, which can be broken without disturbing the turbulent core to keep the pressure drop at low level by providing the absorber plate with artificial roughness in the form of fine wires, ribs and protrusion of different geometries [28-42].

III. METHODOLOGY OF ARTIFICIAL ROUGHNESS

The concept of artificial roughness was given by Joule [22]. Author enhances the heat transfer coefficient for in-tube condensation of steam. The artificial roughness on the absorber plate breaks the laminar sub layer region which is the barrier to the heat transfer between the flowing air and heated absorber plate. Artificial roughness on the absorber plate generates the turbulence which enhances the fluid mixing hence increase in the heat transfer rate but pumping power required for the flow to occur. As the air flows over the heated absorber, a viscous sub-layer (laminar) appears in the vicinity of the absorber. This sub-layer is resistant to the heat transfer between the absorber and the fluid (air). To break it, artificial roughness are provided on the absorber surface. The obstacles or rough elements, whatever their shape, are generating secondary flows or re-circulations, which result in two separation zones on both sides of the obstacle. The generated vortices are responsible of the turbulence and thus increase the heat transfer and pressure losses. Secondary fluid circulation promote a better convective heat transfer. However, it is desirable that the turbulence takes place only in the near-wall region, that is to say within the laminar sub-layer, where the heat transfer takes place, to minimize friction losses, Bhatti [22]. This is achieved by keeping the height of the rough element relatively small in comparison to duct dimensions. For remind, the laminar sub-layer thickness is given by [23].

$$\delta_t = 5\frac{\upsilon}{u_*}$$

for a smooth surface, we have [24],

$$u^+ = u\sqrt{\frac{\tau_w}{\rho}}$$

$$y^+ = y\frac{\sqrt{\frac{\tau_w}{\rho}}}{\nu}$$

where,

$\tau_w = \rho u^{*2}$ is called shear stress at the laminar wall

$\sqrt{\frac{\tau_w}{\rho}} = u^*$ is called frictional velocity,

u^+ is known as non dimensional velocity,

y^+ is non dimensional distance from wall,

υ is kinematic viscosity

and we have,

$u^+ = y^+$ for laminar sub layer, $y^+ \leq 5$

$u^+ = 5 \ln y^+ + 3.5$ for transition layer(buffer layer) , $5 \leq y^+ \leq 30$

$u^+ = 2.5 \ln y^+ + 5.5$ for turbulent boundary layer, $y^+ \geq 30$

There are some basic dimensionless geometrical parameters that are used to characterize roughness [25]:

Relative roughness pitch (P/e): it is defined as the ratio of distance between two consecutive ribs (p) and height of the rib (e).
Relative roughness height (e/D): Relative roughness height (e/D) is the ratio of rib height (e) to equivalent diameter of the air duct (D).

Angle of attack (α): Angle of attack is inclination of rib with direction of air flow in duct.
Aspect ratio (W/H): It is the ratio of duct width to duct height. This factor also plays a very crucial role in investigating thermo-hydraulic performance.

The turbulent flow induced by presence of obstacles is very complex to study that is why it is very difficult to develop analytical models to predict the fluid motion. One of the first study reported on the rough surfaces was provided by Joule [22] to enhance heat transfer coefficient for steam in tube condensation. We could also cite Nikuradse [26] who made an attempt to approach the velocity and temperature distribution on a rough surface . Webb and Eckert [27] developed heat transfer and friction factor correlations for turbulent air flow in tubes having rectangular repeated rib roughness based on the law of wall similarity and application of the heat-momentum transfer analogy to flow over rough surface having relative roughness height of 0.01–0.04 at a relative roughness pitch of 10–40 and range of Prandtl number of 0.71–37.6.

A. Roughness geometry used in solar air heater ducts

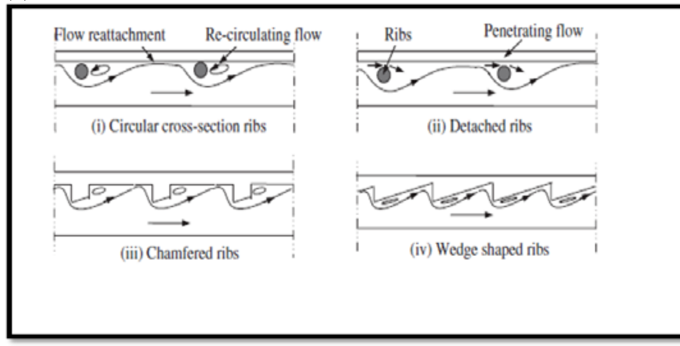
To enhance the thermal performance of solar air heater several types of roughness geometry shapes are employed on the absorber plate. These roughness are classified as regular roughness and irregular roughness. Regular roughness are of many types depending on the shape, orientation and arrangement of the roughness elements on the absorbers plates. The regular geometric roughness may be classified on the basis of shape of rib (rectangular, circular, wedge, chamfered), orientation (transverse, inclined, V shape), arrangement on surface (continuous, discrete, staggered), cavity (groove, pits/dimples) and impermeable or porous rib.

Some of the experimental as well as numerical investigations on the roughness geometry are cited to study the effect of artificial geometric roughness on the heat transfer and friction factor. This includes both regular and irregular roughness of geometry.

1. Transverse, Inclined, V-discrete and V-continuous shaped roughness geometry

Karwa et al. [28] investigated experimentally thermo-hydraulic performance of a solar air heater with 60° V-down discrete rib roughness on the airflow side of the absorber plate along with that for a smooth duct air heater as shown in fig. 1 (a) and 1 (b). The enhancement in the thermal efficiency due to artificial roughness on the airflow side of the absorber plate has been found to be 12.5 - 20% depending on the

(a)



(b)

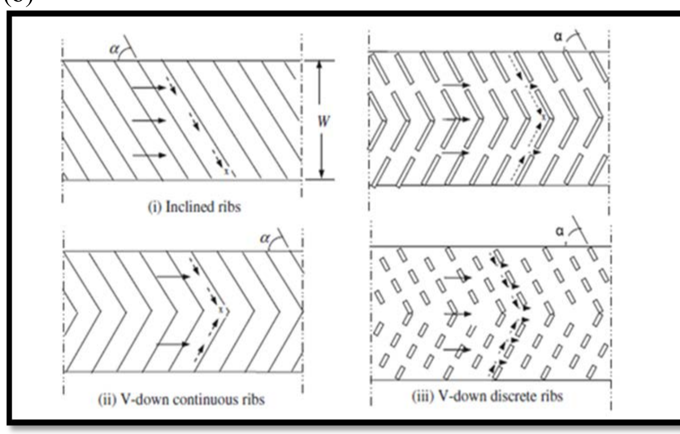


Fig. 1 Effect of rib shape (b) Effect of rib orientation [28].
flow rate, higher enhancement is at the lower flow rate, which is attributed to the enhancement in the heat transfer coefficient due to the employment of the roughness.

IV. RESEARCH METHODOLOGY

A. Theory of the Novel Solar Air Heater

In the present study, a novel solar air heater is considered for the heat transfer enhancement. In convention model of solar air heater the provision of the artificial roughness of various geometries on the absorber plate have remained limited only to one side (top side) of solar air heater duct. But in current study, artificial roughness on the three sides of solar air heater design along with parallel flow arrangement is considered. Two air stream of equal Reynold number through two ducts is considered for heat transfer enhancement. First of all optimization of the duct is done for the maximum thermal efficiency. Three cases are studied for the double duct optimization on the basis of maximum thermal efficiency:

1. Same hydraulic diameter of the inner and outer ducts $(D_{h1} = D_{h2})$,
2. Hydraulic diameter of the outer duct is greater than inner ($D_{h1} > D_{h2}$) and
3. Hydraulic diameter of the outer duct is less than inner duct ($D_{h1} < D_{h2}$).

After optimizing the hydraulic diameter of double duct solar air heater for the maximum thermal efficiency, transverse square sectioned ribs are employed on the both sides of the optimized duct. The square sectioned ribs are employed in a transverse continuous fashion along the length of absorber plate.

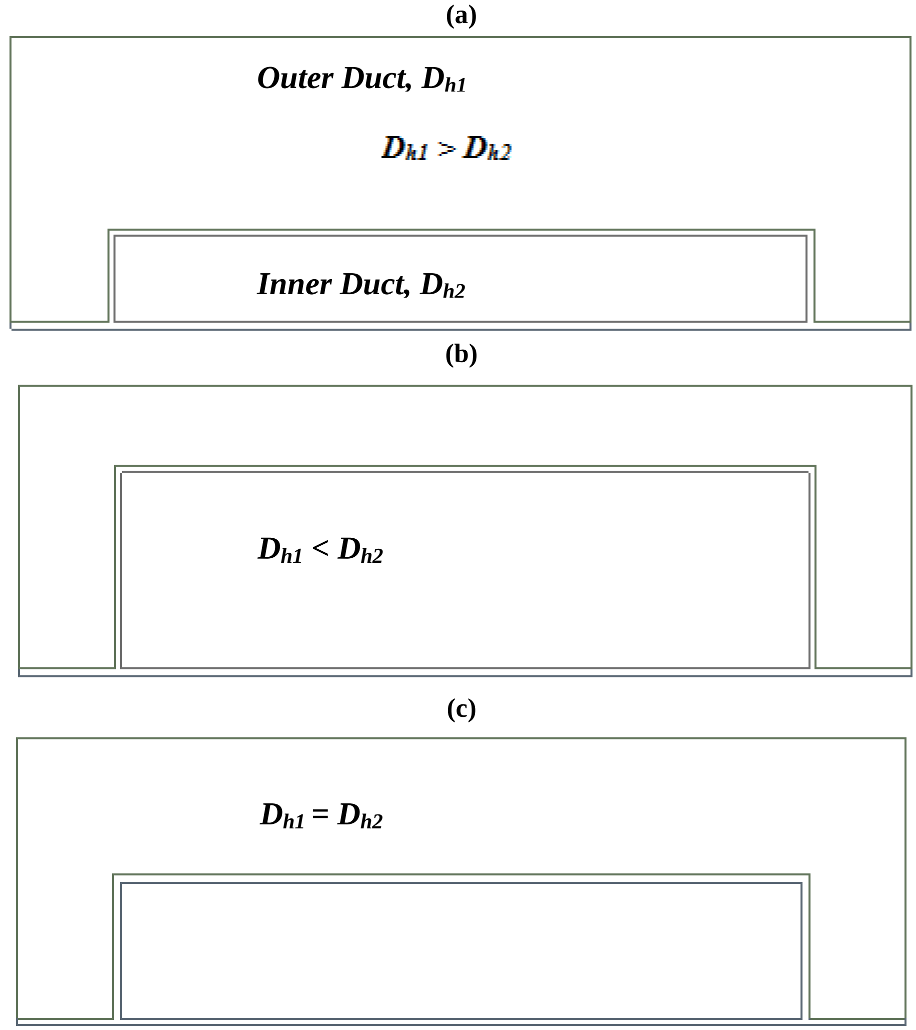


Fig. 2 Optimization of the double duct solar air heater (a) hydraulic diameter of the outer duct is greater than inner duct ($D_{h1} > D_{h2}$), (b) hydraulic diameter of the outer duct is less than inner duct ($D_{h1} < D_{h2}$) and (c) hydraulic diameter of the outer duct is equal to inner duct ($D_{h1} = D_{h2}$).

B. Mathematical Model of Solar Air Heater

Considering the air flow in the channel with heat transfer, the mathematical model is composed of the conservation equations of mass, momentum and energy for incompressible flow in three dimensions with the following assumptions:

1. The flow is turbulent, steady state and incompressible.
2. The thermo-physical properties of the air are supposed to be constant.
3. The thermal conductivity of the walls and ribs is supposed to be constant.

Governing equation of the fluid flow and heat transfer in solar air heate r are as follows:

Continuity equation:

$$\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0\right)$$

Momentum equations:
x-momentum equation:

$$\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{1}{\rho}\left(\frac{\partial p}{\partial x}\right)+\upsilon\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \qquad (2.2.a)$$

y- momentum equation:

$$\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{1}{\rho}\left(\frac{\partial p}{\partial y}\right)+\upsilon\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \qquad (2.2.b)$$

z- momentum equation:

$$\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{1}{\rho}\left(\frac{\partial p}{\partial z}\right)+\upsilon\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \qquad (2.2.c)$$

Energy equation:

$$\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \qquad (2.3)$$

where,

$$\alpha=\frac{k}{\rho C_p}$$

α is called thermal diffusivity.
Since the flow is turbulent, we used Reynolds decomposition to write,

$$u = \bar{u} + \acute{u}$$

where, $\bar{u}$ - mean velocity

$\acute{u}$ - fluctuating velocity component
substituting value of u from above equation to continuity equation and x- momentum equation ,we get,

$$\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0\right)$$

and

$$\rho\left(\frac{\partial \bar{u}\bar{u}}{\partial x}+\frac{\partial \bar{u}\bar{v}}{\partial y}+\frac{\partial \bar{u}\bar{w}}{\partial z}\right)=-\left(\frac{\partial p}{\partial x}\right)+\mu\left(\nabla^2\bar{u}\right)-\frac{\partial\left(\rho\overline{\acute{u}^2}\right)}{\partial x}-\frac{\partial\left(\rho\overline{u'v'}\right)}{\partial x}-\frac{\partial\left(\rho\overline{u'w'}\right)}{\partial x} \qquad (2.5)$$

eqn. 2.4 and 2.5 are called RANS equations (Reynolds-averaged Navier Stokes Equations). where, $(-\rho\overline{u'v'})$ represents the Reynolds stress tensor and must be modeled correctly in order to get simulation results close to actual flow conditions.Hence above described governing equation of the fluid flow and heat transfer for solar air heater are discretized in FLUENT solver using finite volume approach.

C. CFD Approach to Present Study

In the present study three dimensional turbulent flow solar air heater with transverse continuous square sectioned rib on the both sides of the absorber plate is simulated. A general purpose CFD code, ANSYS FLUENT a co mmercial CFD package, is chosen for fluid flow and heat transfer simulation of artificially roughened solar heater. A CFD tool Ansys-fluent is used to solve the basic governing equation of the fluid flow. Ansys-Fluent implements finite volume method to solve the governing equation of the fluid flow.ANSYS Fluent employment process in the present work is shown in fig.2.2. Sketch of the computation domain is done in the design modeler. All the geometric parameters are defined in the design modeler and sketch of the computational domain is exported to ANSYS ICEM CFD meshing where computational domain is divided into number of grids which may be structured or unstructured depending upon the complexity of the geometry . At last the governing equations are solved in the Fluent solver with the suitable algorithms.

D. Computation Solution Domain of The Problem

Computational domain of the proposed solar air heater is three dimensional double duct solar air heater with square sectioned rib employed on the both sides of the absorber plate is shown in fig. 2. In the present work, transverse continuous square sectioned ribs are considered. The square rib height has been taken as 1 mm, 1.4 mm and 2 mm, so that laminar sub-layer would be of the same order as of roughness height and fin/flow passage blockage effect can be avoided.

Present CFD analysis has been performed on nine different configurations of square sectioned transverse rib roughness on the absorber plate, at five different values of Reynolds number. Thus, a total of forty five different combinations of roughness height (e), roughness pitch (P) and Reynolds number (Re) have been investigated for the thermal performance. The range of Reynolds number has been chosen as 2500-16,000 with five different values.

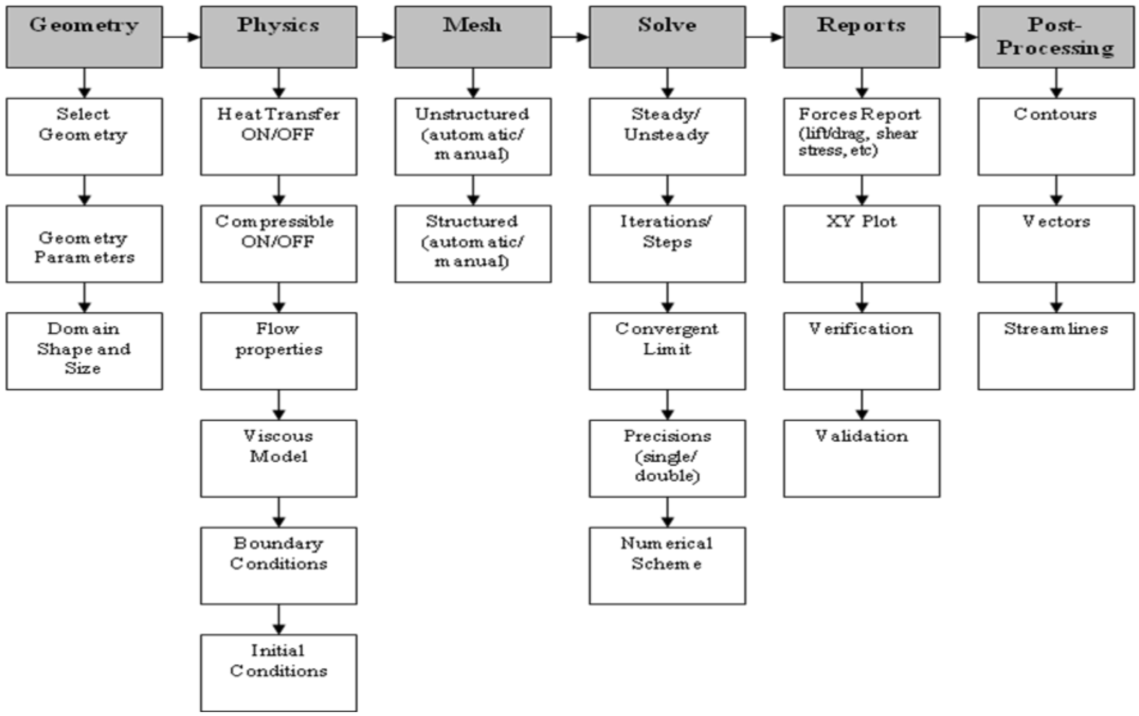


Fig. 3 Ansys Fluent employment process

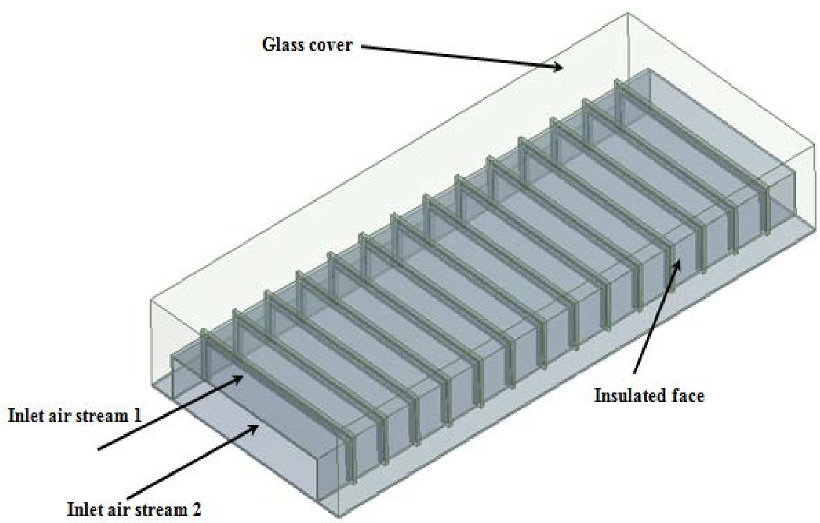


Fig. 4 Sketch of the computational Domain

Solar air heater is operated under three set of relative roughness height viz. 0.03, 0.042 and 0.06 under five different values of the Reynold number. Similarly, rib pitch is also varied as 10, 15, and 20 to examine the effect of rib pitch on the fluid flow and heat transfer characteristics.

On the top of the computational domain solar radiation fall on the glass cover. Solar radiation model named "Discrete ordinate" is used in order to apply solar loading on the glass cover.

Global radiation of 1000 W/m^2 falls on the glass cover. The absorptivity of the absorber plate should as high as possible so that all of the incoming radiation should be absorbed so that temperature of the absorber plate is increased. The duct wall, absorber plate and roughness material are homogeneous and isotropic. No slip boundary condition is given to the wall in contact with the fluid in the model.

The operating parameters employed in the computational domain are listed in table II. The working fluid in all the cases is air and the values of the thermo-physical properties of air has been assumed to be constant and evaluated at a temperature 300 K.

TABLE I GEOMETRICAL PARAMETERS OF THE PROPOSED SOLAR AIR HEATER

Parameters (Solar air heater duct Parameters)	**Values**
Collector length, L	300 mm
Duct width, W	130 mm
Hydraulic diameter of duct (inner and outer)	33.33 mm
Height of solar air heater duct, H	41.10 mm
Height of inner rectangular duct	20 mm
Rib height, e	1-2 mm
Number of glass covers, N	1

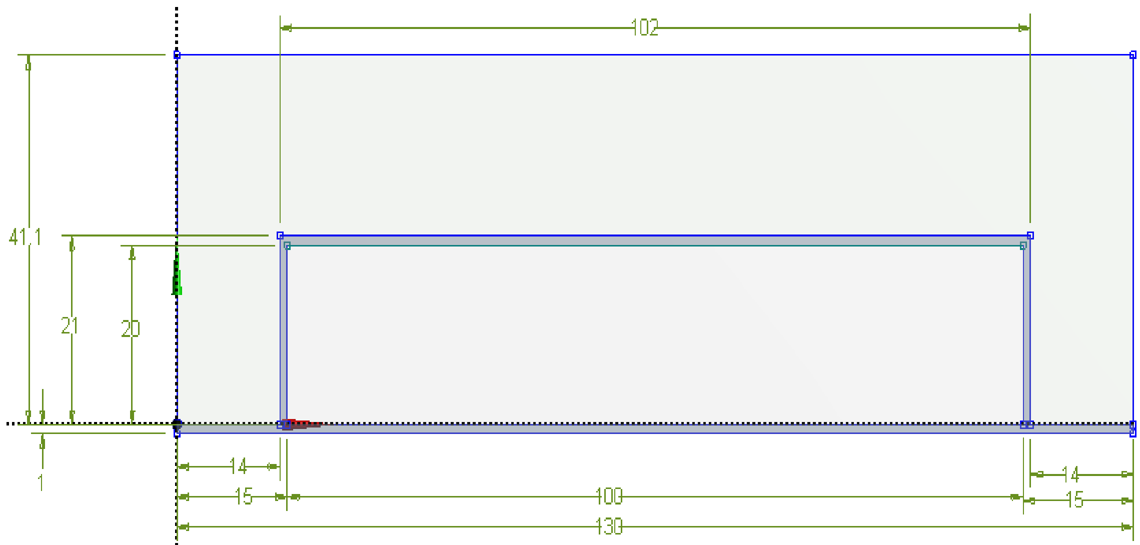


Fig. 5 Front view of proposed solar air heater with all dimensions in mm

TABLE II NINE DIFFERENT CONFIGURATION OF SQUARE RIB USED IN THE PRESENT CFD INVESTIGATION

Hydraulic diameter of the duct, inner and outer (mm)	**Rib height, e (mm)**	**Relative roughness height, e/D**	**Rib pitch, P (mm)**	**Relative roughness pitch, P/e**
33.33	1	0.03	10	10
			15	15
			20	20
33.33	1.4	0.042	10	7.14
			15	10.71
			20	14.29
33.33	2	0.06	10	5
			15	7.5
			20	10

V. RESULTS & DISCUSSIONS

The heat transfer enhancement and pressure drop characteristics of a d ouble duct solar air heater using artificial roughness are investigated by using CFD approach. The double duct of the solar air heater is firstly optimized on the basis of hydraulic diameter for the maximum thermal efficiency, secondly for the optimized d uct the effect of Reynolds number, relative roughness pitch (P/e) and relative roughness height (e/D) on the average heat transfer and fluid friction are considered in this chapter. Moreover, the results have been compared with those obtained in case of smooth ducts operating under similar operating conditions to discuss the enhancement in heat transfer and fluid flow characteristics on account of artificial roughness. Thermal performance of solar air heater is then delineated in terms of Nusselt number and friction factor.

A. Validation of the Proposed Solar Air Heater Model

As we know that validation is the most important part in any numerical investigation in order to build confidence in study. Hence firstly selection of turbulence models is done by comparing the numerical results with the corresponding empirical correlation for smooth solar air heater. Secondly validation of proposed solar air duct is made with available literature. For validation dimension of smooth duct is taken as in accordance with Yadav et al.

1. Selection and validation of the appropriate turbulence model for CFD analysis

In order to select appropriate turbulence model for the simulation of artificially roughened solar air heater, the Nusselt number predicted by five different turbulence models namely, Standard k-ε, RNG (Renormalization-group) k-ε, Realizable k-ε, Standard k-ω and SST (Shear stress transport) k-ω model are compared with the empirical correlation available for smooth duct of a solar air heater i.e. Dittus-Boelter equation and it is found that RNG -(Renormalization-group) k-ε model gives closer result to Dittus-Boelter equation with a maximum deviation of 9.24%. Fig. 3.1 shows the comparison between Nusselt number predicted using different CFD turbulence model with Dittus-Boelter empirical correlation for smooth duct of a solar air heater.

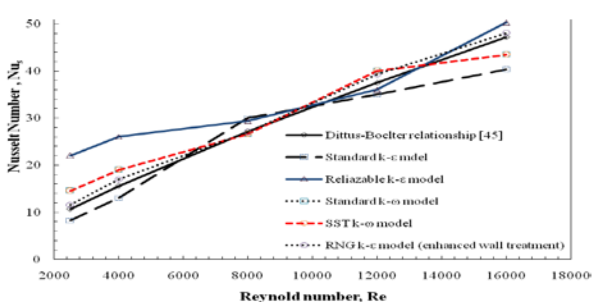


Fig. 6 Comparison between Nusselt number predicted using different CFD turbulence model with Dittus-Boelter empirical correlation for smooth duct of a solar air heater.

2.*Validation of the inner and outer smooth duct with Dittus Boelter empirical correlation*

Both inner (rectangular duct) and outer smooth ducts of double duct solar air heater are validated with Dittus - Boelter empirical correlation in order to validate the numerical study in case of a smooth duct.

The present analysis is for a novel type of solar air heater, and therefore, direct validation of the numerical data could not be possible. However, in light of previous numerical data of the heat transfer parameter in case square transverse ribbed rectangular duct solar air heater of Yadav et al. is analyzed for the same operating conditions. The heat transfer parameter is found to be in agreement with Yadav et al. at a relative roughness height (e/D) of 0.03 and 0.042 with corresponding relative roughness pitch (P/e) of 10 and 7.14 respectively. Verification of numerical methods and CFD code is carried out through grid independent test. A rigorous grid refinement study is performed, which also a methodology for verification of CFD calculations.

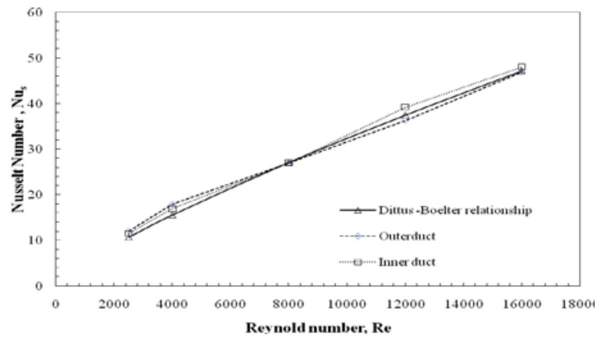
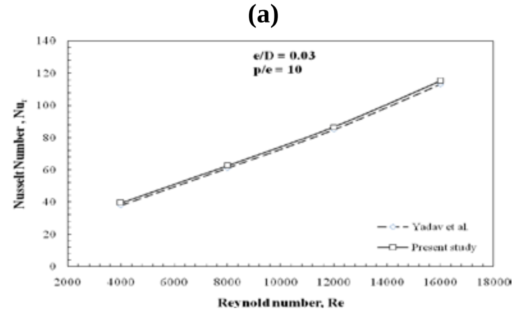


Fig. 7 Validation of inner and outer smooth duct of double duct solar air heater with Dittus-Boelter empirical correlation using RNG k-ε turbulence model.

3 Verification and validation of the proposed artificially roughened solar air heater

Verification and validation are essential methods to be used during the development of simulation of physical processes using CFD techniques.

(a)



(b)

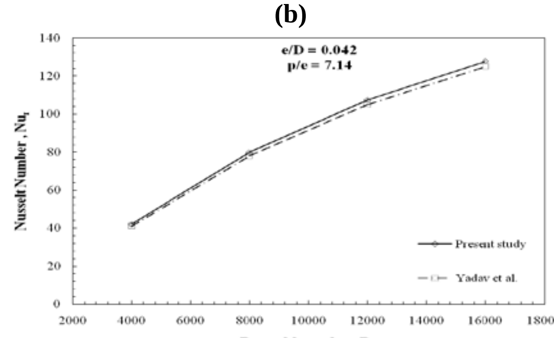


Fig. 8 Validation of CFD model with Yadav et al. for transverse rib roughness with (a) e/D =0.03, P/e = 10 and (b) e/D =0.042, P/e = 7.14

Tests for the confirmation of grid independence of the proposed model is carried out by increasing the grid density until difference in two consecutive sets of results is less than 1%. For grid independence test, the number of cells is varied from 340,810 to 750,890 in three steps. Three different grid distributions are tested on square sectioned transverse ribs, with rib height of 1.4 mm, pitch of 10 mm and Reynolds number of 12,000, to ensure that the calculated results are grid independent.

B. Results of Double Duct Solar Air Heater with Square Transverse Continuous Ribs

In this section results of the double duct solar air heater are presented. First of all, results of variation of hydraulic diameter for the maximum thermal efficiency are presented comprehensively. Then the heat transfer and fluid flow characteristics in terms of Nusselt number and friction factor are described.

1. Optimization of double solar air heater

The effect of hydraulic diameter on the thermal performance of double duct solar air heater is considered. Three cases are studied for the double duct solar air heater on the basis of hydraulic diameter for the maximum thermal efficiency:

1. Same hydraulic diameter of the outer and inner ducts ($D_{h1} = D_{h2}$),
2. Hydraulic diameter of the outer duct is greater than inner duct ($D_{h1} > D_{h2}$),
3. Hydraulic diameter of the outer duct is less than inner duct ($D_{h1} < D_{h2}$).

As discussed in previous chapter, hydraulic diameter of the both duct is varied in order to get optimized duct for the current study. Thermal efficiency is calculated for all of the above three cases discussed at three different mass flow rates viz. 0.01, 0.015 and 0.02 and thermal efficiency is found to be maximum when the hydraulic diameter of the inner and outer ducts is same i.e. $D_{h1} = D_{h2}$. The results in case of varied hydraulic diameters is shown in fig. 9.

Hence it is found that when the hydraulic diameter of inner and outer duct is kept same, maximum thermal efficiency of the solar air heater is achieved and thus this duct is used for employment of artificial roughness.

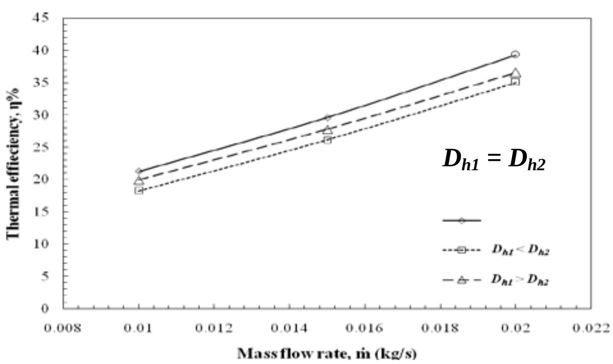


Fig. 9 Optimization of hydraulic diameter for inner and outer duct of solar air heater

VI. CONCLUSIONS

A numerical investigation on heat transfer and fluid flow characteristics of proposed solar air heater is performed. A detailed description of the average heat transfer and fluid flow characteristics in terms of Nusselt number and friction factor, are obtained. The effects of Reynolds number, relative roughness pitch (P/e) and relative roughness height (e/D) on the heat transfer and fluid flow process are discussed. The following conclusions has been drawn on the basis of the present numerical investigation :

1. The use of double duct and three sided artificially roughened solar air heater in the form of square rib roughness effectively enhances the convective heat transfer coefficient , therefore the rate of heat transfer in comparison with smooth solar air heater.
2. Renormalization-group (RNG) k-ε turbulence model gives results very close to the Dittus-Boelter empirical correlation for smooth duct of a solar air heater which yields confidence in the prediction done by numerical analysis in the present study.
3. For the maximum thermal efficiency of double duct parallel flow solar air heater, the hydraulic diameter of both inner and outer duct should be equal.
4. The maximum enhancement of average Nusselt number has been found to be 11.30 times higher than that of a smooth duct for the relative roughness pitch of 10 and relative roughness height of 0.06 at Reynold number of 4000.

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