

Investigating The Effects Of Longitudinal Ribs With Various Configurations Within An Elliptical Tube On Heat Transfer Rate And Thermal Performance

Ebrahim Alabdali¹, Kedar Sant²

^{1,2} Faculty of Mechanical Engineering, Vishwakarma University, Pune, Maharashtra,
India.alabdaliebrahim@gmail.com kedar.sant@vupune.ac.in

*Corresponding Authors;

Ebrahim Alabdali * alabdaliebrahim@gmail.com, Kedar Sant * kedar.sant@vupune.ac.in

Abstract:

Conservation of energy is regarded as a critical issue in contemporary discourse; consequently, further research and investigation are necessary to identify strategies and methods that facilitate this objective. This investigation was conducted to compare the effectiveness of various longitudinal rib geometries applied to an elliptical tube in enhancing the heat transfer rate and improving thermal performance. Longitudinal ribs are structural elements that are affixed to the inner surface of a tube, extending parallel to its length. The primary function of these longitudinal ribs is to increase the effective contact surface area, disrupt the fluid layers, and decrease the hydraulic diameter, thereby improving the heat transfer rate at an acceptable pressure drop. In this investigation, four geometric shapes of ribs, semicircular, triangular, rectangular, and trapezoidal, were employed. The objective is to identify the optimal geometric configuration that maximizes the heat transfer rate at a low penalty for pressure drop, ultimately enhancing the thermal performance factor. Investigations were carried out utilizing Star CCM+ software, employing air as the working fluid, with the Reynolds number varying between 1600 and 6500. The results indicate that longitudinal trapezoidal ribs (LTRs) significantly increased heat transfer by (400% - 690%) compared to plain tube and exhibit a high thermal performance factor, reaching a value of 5, compared to other longitudinal rib geometries.

Keywords: Heat transfer enhancement techniques, Thermal Performance, Longitudinal Ribs, Elliptical tube.

1. Introduction

Heat transfer enhancement techniques significantly contribute to improving the heat transfer rate between the fluid flow within the channel and the channel's surface. They facilitate improved thermal exchange through various mechanisms, including the augmentation of fluid turbulence, disruption of boundary layers adjacent to surfaces, separation and subsequent reattachment of fluid flow layers, and the increase of the contact surface area with the fluid, alongside a reduction in the hydraulic diameter of the channel. Heat transfer enhancement techniques can be categorized into three distinct groups based on their external energy requirements: active, passive, and combined techniques. Active techniques necessitate the use of external energy to augment heat transfer, whereas passive techniques depend on modifications to the geometry of the channel or the incorporation of insert devices that induce swirl flow and disrupt the fluid flow within the channel. The combined technique employs multiple methods to enhance the heat transfer rate. Passive techniques, which do not necessitate external energy sources to enhance heat transfer, have been the subject of numerous studies and investigations aimed at identifying optimal methods for achieving such improvements. Turbulator ribs are among the most effective methods employed to enhance heat transfer rates, and numerous studies have been conducted to investigate the effects of various rib geometries and configurations. Kuwata, Y. [1] The implementation of high-aspect-ratio longitudinal ribs results in a favorable deviation from the Reynolds analogy, wherein the

enhancement of the heat transfer rate exceeds that of the frictional resistance. This phenomenon is attributed to an increase in turbulent heat flux relative to Reynolds shear stress, despite the mitigating impact of rib-induced secondary flow on this effect. Hosseinali Soltanipour, Parisa Choupani, I. Mirzaee [2] found that using γ -Al₂O₃/water nanofluid along with longitudinal ribs in a curved duct significantly improves heat transfer rates. The introduction of nanoparticles enhances the heat transfer coefficient, especially at low Dean numbers. Additionally, longitudinal ribs consistently boost heat transfer rates in water flow, and their combination with the nanofluid leads to a marked improvement over a smooth duct. B. Betti, F. Nasuti, Emanuele Martelli [3] Longitudinal wall ribs can enhance heat transfer in rocket engine thrust chambers by increasing the surface area, but increasing rib height can lead to reduced efficiency due to thermal stratification. Luca Baggetta, F. Satta, and G. Tanda [4] discuss how the introduction of inclined longitudinal ribs (intersecting ribs) aligned with the main flow direction can improve the performance of turbine blade internal cooling. This enhancement occurs by influencing secondary flows and increasing heat transfer coefficients in channels with large aspect ratios. A. Yousefi, A. Nejat, and M. Sabour [5] investigated the enhancement of heat transfer in an internally cooled turbine vane with a ribbed channel using conjugate heat transfer simulation. Their selected ribbed configuration increased total heat transfer by up to 25%, accompanied by only a 3% rise in the friction factor. Additionally, the performance factor improved by up to 24%, and the maximum temperature decreased by approximately 25 K. Wang, Dan et al. [6] found that incorporating longitudinal ribs into a spiral tube significantly enhances fluid flow and thermal efficiency, resulting in increased Nusselt numbers and thermal hydraulic performance parameters (THPP). Among the various designs, the spiral tube with rectangular-shaped ribs achieved the highest Nusselt number. While increasing the depth and number of ribs improves heat transfer performance, it also leads to greater exergy destruction. The overall improvement varies between 18.4% and 27.9% depending on the rib shapes used. Yang Yang, D. S. Ting, and S. Ray [7] discuss how passive turbulence generators, like winglets and wings, can enhance heat transfer rates by creating persistent longitudinal vortices. Furthermore, flexible turbulence generators offer potential for improving heat transfer through the oscillation of turbulent vortex streets.

Combining these enduring vortex streets with periodic fluttering presents a promising approach to maximizing heat convection. S. Gokul and M. Deepu [8] found that helical ribs significantly enhance heat transfer by inducing greater vorticity and turbulence, outperforming longitudinal ribs in thermal performance. Arjumand Rasool and A. Qayoum [9] reported that perforated ribs improve local heat transfer distribution by generating longitudinal vortices, which enhance flow mixing and turbulent kinetic energy. Notably, square perforated ribs achieve a normalized average Nusselt number that is 37.1–57.3% higher than that of solid ribs, demonstrating the best thermal-hydraulic performance despite a higher pressure drop. P. Zhang, Chao Xu, Y. Rao, and Ce Liang [10] conclude that the V rib-dimple hybrid structure significantly enhances heat transfer rates—particularly on the trailing wall—by as much as 39.13% at a rotation number of 0.413.

This structure also minimizes the heat transfer difference between the leading and trailing sides when compared to a channel with only dimples, indicating a more uniform improvement in heat transfer. Zheng, Shao-Fei et al. [11] demonstrate that a novel hierarchical arrangement of ribs can enhance cooling efficiency by reducing friction loss and improving heat transfer for specific rib configurations, resulting in an overall performance improvement exceeding 10%. Yang, Xuguang et al. [12] find that optimizing structural parameters in ribbed channels can significantly boost heat dissipation. In particular, L, V, and W-shaped ribs show improvements in Nusselt numbers of 83.04%,

155.18%, and 197.17%, respectively, compared to smooth channels. Sunu, Putu Wijaya et al. [13] found that installing longitudinal grooves in a heat exchanger system improves heat transfer, with enhancements ranging from 1.05 to 1.15. However, this also results in a pressure drop of nearly 30% compared to a smooth annulus. Sun, Wen-jing et al.

[14] concluded that the Opt-4 optimized structure exhibits the best overall heat transfer performance, characterized by a low and uniform rotor temperature distribution and an acceptable pressure loss. This indicates successful optimization of longitudinal ribs to enhance the heat transfer rate. Garg, Amit, and Sunil Dhingra [15] demonstrated that incorporating longitudinal ribs and winglet vortex generators significantly improves heat transfer rates and reduces friction loss compared to a smooth wall channel. Their combined use yields higher Nusselt numbers and friction factors than either method alone.

S. Naik and S. Probert [16] reported that longitudinal ribs can enhance heat transfer in variable geometry ducts. The optimal spacing of these ribs is influenced by the rib height-to-length ratio and the Reynolds number. Longitudinal ribs provide greater heat transfer than pin fin arrays at specific ratios and exhibit similar frictional characteristics. The local heat transfer coefficient varies and is affected by the clearance above the ribs, with developing flow conditions common in the channels. Pourmahmoud, N. et al. [17] indicated that the use of longitudinal ribs in microchannels significantly impacts flow and heat transfer. While increasing rib height raises frictional irreversibility, there is an optimal rib height that minimizes heat transfer irreversibility. This optimal height for minimizing total entropy generation depends on the Reynolds number and wall heat flux, suggesting opportunities for improving heat transfer efficiency under certain conditions. Tamang, Sajan et al. [18] conclude that novel rib turbulator configurations, particularly discrete v-shaped rib turbulators with a single break, significantly improve heat transfer. This enhancement occurs due to increased longitudinal secondary flow and turbulence intensity, resulting in a 45.07% increase in the Nusselt number and an 88.57% rise in the thermal performance factor. Ali, Shaukat et al. [19] find that using slitted trapezoidal ribs with varying chamfering angles leads to superior heat transfer rates compared to a flat surface without ribs. The slitted ribs create shorter reattachment lengths and enhance heat transfer in the downstream region, while also enlarging the recirculation area to maximize heat transfer. Tatsumi, Kazuya et al.

[20] report that an oblique discrete rib in a square duct significantly boosts heat transfer rates. The rib's inclination and the gaps between the rib ends and the side walls generate strong secondary flow motion. Chaudhary, M. A. [21] suggests that incorporating artificial roughness, specifically circular ribs with a relative gap width of 1, effectively enhances heat transfer in solar air heaters. However, these rough ribs are not economical or easy to design. The improvement in heat transfer increases with the Reynolds number and reaches a peak at a certain gap width. Zhu, Shiquan et al. [22] demonstrate that swallow-shaped bionic ribs can enhance heat transfer in heat exchanger tubes by promoting multi-vortex swirl, leading to improvements in the Nusselt number by 26.4%-95.6% and in the friction factor by 50.4%-345.8% compared to smooth tubes.

2. Model Description

This Investigation examines the influence of various longitudinal rib geometries on heat transfer and fluid flow characteristics within an elliptical tube. The tube is 100 centimeters in length and 10 millimeters in diameter. Four longitudinal ribs are internally positioned along the top, bottom, and lateral sides of the elliptical tube. The rib configurations analyzed include semicircular, triangular, rectangular, and trapezoidal shapes as illustrated in Figure (1).

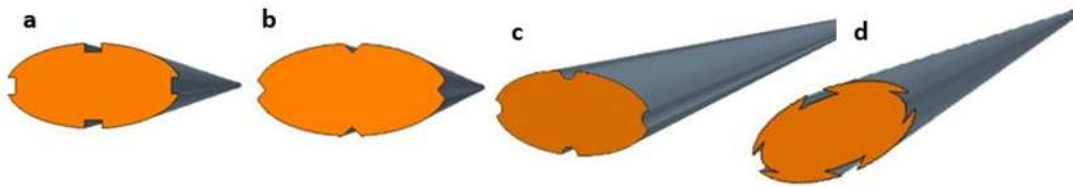


Figure (1): Longitudinal rib geometries a. Rectangular, b. Triangular, c. Semicircular, d. Trapezoid within an elliptical tube.

3. Meshing Parameters & Physics setup

3.1 Mesh Parameters

Node	Property	Set
Base Size	Value	0.0025m
Prism Layer Thickness	Percentage of base	10%
Relative Minimum Size	Percentage of base	10%
Surface Curvature	Circle	36
Surface growth rate	Value	1.3
Relative Target Size	Percentage of Base	100%
Number of Prism Layers	Value	3
Prism Layer Stretching	Value	1.5

Table (1) Meshing Parameters

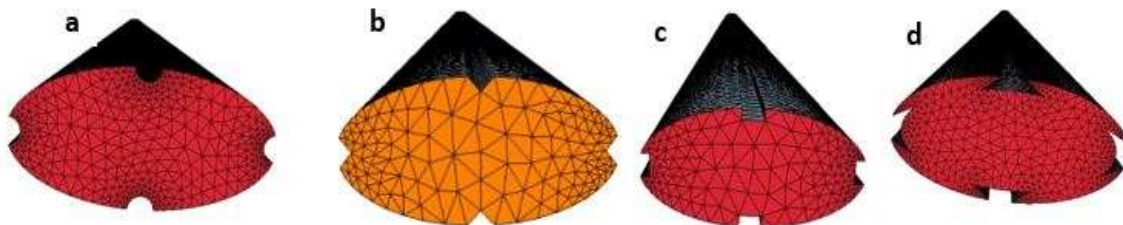


Figure (2): Mesh scene of longitudinal rib a. semicircle, b. triangular, c. square, d. trapezoid within an elliptical tube.

3.2 Physical Criteria

Physics setup	Boundary Condition	Fluid properties
3D Steady Gas Segregated Flow Idea gas Laminar Segregated fluid temperature	$P_0 = 0 \text{ Pa}$ $T_1 = 300 \text{ K}$ Heat flux = 500 w/m^2	$\mu = 0.0000185508 \text{ Pa} \cdot \text{s}$ $k = 0.0260305 \text{ w/m.k}$ Molecular weight= 289664 kg/kmol Specific heat = 1003.62 J/kg.k

Table (2) physics criteria

4. Investigation Result and Discussion:

The primary objective of this investigation is to evaluate the effect of various geometries of the longitudinal ribs within the elliptical tube on heat transfer rate and thermal performance. The longitudinal ribs significantly increase heat transfer and thermal performance through multiple mechanisms, such as increasing the effective heat transfer surface area, boundary layer disruption, and the generation of secondary flow. This investigation utilized different geometric shapes (Triangular, Rectangular, Semi-circular, and Trapezoidal ribs), and the obtained results are detailed as follows:

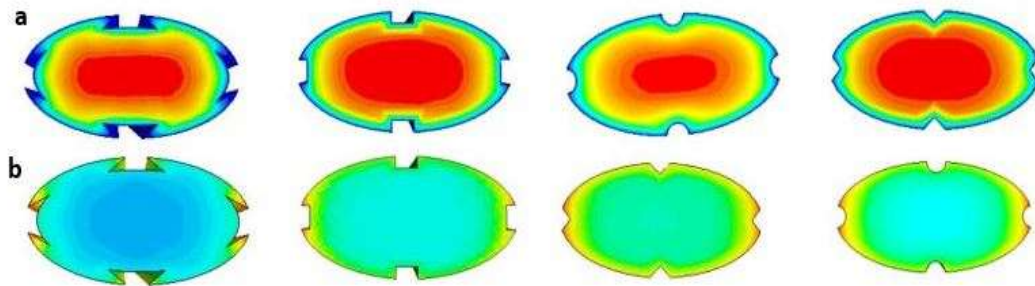


Figure (3): Scalar Scenes a. velocity, b. temperature across an elliptical tube with various rib geometries.

4.1 Nusselt Number:

This investigation examines the effects of various longitudinal rib geometries on the heat transfer rate, termed by the Nusselt number. Specifically, semicircular, triangular, rectangular, and trapezoidal configurations. These longitudinal ribs were affixed to the inner surface of an elliptical tube with the objective of increasing the heat transfer surface area and disrupting the fluid boundary layer to promote mixing and enhance heat transfer. The results indicate a positive correlation between the Nusselt number and the Reynolds number across all rib geometries. The data demonstrates a substantial increase in the Nusselt number upon the incorporation of longitudinal ribs compared to a plain tube. Notably, trapezoidal ribs achieved the highest Nusselt number of (400% - 690%) relative to the plain tube at the same Reynolds number. These findings suggest that longitudinal trapezoidal ribs represent the most effective geometry for augmenting heat transfer in this investigation.

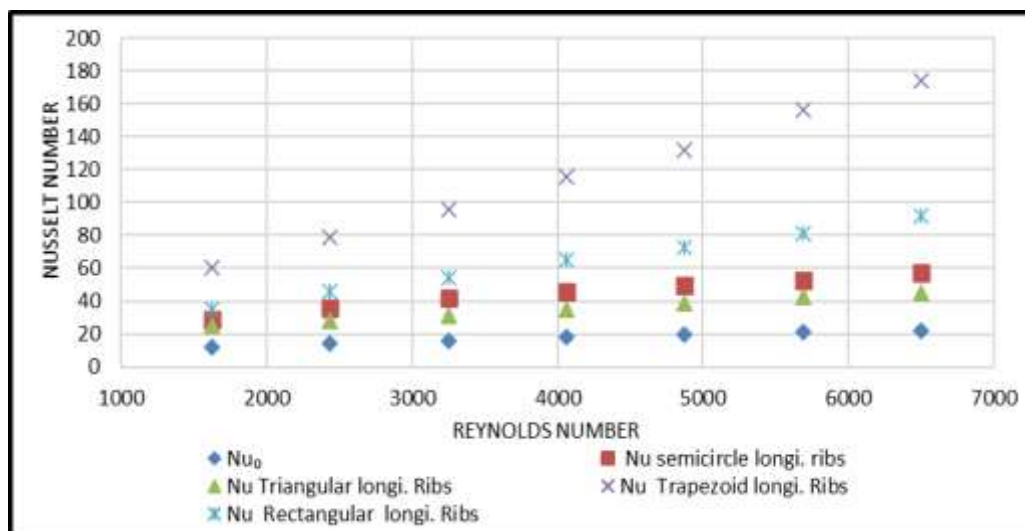
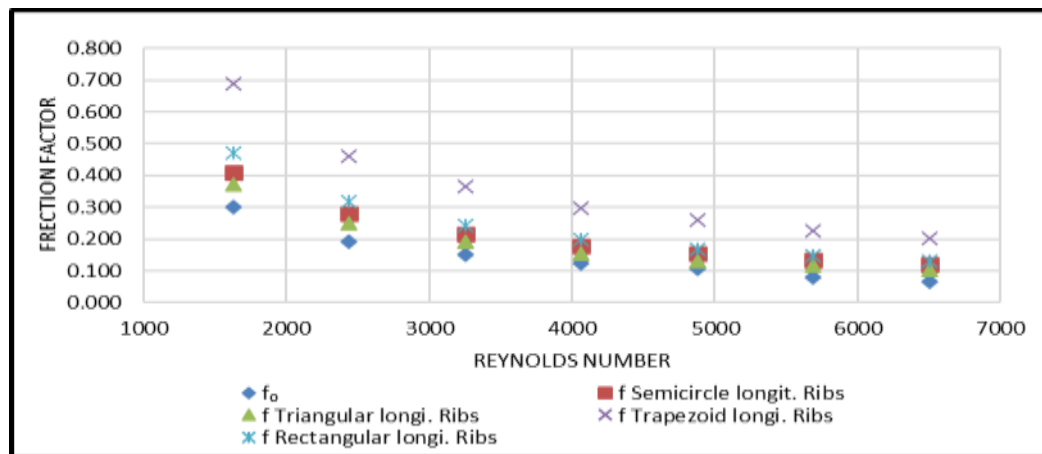


Figure (4) Nusselt number according to Reynolds number value

4.2 Friction Factor:

The friction factor quantifies the resistance to fluid flow within a pipe, a phenomenon significantly influenced by the interaction between the fluid and the pipe wall. This study demonstrates that the incorporation of a longitudinal rib results in an increased pressure drop relative to that observed in a smooth tube. The results obtained reveal that longitudinal trapezoidal ribs provide the highest friction factor among the other geometries utilized in this investigation, and it increased (128 % -200%) compared to the smooth tube. Figure (6) presents the friction factors derived from this investigation across various rib geometries, indicating that trapezoidal ribs yield the highest friction factor.



Figure(5) Friction factor according to Reynolds number value

4.3 Pumping Power:

The flow of fluids in a piping system requires pumping power. This study explores the effects of different longitudinal rib geometries (triangular, rectangular, semicircular, and trapezoidal) integrated into an elliptical tube on fluid flow characteristics and pressure drop inside the tube. As the ribs disturb the boundary layer and increase the effective contact surface area, this leads to an increase in pressure drop inside the tube, leading to an increase in the energy needed for fluid movement. The findings reveal that as the Reynolds number increases, the required pumping power also rises, with ribbed configurations demanding more energy than plain tubes. Among the rib geometries studied, longitudinal trapezoidal ribs exhibit the highest pumping power of 67% compared to smooth tubes. with a peak increase of 67%. The figure (7) shows the value of pumping power associated with each rib geometry.

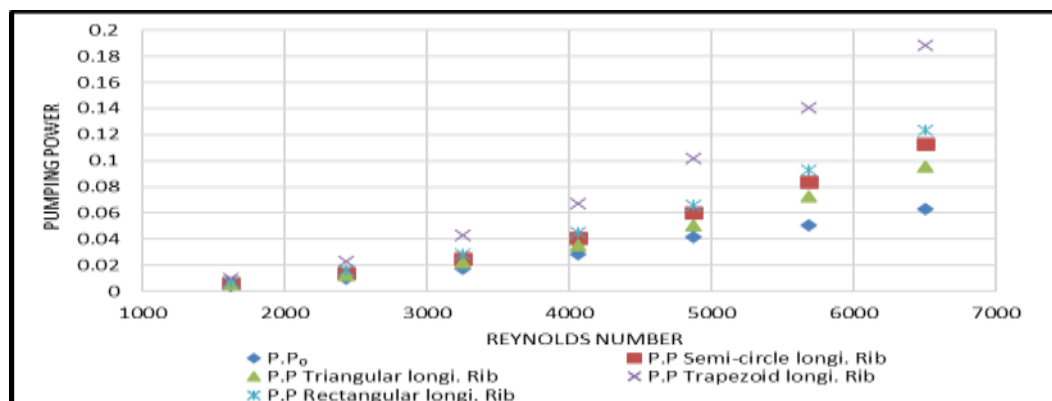
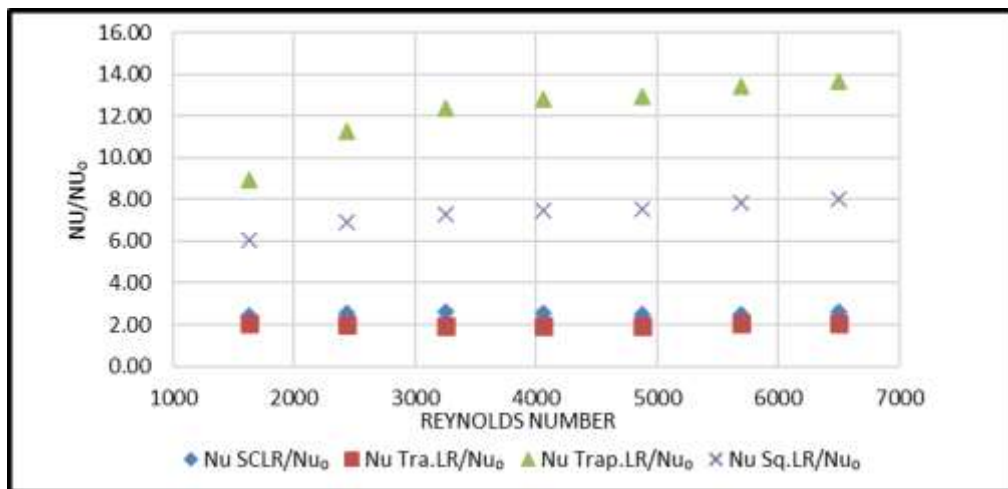


Figure (6) Pumping power according to Reynolds number value**4.4 Nusselt Number Ratio (Nu/Nu_0):**

The Nusselt number ratio is an essential metric for assessing heat transfer efficiency under different conditions. It is defined as the ratio of the Nusselt number for an enhanced surface (Nu) to that of a reference smooth surface (Nu_0) under comparable operating conditions. This dimensionless metric quantifies the relative enhancement in convective heat transfer achieved by longitudinal ribs inside a tube compared to a conventional smooth surface. The figure (8) illustrates that the longitudinal trapezoidal ribs yield the highest Nusselt number ratio in comparison to other rib geometries. This finding suggests that this configuration is the most effective for enhancing heat transfer relative to the other rib configurations examined in this study.

**Figure (7) Nusselt number ratio according to Reynolds number value****4.5 Friction Factor Ratio (f/f_0):**

The ratio of friction factors, derived from heat transfer enhancement techniques, in comparison to a plain tube. It quantifies the hydraulic penalty or cost associated with heat transfer enhancement techniques. The friction factor ratio is indispensable in comprehensive evaluation metrics that balance thermal gains against hydraulic penalties. The figure (9) shows that the longitudinal trapezoidal ribs present the highest friction factor ratio as they provide a high pressure drop compared to other ribs' configurations.

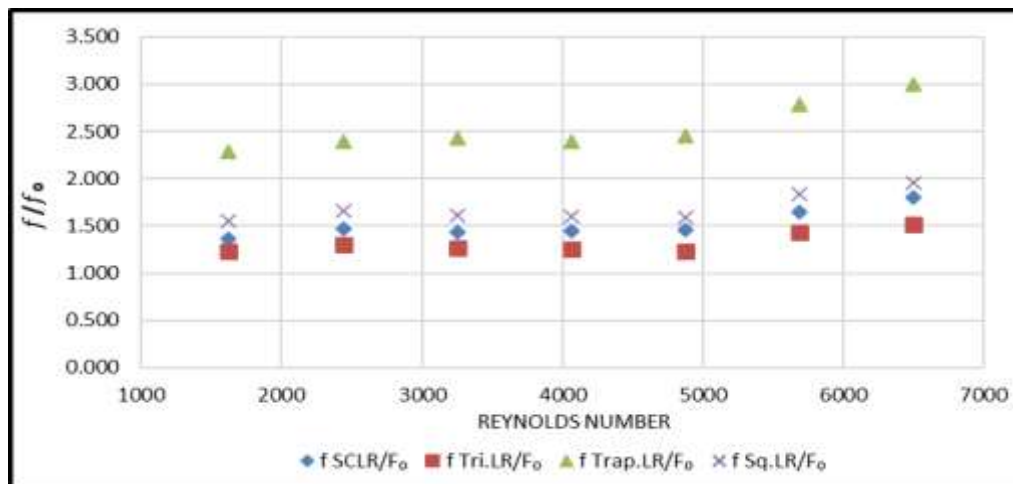
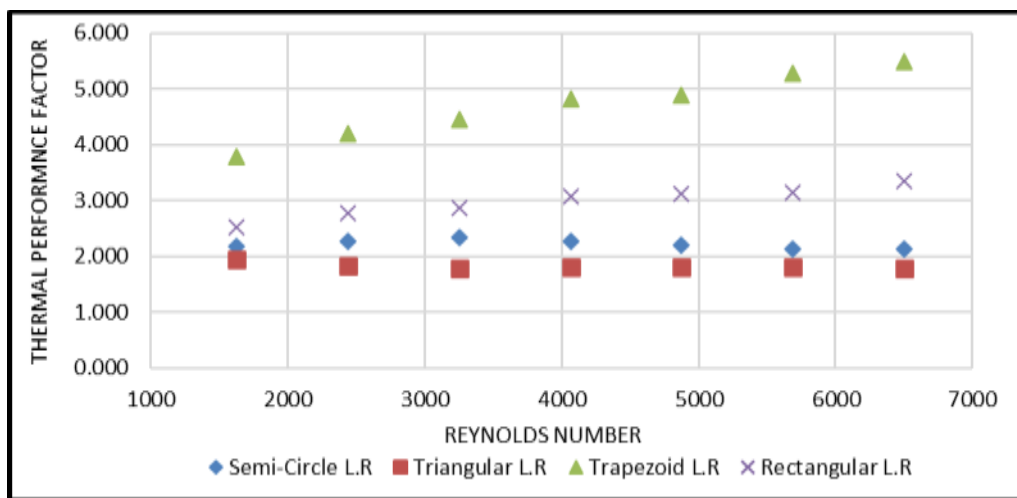


Figure (8) Friction factor ratio according to Reynolds number value**4.6 Thermal Performance Factor:**

The Thermal Performance Factor (TPF) is a crucial metric for evaluating the effectiveness of heat transfer enhancement techniques by simultaneously accounting for thermal gains and hydraulic penalties. This dimensionless parameter allows for a thorough comparison of heat transfer improvements achieved by specific methods against a plain surface. The results obtained from this investigation reveal that trapezoidal ribs yield the highest thermal performance factor of 5. The longitudinal trapezoidal ribs provide the highest thermal performance because they significantly increase the heat transfer rate, despite increasing flow resistance as well.

**Figure (9) Thermal performance factor according to Reynolds number value****5. Conclusion**

This investigation was carried out to find out the impact of longitudinal ribs on heat transfer rate and thermal performance. Various longitudinal rib geometries are situated within an elliptical tube, as this tube configuration has garnered significant attention in heat exchanger design due to its advantageous characteristics and potential for reduced pressure drop relative to other geometrical configurations. The integration of elliptical tube geometry with longitudinal ribs represents a potentially highly effective approach for enhancing heat transfer. The findings derived from this investigation are summarized as follows:

- **Heat transfer rate:** The results of the investigation demonstrated a significant enhancement in the heat transfer rate upon the incorporation of longitudinal ribs on the internal elliptical wall. Among the various rib geometries examined, trapezoidal ribs yielded the highest heat transfer rates. Furthermore, it was observed that as the Reynolds number increased, the Nusselt number also exhibited a corresponding increase, with the maximum Nusselt number achieved through the application of trapezoidal ribs, ranging from 400% to 690% compared to a smooth tube.
- **Friction factor:** Longitudinal ribs increase the fluid flow resistance as they increase the effective surface area and disturb the fluid boundary layers, and this leads to an increase in the pressure drop inside the tube. The investigation results show that among the various rib configurations employed in this investigation, trapezoidal ribs provide a higher friction factor (128% - 200%) in comparison to a plain tube.

- Thermal performance factor: (TPF) is a critical metric for evaluating the efficiency of enhancement techniques and devices in heat transfer applications. This metric quantifies the net benefits of a heat transfer enhancement technique, taking into account the penalty associated with increased pressure drop. The present study investigates various configurations of longitudinal ribs applied to an elliptical tube. These configurations significantly enhance the heat transfer rate; however, this improvement is accompanied by an increase in pressure drop. The findings indicate that all configurations yield satisfactory values of the thermal performance factor, with the highest value of 5 achieved using trapezoidal rib configurations.

Nomenclature

A	area (m ²)	SCLR	Semicircular
C	Specific heat (kJ/ kg. K)	Tr.LR	longitudinal rib
d	diameter (mm)	TLRs	Triangular longitudinal
D	hydraulic diameter (m)	Sq.LR	rib
f	friction factor		Trapezoidal longitudinal
Nu	Nusselt number	Greek	Rib
Re	Reynolds number	symbols	Square longitudinal Rib
Pr	Prandtl number	Δ	
L	length (m)	η	
w	width (m)	μ	difference
k	thermal conductivity (W /	ρ	Efficiency
P	m. k)		dynamic viscosity
h	Pressure (bar)	Subscripts	density
Q	heat transfer coefficient	0	
PP	(W /m ² . k)	b	Subscripts
PEC	heat rate (W)	f	Reference/plain/smooth
TEF	Pumping Power (W)	i	Bulk fluid
Nu/Nu ₀	Performance Evaluation	o	Fluid
f/f ₀	Criterion	s	Inlet
R	Thermal Enhancement	w	Outlet
e/D	Factor		Surface or solid
p/e	Nusselt Number ratio		Wall
LR	Friction Factor ratio		
4SR	Roughness ratio		
	Relative roughness height		
	Relative roughness pitch		
	Longitudinal Ribs		
	Four Side Ribs		

Ethical issue:

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Declarations:

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2- Prof (Dr) Kedar Sant: Reviewed the manuscript.

Competing interests (The authors declare no competing)

Ethics approval (Not applicable)

Consent to participate (Not applicable)

Consent to publish (Not applicable)

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