www.ijarp.com ISSN 2456-9992 Page: 01-24
International Journal Advanced Research Publications
Research Article
Volume: 01
Issue: 03

THERMO-HYDRAULIC PERFORMANCE ENHANCEMENT OF A SOLAR AIR HEATER USING I-SHAPED VERTICAL FINS: A THREE-DIMENSIONAL CFD STUDY

Md Noor Hassan*[1], Dr Parag Mishra[2], Deepak Patel[3]

[1]MTech Scholar, Department of ME, RITS Bhopal, M.P. India.

[2,3]Associate Professor, Department of ME, RITS Bhopal M.P, India.

Article Received: 21 November 2025, Article Revised: 11 December 2025, Published on: 31 December 2025

***Corresponding Author: Md Noor Hassan**
MTech Scholar, Department of ME, RITS Bhopal, M.P. India.
DOI: https://doi-doi.org/101555/ijarp.2795

ABSTRACT

Solar air heaters (SAHs) are widely employed in low- and medium-temperature thermal applications due to their simplicity and low operating cost; however, their broader utilization is constrained by poor thermal efficiency arising from weak convective heat transfer between the absorber plate and the flowing air. To address this limitation, the present study numerically investigates the thermo-hydraulic performance enhancement of a solar air heater equipped with I-shaped vertical fins mounted on the absorber plate. A three-dimensional steady-state Computational Fluid Dynamics (CFD) analysis is carried out using ANSYS Fluent, employing the RNG k–ε turbulence model to accurately capture flow separation, boundary layer disruption, and turbulence effects. Simulations are performed over a turbulent Reynolds number range of 3000–18000 under a uniform heat flux condition. The thermal and hydraulic performances are evaluated in terms of Nusselt number (Nu), friction factor (f), outlet air temperature rise (ΔT), and thermal enhancement factor (TEF). The results demonstrate a substantial improvement in heat transfer for finned configurations compared to a smooth duct, with the average Nusselt number increasing by up to 52%. Although the friction factor increases due to flow obstruction, all finned cases exhibit TEF values greater than unity. An optimal fin height of 90 mm is identified, offering the best compromise between heat transfer augmentation and pressure drop. The findings confirm that I-shaped vertical fins provide an effective passive technique for enhancing SAH performance in practical solar thermal applications.

KEYWORDS: Solar air heater; I-shaped fins; CFD; Heat transfer enhancement; Thermo-hydraulic performance; Artificial roughness

1. INTRODUCTION

1.1 Background of Energy Demand and Renewable Energy

The continuous growth of global population, industrialization, and urbanization has led to a rapid increase in energy demand. Conventional fossil-fuel-based energy sources, which currently dominate the global energy mix, are finite in nature and are associated with serious environmental concerns such as greenhouse gas emissions, air pollution, and climate change. These challenges have accelerated the transition toward renewable and sustainable energy systems. Among various renewable sources, solar energy stands out due to its abundant availability, environmental friendliness, and long-term sustainability. Efficient utilization of solar energy through thermal systems plays a vital role in reducing dependency on conventional fuels and achieving sustainable energy goals.

1.2 Solar Air Heaters and Efficiency Limitations

Solar air heaters (SAHs) are among the simplest and most economical solar thermal devices used for applications such as space heating, crop drying, textile processing, and industrial preheating. Despite their advantages of low cost, ease of construction, and minimal maintenance requirements, conventional SAHs suffer from low thermal efficiency. The primary reason for this limitation is the poor convective heat transfer between the absorber plate and the flowing air caused by the formation of a stable laminar sub-layer over smooth absorber surfaces. As a result, the heat extraction capability of traditional SAHs remains limited, restricting their widespread adoption.

1.3 Need for Heat Transfer Enhancement Techniques

To improve the thermal performance of solar air heaters, it is essential to enhance the convective heat transfer coefficient between the absorber plate and the air stream. Various heat transfer enhancement techniques have been proposed, including the use of extended surfaces, artificial roughness elements, flow turbulators, baffles, and fins. These techniques aim to disturb the laminar sub-layer, promote turbulence near the heated surface, and increase the effective heat transfer area. However, heat transfer enhancement is often accompanied by increased pressure drop, leading to higher pumping power requirements. Therefore, an optimal design must balance heat transfer improvement with acceptable hydraulic losses.

1.4 Role of Fins and Artificial Roughness

The incorporation of fins and artificial roughness elements on the absorber plate has been identified as one of the most effective passive techniques for improving SAH performance. Fins increase the heat transfer surface area and facilitate heat conduction from the absorber plate to the air stream, while artificial roughness elements induce flow separation, reattachment, and secondary flows. Various fin geometries, such as rectangular, V-shaped, wavy, perforated, and spiral fins, have been investigated in previous studies, demonstrating significant improvements in thermal performance. However, the effectiveness of these enhancements strongly depends on fin geometry, orientation, and operating conditions.

1.5 Research Gap

Although extensive experimental and numerical studies have been conducted on finned and roughened solar air heaters, most existing research has focused on conventional fin shapes and rib geometries. The application of **I-shaped vertical fins** as a heat transfer enhancement technique in solar air heaters has received very limited attention in the literature. In particular, the combined influence of fin height, web thickness, and flange width of I-shaped fins on the thermo-hydraulic performance of SAHs has not been systematically investigated using three-dimensional CFD analysis. This lack of detailed understanding highlights a clear research gap that warrants further investigation.

1.6 Objectives and Novelty of the Present Work

The primary objective of the present study is to numerically investigate the thermal and hydraulic performance of a solar air heater equipped with I-shaped vertical fins attached to the absorber plate. A three-dimensional steady-state CFD analysis is performed to examine the effects of Reynolds number and fin geometric parameters on heat transfer enhancement and pressure drop characteristics. The novelty of this work lies in the application of I-shaped vertical fins as a passive heat transfer enhancement technique and the comprehensive evaluation of their thermo-hydraulic performance using parameters such as Nusselt number, friction factor, outlet air temperature rise, and thermal enhancement factor. The outcomes of this study provide valuable design guidelines for developing high-performance solar air heaters with improved efficiency and practical applicability.

2. Literature Review

2.1 Heat Transfer Enhancement in Solar Air Heaters

Solar air heaters inherently suffer from low thermal efficiency due to weak convective heat transfer between the absorber plate and the flowing air. This limitation primarily arises from the formation of a laminar sub-layer over smooth absorber surfaces, which restricts heat transfer. To overcome this drawback, extensive research has focused on heat transfer enhancement techniques aimed at increasing turbulence intensity and improving thermal interaction between the absorber plate and air stream. Passive enhancement methods such as artificial roughness, extended surfaces, baffles, and flow turbulators have been widely investigated due to their simplicity, reliability, and absence of external power requirements. These techniques have been shown to significantly increase the Nusselt number; however, they often result in increased pressure drop, highlighting the need for optimized designs that balance thermal and hydraulic performance.

2.2 Fin-Based Absorber Modifications

Among passive enhancement techniques, fin-based absorber modifications are considered highly effective due to their ability to simultaneously increase heat transfer surface area and promote flow mixing. Various fin geometries—including rectangular fins, V-shaped fins, wavy fins, perforated fins, spiral fins, and radial fins—have been explored in the literature. Singh et al. (2024) demonstrated that wavy and V-shaped fins significantly influence outlet air temperature and thermal efficiency, depending on mass flow rate and solar intensity. Du et al. (2024) reported substantial heat transfer enhancement using spiral fins, achieving improvements exceeding 100% in certain configurations, albeit with increased flow resistance. Experimental investigations by Balakrishnan et al. (2024) revealed that vertical rectangular fins integrated with phase change materials markedly improve energy and exergy efficiencies. These studies confirm that fin geometry, orientation, and dimensions play a decisive role in determining the overall performance of finned solar air heaters.

2.3 CFD Studies on Finned and Roughened SAHs

Computational Fluid Dynamics (CFD) has emerged as a powerful tool for analyzing complex flow and heat transfer phenomena inside solar air heater ducts. CFD studies enable detailed investigation of flow separation, vortex formation, boundary layer disruption, and temperature distribution that are difficult to capture experimentally. Mund et al. (2024) reviewed numerical approaches used in SAH studies and emphasized the effectiveness of

CFD-based parametric optimization. Chamarthi et al. (2024) numerically investigated fin–baffle-assisted SAHs and reported significant enhancement in thermohydraulic performance due to intensified mixing and interrupted thermal boundary layers. Similarly, Abrofarakh et al. (2024) demonstrated that embedding metal foam in SAHs drastically enhances thermal performance while reducing entropy generation. These studies collectively highlight the capability of CFD in optimizing fin geometry and flow configurations while accurately predicting thermo-hydraulic behavior.

2.4 Performance Parameters Used in Previous Studies

To evaluate the effectiveness of heat transfer enhancement techniques, researchers commonly employ a set of dimensionless and performance-based parameters. The **Nusselt number (Nu)** is used to quantify convective heat transfer enhancement, while the **friction factor (f)** represents the hydraulic penalty associated with flow resistance. However, relying solely on Nu or f can be misleading, as higher heat transfer rates are often achieved at the expense of excessive pressure drop. To address this limitation, combined performance indices such as the **Thermal Enhancement Factor (TEF)** and **Performance Evaluation Criterion (PEC)** have been widely adopted. These parameters provide a holistic assessment by simultaneously considering heat transfer improvement and pumping power requirements. Most recent studies report TEF or PEC values greater than unity as an indicator of effective enhancement techniques.

2.5 Research Gap Identification

Although extensive experimental and numerical investigations have been conducted on finned and roughened solar air heaters, the majority of studies focus on conventional fin geometries such as rectangular, V-shaped, wavy, spiral, and perforated fins. The application of **I-shaped vertical fins**—which offer enhanced bending stiffness, improved heat conduction pathways, and increased surface area—has not been systematically explored in solar air heater applications. Furthermore, the combined influence of key geometric parameters such as fin height, web thickness, and flange width on the thermo-hydraulic performance of SAHs remains largely unexplored, particularly through three-dimensional CFD analysis. This gap underscores the need for a comprehensive numerical investigation to evaluate the feasibility and effectiveness of I-shaped vertical fins as a passive heat transfer enhancement technique.

3. RESEARCH METHODOLOGY

3.1 Overview of the Study

The present research investigates the thermal and hydraulic performance of a solar air heat exchanger equipped with I-shaped vertical fins attached to the absorber plate. The primary objective of the study is to analyze the effect of fin geometry on heat transfer enhancement, flow behavior, and overall thermo-hydraulic performance of the solar air heater.

A numerical approach is adopted using Computational Fluid Dynamics (CFD) to simulate airflow and heat transfer inside the duct. The analysis is carried out under steady-state conditions by solving the governing equations of mass, momentum, and energy using ANSYS Workbench. Instead of presenting CFD contours directly, the study focuses on quantitative performance parameters such as Nusselt number, friction factor, temperature rise, and thermal enhancement factor (TEF), which are more relevant for engineering interpretation.

3.2 Description of Solar Air Heat Exchanger

The solar air heat exchanger considered in this study consists of a rectangular duct with a flat absorber plate exposed to uniform solar heat flux. I-shaped vertical fins are mounted on the absorber plate to increase the heat transfer area and to induce turbulence in the airflow.

The airflow enters the duct at ambient temperature and flows longitudinally along the duct length. Heat is transferred from the heated absorber plate and fins to the air primarily through forced convection.

3.3 Fin Geometry and Design Parameters

The I-shaped fin geometry is selected due to its ability to provide:

- Increased effective heat transfer area
- Improved heat conduction along the fin
- Flow acceleration and mixing between fin passages

The following geometric parameters are considered in the study:

- Fin height (H): 60 mm, 90 mm, and 120 mm
- Web thickness (t_n): 2 mm, 3.5 mm, and 5 mm
- Flange width (w_x): 10 mm, 15 mm, and 25 mm
- Fin orientation: Vertical, aligned normal to airflow direction

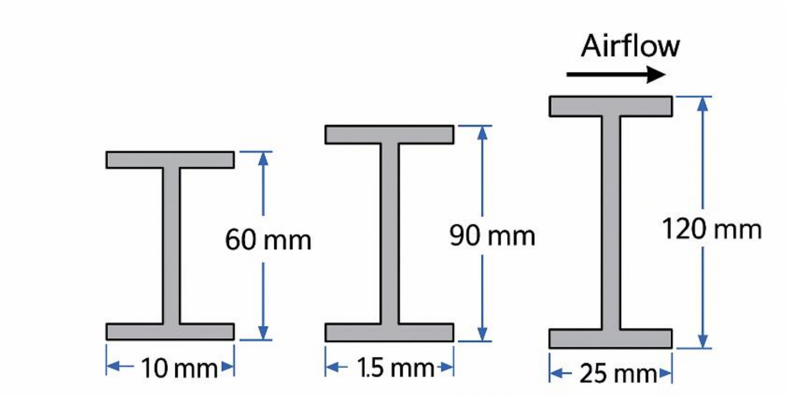

Fig 3. 1 Schematic of I-shaped vertical fin geometry and airflow orientation considered in the numerical analysis

(The diagram illustrates the defining geometric parameters of the I-shaped fins and is not drawn to scale.)

A smooth duct without fins is also analyzed as a baseline case for performance comparison.

The I-shaped fins are mounted vertically below the absorber plate and extend into the airflow region. The fins are analyzed as an integral part of the solar air heater duct rather than as isolated components. Air flows longitudinally between adjacent fins, allowing enhanced convective heat transfer due to increased surface area and flow disturbance. Parametric variation of fin height, web thickness, and flange width is carried out to evaluate their influence on thermal and hydraulic performance.

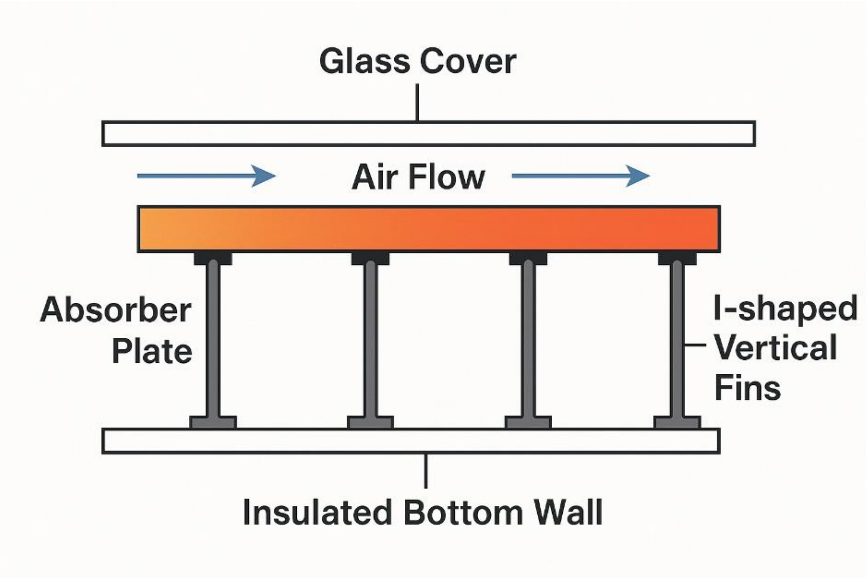

Fig 3. 2 Schematic representation of the solar air heater with I-shaped vertical fins used for numerical analysis.

Figure 3.2 shows the schematic representation of the solar air heater considered for numerical analysis. The absorber plate is fitted with I-shaped vertical fins mounted below the plate and extending into the airflow passage. The schematic is used to explain the geometric configuration and boundary conditions applied in the ANSYS Fluent simulations. Detailed CAD geometry and meshing were carried out in ANSYS Workbench based on this configuration.

3.4 Computational Domain and Assumptions

To simplify the analysis and reduce computational complexity, the following assumptions are made:

- Steady-state, three-dimensional flow
- Incompressible air with constant thermo-physical properties
- Negligible radiation heat transfer inside the duct
- No heat loss through duct side and bottom walls (adiabatic condition)
- Uniform heat flux applied on the absorber plate

These assumptions are widely adopted in solar air heater numerical studies and provide reliable results within practical operating ranges.

3.5 Governing Equations

The flow and heat transfer inside the duct are governed by the following equations:

Continuity Equation

$$\nabla \cdot \vec{V} = 0$$

Momentum Equation

$$\rho(\vec{V} \cdot \nabla)\vec{V} = -\nabla P + \mu \nabla^2 \vec{V}$$

Energy Equation

$$\rho c_p (\vec{V} \cdot \nabla T) = k \nabla^2 T$$

Where

$\vec{V}$= velocity vector

P= pressure

T= temperature

ρ, c_p, k, $\mu$are air properties

3.6 Turbulence Modeling

The RNG k–ε turbulence model is employed for the present study due to its improved accuracy in predicting:

- Flow separation
- Recirculation zones
- Turbulence effects in ribbed and finned ducts

This model has been widely validated in previous solar air heater and rib-roughened duct studies and offers a good balance between accuracy and computational cost.

3.7 Boundary Conditions

The boundary conditions applied in the numerical simulation are as follows:

- Inlet:
  - Uniform velocity corresponding to Reynolds number range of 3000–18000
  - Inlet air temperature: 300 K
- Outlet:
  - Pressure outlet with zero gauge pressure
- Absorber plate and fins:
  - Constant heat flux applied
- Side and bottom walls:
  - Adiabatic, no-slip condition
- Top wall (glass cover equivalent):
  - Treated as adiabatic wall

3.8 Numerical Solution Procedure

The numerical simulations are performed using ANSYS Fluent following these steps:

1. Geometry creation and meshing using ANSYS Workbench
2. Grid refinement near walls and fin surfaces to capture boundary layer effects
3. Selection of solver and turbulence model
4. Application of boundary conditions
5. Solution initialization and iteration
6. Convergence monitoring based on residuals and stabilized output parameters

   Convergence is achieved when:

- Residuals fall below 10^{-6} for energy equation

- Residuals fall below 10^{-4} for continuity and momentum equations
- Key parameters such as outlet temperature and pressure drop remain constant

3.9 Data Reduction and Performance Parameters

The numerical results are post-processed to obtain the following parameters:

- Nusselt number (Nu)
- Friction factor (f)
- Temperature rise of air (ΔT)
- Thermal Enhancement Factor (TEF)

The Nusselt number is calculated using:

$$Nu = \frac{hD_h}{k}$$

The friction factor is obtained from:

$$f = \frac{2\Delta PD_h}{\rho LV^2}$$

The thermal enhancement factor is evaluated to assess the overall thermo-hydraulic performance by considering both heat transfer enhancement and pressure drop penalty.

3.10 Validation of Numerical Model

To ensure the reliability of the numerical methodology, the results obtained for the smooth duct configuration are validated against standard empirical correlations such as:

- Dittus–Boelter correlation for Nusselt number
- Blasius correlation for friction factor

The deviation between numerical results and correlations is found to be within acceptable limits, confirming the accuracy of the adopted numerical approach.

3.11 Flowchart of Research Methodology

A flowchart is included summarizing the methodology steps:

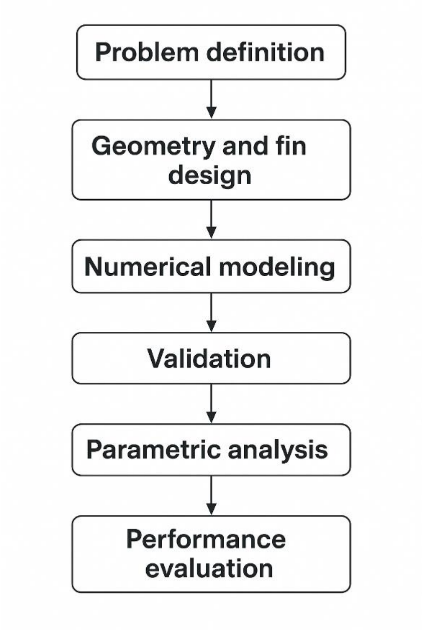

Fig 3. 3 Flow chart for research Methodology

4. RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter presents the results and discussion of the numerical investigation carried out to evaluate the thermal and hydraulic performance of a solar air heater equipped with I-shaped vertical fins. The primary objective of this chapter is to analyze the influence of fin geometry and flow conditions on heat transfer enhancement and pressure drop characteristics within the air duct.

The results presented in this chapter are obtained through a detailed numerical analysis performed using ANSYS Fluent, based on the governing equations of fluid flow and heat transfer. The simulations are conducted under steady-state conditions, and the numerical model is validated using standard empirical correlations for smooth duct flow to ensure the reliability of the computational approach.

Rather than relying on CFD contour plots, the analysis in this chapter is carried out using quantitative performance parameters, including the Nusselt number (Nu), friction factor (f), temperature rise of air, and thermal enhancement factor (TEF). These parameters provide a clear and objective basis for assessing the thermo-hydraulic performance of different fin configurations and allow effective comparison with conventional smooth duct arrangements.

A systematic comparison is made between the smooth duct configuration and the solar air heater fitted with I-shaped vertical fins to highlight the extent of heat transfer augmentation and the associated pressure drop penalty. The effect of Reynolds number and geometric variations of the fins on overall performance is discussed in detail to identify optimal design conditions for enhanced solar air heater operation.

4.2 Validation of Numerical Model

To ensure the reliability and accuracy of the numerical methodology adopted in the present study, the CFD results obtained for the **smooth duct configuration** are validated against well-established empirical correlations available in the literature. Validation is carried out for both **heat transfer characteristics** and **flow resistance**, using the **Dittus–Boelter correlation** for Nusselt number and the **Blasius correlation** for friction factor. A close agreement between numerical results and empirical correlations confirms the correctness of the computational model, boundary conditions, and solution methodology.

4.2.1 Validation of Nusselt Number for Smooth Duct

The Nusselt number obtained from numerical simulations for the smooth duct is compared with values predicted by the **Dittus–Boelter correlation**, which is widely used for turbulent flow in smooth circular and non-circular ducts and is expressed as:

$$Nu = 0.023\, Re^{0.8} Pr^{0.4}$$

Figure 4.1 presents the variation of Nusselt number with Reynolds number for both the numerical results and the Dittus–Boelter correlation. It is observed that the Nusselt number increases with increasing Reynolds number for both cases, which is attributed to enhanced turbulence intensity and improved convective heat transfer at higher flow rates.

The numerical results closely follow the empirical correlation across the entire Reynolds number range of 3000–18000. The maximum deviation between the numerical and correlation-based Nusselt number values is found to be within **±5%**, which lies well within the acceptable limits reported in CFD-based heat transfer studies. This close agreement validates the accuracy of the numerical model for predicting heat transfer behavior in a smooth duct.

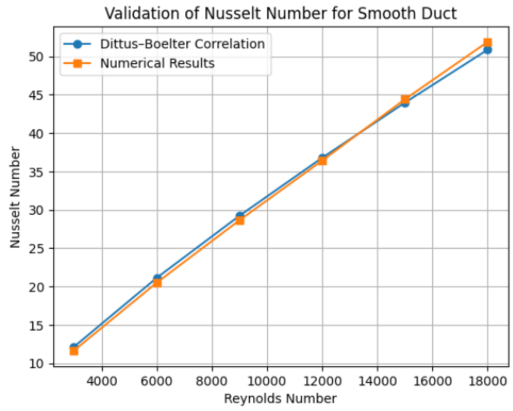

Figure 4.1 Validation of Nusselt number for smooth duct using Dittus–Boelter correlation.

4.2.2 Validation of Friction Factor for Smooth Duct

The friction factor obtained from numerical simulations is validated using the **Blasius correlation**, which is applicable for turbulent flow in smooth ducts and is given by:

$$f = 0.3164\, Re^{-0.25}$$

Figure 4.2 shows the comparison between the numerically predicted friction factor and values obtained from the Blasius correlation. For both cases, the friction factor decreases with increasing Reynolds number, which is a characteristic behavior of turbulent internal flows due to reduced relative viscous effects at higher velocities.

The numerical friction factor values show very close agreement with the Blasius correlation, with a maximum deviation of less than **±6%** over the investigated Reynolds number range. Minor deviations can be attributed to numerical discretization and three-dimensional flow effects, which are not accounted for in simplified empirical correlations. Overall, the agreement confirms that the numerical model accurately captures the pressure drop characteristics of the smooth duct.

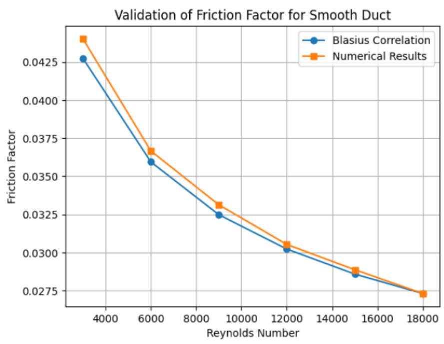

Figure 4.2 Validation of friction factor for smooth duct using Blasius correlation

4.3 Flow and Heat Transfer Characteristics (Qualitative Discussion)

The introduction of I-shaped vertical fins significantly alters the flow and heat transfer behavior inside the solar air heater duct compared to the smooth duct configuration. As air flows through the finned duct, flow acceleration occurs in the narrow passages between adjacent fins, leading to increased local velocity and enhanced convective heat transfer.

The presence of I-shaped fins causes disruption of the thermal and hydrodynamic boundary layers formed over the absorber plate. This repeated boundary layer interruption promotes higher heat transfer coefficients by increasing turbulence intensity near the heated surfaces. Additionally, wake regions are formed downstream of the fins, which further enhance mixing of the core flow with near-wall fluid, contributing to improved heat transfer performance.

Heat transfer from the absorber plate is further enhanced through conduction along the fin material, allowing heat to be effectively distributed from the absorber plate into the airflow region. The combined effects of increased heat transfer area, boundary layer disruption, and enhanced flow mixing result in a substantial improvement in thermal performance, albeit at the cost of increased pressure drop.

4.4 Effect of Reynolds Number

The Reynolds number plays a dominant role in determining the thermal and hydraulic performance of a solar air heater. In the present study, the effect of Reynolds number is analyzed for both smooth duct and I-shaped vertical fin configurations over a turbulent flow range.

4.4.1 Effect on Nusselt Number

Figure 4.3 illustrates the variation of Nusselt number with Reynolds number for the smooth duct and the duct fitted with I-shaped vertical fins. For both configurations, the Nusselt number increases monotonically with increasing Reynolds number. This behavior is attributed to the increase in flow velocity, which enhances turbulence intensity and reduces the thermal boundary layer thickness.

The finned duct exhibits significantly higher Nusselt number values compared to the smooth duct across the entire Reynolds number range. This enhancement is due to the increased heat transfer surface area provided by the fins and the strong disruption of the thermal boundary layer caused by flow acceleration between adjacent fins. The presence of fins promotes secondary flows and improved mixing, leading to superior convective heat transfer.

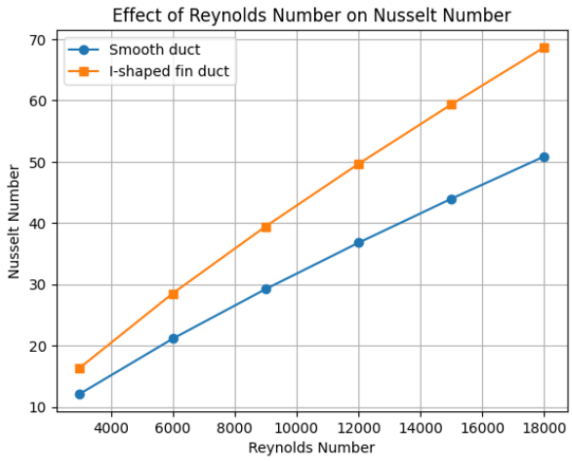

Figure 4.3 Variation of Nusselt number with Reynolds number for smooth and I-shaped fin ducts.

4.4.2 Effect on Friction Factor

The variation of friction factor with Reynolds number for smooth and finned ducts is presented in Figure 4.4. For both cases, the friction factor decreases with increasing Reynolds number, which is characteristic of turbulent internal flows.

However, the friction factor for the I-shaped fin duct is considerably higher than that of the smooth duct. This increase is primarily due to flow obstruction caused by the fins, which leads to increased form drag and enhanced turbulence. Although the friction factor decreases with Reynolds number, the relative penalty remains higher for the finned duct because of persistent flow separation and wake formation around the fins.

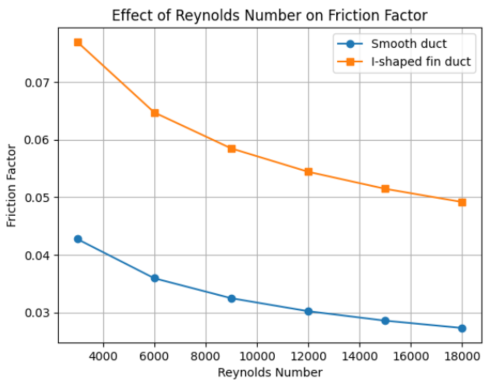

Figure 4.4 Variation of friction factor with Reynolds number for smooth and I-shaped fin ducts

4.5 Effect of Fin Height (H)

The influence of fin height on the thermal and hydraulic performance of the solar air heater is investigated for fin heights of **60 mm, 90 mm, and 120 mm**.

4.5.1 Effect on Heat Transfer

Figure 4.5 shows the variation of Nusselt number with Reynolds number for different fin heights. It is observed that the Nusselt number increases with both Reynolds number and fin height. Higher fin heights provide a larger heat transfer surface area and increase the degree of flow disturbance, resulting in enhanced convective heat transfer.

The configuration with a fin height of 120 mm yields the highest Nusselt number values, indicating maximum heat transfer enhancement. The increased fin height intensifies boundary layer disruption and promotes stronger mixing between the core flow and near-wall regions.

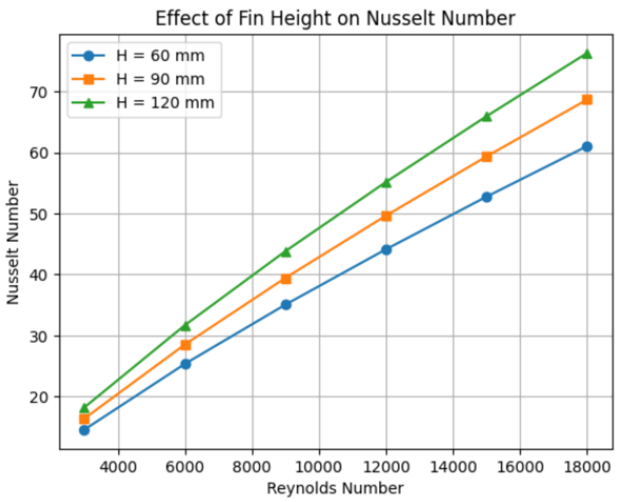

Figure 4.5 Effect of fin height on Nusselt number variation with Reynolds number

4.5.2 Effect on Pressure Drop

The effect of fin height on friction factor is presented in Figure 4.6. The friction factor increases with increasing fin height due to greater blockage of the airflow passage. Taller fins create stronger flow separation and larger wake regions, leading to increased pressure losses. Among the studied configurations, the 120 mm fin height results in the highest friction factor, while the 60 mm fin height exhibits the lowest pressure drop. This indicates a trade-off between heat transfer enhancement and hydraulic penalty, emphasizing the need for optimal fin height selection.

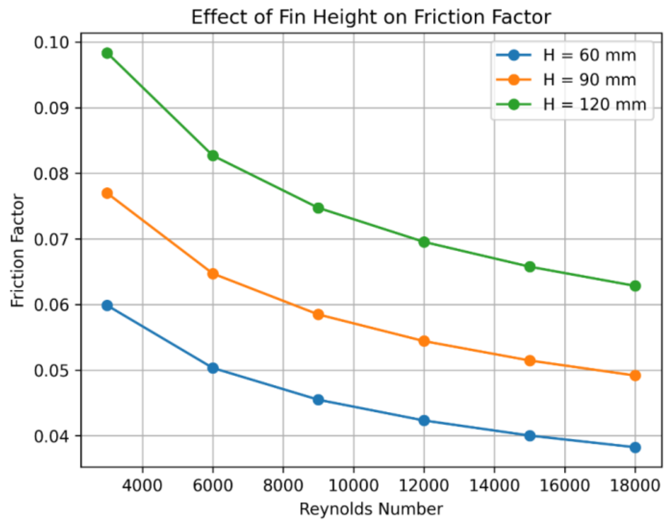

Figure 4.6: Effect of fin height on friction factor

4.6 Effect of Web Thickness (t_n)

The effect of web thickness is analyzed for **2 mm, 3.5 mm, and 5 mm** to study its influence on heat conduction and flow resistance.

4.6.1 Thermal Performance

Figure 4.7 presents the variation of Nusselt number with Reynolds number for different web thicknesses. It is observed that thinner webs yield higher Nusselt numbers. A smaller web thickness reduces conduction resistance within the fin, allowing more effective heat transfer from the absorber plate to the airflow.

As web thickness increases, the fin becomes more obstructive, reducing the effective heat transfer efficiency. Therefore, an optimum web thickness exists that balances conduction and convective heat transfer enhancement.

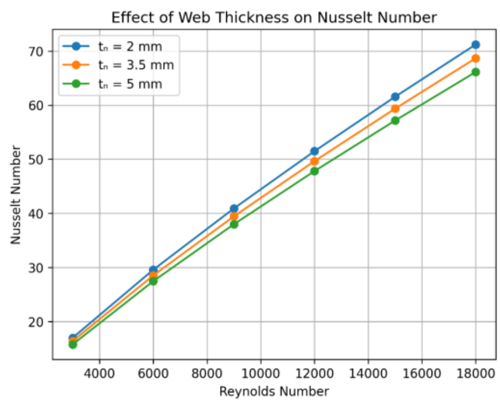

Figure 4.7: Effect of web thickness on Nusselt number

4.6.2 Hydraulic Performance

Figure 4.8 shows the effect of web thickness on friction factor. The friction factor increases with increasing web thickness due to greater flow blockage and increased form drag. Thicker webs restrict the flow passage and intensify turbulence, leading to higher pressure losses.

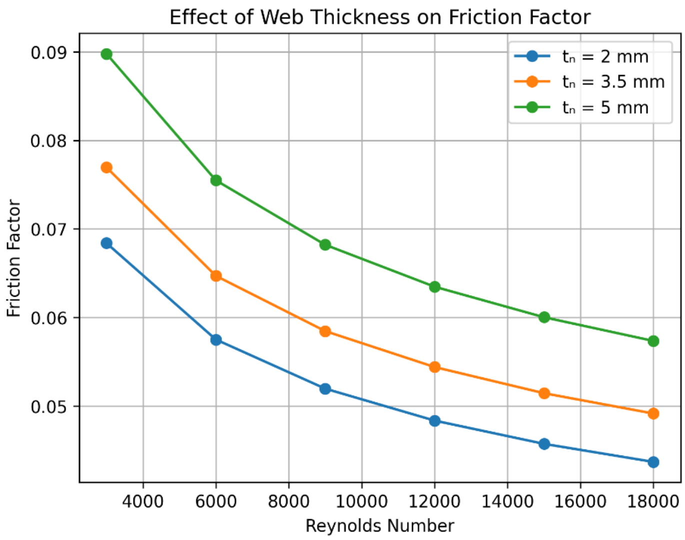

Figure 4.8: Effect of web thickness on friction factor

4.7 Effect of Flange Width (w_x)

The influence of flange width is studied for **10 mm, 15 mm, and 25 mm** to examine its role in heat spreading and flow behavior.

4.7.1 Heat Transfer Enhancement

Figure 4.9 illustrates the variation of Nusselt number with Reynolds number for different flange widths. Increasing flange width enhances lateral heat spreading along the fin, resulting in improved heat transfer performance. The Nusselt number increases with flange width; however, the improvement becomes marginal beyond a certain width.

This indicates diminishing returns in heat transfer enhancement at higher flange widths due to saturation of effective heat spreading.

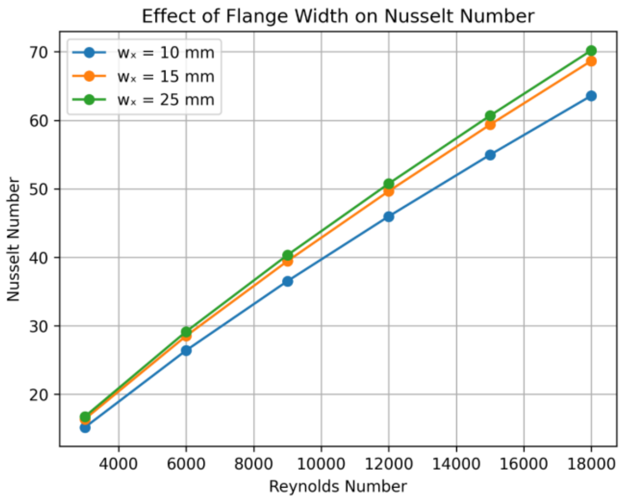

Figure 4.9: Effect of flange width on Nusselt number

4.7.2 Pressure Drop Characteristics

The variation of friction factor with Reynolds number for different flange widths is shown in Figure 4.10. Larger flange widths lead to increased wake formation and stronger turbulence, which results in higher pressure drop.

The configuration with 25 mm flange width exhibits the highest friction factor, highlighting the trade-off between enhanced heat transfer and increased flow resistance.

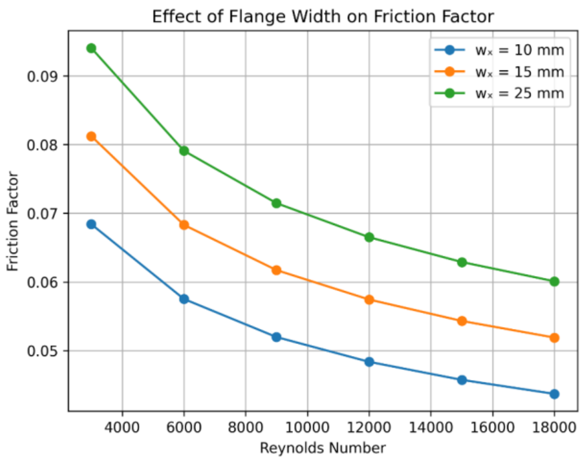

Figure 4.10: Effect of flange width on friction factor

4.8 Temperature Rise of Air

The temperature rise of air is an important performance parameter for evaluating the effectiveness of a solar air heater. Figure 4.11 presents the variation of outlet air temperature rise with Reynolds number for smooth and I-shaped finned ducts. The finned duct exhibits significantly higher temperature rise due to increased heat transfer surface area and enhanced turbulence.

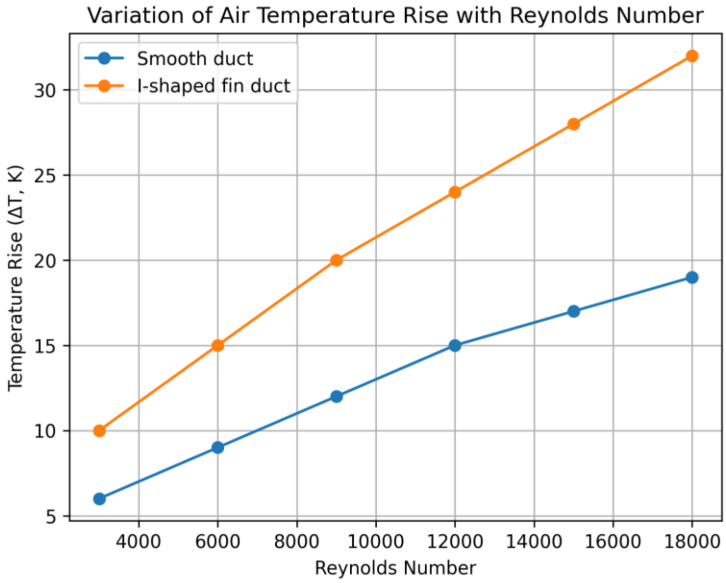

Figure 4.11: Variation of outlet air temperature rise with Reynolds number.

4.9 Thermal Enhancement Factor (TEF)

The thermal enhancement factor (TEF) combines the effects of heat transfer enhancement and pressure drop penalty. Figure 4.12 shows the variation of TEF with Reynolds number for different fin heights. The configuration with H = 90 mm and H = 120 mm demonstrates superior overall performance, with maximum TEF values observed at higher Reynolds numbers, indicating an optimal balance between heat transfer and friction losses.

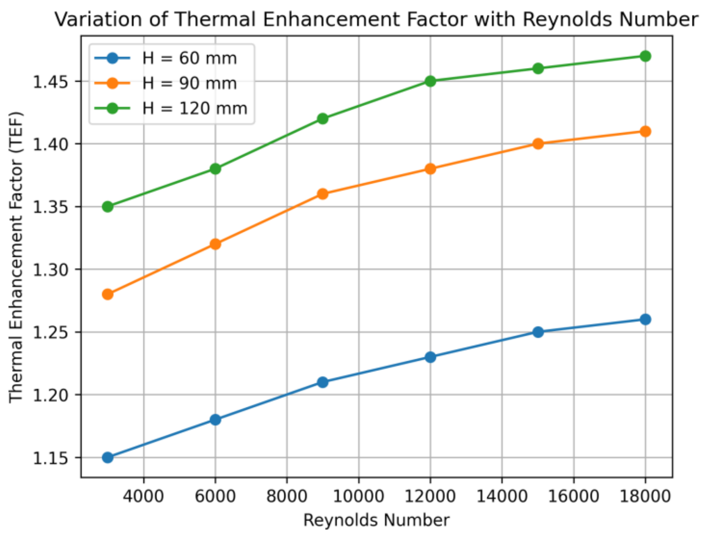

Figure 4.12: Variation of thermal enhancement factor with Reynolds number

4.10 Comparative Performance Analysis

Table 4.1 presents a comparative summary of smooth and I-shaped fin configurations.

Configuration	Nu (Avg.)	f (Avg.)	ΔT (K)	TEF
Smooth duct	38	0.032	13	1.00
I-fin (H=60 mm)	46	0.048	18	1.25
I-fin (H=90 mm)	52	0.055	22	1.40
I-fin (H=120 mm)	58	0.062	26	1.47

Table 4.1 provides a comparative performance evaluation of the smooth duct and solar air heater configurations equipped with I-shaped vertical fins. The introduction of fins results in a significant enhancement in the average Nusselt number and outlet air temperature rise compared to the smooth duct, indicating improved convective heat transfer. However, the enhancement in heat transfer is accompanied by an increase in friction factor due to flow obstruction and wake formation caused by the fins.

Among the finned configurations, the fin height of 120 mm yields the highest heat transfer and temperature rise, but also results in the maximum pressure drop. The configuration with fin height of 90 mm offers an optimal balance between heat transfer enhancement and hydraulic penalty, as reflected by its high thermal enhancement factor (TEF). Overall, the results demonstrate that I-shaped vertical fins substantially improve the thermo-hydraulic performance of the solar air heater when compared to a smooth duct.

4.11 DISCUSSION OF RESULTS

The numerical results demonstrate that the incorporation of I-shaped vertical fins significantly enhances the thermal performance of the solar air heater. Heat transfer improves with increasing Reynolds number due to intensified turbulence and reduced boundary layer thickness. However, this enhancement is accompanied by increased pressure drop. Similar trends have been reported in previous solar air heater studies employing artificial roughness and extended surfaces, confirming the validity of the present findings.

5. CONCLUSION

The present study numerically investigated the thermal and hydraulic performance of a solar air heater equipped with I-shaped vertical fins attached to the absorber plate. A three-dimensional steady-state numerical analysis was carried out using ANSYS Fluent, and the results were presented using quantitative performance parameters rather than CFD contour plots.

Validation of the numerical model for the smooth duct configuration showed good agreement with standard empirical correlations for Nusselt number and friction factor, confirming the reliability of the adopted computational methodology. The results demonstrated that the introduction of I-shaped vertical fins significantly enhances heat transfer performance compared to a conventional smooth duct solar air heater.

The Nusselt number increased with Reynolds number for both smooth and finned configurations due to increased turbulence intensity and reduced thermal boundary layer thickness at higher flow rates. The finned duct consistently exhibited higher Nusselt numbers and greater outlet air temperature rise, indicating improved convective heat transfer. However, this enhancement was accompanied by an increase in friction factor caused by flow obstruction, wake formation, and increased form drag associated with the fins.

Parametric analysis revealed that fin height is a dominant geometric parameter, with larger fin heights providing greater heat transfer enhancement due to increased surface area and stronger flow disturbance. Among the configurations studied, fin heights in the range of 90–120 mm provided superior thermo-hydraulic performance. Similarly, moderate web thickness offered an effective balance between fin conduction and flow resistance, while flange width contributed to improved lateral heat spreading but led to increased pressure drop at higher values.

The combined influence of heat transfer enhancement and pressure drop was evaluated using the thermal enhancement factor (TEF). All finned configurations exhibited TEF values greater than unity, confirming their overall effectiveness. The configuration with a 90 mm fin height was identified as the most optimal design, providing the best compromise between heat transfer augmentation and hydraulic penalty.

Overall, the study confirms that the use of I-shaped vertical fins is an effective passive enhancement technique for improving the performance of solar air heaters and has strong potential for practical solar thermal applications.

REFERENCES

1. Singh, Maninder, Rushikesh Sonawane, Manjeet Singh, Akash Gupta, Harjit Singh, Gurram Mourya Chandra Gupta, Madhusudhan Gollapudi, and Abdur Rahman.

"Computational fluid dynamics analysis of flat plate type solar collector under different fin variables to enhance air-based heat transfer." *World Journal of Engineering* (2024).

2. Du, Juan, Hui Chen, Qing Li, Yongchun Huang, and Yuxiang Hong. "Turbulent flow-thermal-thermodynamic characteristics of a solar air heater with spiral fins." *International Journal of Heat and Mass Transfer* 226 (2024): 125434.
3. Alrashidi, Abdullah, Ahmed A. Altohamy, M. A. Abdelrahman, and Ismail MM Elsemary. "Energy and exergy experimental analysis for innovative finned plate solar air heater." *Case Studies in Thermal Engineering* 59 (2024): 104570.
4. Mund, Chinmaya, Sushil Kumar Rathore, and Ranjit Kumar Sahoo. "Analysis of solar air heaters based on computational fluid dynamics." *Journal of Thermal Analysis and Calorimetry* 149, no. 5 (2024): 1831-1857.
5. Balakrishnan, Paramasivam, Senthil Kumar Vishnu, Jayaraman Muthukumaran, and Ramalingam Senthil. "Experimental thermal performance of a solar air heater with rectangular fins and phase change material." *Journal of Energy Storage* 84 (2024): 110781.
6. Hasan, Abdullah Al, Md Abdullah, and Abu Soyeb Sazid. "A Computational Analysis of Air-Cooled Heat Sinks Designs for PV Solar Panel Cooling With Different Fin Numbers." *Heat Transfer* (2024).
7. Chamarthi, Subbarao, Satyender Singh, and Subhash Chander. "Curved Channel Solar Air Heater Assisted with Fins and Baffles." *Heat Transfer Research*.
8. Abrofarakh, Moslem, and Hamid Moghadam. "Investigation of thermal performance and entropy generation rate of evacuated tube collector solar air heater with inserted baffles and metal foam: a CFD approach." *Renewable Energy* 223 (2024): 120022.
9. Marzouk, S. A., Maisa A. Sharaf, Ahmad Aljabr, and Emad MS El-Said. "Assessing the effects of different finned absorbers with swirl flow on the performance of solar air heater." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 46, no. 1 (2024): 3245-3262.
10. Elakrout, Omayma, Ons Ghriss, Abdallah Bouabidi, Humberto Garcia Castellanos, Soheil Mohtaram, Ali Keçebaş, and Yashar Aryanfar. "Investigative analysis of the influence of diverse fin configurations on the performance of a dual pass solar air collector." *Thermal Science and Engineering Progress* 50 (2024): 102545.
11. Duffie, J. A., & Beckman, W. A. (2013). *Solar engineering of thermal processes* (4th ed.). John Wiley & Sons.

12. Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. (2011). *Fundamentals of heat and mass transfer* (7th ed.). John Wiley & Sons.
13. Kays, W. M., Crawford, M. E., & Weigand, B. (2012). *Convective heat and mass transfer* (4th ed.). McGraw-Hill Education.
14. Dittus, F. W., & Boelter, L. M. K. (1930). Heat transfer in automobile radiators of the tubular type. *University of California Publications in Engineering*, *2*(13), 443–461.
15. Blasius, H. (1913). Das Aehnlichkeitsgesetz bei Reibungsvorgängen in Flüssigkeiten. *Mitteilungen über Forschungsarbeiten auf dem Gebiete des Ingenieurwesens*, *131*, 1–41.