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CFD Analysis on the Performance of Solar Air Heater with Transverse Fixed Roughness in Continuous Distribution

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ABSTRACT

Solar energy is one of the abundant renewable energy sources for the places like India where, we have more than 300 good sunshine days in a year. Extracting solar energy for the thermal needs has found more domestic and industrial applications like water heating and air heating requirements. The flat plate solar collectors are more popular in India as they require minimum tracking. The solar air heaters can be used for crop drying applications with assured hygiene environment for drying. Use of artificial roughness increases the heat transfer rate in the solar flat plate air heater with consequent effect of increased pressure drop due to friction. The present work based on computational fluid dynamic (CFD) approach intends to find better operating point for enhanced heat utilization at lower pressure drop. The study investigates the effect of the nature of the flow i.e. turbulent or laminar obtained by varying mass flow rate between 0.01-0.2 kg/s. The effect of relative roughness height on the overall performance of the system constitutes the important aspect of the proposed research.

Keywords: *Solar Air Heater, Artificial roughness, CFD, BC, Solar Energy, Flat Plate Collectors.*

Nomenclature:

Mass flow rate (m), kg/s Pitch, (p)mm,
Duct height, (D) mm, rib height (e), mm
Relative roughness height (e/D),
Reynolds number (Re), Nusselt number (Nu)
Velocity, (v)m/s, Pressure, (P)Pa
Solar radiation, (I), W/m^2 Inlet/Outlet /ambient air temperature, (T_i/ T_o/ T_a) ºC,

I. INTRODUCTION

The phenomenon like global warming, environmental changes and fossil fuel depletion always made the present generation human race to look for environmental friendly renewable energy sources. Solar energy is considered as one of the perennial energy sources as its availability affects the life on earth. The available solar energy on the earth surface is nearly 1.74x10^5 TW adequate enough to meet the global energy needs. The percentage sharing in global energy production by the potential renewable sources like solar and wind energy systems are increasing day by day, creating new opportunities as well as challenges in this energy harvesting field. The solar energy availability in India, owing to its geographic location provides nearly 80% of good sunshine days in a year sufficient enough to extricate the coal based power plants that contribute 70% of the energy produced in India [1].

The solar energy potential can provide promising solutions to accommodate escalating energy demand simultaneously preserving a clean environment [2]. There are myriad energy conversion technologies applicable to solar energy amongst which, direct conversion of sun energy to high grade electric energy using photovoltaics (PV) with 10-15% conversion efficiency has been at the foremost position [3]. The thermal utilities like air heaters, water heaters, desalination units, pasteurizers, food drying units, water purifier, space heating systems, air-conditioning units and cookers can be compatible to run on solar energy with slightly higher efficiency (30%-60%) as compared to PV panels [4,5,6]. The relative position of earth with respect to sun undergoes variations during a annual cycle thereby inducing a variability factor to the available solar radiation on the earth's surface. The annual variations coupled to diurnal changes amounting from local factors makes it difficult to obtain constant insolation in a particular direction. However, when effective efficiency is considered with an account of energy required for tracking and energy harvested for the Indian geographic conditions two point tracking and fixed tilt at optimized tilt angle are preferable for flat plate collectors/PV panels [7].

The various food processing industries use low/medium temperature (40-80^oC) hot air for drying different food products like fruits, vegetables, fish and seafood. The hot air also found applications in industries like leather, textiles, chemicals, rubber, paper and pharmaceuticals [8]. These low temperature application needs can be fulfilled by the solar flat plate collectors as it deals with the low temperature applications (40-90^oC) [9]. To enhance heat utilization in solar flat plate collectors commonly adopted techniques are forced convection, artificial roughness, turbulators, proper materials for thermal insulation, absorber plate and glazing[10,11].

The uses of artificial roughness to enhance the heat utilization in solar air heaters are found to be popular with its ability to potentially enhance the thermo-hydraulic performance with non-favorable increase in friction factor. This challenges the designer to develop an artificial roughness with maximum thermo-hydraulic heat utilization system with minimum friction losses [12,13]. Computational fluid dynamics (CFD) is emerging as an efficient tool in designing and optimizing the problems involving various aspects of physics like fluid flow, heat transfer, mass transfer, electromagnetic, structural and multiphysics problems. The CFD simulation tools provide virtual flat form to imitate the real world multiphysics involved problems with the help of numerical methods to solve it efficiently [14,15,16]. The CFD solutions for fluid flow and heat transfer involved problems will be based on solution obtained from the continuity, momentum and energy equations indicated in Eq. 1, 2 and 3 respectively.[17,18,19]

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \qquad \text{Eq. 1}$$

$$\frac{\partial u_i}{\partial t} + u_i \frac{\partial (u_j)}{\partial x_i} = -\frac{1}{\rho}\frac{\partial p}{\partial x_j} \qquad \text{Eq. 2}$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial \rho u_j E}{\partial x_i} = \frac{\partial p}{\partial t} - \frac{\partial (u_i \tau_{ij} + Q_{ij})}{\partial x_j} \qquad \text{Eq. 3}$$

In the present work an attempt has been made to enhance the heat utilization with minimum pressure drop through CFD approach conducting parametric study of relative roughness height on the effective efficiency of the solar flat plate air heater.

II. METHODOLOGY

The CFD is efficient tool to analyze problems involving fluid flow, heat transfer and other physics like chemical reactions, combustion chemistry and electromagnetics with the help of computers to solve this problem in the form of numerical methods. This section discusses the details of the problem considered for the study and steps used in the process of solving it.

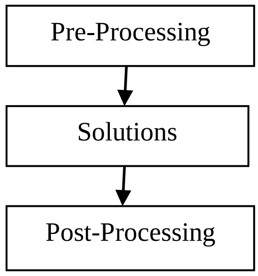

Fig.1. General CFD analysis workflow

The steps involved in common CFD analysis process is shown in the fig. 1. The pre-processing step mainly involves the geometry creation, grid generation and applying initial and boundary conditions. Solution step involves selection of appropriate solution schemes and computation of the solutions based on the pre-processing. The post processing involves the interpretation of the results and graphical representation of the results.

The top view and the side view of the geometry considered for the study has been shown in the Fig. 2a and Fig. 2b. The dimensions and the range of parameters affecting the performance of the flat plate solar air heater with transverse rectangular ribs used for the study are presented in the table 1. The mesh generated for the study were unstructured tetrahedral in nature, the grid sizes were varied to study the grid sensitivity on the results. The sample of mesh generated for the present study has been shown in the fig. 3. The details of the initial and boundary conditions used for the study were indicated in the table 2. The fin and glass material properties required for the solution like diffuse fraction and emissivity are defined according to the standard material properties available. The diffuse fraction of fin surface has been assumed to be unity considering that the fin is coated with black paint.

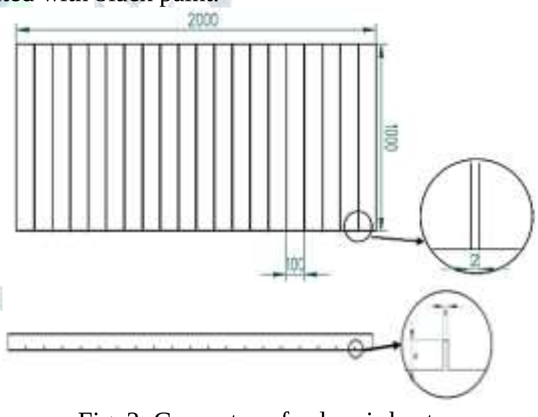

Fig. 2. Geometry of solar air heater

Table 1. Air heater Specifications used in study

Sl. No.	Parameters	Value
1	Mass flow rate, m, kg/s	0.01- 0.2
2	Length ,L ,mm	2000
3	Width, W, mm	1000
4	Duct height, D, mm	50
5	Pitch, p,mm	100
6	Roughness height, e, mm	0-45
9	Roughness thickness, t, mm	2
10	Relative roughness height, e/D	0 - 0.9
11	Relative roughness pitch, p/e	0 - 20
12	Aspect ratio , AR	20

Fig. 3 Sample mesh generated for the present study

Table 2. Details of BC used for the study

Boundary	Boundary Condition	Value
Inlet	Temperature, K	300
	Static pressure, kPa	101.325
Outlet	Mass flow rate, kg/s	0.01-0.2
Fin surface	Emissivity	0.9
	Diffuse fraction	1
Glass	Emissivity	0.8
	Diffuse fraction	0.33
	Incident Radiation, W/m^2	1000
Air Domain	Reference pressure	1 atm

The inlet and outlet boundary conditions were defined to be pressure inlet (atmospheric pressure) and mass flow rate outlet (0.01-0.2 kg/s). Absorber plate and glazing materials with material specific emissivity, diffuse fraction with radiation intensity of 1000 W/m^2 were considered for the study. The simulation study has been conducted using ANSYS CFX 14.5 with total energy, k-Epsilon and discrete transfer as heat transfer, viscosity and radiation models respectively. The reference pressure of the air domain has been set to 1 atmospheric with air as continuous fluid. The results for different relative roughness height ranging from 0-0.9 are discussed.

III. RESULTS AND DISCUSSIONS

The results observed from the CFD analysis were indicated and discussed in this section. As the main objective of our work is to study the behavior of the solar air heater at turbulent flow conditions. Fig. 4 indicates the variation of Reynolds number with the mass flow rate for a smooth duct flow. From this figure it is observed that the flow nature will be turbulent at flow rate of 0.05 kg/s which gives a Reynolds number greater than 2300 for a smooth duct flow. For further study on different relative roughness height the flow rate of 0.05 kg/s has selected as it provides a turbulent nature of the flow with the least pressure drop.

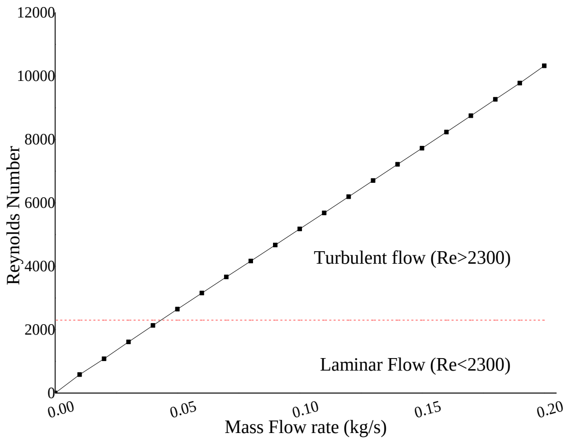

Fig. 4. Variation of Re with mass flow rate

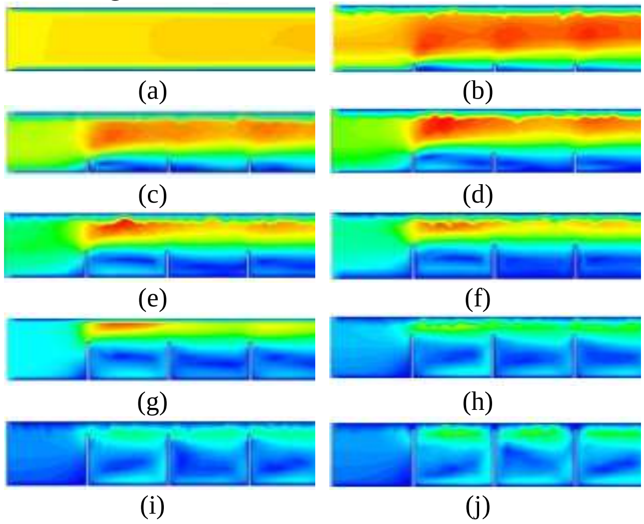

Fig.5. Velocity contours for air flow through duct at e/D between 0-0.9

The velocity contours obtained from CFD simulation for relative roughness height varying from 0-0.9 are depicted in Fig. 5The total temperature contours obtained from the CFD simulation results for relative roughness height varying from 0-0.9 were shown in Fig. 6.

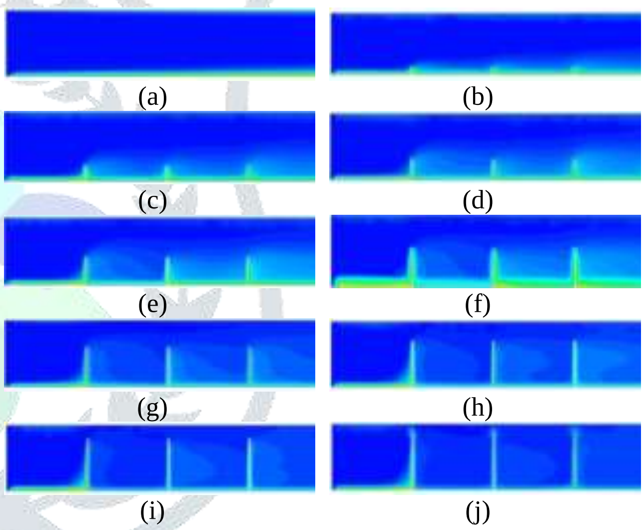

Fig. 6. Temperature contours for air flow through duct at e/D between 0-0.9

The total turbulence eddy dissipation contours obtained from the CFD simulation results for relative roughness height varying from 0-0.9 were shown in Fig. 7.

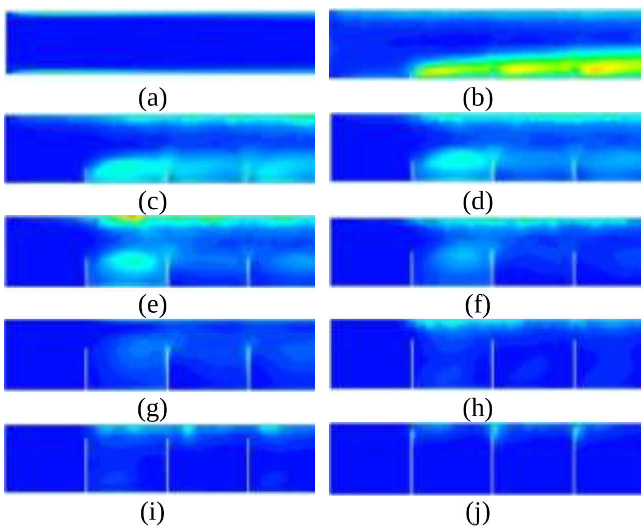

Fig. 7. Turbulence Eddy Dissipationin contours for air flow through duct at e/D between 0-0.9

Fig. 8 showcases the effect of relative roughness height on the pressure drop across the solar air heater. The variation of pressure drop was observed to vary exponentially with respect to the relative roughness height and tends to infinity for relative roughness height of 1 that theoretically depicted no flow condition due to complete blockage of flow area. The pressure drop for the smooth duct flow i.e. 0 relative roughness height was observed to be 0.47656 Pa because of the friction factor involved with the smooth duct flow.

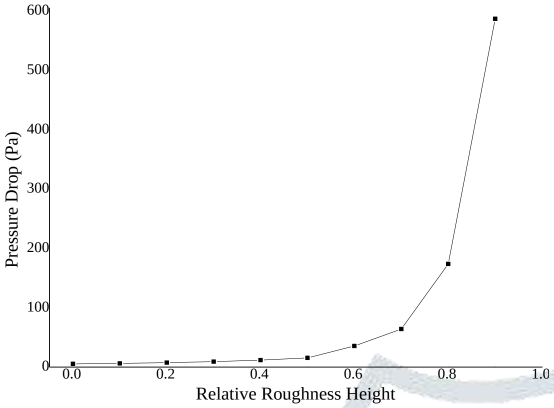

Fig. 8. Variation of pressure drop for air flow through duct at e/D between 0-0.9

Fig. 9 depicts the variation of heat utilized with respect to relative roughness height. The heat utilization increased with e/D ratio owing to rise in the fluid retention time imposed by a higher magnitude of pressure drop across the collector. However the relative roughness height could not be too high owing to its consequent effect on pressure drop requiring relatively high power rated blower to ensure consistent input air to solar collector.

Fig. 10 and Fig. 11 show the variations of heat transfer coefficient and Nusselt number of fin surface with respect to relative roughness height. The heat transfer coefficient and Nusselt number increased with relative roughness height owing to the reason that the absorber plate area in contact with the air increased with relative roughness height. The Nu and h values were related to the temperature dependent fluid properties and geometry of flow domain and hence exhibited similar relationships for varying values of e/D

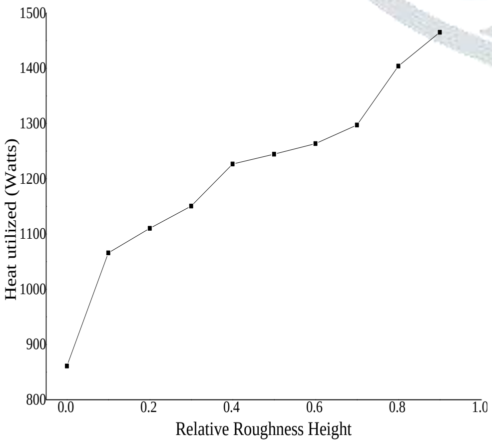

Fig. 9. Variation of Heat utilization for air flow through duct at e/D between 0-0.9

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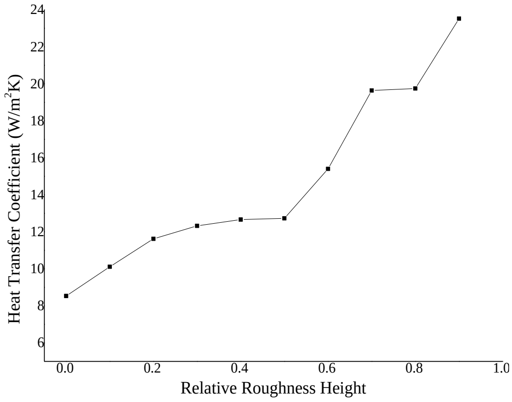

Fig. 10. Variation of heat transfer coefficient for air flow through duct at e/D between 0-0.9

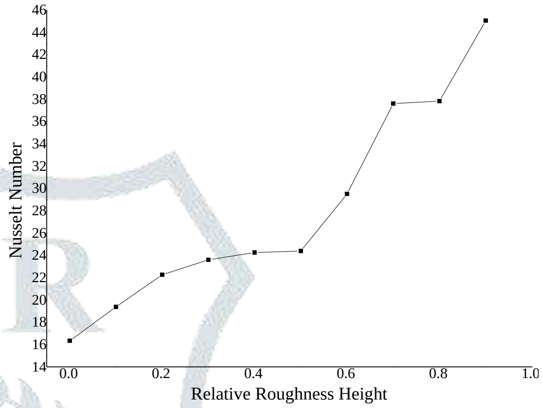

Fig. 11. Variation of Nusselt number for air flow through duct at e/D between 0-0.9

Fig. 12 shows the effect of relative roughness height on the Reynolds number for solar air heater indicates that higher value of e/D lead to increase in Re that was attributed for increase in flow velocity on account of higher e/D values.

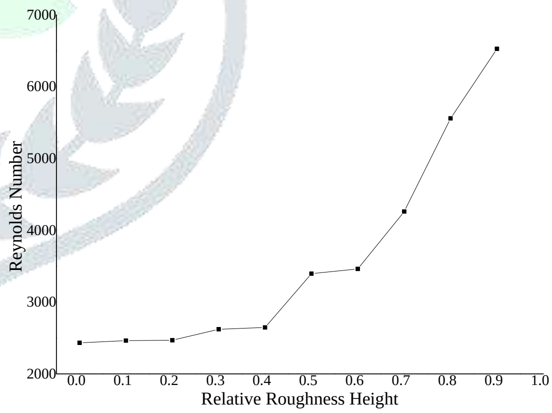

Fig. 12. Variation of Reynolds number for air flow through duct at e/D between 0-0.9

Fig. 13 shows effect of relative roughness height on overall efficiency of solar air heater that indicated increase in overall efficiency with e/D owing to increased fluid retention time and higher heat transfer coefficient between the absorber surface and duct flow medium. The computed overall efficiency was based without accounting blower power consumption and hence the results are likely to be lower than the values depicted in the fig 13.

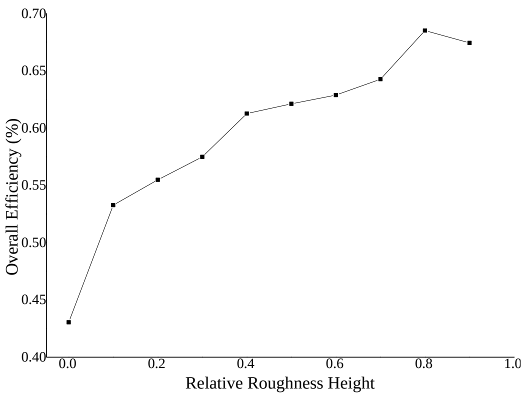

Fig. 13. Variation of Overall Efficiency for air flow through duct at e/D between 0-0.9

The salient observations through application of CFD analysis for fluid flow through the solar air heater duct provided interesting results that revealed the mechanism of heat transfer that lead to configure the device for intended application. The CFD tool as compared to theoretical model provided an improved accuracy of results on account of well defined solvers that were capable to handle the existing fluid flow problem. The time required for execution of solution through CFD approach was lower as compared to theoretical approach that was cumbersome to the defined heat transfer problem. The CFD results of flow velocity, temperature, pressure drop were used to determine the allied parameters like Re, Nu, heat transfer coefficient and overall efficiency to understand the mechanism of fluid flow to a more detailed level.

CONCLUSIONS

The conclusions drawn from the present study are summarized as,

- The CFD approach provided an effective means for selection of absorber surface for enhancement in heat transfer rate. The governing parameters influencing collector useful heat gain included flow parameters like mass flow rate, inlet air temperature and wind speed along with the collector design specifications of relative roughness, aspect ratio and spacing between the absorber and glass cover.
- The CFD post-process results provided tangible qualitative results for all the governing parameters and hence assisted in selection of better combination of relative roughness height and mass flow rate that prevented excessive pressure drop that hindered operation of the blower used for air supply.
- The performance of solar air heater was influenced by operating parameters like mass flow rate and nature of heat transfer surface. The study identified that higher mass flow rate between 0.01-0.2 kg/s lead to higher Reynolds Number that produced improvement in value of heat transfer coefficient.
- The temperature, velocity and Turbulence Eddy Dissipation contours obtained from CFD simulations were super-imposed to assess the influence of relative roughness on duct flow behaviour quantified in terms of convective heat transfer coefficient for the flow. The results favoured the use of 0.8 relative roughness that yeilded an overall efficiency of 68% with heat transfer coefficient of 20 W/m^2 ^{o}C. The estimates of overall efficiency were based upon useful heat gain and the incident solar insolation without accounting for the pumping power.
- The provision of surface roughness on absorber surface initiated a better fluid mixing at the surface that lead to higher convective heat transfer coefficient. This was evidenced in terms of overall efficiency of 68% at relative roughness of 0.8 as compared to corresponding value of 56% for the relative roughness of 0.2 for the absorber surface.
- The quantitative results of the study for rectangular rib geometry have established that selected e/D ratio of 0.8 was optimum, however earlier experimental investigations on a similar system have favored e/D of 0.50 to achieve minimum air flow rate for crop drying applications. The next level of CFD investigations can focus on other geometries of extended surface in the flow domain of solar air heater.

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