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Experimental Investigation of Heat Transfer Enhancement in a Rectangular Duct Using Circular and Triangular Ribs at 90^0 Orientation

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Abstract - **Enhancement of heat transfer in compact heat exchangers is crucial for improving thermal system efficiency in various engineering applications. In the present study, an experimental investigation is carried out to evaluate the effect of artificial roughness in the form of circular and triangular ribs on the convective heat transfer characteristics of a rectangular duct at a fixed rib orientation of 90°. Experiments are conducted for three cases, namely, smooth duct (without ribs), circular ribs, and triangular ribs, over a range of air velocities from 4 to 4.3 m/s. The performance is analyzed in terms of heat transfer coefficient, Nusselt number, and heat transfer rate. The results indicate a significant enhancement in thermal performance for ribbed configurations compared to the smooth duct. The heat transfer coefficient is observed to increase by approximately 64% to 92% for circular ribs and 115% to 124% for triangular ribs relative to the smooth duct. Similarly, the Nusselt number shows an enhancement of about 64% to 73% for circular ribs and 115% to 124% for triangular ribs. The heat transfer rate is also improved by nearly 44% to 49% for circular ribs and 88% to 89% for triangular ribs. Among the tested configurations, triangular ribs exhibit superior performance due to enhanced turbulence generation and improved fluid mixing. The findings demonstrate the effectiveness of rib-induced artificial roughness in augmenting convective heat transfer.**

Keywords - Heat transfer, Convective heat transfer coefficient, Nusselt number, Reynold Number

1. Introduction

Heat exchangers are essential components in numerous industrial and engineering applications such as power generation, chemical processing, refrigeration, and automotive systems, where efficient thermal energy transfer is critical for overall system performance. With the increasing demand for compact and energy-efficient systems, enhancing convective heat transfer has become a key area of research. Heat transfer enhancement techniques are generally classified into active and passive methods. Among these, passive techniques are widely preferred due to their simplicity, cost-effectiveness, and ease of implementation without requiring additional external energy input[1], [2].

Heat transfer is a discipline of thermal engineering that concerns the generation, use, conversion, and exchange of thermal energy and heat between physical systems. Heat transfer is classified into various mechanisms, such as thermal conduction, thermal convection, thermal radiation, and transfer of energy by phase changes. Engineers also consider the transfer of mass of differing chemical species, either cold or hot, to achieve heat transfer. While these mechanisms have distinct characteristics, they often occur simultaneously in the same system. Energy and materials saving considerations, as well as economic incentives, have led to efforts to produce more efficient heat exchange equipment. Common thermohydraulic goals are to reduce the size of a heat exchanger required for a specified heat duty, to upgrade the capacity of an existing heat exchanger, to reduce the approach temperature difference for the process streams, or to reduce the pumping power[3]. The study of improved heat transfer performance is referred to as heat transfer augmentation, enhancement, or intensification. In general, this means an increase in heat transfer coefficient. Attempts to increase "normal" heat transfer coefficients have been recorded for more than a century, and there is a large store of information[4], [5], [6].

Heat transfer augmentation techniques (passive, active or a combination of passive and active methods) are commonly used in areas such as process industries, heating and cooling in evaporators, thermal power plants, air-conditioning equipment, refrigerators, radiators for space vehicles, automobiles, etc. Passive techniques, where inserts are used in the flow passage to augment the heat transfer rate, are advantageous compared with active techniques, because the insert manufacturing process is simple and these techniques can be easily employed in an existing heat exchanger[7]. In design of compact heat exchangers, passive techniques of heat transfer augmentation can play an important role if a proper passive insert configuration can be selected according to the heat exchanger working condition (both flow and heat transfer conditions). In the past decade, several studies on the passive techniques of heat transfer augmentation have been reported. Twisted tapes, wire coils, ribs, fins, dimples, etc., are the most commonly used passive heat transfer augmentation tools[8], [9], [10].

Artificial roughness in the form of ribs or turbulators is one of the most effective passive techniques used to enhance heat transfer in duct flows. The presence of ribs on the heated surface disturbs the viscous sublayer, promotes flow separation and reattachment, and generates secondary flow structures, thereby increasing turbulence intensity and improving convective heat transfer. The performance of rib-roughened surfaces depends on various parameters such as rib geometry, height, pitch, and orientation. Among these, rib geometry plays a significant role in determining the nature of flow disruption and the resulting heat transfer characteristics[11], [12].

Several studies have investigated the effect of rib roughness on heat transfer enhancement. Singh et al. [13] demonstrated that rib-roughened surfaces significantly improve heat transfer due to increased turbulence and fluid mixing. Ravi et al. [14] analyzed different roughness geometries and concluded that both rib shape and orientation strongly influence heat transfer and friction characteristics. Kim KM et al. [15] reported that angled ribs generate secondary flow patterns that enhance thermal performance compared to transverse ribs. Han et al. [16] studied the influence of rib geometry and pitch and observed that triangular ribs provide better heat transfer enhancement due to their sharp edges, which intensify flow disturbances. Similarly, Boulemtafes-Boukadoum & Benzaoui [17] highlighted the importance of artificial roughness in improving the thermal efficiency of solar air heaters, emphasizing the role of rib geometry in modifying flow behavior. Recent investigations by Wang & Sundén et al. [18] and Tanda [19] further confirmed that optimization of rib shape and orientation is crucial for achieving maximum heat transfer enhancement.

Despite the extensive research available in this field, a comprehensive comparison of different rib geometries under identical operating conditions remains limited. Most of the existing studies focus either on a single rib geometry or on varying rib orientations, without isolating the effect of rib shape at a constant angle. In particular, there is a lack of systematic experimental investigations comparing circular and triangular ribs at a fixed orientation of 90° in a rectangular duct under similar flow conditions. This gap limits a clear understanding of the relative performance of different rib geometries and their influence on heat transfer enhancement. In view of this, the present study aims to experimentally investigate the effect of circular and triangular ribs on convective heat transfer characteristics in a rectangular duct at a fixed rib orientation of 90°. The performance is evaluated in terms of heat transfer coefficient, Nusselt number, and heat transfer rate over a range of air velocities. The outcomes of this study are expected to provide valuable insights for the design and optimization of high-performance heat exchangers.

2. Experimental Setup

The experimental investigation was carried out using a specially designed test rig to study the effect of rib geometry on convective heat transfer characteristics in a rectangular duct. The setup consists of a blower, flow control system, test section, heating arrangement, and measuring instruments for temperature, flow, and pressure. A schematic diagram of the complete experimental setup and detailed views of individual components are shown in Fig. 1.

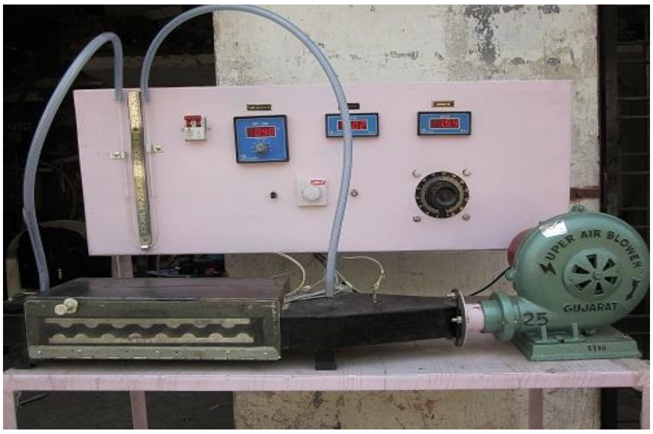


Figure 1. Experimental Setup.

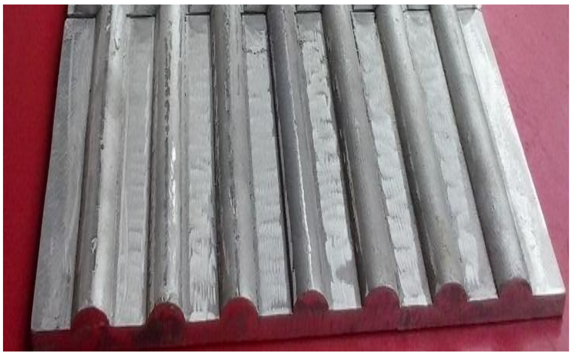
Air is used as the working fluid and is supplied by a centrifugal blower, which draws air through the duct from the entrance to the exit section. The airflow rate is controlled using control valves and measured using an anemometer. To ensure the development of a fully developed flow before entering the test section, an unheated entrance length (commix section) of 150 mm is provided. Similarly, an unheated exit length of 100 mm is maintained after the test section to stabilize the flow at the outlet. These sections help in achieving a uniform and streamlined airflow, minimizing experimental uncertainties.

The test section consists of a rectangular duct with a hydraulic diameter of 0.075 m. The duct has a height (H) of 50 mm and a width (W) of 150 mm, maintaining an aspect ratio of 3. The total length of the duct varies between 500 mm and 650 mm depending on the rib configuration. The heated test section is 300 mm long and is equipped with an electric heating coil to provide a uniform heat flux condition along the test surface. The temperature of the air and the duct surface is measured using calibrated thermocouples connected to a digital temperature indicator.

Artificial roughness in the form of ribs is introduced on the heated surface to enhance heat transfer. In the present study, circular and triangular shaped ribs are used, both having a height (e) of 5 mm and arranged with a uniform pitch (p) of 35 mm. The ribs are fabricated from aluminium, while the duct is made of SR sheet material. The ribs are staggered at an angle of 90° with respect to the flow direction for the present investigation. The systematic arrangement of ribs used in the study is illustrated in Fig. 2 and Fig.3

Figure 2. Systematic Arrangement of Ribs in duct.

(a)



(b)

Figure 3. (a) Triangular ribs with angle 90^0 (b) Circular ribs with angle 90^0

The electrical input to the heater is measured using a voltmeter and an ammeter, which are used to calculate the heat supplied to the system. A U-tube manometer is employed to measure the pressure difference across the test section, ensuring proper flow monitoring. All instruments are carefully calibrated to reduce measurement errors and ensure data accuracy.

The experimental setup is designed to allow systematic variation of flow velocity and rib configurations, enabling a detailed analysis of heat transfer characteristics under controlled conditions. The combination of precise instrumentation, well-defined geometry, and controlled operating parameters ensures reliable and repeatable experimental results.

3. Methodology

The experimental procedure was carried out to evaluate the convective heat transfer characteristics of a rectangular duct under different rib configurations. The study includes three cases, namely, smooth duct (without ribs), circular ribs staggered at 90°, and triangular ribs staggered at 90°. Experiments were conducted by varying the air velocity in the range of 4 to 4.3 m/s under steady-state conditions.

Initially, the experimental setup was operated without any rib to establish baseline data for the smooth duct condition. The blower was switched on, and the airflow rate was adjusted using control valves to obtain the desired velocity. Once the flow stabilized, the heater was powered to provide a uniform heat input to the test section. The system was allowed to reach steady-state conditions, which were confirmed when the temperature readings remained constant over time. At steady state, the temperatures at different locations, airflow velocity, and electrical input parameters were recorded.

The same procedure was repeated for circular and triangular rib configurations at a fixed orientation of 90°. Care was taken to maintain identical operating conditions for all cases to ensure accurate comparison of results. For each test run, multiple readings were taken to minimize experimental error, and the average values were used for further calculations.

The heat supplied to the air was calculated from the electrical input to the heater using the relation:

$$Q = V \times I \tag{1}$$

where Qis the heat input (W), Vis the voltage (V), and Iis the current (A).

The mass flow rate of air was determined using the measured air velocity as:

$$\dot{m} = \rho A V \tag{2}$$

where $\dot{m}$is the mass flow rate (kg/s), ρis the density of air (kg/m³), Ais the cross-sectional area of the duct (m²), and Vis the air velocity (m/s).

The Reynolds number was calculated to characterize the flow regime:

$$Re=\rho VD/\mu \tag{3}$$

Where D is the hydraulic diameter of the duct (m) and μ is the dynamic viscosity of air (Pa·s).

The convective heat transfer coefficient was evaluated using:

$$h=Q/(A\_s\,(T\_s-T\_f)) \tag{4}$$

Where is the heat transfer coefficient (W/m²K), A_s is the heated surface area (m²), T_s is the average surface temperature (K), and T_fis the bulk mean air temperature (K).

The Nusselt number, representing the dimensionless heat transfer coefficient, was calculated as:

$$Nu = hD/k \quad (5)$$

where k is the thermal conductivity of air (W/m·K).

All experimental data were processed to obtain variations of heat transfer coefficient, Nusselt number, and heat transfer rate with respect to air velocity. The results for different rib configurations were compared with the smooth duct to evaluate the enhancement in heat transfer performance. Graphical analysis was performed to interpret the influence of rib geometry on thermal characteristics.

4. Results and Discussion

The experimental results obtained for the smooth duct, circular ribs (90°), and triangular ribs (90°) are analyzed in terms of heat transfer coefficient, Nusselt number, and heat transfer rate. The variation of these parameters with air velocity is presented in Fig. 4, Fig. 5, and Fig. 6, respectively. The results clearly demonstrate the significant influence of air velocity and rib geometry on the thermal performance of the system.

The variation of heat transfer coefficient with air velocity is shown in Fig. 4. It is observed that the heat transfer coefficient increases with increasing air velocity for all configurations. This behavior is primarily due to the increase in Reynolds number, which enhances turbulence intensity and reduces the thickness of the thermal boundary layer. In the smooth duct, the increase is gradual; however, the presence of ribs substantially enhances the heat transfer coefficient. Circular ribs introduce periodic disturbances in the flow, promoting mixing and improving heat transfer. In contrast, triangular ribs exhibit superior performance due to their sharp edges, which generate stronger flow separation and reattachment zones. These mechanisms intensify turbulence and enhance the convective heat transfer process. The 90° rib orientation ensures continuous interruption of the boundary layer, resulting in consistent enhancement across the entire test section.

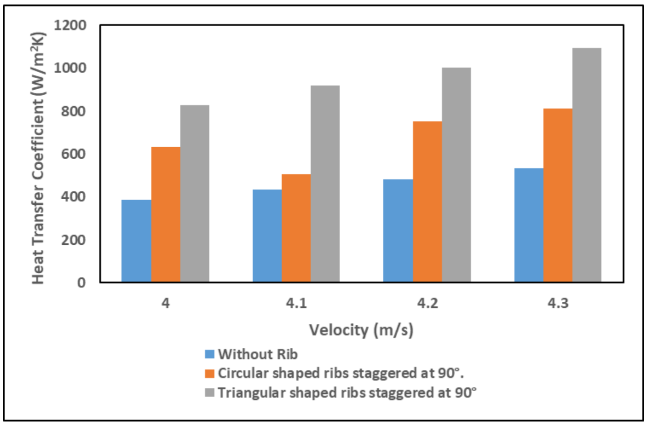


Figure 4. Variation of heat transfer coefficient with air velocity

The variation of Nusselt number with air velocity is presented in Fig. 5. The Nusselt number shows a similar increasing trend with velocity, confirming the enhancement in convective heat transfer. As the velocity increases, the dominance of forced convection becomes more pronounced, leading to higher heat transfer rates. The ribbed configurations significantly outperform the smooth duct due to increased turbulence and secondary flow generation. Triangular ribs, in particular, produce higher Nusselt numbers due to their ability to create strong vortices and localized mixing zones. Circular ribs also enhance the heat transfer, but the effect is comparatively moderate due to smoother flow interaction. The consistency between heat transfer coefficient and Nusselt number trends validates the reliability of the experimental data.

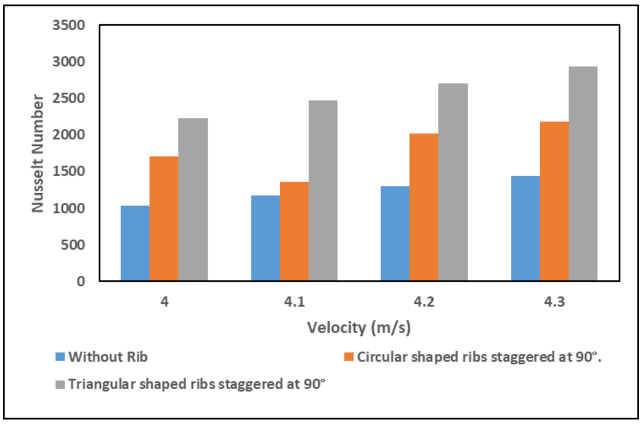


Figure 5. Variation of Nusselt Number with air velocity

The variation of heat transfer rate with air velocity is illustrated in Fig. 6, and it provides deeper insight into the overall thermal performance of the system. It is observed that the heat transfer rate increases significantly with increasing air velocity for all configurations. This is due to the combined effect of increasing mass flow rate and enhanced convective heat transfer coefficient. As the air velocity increases, a larger quantity of air passes through the duct per unit time, thereby increasing the capacity of the fluid to absorb heat from the heated surface. In the smooth duct, the heat transfer rate increases steadily; however, the rate of increase is comparatively lower due to limited turbulence and weaker mixing.

In ribbed configurations, the increase in heat transfer rate is much more pronounced. The presence of ribs not only enhances the heat transfer coefficient but also improves the interaction between the fluid and the heated surface. Circular ribs increase the heat transfer rate by creating repeated flow disturbances, which enhance mixing and energy exchange. However, triangular ribs exhibit the highest heat transfer rate among all configurations. This is attributed to their sharp geometry, which induces stronger vortices, higher turbulence intensity, and more effective disruption of the boundary layer. These effects collectively improve the thermal energy transfer from the heated surface to the flowing air.

Furthermore, the increase in heat transfer rate with velocity is not only a function of thermal enhancement but also a direct consequence of increased fluid momentum. Higher velocity results in reduced thermal resistance and improved convective heat transfer efficiency. The triangular rib configuration maximizes this benefit by combining increased flow mixing with higher surface interaction, resulting in superior thermal performance. A slight deviation observed in the circular rib data at 4.1 m/s may be attributed to experimental uncertainties or localized flow instabilities; however, the overall trend remains consistent and reliable.

Overall, the results clearly indicate that both rib geometry and air velocity have a significant impact on heat transfer performance. Among the tested configurations, triangular ribs at 90° orientation provide the highest enhancement due to their ability to generate strong turbulence, disrupt the thermal boundary layer effectively, and maximize heat transfer rate

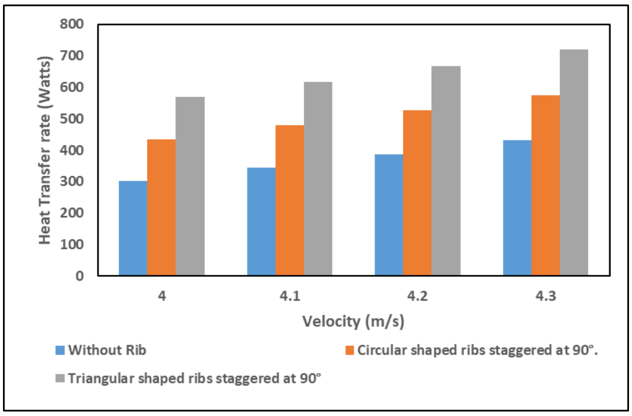


Figure 6. Variation of heat transfer rate with air velocity

5. Conclusions

An experimental investigation has been carried out to study the effect of rib geometry on convective heat transfer characteristics in a rectangular duct at a fixed rib orientation of 90°. The performance of a smooth duct, circular ribs, and triangular ribs has been evaluated over a range of air velocities from 4 to 4.3 m/s in terms of heat transfer coefficient, Nusselt number, and heat transfer rate. Based on the experimental results and detailed analysis, the following conclusions are drawn: The heat transfer coefficient, Nusselt number, and heat transfer rate were found to increase with increasing air velocity for all configurations due to the enhancement in Reynolds number and turbulence intensity. The introduction of ribs significantly improves the thermal performance compared to the smooth duct by disrupting the thermal boundary layer and promoting fluid mixing. Among the tested configurations, triangular ribs exhibited the highest enhancement in heat transfer performance. The heat transfer coefficient for triangular ribs increased by approximately 115% to 124%, while circular ribs showed an enhancement of about 64% to 92% compared to the smooth duct. Similarly, the Nusselt number was enhanced by 115% to 124% for triangular ribs and 64% to 73% for circular ribs. The heat transfer rate also showed significant improvement, with increases of approximately 88% to 89% for triangular ribs and 44% to 49% for circular ribs relative to the smooth duct. The superior performance of triangular ribs is attributed to their sharp edges, which generate stronger flow separation, reattachment, and vortex formation, resulting in enhanced turbulence and improved heat transfer. Circular ribs also enhance performance but to a lesser extent due to comparatively smoother flow interaction. Overall, the results demonstrate that rib-induced artificial roughness is an effective method for enhancing convective heat transfer in ducts. The findings of this study suggest that triangular ribs at 90° orientation are more effective for thermal performance improvement and can be considered for the design and optimization of high-efficiency heat exchangers.

References

[1] H.-M. Kim and K.-Y. Kim, "Design optimization of rib-roughened channel to enhance turbulent heat transfer," *Int. J. Heat Mass Transf.*, vol. 47, no. 23, pp. 5159–5168, 2004.

[2] A. Kumar, R. P. Saini, and J. S. Saini, "Experimental investigation on heat transfer and fluid flow characteristics of air flow in a rectangular duct with Multi v-shaped rib with gap roughness on the heated plate," *Sol. Energy*, vol. 86, no. 6, pp. 1733–1749, 2012.

[3] A. Dewan, P. Mahanta, K. S. Raju, and P. S. Kumar, "Review of passive heat transfer augmentation techniques," *Proc. Inst. Mech. Eng. Part A J. Power Energy*, vol. 218, no. 7, pp. 509–527, 2004.

[4] A. N. Al-Shamani, K. Sopian, H. A. Mohammed, S. Mat, M. H. Ruslan, and A. M. Abed, "Enhancement heat transfer characteristics in the channel with Trapezoidal rib–groove using nanofluids," *Case Stud. Therm. Eng.*, vol. 5, pp. 48–58, 2015.

[5] A. K. Shukla and A. Dewan, "Convective heat transfer enhancement using slot jet impingement on a detached rib surface," *J. Appl. Fluid Mech.*, vol. 10, no. 6, pp. 1615–1627, 2017.

[6] S. Tabatabaeikia, H. A. Mohammed, N. Nik-Ghazali, and B. Shahizare, "Heat transfer enhancement by using different types of inserts," *Adv. Mech. Eng.*, vol. 6, p. 250354, 2014.

[7] H. H. Cho, S. J. Wu, and H. J. Kwon, "Local heat/mass transfer measurements in a rectangular duct with discrete ribs," *J. Turbomach.*, vol. 122, no. 3, pp. 579–586, 2000.

[8] G. Tanda, "Performance of solar air heater ducts with different types of ribs on the absorber plate," *Energy*, vol. 36, no. 11, pp. 6651–6660, 2011.

[9] J. Liu, G. Xie, and T. W. Simon, "Turbulent flow and heat transfer enhancement in rectangular channels with novel cylindrical grooves," *Int. J. Heat Mass Transf.*, vol. 81, pp. 563–577, 2015.

[10] C. Gau and I. C. Lee, "Flow and impingement cooling heat transfer along triangular rib-roughened walls," *Int. J. Heat Mass Transf.*, vol. 43, no. 24, pp. 4405–4418, 2000.

[11] P. Promvonge, T. Chompookham, S. Kwankaomeng, and C. Thianpong, "Enhanced heat transfer in a triangular ribbed channel with longitudinal vortex generators," *Energy Convers. Manag.*, vol. 51, no. 6, pp. 1242–1249, 2010.

[12] S. K. Sharma and V. R. Kalamkar, "Experimental and numerical investigation of forced convective heat transfer in solar air heater with thin ribs," *Sol. Energy*, vol. 147, pp. 277–291, 2017.

[13] P. Singh, J. Pandit, and S. V Ekkad, "Characterization of heat transfer enhancement and frictional losses in a two-pass square duct featuring unique combinations of rib turbulators and cylindrical dimples," *Int. J. Heat Mass Transf.*, vol. 106, pp. 629–647, 2017.

[14] B. V. Ravi, P. Singh, and S. V Ekkad, "Numerical investigation of turbulent flow and heat transfer in two-pass ribbed channels," *Int. J. Therm. Sci.*, vol. 112, pp. 31–43, 2017.

[15] K. M. Kim, B. S. Kim, D. H. Lee, H. Moon, and H. H. Cho, "Optimal design of transverse ribs in tubes for thermal performance enhancement," *Energy*, vol. 35, no. 6, pp. 2400–2406, 2010.

[16] J. C. Han, J. S. Park, and C. K. Lei, "Heat transfer enhancement in channels with turbulence promoters," 1985.

[17] A. Boulemtafes-Boukadoum and A. Benzaoui, "CFD based analysis of heat transfer enhancement in solar air heater provided with transverse rectangular ribs," *Energy*

Procedia, vol. 50, pp. 761–772, 2014.

[18] L. Wang and B. Sundén, “Experimental investigation of local heat transfer in a square duct with various-shaped ribs,” *Heat Mass Transf.*, vol. 43, no. 8, pp. 759–766, 2007.

[19] G. Tanda, “Heat transfer in rectangular channels with transverse and V-shaped broken ribs,” *Int. J. Heat Mass Transf.*, vol. 47, no. 2, pp. 229–243, 2004.