



Shrikant Murlidhar Bante
shrikant.bante769@gmail.com

Lecturer, Mechanical Engineering
Department, Government
Polytechnic, Sakoli, India

Experimental Investigation of Heat Transfer Enhancement in a Rectangular Duct Using Inclined Circular and Triangular Ribs at 45° Orientation

Abstract: Enhancement of convective heat transfer using artificial roughness has gained significant attention for improving the performance of compact heat exchangers. In the present study, an experimental investigation is carried out to evaluate the influence of rib inclination on thermal performance in a rectangular duct. Circular and triangular ribs inclined at 45° are employed to analyze their effect on heat transfer characteristics under identical operating conditions. Experiments are conducted for air velocities ranging from 4 to 4.3 m/s, and the performance is evaluated in terms of heat transfer coefficient, Nusselt number, and heat transfer rate. The results reveal a substantial improvement in thermal performance for inclined rib configurations compared to the smooth duct. The heat transfer coefficient increases by approximately 240% to 255% for circular ribs and 280% to 300% for triangular ribs. Similarly, the Nusselt number shows an enhancement of about 240% to 250% for circular ribs and 280% to 295% for triangular ribs. The heat transfer rate is also significantly improved, with an increase of nearly 92% to 122% for circular ribs and 125% to 166% for triangular ribs relative to the smooth duct. The superior performance of inclined ribs is attributed to the generation of strong secondary flow, streamwise vortices, and improved fluid mixing along the rib direction. The study demonstrates that rib inclination plays a critical role in enhancing convective heat transfer, and among the tested configurations, triangular ribs at 45° orientation provide the highest thermal performance.

Keywords: Heat transfer, Fins, Ribs, Inclination angle

I. INTRODUCTION

Efficient heat transfer is a critical requirement in modern thermal systems such as heat exchangers, gas turbines, refrigeration units, and electronic cooling devices. With the continuous demand for compact and high-performance systems, enhancement of convective heat transfer has become an important area of research. Among the various enhancement techniques, passive methods such as surface

roughening are widely preferred due to their simplicity, low cost, and ease of implementation. Artificial roughness in the form of ribs has proven to be an effective technique for improving heat transfer by modifying the flow structure within the duct[1].

Rib-roughened surfaces enhance heat transfer primarily by disturbing the viscous sublayer, inducing flow separation and reattachment, and generating turbulence. However, the orientation of ribs plays a crucial role in determining the flow behavior and thermal performance. While transverse ribs (90° orientation) mainly create periodic flow separation, inclined ribs introduce a directional component to the flow, resulting in the formation of secondary flow structures and streamwise vortices. These flow features significantly enhance mixing between the fluid layers and improve heat transfer

Article – Peer Reviewed
Published online – 31 December 2021

© 2021 RAME Publishers
This is an open access article under the CC BY 4.0 International License
<https://creativecommons.org/licenses/by/4.0/>

Cite this article – Shrikant Murlidhar Bante, “Experimental Investigation of Heat Transfer Enhancement in a Rectangular Duct Using Inclined Circular and Triangular Ribs at 45° Orientation”, *Int. J. of Analytical, Experimental and Finite Element Analysis*, RAME Publishers, volume 8, issue 4, pp. 129-136, 2021.
<https://doi.org/10.26706/ijaefea.4.8.20211204>

efficiency. The inclination of ribs alters the interaction between the main flow and the surface, thereby increasing the residence time of fluid particles near the heated wall, which contributes to improved thermal performance[2], [3], [4].

Several researchers have investigated the role of artificial roughness in enhancing heat transfer. Onbasioğlu & Onbaşıoğlu [5] reported that rib turbulators substantially increase heat transfer due to enhanced turbulence and boundary layer disruption. Moon et al. [6] studied different roughness geometries and emphasized the importance of rib configuration on thermal and friction characteristics. Alfarawi et al. [7] demonstrated that inclined ribs generate secondary flow patterns, which lead to improved thermal performance compared to transverse ribs. Ghani et al. [8] analyzed various rib geometries and found that sharp-edged ribs such as triangular profiles produce stronger turbulence and higher heat transfer rates. Choi et al. [9] highlighted the effectiveness of rib roughness in solar air heaters, showing that rib inclination significantly influences thermal efficiency. More recent studies by Fouladi et al. [10] and Katti & Prabhu [11] further confirmed that inclined ribs enhance convective heat transfer by promoting flow mixing and increasing interaction between the fluid and heated surface.

In addition to rib geometry and inclination, parameters such as rib height, pitch, and flow Reynolds number also influence the overall thermal performance. The combined interaction of these parameters determines the strength of turbulence, flow recirculation zones, and heat transfer augmentation. Therefore, a systematic evaluation of rib configuration under controlled experimental conditions is essential to understand their individual and combined effects on heat transfer enhancement[12], [13].

Despite the extensive research on ribbed surfaces, most studies have either focused on transverse ribs or investigated inclined ribs without a detailed comparison of different rib geometries under identical conditions. In particular, there is limited experimental work comparing

circular and triangular ribs at a fixed inclination angle of 45° in a rectangular duct[14]. Furthermore, the combined effect of rib inclination and geometry on key thermal parameters such as heat transfer coefficient, Nusselt number, and heat transfer rate has not been comprehensively explored. This creates a gap in understanding the role of rib inclination in enhancing heat transfer performance[15], [16].

In view of the above, the present study aims to experimentally investigate the effect of inclined circular and triangular ribs at 45° orientation on the convective heat transfer characteristics of a rectangular duct. The performance is evaluated in terms of heat transfer coefficient, Nusselt number, and heat transfer rate over a range of air velocities. The objective is to analyze the influence of rib inclination on flow behavior and thermal performance, and to identify the most effective rib geometry for enhanced heat transfer applications.

II. EXPERIMENTAL SETUP

The experimental investigation was conducted using a specially designed test facility developed to analyze the effect of rib inclination on convective heat transfer characteristics in a rectangular duct. A comprehensive schematic of the complete experimental setup is presented in Fig. 1, while detailed views of individual components such as the blower, test section, rib arrangements, and instrumentation are illustrated in Fig. 2 to Fig.5.

The system consists of a centrifugal blower, flow control mechanism, rectangular duct test section, heating arrangement, and measuring instruments. Air is used as the working fluid and is drawn into the duct by the blower, as shown in Fig. 2. The airflow rate is regulated using control valves to achieve the desired velocity range. An anemometer is used to measure the air velocity at the inlet, ensuring accurate determination of flow conditions.

To ensure the development of a stable and uniform flow before entering the test section, an unheated entrance length (commix section) of 150 mm is provided, as shown

in Fig. 3. This section allows the flow to become hydrodynamically developed and minimizes disturbances caused by the blower. Similarly, an unheated exit section of 100 mm is provided downstream of the test section to stabilize the flow before discharge. These sections play a crucial role in maintaining flow uniformity and improving the accuracy of experimental measurements.

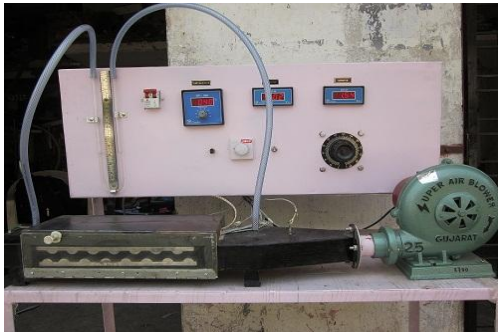


Figure 1. Experimental Setup.



Figure 2. Blower



Figure 3. Rectangular Duct

The main test section, shown in Fig. 3, consists of a rectangular duct having a hydraulic diameter of 0.075 m. The duct dimensions include a height (H) of 50 mm, width (W) of 150 mm, and a total length of approximately 500–650 mm. The heated portion of the duct is 300 mm long and is equipped with an electrical heating coil to provide a uniform heat flux condition along the test surface. The temperature distribution along the duct is measured using

calibrated thermocouples connected to a digital temperature indicator, as depicted in Fig. 4

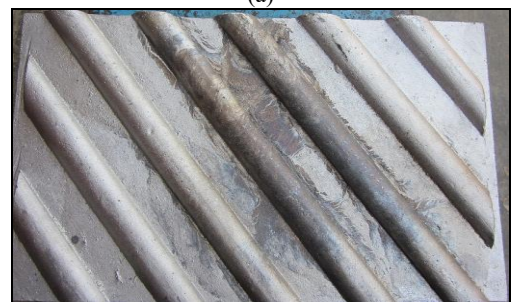


Figure 4. Digital Temperature Indicator

Artificial roughness in the form of ribs is introduced on the heated surface to enhance heat transfer. In the present study, circular and triangular ribs inclined at an angle of 45° with respect to the flow direction are used. The detailed rib configurations are shown in Fig. 5. Each rib has a uniform height (e) of 5 mm and is arranged with a constant pitch (p) of 35 mm. The inclined arrangement of ribs modifies the flow path, introducing a component of velocity along the rib direction, which promotes secondary flow and enhanced mixing. The ribs are fabricated from aluminium, while the duct is constructed using SR sheet material.



(a)



(b)

Figure 5. (a) Circular rib with inclination angle 45° (b) Triangular rib with inclination angle 45°

The electrical input to the heating system 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, providing an indication of flow behavior. All measuring instruments are calibrated prior to experimentation to ensure accuracy and reliability of data.

The experimental setup is designed to facilitate controlled variation of air velocity and rib configuration while maintaining consistent boundary conditions. The inclusion of inclined ribs introduces complex flow interactions, making the setup suitable for analyzing the influence of rib orientation on heat transfer enhancement. The combination of precise instrumentation, well-defined geometry, and controlled operating conditions ensures repeatable and reliable experimental results.

III. METHODOLOGY

The present study employs a systematic experimental approach to investigate the influence of rib inclination on convective heat transfer behavior in a rectangular duct. Unlike conventional transverse rib configurations, the current work focuses on ribs inclined at 45°, which are expected to alter the internal flow structure by introducing a directional component along the rib axis. The experiments are performed for three configurations, namely, a smooth duct (without ribs), circular ribs at 45°, and triangular ribs at 45°, under identical thermal and flow conditions.

The experimental procedure begins with establishing a reference case using a smooth duct configuration. Air is drawn through the duct using a centrifugal blower, and the flow rate is regulated to achieve the required velocity range of 4 to 4.3 m/s. Once the desired flow condition is attained, electrical heating is applied to the test section to impose a uniform heat flux. The system is allowed to reach steady-state conditions, which are ensured when the temperature readings at various locations become constant over time. At this stage, all relevant parameters including air velocity,

surface temperature, air temperature, and electrical input are recorded.

Subsequently, the experiments are conducted with ribbed configurations. Circular and triangular ribs are mounted at an inclination of 45° with respect to the main flow direction. This inclined arrangement modifies the flow dynamics by inducing a component of velocity parallel to the rib orientation, resulting in the formation of streamwise vortices and secondary flow structures. These flow features enhance the interaction between the fluid and the heated surface, leading to improved convective heat transfer. The experimental conditions are carefully maintained identical to those of the smooth duct to ensure a consistent basis for comparison.

The heat supplied to the system is calculated from electrical measurements using the relation:

$$Q = V \times I \quad (1)$$

The mass flow rate of air is determined based on the measured velocity as:

$$\dot{m} = \rho AV \quad (2)$$

The Reynolds number, representing the flow regime, is evaluated using:

$$Re = \rho VD / \mu \quad (3)$$

The convective heat transfer coefficient is obtained from:

$$h = Q / (A_s (T_s - T_f)) \quad (4)$$

and the corresponding Nusselt number is calculated as:

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

In contrast to transverse rib arrangements, the inclined ribs increase the residence time of fluid particles near the heated surface and promote continuous mixing along the flow direction. This results in a more effective disruption of the thermal boundary layer and enhanced energy transfer. The collected experimental data are processed to analyze the variation of heat transfer coefficient, Nusselt number, and heat transfer rate with respect to air velocity.

The methodology emphasizes understanding the role of rib inclination in modifying flow behavior and improving thermal performance.

IV. RESULTS AND DISCUSSION

The experimental results obtained for the smooth duct, circular ribs at 45°, and triangular ribs at 45° are analyzed in terms of heat transfer coefficient, Nusselt number, and heat transfer rate. The variation of these parameters with air velocity is illustrated in Fig. 6, Fig. 7, and Fig. 8, respectively. The results highlight the significant influence of rib inclination on flow behavior and thermal performance.

The variation of heat transfer coefficient with air velocity is presented in Fig. 6. It is observed that the heat transfer coefficient increases consistently with increasing air velocity for all configurations. This is primarily due to the increase in Reynolds number, which enhances turbulence intensity and reduces the thermal boundary layer thickness. However, the effect of rib inclination is highly pronounced in this case. The circular ribs inclined at 45° show a substantial increase in heat transfer coefficient compared to the smooth duct, with values rising from 1317.84 W/m²K to 1571.21 W/m²K, while triangular ribs exhibit even higher values ranging from 1466.6 W/m²K to 1722.25 W/m²K. The enhancement is significantly higher than that observed for transverse ribs, indicating the strong influence of rib inclination.

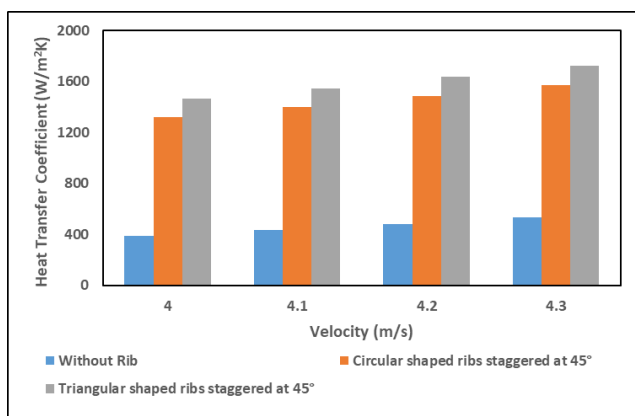


Figure 6. Variation of heat transfer coefficient with air velocity

This improved performance can be attributed to the flow redirection caused by inclined ribs. Unlike transverse ribs, which primarily induce flow separation, inclined ribs introduce a component of velocity along the rib direction. This generates streamwise vortices and secondary swirling motion, which enhance mixing between the core flow and the near-wall fluid. As a result, the thermal boundary layer is continuously disrupted and reformed, leading to higher convective heat transfer coefficients. Triangular ribs further intensify this effect due to their sharp edges, which produce stronger flow separation and localized turbulence.

The variation of Nusselt number with air velocity is shown in Fig. 7, and it follows a trend similar to that of the heat transfer coefficient. The Nusselt number increases with velocity for all configurations, confirming the enhancement in convective heat transfer. For circular ribs at 45°, the Nusselt number increases from 3542.5 to 4223.6, while triangular ribs show a higher range from 3942.47 to 4629.7. The magnitude of enhancement is considerably higher than that of the smooth duct, indicating the effectiveness of inclined ribs in improving heat transfer performance.

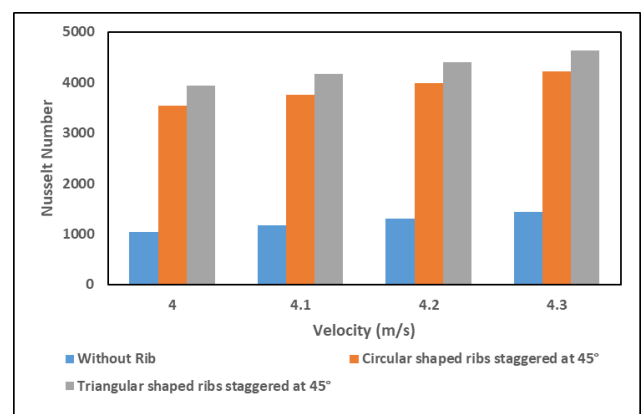


Figure 7. Variation of Nusselt number with air velocity

The underlying reason for this behavior lies in the modification of flow structures due to rib inclination. The inclined ribs create a helical or swirling motion in the flow, which increases the interaction between fluid layers and enhances heat transfer. The presence of streamwise vortices ensures that high-energy fluid from the core region continuously interacts with the heated surface, thereby

increasing the temperature gradient and improving heat transfer. Additionally, the triangular ribs generate sharper and more intense vortices compared to circular ribs, leading to higher Nusselt numbers across all velocity ranges.

The variation of heat transfer rate with air velocity is depicted in Fig. 8, which provides a comprehensive understanding of the overall thermal performance of the system. The heat transfer rate increases significantly with increasing air velocity for all configurations due to the combined effect of increased mass flow rate and enhanced heat transfer coefficient. For circular ribs at 45°, the heat transfer rate increases from 669.63 W to 827.83 W, while triangular ribs show a higher increase from 803 W to 972 W

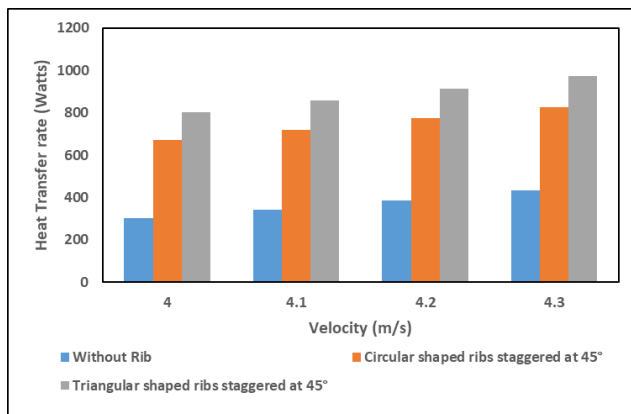


Figure 8. Variation of heat transfer rate with air velocity

The substantial enhancement in heat transfer rate for inclined rib configurations is a direct consequence of improved flow dynamics. As the velocity increases, the mass flow rate of air increases, allowing more fluid to carry heat away from the surface. Simultaneously, the inclined ribs enhance the convective heat transfer coefficient by promoting continuous mixing and increasing the effective heat transfer area. The directional flow induced by the 45° ribs increases the residence time of fluid particles near the heated surface, allowing more energy exchange. This effect is more prominent in triangular ribs due to their ability to generate stronger turbulence and more effective boundary layer disruption.

Furthermore, the combined influence of rib inclination and geometry leads to a synergistic enhancement in thermal performance. While circular ribs provide a smoother redirection of flow, triangular ribs create sharper disturbances, resulting in higher turbulence intensity and improved heat transfer. The consistent increase in heat transfer rate with velocity also indicates that the system operates effectively under higher flow conditions without any adverse thermal behavior.

Overall, the results clearly demonstrate that rib inclination plays a crucial role in enhancing convective heat transfer. The inclined rib configurations significantly outperform the smooth duct, and among them, triangular ribs at 45° orientation provide the highest thermal performance due to their superior ability to generate strong secondary flow, increase turbulence intensity, and enhance fluid mixing.

V. CONCLUSIONS

An experimental investigation has been carried out to evaluate the influence of rib inclination on convective heat transfer characteristics in a rectangular duct using circular and triangular ribs at 45° orientation. The performance has been analyzed in terms of heat transfer coefficient, Nusselt number, and heat transfer rate over a range of air velocities from 4 to 4.3 m/s. The variations of these parameters clearly demonstrate the effectiveness of inclined rib configurations in enhancing thermal performance. The results indicate that all thermal parameters increase with increasing air velocity due to the corresponding rise in Reynolds number and improved convective heat transfer. The introduction of ribs inclined at 45° significantly enhances the thermal performance compared to the smooth duct by modifying the internal flow structure and promoting strong secondary flow and mixing. The heat transfer coefficient shows a substantial enhancement of approximately 240% to 255% for circular ribs and 275% to 300% for triangular ribs compared to the smooth duct. Similarly, the Nusselt number is enhanced by nearly 240% to 250% for circular ribs and 280% to 295% for triangular

ribs, as observed in Fig. 4.2. The heat transfer rate also increases significantly, with an improvement of about 92% to 122% for circular ribs and 125% to 166% for triangular ribs relative to the smooth duct. The superior performance of inclined ribs is attributed to the generation of streamwise vortices, enhanced turbulence, and improved fluid mixing along the rib direction. The 45° orientation introduces a directional component to the flow, which increases the interaction between the fluid and the heated surface, thereby improving heat transfer. Among the tested configurations, triangular ribs exhibit the highest thermal performance due to their sharp geometry, which induces stronger flow separation and more effective boundary layer disruption. Overall, the study demonstrates that rib inclination is a critical parameter in heat transfer enhancement, and the use of triangular ribs at 45° orientation can significantly improve the efficiency of heat exchangers. The findings provide valuable insights for the design and optimization of advanced thermal systems.

REFERENCES

- [1] W. Peng, P.-X. Jiang, Y.-P. Wang, and B.-Y. Wei, "Experimental and numerical investigation of convection heat transfer in channels with different types of ribs," *Appl. Therm. Eng.*, vol. 31, no. 14–15, pp. 2702–2708, 2011.
- [2] M. Imbriale, M. Panelli, and G. Cardone, "Heat transfer enhancement of natural convection with ribs," *Quant. Infrared Thermogr. J.*, vol. 9, no. 1, pp. 55–67, 2012.
- [3] I. A. Ghani, N. Kamaruzaman, and N. A. C. Sidik, "Heat transfer augmentation in a microchannel heat sink with sinusoidal cavities and rectangular ribs," *Int. J. Heat Mass Transf.*, vol. 108, pp. 1969–1981, 2017.
- [4] P. Singh and S. Ekkad, "Experimental study of heat transfer augmentation in a two-pass channel featuring V-shaped ribs and cylindrical dimples," *Appl. Therm. Eng.*, vol. 116, pp. 205–216, 2017.
- [5] S. U. Onbasioğlu and H. Onbaşıoğlu, "On enhancement of heat transfer with ribs," *Appl. Therm. Eng.*, vol. 24, no. 1, pp. 43–57, 2004.
- [6] M.-A. Moon, M.-J. Park, and K.-Y. Kim, "Evaluation of heat transfer performances of various rib shapes," *Int. J. Heat Mass Transf.*, vol. 71, pp. 275–284, 2014.
- [7] S. Alfarawi, S. A. Abdel-Moneim, and A. Bodalal, "Experimental investigations of heat transfer enhancement from rectangular duct roughened by hybrid ribs," *Int. J. Therm. Sci.*, vol. 118, pp. 123–138, 2017.
- [8] I. A. Ghani *et al.*, "Heat transfer enhancement in microchannel heat sink using hybrid technique of ribs and secondary channels," *Int. J. Heat Mass Transf.*, vol. 114, pp. 640–655, 2017.
- [9] E. Y. Choi, Y. D. Choi, W. S. Lee, J. T. Chung, and J. S. Kwak, "Heat transfer augmentation using a rib-dimple compound cooling technique," *Appl. Therm. Eng.*, vol. 51, no. 1–2, pp. 435–441, 2013.
- [10] F. Fouladi, P. Henshaw, D.-K. Ting, and S. Ray, "Flat plate convection heat transfer enhancement via a square rib," *Int. J. Heat Mass Transf.*, vol. 104, pp. 1202–1216, 2017.
- [11] V. Katti and S. V. Prabhu, "Heat transfer enhancement on a flat surface with axisymmetric detached ribs by normal impingement of circular air jet," *Int. J. Heat Fluid Flow*, vol. 29, no. 5, pp. 1279–1294, 2008.
- [12] N. Zheng, W. Liu, Z. Liu, P. Liu, and F. Shan, "A numerical study on heat transfer enhancement and the flow structure in a heat exchanger tube with discrete double inclined ribs," *Appl. Therm. Eng.*, vol. 90, pp. 232–241, 2015.
- [13] B. Lu and P.-X. Jiang, "Experimental and numerical investigation of convection heat transfer in a rectangular channel with angled ribs," *Exp. Therm. Fluid Sci.*, vol. 30, no. 6, pp. 513–521, 2006.
- [14] A. Chaube, P. K. Sahoo, and S. C. Solanki, "Analysis of heat transfer augmentation and flow characteristics

due to rib roughness over absorber plate of a solar air heater,” *Renew. Energy*, vol. 31, no. 3, pp. 317–331, 2006.

[15] J.-M. Buchlin, “Convective heat transfer in a channel with perforated ribs,” *Int. J. Therm. Sci.*, vol. 41, no. 4, pp. 332–340, 2002.

[16] A. P. Rallabandi, D.-H. Rhee, Z. Gao, and J.-C. Han, “Heat transfer enhancement in rectangular channels with axial ribs or porous foam under through flow and impinging jet conditions,” *Int. J. Heat Mass Transf.*, vol. 53, no. 21–22, pp. 4663–4671, 2010.