ENHANCING SOLAR AIR HEATER EFFICIENCY: A COMPUTATIONAL FLUID DYNAMICS ANALYSIS FOR CENTRAL INDIA

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Abstract: - *Solar air heaters have emerged as promising solutions for harnessing solar energy to heat air for various applications. This paper explores the optimization of solar air heater designs using computational fluid dynamics (CFD) analysis to enhance thermal efficiency. The study investigates novel rib patterns and design modifications to improve performance, particularly in regions with abundant solar irradiance like Central India. Through mathematical modeling and CFD simulations, different solar air heater configurations are evaluated, focusing on maximizing thermal performance. The analysis includes comparisons of temperature distributions, heat transfer efficiency, and overall system performance for various design proposals.*

Keywords: *Solar air heater, computational fluid dynamics (CFD), thermal efficiency, design optimization, Central India, heat transfer, renewable energy.*

I. INTRODUCTION

Solar air heater efficiency enhancement is a critical area of research aimed at maximizing the performance of these sustainable energy systems. With a growing emphasis on renewable energy sources, solar air heaters have emerged as promising solutions for harnessing solar energy to heat air for various applications, including space heating, drying, and ventilation. The efficiency of solar air heaters depends on several factors, including design parameters, airflow characteristics, and thermal properties of the materials used. Researchers are increasingly turning to computational fluid dynamics (CFD) analysis to optimize solar air heater designs by studying the fluid flow patterns, heat transfer mechanisms, and energy losses within the system[1]. By exploring novel rib patterns and other innovative design modifications, engineers seek to improve thermal efficiency and enhance the overall performance of solar air heaters, particularly in regions like Central India where solar irradiance is abundant. This pursuit of efficiency enhancement holds significant promise for advancing the adoption of solar air heating technology and contributing to the transition towards sustainable energy solutions. In our daily activities, energy is a necessary component of life, and different types of energy have a big impact on people's lives. Concerning global climate conditions and the exhaustion of traditional energy sources have led to an increasing need for renewable energy. Solar thermal energy is emerging as clean and sustainable energy to fulfil the energy requirement in many spheres of life. Solar air heaters (SAHs) are used to harness this energy for low- to medium-temperature applications. The absorber's black surface receives sun radiation through glass in the SAH, acting as a heat source that transfers heat to the fluid running above. Low air thermal conductivity results in less convective heat transfer from the air to the absorber, which dramatically lowers SAH efficiency [2].

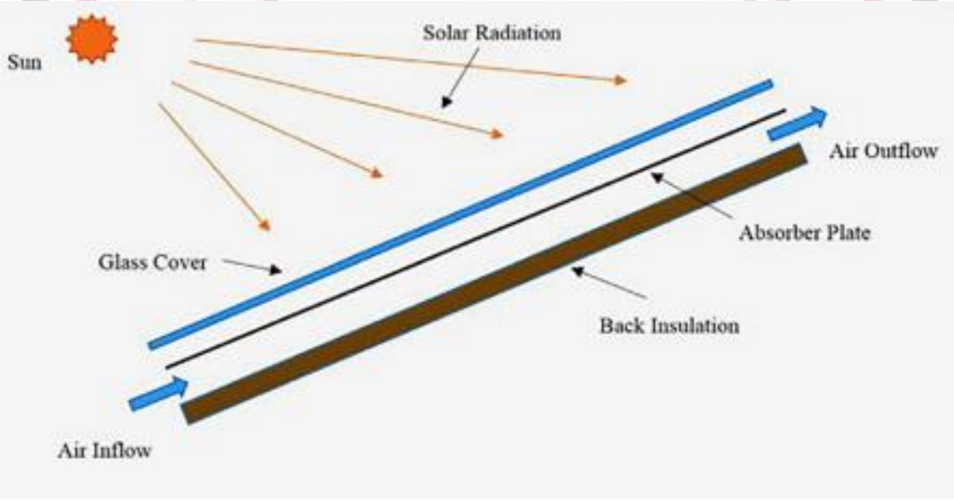

Figure 1 Conventional solar air heater [3].

The effective heat of liquid collection determines the thermal efficiency of solar air heater [4]. Since the heat transfer coefficient of air is low, the heat exchange decreases, which causes the temperature of the medium to decrease. It is assumed that a layered viscous sublayer exists. When the heat changes the resistance on the surface of the heated plate. Including the rough shape to interrupt the flow is a good idea to improve the heat transfer [5]–[7]. The quality of heat collected from the fluid determines the thermal efficiency of the solar wind water heater. Since the difference between hot air and hot air is less electrical, the heat transfer rate decreases, causing the average temperature to decrease. Assume there is a viscous substrate. When heat changes the resistance of the heat plate surface. Having a rough shape that interrupts the flow is a good idea to improve heat transfer.

A. Different Types of Solar Air Heaters

Solar air heaters represent a pivotal technology in the realm of renewable energy, offering a sustainable solution for harnessing solar radiation to meet heating and ventilation needs across various sectors. With the ever-growing emphasis on mitigating climate change and reducing dependence on fossil fuels, solar air heaters have emerged as viable alternatives, embodying the promise of clean, abundant energy [4]–[8]. This introduction sets the stage for delving into the world of solar air heaters, exploring their principles, applications, and potential for efficiency enhancement. In this era of environmental consciousness and energy transition, the importance of renewable energy sources cannot be overstated. Solar energy, in particular, stands out as a ubiquitous and inexhaustible resource, offering immense potential for powering a greener future. Solar air heaters, a subset of solar thermal technologies, leverage this abundant resource to heat air for various purposes, ranging from space heating in buildings to industrial processes and agricultural applications. The fundamental principle underlying solar air heaters is simple yet ingenious: harnessing solar radiation to heat air [9]–[12]. This process typically involves capturing sunlight using a solar collector, transferring the absorbed heat to the air, and circulating the heated air to the desired space. While the basic concept remains consistent, solar air heaters come in diverse configurations, each tailored to specific applications and performance requirements. The versatility of solar air heaters is exemplified by their various types, ranging from flat plate and transpired solar air heaters to glazed and unglazed variants. Each type offers unique advantages and is suited to different environments and usage scenarios. Moreover, advancements in materials, design, and control systems continue to push the boundaries of efficiency and applicability, driving innovation in the field [13]–[17].

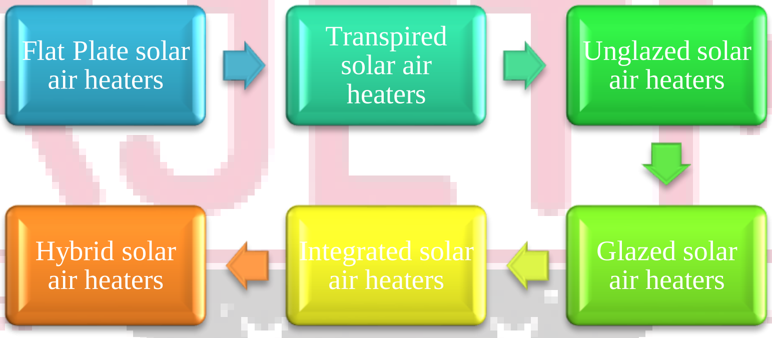

Figure 2 Types of Solar Air Heaters

B. Understanding Thermal Efficiency in Solar Air

Understanding thermal efficiency in solar air heaters is paramount for optimizing their performance and maximizing energy utilization. Thermal efficiency refers to the effectiveness of a solar air heater in converting solar radiation into usable heat energy for heating air. Several factors influence the thermal efficiency of these systems, including design parameters, absorber plate materials, airflow characteristics, and insulation. Efficient design configurations, such as maximizing the surface area exposed to sunlight and minimizing heat losses, are crucial for enhancing thermal efficiency. Additionally, the choice of absorber plate materials with high thermal conductivity and low emissivity plays a pivotal role in improving heat transfer efficiency. Proper insulation and sealing mechanisms are also essential to minimize thermal losses and maximize heat retention within the system [18]–[23]. By comprehensively understanding and optimizing these factors, researchers and engineers can enhance the thermal efficiency of solar air heaters, making them more effective and sustainable solutions for heating and ventilation applications. Recyclable materials can be used to simply make solar air heaters at home. We will attempt to clarify the best techniques for producing solar air heaters that are efficient in this article [24].

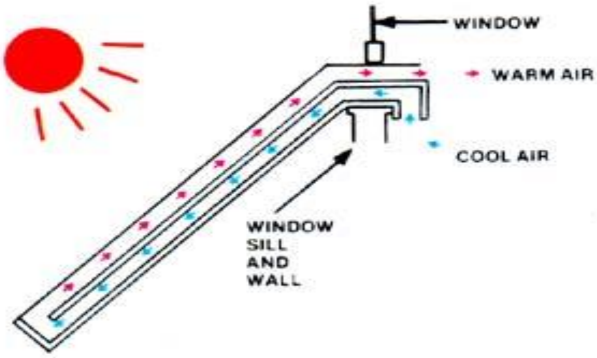

Figure 3 Understanding Solar Air Heaters [10]

Solar thermal heating is one of the best ways to produce heat and air. Since most of the product is permanent, solar heating is easy to do almost for free. In order to do good heating, we need to understand the process that we will try to explain in this article[13]. There are many solar heating systems available on the internet[25]. Many use cans to make suction tubes. The good thing about tin cans is that they are easy to obtain and have small walls. This means that the air inside can be heated effectively. The solar air heater has three main features. Absorbent, transparent cover and case[26].

II. LITERATURE REVIEW

Panda and Kumar (2022) highlight the crucial role of solar air heaters in harnessing solar energy efficiently. They emphasize the conversion of solar radiation into thermal energy, which is then utilized for various applications such as space heating and agricultural drying. Despite their cost-effectiveness and simple design, solar air heaters face challenges like low heat transfer coefficients. To address this, strategies like incorporating artificial roughness elements onto the absorber surface are explored to enhance heat transfer. Their research aims to review various roughness geometries to improve the thermal and thermohydraulic performance of solar air heaters.

Chabane et al. (2013) conducted experiments to assess the thermal efficiency of flat plate solar air heaters at different mass flow rates. They discovered optimal thermal efficiency at a maximum mass flow rate of 0.0202 kg/s, with single-flow collectors performing better under these conditions. Their study provides valuable insights into the relationship between thermal efficiency and mass flow rates, particularly highlighting efficiencies achieved in specific operational scenarios.

Patil (2015) discusses the significant improvement in heat transfer achieved by applying roughness to broad walls in solar air heaters. Although this increases fluid friction moderately, selecting appropriate roughness patterns and geometrical parameters is crucial for optimizing heat transfer and friction levels. Their review examines various roughness patterns and their impact on fluid flow behavior and heat transfer mechanisms, offering insights for enhancing solar air heater performance.

Karmveer et al. (2022) emphasize the effectiveness of implementing artificial roughness on solar air heater absorbers to enhance performance. They evaluate thermo-hydraulic performance to balance pumping power needs with useful heat gain. The study explores various parameters affecting solar air heater performance and recommends specific roughness geometries to achieve optimal efficiency under different conditions.

Saxena et al. (2023) discuss the widespread adoption of solar air heaters and strategies to augment heat transfer within their ducts through artificial roughness. Their comprehensive examination of various roughness geometries highlights the potential of combining distinct rib forms to elevate the thermal performance of solar air heaters.

Pachori et al. (2023) review recent investigations focused on enhancing the thermohydraulic performance of solar air heaters, particularly through double-pass configurations and artificial flowing modifications. They compare the efficiency of different configurations and materials, offering insights into sustainable approaches to improve thermal performance.

Saxena and Goel (2013) evaluate different thermal energy storage methods used in solar air heaters, identifying options tailored for solar heaters' specific needs. Their theoretical examination underscores the importance of effective thermal storage in maximizing solar air heater efficiency.

Sahu et al. (2023) provide an overview of efforts to enhance the thermal and exergetic performance of conventional solar air heater ducts through extended surfaces or fins. Their comprehensive review aims to offer valuable insights for researchers engaged in optimizing solar air heater performance.

Aravindh and Sreekumar (2016) describe various adaptations made to solar air heater absorber plates to increase heat transfer rates and turbulence, ultimately improving efficiency. They emphasize the intricate balance between efficiency enhancements and increased pumping power, crucial for optimizing solar air heater performance.

III. OBJECTIVE

There are following objective of the present work

- The main objective of the present work to do CFD analysis on base model to enhance the thermal performance of solar air heater for the location of central India.
- To prepare different proposed CAD models of solar air heater by changing its roughness width for maximizing the thermal performance.
- To perform computational fluid dynamics analysis on proposed design of solar air heater.
- To compare the results for all designs of solar air heater and suggest the best one.

III. METHODOLOGY

The ‘solar air heater’ comprises an absorberss plate with a parallel plate positioned below, creating a narrow passage through which the air flows for heating. Above the absorber plate, there is a transparent cover system. The assembly is enclosed within a sheet metal container filled with insulation on the bottom and sides, all housed within a sheet metal box inclined at an appropriate angle. This chapter necessitates both mathematical and (Computational Fluid Dynamics CFD) analyses for the solar air heater. The mathematical analysis involves designing the solar air heater, calculating heat transfer within the system, and determining solar loads for the chosen location. On the other hand, the CFD analysis entails simulating various solar air heater designs to assess their thermal performance.

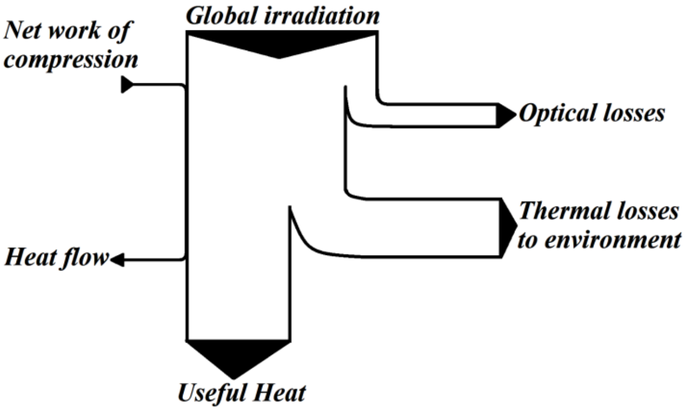

Figure 4 Energy flow for solar air heater

From the above energy flow diagram of solar air heater it has been observed that useful heat gain can be obtained by subtracting the optical losses and thermal losses to environment as shown in figure 4.1.

Mathematical analysis:

Analysis of solar air heater

The following assumption have been considered

- The bulk mean temperature of the air change from T_f *to* (T_f+dT_f) as it flow through the distance dx
- The air mass flow rate is $\dot{m}$
- The mean temperature of the absorber plate and the plate below are T_{pm} & T_{bm} their variation may neglected.
- Side loss can be neglected.

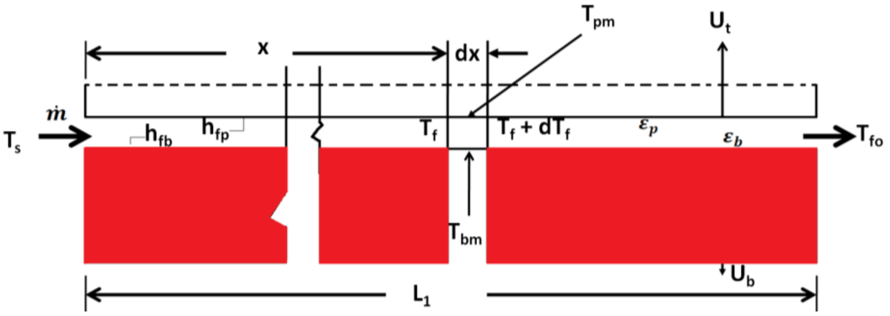

Figure 5 Analysis of 'conventional solar air heater'

Analysis Using 'Computational Fluid Dynamics' for 'Solar Air Heaters'

Computational fluid dynamics is the analysis of systems involving fluid flow, heat switch by means of use of pc-based totally simulation. The technique is very powerful and spans a wide range of industrial and non-industrial application regions. in the gift paintings computational fluid dynamics analysis is done the usage of Ansys fluent for sun air heater at exclusive mass waft rate. The governing equations inclusive of continuity equation, momentum equation, and power equations are used to carry out this computational evaluation.

The structure of computational fluid dynamics revolves around numerical algorithms capable of solving fluid flow issues. All computational fluid dynamics software come with advanced user interfaces for entering problem parameters and viewing the outcomes, making it simple to access their solution capabilities. In order to solve the computational fluid dynamics problems, three key components are used.

1) 'Pre-processor',

2) 'Solver and'

3) 'Post-processor'.

Algorithm' used for 'Computational fluid dynamics analysis'

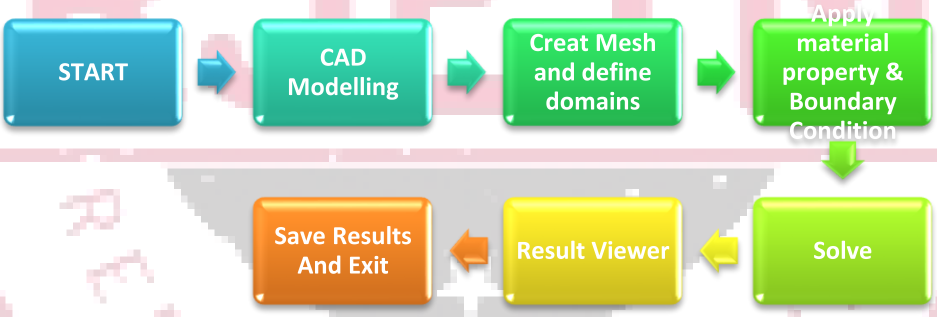

Figure 6 Algorithm' used for (CFD) analysis

Table 1 Constant A, B & C for predicting hourly solar radiation on clear days *[BH Khan]*

'Months	**'A (W/m^2)'**	**'B'**	**'C'**
'January 21'	1202	0.141	0.103
'February 21'	1187	0.142	0.104
'March 21'	1164	0.149	0.109
'April 21'	1130	0.164	0.120
'May 21'	1106	0.177	0.130
'June 21	1092	0.185	0.137
'July 21'	109)	0.186	0.138
'August 21'	1107	0.182	0.134
'September 21'	1136	0.165	0.121
'October 21'	1136	0.152	0.111
'November 21'	1190	0.144	0.106
'December 21'	1204	0.141	0.103

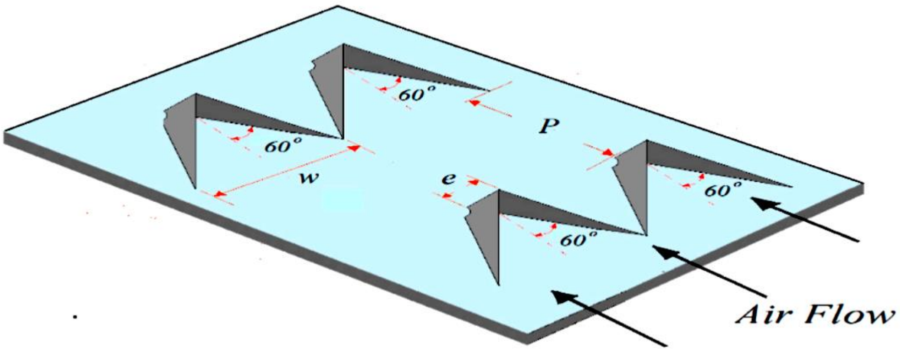

Figure 7 Schematic diagram winglet ribs arrangement on collector surface

(CAD) ‘modeling’ of winglet type ‘solar air heater’:

ANSYS design module was used to construct a three-dimensional computer-aided design (CAD) model of a winglet type solar air heater. The dimensions used to build the solar air heater are derived from A. Kumar (2021); as illustrated in the picture, the collector's length is 1.24 meters, its duct depth is 0.04 meters, its width is 0.16 meters, and its winglet's roughness height is 3 mm at a 60-degree angular position.

Figure 8 CAD model of Winglet ribs solar air heater

Meshing:

The CAD geometry of the winglet category solar air heater is completed and then imported for meshing. Meshing is a crucial process that involves breaking down the CAD geometry into several nodes and components. This process of breaking the CAD geometry into smaller parts is known as meshing. In the present work is 40051 and total no. of elements is 162460. Types of elements used are tetrahedral in shape sue to complexity of geometry.

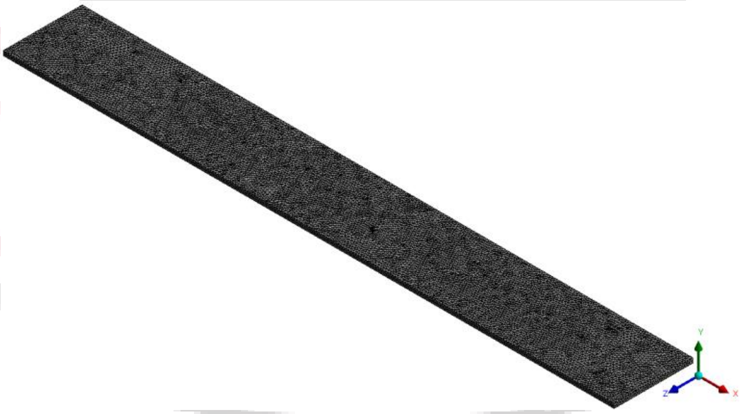

Figure 9 Meshing for winglet ribs (SAH)

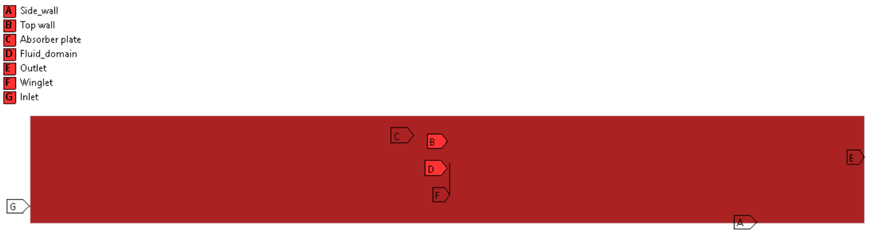

Figure 10 Boundary condition of winglet ribs solar air heater

CAD modeling of V-pattern ribs category ‘solar air heater’:

ANSYS design module was used to construct a three-dimensional computer-aided design (CAD) model of a solar air heater with V-pattern ribs. The dimensions used to construct a (solar air heater) are 1.24 feet for the collector's length, 0.04 meters for the duct depth, and 0.16 meters for the collector's width, for the creation of V-pattern ribs inclination angle is 45^o each with 5 mm air gap with roughness height of 3 mm respectively as shown in figure.

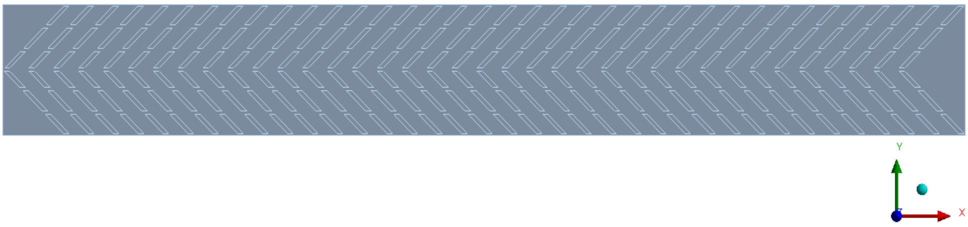

Figure 11 CAD model of ‘V-pattern’ ribs type “SAH”

Meshing:

After completing of CAD geometry of V-pattern ribs type solar air heater is imported for meshing, meshing is a critical operation in which CAD geometry is divided into large numbers of nodes and elements and the procedure to converting into small pieces or elements are called mesh. In the present work is 42080 and total no. of elements is 187019. Types of elements used are tetrahedral in shape sue to complexity of geometry.

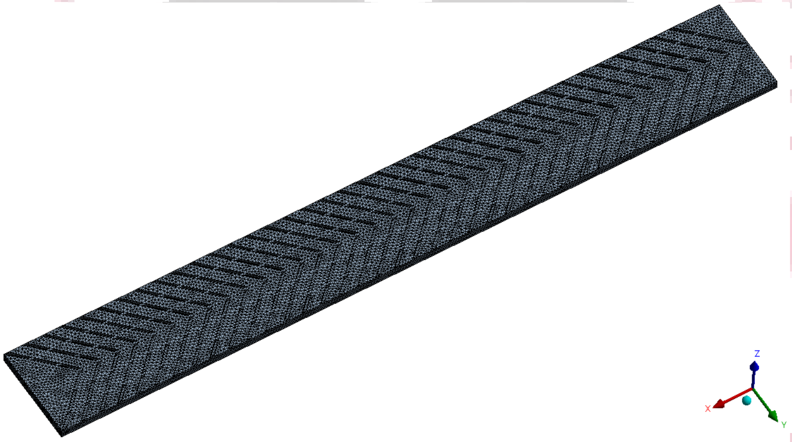

Figure 12 Meshing for V-pattern ribs type solar air heater

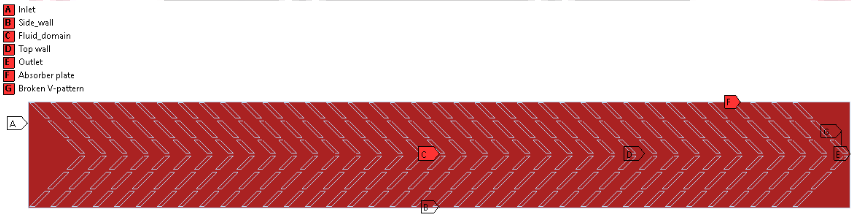

Figure 13 Boundary condition of “V-pattern ribs” type “solar air heater”

CAD modeling of broken V-pattern ribs type “solar air heater”:

ANSYS design module has been used to generate a three-dimensional computer-aided design (CAD) model of a broken V-pattern rib type solar air heater. The dimensions used to construct the solar air heater are 1.24 meters for the collector's length, 0.04 meters for the duct depth, and 0.16 meters for the collector's width, for the creation of broken V-pattern ribs with 5 mm air gap with roughness height of 3 mm respectively as shown in figure.

Figure 14 CAD model of ‘broken’ (V-pattern) ribs type ‘solar air heater’

Meshing:

Figure 15 Mesh repair for damaged V-pattern solar air heater the ribs

After completing of CAD geometry of broken V-pattern ribs type solar air heater is imported for meshing, meshing is a critical operation in which CAD geometry is divided into large numbers of nodes and elements and the procedure to converting into small pieces or elements are called mesh. In the present work is 42506 and total no. of elements is 188154. Types of elements used are tetrahedral in shape sue to complexity of geometry.

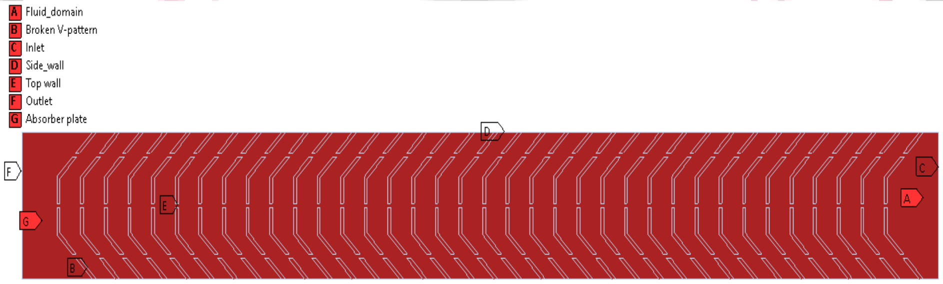

Figure 16 Boundary condition of broken V-pattern ribs type solar air heater

CAD modeling of multi L-pattern ribs type solar air heater:

A three-dimensional CAD model of a solar air heater with multi L-pattern ribs has been developed using the ANSYS design module. The dimensional specifications utilized for constructing the solar air heater include a collector length of 1.24 meters, a duct depth of 0.04 meters, and a collector width of 0.16 meters for the creation of multi L-pattern ribs inclination angle is 45^{o} each with uniform air gap with roughness height of 3 mm respectively as shown in figure.

Figure 4.17 CAD model of multi ‘L-pattern’ ribs form solar air heater

Meshing:

After completing of CAD geometry of ‘multi L-pattern ribs type solar air heater’ is imported for meshing, Mesh generation is a crucial process that involves breaking down huge CAD geometry into numerous nodes and elements. This process of breaking the geometry up into smaller bits or elements is known as meshing. In the present work is 43303 and total no. of elements is 194567. Types of elements used are tetrahedral in shape sue to complexity of geometry.

Figure 4.18 Meshing for multi L-pattern ribs type solar air heater

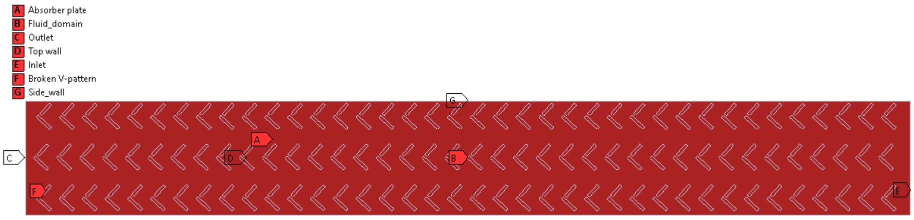

Figure 19 Boundary condition of multi L-pattern ribs type ‘solar air heater’

‘Boundary conditions’:

- Thermal distribution is determined by solving the energy equation.
- The working fluid (heat transfer fluid) chosen is air, with a maximum velocity set at 5.23 meters per second.
- The air inlet temperature is maintained at 300 Kelvin.
- The wall boundary condition incorporates a solar radiation value of 935.8735 watts per square meter, representing the maximum solar radiation calculated for the specific location.
- The left, right, and bottom walls of the air heater are fully insulated to prevent heat losses.
- Outlet boundary conditions are set to zero gauge pressure, reflecting the atmospheric conditions for the flow of heat transfer fluid within the domain.
- Fluent solver is employed for Computational Fluid Dynamics (CFD) analysis.

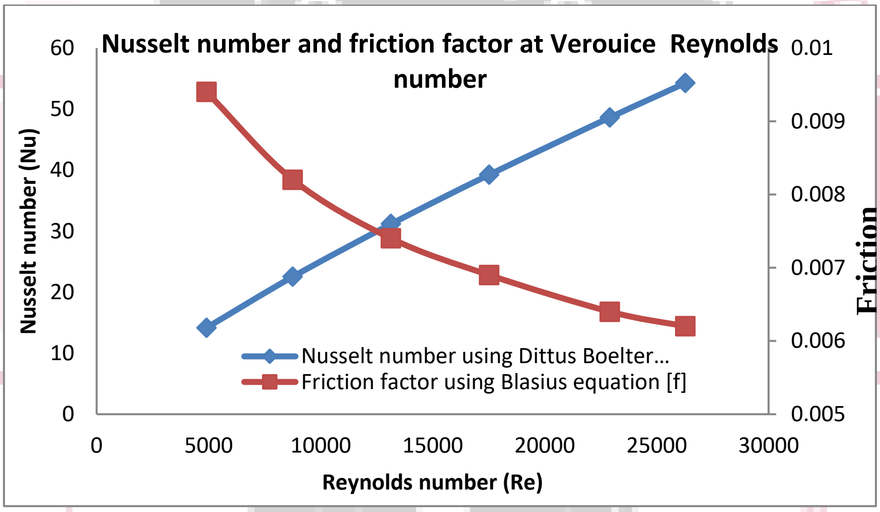

Figure 20 The friction factor to the Nusselt value at various Reynolds numbers *[Present work]*

The compared results between the base paper and present work with the same parameters, it is clearly observed that as the Reynolds number increasing the nusselt number also increasing and friction factor decreasing as published by *A. Kumar 2021* and the calculated values of Nusselt number using Dittus Boelter equation and Friction factor using Blasius equation for Reynolds number in the present work at different air velocity from 1.12 to 5.23 m/sec as shown in figure no, 4.18 & 4.19. From the validation work it also observed that with increasing of air velocity overall thermal efficiency also increased, hence the CFD analysis on other proposed designs of ‘solar air heater’ will performed at 5.23 m/sec.

IV. RESULT AND DISCUSSION

The primary aim of this study is to conduct computational fluid dynamics (CFD) analysis to forecast the thermal efficiency of a solar air heater at the Bhopal location. To achieve this, four distinct models of solar air heaters were devised: winglet ribs type, V-pattern ribs type, Broken V-pattern ribs type, and multi L-pattern ribs type. Steady-state CFD analysis was performed utilizing ANSYS Fluent, focusing on the selected location at Latitude 23° 17’ 00” N and Longitude 77° 27’ 21’’ E. The analysis aimed to ascertain the maximum temperature distribution within the solar air heater, maintaining an air inlet temperature of 300 K under calculated solar radiations for the chosen location. This chapter discusses various results obtained from computational fluid dynamics alongside outcomes derived from mathematical calculations, presented through contour plots, graphs, and tables.

Table 2 Comparative results of 'different design's of solar air heater

solar air heater type	Inlet temperature [K]	Average temperature [K]	Maximum Temperature [K]
Winglet ribs	300	319.5	338.9
V-pattern ribs	300	320.2	340.4
Broken V-pattern ribs	300	321.0	342.0
Multi L-pattern ribs	300	322.3	344.6

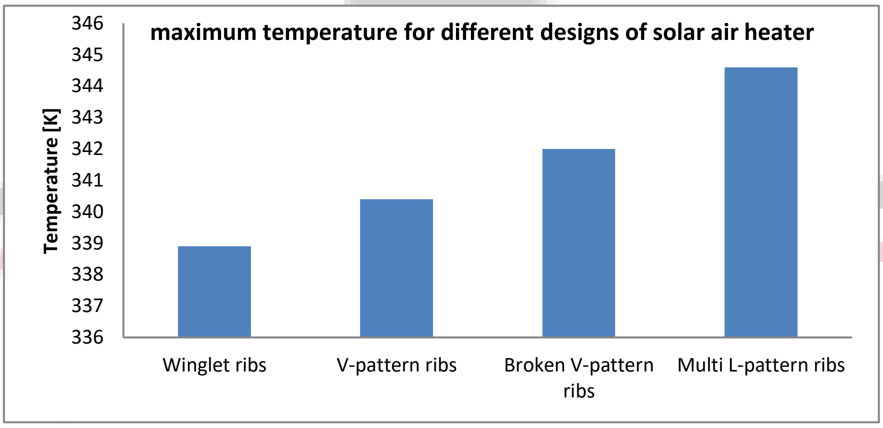

Figure 21 Comparative results of 'maximum temperature' for 'different designs' of solar air heater

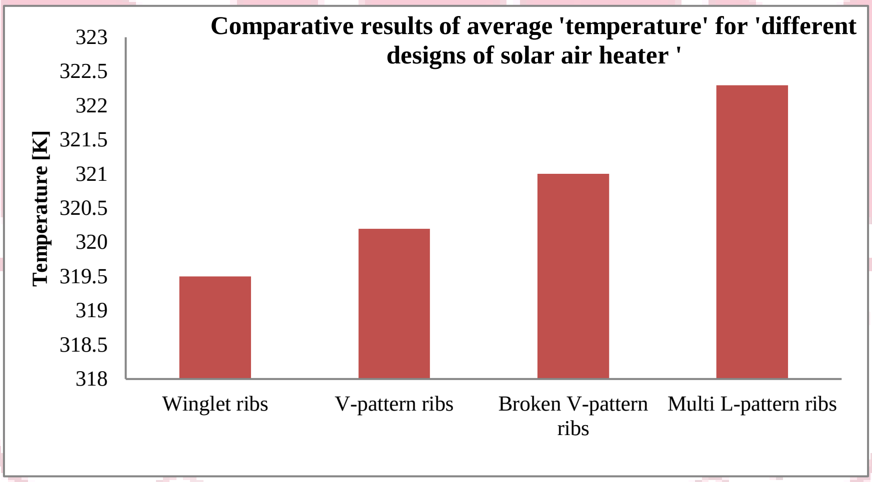

Figure 22 'Comparative results' of average temperature for 'different designs' of 'solar air heater'

Table 3 Radiative heat transfer coefficient for different designs of solar air heater

solar air heater type	Radiative heat transfer coefficient $[\mathrm{W/m^2.K}]$
Winglet ribs	592.958
V-pattern ribs	596.864
'Broken V-pattern ribs'	601.349
'Multi L-pattern ribs'	608.684

Calculation of overall losses from the solar air heater

Table 4 Average wind speed for last five year in the central India

Average wind speed Bhopal

Month	2017	2018	2019	2020	2021	Average wind speed
Jan	8.6	6.8	9.4	10.8	9.9	**9.10**
Feb	9.4	7.5	10.9	11.1	8.7	**9.52**
Mar	9.9	10.1	12.4	12.1	11.8	**11.26**
Apr	14.3	12.0	13.8	13.0	12.1	**13.04**
May	12.4	14.3	16.3	16.3	15.6	**14.98**
Jun	13.0	16.3	16.9	15.2	17.3	**15.74**
Jul	16.5	17.1	17.7	13.8	16.5	**16.32**
Aug	13.4	16.5	18.2	19.2	15.1	**16.48**
Sep	9.3	12.8	13.9	9.4	11.9	**11.46**
Oct	7.4	7.0	8.0	9.0	7.4	**7.76**
Nov	6.3	6.3	6.7	4.4	9.6	**6.66**
Dec	8.7	8.3	9.8	8.4	9.4	**8.92**

https://www.worldweatheronline.com/bhopal-weather-averages/madhya-pradesh/in.aspx

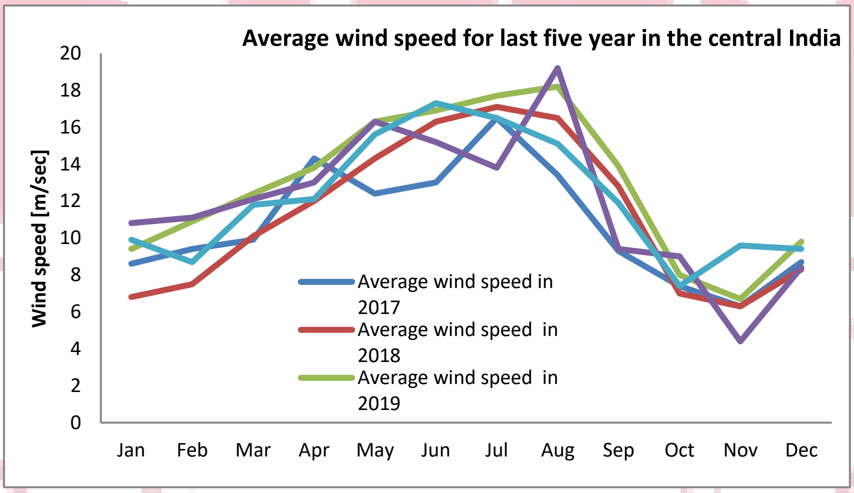

Figure 23 Average wind speed for last five year in the central India

Table 5 The value of e for different design of solar air heater

solar air heater type	$e = 0.430(1 - 100/T_{pm})$
Winglet ribs	0.2954
V-pattern ribs	0.2957
(Broken V-pattern ribs)	0.296
(Multi L-pattern ribs)	0.2966

Table 5.9: Overall heat loss for different design of solar air heater

solar air heater type	$U_T\ [w/m^2\_k]$	$U_B\ [w/m^2\_k]$	$U_{side}\ [w/m^2\_k]$	$U_L\ [w/m_k^2]$
Winglet ribs	5.655	0.74	0.209	6.604

V-pattern ribs	5.618	0.74	0.209	6.567
Broken V-pattern ribs	5.595	0.74	0.209	6.544
Multi L-pattern ribs	5.575	0.74	0.209	6.524

Table 6 Suitable ‘heat gain for different ‘design of ‘solar air heater’

solar air heater type	**Useful heat gain [watt]**
Winglet ribs	3.627
V-pattern ribs	3.563
Broken ‘V-pattern’ ribs	3.496
Multi ‘L-pattern’ ribs	3.386

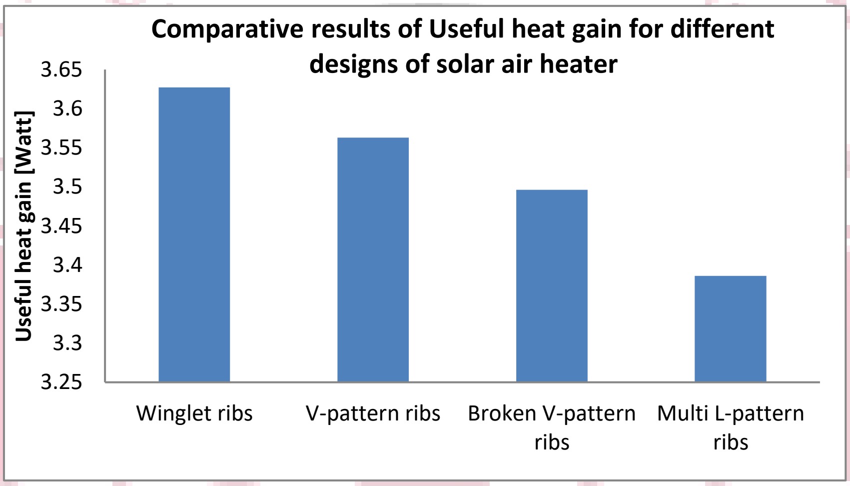

Figure 24 Comparative findings of useful heat gain for various solar air heater designs

Table 7 Collector efficiency & heat removal factor and Thermal efficiency of collector for different designs of solar air heater

solar air heater type	**Collector efficiency factor F'**	**heat removal factor F_r**	**Thermal efficiency of collector using heat removal factor**
Winglet ribs	0.4509	0.451	0.3348
V-pattern ribs	0.4502	0.450	0.3322
Broken V-pattern ribs	0.4493	0.449	0.3292
Multi L-pattern ribs	0.4479	0.448	0.3246

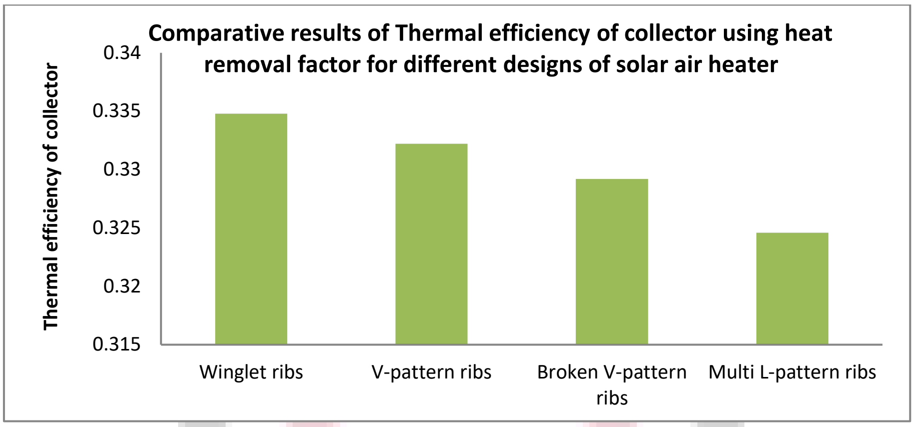

Figure 25 Comparative results of Thermal efficiency of collector using heat removal factor for different designs of solar air heater

Table 8 Overall thermal efficiency for different designs of solar air heater

solar air heater type	Overall thermal efficiency (η_{th})
Winglet ribs	0.4568
V-pattern ribs	0.4632
Broken V-pattern ribs	0.4920
Multi L-pattern ribs	0.5224

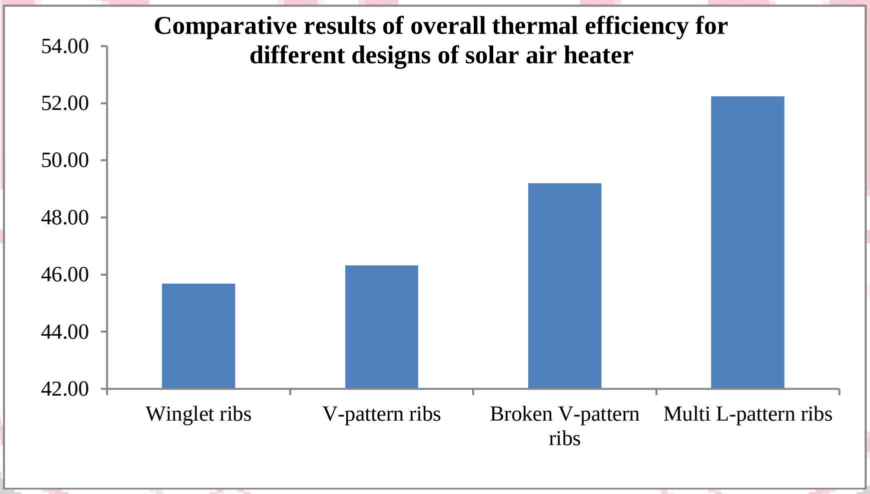

Figure 26 Comparative results of overall thermal efficiency for different designs of solar air heater

V. CONCLUSION

This research highlights the significance of computational fluid dynamics analysis in optimizing solar air heater designs for enhanced thermal efficiency. By exploring novel rib patterns and design modifications, researchers can improve the performance of solar air heaters, particularly in regions with high solar irradiance like Central India. The study underscores the importance of efficient heat transfer mechanisms and proper design configurations in maximizing energy utilization and advancing sustainable energy solutions. Through comprehensive analysis and comparison of different design proposals, this research provides valuable insights for engineers and researchers aiming to optimize solar air heater performance for various applications.

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