Performance Evaluation of a Solar Air Heater System Based on Heat Transfer Enhancement and Friction Loss Characteristics

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Abstract

Solar air heater is a widely used renewable heat generation system for heating applications but due to poor heat transfer characteristics of the system, the thermal efficiency is restricted. The primary objective of the present research is to investigate the performance of solar Air Heater system using the heat transfer characteristics and friction loss for different solar air heater systems were selected from secondary source. They show that with artificial roughness techniques, the thermal performance is enhanced with increase in turbulence but the extent of friction loss and pressure drop becomes more. The study highlights the need for maintaining the balance between the thermal enhancement and the thermo-hydraulic performance to design efficient system.

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Introduction

Background of the study

Due to increased demand for renewable energy technologies, scientists are encouraged to develop efficient solar thermal systems for sustainable energy. With their low maintenance, simple design, and eco-friendly operation, solar air heaters (SAHs) are widely applied in space heating, crop drying, and industrial heating applications (Senger *et al.* 2024). In a traditional solar air heater, the heat transfer rate from the absorber plate to the flowing air is not high, and therefore, the thermal efficiency of air heaters is not attained. To overcome this drawback, it is found that various techniques have been developed to improve the rate of transferring, such as Artificial Roughness, Ribbed surfaces, turbulence promoters, etc. These techniques improve the level of turbulence of the flow in the vicinity of the surface of the absorber and consequently increase the rate of heat transferred and therefore the thermal efficiency.

Problem Statement

Artificial roughness methods can be used in solar air heaters for improvement of their performance in terms of heat transfer enhancement, but increase the pressure drop of the component system and frictional losses. Most studies focus only on the thermal enhancement, and the thermal enhancement–frictional loss interaction, which affects the overall thermo-hydraulic performance, is poorly represented.

Research Aim and Objectives

Aim

To determine the performance of a solar air heater system using different methods of heat transfer augmentation and pressure drop characteristics for optimizing the overall thermodynamic performance of the solar system and the thermo-hydraulic performance of solar air heater.

Objectives

- To know the different methods of augmentation of heat transfer in the solar air heater system.
- To study the effect of artificial roughness on the thermal efficiency and heat transfer characteristics.
- To explore the friction loss and pressure drop of enhancement techniques.
- To compare the of previous research done on thermo-hydraulic performance results.
- To determine which of the methods are most effective, giving the most heat transfer and at the same time the least friction loss.

Research Question

- Which of the following enhancement techniques can be applied in solar air heater systems to enhance the heat transfer?
- What is the importance of using artificial roughness on the thermal performance and heat transfer properties of solar air heaters?
- A general overview of increasing of heat transfer to increase friction losses of solar air heater's duct.
- What are the most beneficial enhancement techniques in terms of thermo-hydraulic performance out of the various possibilities?

Literature Review

Theories and Models

In the past, several theories and models were used to calculate the thermal and thermo-hydraulic performance in solar air heater (SAH) system. Heat Transfer Theory is one of the important concepts that are used in the analysis of Solar Air Heater (Hai and Phu, 2023). The theory is to explain how convective transfer of heat energy takes place from the heated absorber plate to the flowing air. If necessary, to bring the above the laminar sub-layer, generally an artificial roughness is applied to increase the turbulence level, which in turn increases the convective heat transfer rate and hence the thermal efficiency of the system.

Another significant use of the Thermo-Hydraulic Performance Theory is the study of the trade-off between heat-transfer augmentation and friction loss (Yan *et al.* 2024). This model is created to address whether installing roughness elements is worth it from a thermal efficiency standpoint, as the fluid experiences a large pressure drop, resulting in a greater increase in pumping power. To assess the performance of the different roughness geometries in different operating conditions, several thermo-hydraulic performance parameters are used.

Heat Transfer Enhancement Techniques in Solar Air Heaters

Due to the poor thermal efficiency of the conventional solar air heaters (SAH) obtained due to the low heat transfer coefficient of air, one of the latest research area being focused is on enhancing heat transfer. A large number of studies have been conducted to enhance the turbulence and hence the convective heat transfer between the absorber plate and airflow moving in the duct through various artificial roughness methods. One of the best passively improved methods for the thermal/thermohydraulics performance of solar air heater is explained by **Panda and Kumar (2021)** by artificial roughness. During their review, they stated different kinds of roughness conditions which are present in the absorbers, such as On Transverse Ribs, V-shaped ribs, inclined ribs and On wire roughness, which plays a role in violating the laminar sublayer near absorber thus increasing the turbulence intensity and in turn enhancing the heat transfer intensity.

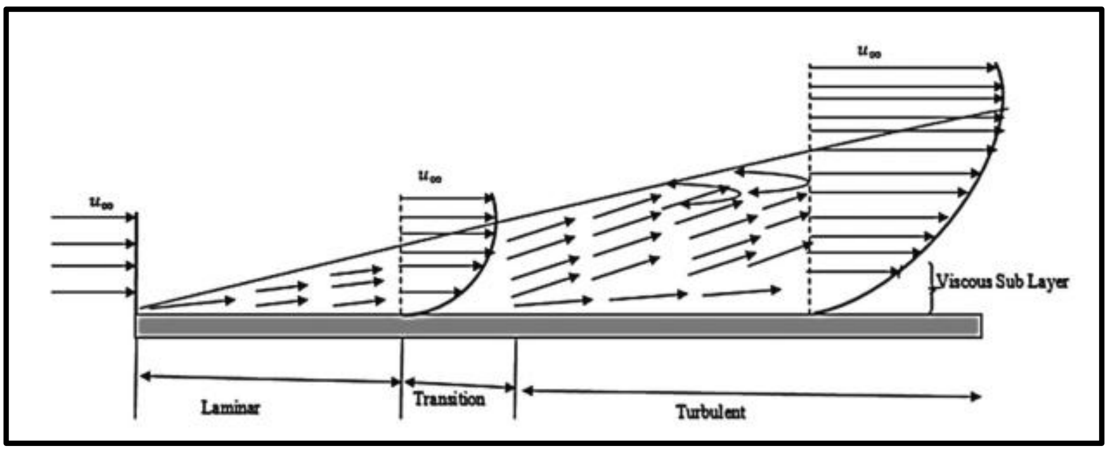

Figure 1: Mechanism of boundary layer formation
(Source: Panda and Kumar, 2021)

Therefore, **Singh *et al.* (2022)** conducted a critical review of recent advancements in solar air heater technology and concluded that by adding passive devices such as fins, ribs, turbulators and porous material, etc., the heat transfer performance of the solar air heater is increased significantly. The authors have pointed out that the usual systems with their heated absorber plate experience losses in thermal efficiency due to the formation of a laminar sub-layer over the absorber plate. The methods to disrupt this 'viscous layer' and improve the transfer of energy from the heat of the skin are known as roughness techniques.

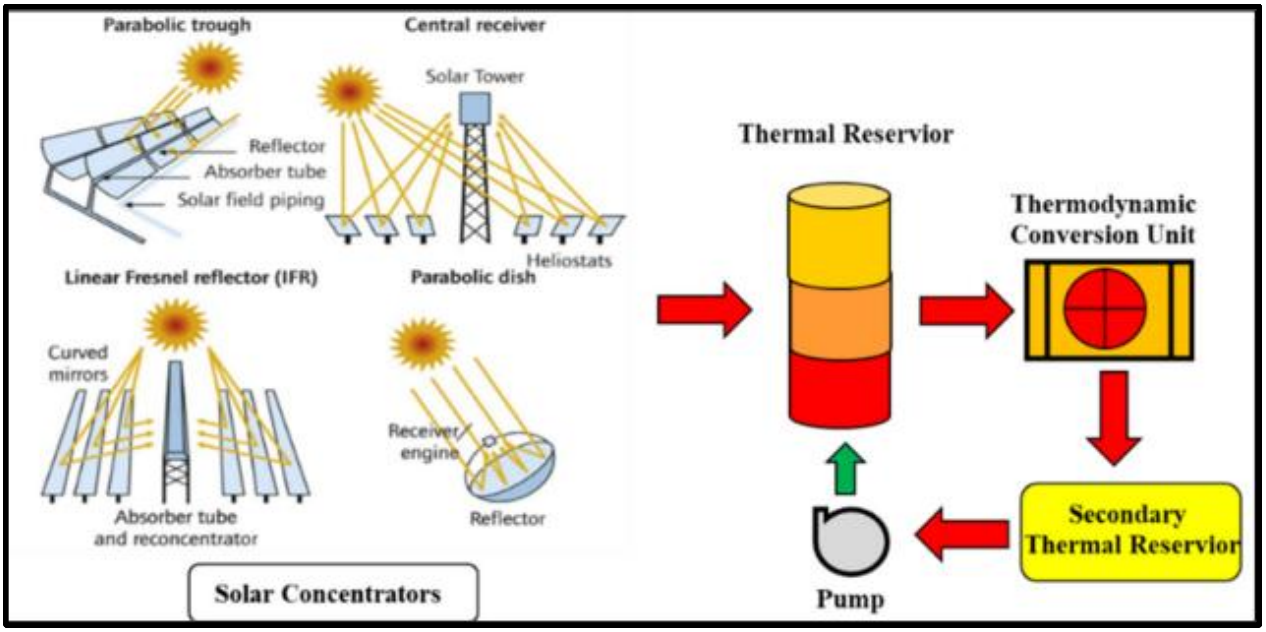

Figure 2: Different solar concentrator- linear Fresnel reflector
(Source: Singh *et. al.* 2022)

Moreover, **Kedar *et al.* (2023)** claimed passive enhancement methods have greater value for usage because they do not require any maintenance or operate in a complicated manner. The ribs, baffles, fins, and winglets are found to significantly improve thermal performance. But the authors critically mentioned that near the value of 81.9% thermal efficiency, the effective efficiency was much less due to the increase in the friction factors.

Friction Loss and Thermo-Hydraulic Performance Characteristics

The impelling losses and thermo-hydraulic characteristics are important as it is used to assess the overall performance of the solar air heater blockage. The artificial roughening techniques have been shown to significantly affect the enhancement of the heat transfer rate, but also increase the friction factor and/or the pressure loss of the duct. **Panda and Kumar (2021)** pointed out that the hallucinating geometries with larger roughness would result in large airflow resistance, that will increase its pumping power requirement. This clearly indicates that the thermal enhancement is not a key to the effectiveness of a solar air heater system.

In the same sense, **Singh *et al.* (2022)** found that, while conducting thermo-hydraulic performance analysis is important, this study can be used to determine the optimum roughness configuration as some geometries can offer a high enhancement in heat transfer but do not exhibit good flow characteristics. **Kedar *et al.* (2023)** critically commented that higher thermal efficiencies were achieved by few solar air heaters with frosted surfaces, but the effective efficiencies are kept very low because of the high friction losses. They conclude one of the great challenges in developing efficient and sustainable systems based on solar air heaters is to achieve both efficient heat transfer and well tolerate friction characteristic.

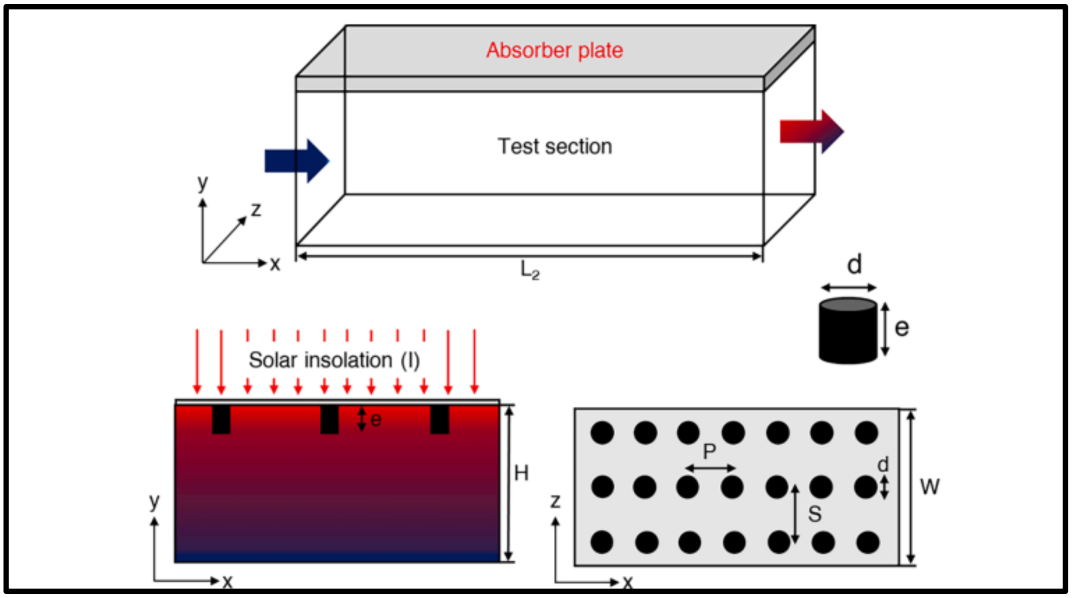

Figure 3: Schematic of roughened SAH with vertical cylindrical ribs
(Source: Singh *et. al.* 2022)

CFD and Numerical Analysis of Solar Air Heater Systems

Computational Fluid Dynamics (CFD) is one of the important numerical tools that is used to analyse the thermal and thermo-hydraulic performance of solar air heater systems. In their modelled investigation, **Kumar and Verma (2021)** concluded that increasing the flow velocity of air and increasing the absorber plate temperature enables both the thermal efficiency of the solar air heater increases. They have performed their study with the help of k-ε RNG turbulence model and ANSYS software which has been used to study the performance of airflow and heat transfer at different Reynolds numbers. The research was able to show that CFD modelling is capable of accurately predicting thermal performance and can aid in optimising the geometric parameters to optimize the thermal performance.

In the same manner, **El-Sebaey *et al.* (2023)** conducted a 3D CFD simulation to study the use of rotating cylindrical ribs as an artificial roughness in solar air heaters. They discovered that rotating ribs resulted in enhanced thermo-hydraulic performance as compared to conventional rigid ribs and reduced the pressure drop penalties. But both of the studies suggest that care needs to be taken in the validation of CFD models, as numerical assumptions and turbulence models can affect the accuracy of the prediction and the reliability of the results.

Literature Gap

Investigation of solar air heater with different forms of artificial roughness was mainly done to enhance the thermal performance in previous studies and CFD investigation was done to find out the nature of flow in the collector. However, little research critically compares the heat transfer enhancement and friction loss characteristics. There is lack of detailed secondary analysis of earlier experimental and numerical studies to also find the optimum thermo-hydraulic performance configurations.

Conceptual Framework

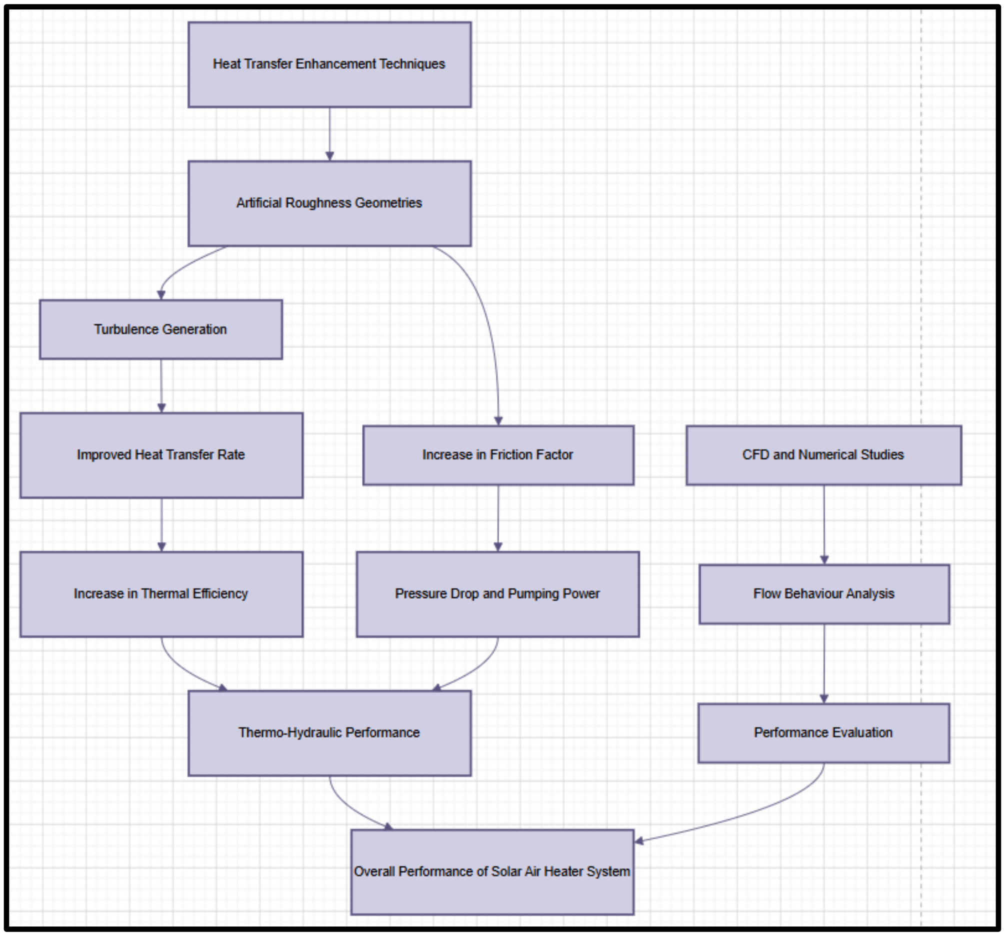

Figure 4: Conceptual Framework
(Source: Self-made)

Methodology

Research Approach

The secondary research for this study is done qualitatively to check the performance of the solar air heater system using heat transfer enhancement and friction loss characteristics (Abulkhair *et al.* 2023). A qualitative approach is suitable for this study because the approach used does not need to be immersed in the primary data to present numerical differences, but to analyze and interpret the data that has been presented by others and published in existing studies. This offers the researcher a chance to investigate critically various heat transfer enhancement techniques, thermo-hydraulic performance, and CFD-based investigations for different solar air heaters reported in the various academic literature.

Research Design

It is a descriptive and exploratory type of study that has analyzed the existing studies relating to the performance of solar air heaters (Chamarthi and Singh, 2021). The descriptive design explains the behavior of the friction loss, thermo-hydraulic characteristics, and enhancement of heat transfer methods based on the observations from previous studies. The exploratory aspect has been utilized to observe the emerging trends in this field and areas where there are no detailed investigations related to the use of artificial roughness techniques and CFD investigations. This design is suitable because students can use this to examine what they learn in various academic published materials, and check their findings.

Research Method

Only the secondary research technique by published academic and professional sources has been followed (Felizardo *et al.* 2020). A collection of essential data from Journal articles, Conference papers, Review studies, Books, and web-based Scientific databases in Solar Air heater aspects and thermal performance enhancement is carried out. The methodology enables the researcher to look at the previous work done on the artificial roughness techniques, friction factor, thermo-hydraulic performance, and CFD investigation. Identify patterns and comparisons in the literature collected; identify gaps in literature inherent in the literature.

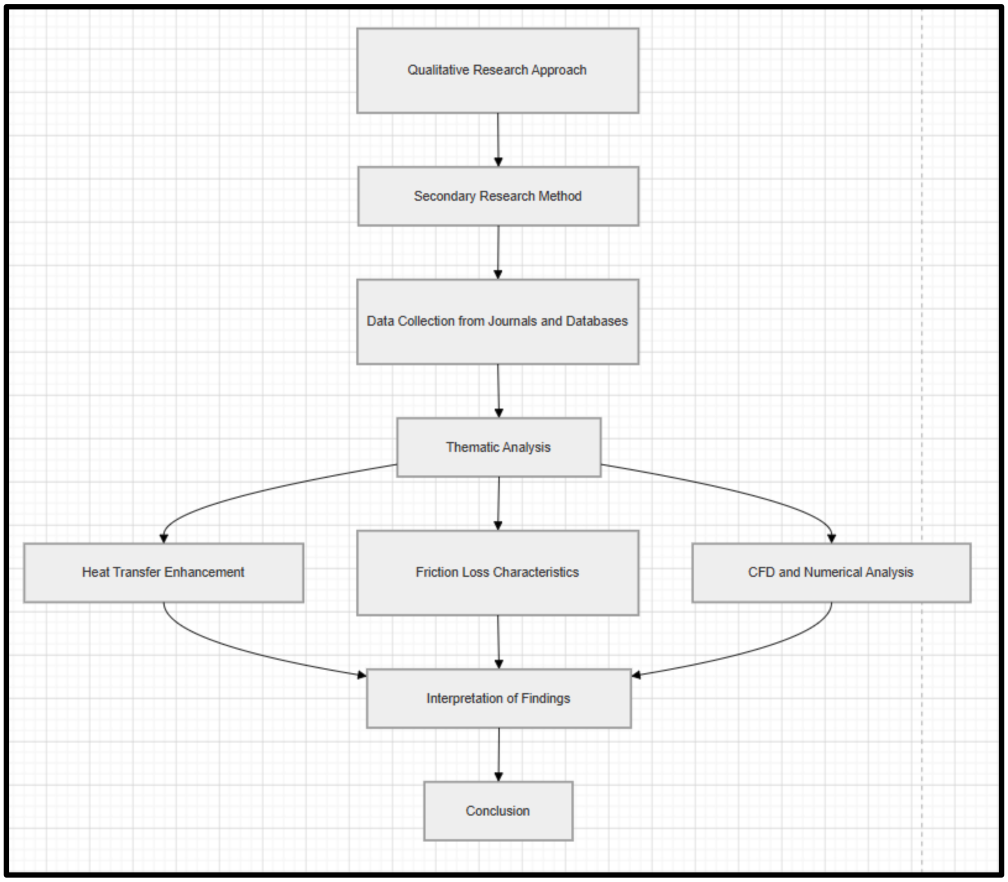

Figure 5: Overall Methodology
(Source: Self-made)

Data Collection

This is survey research that relies on secondary data taken from publications or sources of academics that can be trusted. They will get information from the different journals related to renewable energy and thermal engineering from Science Direct publication, Springer Publisher, Google Scholar, Taylor and Francis publication, and IEEE publication (Yasin *et al.* 2020). During the search process, keywords like "Solar air heater", "heat transfer enhancement", "artificial roughness", "friction factor", and "thermo-hydraulic performance" are used. Only research studies that are relevant and peer-reviewed, and relatively updated studies, are taken to ensure the reliability and accuracy of gathered information.

Research Ethics

Research Ethics are maintained throughout the research by ensuring that the authenticity and credibility of academic sources is followed. Citations and references are properly noted, which shows good practices and no plagiarism and/or insufficient academic honesty. The study objectively discusses the previous results developed without any change or distortion in the results obtained from the published articles. No confidentiality or participant consent issues, as it is a secondary research study only.

Results

Analysis of Heat Transfer Enhancement Techniques

The outcomes evaluated from the works surveyed indicate that there is an appreciable effect of the use of artificial roughness techniques on the performance of the solar air heater system. The various elements included in the study, such as rib roughness, fins, baffles, and turbulators, were to induce disturbances in the laminar sub-layer near the absorber plate. The analysis of the results conducted by Panda and Kumar (2021) indicated that the ribs fitted with V-shaped and inclined ones had higher turbulent intensity, which led to higher heat transfer rate and thus higher Nusselt number. Coinciding with this, Singh *et al.* (2022) found that the passive enhancement techniques were taken into account, which showed improvements in thermal efficiencies of the duct through the process of mixing the airflow.

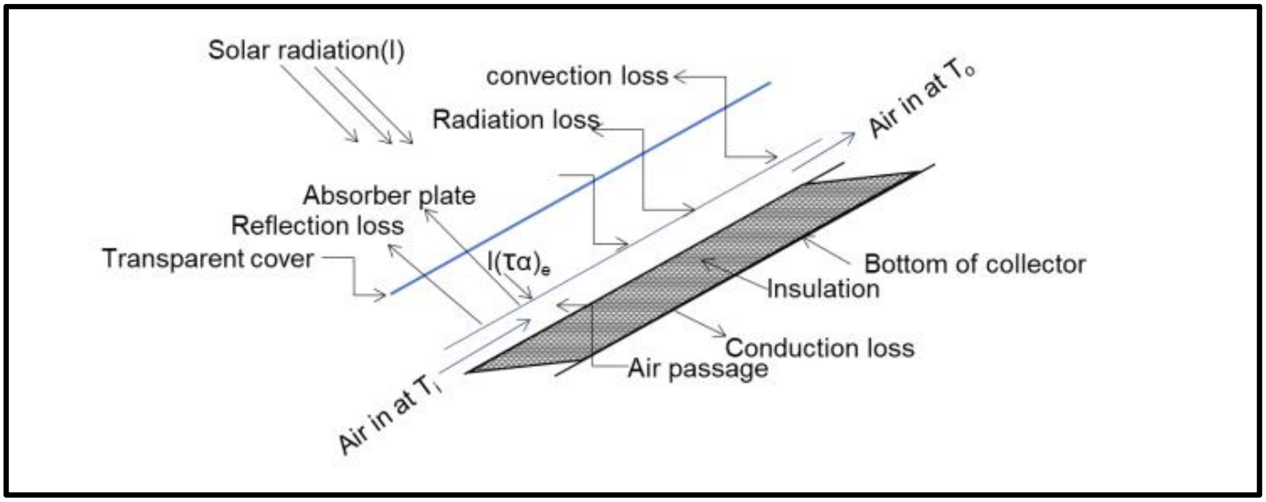

Figure 6: Conventional solar air heater
(Source: Panda and Kumar, 2021)

Analysis of Friction Loss Characteristics

Previous investigations have indicated that considerable friction losses result from the use of artificial roughness in the duct of solar air heaters. However, roughness elements also tend to promote turbulence and transfers of heat, but they also create resistance to the passage of air and pressure drop. It was observed that the rib height and complex geometry of the roughness resulted in greater values of the friction factor, as stated by Panda and Kumar (2021), which consequently increased the pump power requirement. Kedar *et al.* (2023) have also reported decreased effective efficiency for some systems with high friction losses with increased thermal enhancement (Matheswaran *et al.* 2022). The main findings from the analysis is that, for the most part, the various roughness techniques have an effect of increasing heat transfer, but there is a need for control over pressure drop for overall efficiency and energy conservation.

Analysis of Thermo-Hydraulic Performance

To evaluate its overall performance, the effect of heat transfer enhancement and friction loss for the solar air heaters should be considered together and examined by carrying out a thermo-hydraulic performance analysis. From the results of the previous studies, the higher thermal efficiency system with relatively moderate pressure drop characteristics is identified as the best system. Singh *et al.* (2022) have highlighted that a comparative evaluation of the roughness geometry is needed to find the optimum performance of any configuration. Kedar and others 2023) have reported that the use of ribs and baffles provided excellent improvement in thermal performance; however, a high friction factor hurt the optimum performance. Analysis shows that optimisation of solar air heater is important in achieving a balance between improved heat transfer and an acceptable friction loss.

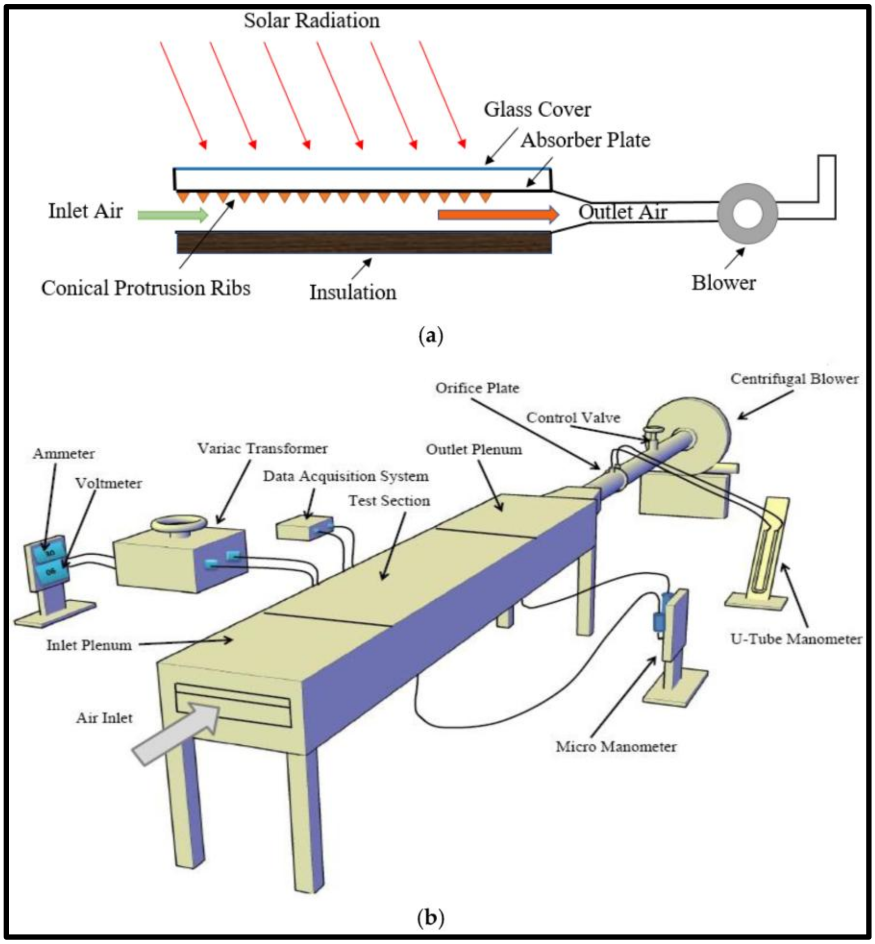

Figure 7: Exergy-Based Thermo-Hydraulic Performance of Roughened Absorber in Solar Air Heater Duct

(Source: Alam *et al.* 2022)

Discussion

It is pointed that the use of artificial roughness techniques had significantly enhanced the thermal performance in terms of turbulence enhancement and convective heat transfer of solar air heater system. The results also demonstrated that the higher turbulence level yields higher value of frictional loss and higher pressure drop, leading to reduced effective efficiency and to high pumping power consumption. Comparative analysis of previous literatures it is observed that the efficiency of the system is more appropriate to measure the effectiveness of the system in overall performance in terms of thermo-hydraulic performance of the system than only in terms of its thermal efficiency.

Conclusion

To sum up, the application of solar air heater systems in renewable thermal energy has great potential, but its performance is highly dependent on the ability to enhance heat transfer and to reduce friction losses. One identified from the study is the use of artificial roughness (rib, fin, and turbulator) to enhance the heat transfer rate and turbulence for increased thermal efficiency. These methods, however, have the drawback of also leading to an increase in friction factor and pressure drop, consequently influencing overall thermo-hydraulic performance.

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