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A Numerical Analysis on Different Types of Solar Air Heaters

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Abstract

Solar air heater is a type of heat exchanger which transforms solar radiation into heat energy. The thermal performance of conventional solar air heater has been found to be poor because of the low convective heat transfer coefficient from the absorber plate to the air. Use of artificial roughness on surface is effective way to break laminar boundary sub layer. It enhances rate of heat transfer from absorber plate to flow of air stream. An attempt has been made to carry out CFD based analysis using Fluent to fluid flow and heat transfer characteristics of solar air heater. Model of solar air heater involving air inlet, absorber plate, glass, and solar air heater with baffles was modelled by ANSYS Workbench and the results were obtained by using ANSYS FLUENT software. It is evident from the simulation that solar air heater with fins increases the heat transfer area and also help in creating turbulence which in turn increases the temperature of the air. Use of polyethylene (green house plastic) as a glazing material for solar air heater is a great choice because though it collects 5% less solar irradiation from the sun but it traps the heat for longer time, acts as an insulating material. As they form a bond with water to assist evaporation by absorption of broadband light, they are utilized as good solar thermal absorber materials. During the study, the heat carrier's maximum temperature reached 48°C at a solar radiation intensity 9 W/m^2 and an ambient air temperature of about 30°C. Also, it has been observed that the solar radiation intensity and the outlet air temperature increases from 10 AM to 2.00 PM of the day as the intensity of solar radiation at Gangtok used in the study is maximum up to 2.00 PM and then it decreases.

Keywords: Solar air heater; Solar Energy; CFD; Heat transfer; Baffles and fins; Temperature distribution

Introduction

India is endowed with vast solar energy potential. About 5000 trillion kWh per year energy is incident over India's land area with most parts receiving 4-7 kWh per sq. m per day. Solar photovoltaics power can effectively be harnessed providing huge scalability in India. Solar also provides the ability to generate power on a distributed basis and enables rapid capacity addition with short lead times. There has been a visible impact of solar energy in the Indian energy scenario during the last few years. Solar energy based decentralized and distributed application have benefited millions of people in Indian villages by meeting their cooking, lightning, and other energy needs in an environmentally friendly manner. The social and economic benefits include reduction in drudgery among rural women and girls engaged in the collection of fuel wood from long distance and cooking in smoky kitchens, minimization of the risk of contracting lung and eye ailments, employment generation at village level, and ultimately, the improvement in the standard of living and creation of opportunity for economic activities at village level. Further solar energy sector in India has emerged as a significant player in the connected power generation capacity over the years. It supports the government agenda of sustainable growth, while, emerging as an integral part of the solution to meet the nation's energy need and an essential player for energy security.

Solar air heaters form a major component of solar energy utilization system which absorbs the incoming solar radiation, converting it into thermal energy at the absorbing surface, and transferring the energy to a fluid flowing through the collector. Solar air heaters are cheap and widely used. Solar air heaters have several applications including space heating and crop drying. The efficiency of normal solar air heater is found to be low because of low heat transfer coefficient between absorber plate and the flowing air which increases the absorber plate temperature, leading to higher heat losses to the environment resulting in low thermal efficiency of such collector. Several methods, including the use of fins, artificial roughness and packed beds in the ducts, have been proposed for the enhancement of thermal performance.

It is well known that the use of artificial roughness on the absorber plate of a solar air heater enhances its thermal efficiency as flow rate increases. However, a higher mass flow rate also results in higher friction losses. Also, the thermal performance of solar air heaters increases up to a certain limit of Reynolds number and then starts decreasing; this is accompanied by a certain pumping power penalty. The roughness geometry should be selected based on maximum thermal gain and minimum friction losses. Hence, the selection of roughness geometry has to be based on parameters that take thermo hydraulic performance into account.

Glazing is the top cover of a solar collector. It performs three major functions in particular: to minimize convective and radiant heat loss from absorber, to transmit the incident solar radiation to the absorber plate with minimum loss, and to protect the absorber plate from outside environment.

The major heat losses in the collector are from the front cover (glass cover), since the sides and the back of the collector are often adequately insulated. Therefore, accurate prediction of the thermal performance of solar collector system strongly depends on how the glass cover material is analysed. Though almost all the studies reported assume that glass cover of a system is transparent for the solar range and opaque for the infrared radiation.

Sohel Chaudhari et al. [1] carried out CFD based analysis using FLUENT to fluid flow and heat transfer characteristics of solar air heater where 3D models of solar air heater involving air inlet, absorber plate, glass, modelled by ANSYS Workbench. They showed that increase the value of heat flux increase the thermal efficiency of solar air heater. P.W.Ingle, et al. [2] experimentally investigated that the flow of air in the solar flat plate collector is not properly distributed. In order to overcome the issues, they introduced baffles at the inlet of collector which improves the efficiency of solar flat plate collector. Ebrahim Momin et al. [3] have performed an experimental investigation of the effect of geometrical parameters of V-shaped ribs on heat transfer and fluid flow characteristics of rectangular duct of solar air heater with absorber plate having V-shaped ribs on its underside have been reported. It was found that for relative roughness height of 0.034 and for angle of attack 60 degree, the V-shaped ribs enhance the values of Nusselt number by 1.14 and 2.30 times over inclined ribs and smooth plate case at Reynolds number of 17034. It means that V-shaped ribs have definite advantage over the inclined ribs for similar operating conditions. Anil Singh Yadav and J.L.Bhagoria [4] presented the study of heat transfer and fluid flow processes in an artificially roughened solar air heater by using computational fluid dynamics (CFD). They concluded that Solar air heater with triangular rib roughness gives 1.4 to 2.7 times enhancement in Nusselt number compared to small duct. Vortex formation at top of the rib surface provides rolling action of the flow. Siddharth Suman et al. [5] have done Performance enhancement of solar collectors— A review. They found that the use of solar selective coating enhances the collector performance significantly. There is a need to develop a cost-effective method to produce the coating on the absorber surface. These coatings could not be commercialized due to their high cost, low productivity, and complexity in the process. The modification in surface/ribs/corrugation results in enhanced performance. E. Kabeel et al. [6] experimentally observed that using fins improves the area of heat transfer and hence enhances the performance. Artificial roughness enhances both heat transferred thermos hydraulic performance of SAHs. Using artificial roughness, thee Nusselt number and friction coefficient can reach an increase of 3.073 times and 3.92 times over smooth duct, respectively, and maximum efficiency can reach 64.24%. Using selective coated absorber increases the heaters efficiency. For example, using (Ni-Sn) increases the annual daily efficiency by 29.23% compared to black paint absorber. Hrishikesh A. Dhandha and Anjali A. Vyas. [7] have done CFD Analysis of Solar Air Heater with Perforated Baffle on the Absorber Plate. A kinetic energy turbulence model was taken for analysis in which heat transfer coefficient increases due to artificial roughness. Nusselt number increases with increase in Reynolds number for range of simulation. Raj Kumar et al. [8] in their experimental analysis the Broken V-type baffle was used. The Broken V-type baffles are thermo-hydraulically superior as compared to the other baffles shaped solar air channel. CFD analysis was not initiated. Ji-Suk yu et al. [9] have performed an experimental analysis for comparisons of conventional flat plate solar collectors and collectors integrated with different numbers of baffles. In this increase in the output temperature was seen using baffles. Ho Chii-Dong, Chang Hsuan, Wang Rei- Chi, Lin Chun-Sheng [10] analytically shown the advantages of baffled solar air heaters with internal fins attached provide higher turbulence and extending the heat transfer area, and thus, the enhancement of heat- transfer efficiency. It is believed that the availability of such a mathematical formulation as developed here for a recycling baffled solar air heater with internal fins attached is an important contribution to the design and analysis of double-pass devices with internal or external recycle. Rajendra Karwa and V. Srivastava [11] have done thermal performance analysis of Solar Air Heater Having Absorber Plate with V-Down Discrete Rib Roughness. They have shown that the thermal efficiency of the roughened duct air heater is 6-26% higher than that of a smooth duct air heater is the highest advantage is at the lowest flow rate of 0.01 kgs^{-1} m^{-2} of the study. The mass flow rate of air per unit area of absorber plate needs to be varied according to the variation in the solar insolation during the day for constant temperature rise of air through the collector and greater overall heat collection. With the increase in the ambient temperature from 278 K to 288 K, the thermal efficiency increases by 7.5% to 17.8%, increasing with solar insolation.

Problem Formulation

1. The objective of this study is to perform CFD modeling of solar air heater of different configurations with different roughness.
2. To analyse heat transfer inside the different types of solar air heaters.
3. To analyse velocity and temperature distribution for the solar air heaters with fins and baffles.
4. To check the outlet temperature of different modeled solar air heaters.

Materials and Methods

Modelling and CFD Simulation

Computational fluid dynamics simulation of three-dimensional solar air heater, three-dimensional artificial roughened solar air heater duct along with broken W pattern baffles and three-dimensional solar air heater with rectangular fins is carried out using ANSYS FLUENT 2021 software.

The general assumptions considered for the analysis are as follows.

1. The flow is considered as being steady, three-dimension, and turbulent.
2. The flow is single phase across the duct.
3. The wall in contact with the fluid, are assigned no-slip boundary condition.
4. The thermodynamics properties of both the air and the absorber plate are constant.
5. Radiation heat transfer is considered negligible in the analysis.

Solar Air heater with baffles Modelling-1

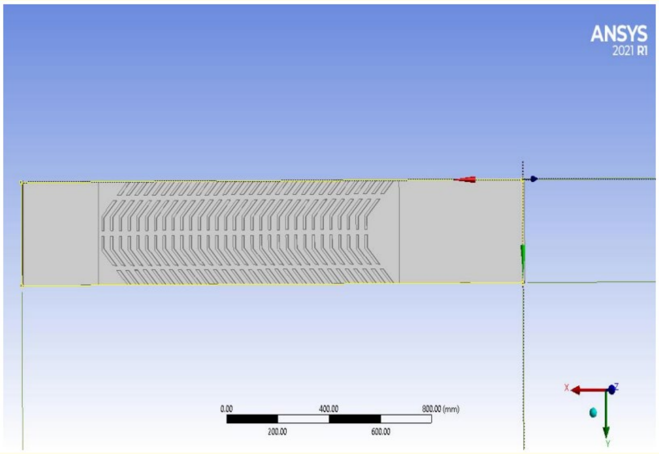

Figure 1: V pattern solar heater geometry.

Description	***Specification***
Length (L) of Absorber plate	2000 mm
Width (w) Absorber plate	300 mm
Height of the flow path	30 mm
The space between the baffle	15 mm
Height of the baffle	10 mm
Length of each baffle	50 mm

Table 1: Model 1 description.

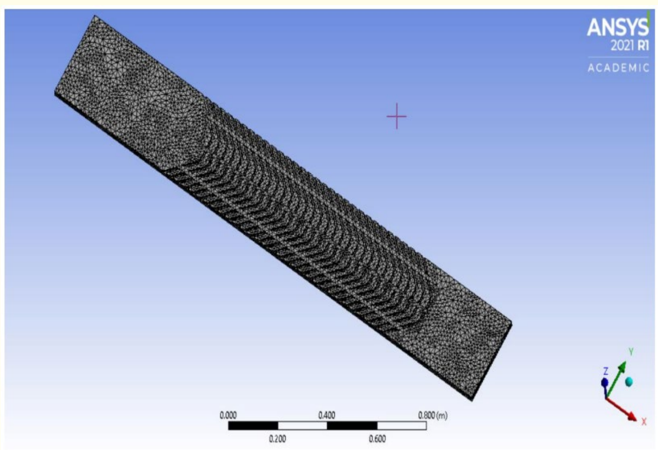

Figure 2: Meshed geometry.

The unstructured computational grid structure generated in ANSYS 2021 is used for numerical simulation. The grid made in fine sizing with medium smoothing in fluid domain.

Boundary Conditions and Materials Properties

The simulation is carried out considering Steady state and k epsilon (2eqn), RNG turbulence model.

Property	*Value*
Density	1.225 kg/m^3
Specific Heat	1006.43 J/kg K
Thermal Conductivity	0.0242 W/m K

Table 2: Properties of air.

Parameter	*Value*
Inlet velocity magnitude	1.5 m/s
Inlet Temperature	300 K
Absorber plate Thermal- Heat flux	800 W/m^2
Wall thickness	0.005 m

Table 3: Operating parameters.

Solar Air heater Modelling-2

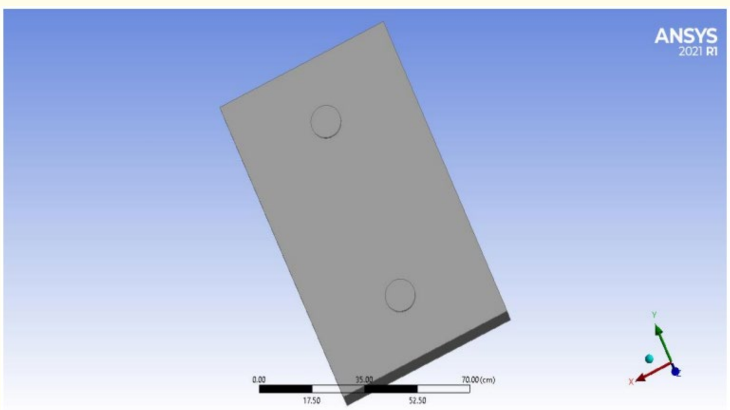

Figure 3: Solar air heater geometry.

Dimensions of the geometry

Length(L)= 100 cm.
Width(w)= 60 cm.
Height of the flow path= 10 cm.

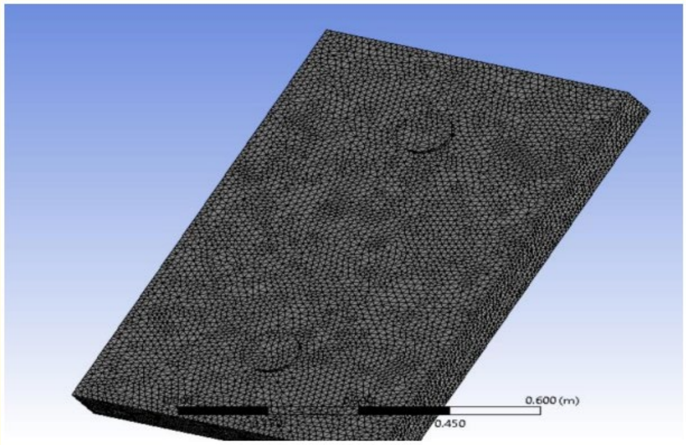

Figure 4: Meshed geometry.

The unstructured computational grid structure generated in ANSYS 2021 is used for numerical simulation. The grid made in fine sizing with medium smoothing in fluid domain.

Boundary Conditions and Material Properties

The simulation is carried out using the following conditions

1. Steady State.
2. Viscous Model- k-epsilon (2eqn), Realizable Near wall treatment- Enhanced wall treatment.
3. Radiation Model- Rosseland.
4. Sunshine Factor= 1.

Global Positioning
Longitude- 88.614
Latitude- 27.3325
Timezone- +5.30

Table 4: Solar Ray tracing.

North	***South***
1	0
0	0
0	1

Table 5: Mesh Orientation.

Property	***Value***
Density	2500 kg/m^3
Thermal Conductivity	744.6 W/m K
Specific Heat	670 J/kg K

Table 6: Properties of glass.

Property	Value
Density	953 Kg/m^3
Thermal conductivity	0.50 W/m K
Specific Heat	1500 J/kg K

Table 7: Properties of Polyethylene.

Absorber Plate	Inlet	Wall
Heat transfer coefficient= 2 (W/m^2 K)	Velocity inlet= 0.5 m/s (magnitude)	Heat transfer coefficient= 2 (W/m^2 K)
Free stream temperature= 273 K	Temperature= 273 K	Wall Thickness (m)= 0.05

Table 8: Boundary Conditions.

Solar Air heater with fins Modelling-3
Geometry dimensions

Length(L)= 150mm.
Width(W)= 80mm.
Height(H)= 15mm.
Diameter of Hole(D)= 17.65mm.
Fins Height= 11mm.
Width= 2.5mm.

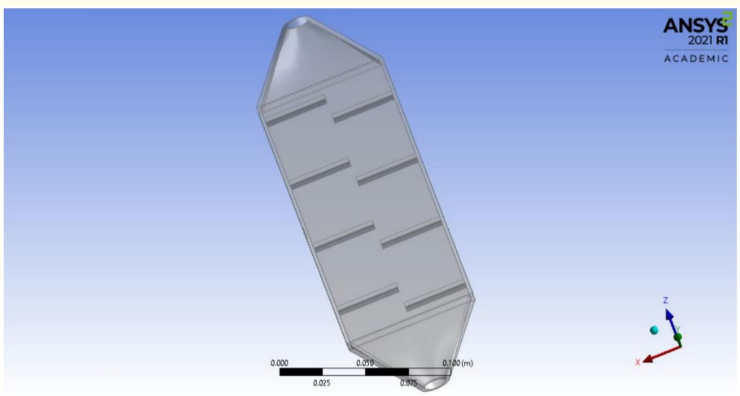

Figure 5: Solar air heater modelling with fins.

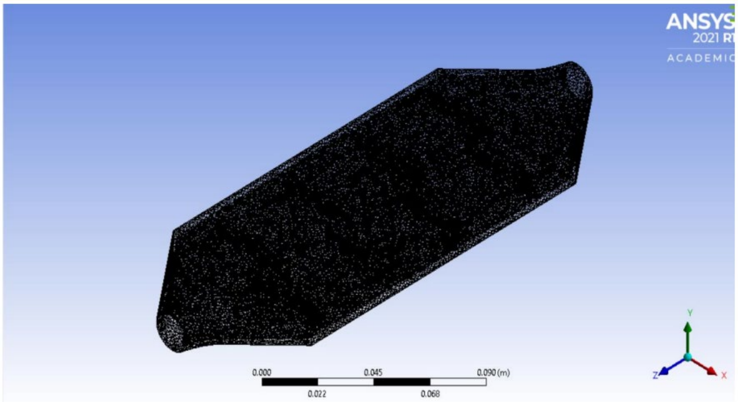

Figure 6: Meshed geometry.

The unstructured computational grid structure generated in ANSYS 2021 is used for numerical simulation. The grid made in fine sizing with medium smoothing in fluid domain.

Boundary Conditions and Material Properties

The Boundary Conditions and Material Properties values considered for this model are same as the previous models.

Solar Air heater with triangular fins Modelling-4

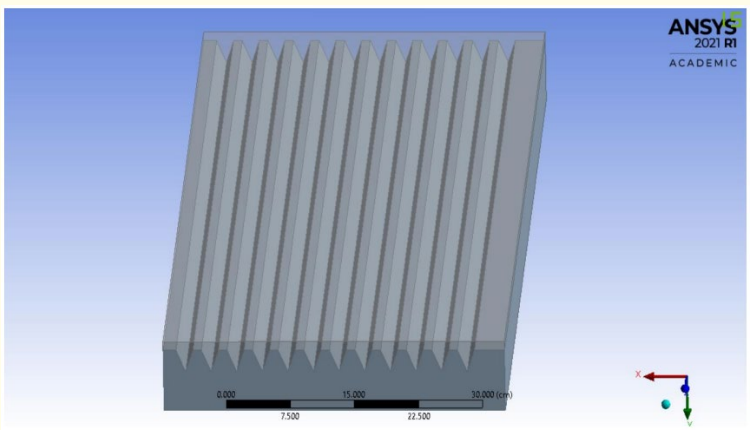

Figure 7: Solar air heater with triangular fins.

Dimensions

Length(L)= 50cm.
Width(w)= 40cm.

Height(H)= 7cm.
Fin height: 2.5cm.
Width= 2cm.

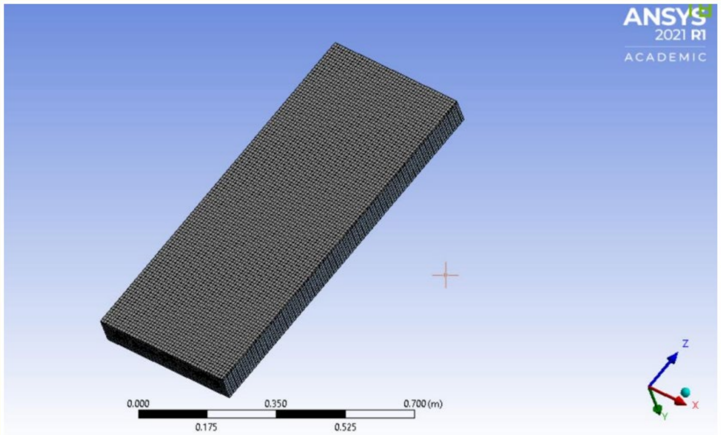

Figure 8: Meshed geometry.

The unstructured computational grid structure generated in ANSYS 2021 is used for numerical simulation. The grid made in fine sizing with medium smoothing in fluid domain.

Boundary Conditions and Material Properties

The Boundary Conditions and Material Properties values considered for this model are same as the model-2.

Governing Equations

Computational fluid dynamics governing equation are used to investigate the interactive motion of large number of individual particles inside the fluid domain. Which defines the various parameters e.g velocity, pressure, temperature at individual point inside fluid domain. The principle governing equation are as follows:

Continuity equation:

$$\frac{du}{dx}+\frac{dv}{dy}+\frac{dw}{dz}=0$$

Momentum Equations:

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

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

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

Energy equation:

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

Radiation Model: P-1 Model

$$q_r = -\frac{1}{3(\alpha+\sigma_s)-C\sigma_s}\nabla G \qquad \text{(i)}$$

$\propto$= Absorption Coefficient.
σs= Scattering Coefficient.
G= Incident Radiation.
C= Linear- Anistropic Phase Function.

$$\Gamma = \frac{1}{(3(\alpha+\sigma_s)-C\sigma_s)} \qquad \text{(ii)}$$

$$q_r = -\Gamma\nabla G \qquad \text{(iii)}$$

The transport equation for G is

$$\nabla.(\Gamma\nabla G) - \alpha G + 4\alpha n^2 \sigma T^4 = S_G \qquad \text{(iv)}$$

Radiation Model: Rosseland

The Rosseland or diffusion approximation for radiation is valid when the medium is optically thick ((a + σs)L >>1), and is recommended for use in problems where the optical thickness is greater than 3. It can be derived from the P-1 model equations, with some approximations. This section provides details about the equations used in the Rosseland model.

The radiative heat flux vector in a gray medium can be approximated by Equation:

$$q_r = -\Gamma\nabla G \qquad \text{(v)}$$

The Rosseland radiation model differs from the P-1 model in that the Rosseland model assumes that the intensity is the black-body intensity at the gas temperature. (The P-1 model actually calculates a transport equation for G) Thus $G = 4\sigma n^2 T^4$, where n is the refractive index. Substituting this value for G.

$$q_r = -16\sigma\Gamma n^2 T^3 \nabla T \qquad \text{(vi)}$$

Since the radiative heat flux has the same form as the Fourier conduction law, it is possible to write.

$$q = q_c + q_r \qquad \text{(vii)}$$

$$= -(k + kr)\nabla T$$

$$k_r = 16\sigma\Gamma n^2 T^3 \qquad \text{(viii)}$$

where k is the thermal conductivity and k_r is the radiative conductivity. Equation v-vi is used in the energy equation to compute the temperature field.

Convective heat transfer

Convection is related to heat flux by use of newtons law of cooling:

$$q/A = h(t_s - t_f) \quad \text{(ix)}$$

Where

- q/A is a heat flux out of the face (calculated within the application).
- h is the film coefficient we provide.
- t_s is the temperature on the face (calculated within the application).
- t_f is the bulk fluid temperature (we provide).

When the fluid temperature exceeds ace temperature, energy flows into the part. When the face temperature exceeds the fluids temperature, a part loses energy.

If we select multiple faces when defining convection, the same bulk temperature and film coefficient is applied to all faces.

Heat Flux

Heat flux simulates the transmission across flat or curved surfaces of a specified amount of heat energy per unit area unit time. As a result, heat flux adds energy to or from a body.

Results and Discussion

Solar Air heater with baffles Modelling-1

Temperatures Distribution

The temperature distribution is obtained by CFD simulation. The contour plots obtained for temperature distribution is given by Figure 9.

As air passes above absorber the heat exchanger takes place from the surface to air. The air very close to surface gets heated due to convection. The primary hot layer mixes with the secondary cold air due to baffles, and heat transfer take place due to the conduction and convection.

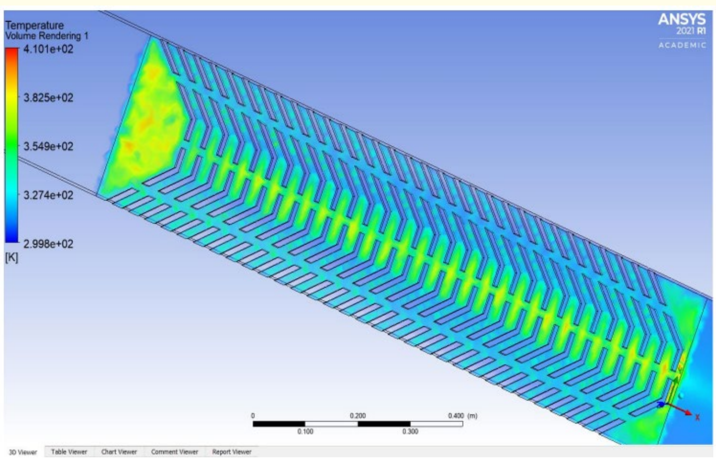

Figure 9: Temperature Volume rendering.

Velocity Distribution

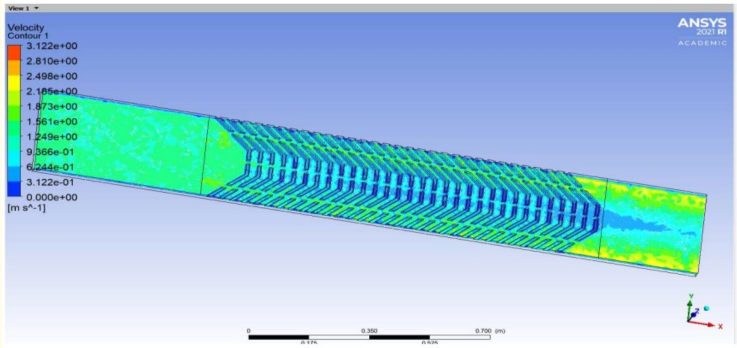

Figure 10: Velocity Contour.

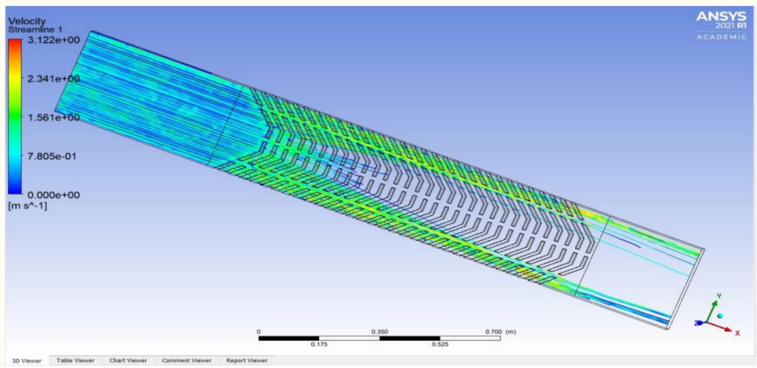

Figure 11: Velocity Streamline.

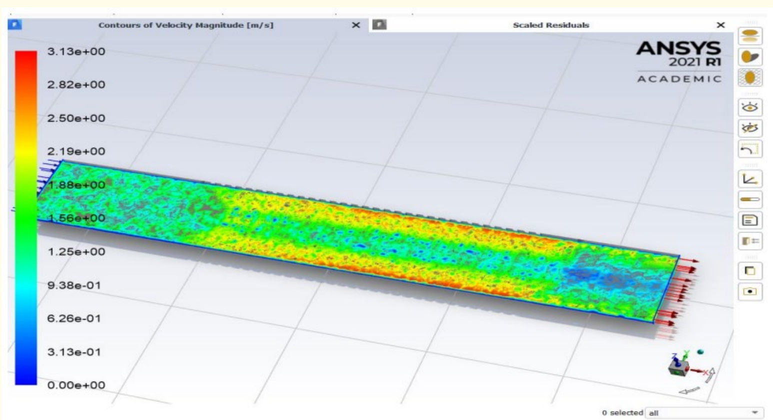

Figure 12: Velocity Magnitude.

Pressure Components

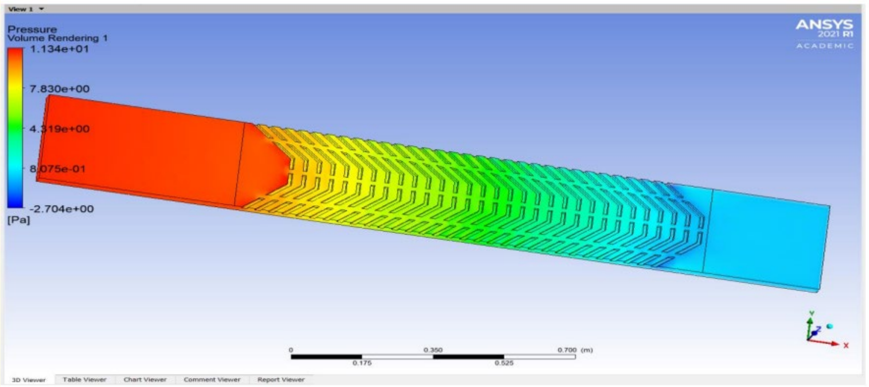

Figure 13: Pressure Components.

Baffles changes the direction of flow, which increases velocity and creates turbulence which enhances heat transfer.

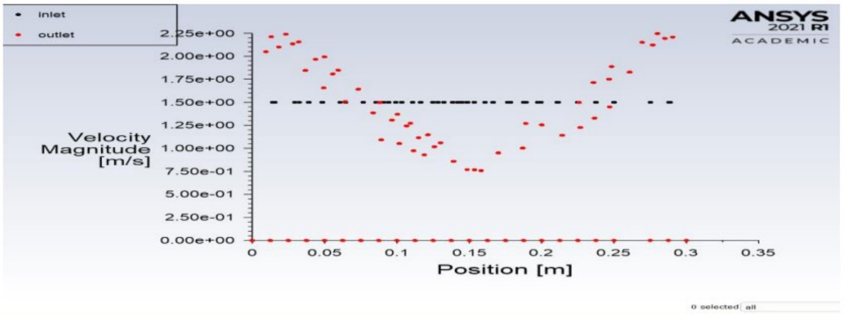

Figure 14: Graph of Velocity Magnitude vs Position.

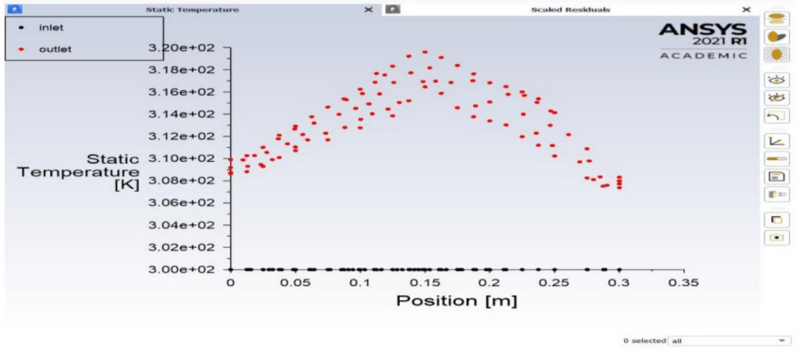

Figure 15: Graph of Static Temperature vs Position.

Solar Air heater Modelling-2
Temperatures Field

The temperature distribution is obtained by CFD simulation. The contour plots obtained for temperature distribution is given by Figure 16.

As air passes above absorber the heat exchange takes place from the surface to air. The air very close to surface gets heated due to convection. The primary hot layer mixes with the secondary cold air due to baffles, and heat transfer take place due to the conduction and convection.

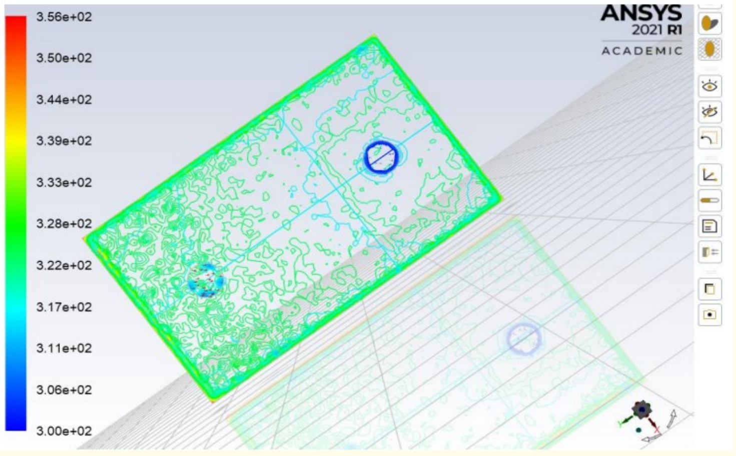

Figure 16: Temperature contour.

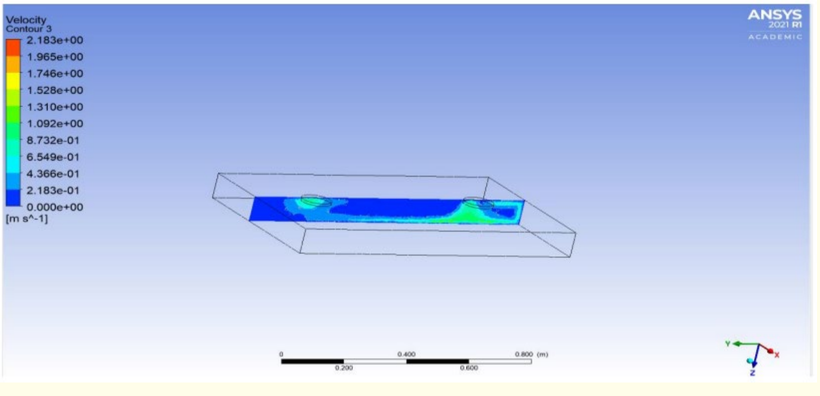

Figure 17: Velocity contour.

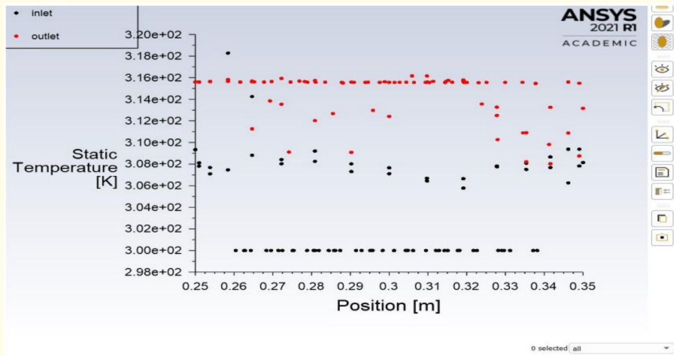

Figure 18: Graph of Temp vs Position (Time: 1pm).

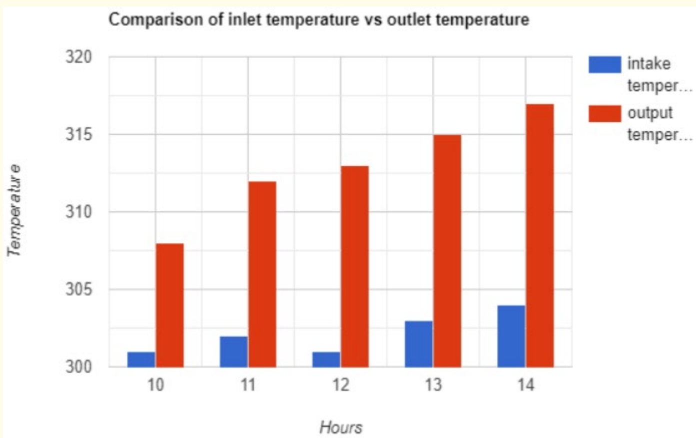

Figure 19: Comparison of Inlet vs outlet temperature.

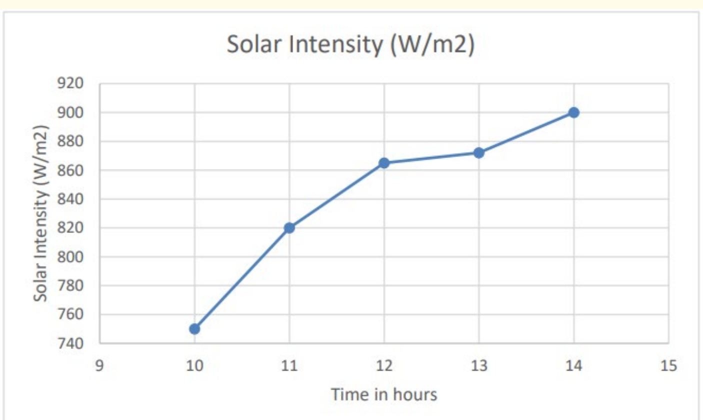

Figure 20: Variation of Solar intensity with time.

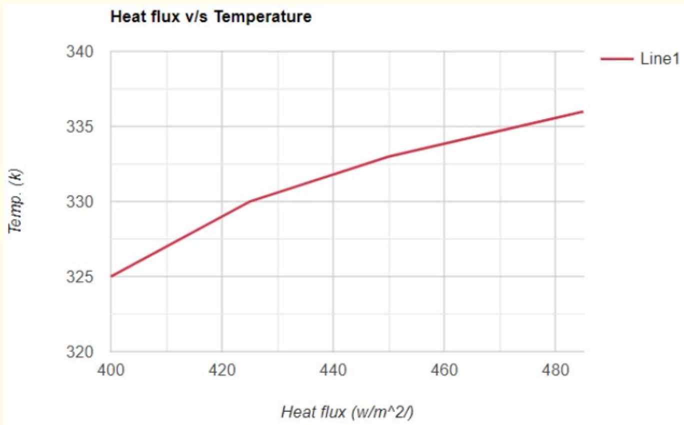

Figure 21: Variation of Heat flux with temperature.

Solar Air heater Modelling-3
Temperatures Field

The temperature distribution is obtained by CFD simulation. The contour plots obtained for temperature distribution is given by Figure 22.

As air passes above absorber the heat exchanger takes place from the surface to air. The air very close to surface gets heated due to convection. The primary hot layer mixes with the secondary cold air due to baffles, and heat transfer take place due to the conduction and convection.

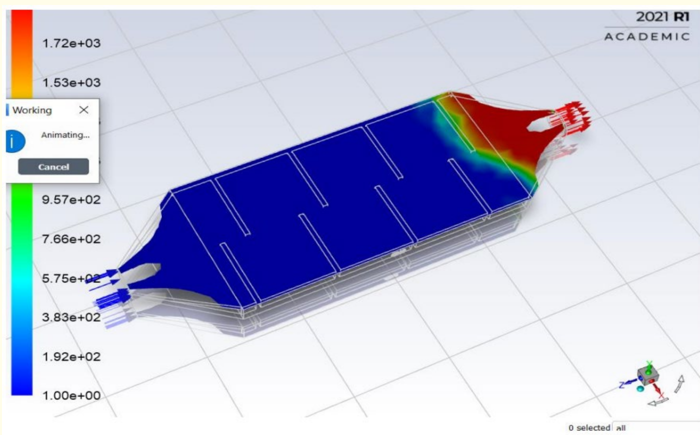

Figure 22: Temperature Contour.

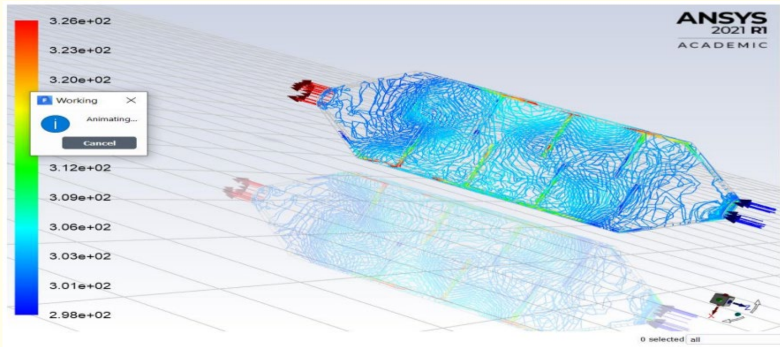

Figure 23: Effect of fins in the heater.

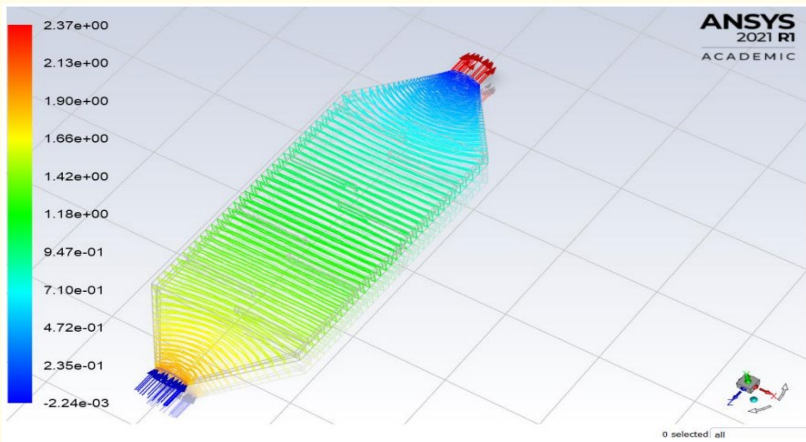

Figure 24: Pressure Contour.

Solar Air heater Modelling-4

Temperature Field

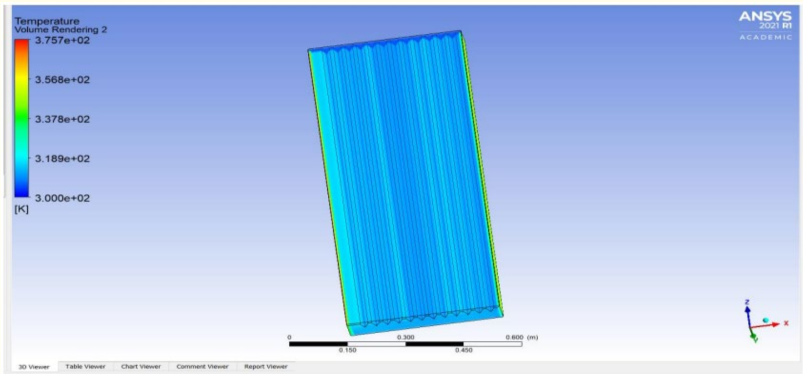

Figure 25: Temperature Contour.

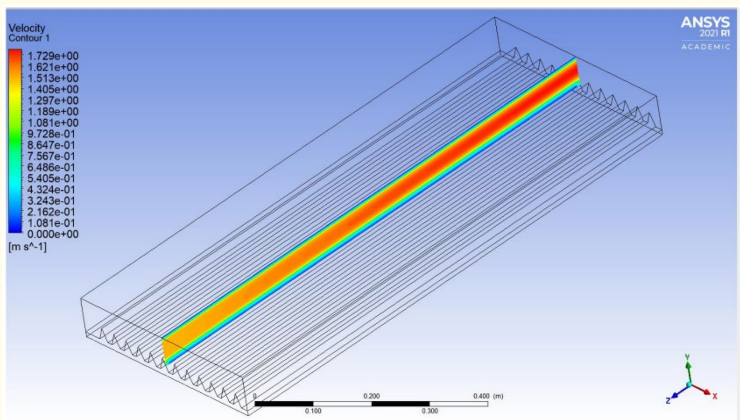

Figure 26: Velocity Contour.

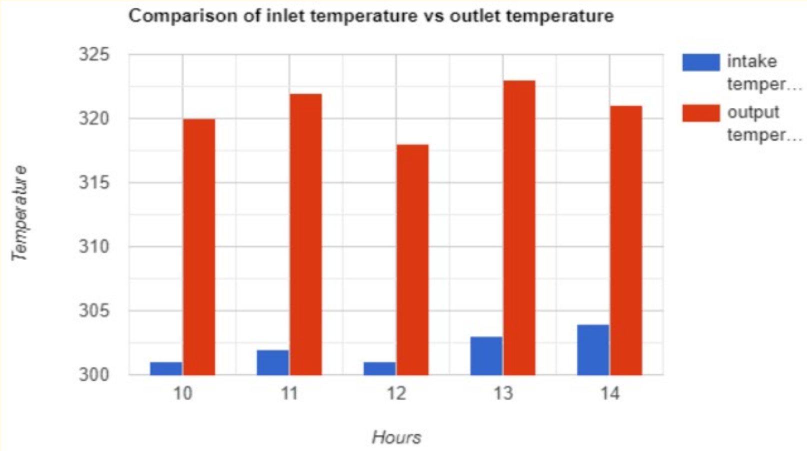

Figure 27: Comparison of Inlet and outlet temperatures.

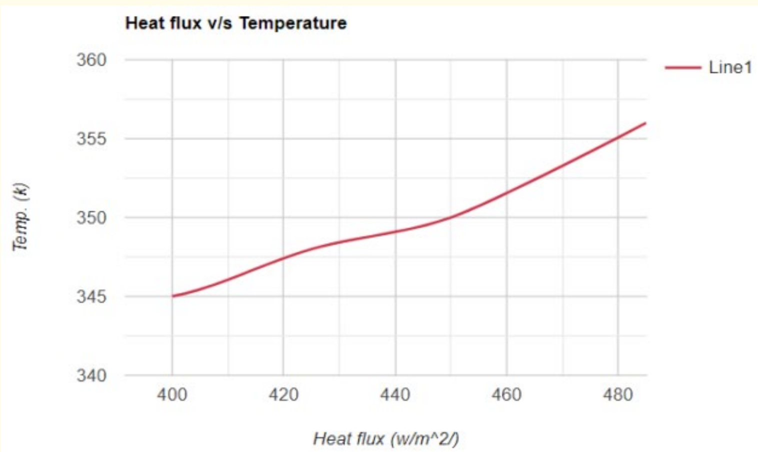

Figure 28: Variation of Heat flux with temperature.

Conclusion

1. From the various viewpoints encountered in the study of solar air heaters, it becomes evident that introduction of suitable baffles in solar air heater increases the velocity and changes the direction of flow which creates turbulence and increase heat transfer rate. These baffles, placed in the air channel situated between the insulator and the absorber, have the particularity of extending the trajectory of the circulation, to keep the caloporting air constantly in contact with the absorber, and finally to play the role of wings and improving the heat transfer from the absorber to the caloporting air.
2. Effect of different heat flux value on solar air heater shown that increase the value of heat flux increase the thermal efficiency of solar air heater.

3. As it is evident from the simulation that solar air heaters with fins increases the heat transfer area and also help in creating turbulence which in turn increases the temperature of the air.
4. Use of polyethylene (green house plastic) as a glazing material for solar air heater is a great choice because though it collects 5% less solar irradiation from the sun but it traps the heat for longer time, acts as an insulating material.
5. In recent years CFD has been applied in design of solar air heaters. The studies reported that the quality of solution obtained from CFD simulation are largely within the acceptable range. CFD is an effective tool for predicting the behaviour and performance of solar air heaters.

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