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Article

The Influence of The Hybrid Technique Utilizing Trapezoidal Longitudinal Ribs and Hemispherical Dimples Within an Elliptical Tube on Thermal-Hydraulic Performance

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Abstract: : This paper introduces a novel hybrid heat transfer enhancement technique combining Longitudinal Trapezoidal Ribs (LTRs) and Inline Hemispherical Dimples (IHDs) on the surface of an elliptical tube. A three-dimensional numerical investigation was conducted using Software STAR-CCM+ to evaluate thermal-hydraulic performance under constant heat flux boundary conditions, with air as the working fluid across a Reynolds number (Re) range of 2,900 to 10,300. The hybrid geometry expands the heat transfer surface area while generating secondary flows and longitudinal vortices that disrupt the hydrodynamic and thermal boundary layers. Quantitative results indicate that the proposed configuration increases the Nusselt number by up to 1,200% compared to a smooth elliptical tube, accompanied by a 410% increase in pumping power. Consequently, a maximum thermal performance factor of approximately 5.8 was achieved, demonstrating that this hybrid geometry is a highly effective passive technique for thermal performance enhancement.

Keywords: Heat transfer enhancement Techniques; Elliptical tube; Longitudinal Trapezoidal ribs; Hemispherical dimple; Thermal performance factor.

1. INTRODUCTION

The increasing demand for the development of high-quality and energy-efficient thermal devices has prompted researchers to dedicate their efforts towards identifying new techniques for enhancing heat transfer. These techniques have the potential to significantly improve the rate of heat transfer within a given system, thereby decreasing the required surface area for heat transfer and increasing overall system efficiency. Heat transfer enhancement techniques play a vital role in various processes where efficient heat transfer is crucial for optimal performance and energy conservation. By increasing the heat transfer rate, these techniques offer opportunities to reduce energy consumption and enhance performance in many systems. Recently, numerous research studies have been conducted to identify the most effective approaches for achieving these desired outcomes. Liu et al. [1] conducted a numerical simulation to examine and emphasize the heat transfer and flow characteristics of vortex tubes in comparison with dimpled tubes and smooth tubes. The findings indicate that the outward protrusions and smooth edges of the vortex tube differ from those found in simple tubes. Santos et al. [2] performed computational fluid dynamics (CFD) analysis to evaluate the thermal-hydraulic efficiency of two enhanced heat transfer tubes against a smooth surface tube. The results revealed that the height of the dimples significantly influences thermal-hydraulic performance more than their diameter. Charaghi et al. [3] explored a new configuration for enhanced tubes through numerical investigation. This novel tube design featured deep dimples on a standard tube, resulting in substantially higher heat transfer rates up to 600% with increased depth and reduced pitch. The performance enhancement coefficient (PEC) observed for these deep dimpled tubes ranged from 1.15 to 3.3. Xie et al. [4] performed a numerical analysis on flow characteristics and heat transfer efficacy of enhanced tubes with tear-drop dimples compared to spherical dimples. Their investigation concluded that the strength and extent of recirculation flows generated by tear-drop dimples significantly enhance heat transfer performance while minimizing pressure loss due to smoother fluid flow along streamlined surfaces. Zheng et al. [5] conducted a numerical study to study bidirectional heat transfer efficiencies in the interior and external vicinity of augmented tubes with ellipsoidal dimples and protrusions. The authors presented the results of their work which indicated that the structures induce vigorous impingement and boundary layer disruptions, benefiting heat transfer for both internal and external flows, as well as the observation that staggered arrangements outperformed aligned ones on overall heat transfer performance with peak PEC values of 1.4 and 142 respectively for internal and external flow. Kim et al. [6] investigated an optimal design for cooling tubes incorporating angled rib turbulators to identify effective geometries; they achieved maximum thermal performance at 54.67. Singh et al. [7] examined straight square channels equipped with criss-cross patterned rib turbulators created by 45° angled ribs and reported differences in thermal-hydraulic characteristics between 1.2 and 1.5 for Reynolds numbers from 30,000 to 60,000, by numerical and experimental methods. Hajabdollahi et al. [8] studied an internally ribbed and grooved tube using numerical simulations to analyze several turbulator rib parameters including groove height (DR), pitch ratio (PR), and Reynolds numbers ranging from 10,000 to 38,000. The results indicated a notable improvement in Nusselt number by approximately 46% compared to experimental outcomes while revealing that friction factors decrease as step height ratios increase.Rasool and Qayoum [9] quantified the influence of perforated ribs on the bottom wall of a two-pass square duct looking into the influence of inclination angles (0°–30°) and hole shape (from circular to square) on internal heat transfer rates as well as frictional forces as turbulence results. The observed performance indicated that perforated ribs distributed the heat transfer of the downstream end wall higher than solid ribs after rib placement; square perforated ribs produced the average Nusselt numbers from 37.1%-57.3% higher than solid ribs, however, had significant pressure decreases and particularly square perforated ribs (Case-3) had the best thermal-hydraulic performance. Ali et al. [10] explored the impact of trapezoidal ribs inserted in a rectangular duct at various Reynolds numbers on various chamfer angles numerically. Change in trapezoidal angle has an effect on small-scale vortices of the leeward corner and may contribute to the decrease of hot spots. Singh et al. [11] investigated four rib shapes: W, M, V and one with an angle 45° within a square channel. They showed that with configurations based on V-shaped ribs and 45° angle, heat transfer rates improved and the thermal-hydraulic performances were greater even than those from dimples or ribs alone. In other studies, Prajapati & Tariq [12] studied local and average heat transfer enhancement distributions in sub-channels with a rib angle of 35° by fluid crystal thermography. They determined a better thermo-hydraulic performance factor (≥ 1) for a sub-channel aspect ratio equal to 1.2. Al-Jibory et al. [13] studied the heat transfer enhancement experimentally for an elliptical passage with different rib geometries. The increase of the mean Nusselt number is associated with higher Reynolds numbers, with the highest value found for rib type 1 combined with channel aspect ratio 2. Moreover, they observed with an increase in Reynolds number, the friction factor increased as well, but rib type 1 had the least pressure drop seen. Rashid et al. [14] performed the numerical studies in the elliptical passage with various rib sizes and aspect ratios on heat transfer improvement. Average Nusselt number was found to increase as the aspect ratio of channel increased; for the aspect ratio of 2 it reached a maximum. In contrast, it was found that as the Reynolds number increased, the friction factor also raised, and rib type 1 also retained less pressure drops among all tested aspect ratios. Sharma et al. [15] researched the effect of pentagonal rib placement in a rectangular duct through which one could maximize heat transfer, indicating enhancement in the region adjacent to square ribs is superior through pentagonal configuration. Bahiraei et al. [16] studied two passive methods V-shaped ribs and nanofluids to obtain passive second-law characteristics of the material with two-phase improvement into a square channel. As their findings suggested, enhanced second law efficiency resulted from both increasing rib height and decreasing pitch. Manjunath et al. [17] performed a study to study the influence of U-shaped turbulator ribs on the heat transfer properties of flat plate solar air heaters performing two-dimensional computational fluid dynamics (CFD) analysis. The U-shaped rib increases the Nusselt number by approximately 1.76 times, and the friction factor goes up by about 1.95 times when compared to the smooth duct. The highest thermal enhancement factor was obtained as 1.5 for a configuration with $P/e=25$. Jang et al. [18] analysed how different shapes of dimples or protrusions within a channel with angled ribs affect the heat transfer coefficient and overall thermal performance. They found that the rib-dimple combined configuration provided the highest performance, but also the greatest pressure drop. Bavil & Razavi [19] Numerically examined rectangular ducts equipped with skewed circular ribs arranged on opposite walls in a staggered formation to assess heat transfer improvement. Their results favored circular ribs over block types for enhancing heat transfer. Additionally, they found that angled ribs significantly improve heat transfer efficiency compared to those positioned at 90°, due to the generation of secondary flows. Hagari et al. [20] investigated how rib density affects heat transfer enhancement in channels fitted with rib turbulators through numerical methods. With lower rib density, small vortices were generated from each rib but dissipated into the mainstream before reaching subsequent ribs. In contrast, higher rib density resulted in larger vortices forming above the ribs and additional smaller vortices within the spaces between them. From behind every second rib, the bigger vortex was formed intermittently and expanded by the interaction with the small downstream vortices. Al-Kayiem et al. [21] investigated the influence of difference of rib turbulator height, on thermal-hydraulic performance of double pipe heat exchangers. Ribs of a lower height in relation to hydraulic diameter

(0.0595) were found to be more effective than larger heights (0.107). Erelli and Saha [22] evaluated the performance of both heat transfer and pressure drop under static two-pass square duct with two joints joints (90° and 60°-V in geometry) with a fixed two-set ribs. The experimental results reported a significant advantage of the 60°-V rib configuration in terms of thermal transfer over the 90° ribs. Tang et al. [23] studied the influence of deflectors on heat transfer and flow forces using elliptical ribbed channels. In elliptical ribbed channels their heat transfer coefficient is roughly 3-4 thrice that of grooved channels, which also demonstrated the increase of heat transfer coefficient and pressure drop with higher rib height. Kumar et al. [24] performed simulations, numerical and experimental studies, to enhance heat transfer for dimpled ribbed tubes that are employed as heat exchangers. In their simulation, they achieved an impressive 3.18 times increase in heat transfer, and 2.87 times in thermal-hydraulic performance.

2. Model Description

This work aims to enhance the efficiency of the elliptical tube by shaping its geometry. The longitudinal trapezoidal ribs (LTRs) and the inline hemispherical dimples located on the inner wall of the tube were found to facilitate this process. Ribs and Dimples are known passive enhancement techniques that may increase contact surface area, separate and reattach fluid, create vortices, reduce the thickness of boundary layers located close to the wall, and develop secondary flow. These effects result in a higher heat transfer rate. The elliptical tube used in this investigation has a cross-sectional area of 40 mm for the major axis, 20 mm for the minor axis, and a length of 50 cm, as illustrated in Figure 1. The dimples, with a radius of 2mm, are arranged in an inline configuration on the inner wall of the modified elliptical tube shown in Figure 2.

Fig (1). Elliptical duct's length (50 cm)

Fig (2): (a). Cross-section of plain elliptical duct (b). Cross-section of an Elliptical duct with 2 side longitudinal trapezoidal ribs and 2 side dimples (c). Cross-section of an Elliptical duct with 4 side longitudinal trapezoidal ribs and 4 side dimples.

3. Parameters Definition

This investigation conducts a computational fluid dynamics (CFD) analysis of heat transfer and friction factor characteristics in a modified elliptical tube equipped with longitudinal trapezoidal ribs and inline dimples, for low Reynolds number conditions and constant heat flux. Key parameters, including the Nusselt number, friction factor, Nusselt number ratio, friction factor ratio, and thermal performance factor, are calculated to evaluate the efficacy of the enhancement techniques. The present investigation utilizes Star CCM+ software to perform the simulation, aiming to identify the effects of this innovative configuration. The governing equations for fluid flow and heat transfer in this simulation are based on the principles of conservation laws.

Conservation of Mass equation: The rate of increase of mass in a fluid element is equal to the net flow of mass into the fluid element.

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0 \qquad (1)$$

Conservation of Momentum: The rate of change of momentum of a fluid particle equals the sum of the forces on the fluid particle.

$$\rho(u.\nabla u) = -\nabla p + \mu\nabla^2 u \qquad (2)$$

Conservation of Energy: The rate of change of energy of a fluid particle is equal to the rate of heat addition to the fluid particle plus the rate of work done on the particle.

$$\rho C_p\,(u.\nabla T = k(\nabla^2 T) \qquad (3)$$

Navier-Stokes equations: They are partial differential equations that describe the motion of viscous fluid substances. Mathematically, they express momentum balance and conservation of mass for Newtonian fluids. They can be written in the most useful form for the development of the finite volume method

$$\rho\,\frac{Du}{Dt} = -\frac{\partial\rho}{\partial x} + div(\mu\,grad\,u) + S_{Mx} \qquad (4)$$

$$\rho\,\frac{Dv}{Dt} = -\frac{\partial\rho}{\partial y} + div(\mu\,grad\,v) + S_{My} \qquad (5)$$

$$\rho\,\frac{Dw}{Dt} = -\frac{\partial\rho}{\partial z} + div(\mu\,grad\,w) + S_{Mz} \qquad (6)$$

3.1 Convection heat transfer:

A fundamental concept in thermodynamics that plays a crucial role in various engineering processes. It refers to the transfer of heat energy between a solid surface and a fluid, such as air or liquid, through the bulk movement of the fluid. This transfer occurs due to differences in temperature and fluid density. By enhancing convection heat transfer, the efficiency of any device can be improved. The expression for convection heat transfer is as follows:

$$qconv = h(Ts - T\infty) \qquad (7)$$

3.2 Reynolds number (Re):

It is a dimensionless quantity that is utilized to determine the type of flow regime (laminar, transitional, or turbulent). The Reynolds Number is also employed in the design of hydraulic systems and piping networks, aiding in the optimization of flow rates and the minimization of pressure drop. This number is crucial in the field of fluid dynamics and is extensively utilized in the study of various phenomena, including heat transfer, hydrodynamics, and aerodynamics.

$$Re = \frac{\rho V\,D_h}{\mu} \qquad (8)$$

3.3 Prandtl Number (Pr):

It is a dimensionless number that represents the viscosity of a fluid. It has become one of the most crucial tools in the field of fluid mechanics as it determines the characteristics of fluid flow and its heat transfer properties. Additionally, it defines the relative thickness of the boundary layer around a moving object. The Prandtl number is defined as the ratio of momentum diffusivity to thermal diffusivity.

$$Pr = v\,/\,\alpha \qquad (9)$$

3.4 Nusselt Number:

It is a significant dimensionless parameter utilized in convection analysis to determine the rate of heat transfer from a surface. It provides crucial information about the rate of heat transfer from a solid surface to a surrounding liquid or gas. The Nusselt number increases with higher fluid velocity or a decrease in boundary layer thickness, resulting in an enhanced heat transfer rate. It is defined as the ratio of convective to conductive heat transfer across the solid-fluid boundary.

$$Nu = \frac{hD_h}{k} \qquad (10)$$

3.5 Friction factor:

The friction factor is a dimensionless value that quantifies the energy loss caused by friction in fluid flow through a pipe. Several factors, including the pipe material, surface roughness, and fluid properties such as nature and velocity, influence it.

$$f = \frac{\nabla p}{(\frac{1}{2}pu^2)(\frac{L}{D_h})} \quad (11)$$

3.6 Pumping Power:

Pumping power refers to the mechanical energy needed to overcome flow resistance and sustain fluid circulation through a heat exchanger.

$$P = Q \cdot \Delta P \quad (12)$$

3.7 Thermal Performance Factor:

The TPF is a dimensionless factor that quantifies the efficiency of heat transfer within a system. Maximizing the thermal performance factor helps to minimize energy waste and improve overall process efficiency. It is defined as the ratio of the actual heat transfer rate in a system to the maximum achievable heat transfer rate.

$$TPF = \frac{Nu/Nu_0}{(f/f_0)^{1/3}} \quad (13)$$

4. Meshing Parameters & Physics setup

4.1 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

• Grid independence study

Mesh Case	Base Size (m)	Nusselt Number (Nu)	Friction Factor (f)
M1	0.0050	10.8	0.275
M2	0.0025	12:00	0.302
M3	0.00125	12.15	0.304

. Table (2) Mesh Convergence

The mesh with a base size of 0.0025 m was selected based on the grid independence study, as it provides mesh-independent results with high accuracy and minimal computational expense.

4.2 Physical Criteria

Physics setup	Boundary Condition	Fluid properties

3D Steady Gas Segregated Flow Idea gas Laminar Segregated fluid temperature	$P_0 = 0$ Pa $T_I = 300$ K Heat flux = 500 w/m^2	$\mu = 0.0000185508 Pa - s$ $k = 0.0260305\ w/m.k$ Molecular weight= $289664\ kg/kmol$ Specific heat $= 1003.62\ J/kg.k$

Table (3) Physics criteria

5. Results and Discussion

Heat transfer enhancement techniques are typically employed to reduce thermal resistance in a system by either increasing the effective heat transfer surface area or creating turbulence. The focus of the present investigation was on conducting a numerical investigation to determine the heat transfer characteristics and pressure drop in an elliptical tube with an inline arrangement of ribs and dimples. In this model, the modified elliptical tube allows for an increase in the heat transfer surface area, while the dimples promote swirl flow within the tube and enhance the fluid flow turbulence. This combination results in a significant improvement in heat transfer. Additionally, this augmentation is accompanied by an acceptable increase in pressure drop, leading to a significant improvement in the thermal performance factor. The following figures show the elliptical tube geometries, meshing, and temperature and velocity scalar scenes.

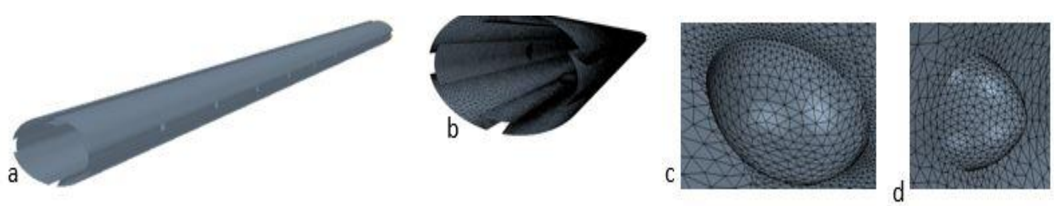

Fig. (3). (a) Geometrical shape of the enhanced elliptical tube. (b) Meshing of the enhanced elliptical tube. (c) Upper and bottom dimples (d) Side dimples.

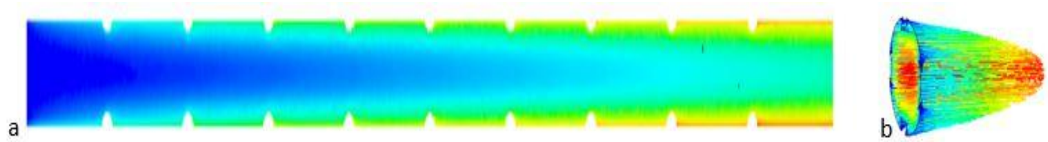

Fig. (4). (a). Scalar Scene of Longitudinal cross-section of Temperature distribution inside the tube.

(b) Vector scene of velocity.

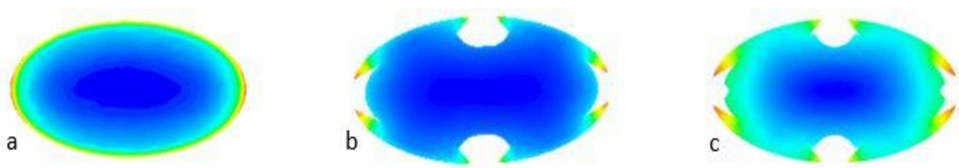

Fig. (5). Temperature Scalar Scene (a). Plain elliptical tube. (b) Elliptical duct with 4 side longitudinal trapezoidal ribs and 2 side dimples (c) Elliptical duct with 4 side longitudinal trapezoidal ribs and 4 side dimples.

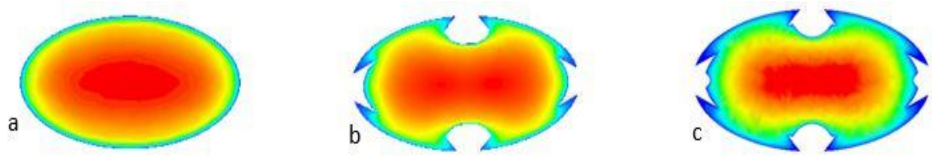

Fig. (6). Velocity Scalar Scene (a). Plain elliptical tube. (b) Elliptical duct with 4 longitudinal trapezoidal ribs and 2 side dimples (c) Elliptical duct with 4 side longitudinal trapezoidal ribs

and 4 side dimples

- **Validation against Smooth Tube Correlations**

To validate this investigation, the Nusselt number obtained from the simulation results for a smooth elliptical tube with a hydraulic diameter is compared with the Nusselt number calculated using the Gnielinski correlation. The Gnielinski correlation is considered the gold standard for the transitional to low-turbulent regime (2300 < Re < 106) and for air with a Prandtl number (Pr) of 0.7.

$$Nu = \frac{(f/8)(Re-1000)P_r}{1+12.7(f/8)^{0.5}({P_r}^{2/3}-1)} \qquad (13)$$

For smooth tubes in the transition and turbulent regimes, the Petukhov correlation is the most common and accurate method for determining the friction factor:

$$f = (0.79 \ln Re - 1.64)^{-2} \qquad (14)$$

As Figure 4 illustrates, the numerical results strongly correlate with the Gnielinski correlation. With a maximum deviation of less than 8%, the CFD model is validated for this heat transfer investigation.

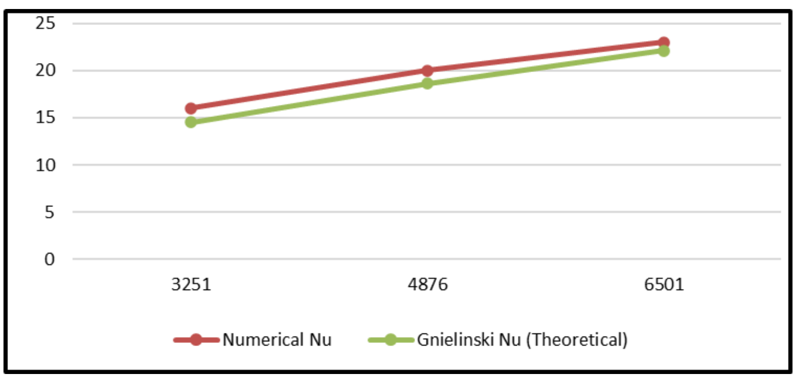

Figure (7) Validation of the numerical Nusselt number against the

Gnielinski correlation for an elliptical tube

The diverse parameter data obtained from this investigation are detailed below:

5.1 Nusselt Number:

As this parameter serves as a measure of the heat transfer rate and is a critical factor in the design and analysis of equipment, the results obtained from this study indicate that the elliptical tube with four-sided longitudinal trapezoidal ribs and inline semicircular dimples on all four sides provides the highest Nusselt number, 1200%, compared to the plain tube. This design demonstrates superior heat transfer performance compared to the other configurations examined. The incorporation of trapezoidal ribs serves to augment the heat transfer surface area, facilitating increased fluid interaction with the heated surface while also disrupting the thermal boundary layers adjacent to the wall. Conversely, the presence of dimples enhances heat transfer by generating vortices, which promote fluid mixing in proximity to the surface, further disrupting the thermal boundary layer and promoting turbulence.

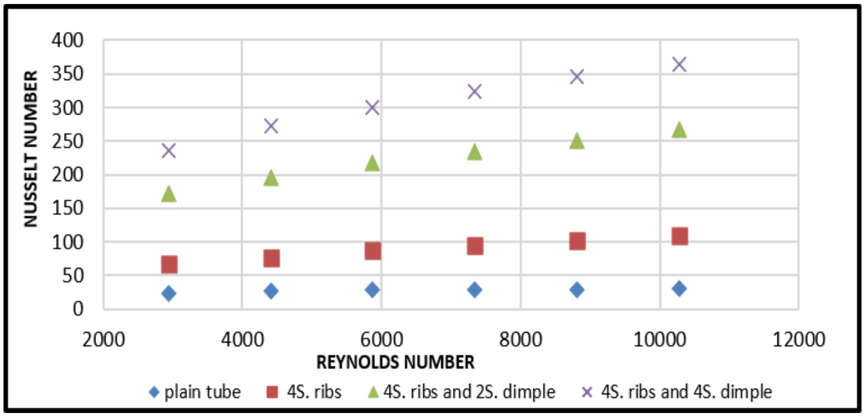

Fig. (8). Nusselt number versus Reynolds number.

5.2 Friction factor:

The value determines the magnitude of energy loss resulting from friction in a fluid flowing through a channel. It depends on several factors, including the pipe material, the roughness of the pipe surface, the velocity of the fluid, and the nature of the fluid. In this investigation, the implementation of longitudinal trapezoidal ribs enhances the contact surface area between the tube wall and the fluid, resulting in an increase in friction and consequently leading to a heightened pressure drop. Additionally, the presence of dimples exerts a further influence on pressure drop by generating vortices, disrupting boundary layers, and promoting turbulence. Collectively, these factors contribute to an increase in pressure drop within the tube. As illustrated in Figure (9), the friction factor diminishes with an increase in the Reynolds number. The most significant pressure drop is observed when employing four-sided longitudinal trapezoidal ribs in conjunction with four-sided inline semicircular dimples.

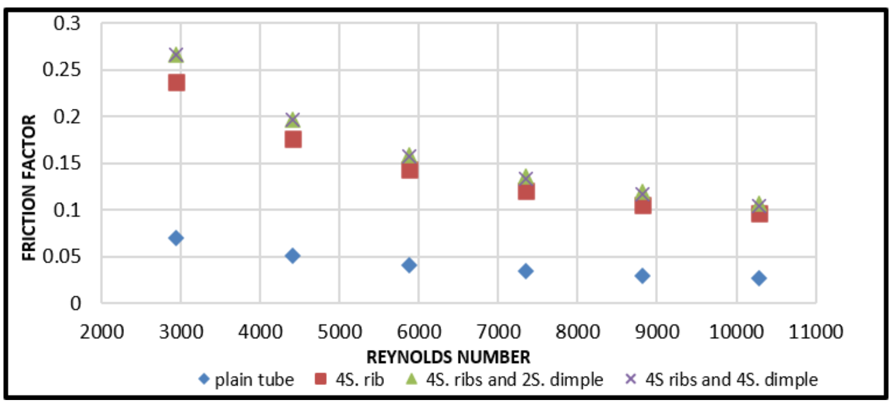

Fig. (9). Friction factor versus Reynolds number

5.3 Pumping Power:

It refers to the energy required to move the fluid through the system. Optimizing pumping power is crucial for minimizing energy consumption and reducing costs. In this numerical investigation, the pumping power increases with increasing Reynolds number. The highest value of pumping power (410%) is observed by using four-sided (LTRs) and four-sided (IHDs) compared to the smooth elliptical tube. The increase in pumping power can be attributed to an augmented pressure drop within the tube, which is induced by the presence of longitudinal trapezoidal ribs. These ribs enhance the contact surface area and disrupt the fluid flow. Furthermore, the incorporation of turbulator dimples exacerbates the pressure drop by generating vortices and disrupting the boundary layer adjacent to the wall, thereby facilitating the formation of secondary flow.

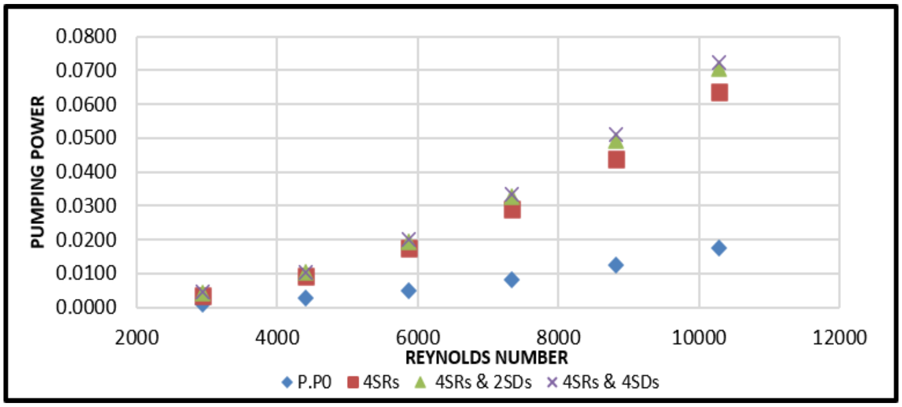

Fig (10). Pumping Power versus Reynolds number

5.4 Nusselt Number ratio:

It is a dimensionless parameter utilized in the analysis of heat transfer. The Nusselt number ratio is defined as the ratio between the average Nusselt number of a specific flow geometry and the average Nusselt number of a reference flow geometry. According to the results of the investigation, Figure (11) illustrates a marginal increase in the ratio of the Nusselt number values as the Reynolds number increases. The ratio exceeds one, which is indicative of a favorable outcome, suggesting that this configuration facilitates an enhancement in the heat transfer rate. Notably, the most significant augmentation of 12 is observed when utilizing four sides (LTRs) in conjunction with four sides (IHDs)

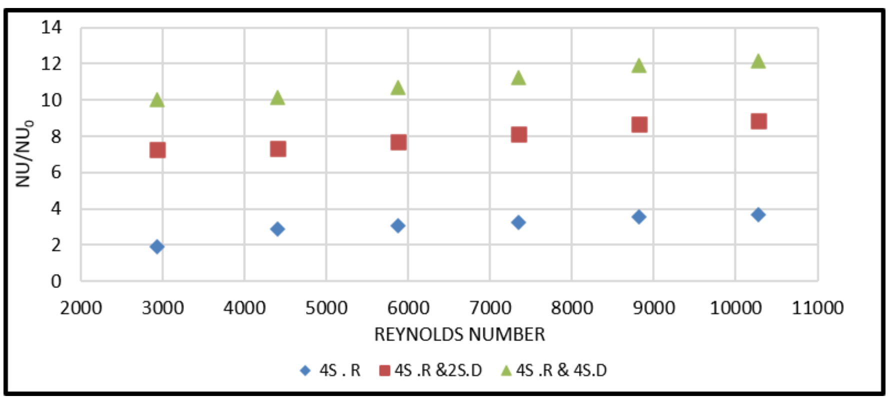

Fig. (11). Nusselt Number Ratio versus Reynolds number

5.5 Friction factor ratio:

The friction factor ratio is a critical parameter utilized in fluid mechanics, significantly impacting the design and analysis of pipe systems. This ratio quantifies the resistance to flow in an enhanced tube or channel relative to that in a smooth tube, thereby serving as an indicator of the feasibility of employing enhancement techniques in terms of pressure drop penalties. In this study, as illustrated in Figure 12, the application of Longitudinal Trapezoidal Turbulator Ribs (LTRs) and Inline Hemispherical Dimples (lHDs) on all four sides of the elliptical tube results in the highest observed ratio of 4. This value is considered a positive outcome when compared to the enhancement values noted in the Nusselt number ratio factor, which indicates high enhancement.

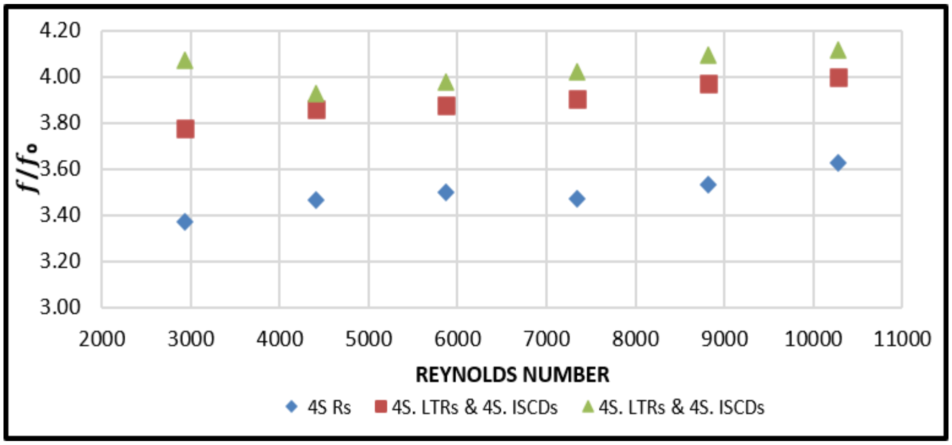

Fig. (12). Friction factor Ratio versus Reynolds number

5.6 Thermal Performance Factor (TPF):

The thermal performance factor serves as a comprehensive metric that quantifies the relationship between heat augmentation and the associated pressure drop penalty. It provides a singular metric for evaluating overall performance. When heat transfer enhancement techniques achieve substantial heat transfer with minimal pressure drop penalties, a high thermal performance factor is realized. Optimizing thermal performance factors consequently reduces energy consumption and allows for a reduction in the size of devices under equivalent operating conditions. The implementation of longitudinal trapezoidal ribs in conjunction with inline semicircular ribs results in an elevated thermal performance factor, attributable to the hyper technique's ability to deliver a high heat transfer rate with an acceptable pressure drop penalty. According to the findings of this investigation, the maximum thermal performance factor of 5.7 was attained by employing four-sided longitudinal trapezoidal ribs alongside four-sided inline semicircular dimples. This result is of considerable significance within the context of this study.

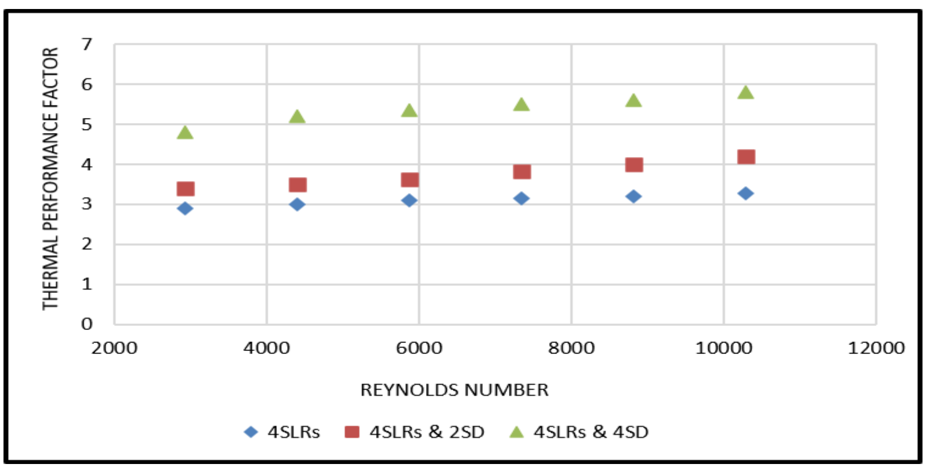

Fig. (13). Thermal performance factor versus Reynolds number

6. Conclusion

The present investigation demonstrates that the innovative elliptical tube, which is equipped with longitudinal trapezoidal ribs and inline hemispherical dimples, exhibits enhanced heat transfer capabilities with acceptable pressure drop penalties, thereby yielding significant improvement in thermal performance. This enhancement can be attributed to the increased heat transfer contact surface area and the disruption of thermal boundary layers facilitated by the incorporation of Longitudinal Trapezoidal Ribs (LTRs). Additionally, the generation of vortices and secondary flow further disrupts the thermal boundary layers near the wall through the use of inline hemispherical dimples (IHDs). This conclusion encapsulates the findings obtained through the application of this innovative technique as follows:

► **Heat transfer rate**: The heat transfer rate, as characterized by the Nusselt number, exhibits significant increase when employing this enhancement technique. The results of the investigation reveal that the utilization of four-sided Longitudinal Trapezoidal Ribs (LTRs) in conjunction with four-sided inline hemispherical dimples (HCDs) leads to an enhancement in the heat transfer rate by 1200% in comparison to a smooth tube.

► **Pumping Power**: The energy required to transport fluid within a tube escalates due to heightened fluid resistance, which results from an increased contact surface area associated with the implementation of four-sided Longitudinal Trapezoidal Ribs (LTRs). Additionally, the introduction of four-sided inline hemispherical dimples (IHDs) contributes to the formation of vortices and the disruption of thermal boundary layers in proximity to the wall. The most significant increase in pumping power observed was 410% when utilizing this approach compared to a plain tube.

► **Thermal Performance Factor**: This metric assesses the efficacy of enhancement techniques. The findings of this investigation reveal that a maximum value of 5.8 was attained through the implementation of four-sided Longitudinal Trapezoidal Ribs (LTRs) in conjunction with four-sided inline hemispherical dimples (IHDs). Consequently, this combination is regarded as one of the most effective methods for enhancing heat transfer and overall thermal performance.

Nomenclature

A	area (m^2)
C	Specific heat ($kJ/kg.K$)
d	diameter (mm)
D	hydraulic diameter (m)
f	friction factor
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
L	length (m)
w	width (m)
k	thermal conductivity ($W/m.k$)
P	Pressure (bar)
h	heat transfer coefficient ($W/m^2.k$)
Q	heat rate (W)
PP	Pumping Power (W)
PEC	Performance Evaluation Criterion
TPF	Thermal Enhancement Factor
Nu/Nu_0	Nusselt Number ratio
f/f_0	Friction Factor ratio
R	Roughness ratio
e/D	Relative roughness height
p/e	Relative roughness pitch
LR	Longitudinal Ribs
4SR	Four Side Ribs

2SD	Two Side Dimples
4SD	Four Side Dimples
LTRs	Longitudinal Trapezoidals
IHDs	Inline Hemispherical Dimples
Greek symbols	
Δ	difference
η	Efficiency
μ	dynamic viscosity
ρ	density
Subscripts	Subscripts
0	Reference/plain/smooth
b	Bulk fluid
f	Fluid
i	Inlet
o	Outlet
s	Surface or solid
w	Wall

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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.

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