Enhancement of Thermal Performance of Solar Air Heater using Computational Fluid Dynamics Analysis

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Abstract: - *Solar air heating is a solar thermal technology in which the energy from the sun is captured and used to heat air which further use for various applications in different sectors such as space heating, process heat applications, agricultural product drying, space heating for warehouses, factories etc. The primary goal of the current research is to conduct mathematics [elementary and computationally fluid dynamics study to improve the thermal efficiency of the solar air heater for the region of central India. The results indicate that the 344.6K multi-L-pattern ridges type solar air heater has a maximum temperature with just an overall thermal performance of 52.24 percent, which is 14.36 percent higher than the basic design. Hence For optimal thermal efficiency, a solar air heaters with several L-pattern ribs is recommended.*
Keywords *- SAH, renewable energy, CFD, L-pattern ridges*

I. Introduction

The increase in energy demand, as well as decrease of the world's fossil fuel reserve hugely, led to an increase in concern towards renewable energy resources. The fossil fuel is considered to be very harmful to the environment because mining of these can damage the life cycle of plants and animal as well as the generation of electricity from these fuels may cause a noxious pollution effect on the environment. Solar energy is essentially an inexhaustible energy source, can meet the whole world's energy demand with a minimum consequence of harming of environment. The efficient way to disciple solar energy into thermal energy for the heating purpose is solar air heater mainly because of its cost and simple design, which do not contribute any pollution to the environment.[A. Kumar 2021] Converting the sun's radiant energy to heat is very common from historical times and has evolved into a well-developed solar conversion technology today. The fundamental idea behind solar thermal collecting is that when solar radiation hits a surface, some of it is absorbed, raising the surface's temperatures. [D. Yogi 2015] Solar energy is immediately transformed into heat energy by solar panels and electric power by photovoltaic solar cells. Due to its straightforward design, simple operation, low maintenance requirements, and inexpensive initial investment, a solar collector for air heating is particularly beneficial for low grade thermal power applications. The amount of heat that a working fluid absorbs from a solar collector determines how well the collection performs. By raising the heat transfer characteristics or the heat transfer surface area between the absorber surface and the airflow, the solar air heater's performance can be improved [Kapil 2020].

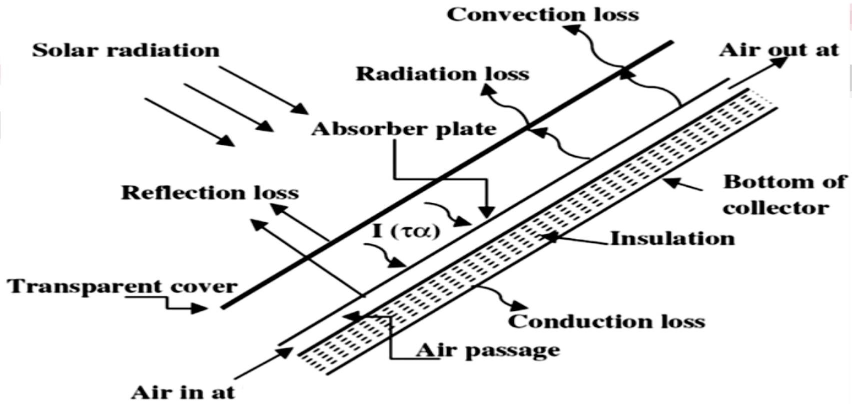


Fig. 1 Conventional Solar Air Heater [Inderjeet Singh 2018]

Solar air heater classification: Based on the type of absorption, solar air heaters may be divided into two general categories:
Nonporous absorption and solar air warmer
Solar air heating with absorbers that is porous

Nonporous absorbers and solar air warmer: In a simple flat plate air collector, commonly known as non-porous absorbers, the air stream flow through the absorber plate without any obstruction. [M. Pradhapraj 2010] some examples of nonporous absorbers are-
Type I Non-porous solar air heater (flow above the absorber),
Type II Non-porous solar air heater (flow under the absorber),
Type III Non-porous solar air heater (flow both above and beneath the absorber) etc. [shreekumar 2007]

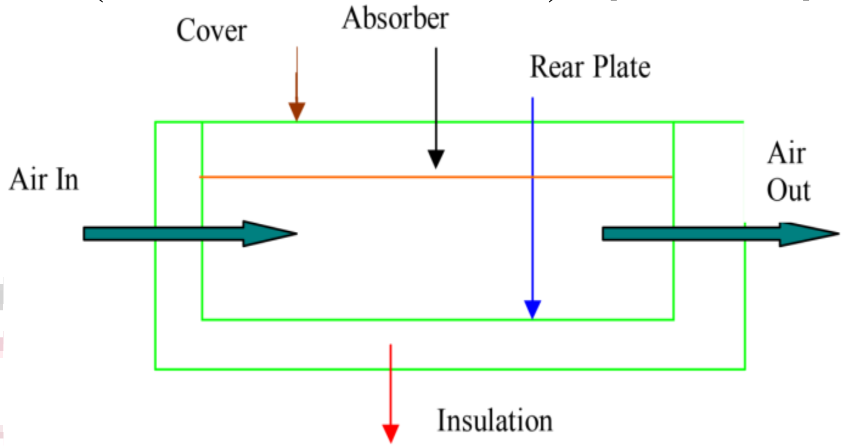


Fig. 2 Solar air heater with nonporous absorber [Ram Chandra IGNOU 2018]

In the porosity bed air heater: solar air heater with porosity absorbers, the matrix material is arranged and the back absorber plate is eliminated. [M. Pradhapraj 2010] In porous type solar air heaters, absorber plate is porous. This type of heaters has several advantages. Solar radiation penetrates to greater depth and is absorbed along its path. Some examples of most economic porous absorbers. Matrix type solar air heaters, Honeycomb porous —
bed solar air heater,
Overlapped glass plate air heater,
Jet plate solar air heater etc.[shreekumar 2007]

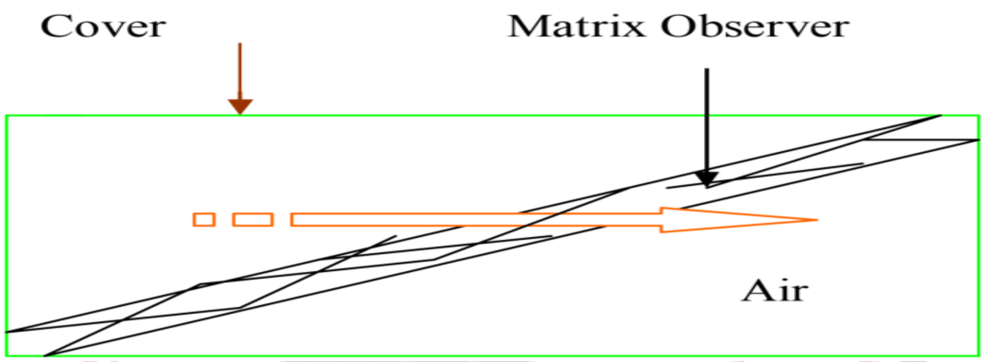


Fig.3 Solar air heater with porous absorber [Ram Chandra IGNOU 2018]

II. Application of solar air heater

Solar air collecting could be used for a variety of purposes, including air heaters in cold climates and the removal of warm, stale air from homes, offices, factories, and other industrial and commercial facilities in the summers. [Sanda 2014] Solar air heating has a wide range of uses for lowering carbon footprints. Solar air heat systems can be used for tasks like home heating, extending the growing season in greenhouses, pre-heating ventilated makeup air, or heat sources.
Industrial purposes: Air pre heating for combustion processes That include so many applications such as: drying minerals, coal, paper, bricks, food industry etc, space heating for warehouses, factories, etc.
Agricultural purposes: Crop drying; meat. Grains, vegetables, fruit etc. main advantages can be that harvesting the crop very early before the time of actual harvesting an drying it and protect it from mildew, rodents, etc. space heating for warehouse, animal forms and greenhouses fruit and other dryers. Space heating for recreational camping and expeditions in winter. Space heating for buildings, office buildings, shopping centers etc.
Ventilation applications: Three mathematical methods could be used to determine natural ventilation in the summer in manufacturing or residential buildings. The first model considers internal thermal pressure; the second model considers the influence of external air currents; and the third approach considers thermal performance from within solar panels that are located on the roof of a building. [Sanda 2014] Utilizing solar air collecting is an effective way to create more ventilation system.

Literature review

Anil Singh Yadav et al. (2021) [1]New CFD-based correlations for ribbing rough surfaces solar air heaters are presented in this research. This article analyzes a solar air heater's absorber plate that is attached by circular ribs. To examine the turbulence airflow for various rib layouts, ANSYS Fluent v16 is used. CFD (computational fluid dynamics) simulations constitute the foundation for all of the outcomes

Binguang Jia et al. (2021) [2]Three-dimensional mathematical equations of following four kinds of spiral solar air heaters, including right angle spiral solar air heaters (RA-SSAHs), arc spiral solar air heaters (ARC-SSAHs), arc spiral solar air heaters with rectangular holes (ARC-RH-SSAHs), and rectangular holes spiral solar air heaters (RH SSAHs), were established by CFD to measure the influence of baffles structural system on the thermal efficiency of the spiral solar air heaters.

G Sureandhar et al. (2021) [3] For the purpose of analyzing the effects of the lengths of the absorber surface and the arrangement of the arc rib fins on the heat transfer properties of a solar air heater, a thermal model is built

Kottayat Nidhul et al. (2021) [4]The formation of a laminar sub-layer close to the heating absorber surface is the cause of the flat plate solar air heater's (SAH) low heat transfer rate. As a result, there is a significant increase in plate temperatures, which causes losses and lowers efficiency. In-depth study has been done to address this issue, and a passive technology has shown promise as a potential remedy. To breach the boundary condition, fins, turbulators, or ribs are applied to the surface where it grows as part of the passive technique.

Amit Kumar & Apurba Layek (2021) [5]The current work includes a comparison of energetic and exergetic efficiency of solar air heaters with Winglet type roughness over the absorber plate utilizing numerical optimization. Therefore, in order to properly estimate how much energy is used by a solar air heater, it is important to compute both effective and exergetic efficiency. By taking temperature increase and parametric design elements into account, these efficiency are assessed. A mathematical formalism for the solar air heater is offered, and its impact on every design parameter is looked at.

M. Vivekanandan et al. (2021) [6]Fruits, vegetables, and other agriculture items are frequently dried using solar air heaters. The issue with previous solar air heaters is the inability to create a fully developed flowing within the solar air heater's housing. The trapezoidal-shaped duct is necessary since the blower's exit is constrained by the makers to a narrow cross-section.

Tingting Zhu & Ji Zhang (2021) [7]A simple and practical device for using energy from the sun is the solar air heater. In order to determine the ideal operating circumstances and geometric specifications for the solar air heater, an optimisation study for a micro-heat pipes arrays-based solar air heater was conducted. Based on the physical heat transfer processes in the solar air heater, a 3-D CFD model was created and validated using the experimental data. The impact of the parameters chosen—ambient temperatures, air flow rate, air layer thickness, air duct anamorphic widescreen, and fins design parameters (height and spacing)—on the efficiency of the method and the thermal properties of the air flow were examined.

Varun Goel et al. (2021) [8]There are numerous reports in the literature about the usage of solar air heaters (SAH) for the collecting and efficient utilization of solar irradiation for thermal applications. The purpose of the current article was to give a thorough assessment of the literature on the background, principles, and most recent developments in solar thermal air heaters. A cross-section of the flow tunnel, an evacuation tubes, a flat plate, several passages, and other solar collector concepts are described and explored.

Dengjia Wang et al. (2020) [9]Solar air heaters often have low thermal efficiencies when compared to liquid solar collectors. A better sun air heaters with s-shaped ribs and gaps is presented to increase the thermal efficiency of the solar collector system; the solar air heater may effectively increase thermal performance among air and the heat absorption panel. A gap of a specific width was also formed on the ribs to lessen air flow resistance. The findings of an experiential inquiry on collector effectiveness and pressure loss in a solar air heater with numerous s-shaped ridges with gaps as the roughness elements are reported in this article.

Kapil Dev Yadav & Radha Krishna Prasad (2020) [10] The theoretical study of a parallel flow thermal performance with an absorber panel roughened with arc-shaped wires is the subject of this paper. To investigate the impacts of different operations and system factors on the thermally performance of a solar air heater, a mathematical analysis representing the fluids flows and heat transfer characteristics of such a parallel and counter flow roughened absorption plate solar air heat source has been constructed..

III. METHODOLOGY

Solar air heater consists of an absorber plate with a parallel plate below forming a small passage through which the air to be heated. A transparent cover system is provided above the absorber plate. A sheet metal container filled with insulation on the bottom and sides. Whole assembly is contained in a sheet metal box and inclined at a suitable angle.

In this section mathematical and CFD analysis have to perform for the solar air heater. In the quantitative equations of the solar air heater layout, the temperature distribution from the systems, the solar load calculations for the chosen location, and the commercial cfd study of the thermal efficiency of several solar air heater designs are required.

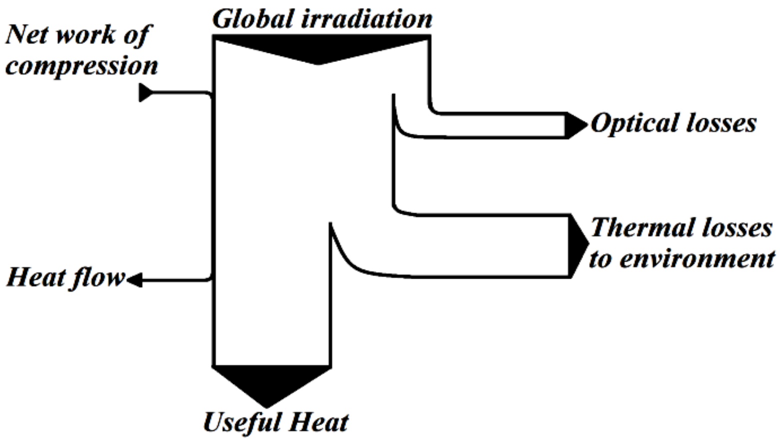


Fig.4 Energy flow for solar air heater

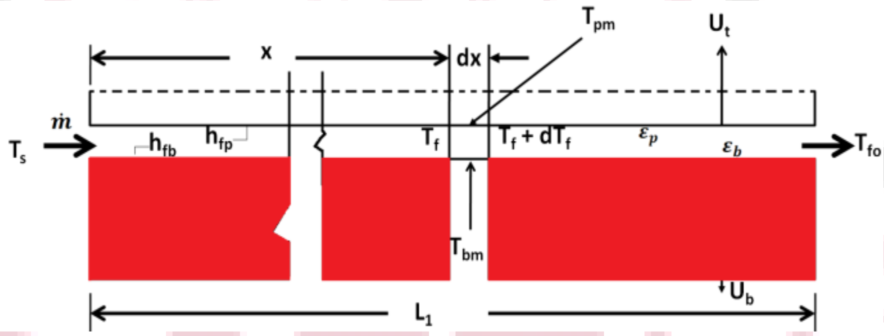


Fig.5 Analysis of conventional solar air heater [SP Sukhatmne 2008]

For absorber plate

$$SL_2.dx = U_t.L_2dx(T_{pm} - T_a) + h_{fp}L_2dx(T_{pm} - T_f) + \frac{\sigma L_2 dx}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_b} - 1\right)}({T_{pm}}^4 - {T_{bm}}^4)$$

For bottom plate

$$\frac{\sigma L_2 dx}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_b} - 1\right)}({T_{pm}}^4 - {T_{bm}}^4) = h_{fb}L_2dx(T_{pm} - T_f) + U_b.L_2dx(T_{bm} - T_a)$$

For air stream

$$mc_p dT_f = h_{fp}L_2dx(T_{pm} - T_f) + h_{fb}L_2dx(T_{bm} - T_f)$$

Radiative heat transfer coefficient

$$h_r(T_{pm} - T_{bm}) = \frac{\sigma}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_b} - 1\right)}({T_{pm}}^4 - {T_{bm}}^4)$$

Where

$$T_{av} = \frac{(T_{pm} - T_{bm})}{2}$$

Then

$$h_r = \frac{4\sigma {T_{av}}^3}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_b} - 1\right)}$$

Top loss

$$U_T = \left[\frac{N}{\frac{C}{T_{pm}}\left[\frac{(T_{pm} - T_a)}{N+f}\right]^e} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma({T_{pm}}^2 + {T_a}^2)(T_{pm} + T_a)}{(\varepsilon_p + 0.00591.N.h_w)^{-1} + \frac{(2N+f-1+0.133.\varepsilon_p)}{\varepsilon_g} - N}$$

Where
Bottom loss:

$$U_B = \frac{K_{insultaion}}{t_b}$$

Side loss:

$$\boldsymbol{U_{side} = \frac{(L+W).t_e.K_{insultaion}}{L.W.t_b}}$$

Overall heat loss

$$\boldsymbol{U_L = U_T + U_B + U_{side}}$$

Useful heat gain of air in terms of mean plate temperature without collector efficiency factor

$$\boldsymbol{Q_u = A_p[I_{si}(\tau\alpha) - U_L(T_{out} - T_{in})]}$$

$$\boldsymbol{\eta_{th} = F_r\left[(\tau\alpha) - U_L\left(\frac{T_{pm} - T_a}{I_{si}}\right)\right]}$$

$$\boldsymbol{F_r = \frac{m.C_p}{A_p.U_L}\left[exp\left(\frac{F'.U_L.A_p}{m.C_p}\right) - 1\right]}$$

F' = Collector efficiency factor $\boldsymbol{F' = \frac{h}{h+U_L}}$

Pressure drop

$$\boldsymbol{\Delta P_d = \frac{4fL\rho V^2}{2.D_e}}$$

Where

Solar load calculation:
The solar load calculation for the selected location with Latitude 23° 17' N, Longitude: 77° 27' 21'' E has been used

Declination δ

$$\boldsymbol{\delta = 23.45\ \sin\left[\frac{360}{365}(284+n)\right]}$$

Solar Day length:
At sunrise the sun's rays are parallel to the horizontal surface hence the angle of incidence $\theta_i = \theta_z = 90^o$

$$\omega_s = \cos^{-1}[-\tan\emptyset.\tan\delta]$$

The angle between sunrise and sunset is

$$2\omega_s = 2\cos^{-1}[-\tan\emptyset.\tan\delta]$$

Since 15° of hour angle is equivalent to one hour duration, the duration of hour, S_{max} or daylight hour is given by

$$S_{max} = (2/15)\cos^{-1}[-\tan\emptyset.\tan\delta]$$

Extraterrestrial radiation in kW/m2 may be calculate as

$$I_{ext} = I_{sc}\left[1.0 + 0.033\ \cos\left(\frac{360n}{365}\right)\right]$$

On the horizontal surface, $I_{ext}.\cos\theta_z$
where

$$\cos\theta_z = (\cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi)$$

$$I_{ext} = I_{sc}\left[1.0 + 0.033\ \cos\left(\frac{360n}{365}\right)\right](\cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi)kW/m^2$$

To get hourly radiated energy per square meter (kJ/m^{2}h) the equation is to be multiplied by a factor of 3600

$$I_{ext} = 3600 \times I_{sc}\left[1.0 + 0.033\ \cos\left(\frac{360n}{365}\right)\right](\cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi)\ (kJ/m^2h)$$

Monthly Average, Hourly global radiation:

$$\frac{\overline{H}_g}{\overline{H}_o} = a + b\left(\frac{S}{S_{max}}\right)$$

Hourly Global, Diffuse and beam radiations on horizontal surface under cloudless skies

$$I_g = I_b + I_d$$

If the I_{bn} is the beam radiation on the surface normal to the direction of the sun rays, the beam radiation received on a horizontal surface may be given as

$$I_b = I_{bn} \cos \theta_z$$
$$I_g = I_{bn} \cos \theta_z + I_d$$

I_{bn} and I_d are estimated as

$$I_{bn} = A \exp(-B / \cos \theta_z)$$
$$I_d = C I_{bn}$$

Where S = monthly average daily hours of bright sunshine. For Bhopal local climatic condition value of S is 9.42 h *[NP shukla 2015]*.
Where S_{max} = monthly average of the maximum possible daily hours of bright sun shineand
a&b= constant for particular location. [Bhopal a = 0.26, b = 0.5] *(NP shukla 2015)*

$$\frac{\overline{H}_d}{\overline{H}_g} = 0.8677 - 0.7365 \left(\frac{S}{S_{max}}\right)$$
$$\overline{H}_b = \overline{H}_g - \overline{H}_d$$

One day radiation, H_o in $kJ/m^2 day$ can be obtained by integrating the above expression over the day length where the time is expressed in hours.
Hence

$$H_o = 3600 \times \frac{24}{\pi} \times I_{sc} \left[1.0 + 0.033 \cos\left(\frac{360n}{365}\right)\right] (\cos\phi \cos\delta \sin\omega_s + \omega_s \sin\delta \sin\phi)$$

$\overline{H}_g$= monthly average, daily total radiation on horizontal surface
$\overline{H}_o$ = monthly average, daily extraterrestrial radiation that would fall on horizontal surface (in the absence of atmosphere)
s = monthly average, daily hours of bright sunshine obtained from actual records
S_{max} = monthly average of possible daily hours of sunshine
a&b= regression parameters are constant for particular location. [Bhopal a = 0.26, b = 0.5] *(NP shukla 2015)*

Computational Fluid Dynamics Analysis of Solar air heater

Analysis of systems that involve fluid flow and heat transport using computer-based simulations is known as computational fluid dynamics. The method is extremely effective and has both industrial and non-industrial applications. Using Ansys Fluent, commercial cfd analysis is done in the current work for solar air heaters operating at various mass flow rates.

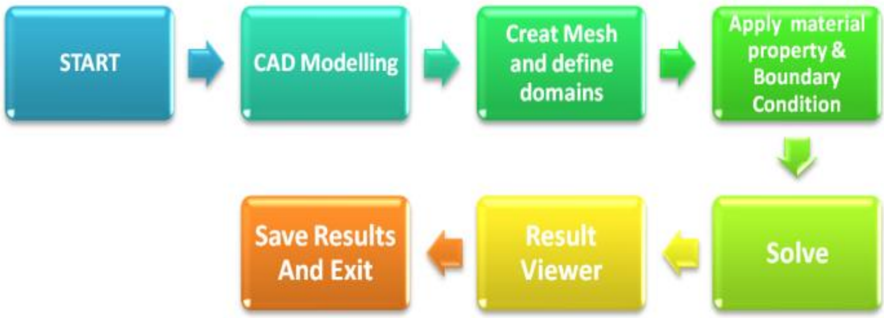
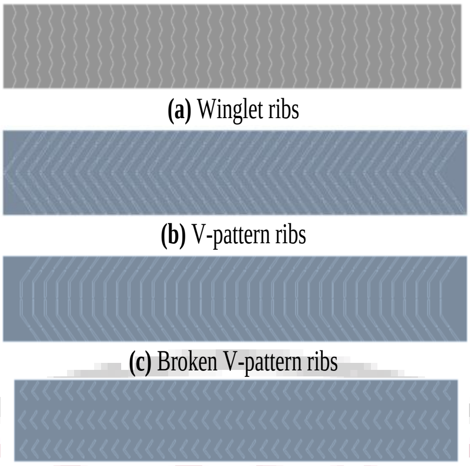


Fig. 6 Algorithm used for Computational fluid dynamics analysis

CAD modeling of winglet type solar air heater

Three dimensional CAD model of winglet type solar air heater has been created using ANSYS design modular. The dimensional parameters are use to create solar air heater are taken from *A. Kumar (2021)*, length of collector is 1.24 m, duct depth is 0.04 m, width of collector 0.16 m, roughness height of winglet is 3 mm with 60^o angular position respectively as shown in figure.



(a) Winglet ribs

(b) V-pattern ribs

(c) Broken V-pattern ribs

(d) Multi L-pattern ribs

Fig.7 CAD model solar air heater

Boundary conditions:

- To determine the thermal distribution need to on energy equation.
- Set working fluids (Heat transfer fluid) as air with maximum velocities of 5.23 m/sec.
- Air inlet temperature of 300 K.
- Wall boundary condition: the value of solar radiations of 935.8735W/m^2 was used (the maximum solar radiation calculated for the selected location).
- Left, right and bottom wall of the air heater is kept fully isolated to prevented losses from them.
- Outlet boundary condition set as the zero gauges pressure, because the flow of heat transfer fluid inside the domain is at atmospheric condition.
- For CFD analysis fluent solver is used.

Validation of work:

Solar Energy Materials & Solar Cells 230 (2021) 111147. doi.org/10.1016/j.solmat.2021.111147. The dimensional parameter for the solar air heater is begun taking from a research study by Amit Kumar & Apurba Layek (2021) "Energy and exergy based performance measurement of thermal performance having winglet type roughnes on absorber plate."

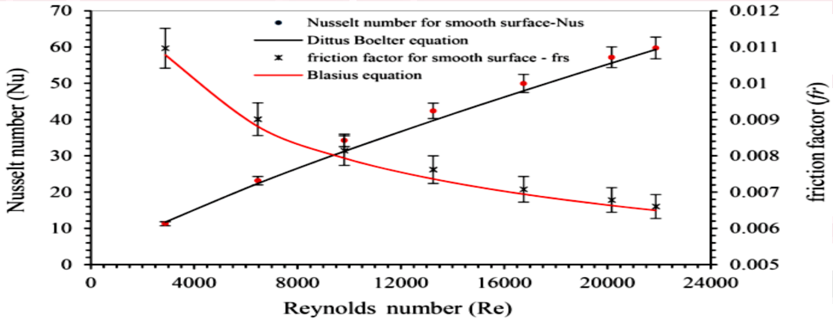


Fig.8 Nusselt number and friction factor at different Reynolds number *[A. Kumar 2021]*

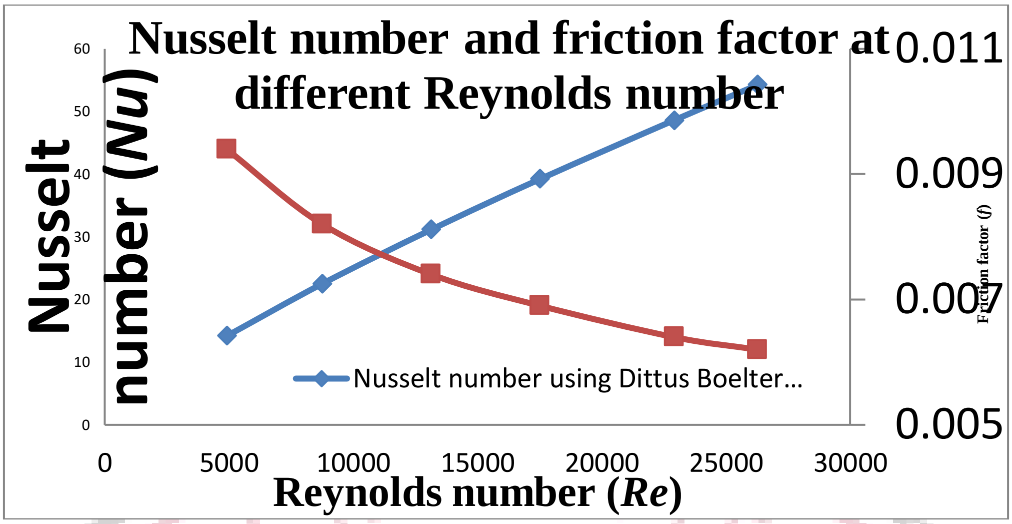


Fig.9 Nusselt number and friction factor at different Reynolds number ***[Present work]***

After performing of computational fluid dynamic analysis on winglet ribs type solar air heater at 5.23 m/sec for temperature distribution, it has been observed the maximum temperature of 338.9K is attained at the winglet bottom edge of the rough surface of the absorber plate in the solar air heater as shown in figure

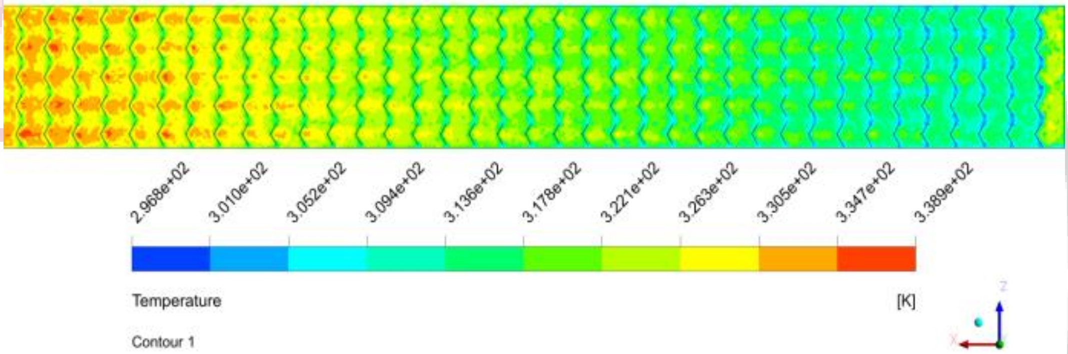


Fig.10 Temperature distribution over the winglet ribs type solar air heater

After performing of computational fluid dynamic analysis on V-pattern ribs type solar air heater at 5.23 m/sec for temperature distribution, According to observations, the solar air heater's absorption plate's bottom edge, which has a rough surface, reaches a maximum temperatures of 340.4 K.

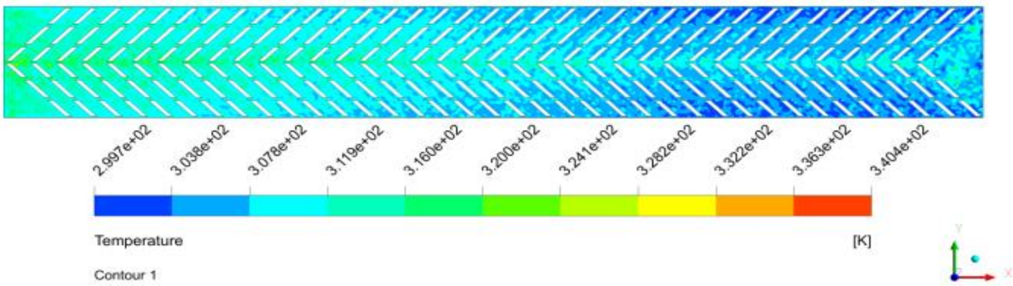


Fig.11 Temperature distribution over the V-pattern ribs type solar air heater

The maximum temperature of 342.0 K is reached at the bottom border of the solar air heater's rough absorber surface after performing computational fluid dynamic analysis on a broken V-pattern ribs kind thermal performance at 5.23 m/sec for temperature profile.

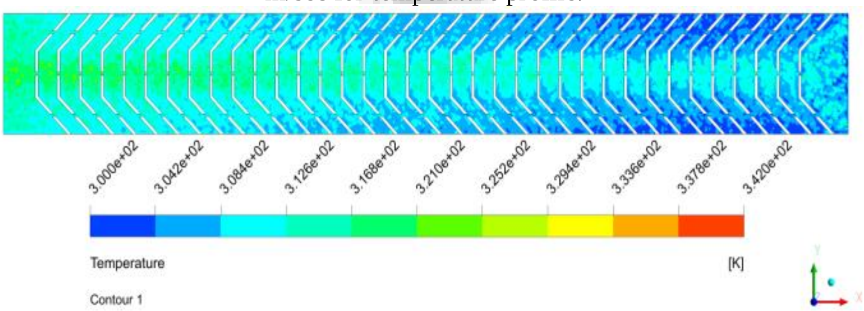


Fig.12 Temperature distribution over the Broken V-pattern ribs type solar air heater

After performing of computational fluid dynamic analysis on multi L-pattern ribs type solar air heater at 5.23 m/sec for temperature distribution, It has been noted that the solar air heater's absorption plate's bottom edge, which has a rough surface and a max temp of 344.6 K, is where this temperature is reached.

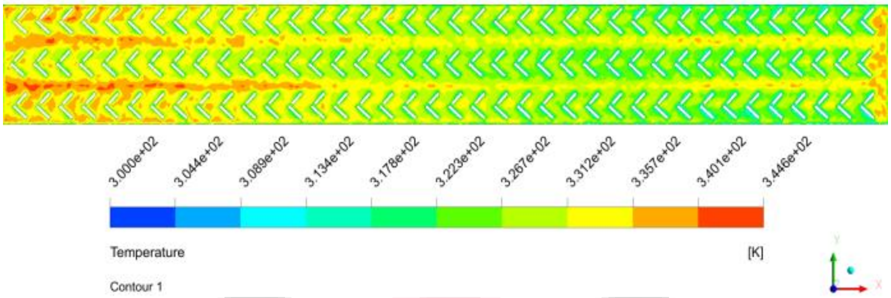


Fig.13 Temperature distribution over the multi L-pattern ribs type solar air heater

IV. Results

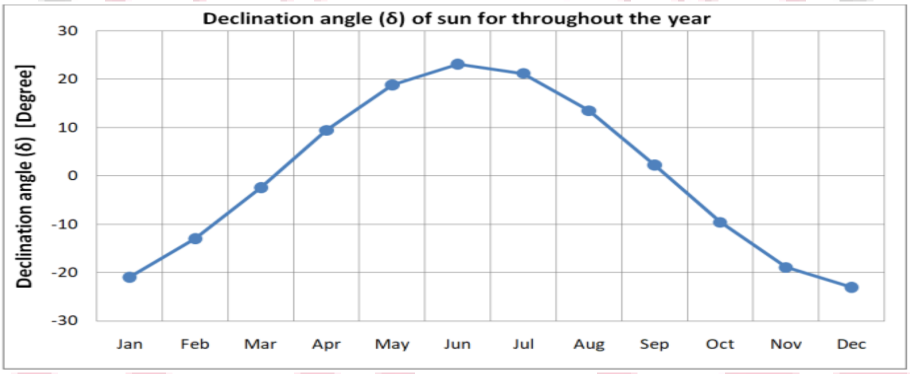


Fig. 14 Declination angle of sun for throughout the year

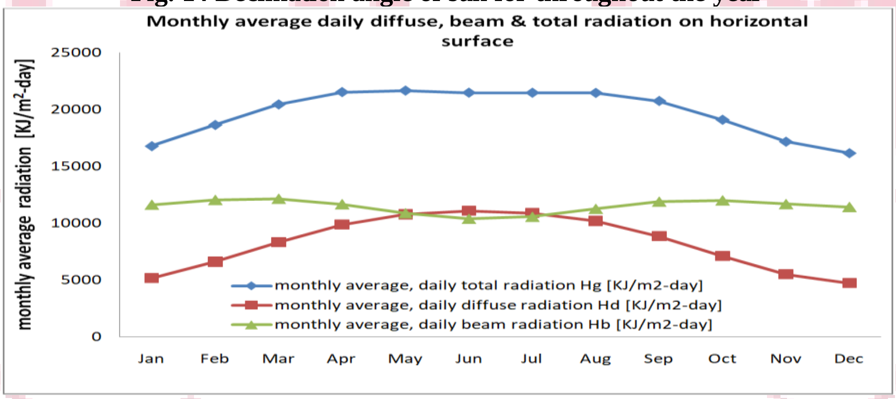


Fig.15Monthly average daily diffuse, beam & total radiation on horizontal surface

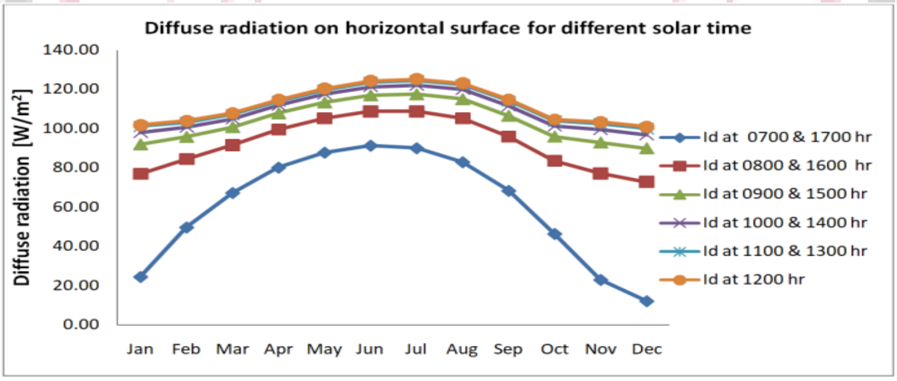


Fig.16 Diffuse radiation on horizontal surface for different solar time

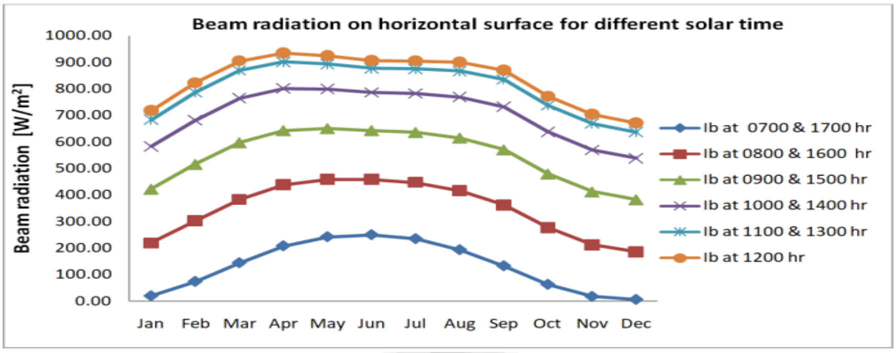


Fig.17 Radiation on horizontal surface for different solar time

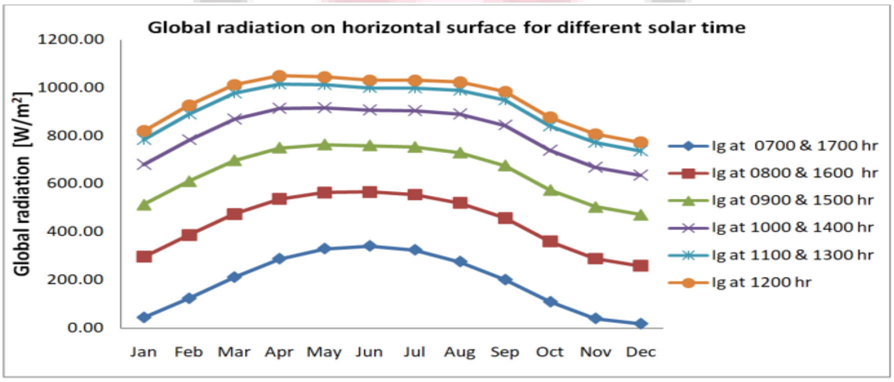


Fig.18 Global radiation on horizontal surface for different solar time

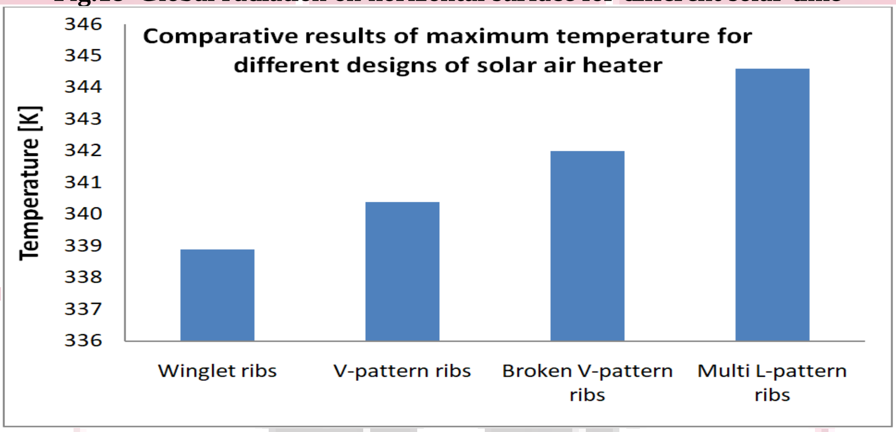


Fig.19 Comparative results of maximum temperature for different designs of solar air heater

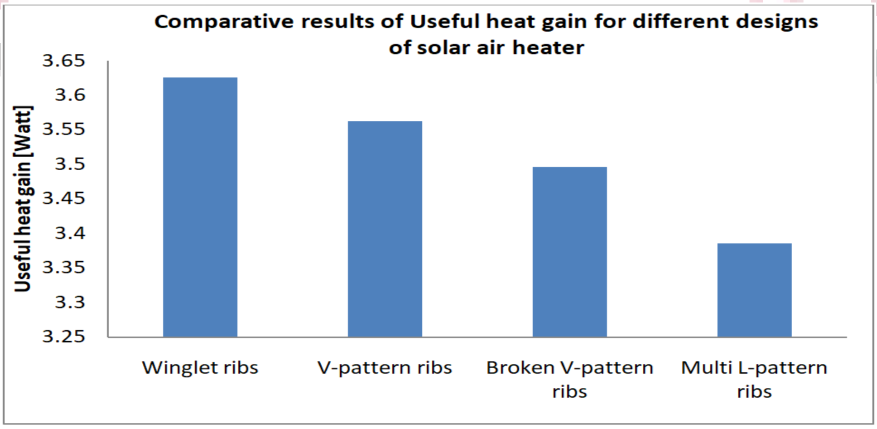


Fig.20 Comparative results of Useful heat gain for different designs of solar air heater

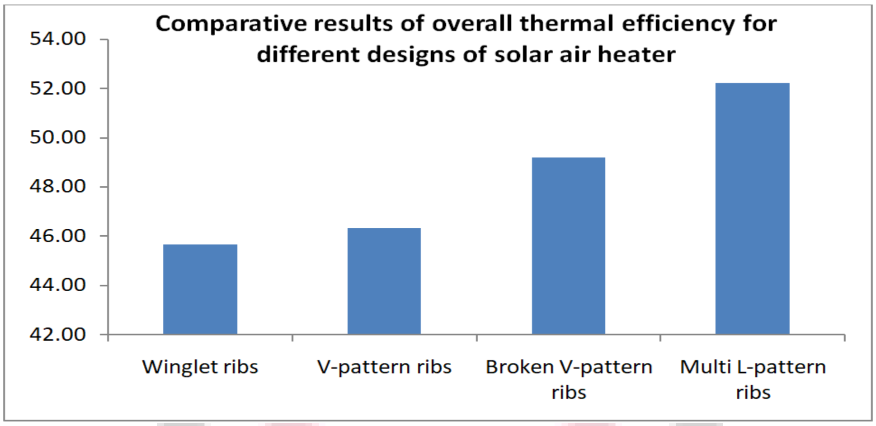


Fig.21 Comparative results of overall thermal efficiency for different designs of solar air heater

IV. Conclusion

After performing mathematical and computational fluid dynamics analysis on winglet ribs type solar air heater at 5.23 m/sec. It has been observed that the maximum temperature of 338.9 K is attained at the winglet bottom edge of the rough surface of the absorber plate. The average temperature of 319.5 K, Overall heat loss of 6.604 w/m^2-K, Useful heat gain is 3.627 watt and overall thermal efficiency is 45.48%.

After performing mathematical and computational fluid dynamics analysis on V-pattern ribs type solar air heater at 5.23 m/sec. It has been observed that the maximum temperature of 340.4 K is attained at the bottom edge of the rough surface of the absorber plate. The average temperature of 320.2 K, Overall heat loss of 6.567 w/m^2-K, Useful heat gain is 3.563 watt and overall thermal efficiency is 46.32% which is 1.4% more than base design.

After performing mathematical and computational fluid dynamics analysis on broken V-pattern ribs type solar air heater at 5.23 m/sec. It has been observed that the maximum temperature of 342.0 K is attained at the bottom edge of the rough surface of the absorber plate. The average temperature of 321 K, Overall heat loss of 6.544 w/m^2-K, Useful heat gain is 3.496 watt and overall thermal efficiency is 49.20% which is 7.71% more than base design.

After performing mathematical and computational fluid dynamics analysis on the multi L-pattern ribs type solar air heater at 5.23 m/sec. It has been observed that the maximum temperature of 344.6 K is attained at the bottom edge of the rough surface of the absorber plate. The average temperature of 322.3 K, Overall heat loss of 6.524 w/m^2-K, Useful heat gain is 3.386 watt and overall thermal efficiency is 52.24% which is 14.36% more than base design.

From the above conclusion it has been observed that the maximum temperature of 344.6K multi L-pattern ribs type solar air heater with overall thermal efficiency is 52.24% which is 14.36% more than base design. Hence Solar air heater with multi L-pattern ribs is suggested for better thermal performance.

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