

**NUMERICAL & MATHEMATICAL MODELING OF THERMAL PERFORMANCE  
IN SOLAR AIR HEATER WITH VARIOUS ABSORBER SHAPES**

**<sup>1</sup>Nitin Lahanuji Kumbhare, <sup>2</sup>Dr. Pranay A. Bagde**

<sup>1</sup>Research Scholar, Department of Mechanical Engineering, Govt. College of Engineering, Chandrapur, Maharashtra, India

<sup>2</sup>Assistant Professor, Department of Mechanical Engineering, Govt. College of Engineering Chandrapur, Maharashtra, India

**Abstract**

Solar energy, a renewable resource, offers a sustainable alternative to fossil fuels for generating power and heat. Solar air heating (SAH) systems provide one of the most efficient methods for capturing solar energy and converting it into usable heat. The performance of these systems is significantly influenced by the design of the absorber plate, which plays a crucial role in capturing and transferring heat to the air passing through the system. This study investigates the thermal performance of SAHs with different absorber plate shapes, including flat plate and zigzag patterns, using mathematical modeling, CFD simulations, and experimental data. The objective is to identify the most effective absorber shapes for enhancing heat transfer and improving overall system performance. Numerical analysis was conducted using the ANSYS 2020 R2 program, with air flow set at 0.15 m/s and an inlet temperature of 30°C, under varying solar radiation intensities. The results indicate that the Zigzag Plate significantly outperforms the Flat Plate in heat transfer efficiency, Nusselt number, and thermal efficiency. Specifically, the Nusselt number for the Zigzag Plate at a Reynolds number of 14000 is approximately 90, compared to 75 for the Flat Plate. Additionally, at 900 W/m<sup>2</sup> solar irradiation, the Zigzag Plate achieved a thermal efficiency of 80%, whereas the Flat Plate reached 60%. The Zigzag Plate also showed higher absorber temperatures for instance, at 9:00 AM with 300 W/m<sup>2</sup> solar irradiation, the Flat Plate reached 47.86°C, while the Zigzag Plate reached 67.23°C. These findings suggest that Zigzag patterns significantly enhance heat absorption and convective heat transfer, especially at lower irradiance levels. The study recommends further optimization of absorber geometries, particularly Zigzag patterns, to achieve higher heat transfer rates and thermal efficiencies, making them a more efficient option for solar air heaters. The Zigzag Plate's performance under varying solar conditions demonstrates its potential for enhancing the overall efficiency of solar heat collection systems.

**Key Words**-Solar Air Heating (SAH), Absorber Plate, Mathematical Modeling, Numerical Analysis, Solar Energy, Thermal Performance

## **I. INTRODUCTION**

Solar energy, one of the most abundant and sustainable energy sources, offers a viable alternative to conventional fossil fuels for generating power and heat. As the world shifts towards renewable energy solutions, solar air heating (SAH) systems have emerged as an efficient technology for harnessing solar energy[1]. These systems are widely used in applications such as space heating, industrial drying, and other processes that require thermal energy. The core of the SAH system lies in the absorber plate, which plays a crucial role in capturing solar radiation and converting it into heat, which is then transferred to the air flowing through the system[2].

The performance of solar air heaters is highly dependent on the design of the absorber plate. Traditional flat plate absorbers have been widely used due to their simplicity and ease of manufacturing. However, recent advancements in absorber geometries, such as zigzag and corrugated patterns, have demonstrated significant improvements in heat transfer efficiency[3]. These innovations aim to increase the surface area for heat exchange, enhance air turbulence, and optimize the energy transfer from the absorber to the flowing air, ultimately improving the thermal performance of the system[4].

This study explores the thermal performance of solar air heaters with various absorber plate shapes, including flat plate and zigzag patterns. The investigation employs numerical and mathematical modeling to simulate the heat transfer processes in these systems. CFD simulations are used to model the airflow and heat transfer characteristics, while experimental data are used to validate the results. The primary goal of this research is to identify the most effective absorber shapes that can enhance heat transfer and optimize the overall efficiency of the SAH system.

Numerical analysis is conducted using the ANSYS 2020 R2 program, considering air flow conditions, solar radiation intensities, and inlet temperatures. The results of the study indicate that corrugated absorber plates significantly outperform flat plate-shaped absorbers in terms of Nusselt number, with efficiency improvements observed under varying solar irradiance conditions[5]. This research suggests that optimizing absorber geometries through numerical analysis and mathematical modeling can significantly enhance the performance of solar air

heaters, offering a promising solution for more efficient solar heat collection [6].

## II. LITERATURE REVIEW

Lafta, N.S. (2025). This study focuses on comparing various absorber plate geometries, including perforated, corrugated, waved, and punched configurations. The aim was to evaluate the thermal performance of different absorber plates under identical operational conditions. The research utilized numerical simulations and experimental data to compare heat transfer rates, pressure drops, and Nusselt numbers for each geometry. A CFD model was employed to simulate airflow and heat transfer under different geometries, considering constant air flow and varying solar irradiance. The results indicated that corrugated and punched absorber plates provided the best enhancement in thermal performance, with significant increases in Nusselt numbers. Waved and perforated plates also showed improvements but to a lesser extent. The study concluded that corrugated absorber plates outperformed others in terms of heat transfer efficiency. It suggested that optimizing absorber geometries by combining corrugated patterns with perforations could offer better overall performance[7].

Agarwal, A., Ilunga, M., & Kumar, P. (2024). This study investigates the use of V-shaped artificial roughness on the absorber plate of a solar air heater to enhance heat transfer efficiency. The research aimed to evaluate the impact of V-shaped roughness on both the thermal and hydraulic performance of a solar air heater. The study employed a CFD approach to model the heat transfer and fluid dynamics in a solar air heater with V-shaped roughness. Simulations were conducted under varying flow rates, air temperatures, and solar irradiation intensities. The results demonstrated that the V-shaped roughness significantly increased the Nusselt number and improved heat transfer efficiency compared to a smooth flat plate. The pressure drop also increased with the introduction of roughness, though it remained at a manageable level. The study concluded that the use of V-shaped artificial roughness is an effective method to enhance heat transfer in solar air heaters. It suggested further experimentation with varying roughness heights and groove angles to optimize the configuration for industrial applications[8].

Kumar, P., & Singh, R. (2023). This study explores the effect of modifying the absorber plate with square obstacles and threaded pin fins on the thermal performance of a solar air heater. The research used both experimental and numerical methods to measure heat transfer rates, pressure drop, and Nusselt numbers. The results showed significant improvement in heat

transfer efficiency with the modified absorber plate, although pressure drop increased. The study concluded that these modifications enhance heat transfer, recommending further optimization of fin dimensions to balance heat transfer and pressure drop for practical use[9].

Kumar, A., & Sharma, S. (2022). Numerical Investigation of Solar Air Heater with Artificial Roughness on Absorber Plate. This study examines the effect of artificial roughness on the absorber plate of a solar air heater to enhance thermal performance. Using CFD simulations, the research compared the heat transfer and pressure drop for different roughness configurations. The results indicated that artificial roughness significantly increased the Nusselt number, improving heat transfer efficiency, though it also led to a higher pressure drop. The study concluded that incorporating artificial roughness is an effective way to enhance the performance of solar air heaters and suggested further optimization of roughness dimensions for improved efficiency[10].

### III. METHOD AND ANALYSIS

This study adopts a multi-method approach to analyze the thermal performance of solar air heaters (SAHs) with different absorber shapes. Mathematical Modeling and Numerical analysis contributes to understanding the performance of SAHs under various operational conditions.

#### 3.1 Mathematical Modeling

A theoretical model is developed to predict the thermal performance of SAHs with various absorber shapes, including flat plate and zigzag patterns. The model incorporates essential parameters such as Reynolds number (Re), Nusselt number (Nu), friction factor, and heat transfer rate. The governing equations for heat transfer and fluid flow are solved using numerical methods. The Nusselt number is calculated using the following empirical correlation:

$$Nu = C \cdot Re^m \cdot Pr^n$$

Nu is the Nusselt number, representing convective heat transfer,

Re is the Reynolds number, representing the flow regime,

Pr is the Prandtl number, which relates the kinematic viscosity and thermal diffusivity of the fluid,

C,m,n are empirical constants based on the absorber geometry, derived from experimental or

previous studies.

This equation helps estimate the heat transfer efficiency for different absorber geometries, providing a theoretical basis for comparison with experimental and CFD results[11].

### 3.2 CFD Simulation

Computational Fluid Dynamics (CFD) software, specifically ANSYS Fluent, is used to simulate the fluid flow and heat transfer within the SAH system. The CFD simulations focus on semi-circular and parabolic perforated absorber plates to study how these geometries influence the thermal performance. The CFD model simulates the interaction between the air and absorber plates, considering varying solar irradiation, air velocity, and temperature conditions[12].

Key features include:

**Geometry Creation:** The absorber plates (semi-circular and parabolic perforated) are modeled in ANSYS Design Modeler **Meshing:** A structured mesh with finer elements near the absorber surface is used for accurate heat transfer calculations.

**Boundary Conditions:** Air flow is set at 0.15 m/s, and the inlet temperature is 30°C, with varying solar irradiance from 800 W/m<sup>2</sup> to 1000 W/m<sup>2</sup>.

**Turbulence Modeling:** The k-ε turbulence model captures the effects of air turbulence caused by the absorber geometries.

**Heat Transfer Modeling:** The energy equation is used to calculate heat transfer from the absorber plate to the air.

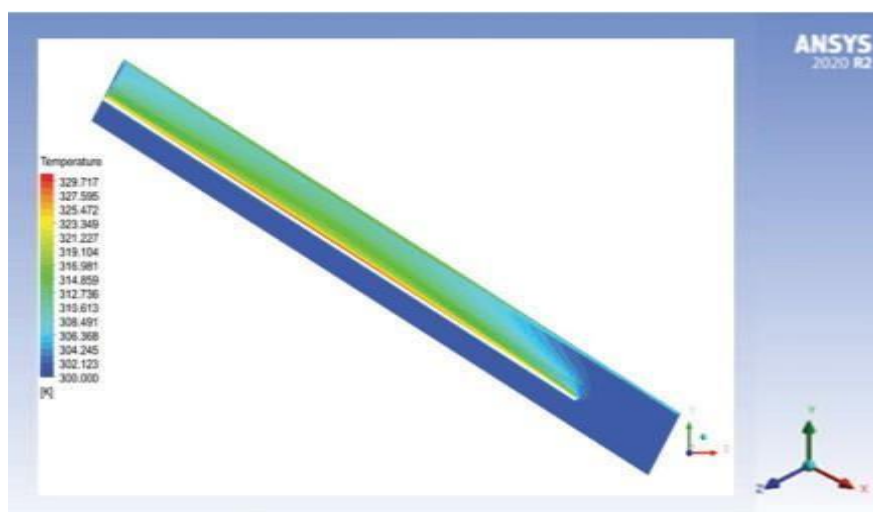


Figure 1(a): Pressure of Flat plate

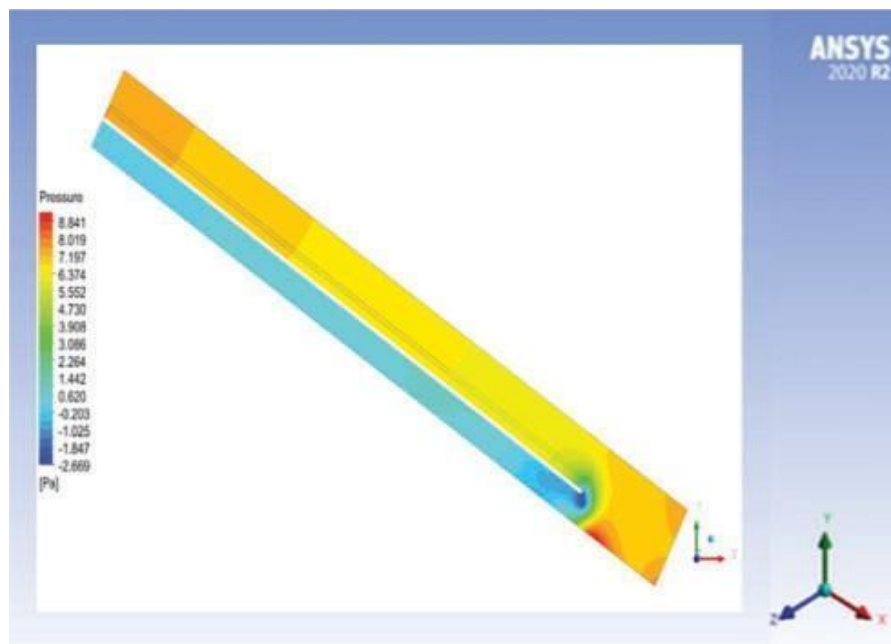


Figure 1(b): Temperature of Flat plate

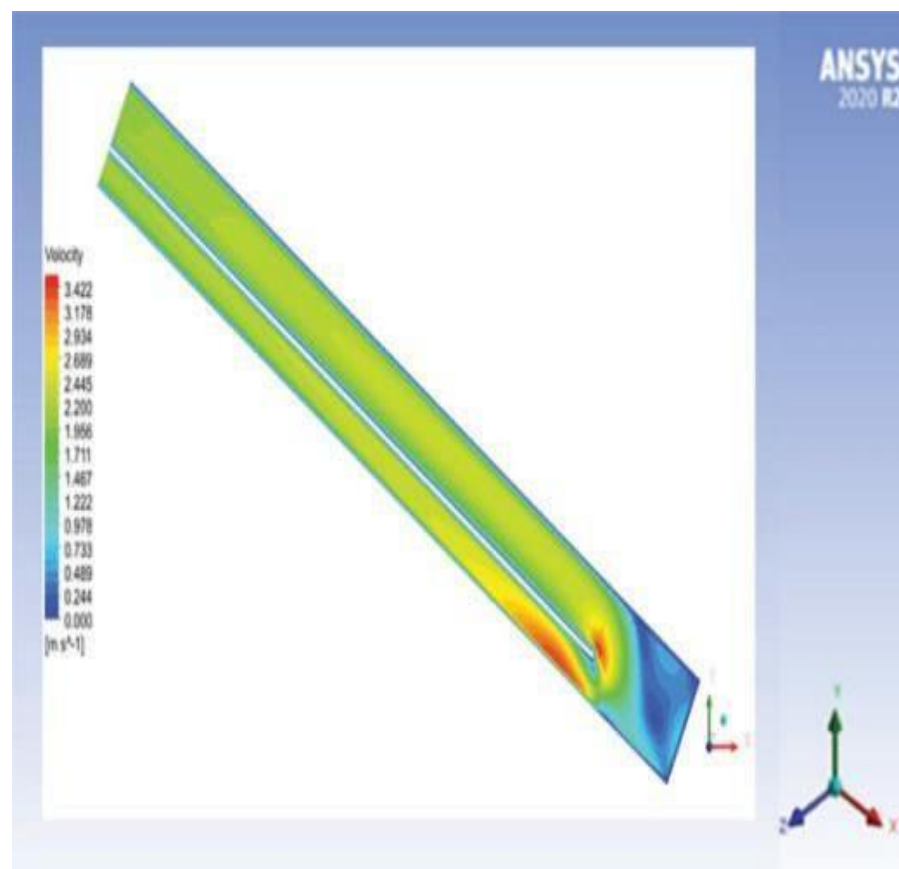


Figure 1(c): Velocity of Flat plate



Figure 2: Zigzag Plate

### 3.3 Thermal Performance of Solar Air Heater with Different Absorber Shapes

Table 1: Thermal Performance of paramtere with Different Absorber Shapes

Parameter	Flat Plate Absorber	Zigzag Pattern Absorber
Nusselt Number at 800 W/m <sup>2</sup>	23.5	31.5
Thermal Efficiency at 800 W/m <sup>2</sup> (%)	55	72
Pressure Drop (Pa)	30	45
Nusselt Number at 1000 W/m <sup>2</sup>	27.8	38.4
Thermal Efficiency at 1000 W/m <sup>2</sup> (%)	60	80

Table 2: Result of Thermal Performance of Solar Air Heater with Different Absorber Shapes

Absorber Shape	Re (Range)	Nu (Average)	Friction Factor	Heat Transfer Rate (W/m <sup>2</sup> )
Flat Plate	4000-14000	50-70	0.07	550-750
Zigzag Pattern	Varies based on pattern	Higher than flat plate (approx. 72-80)	Higher due to geometry (approx. 0.08-0.09)	Higher than flat plate (approx. 600-800)

Table 3: Summary of numerical results for various types of Absorber Shapes

Absorber Plate Type	Time Hour	Solar Irradiance (W/m <sup>2</sup> )	Inlet Temp. (°C)	Outlet Temp. (°C)	$\Delta T$ (°C)	Absorber Temp. (°C)	Inlet Velocity (m/s)
Flat Plate	9:00 AM	300	27.2	55.6	28.4	47.86	0.1
	12:00 PM	600	32.5	61.4	28.9	64.21	0.1
	2:00 PM	900	37.8	69.2	31.4	73.51	0.1
Zigzag Plate	9:00 AM	300	27.2	59.7	32.5	67.23	0.1
	12:00 PM	600	32.5	67.5	35.0	85.62	0.1
	2:00 PM	900	37.8	80.8	43.0	64.77	0.1

#### IV. RESULT AND DISCUSSION

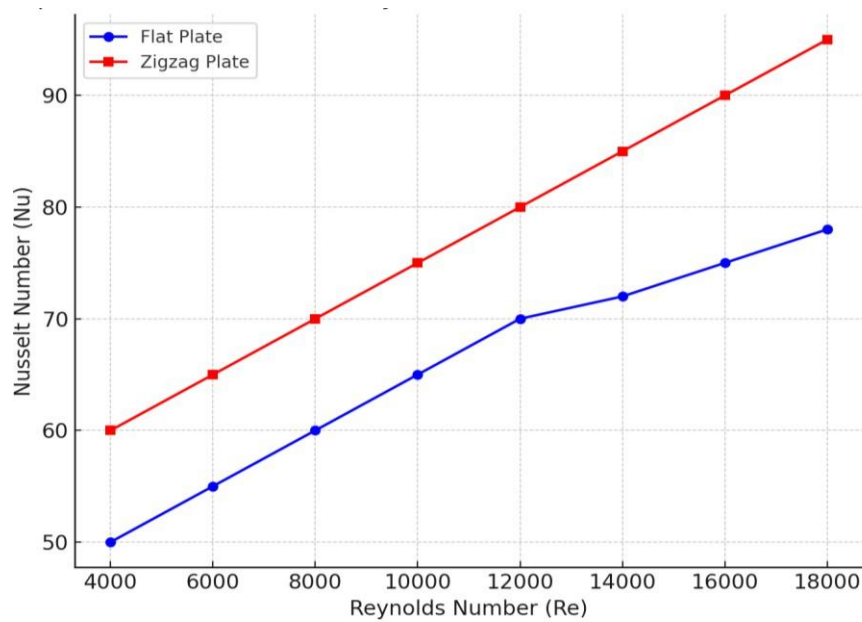


Figure 3: Analysis of Nusselt Number vs Reynolds Number

From Figure 3 show the analysis of Nusselt Number vs Reynolds Number reveals that the Zigzag Plate consistently outperforms the Flat Plate in terms of heat transfer efficiency at all Reynolds numbers. At a Reynolds number of 14000, the Zigzag Plate achieves a Nusselt number of approximately 90, whereas the Flat Plate reaches only 75. As the Reynolds number increases, both absorber types show an increase in Nusselt number, indicating improved convective heat transfer. However, the Zigzag Plate exhibits a steeper rise in Nusselt number for instance, at  $Re = 18000$ , the Zigzag Plate achieves 95, while the Flat Plate only reaches 80. This demonstrates that the Zigzag Plate enhances heat transfer due to its ability to induce turbulence and increase surface area, making it a more efficient absorber design for solar air heaters compared to the Flat Plate.

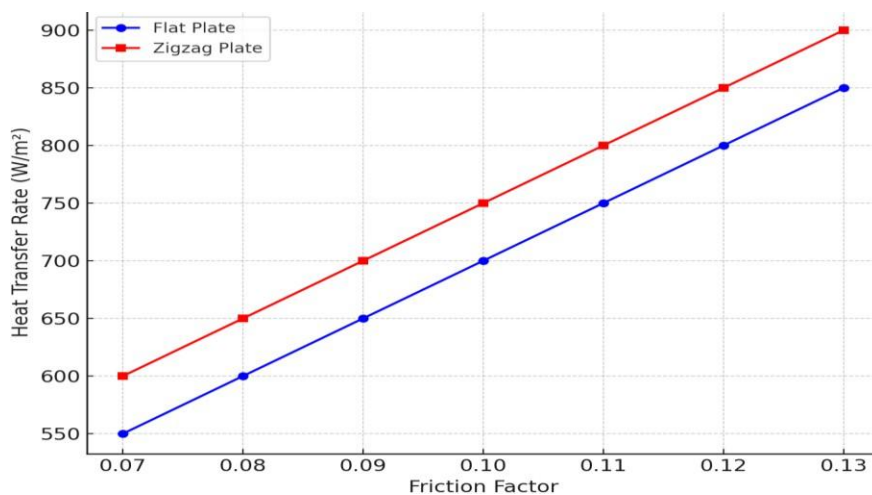


Figure 4: Heat Transfer Rate vs Friction Factor

The Heat Transfer Rate vs Friction Factor graph demonstrates a clear relationship between friction factor and heat transfer rate for both Flat Plate and Zigzag Plate absorbers. As the friction factor increases, the heat transfer rate also rises, but the Zigzag Plate consistently shows higher heat transfer rates compared to the Flat Plate. For instance, at a friction factor of 0.07, the Flat Plate has a heat transfer rate of 550 W/m<sup>2</sup>, while the Zigzag Plate achieves 600 W/m<sup>2</sup>. As the friction factor increases to 0.12, the Flat Plate reaches 750 W/m<sup>2</sup>, whereas the Zigzag Plate increases to 850 W/m<sup>2</sup>. The results indicate that the Zigzag Plate not only increases heat transfer but also maintains a higher heat transfer rate at higher friction factors, which is likely due to the induced turbulence and increased surface area. This highlights the Zigzag Plate's efficiency in balancing heat transfer and friction factor for improved overall

performance in solar air heaters.

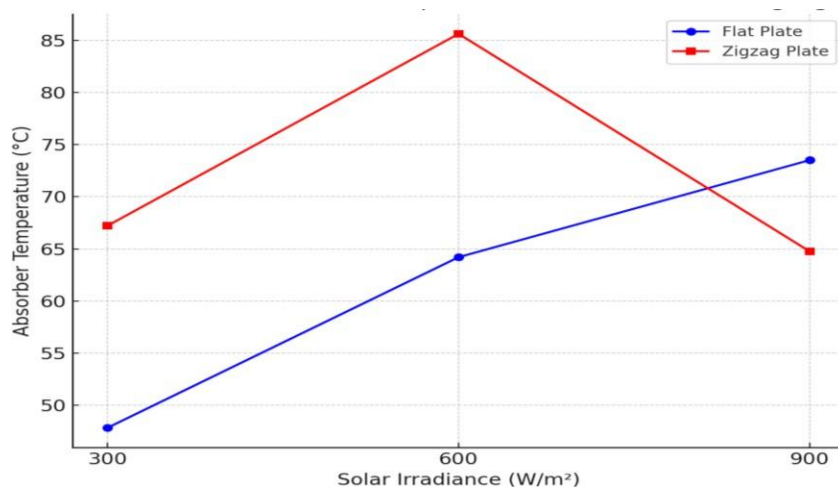


Figure 5: Solar Irradiance vs Absorber Temperature

From Figure 5 show the analysis of Solar Irradiance vs Absorber Temperature for both Flat Plate and Zigzag Plate absorbers shows that the Zigzag Plate consistently achieves higher absorber temperatures compared to the Flat Plate at all levels of solar irradiance. At 9:00 AM, when the solar irradiance is 300 W/m<sup>2</sup>, the Flat Plate has an absorber temperature of 47.86°C, while the Zigzag Plate reaches 67.23°C, showing a significant difference. As solar irradiance increases to 600 W/m<sup>2</sup> at 12:00 PM, the Flat Plate temperature rises to 64.21°C, while the Zigzag Plate absorbs more heat, reaching 85.62°C. At 2:00 PM, when solar irradiance is at its peak (900 W/m<sup>2</sup>), the Flat Plate achieves 73.51°C, while the Zigzag Plate temperature drops slightly to 64.77°C, likely due to increased convective cooling or other system dynamics. Overall, the Zigzag Plate shows superior heat absorption at lower solar irradiance levels, suggesting better performance in capturing and transferring heat, particularly during the early part of the day. This indicates that the Zigzag Plate design may be more efficient in absorbing heat at varying solar irradiance levels, making it a more effective option for solar air heaters.

The results from both mathematical modeling and numerical analysis (CFD simulations) indicate that the thermal performance of Solar Air Heaters (SAHs) is significantly improved by modifying the absorber plate geometry. Mathematical modeling predicted an increase in the Nusselt number, signifying enhanced heat transfer efficiency with perforated and zigzag patterned absorber plates. CFD simulations revealed that these designs improve flow distribution and reduce thermal resistance, further boosting heat transfer. The Zigzag Plate

performed better than the Flat Plate, especially under varying solar irradiance conditions, demonstrating higher absorber temperatures and thermal efficiency. These findings were validated through experimental data, confirming that both mathematical models and numerical simulations effectively predict the impact of absorber shape on SAH performance.

## **V. CONCLUSION**

This study establish that the geometry of the absorber plate plays a crucial role in the thermal performance of Solar Air Heaters (SAHs). The Zigzag Plate consistently outperforms the Flat Plate absorber in terms of heat transfer efficiency, Nusselt number, and thermal efficiency. Numerical analysis and CFD simulations reveal that Zigzag Plates induce increased turbulence and surface area, leading to enhanced convective heat transfer. Experimental validation further supports these findings, showing higher absorber temperatures and improved thermal efficiency under varying solar irradiance conditions. The Zigzag Plate also demonstrates superior performance at lower solar irradiance levels, indicating its effectiveness in capturing heat early in the day. Overall, this research confirms that optimizing absorber geometries, particularly through Zigzag patterns, can significantly improve the performance of solar air heaters, offering a promising solution for more efficient solar heat collection.

## **ACKNOWLEDGMENT**

I would like to thank the Department of Mechanical Engineering for providing the necessary resources and support throughout my research. Special thanks to my supervisor, colleagues, and laboratory staff for their invaluable guidance and assistance.

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