DECLARATION

We, hereby declare that the dissertation report entitled **"CFD Simulation for rectangular solar air heater having spherical and inclined rib protrusions as roughness elements"** is carried out under the supervision of **Dr. Ravi Kant Ravi**, for the partial fulfillment of degree of Bachelor of Technology in **Mechanical Engineering** is an authentic record of our research work to the best of our knowledge. The matter embodied in this dissertation report has not been submitted to any other University/ Institute for the award of any degree or diploma. Any other sources of information that have been used are acknowledged properly.

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CERTIFICATE

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(Signature of the Internal Examiner) **(Signature of the External Examiner)**

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ABSTRACT

Energy is available in multiple forms and plays a significant role in worldwide economic growth and industrialization. The growth of world population is accompanied with rising material needs and higher rate of energy usage. Continuous energy usage characteristics of past years cannot continue indefinitely as energy resources of earth are exploitable. On the other hand, environmental degradation with use of fossil fuels is a menace to the life. Thus, development of renewable energy sources receive the importance.

Among many alternations, the solar energy stand out as noticeable energy source for meeting the energy demand. It is considered as suitable renewable energy source due to its huge potential. The easiest way to utilize solar energy for heating application is to convert it into thermal energy. Thermal performance of the conventional solar air heaters are relatively very low due to high thermal losses from the collector and less heat transfer coefficient between flowing fluid and heated plate. Several efforts have been made to enhance the performance of solar air heater by applying various designs techniques and flow provisions.

From the literature review it has been found that although a considerable amount of work has been carried out on roughened solar air heaters having different shapes and geometric parameters. However it has also been found that most of the work on solar air heaters have been focused on experiments and few work is available on CFD simulation of solar air heater with combination of two different shapes of protrusion ribs.

In present work, a numerical investigation based on CFD analysis has been carried out to analyze the heat transfer and fluid flow behavior through an artificially roughened solar air heater duct. A combination of spherical and inclined rib protrusions having roughness parameters like relative roughness height (e/D) as 0.04 and relative roughness pitch (p/e) as 20 and operating parameters as reynolds number varied from 4000-12000 have been investigated. Various results have been obtained for the roughened duct and compared with the solar air heater without roughness. It has been observed that there is a considerable enhancement in nusselt number and friction factor as a result of roughness element. In order to prove the advantage of roughness geometry the hydraulic performance has also been investigated.

NOMENCLATURE

D	Hydraulic diameter of rectangular duct, m
e	Rib height, m
e/D	Relative roughness height
f_s	Friction factor without rib surface
f	Friction factor of roughened surface
f/f_s	Friction factor ratio
H	Depth of solar duct, m
h	Heat transfer coefficient, W/m^2K
Nu	Nusselt number of roughened surface
Nu_s	Nusselt number without rib surface
Nu/Nu_s	Nusselt number ratio
P	Pitch of the rib, m
P/e	Relative roughness pitch
Pr	Prandtl number
Re	Reynolds number
α	Angle of attack

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CHAPTER 1

INTRODUCTION

1.1 ENERGY

Energy is present everywhere. Every subdivision of an atom to present in a molecule of any matter or an object possess energy. Energy is that quantitative property which must be transferred to an object in order to perform work on or to heat the object. Energy is also defined as the capacity to do work. The sun is the primary source of energy for earth.

Energy is found in various forms such as potential energy, kinetic energy, solar energy, wind energy, mechanical energy, heat energy, sound energy, etc .

1.1.1 Sources of Energy

Energy can be obtained from various sources. The sources of energy can be classified as renewable sources of energy and non-renewable sources of energy.

1.1.1.1 Renewable Sources of Energy

Renewable sources can be used again and again. Renewable sources of energy are replenished constantly such as solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels. The renewable sources of energy will not vanish with time as they as replenished constantly.

1.1.1.2 Non-renewable Sources of Energy

Coal, natural gas, petroleum etc. are the non- renewable sources of energy. They are also known as fossil fuels. Fossil fuels are known as non-renewable sources of energy because they do not get replenished with time and their supply is limited. The non-renewable sources of energy take a long amount of time to form and hence these resources will vanish some-day. Most of the energy produced is obtained from the non-renewable energy sources only.

1.2 ENERGY CRISIS

Energy crisis is a major problem that the world is facing today which is causing depletion of natural resources due to increasing demand of power. The natural resources which are available to the mankind are in limited supply and take a very long time to replenish. The huge demand of energy is causing an impact on the pricing of conventional resources of energy and there by impacting the prices of other commodities. Energy is considered as prime agent in the generation of wealth and significant factor in economical development. Man has used the energy at an increasing rate for his sustenance & wellbeing ever since he came on the earth. The importance of energy in economical development is recognized universally and historical data verify that there is a strong relationship between the availability of energy and the economical activities. The per capita annual energy consumption in USA is 8000 kWh in comparison of 400 kWh in India shows that USA having 7% of world's population consumes 32% of total world's energy, while India with 20% population hardly gets 1% of world energy share.

Conventionally, energy is extracted from fossil fuels, crude oil systems and fuel wood. However, in the recent years oil crisis triggered off speculation on certain long term changes in the world economy as well as ecology. The present energy scenario is biased towards the conventional energy sources though it has been established that these are finite in nature, economically out of reach to many developing countries and cause environmental degradation. This concern has focused worldwide attention on the potential of harnessing renewable energy resources. The various sources of energy being used by humans is shown below in Fig 1.1,

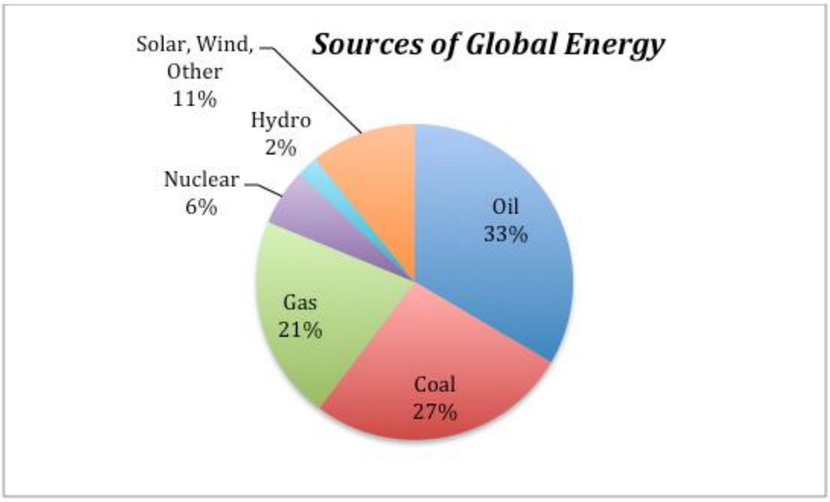


Fig 1.1: Sources of global energy [1].

1.2.1 Causes of Energy Crisis

a) Increasing Population

b) Environmental Pollution

c) Over dependence on Conventional Sources of Energy

d) Less use of Renewable Sources of Energy

e) Industrial Actions

1.2.2 Remedies for Energy Crisis

a) Reduce, Reuse and Recycle

b) Use of energy efficient products

c) Use of Renewable sources of Energy

d) Planting of trees

e) Accepting that there is a crisis and working towards addressing it

1.3 SOLAR ENERGY

The sun is the ultimate source of all the energy available on the earth including solar energy in the form of solar radiation. Solar energy on the earth can be converted into thermal energy and electric energy i.e. electricity. The conversion of solar energy into thermal energy can be done by solar collectors and the conversion of solar energy into electricity can be done by Solar Photo Voltaic (SPV) system used in solar power plants.

Solar radiation that reaches to a receiving surface on the earth consists of three components, the three components of the solar radiation reaching the earth`s surface are given below:

a) Beam or direct radiation which reaches the earth surface without change in direction
b) Diffuse radiation which reaches the earth after scattering and re radiation of solar energy through dust particles, water vapors and air molecules.
c) Total radiation: the sum of beam radiation and diffuse radiation is termed as total radiation or global radiation.

The rapid depletion of fossil fuel resources has necessitated an urgent search for alternative sources of energy. Among the many alternatives, solar energy stands out as the brightest long range promise towards meeting the continually increasing demand for energy. Solar energy is available freely, omnipresent and an indigenous source of energy provides a clean and pollution free atmosphere. The simplest and the most efficient way to utilize solar energy is to convert it into thermal energy for heating applications by using solar collectors.

Solar air heaters, because of their inherent simplicity are cheap and most widely used collector devices. Solar air heaters are being used for many applications at low and moderate temperatures.

Some of these are crop drying, timber seasoning, space heating, chicken brooding and curing / drying of concrete / clay building components.

1.3.1 Advantages of Solar Energy

a) It is a natural source of energy.
b) It is available in plenty.
c) It is a renewable source of energy.
d) It is a non-polluting source of energy and does not emit greenhouse gases.
e) It does not require destruction of forests and ecosystems

1.3.2 Disadvantages of Solar Energy

a) It requires high initial investment

b) Solar energy is not available during the night

c) It is dependent on change in seasons

d) Solar panels are bulky

1.4 SOLAR COLLECTORS

A solar collector is a device that collects solar radiation coming from the sun. They are mainly used for active solar heating and can also be used for the heating of water for personal use. The solar collector are generally mounted on the roof and they must be very sturdy. The use of solar collector provides an alternative for water heating, thereby reducing energy cost and combustion. It is further classified into two:

1.4.1 Flat Plate Collector

Flat plate collector consists of a black painted flat surface called absorber plate, transparent glass cover and air passage having high aspect ratio as shown in. In this absorber plate transfers absorbed radiations to carrier fluid whereas thermal insulation is also provided to minimize the heat losses. The front side of flat plat collector has transparent cover to allow the incoming of solar radiation. Tracking of sun is not required in these type of collectors and temperature up to a maximum of 100^{o}C above an ambient can be obtained through these.

Based on the type of heat transfer fluid, flat plate collectors are divided into two types:

a) Liquid heating collectors

b) Air heating collectors

The collector should be oriented facing south in northern hemisphere and facing north in southern hemisphere. For the winter, tilt angle of flat plate collector should be approximately 10^o to 15^o less than the latitude.

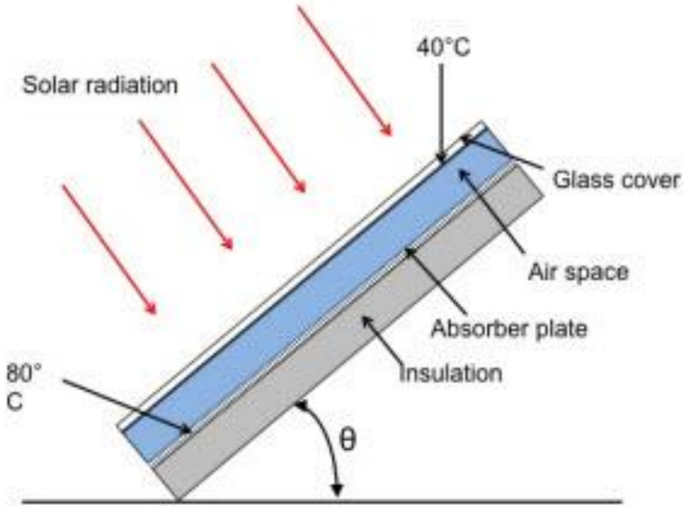


Fig 1.2: Flat Plate Solar Collector [2].

1.4.2 Focusing Collector

Focusing type solar collector are also known as concentrating type solar collector. They collect solar energy with high intensity with high intensity of solar radiation on the energy absorbing surface. They generally use optical systems in the form of refractors or reflectors. It is a spherical form flat plate collector modified by introducing or reflecting surface between the absorber and the solar radiation. In this type of collector the amount of radiation falling on a larger surface area is focused on a smaller surface area.

Solar Collectors can be further classified on the basis of its application:

1.5 SOLAR WATER HEATER

Solar Water heater are devices which uses natural sunlight to heat water. This is an effective way to generate hot water by using a renewable form of energy such as sunlight, thereby saving costly power and are also environment friendly. The major parts of the solar water heater are:

- Thermal panel
- A tank to store hot water
- Accessories such as circulating pump to carry the solar energy from the collector to the tank.

1.6 SOLAR AIR HEATER

Solar air heater is a device which absorbs the energy coming from the sun, insolation, with the help of an absorbing medium and then uses this energy to heat air which passes through the solar air heater. In solar air heater, heat transfer occurs from an energy source which spreads radiation to the air. It consists of an absorber plate, supportive walls, ducts or channels of fluid flow, glazing, air blower or fans (if forced convection), and insulation to minimize heat losses. Almost all the parts of solar air collector or heaters are thermally well insulated to reduce thermal heat losses. Glazing minimizes convective and radiative losses to the atmosphere and obtains solar radiation to stay between absorber and glazing, and to be absorbed by blackened absorber. Heat transferred to air by an air duct between glazing and absorber plate.

In a solar air heater the absorber plate absorbs the incoming solar radiation and energy gets stored in the absorber plate, when air is made to flow over the absorber plate with the help of an air blower the energy stored in the absorber plate gets transferred to the flowing air and hence the temperature of the air flowing through the solar air heater gets increased. In solar air heating process a renewable source of energy is used for carrying out the heating process hence it is eco-friendly.

Solar air heaters are generally used to dry agricultural products, to dry fabrics space heating. Drying grains, fruits, vegetables, tea, and building heating are a few examples of solar air heater.

1.6.1 Parts of a Solar Air Heater

The various parts of a solar air heater are listed below:

a) The absorber plate
b) Supporting walls

c) Ducts or channels of fluid flow
d) Glazing
e) Air blower or fans
f) Insulation to minimize heat losses

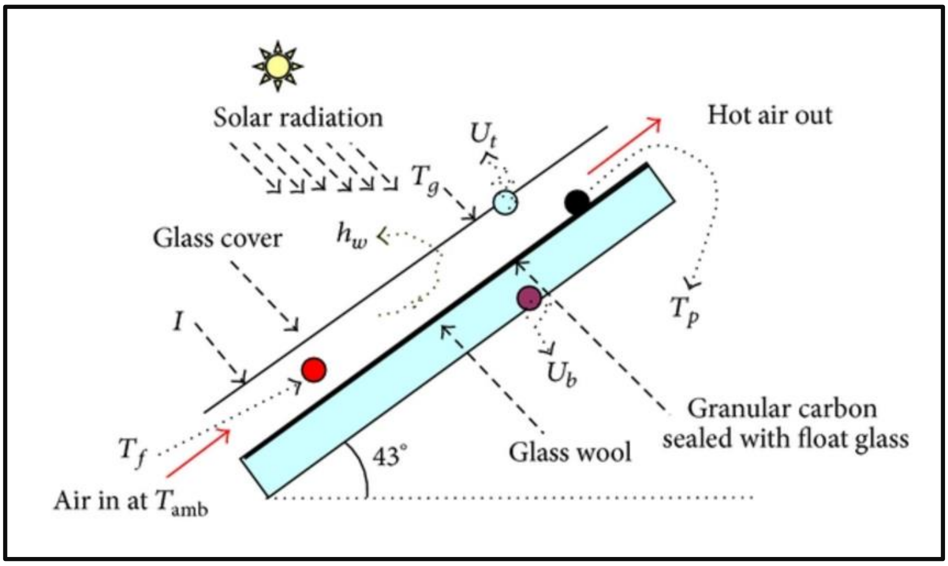


Fig 1.3: Parts of a solar air heater[3].

1.6.2 Advantages of Solar Air Heater

a) The need to transfer heat from working fluids to another fluid is eliminated as air is being used directly as the working substance. The system is compact and less complicated.
b) Corrosion is a great problem in solar water heater. And this problem is not experienced in solar air heaters.
c) Leakage of air from the duct does not create any problem.
d) Freezing of working fluid virtually does not exist.
e) The pressure inside the collector does not become very high.
f) Thus air heater can be designed using cheaper as well as lesser amount of material and it is simpler to use than the solar water heater

1.6.3 Disadvantages of Solar Air Heater

a) Air heaters have certain disadvantages also the first and foremost is the poor heat transfer properties of air. Special care is required to improve the heat transfer.
b) Another disadvantage is the need for handling large volume of air due to its low density.
c) Air cannot be used as a storage fluid because of its low thermal capacity.
d) In the absence of proper design the cost of solar air heaters can be very high.

1.6.4 Applications of Solar Air Heater

The heated air that is obtained from the solar air heater can be used for various purposes such as :

•Industrial purposes:

Air-preheating for combustion processes, that means thousands of application, Drying minerals, coal, paper, bricks, food industry products, etc. Especially the drying of brown coal would be very important for power plants.Space heating for warehouses, factories, etc.

•Household purposes:

Space heating small driers

Commercial purposes:

Space heating for public buildings, office buildings, shopping centers .Space heating for emergency relief camps or military camps

Space heating for recreational camping and expeditions in cold climate

1.7 HEAT TRANSFER ENHANCEMENT TECHNIQUES

The low value of convective heat transfer coefficient between the air and absorber plate is a major factor for low thermal efficiency of solar air heater. Many investigators have proposed different configurations of the collector passages to increases the heat transfer coefficient between the air and absorber plate, which are classifies as:

1.7.1 Smooth Double Pass Solar Air Heater

Satcunanathan and Deonarine [4] introduced the idea of double pass counter flow solar air heater. The air flows in two passes, firstly in the space between glass cover and absorber plate and then induced through the duct. The thermal losses are suppressed by using such systems. These systems are 10–15% more efficient then single pass system.

A heat transfer model for two pass system is given by Wijeysundera et al. [5] and results were then compared with single pass system. It is encountered that the open systems, with inlet fluid at ambient temperature, the double exposure systems are 10–15% more efficient then the single exposure for a wide range of operating conditions.

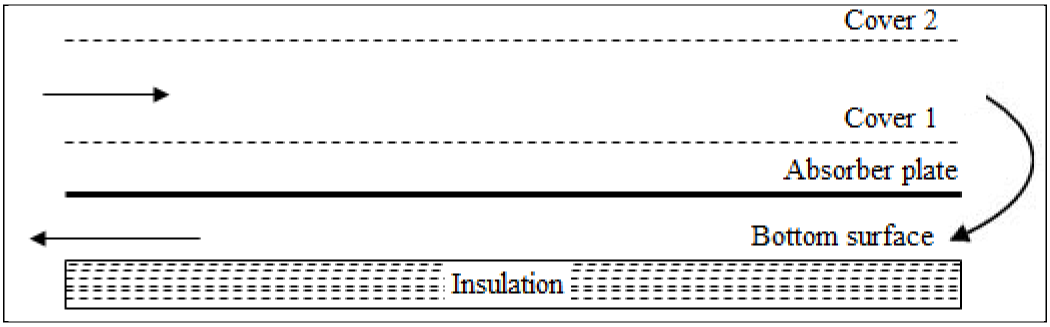


Fig.1.4: Schematic view of double pass solar air heater [5].

1.7.2 Double Pass Solar Air Heater with Recycle

The concept of recycle was introduced by Ho and Yeh[6]. In recycling, the inlet air was preheated and mixed with the hot outgoing air before flown through the duct, due to this, two conflict effects was produced. One is the desirable effect of increase in the convection coefficient and other is undesirable effect of decrease in the driving force i.e. temperature difference of heat transfer. The considerable enhancement in the collector efficiency may be obtained if the systems operated under external recycle.

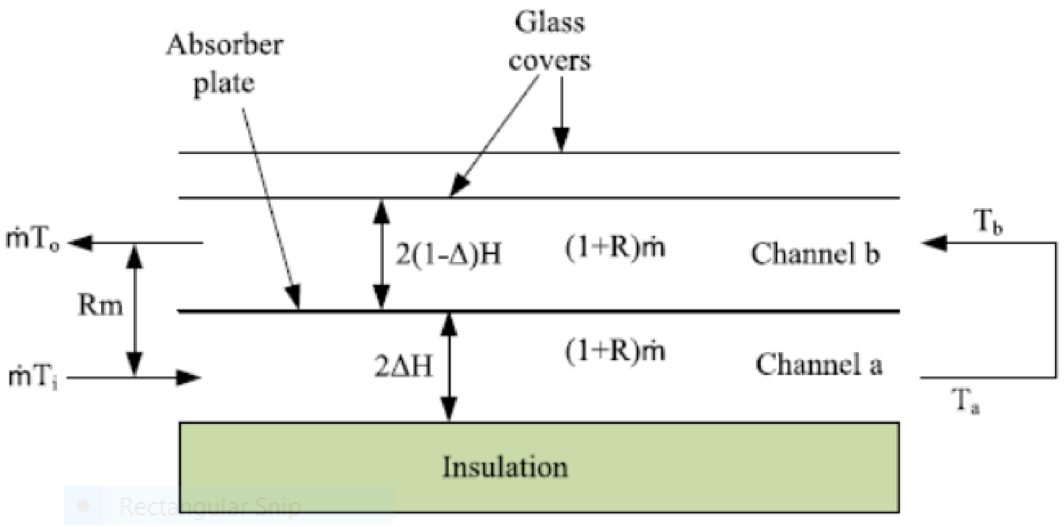


Fig. 1.5: Schematic diagram of a Double Pass Solar Air Heater with external recycle [7]

1.7.3 Double Pass Solar Air Heater with Packed bed/porous materials

Due to small thickness of absorber plate the heat transfer rate in solar air heater becomes very low which can be enhanced by using a packed bed absorbing surface. Packed bed materials used in solar air heaters act as thermal energy storage media. A packed bed is a volume of porous media attain by packing particles of selected materials into a box, these particles produces an increament in the turbulence which enhances the rate of heat transfer.

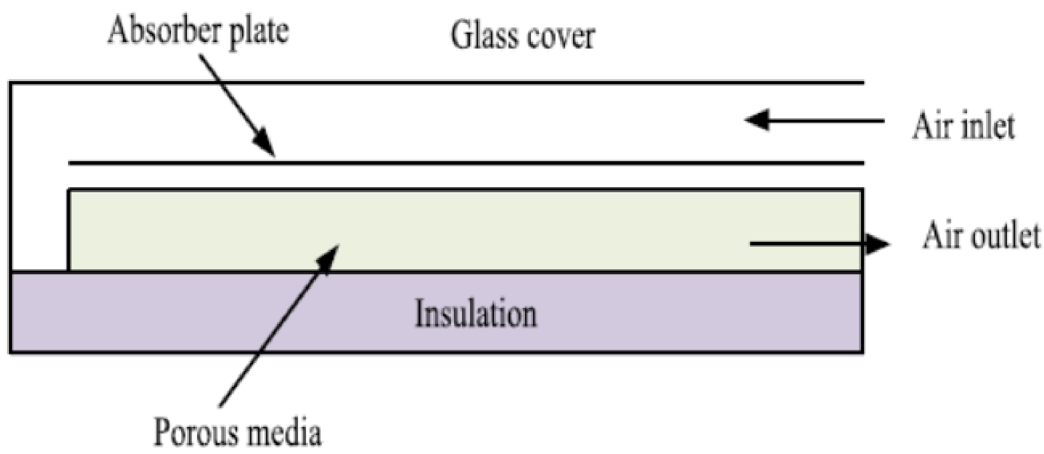


Fig.1.6: Double Pass Solar Air Heater with Porous media [8].

1.7.4 Double Pass Solar Air Heater with Extended Surface

Extended Surfaces are used in double pass solar air heater in the form of fins and turbulators. These fins and turbulators in the fluid flow channel provides a larger area for heat transfer due to which convection coefficient between the absorbing surface and the working fluid is enhanced, and thus the thermal efficiency of the duct increases.

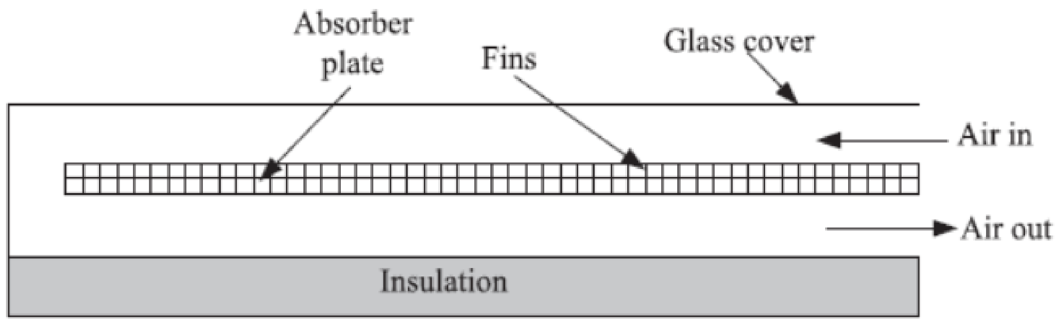


Fig. 1.7: Double Pass Solar Air Heater with longitudinal fins [9].

1.7.5 Double Pass Solar Air Heater with Artificial Roughness

Heat Transfer from the surface of solar air heater duct is very poor due to the generation of laminar sub layer near the walls of the heat transferring surface. To achieve better heat transfer rate from the duct it is necessary to break this layer. Artificial roughness in the form of repeated ribs on the absorber plate is used to disturb the laminar sub layer in the turbulent boundary region and create the turbulence in the fluid flowing just close to the wall of the duct.

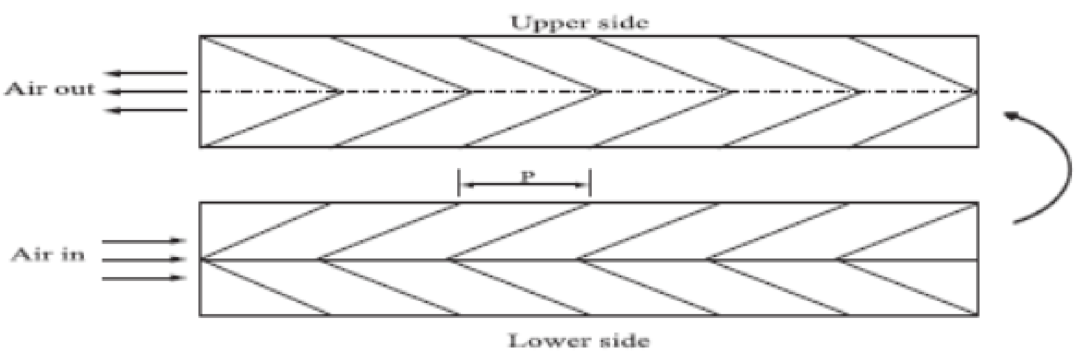


Fig. 1.8: Double Pass Solar Air Heater with V shaped ribs [10].

1.8 CONCEPT OF ARTIFICIAL ROUGHNESS

Solar air heaters are generally used for collecting solar energy which absorbs the incoming solar radiations, converting it into thermal energy at absorbing plates and transferring heat to fluid(air) flowing through the collector. Solar air heaters due to simplicity and low cost are most widely used collection devices. They are used for several applications such as space heating, crop drying etc.

The thermal efficiency of solar air heater is comparatively poor due to the low heat transfer coefficient between the absorber plates and flowing air. Therefore in order to make solar air heater more economical their thermal efficiency need to be improved which can be achieved by increasing heat transfer coefficient. The heat transfer coefficient of solar air heater can be enhanced by breaking the laminar sub layer formed on the vicinity of absorber plates.

The use of artificial roughness on the surface of absorber plate is an effective technique to enhance the heat transfer between absorber plate and air flowing over it. The application of artificial roughness in the form of fine wires and ribs of different shapes has been recommended to enhance the heat transfer coefficient by several investigators. The use of artificial roughness would also result in an increase in friction losses and hence greater power is required for pumping 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 surface. A number of investigations have been carried out on the heat transfer characteristics and friction factor characteristics of solar air heater with different types of roughness element on it.

Artificial roughness is basically a passive heat transfer enhancement technique by which thermo-hydraulic performance of a solar air heater can be improved. The artificial roughness has been used extensively for the enhancement of forced convective heat transfer, which further requires flow at the heat-transferring surface to be turbulent. However, energy for creating such turbulence has to come from the fan or blower and the excessive power is required to flow air through the duct.

Therefore, it is desirable that the turbulence must be created only in the region very close to the heat transferring surface, so that the power requirement may be lessened. This can be done by keeping the height of the roughness elements to be small in comparison with the duct dimensions.

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.

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.

1.9 THE COMPUTATIONAL FLUID DYNAMICS APPROACH

Computational fluid dynamics (CFD) is a branch of fluid Mechanics that uses numerical analysis and data structures to analyse and solve problems that involve fluid flows. Computers are used to perform the calculations required to simulate the free-stream flow of the fluid, and the interaction of the fluid (liquids and gases) with surfaces defined by boundary conditions. With high-speed supercomputers, better solutions can be achieved, and are often required to solve the largest and most complex problems. Ongoing research yields software that improves the accuracy and speed of complex simulation scenarios such as transonic or turbulent flows. Initial validation of such software is typically performed using experimental apparatus such as wind tunnels. In addition, previously performed analytical or empirical analysis of a particular problem can be used for comparison. A final validation is often performed using full-scale testing, such as flight tests.

Conventional techniques used for the design and development of an artificially roughened solar air heater are mostly tedious, expensive and time consuming. CFD approach has emerged as a cost effective alternative and it provides speedy solution to design and optimization of an artificially roughened solar air heater. Computational fluid dynamics (CFD) is a design tool that has been developed over the past few decades and will be continually developed as the understanding of the physical and chemical phenomena underlying CFD theory improves. The goals of CFD are to be able to accurately predict fluid flow, heat transfer and chemical reactions in complex systems, which involve one or all of these phenomena. CFD uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. High speed computers are used to perform the calculations required to simulate the interaction of gases and liquids with surfaces defined by boundary conditions. With the development of numerical methodology and high speed computers, better solutions of fluid flow problems can be achieved. Ongoing research yields software that improves the speed and accuracy of complex simulation scenarios such as turbulent flows, transonic flows etc. Literature search in the area of artificially roughened solar air heater revealed that very few

CFD investigation of artificially roughened solar air heater has been done to evaluate the optimum rib shape and configuration, which can enhance convective heat transfer with minimum pumping power requirement.

The major steps involved in simulation are indicated through a Fig 1.8

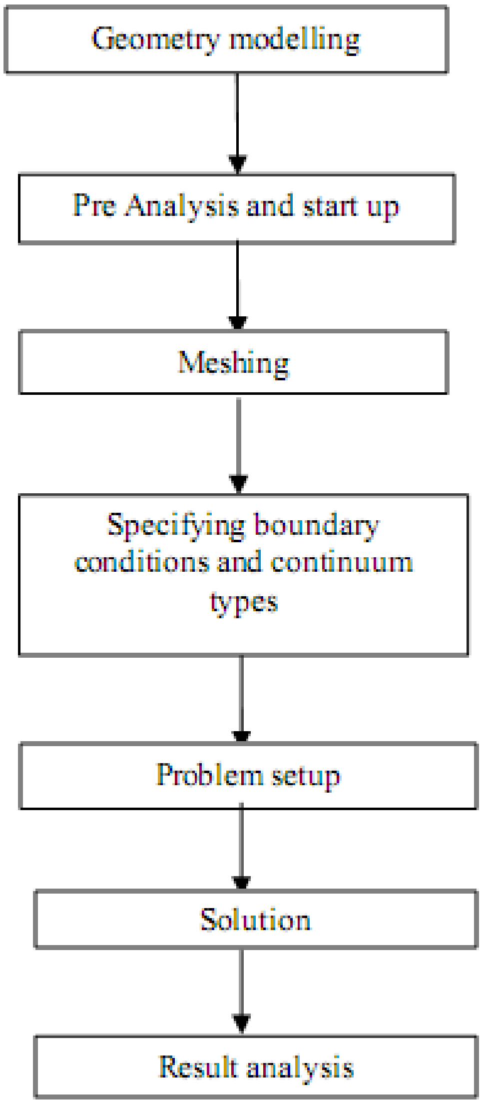


Fig. 1.9: Simulation methodology [11].

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

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. 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.

A number of studies on various design of solar air heater with artificial roughness carried out by several investigators are discussed in this chapter. The literature review shows several studies on solar air heater that are available, which are categorized into experimental and computational studies.

2.2 EXPERIMENTAL STUDIES ON ARTIFICIALLY ROUGHENED SOLAR AIR HEATER

2.2.1 Artificially Roughened Solar Air Heater Duct with 'Conical' Shape Ribs

In this experiment Alam[12] has taken the conical shaped ribs to increase the heat transfer in solar air heater duct. Height, length and width of computational flow domain of SAH are considered as 25 mm, 1000 mm and 300 mm, respectively as per ASHARE's recommendation Although, actual solar air heater consisted inlet plenum and outlet plenum along with test section which are omitted in present numerical studies to make the model simple. Only test section has been considered in the present numerical studies. One broad wall of model is considered as absorber plate on which protrusion ribs of conical shape have been attached. Absorber plate has been exposed to uniform heat flux of 1000 W/m^2 which is done to provide insolation, falling on absorber plate. Three sides of the duct were smooth and insulated. Air enter in the duct at inlet section, extract heat from absorber plate when air comes in contact with absorber plate and then air comes out from the duct at outlet section. The computational flow domain of the solar air heater has been showing in the ranges of relative ribs height (e/D) and relative ribs pitch (p/e) of conical protrusion ribs have been chosen as 0.020–0.044 and 6–12, respectively, which are similar to previous studies, conducted for spherical ribs. All the simulations have been carried out at four values of Reynolds number (Re) in the range.

Various results have been found out. The variation in the nusselt number and friction factor has been found out and a comparative study between a solar air heater with smooth duct , a solar air heater with conical ribs as roughness geometry and a solar air heater with spherical ribs as roughness geometry has been carried out for various reynodls number and different roughness parameter . The thermo hydraulic performance for various cases has also been found out. Correlations of friction factor and nusselt number have also been developed as function of Reynolds number and roughness parameters of conical ribs. The computational fluid domain has been shown in Fig 2.1

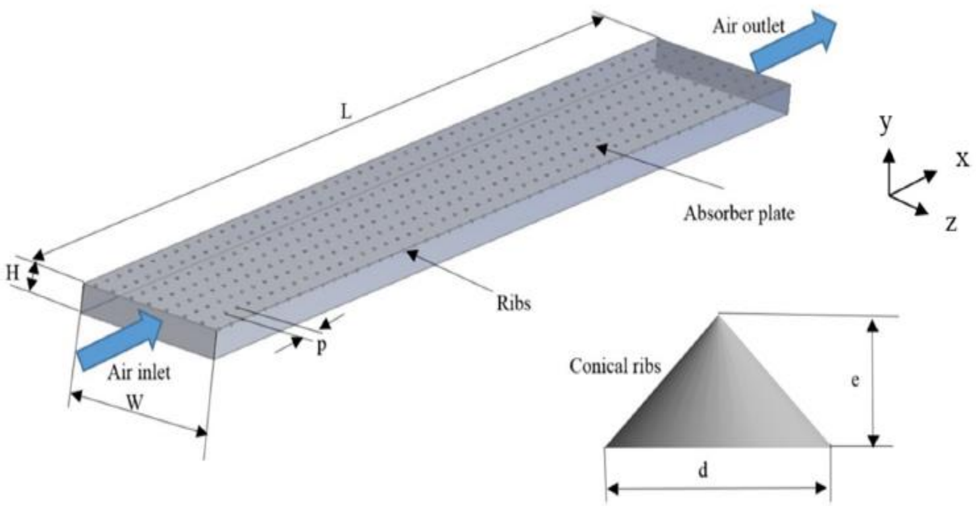


Fig 2.1: computational fluid domain[12]

2.2.2 Artificially Roughened Solar Air Heater Duct with Small Diameter Protrusion Wire

Prasad et al.[13] investigated experimentally the effect of relative roughness pitch (p/e) and relative roughness height (e/D) on the heat transfer coefficient and friction factor of a fully developed turbulent flow in a solar air heater duct with small diameter protrusion wires on the absorber plate. The type and orientation of the geometry is depicted in Fig 2.2

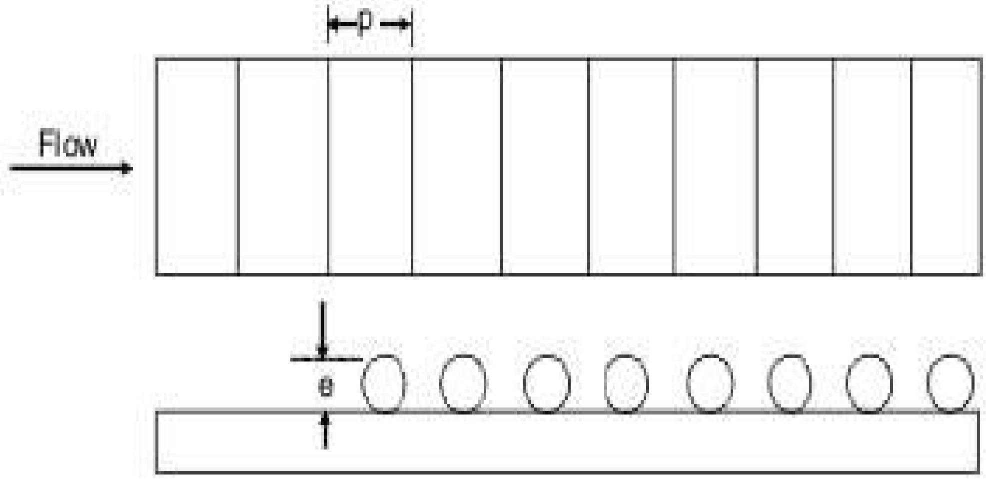


Fig 2.2: Type and orientation of roughness element investigated by Prasad and Saini [13]

2.2.3 Artificially Roughened Solar Air Heater Duct with Equilateral Triangle Section Ribs

Yadav and Bhagoria [14] studied the effects of using a equilateral triangular section rib as roughness element in solar air heater.For this he created a 2-dimensional computational domain of artificially roughened solar air heater which is similar to the computational domain of Yadav and Bhagoria [15]. The computational domain is simply the physical region over which the simulation has been performed. The computational domain is a simple rectangle of length 640 mm and height 20 mm and consisted of three sections, namely, entrance section (L1 = 245 mm), test section (L2 = 280 mm) and exit section (L3 = 115 mm) (Fig. 2.3). In his numerical work, 2-dimensional equilateral triangular sectioned transverse ribs have been considered as roughness element. The equilateral triangular sectioned transverse ribs are considered on the underside of the top absorber plate while other sides are considered as smooth surfaces. The absorber plate is 6 mm thick aluminum plate and the lower surface of the plate provided with artificial roughness in the form of equilateral triangular sectioned transverse ribs. A typical absorber plate with equilateral triangular sectioned transverse ribs is shown in Fig. 2.4. The maximum and minimum height of equilateral triangular sectioned rib has been selected to 1.4 and 0.7 mm respectively, so that the fin/flow passage blockage effects may be negligible and laminar sub-layer would be of the same order as of roughness height, as reported by Verma and Prasad[16]

In his CFD analysis, twelve different configurations of equilateral triangular sectioned transverse rib roughness on the absorber plate have been simulated. Each of the combinations has been performed on six different values of Reynolds number. Thus, a total of seventy-two sets of CFD simulations having different combinations of Reynolds number (Re), relative roughness pitch (P/e) and relative roughness height (e/D) have been investigated. Each of the combinations has been carefully simulated to predict the heat transfer and flow friction behavior. The simulations are conducted over the relevant range of Reynolds number, 3800 6 Re 6 18,000

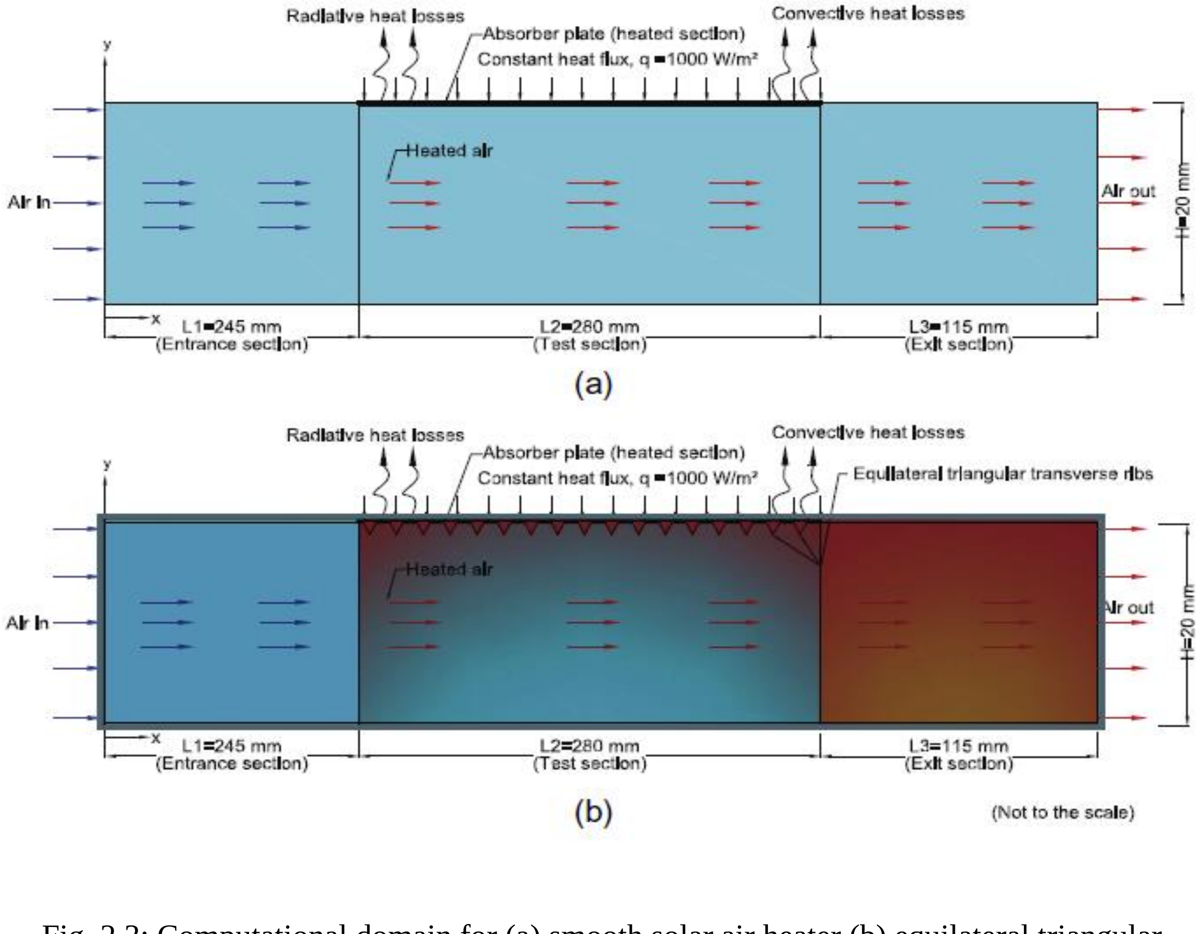


Fig. 2.3: Computational domain for (a) smooth solar air heater (b) equilateral triangular sectioned rib roughened solar air heater[14]

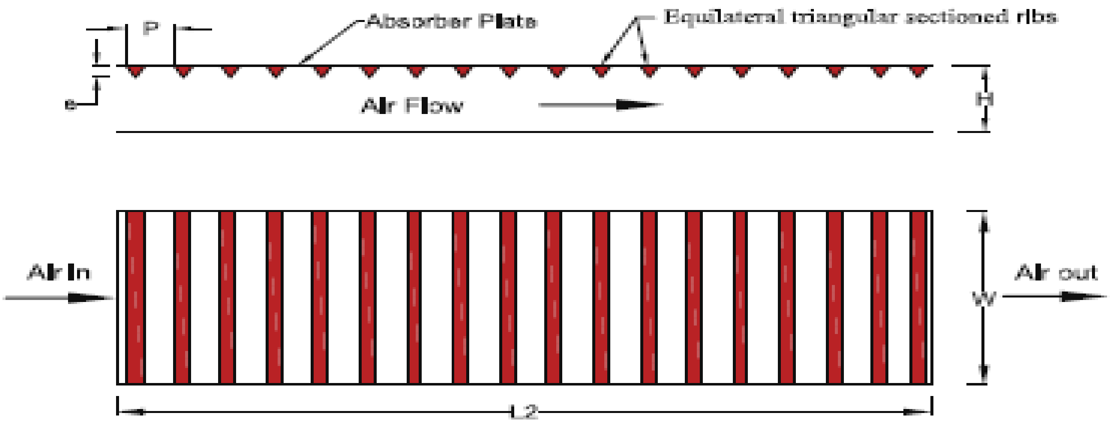


Fig. 2.4: Schematic representation of a roughened absorber plate[14]

2.2.4 Artificially Roughened Solar Air Heater Duct with 's' Shape Ribs

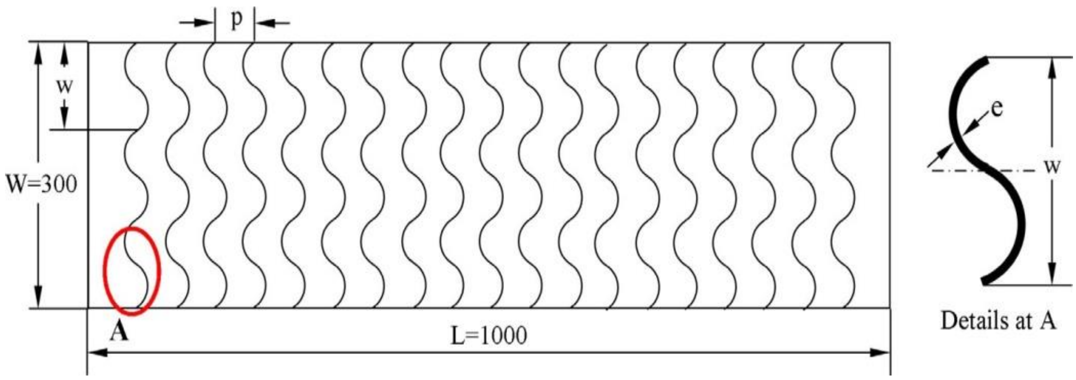


Fig 2.5 : S-shaped ribs[17]

A schematic diagram of the experimental set-up is shown in Fig 2.5. The air is sucked by means of a centrifugal blower through a rectangular duct. The rectangular duct has three consecutive sections - an entrance section, a test section and an exit-section the inner dimension of the duct is 2300 mm *300mm*25mm with an aspect ratio (w/h) of 12 and also an electric heater having size of 1000 mm 300 mm is fabricated by fixing a nichrome wire on an asbestos sheet; fixed on the lower surface of the top cover of duct. A mica sheet is also placed on the nichrome wire to get uniform radiations on the absorber plate

Arc shaped circular wires arranged in 'S' shape pattern are used as roughness elements on the absorber plate to create roughness. The various dimensions of the roughness elements (ribs) are expressed in terms of non-dimensional parameters with respect to Duct dimensions as, relative roughness pitch (p/e), relative roughness height (e/D_h), and relative roughness width (W/w). The range of these roughness parameters and operating parame- ters used for the present experimental investigation are given in Table.2.1

Table 2.1:Range of parameters.

S.No.	Parameters	Range
1	Reynolds number(Re)	2400-20,000(7 values)
2	Duct aspect ratio(W/H)	12(fixed)
3	Relative roughness height (e/D)	0.022-0.054(4 values)
4	Relative roughness pitch(p/e)	4-16(4 values)
5	Arc angle	30-75°(4 values)
6	Relative roughness width(W/w)	1-4(4 values)

2.2.5 Investigations on Thermo-hydraulic performance due to Flow-attack-angle in V-down rib with gap in a Rectangular duct of Solar Air Heater

In his investigation Singh et al.[18], planned to experimentally study the effect of variation in angle of attack of V-down rib having gap. For application of rib roughness in SAH, one side of the duct is roughened and given constant heat flux and other three sides are insulated and kept smooth.

The general geometry of V-down rib having gap is shown in Fig. 2.6. The V-down rib has gap equal to rib height at the centre of both legs of V. The relative roughness height (e/Dh) and relative roughness pitch (P/e) were 0.043 and 8 respectively. The rib height

(e) was chosen such that it breaks the viscous sublayer and at the same time, fin and flow passage blockage effects are negligible . The relative roughness pitch (P/e) was selected as 8 for the present investigation on 'V-down rib with gap' because it was reported as optimum for continuous V-down rib by Hans et al. [19] and for inclined rib with gap by Aharwal et al. [20]. The investigation was carried out to determine the friction factor and Nusselt number due to change in α. Five roughened plates were prepared for angle of attack (α) of 30°, 45°, 52°, 60°and 75°. Artificial rib roughness was created by fixing aluminium wires of circular cross-section on the lower side of absorber plate. The Re was varied from 3000 to 15,000.

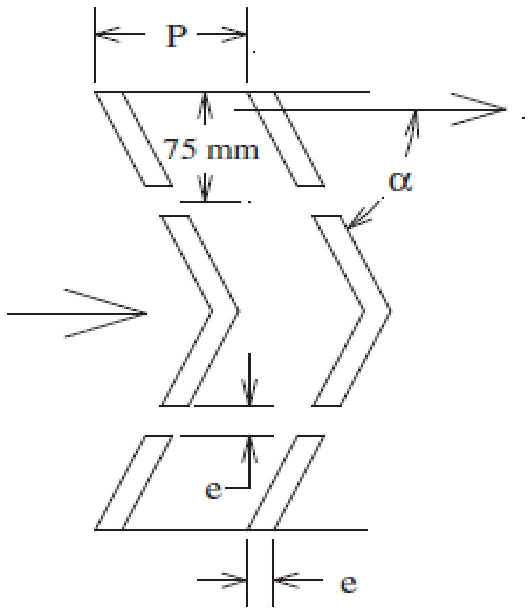


Fig. 2.6: General geometry of V-down rib having gap[18]

2.2.6 Artificially Roughened Solar Air Heater Duct with Wedge Shaped Ribs

Bhagoria [21] has performed experiments in order to find out the effect of relative roughness height, relative roughness pitch and wedge angle on the heat transfer and friction factor in a solar air heater roughened duct having wedge shaped rib roughness.

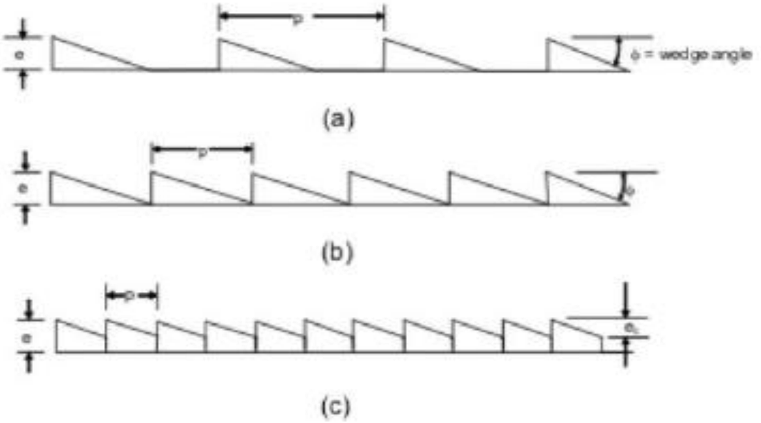


Fig 2.7: Wedge shaped roughness element[21]

2.2.7 Artificially Roughened Solar Air Heater Duct with Arc Shaped Ribs:-

Saini et al. [22]investigated experimentally the effect of relative roughness height (e/d) and relative angle of attack of arc-shape parallel wire on the heat transfer coefficient and friction factor. The maximum enhancement in the Nusselt number was obtained as 3.80 times corresponding to the relative arc angle of 0.3333 and relative roughness height of 0.0422. The investigated roughness geometry is shown in Fig 2.8

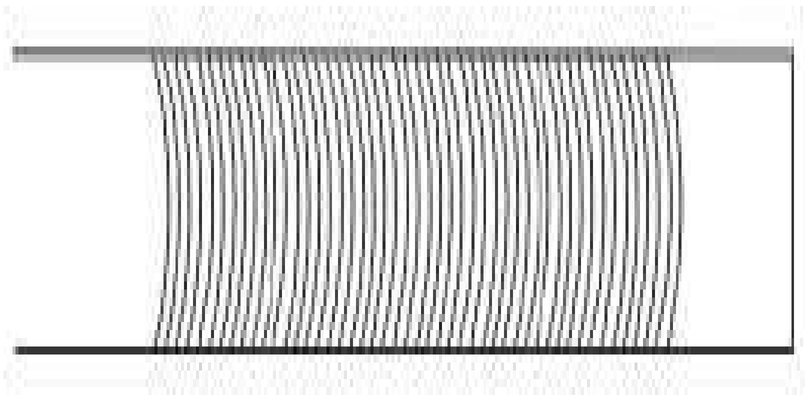


Fig 2.8: Orientation of arc shaped roughness element[22]

2.3 NUMERICAL STUDIES ON ARTIFICIALLY ROUGHENED SOLAR AIR HEATER

2.3.1 Artificially Roughened Solar Air Heater Duct with 'Conical' Shape Ribs

Numerical simulations was conducted by Alam[12]to predict the thermal hydraulic performance of SAH duct, roughened with conical protrusion ribs. The effect of roughness parameters on heat transfer, friction factor, and thermal efficiency is obtained. Providing the conical protrusion ribs results in considerable heat transfer enhancement in comparison to spherical ribs. Average enhancement in Nusselt number and friction factor of conical protrusion ribs over spherical ribs have been observed as 1.30 and 1.07, respectively for relative ribs pitch of 10 and relative ribs height of 0.0298

Maximum Nusselt number and friction factor occurred at relative pitch of 10 and 6, respectively. Maximum enhancement in Nusselt number and friction factor of roughened duct with respect to smooth duct have been observed as 2.49 and 7.29, respectively for relative ribs pitch of 10 and relative ribs height of 0.044.

Due to the increment in the nusselt number a considerable amount of increase in the heat transfer from the absorber plate to the air flowing in the duct was observed.

Maximum thermal efficiency and efficiency enhancement factor have been found as 69.8% and 1.346, respectively for relative roughness height of 0.044 and relative rib pitch of 10.

Nusselt number and friction factor correlations were also developed as function of roughness and operating parameters. Nusselt number and friction factor correlations predict the data with average absolute standard deviation of 2.78% and 5.25%, respectively.

2.3.2 Artificially Roughened Solar Air Heater Duct with Small Diameter Protrusion Wire

In the study of Prasad[13], it was observed that the average Nusselt number and as 2.10, 2.24, 2.38 and 3.08, 3.67, 4.25 times that of the smooth duct for relative roughness height of 0.020, 0.027, and 0.033, respectively. It was also found that increase in the average Nusselt number and average friction factor in the roughened duct were about 2.38, 2.14, 2.01 and 4.25, 3.39, 2.93 times of that of the smooth duct for a relative roughness pitch of 10, 15, and 20, respectively. The maximum enhancement in the heat transfer coefficient and friction factor were as 2.38 and 4.25 times than that of smooth duct respectively.

2.3.3 Artificially Roughened Solar Air Heater Duct with 'Equilateral Triangle Section Ribs'

Yadav [14] created a two-dimensional CFD model of an artificially roughened solar air heater having equilateral triangular sectioned rib roughness on the absorber plate and used it to predict the heat transfer and flow friction characteristics. Using this approach a detailed study was performed to analyze the impact of three parameters on the thermal and hydraulic performance of an artificially roughened solar air heater: relative roughness pitch (P/e), relative roughness height (e/D) and Reynolds number (Re). The average Nusselt number increased as the Reynolds number was increased in all cases. The average Nusselt number tends to decrease as the relative roughness pitch increases for a fixed value of relative roughness height and it also tends to increase as the relative roughness height increases for a fixed value of relative roughness pitch. The maximum enhancement in the Nusselt number was found to be 3.073 times over the smooth duct corresponds to relative roughness height (e/D) of 0.042 and relative roughness pitch (P/e) of 7.14 at Reynolds number (Re) of 15,000 in the range of parameters investigated.

The average friction factor tends to decrease as the Reynolds number increases in all cases. The average friction factor tends to decrease as the relative roughness pitch increases for a fixed value of relative roughness height and it tends to increase as relative roughness height increases for a given value of relative roughness pitch.

The maximum enhancement in the friction factor was found to be 3.356 times over the smooth duct corresponds to relative roughness height (e/D) of 0.042 and relative roughness pitch (P/e) of 7.14 at Reynolds number (Re) of 3800 in the range of parameters investigated.

A significant enhancement in the value of the thermo-hydraulic performance parameter was found. The value of the thermo-hydraulic performance parameter varies between 1.36 and 2.11 for the range of parameters investigated.The optimum value of thermo-hydraulic performance parameter was found corresponds to relative roughness height (e/D) of 0.042 and relative roughness pitch (P/e) of 7.14. The optimum value of thermo-hydraulic performance parameter was found to be 2.11 for Reynolds number (Re) of 15,000.

2.3.4 Artificially Roughened Solar Air Heater Duct with 's' Shape Ribs

In his experimental study the effect of arc shape ribs arranged in 'S' shape pattern on one of the broad wall of solar air heater duct has been investigated. The effect of the relative roughness width (W/w), relative roughness pitch (p/e), arc angle (a) and relative roughness height (e/Dh) on heat transfer (Nusselt number) and friction factor has been studied. Based on this investigation the following conclusions are made.Significant enhancement in heat transfer and friction factor can be achieved by creating the artificial roughness in the solar air heater; compared to the smooth duct. Reynolds number has strong impact on both the Nusselt number and friction factor as Nusselt number increases while friction factor decreases with increase in Reynolds number.

Maximum enhancement in heat transfer (Nu) and friction factor (f) occurs for arc angle (a) value of 60°and relative roughness height (e/Dh) value of 0.043, and it decreases on either side of these values. Maximum enhancement in heat transfer (Nu) occurs for relative roughness width (W/w) value of 3 while the friction factor goes on increasing with further rise in the value of relative roughness width (W/w). The statistical correlations for Nusselt number and friction factor are developed in terms of roughness parameters. The developed correlations predict the values of Nusselt number and friction factor with maximum deviation of ±10.8% and ±10% respectively.

2.3.5 Investigations on Thermo-hydraulic Performance due to Flow-attack-angle in v-down Rib with Gap in a Rectangular Duct of Solar Air Heater

In this investigation, thermo-hydraulic performance of rectangular ducts roughened with a new configuration of 'V-down rib having gap' on one wide wall is determined.

As a increases from 30◦to 60◦, the Nusselt number and friction factor increase and the both reduce with further increase in angle of attack(α). This variation may be caused by interaction of, secondary flow and boundary layer, at front side of rib. The boundary layer is due to main flow with the roughened surface and originates from flow reattachment point between the ribs up to the succeeding downstream rib. The strength of secondary flow along the rib changes with change in angle of attack. These two factors determine the value of Nusselt number and friction factor at different α.

The effect of gap in continuous V-down rib in SAH duct is studied by comparing the results of present study with continuous V-down rib tested under identical conditions. The V-down rib having gap with $\alpha = 60^\circ$was considered for comparison as it yielded best thermo-hydraulic performance.

The rib roughness parameters for continuous V-down rib were same. These parameters were $P/e = 8$, $\alpha = 60^\circ$ and $e/Dh = 0.043$. The duct aspect ratio was also same for the two studies. The Nusselt number is more for V-down rib having gap in comparison with continuous V-down rib .The friction factor is more for V-down rib having gap up to Reynolds number of 9000 . For a V-down rib, the local Nusselt number in transverse direction between adjacent ribs reduces from leading edges to the V-apex due to increase in boundary layer thickness and with the creation of gap in the rib, a region of high local Nusselt number develops downside of the gap. In this study, symmetrical gap at the centre of both legs of V-down rib helps in increasing the local Nusselt number downstream of the gap. Hence the average Nusselt number is more for V-down rib having gap than continuous V-down rib.

2.3.6 Artificially Roughened Solar Air Heater Duct with Wedge Shaped Ribs

In the experiment by Bhagoria[21] for the analysis of the effects on wedge shaped ribs on the heat transfer and friction factor ,it has been observed that the maximum heat transfer occurred for a relative roughness pitch of about 7.57, while the friction factor decreased as the relative roughness pitch increased.

A maximum enhancement of heat transfer occurred at a wedge angle of about 10°. As compared to the smooth duct, the presence of ribs yielded a Nusselt number up to 2.4 times while the friction factor raised up to 5.3 times for the range of parameters investigated.

2.3.7 Artificially Roughened Solar Air Heater Duct with Arc Shaped Ribs

In the experiment to find out the effect of arc shaped ribs as roughness elements. The maximum enhancement in the Nusselt number was obtained as 3.80 times corresponding to the relative arc angle of 0.3333 at relative roughness height of 0.0422. However, the increment in the friction factor corresponding to these parameters was found to be only 1.75 times.

2.4 RESEARCH GAPS IDENTIFIED

An extensive literature review has been conducted on the performance of artificially roughened solar air heater, based on which it can be found that there are many types of roughness geometries depending upon shape, size, arrangement and orientation of roughness elements. Most of the studies presented in literature are focussed on the experiment. Few studies has been found on CFD analysis. In literature very studies are available on solar air heater with protruded absorber plate which are based on CFD analysis. Further no study has been found in literature which is based on CFD analysis on solar air heater roughened with the combination of two different shapes. It is therefore, the present work has been focussed on CFD analysis of two different shapes of protrusion elements i.e. combination of inclined and spherical protrusions.

2.5 OBJECTIVES OF PRESENT STUDY

Based on the research gaps found in the literature survey, following are the objectives of present work.

a) To develop a CFD model of solar air heater rectangular duct roughened with inclined and spherical rib protrusions.
b) To investigate the effect of roughness and operating parameters on heat transfer and fluid flow characteristics.
c) To investigate the thermo-hydraulic performance of the solar air heater duct.

CHAPTER 3

COMPUTATIONAL INVESTIGSTION AND DATA PROCESSING

3.1 GENERAL

The review of literature revealed that use of artificial roughness of heat transferring surface of a Solar Air Heater brings about considerable enhancement to heat transfer accompanied by an increase in pumping power. In this context, one extensive computational study on thermal and hydraulic performance of solar air heater provided with inclined and spherical rib protrusions has been conducted and presented in this chapter.

3.2 DETAIL OF COMPUTATIONAL MODEL

In the present work, numerical simulations have been carried out using finite volume method. The fluid flow and heat transfer when a fluid flows through a rectangular duct having a combination of spherical and inclined ribs as roughness elements and with a constant heat flux has been investigated. The details of geometry, computational flow domain, mesh generation, boundary conditions, solution method and results validation have been discussed in following sub-sections.

3.3 GEOMETRY

The geometry being used for the analysis of fluid flow and heat transfer is a rectangular duct. The dimensions of the rectangular duct i.e height, length and width of computational flow domain are considered as 25 mm, 500 mm and 150mm, respectively. Three faces of the rectangular duct has been considered to be smooth and the fourth face have spherical and inclined ribs as roughness elements . The top face of the rectangular duct with spherical and inclined ribs has been exposed to a heat flux of 1000W/m^2 and the other 3 faces are considered to be smooth without any heat flux exposed to it. The top surface of the rectangular duct on which the heat flux is supplied acts as an absorber plate with artificial roughness geometries. Air enter in the duct at inlet section, extract heat from absorber plate when air comes in contact with absorber plate and then air comes out from the duct at outlet section.

The relative ribs height (e/D) and relative ribs pitch (p/e) of conical protrusion ribs have been chosen as 0.04 and 20, respectively. All the simulations have been carried out at three values of Reynolds number (Re) in the range 4000-12000. The Reynolds number being used for the calculation here are 4000, 8000 and 12000.Angle of attack (a) is 60◦based on the optimum values of all parameters described in the literatures.

The computational flow domain has been shown in fig 3.1.

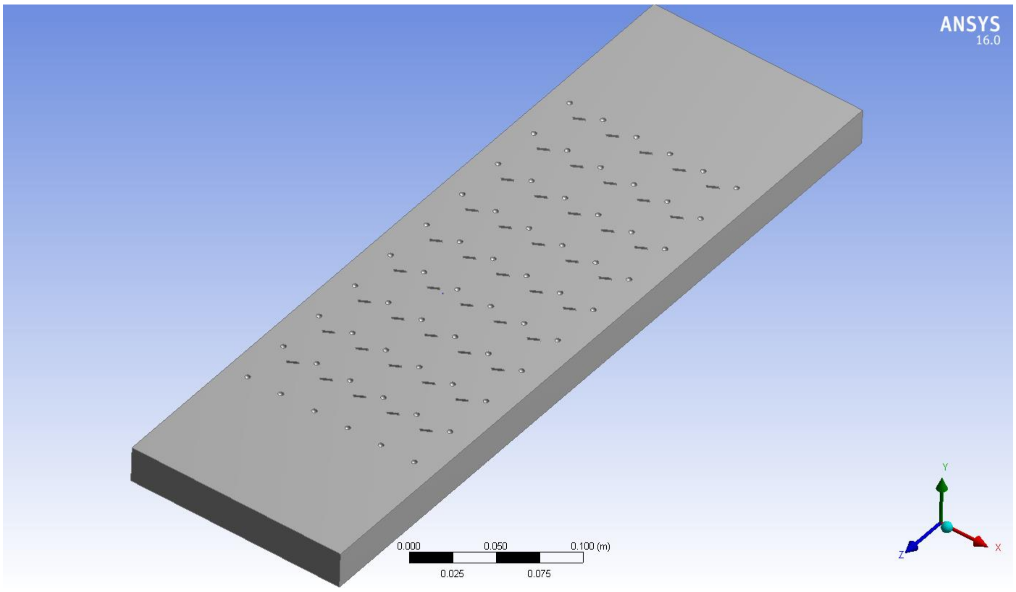


Fig. 3.1: Computation flow domain.

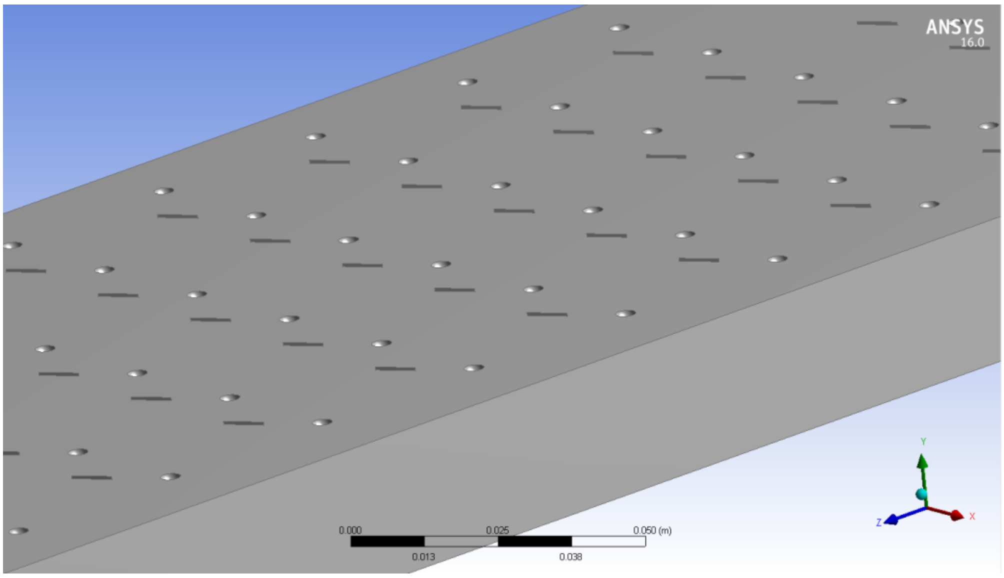


Fig 3.2: Roughened surface with spherical and inclined ribs.

Table 3.1:The values of the operating parameters has been shown in the table given below.

OPERATING PARAMETERS	VALUES
Uniform heat flux, ‘q’	1000 W/m2
Reynolds number, ‘Re’	4000-12000 (3 values)
Prandtl number, ‘Pr’	0.71
Relative roughness pitch, ‘P/e’	20
Relative roughness height, ‘e/D’	0.04
Duct aspect ratio, ‘W/H’	12

3.4 CREATING A MESH

Mesh generation is the practice of creating a mesh, a subdivision of a continuous geometric space into discrete geometric and topological cells. Often these cells form a simplicial complex. Usually the cells partition the geometric input domain. Mesh cells are used as discrete local approximations of the larger domain. Meshes are created by computer algorithms, often with human guidance through a GUI, depending on the complexity of the domain and the type of mesh desired. The goal is to create a mesh that accurately captures the input domain geometry, with high-quality (well-shaped) cells, and without so many cells as to make subsequent calculations intractable. The mesh should also be fine (have small elements) in areas that are important for the subsequent calculations. Meshing is any typical FEA software is discretization. The continuum needs to be discretized into finite number of “elements”. This process is kown as meshing process in ansys. Meshing does affect the results a lot. Good mesh is required in the critical areas such as areas of stress concentration, or areas of interest in the stress distribution we are looking for. A very crude rule might be, a mesh which looks good is good. This may not be applicable everywhere but is applicable at many places. Fine mesh is required in the area of interest. Ideally a mesh convergence study is recommended. That is the mesh needs to be refined till there is no or no significant change in the stress values after mesh refinement. Selection of elements does affect an analysis.

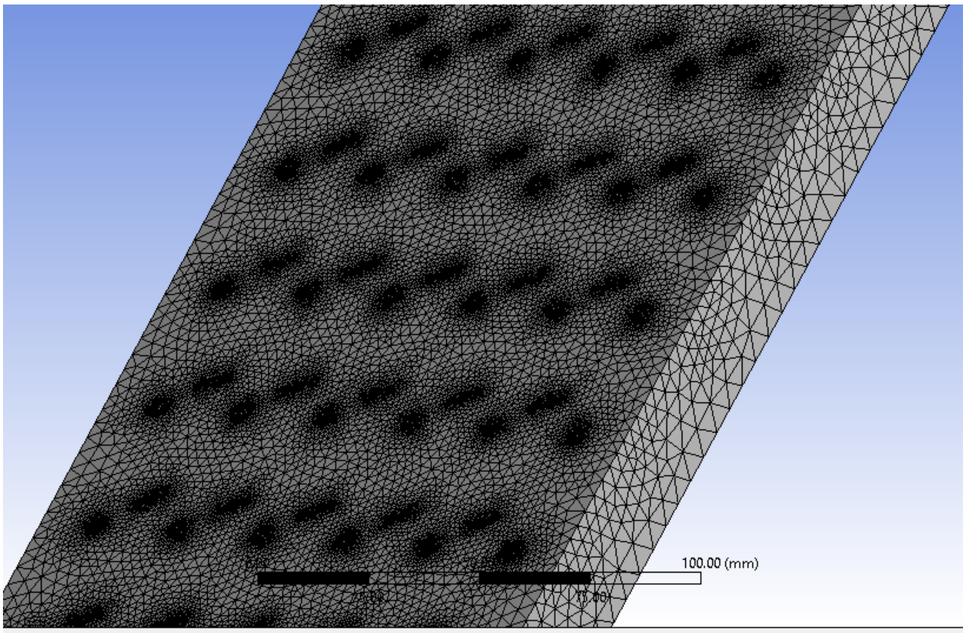


Fig 3.3: Meshing of solar air heater duct

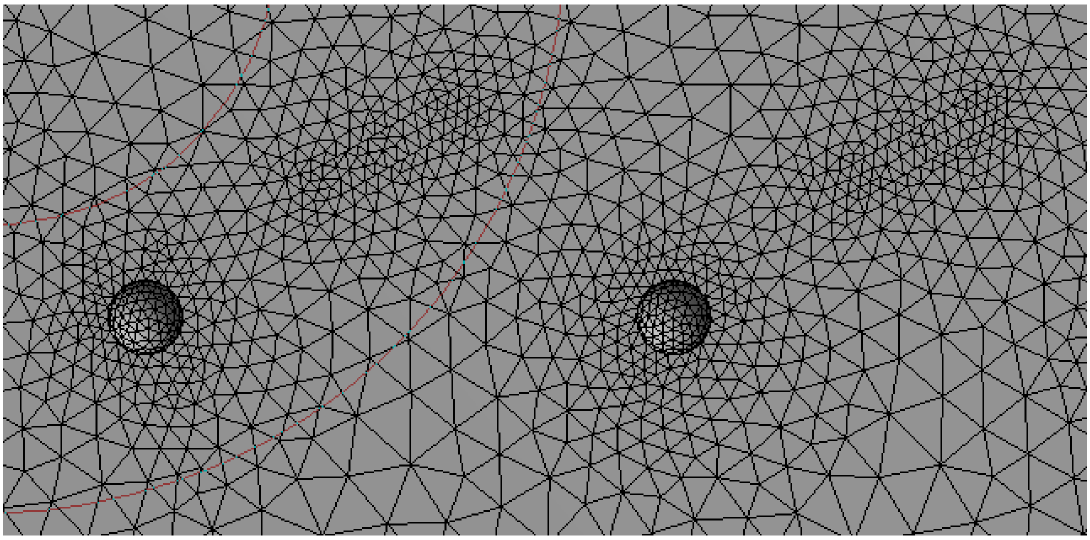


Fig 3.4: Meshing of Roughness Geometry

3.5 BOUNDARY CONDITIONS

After generating the mesh, similar boundary conditions have been imposed on the flow domain as found on actual solar air heater. The top side of domain has been considered as absorber plate on which spherical and inclined ribs have been created and heat flux of 1000 W/m², equivalent to typical insolation has been imposed on the absorber plate.

Sides and bottom plane are considered to be smooth and insulated and no slip boundary condition has been imposed. Pressure outlet and velocity inlet conditions have been assigned on the outlet and inlet section of the domain, respectively. The remaining faces of the rectangular duct have been assigned to be walls and different names have also been given to them for identification. Based on the desired Reynolds number, values of inlet velocities have been determined at uniform temperature of 300 K. Due to small rise in temperature of air, all physical properties are considered to be fixed which are determined on 300 K temperature and listed in Table 3.2.

Table 3.2: Properties of air

Property name	Value
Density(ρ)	1.117 kg/m³
Prandtl number (Pr)	0.71
Specific heat(C_p)	1007 J/kgK
Viscosity(μ)	1.857×10^{-8}Ns/m²

3.6 CREATING NAMED SELECTIONS

The Named Selection feature allows you to create named selections that can be transferred to the ANSYS Mechanical application, or used in the creation of some features. The named selection feature is used to give names to various surfaces or lines so that we can recognise them easily at the later stages The various names given to the different faces of the rectangular duct are shown below in the given table 3.3

Table 3.3: Named selections

Model (B3) > Named Selections > Named Selections

Object Name	*heatedsection*	*inlet*	*outlet*	*walls*
State	Fully Defined			
Scope				
Scoping Method	Geometry Selection			
Geometry	1 Face			3 Faces
Definition				
Send to Solver	Yes			
Visible	Yes			
Program Controlled Inflation	Exclude			
Statistics				
Type	Imported			
Total Selection	1 Face			3 Faces
Suppressed	0			
Used by Mesh Worksheet	No			

3.7 PERFORMANCE PARAMETERS

To calculate the Nusselt number (Nu) and friction factor (f) characteristics of the investigated solar air heater duct, properties of the air are calculated at the average value of the entry and exit temperatures of the flowing fluid and temperature of the heated surface under quasi static situation. The experimental observations are adopted to compute the dimensionless Nu as representative of convective heat coefficient while the f as envoy of pumping power.

The equation used for the calculation of the average friction factor is determined as [23-25]:

$$f = \frac{2(\Delta p)D}{4\rho L V^2} \tag{3.1}$$

The nusselt number calculation for the heated section is done through ansys automatically The velocity at the inlet is calculated according to the Reynolds number by the following equation:

$$Re = \frac{VD}{\upsilon} \tag{3.2}$$

3.8 SOLUTION CONTROL

The geometry is first created in design modeler and then the meshing is done. Different names have been given to the different surfaces so that the boundary conditions can be given to them. Double precision pressure based solver is selected in order to solve the set of equations used. Second order upwind discretization scheme is selected for all the transport equations as suggested by Kumar and Saini [26]. The continuity equation, energy equation and the Navier–Stokes equations in their steady, incompressible form, along with the associated boundary conditions are solved using the multipurpose finite volume based CFD software package, ANSYS FLUENT. In the present numerical study standard k–ε turbulence model with 'enhanced wall treatment' is used. In the discretization of governing equations, SIMPLE (semi implicit method for pressure linked equations) algorithm is used in pressure–velocity coupling as suggested by Kumar and Saini [25]. In the present simulation, the convergence criteria between two consecutive iterations is set to be relative deviation less than 10^{-6} for energy equation and less than 10^{-3} for solution in velocity and continuity equation.

Various results for both the rectangular duct with smooth surface and the rectangular duct with one artificially roughened surface with spherical and inclined ribs as roughness elements have been calculated and then a comparative study about the effects of roughness elements has been done. For this the values of nusselt number , friction factor, and temperature at the outlet of the rectangular duct have been calculated and various graphs have been made for this comparative study.

3.9 VALIDATION OF MODEL

For the validation purpose results were found out for the rectangular duct with smooth surface and various results were compared with the theoretical values at that condition. Dittus-Boelter correlation was used for the calculation of the theoretical values of nusselt number and blasius equation was used for the calculation of theoretical values of the frictional factors

Heat transfer rate and friction factor calculated against the data obtained for each flow channel with plane absorber plate has been correlated with theoretical data collected from Dittus–Boelter correlation and Modified Blasius Eq. for the Nusselt number(Nu) and friction factor (f) accordingly employed for turbulent flow and used by many investigators for validation of the solar air heating ducts

$$Nu_s = \frac{0.023 \times Re^{0.8}}{Pr^{-0.4}} \tag{3.3}$$

$$f_s = \frac{0.085}{Re^{0.25}} \tag{3.4}$$

Here ,

Nu_s= Nusselt number at the heated surface

Re=Reynolds number

Pr=Pandtl number

f_s=friction factor at the heated surface

The comparison of the theoretical and the values obtained from CFD analysis show that the maximum deviation of the nusselt number and the friction factor are 11.6% and 7.22% respectively , which is acceptable. Thus, logically an acceptable agreement of the two arrangements of values establishes the truthfulness of the data composed testing this model. The Fig 3.5 and Fig 3.6 shows the variation of nusselt number and frictional factor for the smooth duct for different Reynolds number .

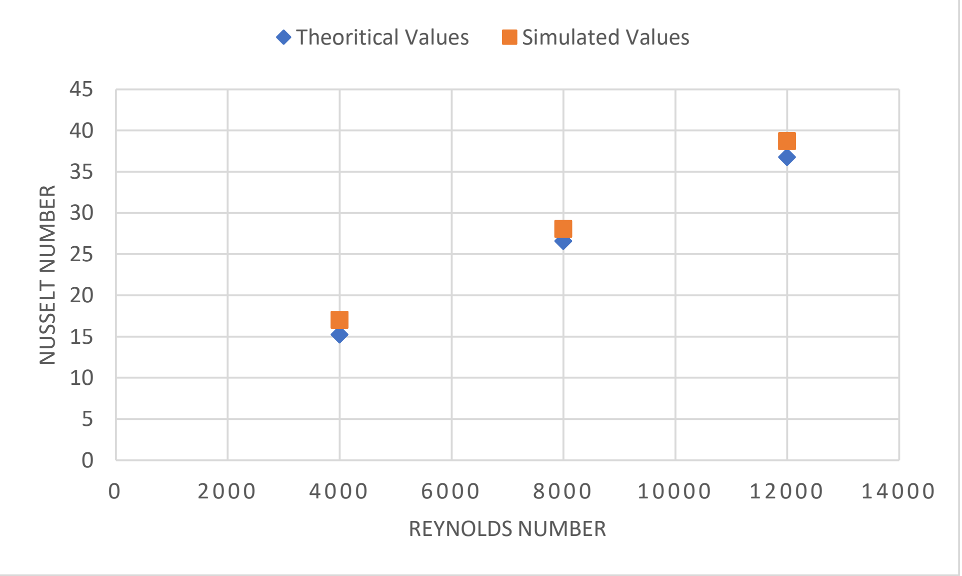


Fig 3.5: Variation in theoretical and simulated values of nusselt number with Reynolds number

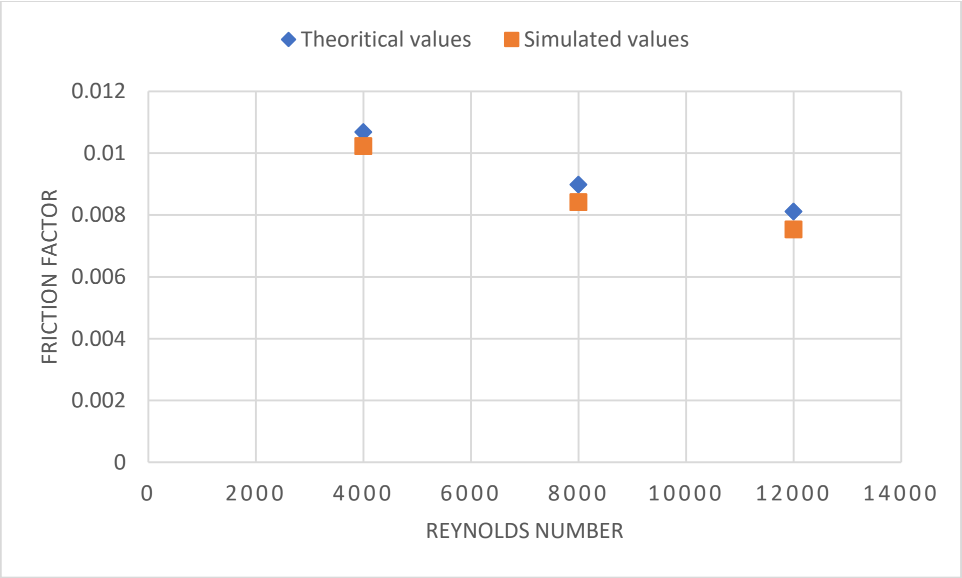


Fig 3.6: Variation in theoretical and simulated values of friction factor with Reynolds number

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 GENERAL

It has been pointed out in previous chapter that the rate of heat transfer from absorber plate to the air can be substantially enhanced as a result of additional turbulence generated in the flow by using artificial roughness. Further the presence of roughness is also found to increase the frictional losses in the flow, which results in an increase in pumping power. Therefore, foe better performance of a solar air heater it is desirable to obtain the roughness element which enhances the heat transfer with minimum increase in pumping power.

In this chapter, the results of the numerical investigation are being presented and discussed in detail.

4.2 VARIATION OF TEMPERATURE DUE TO THE ROUGHNESS

The variation in the temperature because of the roughness elements has been calculated. The values of temperature at different surfaces has been found out using ansys at different values has been calculated. The values of the temperature at different surfaces at different Reynolds number is shown below in tables 4.1,4.2 and 4.3.

Table 4.1: Temperature variation for Re=4000

SURFACE	SMOOTH	ARTIFICIALLY ROUGHENED
INLET	300 K	300 K
OUTLET	312.10 K	312.9398 K
WALLS	301.78271 K	302.31512 K
INTERIOR SOLID	306.03194 K	312.6755 K
HEATED SECTION	404.8586 K	380.246 K

Table 4.2: Temperature variation for Re=8000

TEMPERATURE	SMOOTH	ARTIFICIALLY ROUGHENED
INLET	300 K	300 K
OUTLET	305.9 K	306.49223 K
WALLS	300.82471 K	301.07634 K
INTERIOR SOLID	302.98233 K	306.4389 K
HEATED SECTION	362.34943 K	355.59666 K

Table 4.3: Temperature variation for Re=12000

TEMPERATURE	SMOOTH	ARTIFICIALLY ROUGHENED
INLET	300 K	300 K
OUTLET	303.95029 K	304.31747 K
WALLS	300.53658 K	300.76206 K
INTERIOR SOLID	301.96277 K	304.13722 K
HEATED SECTION	346.03194 K	343.03703 K

It can be seen from the above results that the increment in the temperature at various surfaces takes place due to the spherical and inclined rib protrusions as roughness elements. This is due to the fact that the roughness elements break the laminar sub-layer and make the flow turbulent due to which heat transfer coefficient between the air and the absorber plate increases and hence the heat transfer also increases and more heat energy gets transferred from the absorber plate to the air flowing in the solar air heater. Due to more heat transfer the temperature of the air flowing in the duct also increases and the air gets heated more efficiently. The variation of the outlet temperature at different Reynolds number is shown below in fig 4.1 for both the rectangular duct with smooth surface and the rectangular duct with artificially roughened surface. The comparison of the graphs show that the temperature at the outlet increases due to the use of spherical and inclined ribs as roughness elements and hence the use of this rib geometry is useful for better heating of the air flowing inside the solar air heater.

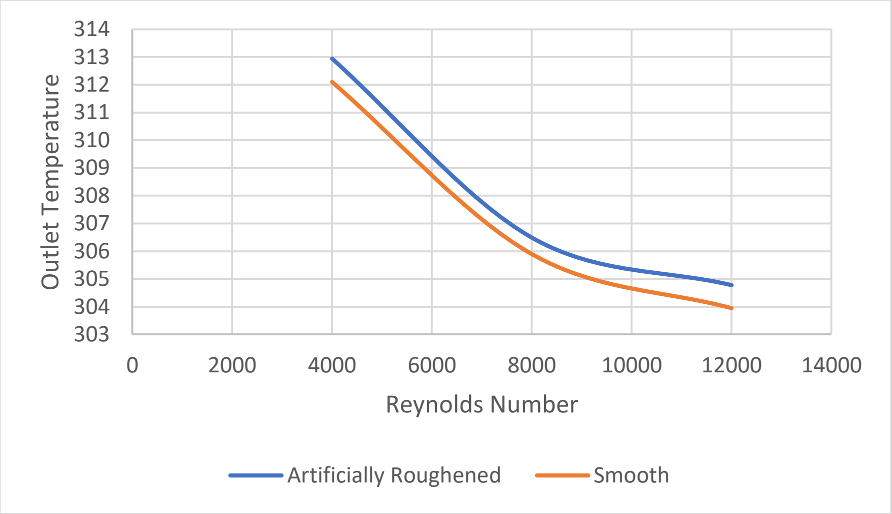


Fig 4.1: variation of oulet temperature with Reynolds number for smooth and artificially roughened duct

4.3 EFFECT OF RIB SHAPES

The nusselt number of artificially roughened duct with spherical and inclined ribs and nusselt number have been compared with the nusselt number of smooth duct duct without artificial roughness found out using Dittus-Boelter correlation as a function of Reynolds number for a relative roughness height (e/D) of 0.04 and relative roughness pitch (P/e) of 20

A considerable increase in the nusselt number due to the use of artificial roughness can be observed . It has been found that the artificial roughness applied to the absorber plate, penetrates the viscous sub-layer to promote turbulence that, in turn, increases the heat transfer coefficient between the air flowing in the duct and the heated surface with artificial roughness and therefore an increment in the nusselt number can be observed when compared to the rectangular duct with smooth surface and hence the heat transferred to the air also increases due to the increase in the heat transfer coefficient. The variation of the nusselt number with Reynolds number has been shown for both ,the artificially roughened surface and the smooth surface in fig 4.2.

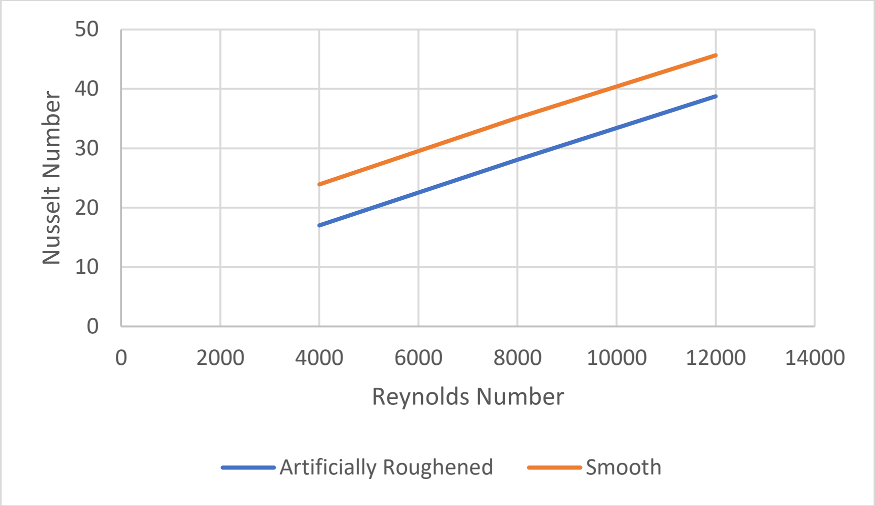


Fig 4.2 : Vartiation of nusselt number with Reynolds number for smooth and artificially roughened duct

The inclined ribs perform better than the spherical ribs and it will provide better results if only one type of roughness element geometry was to be used. In this context, the velocity vectors around the spherical and the inclined ribs has been shown in Fig 4.4. Sharp edge of inclined ribs is attributes to high turbulence in the flow along with strong re-attachment point on surface. Strong re-attachments on the surface disturb sub-laminar layer and high turbulence help to mix the flow near surface to core flow. However, re-attachment point has also been observed in case of spherical ribs but intensity of reattachment point is too weak to enhance the heat transfer rate. Hence it can be concluded that the inclined ribs perform better than the spherical ribs and provide better results in case of single use.

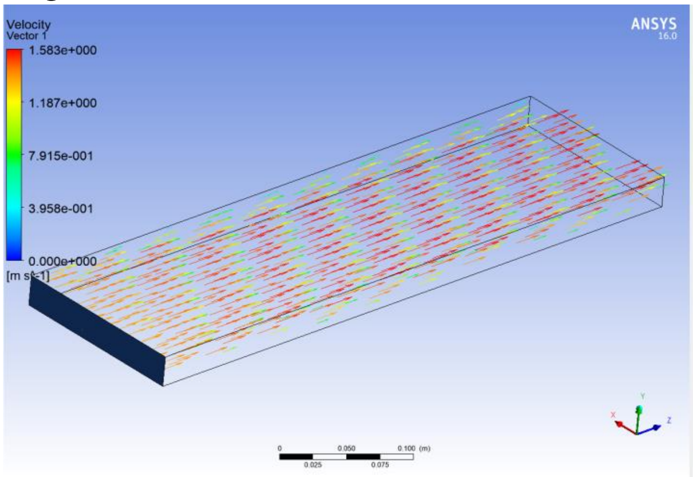
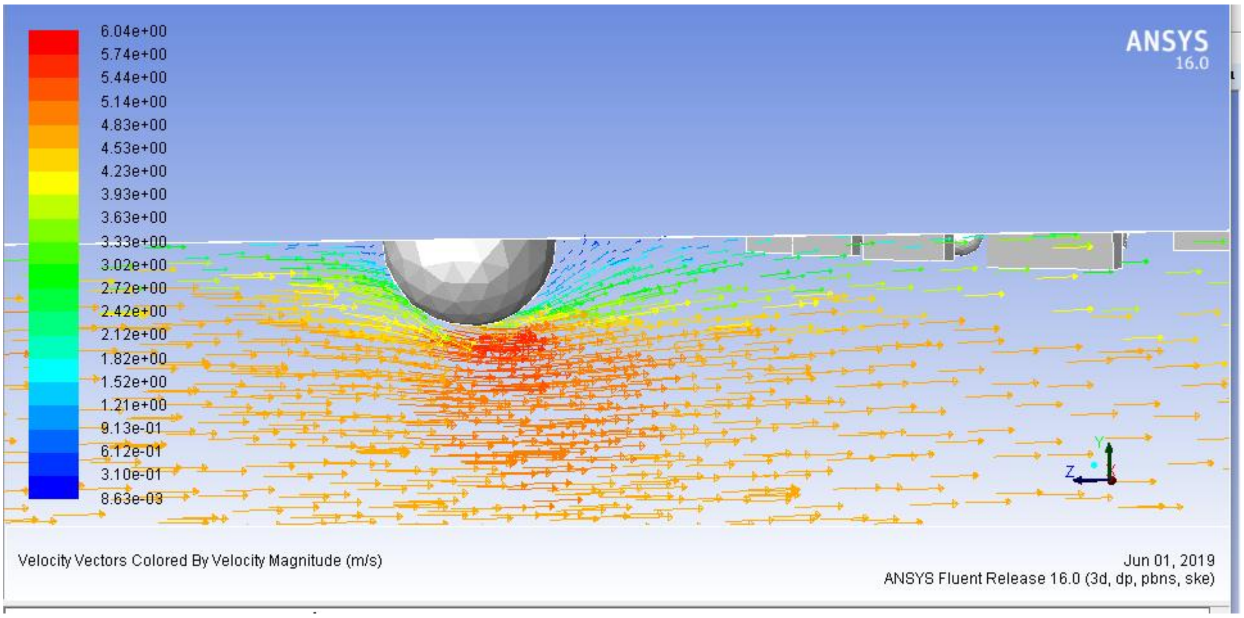
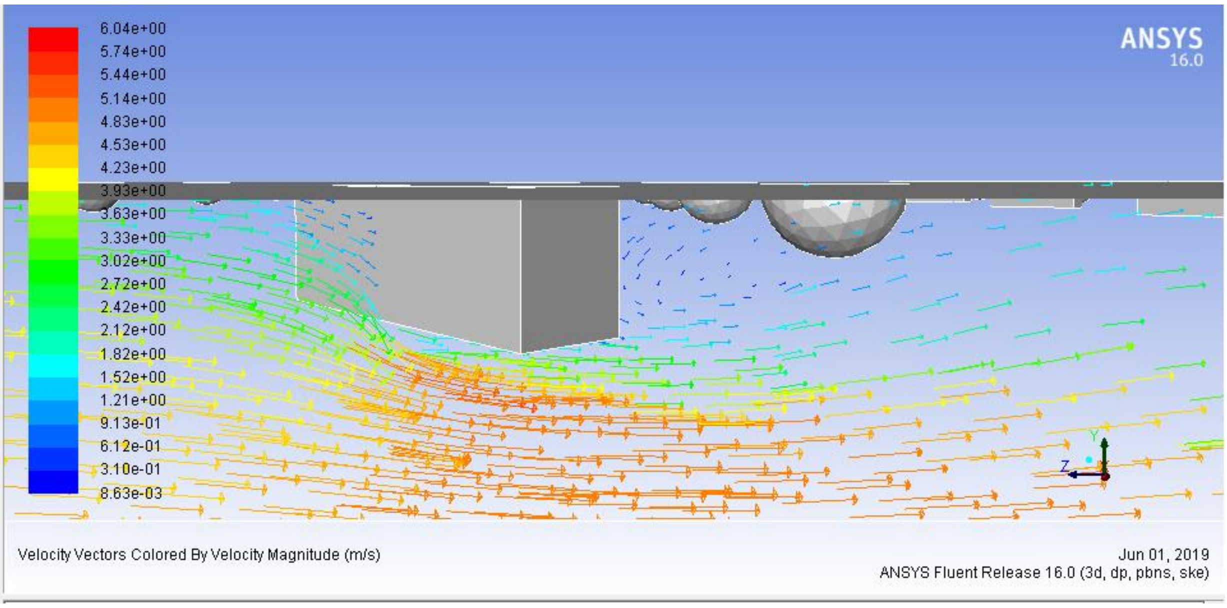


Fig 4.3: velocity vectors for smooth duct



(a)



(b)

Fig 4.4: velocity vectors for a) spherical and b)inclined ribs

4.4 EFFECT ON FRICTION FACTOR

The variation of friction factor of smooth duct (using Blasius Equation)and roughened ducts with inclined protrusion ribs and spherical ribs as a function of Reynolds number have been presented in Fig. 4.5. As the value of Reynolds number increase, friction factor of smooth duct and both the roughened ducts decrease due to deterioration of laminar-sub layer. With increase in the friction factor more power is required to pump the air through the rectangular duct, therefore, large increase in friction factor must not be there so that less power is required for pumping of air through the air blower or fan.

The variation of the friction factor with the Reynolds number is shown in Fig 4.5. It can be seen from the graph given below that the friction factor decreases with the increase in the Reynolds number for smooth as well as artificially roughened duct and also the value of friction factor for artificially roughened duct is more than that of the smooth duct at the same Reynolds number hence more power is required by the air blower or fan to blow the air through the duct in case of artificially roughened duct than the smooth duct.

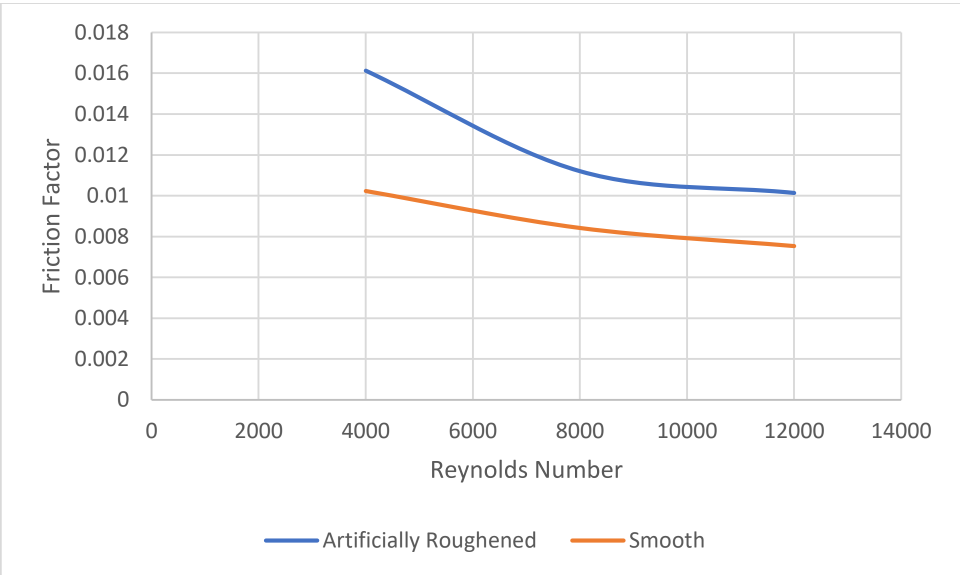


Fig 4.5: variation of friction factor with Reynolds number for smooth and artificially roughened duct

4.5 ENHANCEMENT IN NUSSELT NUMBER (Nu/Nu_s)

The use of artificial roughness in solar air heaters results in an increase in the nusselt number. The enhancement in nusselt number is the ratio between the nusselt number of artificially roughened solar air heater (Nu) and nusselt number of solar air heater with smooth duct (Nu_s). The variation of Nu/Nu_s with the Reynolds number is shown in Fig 4.6

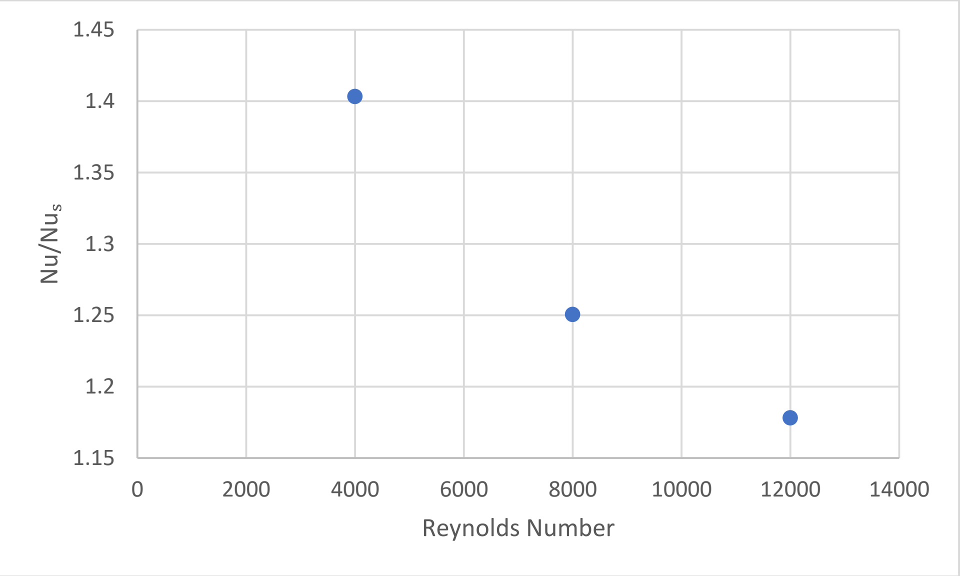


Fig 4.6: Enhancement in nusselt number

4.6 INCREMENT IN FRICTION FACTOR (f/f_s)

The friction factor of artificially roughened solar air heater is more than the smooth duct because the ribs offer resistance to the fluid flow. With increase in friction factor more power is required by the fan or blower to flow air through the solar air heater duct. The increment in friction factor with Reynolds number is represented in Fig 4.7

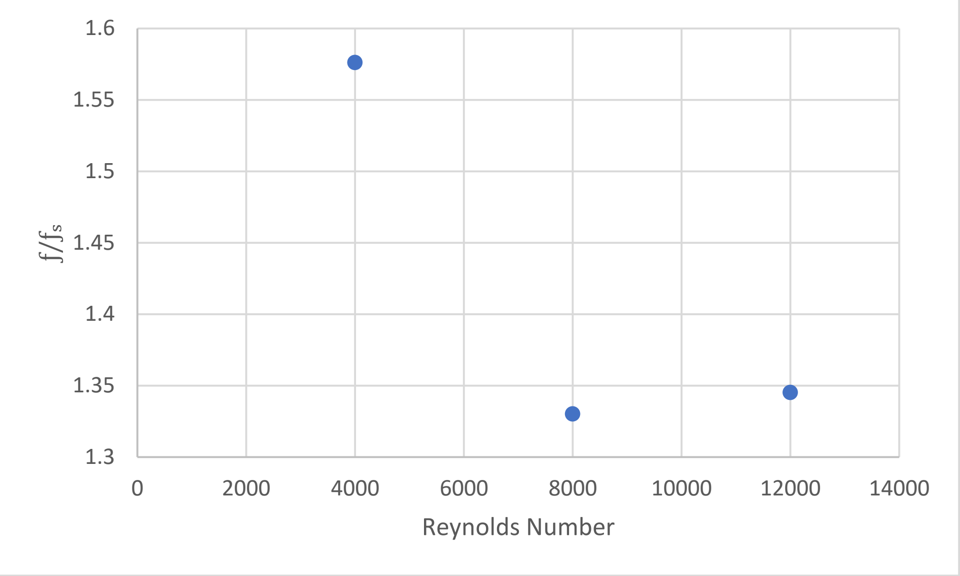


Fig 4.7 Increment in friction factor

4.7 THERMO HYDRAULIC PERFORMANCE

It has been found that the artificial roughness in the form of spherical and inclined ribs on the absorber plate results in substantial enhancement of heat transfer. This enhancement is, however, accompanied by a considerable increase in the friction factor. It is, therefore, desirable to choose the roughness geometry such that the heat transfer is maximized while keeping the pumping losses at the least possible value. In order to analyse overall performance of a solar air heater, thermo-hydraulic performance should be evaluated by simultaneously consideration of thermal as well as hydraulic performance. Thermal performance of a solar air heater concerns with the heat transfer process within the collector while hydraulic performance concerns with pressure drop in the duct.

Webb and Eckert [27] in heat transfer of a roughened duct compared to that of the smooth duct for the same pumping power requirement and is defined as

$$Thermo - hydraulic\ performance = \frac{(\frac{Nu}{Nu_s})}{(\frac{f}{f_s})^{1/3}} \tag{3.5}$$

The thermo-hydraulic performance parameter is used to estimate how effectively an artificially roughened surface enhances the heat transfer under constant pumping power constraints, for this purpose the friction factor value must not be increases to a large extent A value of thermo-hydraulic performance parameter greater than one ensures the effectiveness of using an enhancement device and can be used to compare the performance of number of arrangements to decide the best among these. Nu_s represents Nusselt number for smooth duct of a solar air heater and can be obtained by Dittus–Boelter equation and f_s represents friction factor for smooth duct of a solar air heater and can be obtained by :

$$f_s = \frac{0.085}{Re^{0.25}} \tag{3.6}$$

$$Nu_s = \frac{0.023 \times Re^{0.8}}{Pr^{-0.4}} \tag{3.7}$$

The values of the thermo-hydraulic performance for artificially roughened duct with spherical and inclined fins as roughness elements has been shown below in table 4.4 It can be seen from the values that the thermo-hydraulic performance parameter is greater than one which proves that it is beneficial to use this type of roughness geometry to increase the heat transfer .With this kind of roughness geometry the efficiency of the solar air heater increases and better heating of the air inside the duct occurs.

Table 4.4:Values of thermo-hydraulic performance at different Reynolds numbers

Reynolds number	Thermo hydraulic performance
4000	1.205685933
8000	1.13723688
12000	1.06733787

CHAPTER 5

CONCLUSION

In this work the nusselt number and friction factor characteristics of the artificially roughened solar air heater duct has been obtained. The CFD analysis based on finite volume application has been used to simulate the results. The effects of the roughness parameters of spherical and inclined protrusions on thermal and thermo-hydraulic performance of solar air heater has been investigated. Various results have been presented for different Reynolds number ranging from 4000-12000. Based on the present investigation, following conclusions are drawn

i. The 3-D model of artificially roughened solar air heater duct has been prepared and flow behavior of flow inside the duct has been investigated.
ii. The heat transfer coefficient between absorber plate and flow has been increased due to reattachment and separation of the flow.
iii. The maximum absolute deviation between theoretical and numerical values of the nusselt values for nusselt number and friction factor has been obtained as 11.6% abd 7.22%.
iv. The temperature of air at outlet of the duct is more in case of artificially roughened duct as compared to smooth duct. It is found that the presence of roughness geometry break the viscous sub-layer and promotes the turbulence in flow field which ultimately increase the heat transfer in the air.
v. The average nusselt number increase with increase in Reynolds number. The maximum enhancement in nusselt number is found to be 1.40336 times that of smooth duct.
vi. The friction factor decreases with increase in Reynolds number. The maximum increase in friction factor is found to be 1.5764 times that of smooth duct.
vii. A significant enhancement in thermo-hydraulic performance has been obtained. The value of the thermo-hydraulic performance parameter varies between 1.067 to 1.205.
viii. The optimum value of the thermo-hydraulic performance parameter has been found to be as 1.20585 corresponding to Reynolds number of 4000.

5.1 RECOMMENDATION FOR FUTURE WORK

i. More values of the roughness parameters can be investigated in future to investigate the heat transfer fluid flow characteristic.

ii. Meshing can be done in more detailed manner to calculate heat transfer in the inter rib region. To get more accurate results more finer mesh can be generated.

iii. The other roughness geometries like circular arc, V-shaped, discrete multi V shaped and staggered ribs can also be investigated in future.

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