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PREDICTING HEAT TRANSFER BEHAVIOUR IN TUBE SECTIONS WITH HIGH VISCOUS FLUIDS USING NUMERICAL SIMULATION

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Abstract

The outcomes of this research showcase the predictive analysis of the behaviour of Newtonian and non-Newtonian fluids while being heated during their flow through a tube with ellipsoidal dimples, employing numerical simulations. The findings have significant implications for manufacturers who rely on constant viscosity values for heat exchanger design or lack information about viscosity variations during processing. By changing the elliptical dimple angles to 0°, 45°, and 90° and using cross-combined configurations, the research looked at how heat is transmitted in tube sections with Reynolds numbers ranging from 3000 to 8000. Additionally, pitch lengths (PL) of 10–30 mm were tested while keeping the heat flux constant at 20000 w/m2 and maintaining a wall thickness of 1 mm. Results showed that cross-combined dimple tubes improved heat transfer by an average of 25.6%. The highest Nusselt number was achieved using a tube with an 8 mm diameter ratio, a twist angle of 90°, and a PL of 10 mm, specifically at Re of 8000. On the other hand, the tube with the 8 mm dimple diameter (Dd), cross-combined with a 10 mm PL, notably at a Re of 3000, was found to have the lowest friction factor (f).

Keywords: Numerical Simulation, High viscous fluids, Ellipsoidal dimple, Flow Characteristics.

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1. Introduction

Heat transfer is a vital process in many engineering applications, including food processing, power production, chemical processing, and refrigeration. The use of highly viscous fluids in different industrial processes has grown in popularity in recent years. Unfortunately, the heat transfer behavior of these fluids in tube sections is poorly known. As a result, it is critical to developing accurate and efficient techniques for predicting the heat transfer behavior of extremely viscous fluids in tube sections to improve the design and operation of industrial processes.

Liang Zhang et al. [1] For the first time, a numerical simulation utilizing the K- model was utilized for Developing a technology enhancement model for a tube with cross-combined dimples on a composite-shaped surface to examine the thermal-hydraulic characteristics of fluid flow. Toygun Dagdevir et al. [2] Dimpled tubes have been suggested as a suitable solution for achieving efficient heat transfer with minimal pressure drop in various industrial applications. This is because the dimples on the tube's surface disrupt the boundary layer and induce turbulence, which enhances heat transfer rates. Shuai Xie et al. [3] By examining their impact on overall performance, the study examined how variables such as dimple height, the distance between two dimple centers, and axis ratio affect a surface's ability to conduct heat exchange and fluid behaviour. M. Li et al. [4] Heat transport in the fluid flow is argued because dimples cause the creation of vortices and turbulence. Zahir Shah's [5] article explores various methods for enhancing heat transfer in different processes, such as heat exchangers, refrigeration, chemical processes, and automotive cooling, categorized as either active or passive techniques. Zheng Liang [6] examined the parameter like protrusion height, pitch length, and radius on the heat transfer characteristics was examined to determine their impact. These findings offer theoretical guidance and recommendations for potential applications of the ETDP. Rizwan Sabir [7] The study uses a parametric approach to investigate the optimal pitch length, geometry, and arrangement configurations under steady flow conditions using Reynolds Averaged Navier Stokes (RANS) simulations. S. Eiamsa et al. [8] Dimpled tubes are tubes that have been modified by creating small indentations on the inside surface of the tube. These indentations disrupt the flow of fluid passing through the tube, creating turbulence, and increasing the surface area available for heat transfer. Lu Zheng [9] By utilizing the effects of reattachment and up-washing, the aim is to produce a conclusion in the discussion of heat transfer in fluid flow Performance of the thermal-hydraulic system is enhanced by more intense secondary flow, improved flow mixing, and creation of local flow impingement. Zhimin Han [10] generates longitudinal vortices using Although the use of vortex generators has the potential to augment heat transfer, it may increase pressure loss. Consequently, vortex generators are commonly utilized in heat exchangers to augment their heat transfer efficiency. J.I. Córcoles-Tendero [11] This model incorporates variations in tube geometry. The employed methodology utilizes a meshing process and applies conservation equations in fluid dynamics. Shuai Xie [12] The research examined the performance of ETTD (Enhanced Tube Thermal Diffuser) Re of higher values by modelling the flow and heat transfer behaviour and contrasting their outcomes, with those obtained from spherical or elliptical dimples to better understand the heat transfer enhancement mechanisms in ETTD. Harish H. V. [13] One preferred method is to use passive approaches. The use of flow modifiers, such as inserts in the flow path, can enhance heat transfer rates. Passive techniques are favorable since they have a simple manufacturing process and can be integrated into existing heat exchangers. Koray Demir [14] analyzed how heat transfers and pressure change in a specific setup: a hollow cylinder where the inside wall is heated and fluids are used to help the flow. S. Rainieri [15] At all Reynolds numbers in the range of 150–1500, the curved wall design improves heat transfer, whereas the corrugated wall design only improves heat transfer at higher Reynolds numbers. Ming Li's study [16] used a numerical approach called the realizable k-e method to analyze how turbulent flow behaves in tubes with dimples to enhance heat transfer. They used a mathematical technique to solve the pressure-velocity coupling, and a consistent SIMPLE algorithm was utilized. They found that tubes with dimples had better heat transfer performance and that dimples arranged in a straight line (rather than staggered) resulted in the best overall heat exchange. Hairong Yue [17] describes the characteristics of EG (ethylene glycol) and its latest developments in synthesis and applications. The focus is on the chemical reactions and mechanisms involved in its production, as well as how it is used in various applications.

Henry C. Fuller [18] Ethylene glycol is a suitable substance for preserving various types of food and beverages. Applications in the domain of food and beverage domain mostly like fruit juices. Weikang Sun [19] A group of researchers created a laboratory system using five enzymes to produce ethylene glycol from glycerol. K. Wongcharee [20] In the study, empirical formulas were used to calculate the f and Nu for the system under study. Ruifang Shi [21] Changes in the quantity and dimensions of particles in the flow will impact both the pressure drop and heat transfer. D. DAS [22] A research investigation was performed on the dehydration process of pomelo fruit juice, which involved the approach employed in this study, which utilized a procedure that combines spray drying with block freeze concentration. N.L. Chin [23] The concentration of juice concentrates, as determined by their total soluble solids content, can lead to either shear thinning or pseudoplastic behavior, as indicated by flow behavior index values (n) that are less than 1. As the shear rate increases, the viscosity of the concentrates decreases, resulting in improved flowability. MIKAIL A [24] Using a coaxial-cylinder technique, the thermal conductivities of pummelo juice was determined through the steady-state method. In Norazlin Abdullah's [25], To The power law model was used with the shear rate-temperature-concentration superposition method to examine the rheological properties of Pummelo juice. Palash Goya [26] Compact and efficient heat exchangers are favored over straight and shell-type heat exchangers due to their higher heat transfer capability and larger heat transfer area. Saman Rashidi [27] says these compact and efficient heat exchangers are preferred due to their ease of fabrication, low maintenance costs, small pressure drop penalty, and lightweight construction. A. Garcia [28] When Reynolds numbers exceed 2000, corrugated and dimpled tubes are a more favorable choice than wire coils, as they offer a similar level of heat transfer coefficient while maintaining a lower pressure drop.

In this research paper, we discuss a numerical simulation method for forecasting the heat transfer properties of fluids with high viscosity within tube sections. Our approach is based on computational fluid dynamics (CFD) techniques and incorporates various geometric models of dimples to accurately capture the complex heat transfer phenomena. We apply our approach to a range of tube section geometries and fluid properties to demonstrate its effectiveness in predicting the heat transfer behavior of highly viscous fluids. As a result, a numerical investigation was carried out to analyze how ellipsoidal-shaped in a modified tube, dimples alter the flow and heat transmission qualities. The investigation considers factors like the angles of the ellipsoidal dimples (0°, 45°, 90°, and cross-combined), the diameter of the dimples (Dd = 8 mm), the pitch's duration (PL = 10–30 mm), and the operation under transient and turbulent flow conditions, which were analyzed across a range of 3000 to 8000 Reynolds numbers in the study.

2. Computational Methodology

2.1. Model Specifications and Boundary Conditions

This study's goal is to use numerical simulations to examine the effects of different ellipsoidal dimple surface parameters on a circular tube that is being subjected to a continuous heat flux. The computational domain comprises an annular tube with dimensions of 17.272 mm in diameter; the ellipsoidal dimple's major axis measures 8 mm, minor axis measures 2 mm, and an overall section length of 1000 mm, as per the technical specifications. Simulations are conducted under transient and turbulent flow conditions, with the Re range of 3000 to 8000 having an impact on the heat transfer behaviour of tube segment, with varying dimple angles, i.e., 00, 450, 900, and cross-combined as shown in Fig. 1, by varying pitch 10, 20, and 30 mm as shown in Table 1. The ellipsoidal dimpled parameters under investigation tube encompass the diameter of the dimple, the ellipsoidal angle of the dimple, and the pitch length. The entrance length is set at 10 times the tube diameter, with an exit section of 5 times the tube diameter to hinder reverse flow effects during numerical calculations. A no-slip condition at the walls is one of the boundary conditions that was imposed, furtherly with velocity magnitude at the entrance and pressure at the exit chosen as the boundary types for the solution domain. The calculations tested a tube with a 1 mm wall thickness using an assumed fluid temperature of 300 K and a surface heat flow of 20 kW/m2, as shown in Fig. 2. In this study, the working fluids used are water, ethylene glycol, and pummelo juice. In numerical simulations, the properties of fluids are typically incorporated, taking into consideration experimentally measured rheological properties as shown in Table 2.

Table 1. The geometric parameter investigated in the current study

Specified tube diameter [mm]	The dimple secondary axis [mm]	The dimple principal axis [mm]	Ellipsoidal Dimple angle [°]	Pitch Length [mm]
17.272	2	8	0	10
			45	20
			90	30
			Cross combined	

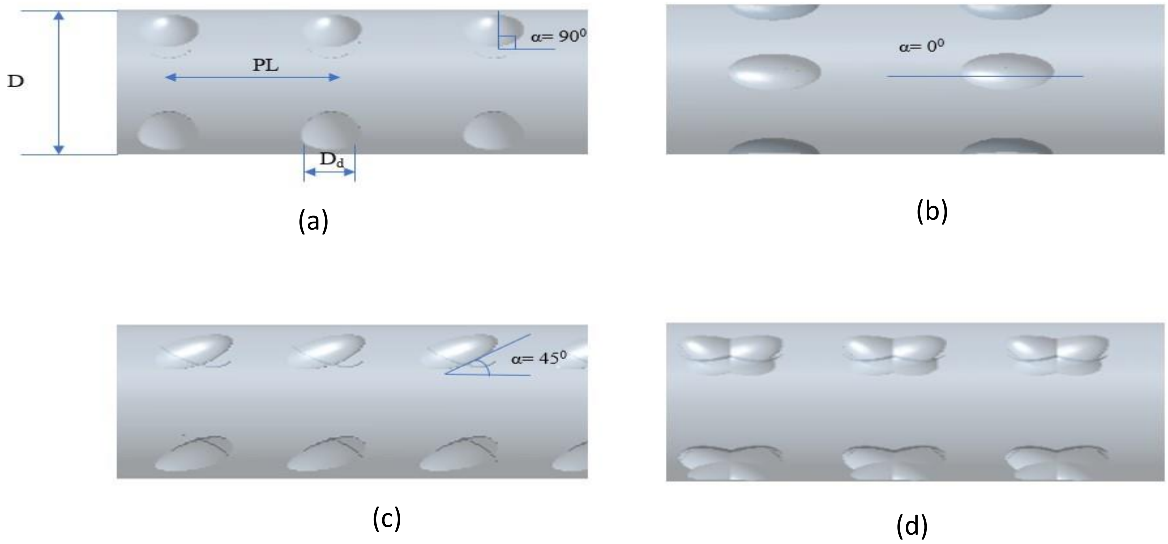


Fig 1. Geometry modeling of various ellipsoidal dimple angles = 0^0, 45^0, 90^0, and cross-combined, respectively.

Table 2. Highly viscous fluids with experimentally measured rheological properties.

Properties	Pummelo Juice	Ethylene glycol	Water
Formula	$C_{20}H_{28}O_{12}$	$C_2H_6O_2$	H_2O
Molecular mass/g mol^{-1}	180.16	62.07	18.02
Freezing point / ^0C	-2	-12.7	0
Boiling point at 101.3kpa/^0C	100.5	198	100
Viscosity at 20 ^0C/m-pas	0.001	20.9	1
Density Kgm^{-3}	1050	1115	997.5
Temperature Coefficient w/mk-1	0.5	0.258	0.609
Specific heat at 20 ^oC/J Kg^{-1} K^{-1}	3740	2347	4186

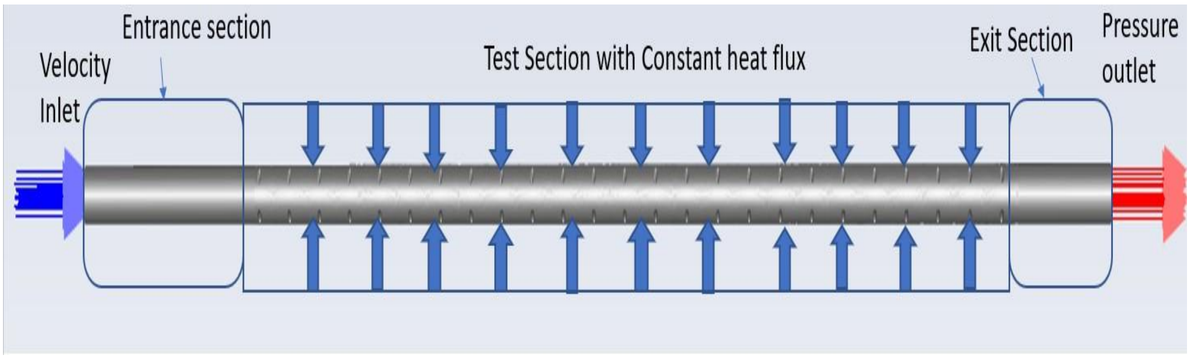


Fig 2. Computational domain in the current study with its Boundary assumptions

2.2. Principal Equations

The governing equations for computational fluid dynamics (CFD) are mathematical expressions that describe the behavior of fluid flow in each domain:

Equation of Mass Conservation in Fluid Dynamics:

$$\nabla(\rho V) = 0$$

Equation of Momentum Conservation in Fluid Dynamics:

$$\rho(u.\nabla)u = -\nabla P + \mu^2 \nabla u + \rho g$$

Energy conservation equation:

$$\rho Cp(u.\nabla)T = \alpha \nabla^2 2T + Q$$

"Transport equations for the dissipation rate and turbulent kinetic energy in fluid flow are examined using the Renormalization Group (RNG) model.

$$\frac{\partial^2}{\partial t}(\rho k) + \frac{\partial}{\partial x_t}(\rho u k_i) = \frac{\partial}{\partial x_j}\left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon - Y_m + S_k$$

2.3. Parametric definition

To simplify the analysis, it is customary to group variables into dimensionless numbers, thereby reducing their number. The subsequent dimensionless parameters are frequently utilized to quantify the thermal-hydraulic properties of internal flows:

$$Re = (\rho D L) / \mu$$

$$Nu = h * D / k$$

$$f = (2 * \nabla P * D) / (\rho * V^2 * L)$$

2.4. Grid Independence test

Table 3. A test to assess the grid independence of water flowing through a tube with a smooth inner surface at a Re of 6000

Number of Elements	Nusselt analysis in current study	Nusselt analysis difference in %	Friction factor analysis in current study	Friction factor difference in %
615942	58.67	-	0.0308	-
716638	52.98	9.70	0.0323	4.87
1063164	50.771	4.17	0.0338	4.64
1890122	48.984	3.52	0.0343	1.48

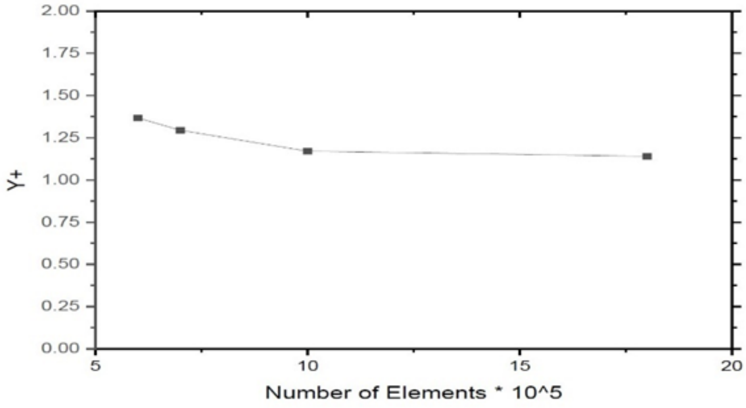


Fig 3. Number of elements vs. Wall Y+ value along the tube wall

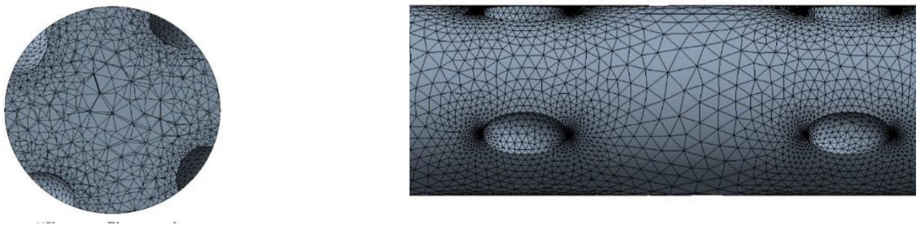


Fig 4. Meshing of a straight ellipsoidal dimple tube in the current study

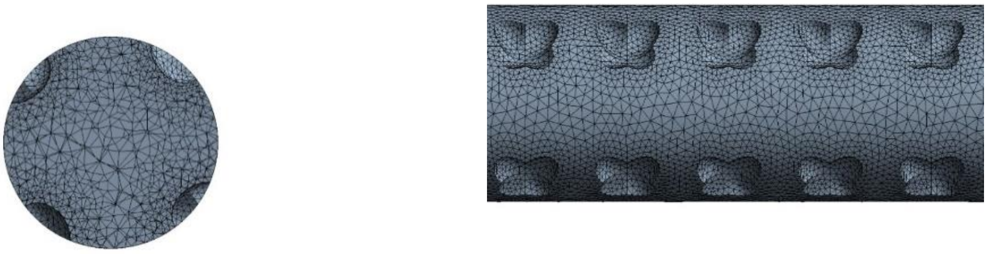


Fig 5. Meshing of a cross combined ellipsoidal dimple tube in the current study

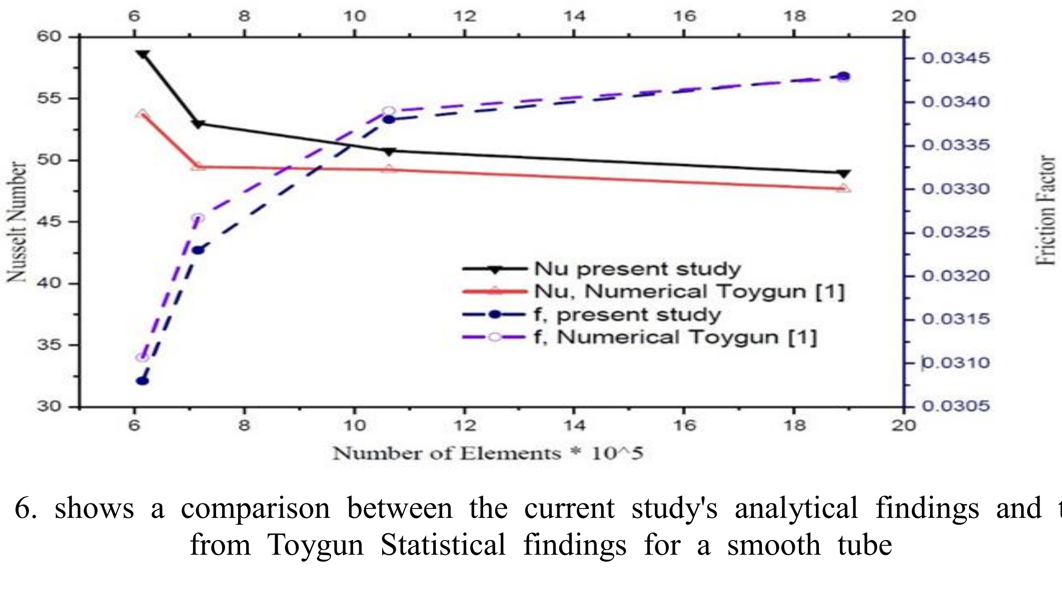
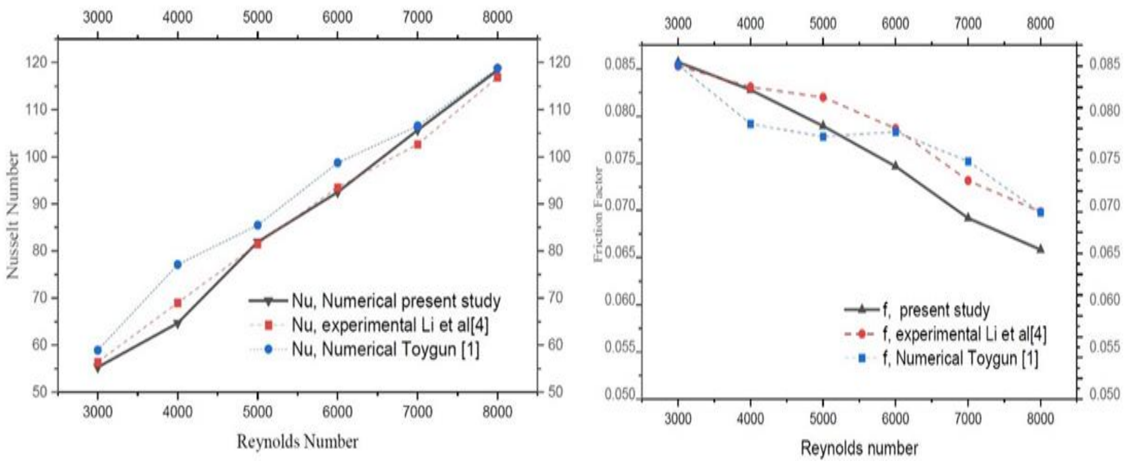


Fig 6. shows a comparison between the current study's analytical findings and those from Toygun Statistical findings for a smooth tube

The purpose of this test is to ensure that the numerical solution obtained from the simulation is independent of the grid or mesh resolution. The results of grid independence verification are shown in Table 3, where different grid structures with varying numbers of cells were utilized. The grid structure employed for this study consisted of approximately 1.8 million cells, and it was observed in Fig.4 & 5. The study found that changes in the grid structure had minimal Simply put, how it affects the Nu and f, which remained relatively. Briefly stated, the Nusselt number remains roughly constant at around 0.2, and the friction factor remains around 2.0. Furthermore, the average y+ value along the tube wall for this grid structure was calculated to be approximately 1.1269 as shown in Fig.3. In a straightforward manner, the numerical simulations conducted in the present study were compared to Toygun [1] is depicted in Fig.6. The graph illustrates the relationship between the number of elements variable and. the simulations revealed that both the Nu and f varied between the two cases. It is observed that beyond a certain point, increasing the number of elements results in a marginal change of 5 to 10%, in the magnitude of the Nu and f values. which then remain relatively constant. Thus, the addition of extra parts has little impact on the Nu and f.

2.5. Validation of Numerical Technique



(a) (b)

Fig 7. Li et al. [4] and Toygun [1]'s validation of the numerical study Re vs. f and Nu for Improved Tube Flow

The analysis of the numerical simulation results in comparison with experimental data, depicted in Fig. 7, indicated that the largest disparities in Nu and f were 9.7% and 4.87%, respectively. These differences were found to be well below the acceptable threshold of 20%. Thus, a validation analysis of the single ellipsoidal tube as well as the cross-combined tube with dimples as shown in Fig. 7 indicates that the simulation approach employed in the study is accurate. This suggests that the numerical model effectively represents the physical problem and can be relied upon for subsequent analysis and optimization tasks.

3.Findings and Analysis

3.1 Thermal Performance Analysis

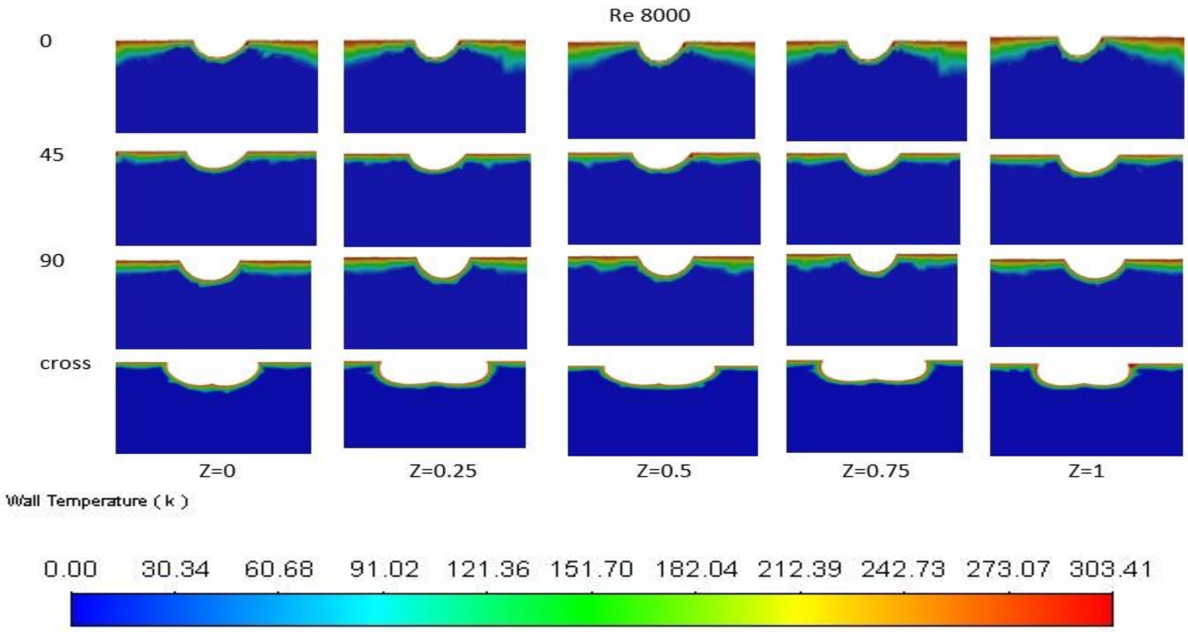


Fig 8. Axial Temperature Contours for Dimple Angle (0, 45, 90, Cross) of Ethylene Glycol, Pitch Length = 10 mm at Reynolds Number of 8000

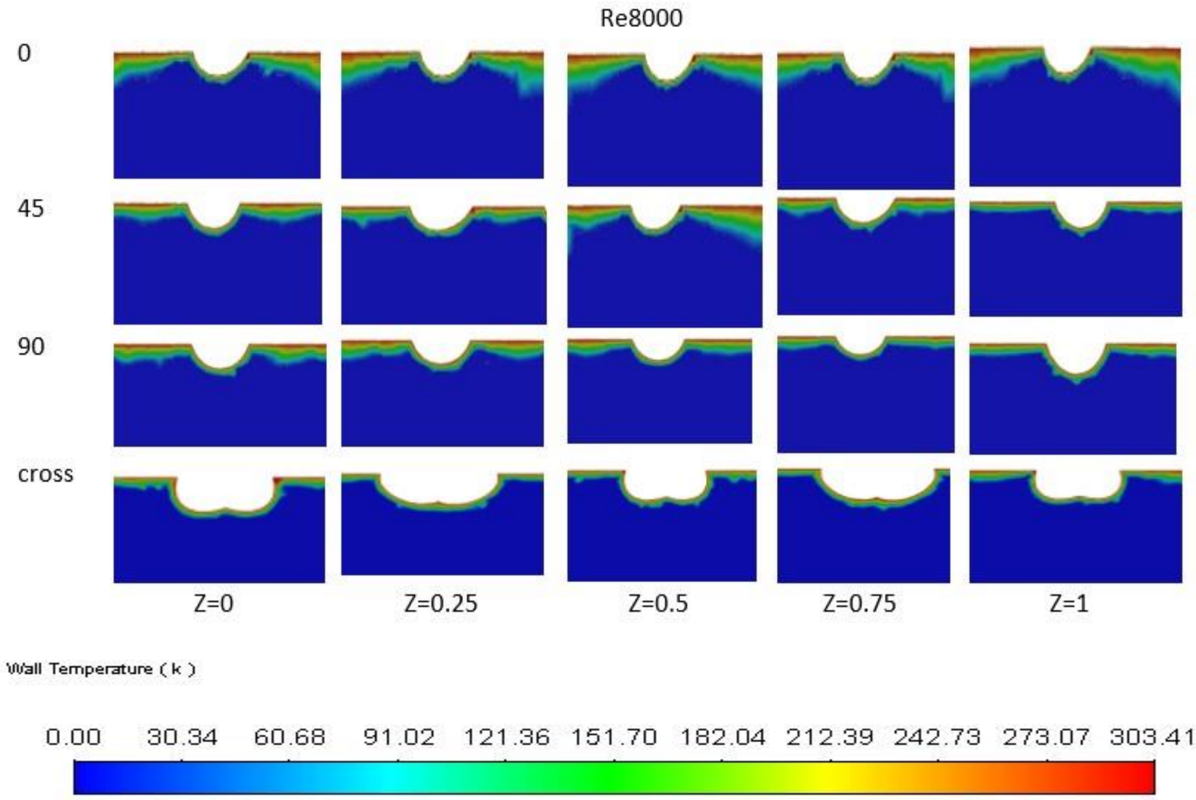


Fig 9. Axial Temperature Contours for Dimple Angle (0, 45, 90, Cross) of Pummelo Juice, Pitch Length = 10 mm at Reynolds Number of 8000

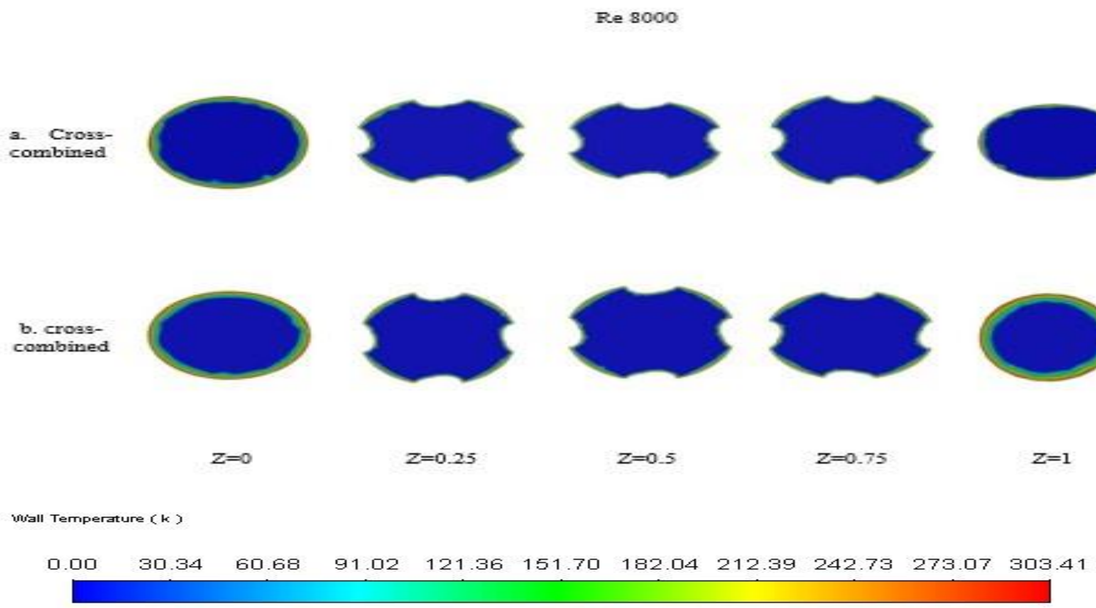


Fig 10 shows the cross-sectional temperature contours for a combined dimple of ethylene glycol and pummelo juice (labelled as a and b, respectively), with a PL of 10 mm and an 8000 Re.

3.1.1 Effects of Ellipsoidal Dimple Vary with Angle

The findings from the data on ellipsoidal angles reveal similarities to the results from the dimple diameter and throughout the length section data in terms of heat transfer effectiveness, as shown in Figs. 8 to 10. The study investigates the temperature distribution in dimple tubes with fixed ellipsoidal angles (=0°, 45°, 90°, and cross-combined), Reynolds numbers (3000, 5000, and 8000), and a dimple diameter of 8 mm. The pitch lengths vary between 10 mm and 30 mm. A stagnation zone forms behind the dimples, resulting in the ends of the dimples experienced the warmest temperatures. Increasing the ellipsoidal angle results in a larger near the end of the dimples, there is a stagnation zone., which causes significant disruption to the thermal boundary layer along the tube. The maximum Nusselt (Nu) number is observed where flow separation causes a quick contraction of the boundary layer of the thermal systema pitch length of 30 mm and a 90° angle give the nu its maximum value at this location, where there is a sharp separation between the flow and the windward surface. The Nu values in the surrounding areas are higher when there are dimples on the surface compared to areas without dimples. Increasing the ellipsoidal angle of the dimple increases the base surface area, which, in turn, produces a bigger area for the creation of a thin thermal boundary layer, especially at higher ellipsoidal angles.

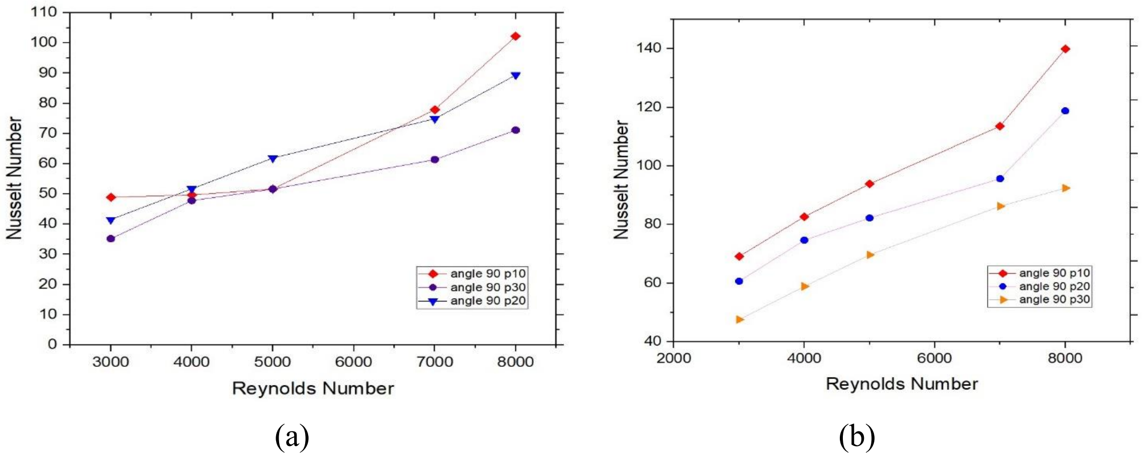


Fig 11. compares the Nu and Re for ethylene glycol and pummelo juice with a dimple angle of 90^0 and a PL of 10 mm (a, b, respectively)

The Nu distribution and Re for a cross-combined dimple tube are shown in Fig. 11. The Nu increases. An increase in ellipsoidal angle, Reynolds number, and pitch length is associated with a decrease in pitch. The Nu with a peak value of 139.9074 is obtained at 90°, PL = 10 for Re = 8000 for pummelo juice, and the Nu value of 102.1791 is obtained at 90°, PL = 10 for Re = 8000 for ethylene glycol.

3.1.2. Influence of Dimple Pitch Length on Outcomes

When the distance between dimples on a tube gets smaller, more dimples are added, causing more disturbance in the flow zones. This leads to an increased Nusselt number, which indicates better heat transfer ability. Figure 11 shows how adjusting the pitch length of dimples on a tube can greatly affect flow characteristics and heat transfer efficiency, as demonstrated by the link between the Re and the average Nu for various dimple pitch lengths and ellipsoidal angles. When examining the temperature contours in Fig. 10 using radial cross-sections, four distinct zones can be identified the temperature gradient is lessening away from the dimple region and toward the cross- section but exhibits significant variability in proximity to the wall. The gradient in core temperature is greater at z = 0 mm than at z = 1000 mm as the fluid shifts from laminar flow to turbulence. The temperature distribution in the smooth region at z = 250 mm is like that of the preceding cross-section of a dimple at z = 0 mm. Additionally, the gradient in core temperature in the sections with dimples is much larger than it is in the sections with smooth surfaces. The average Nusselt (Nu) values for the smooth section at z = 1000 mm and the dimple section are 25.23 and 120.13, respectively, at z = 0 mm. Additionally, the dimple section's maximum and minimum Nu values are higher than the smooth sections. Due to the tube section length and the periodic variation in the dimple section, the smooth sections corresponding to the entrance and exit extensions are negligibly affected in terms of Nusselt number (Nu) variation. However, significant Nu variation is observed in the dimple section, with the maximum local Nu occurring at the peak of the dimple. In summary, the three portions' average Nusselt (Nu) values are 69.73, 82.95, and 139.278, respectively. This demonstrates how the presence of dimples on the tube surface significantly improves heat transmission performance.

3.2 Flow Characteristics

3.2.1 Effects of Ellipsoidal Dimple Vary with Angle

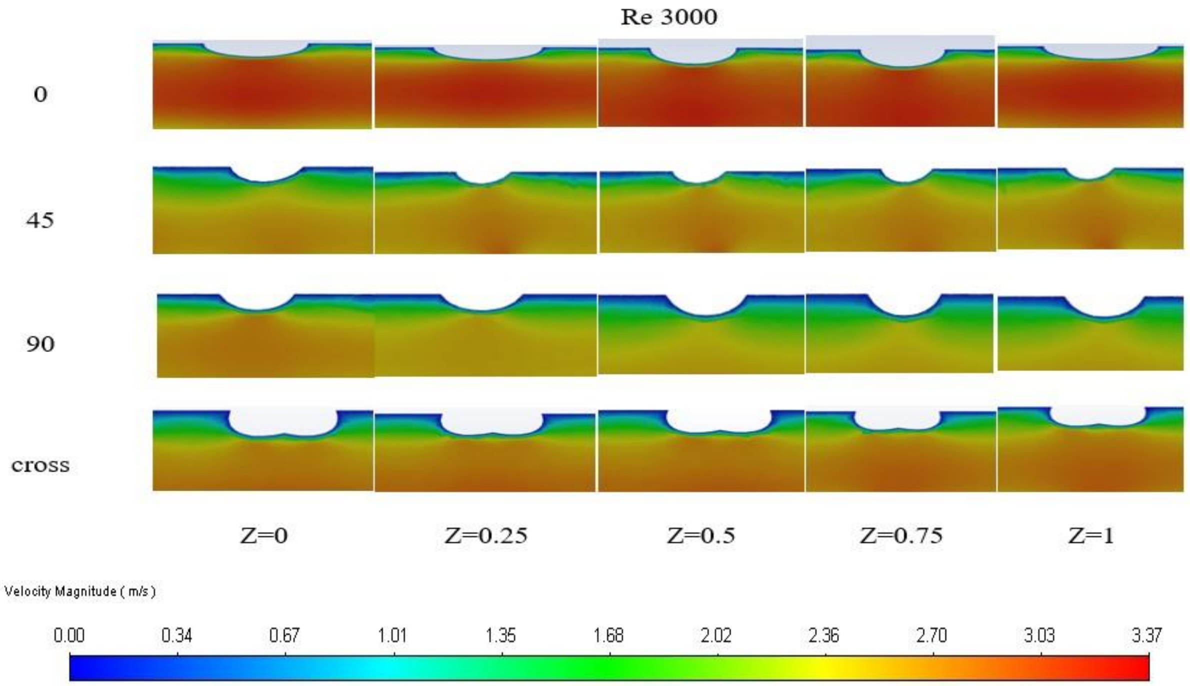


Fig 12. Velocity contours for dimple angles (0, 45, 90, cross) of Ethylene glycol, PL of 10 mm at a Re of 3000

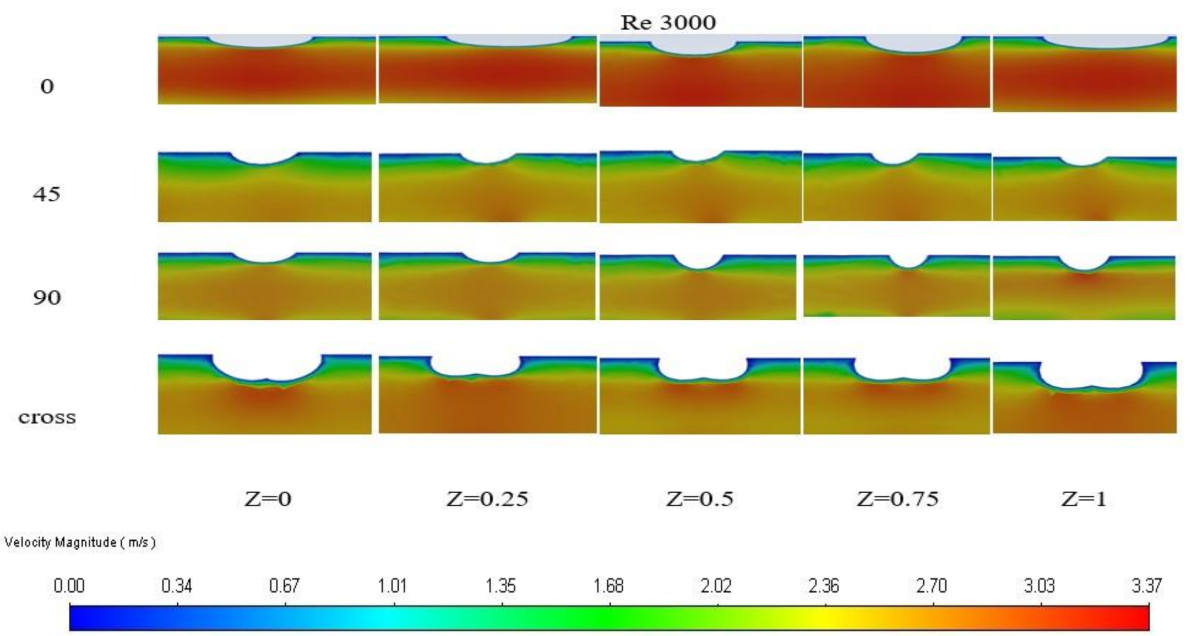


Fig 13. Velocity contours for dimple angles (0, 45, 90, cross) of Pummelo Juice, PL of 10 mm at a Re of 3000

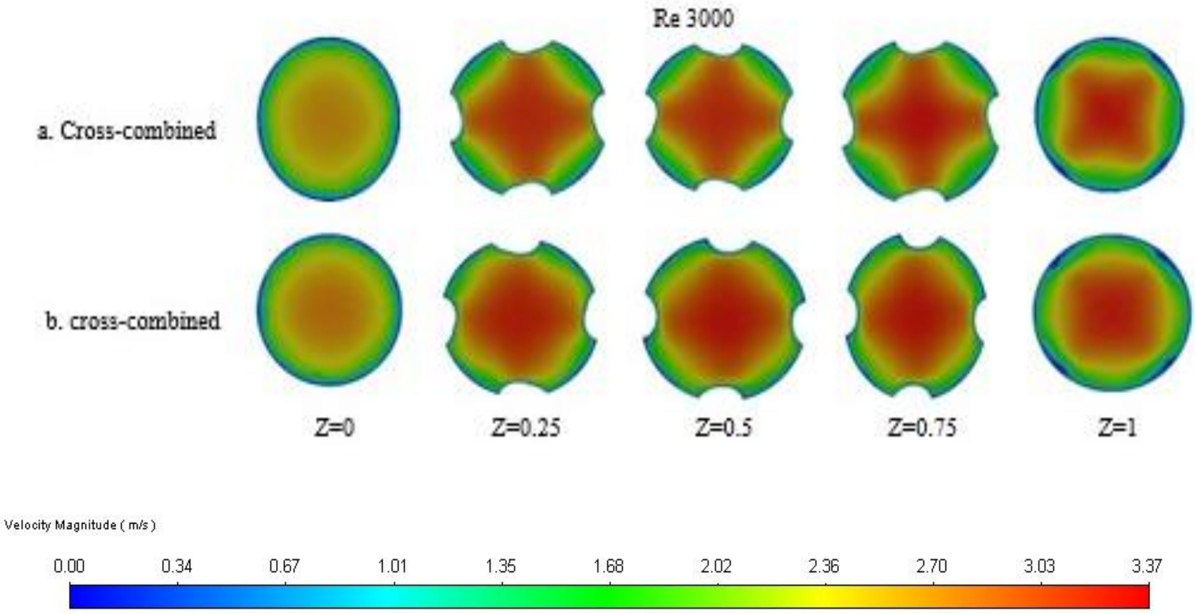
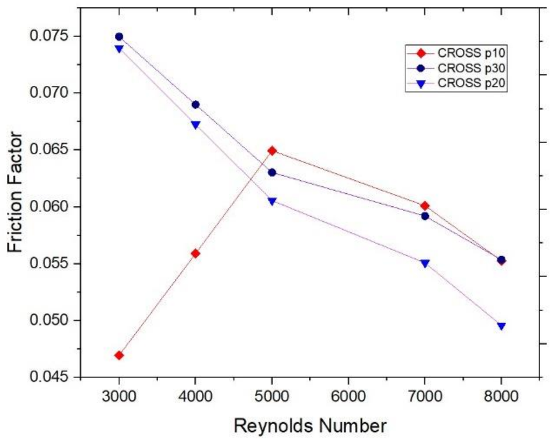
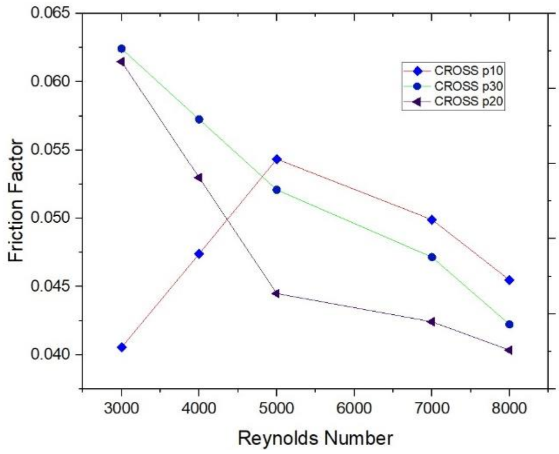


Fig 14. Cross-sectional Velocity Contours for the Cross-Combined Dimple of Ethylene Glycol and Pummelo Juice (a, b, respectively), PL of 10 mm at Re of 3000.

The average velocity magnitude increases as the ellipsoidal angle increases due to the dimples' higher obstructive impact, as shown in Fig. 12 to 14. At lower ellipsoidal angles, the flow separates more gradually from the dimple's windward surface. However, as the ellipsoidal angle increases, the influence of the barrier on the flow becomes more significant, increasing the pressure on the windward side.



(a)



(b)

Fig 15. f versus Re for a cross-combined dimple with a pitch length of 10 mm of ethylene glycol and pummelo juice (a, b, respectively)

The results of the friction factor investigation for various ellipsoidal angles (0°, 45°, 90°, and cross-combined), lengths of the pitches (10 mm, 20 mm, and 30 mm), and an 8 mm dimple diameter are presented in Fig. 15. As the ellipsoidal angle increases, the f substantially rises. At a

Reynolds number of 3000, the lowest friction factor is 0.04695, which occurs when the cross-combined pitch length is 10 mm and the dimple width is 8 mm for ethylene glycol, and at the same conditions, the value of the friction factor is 0.04056 for pummelo juice.

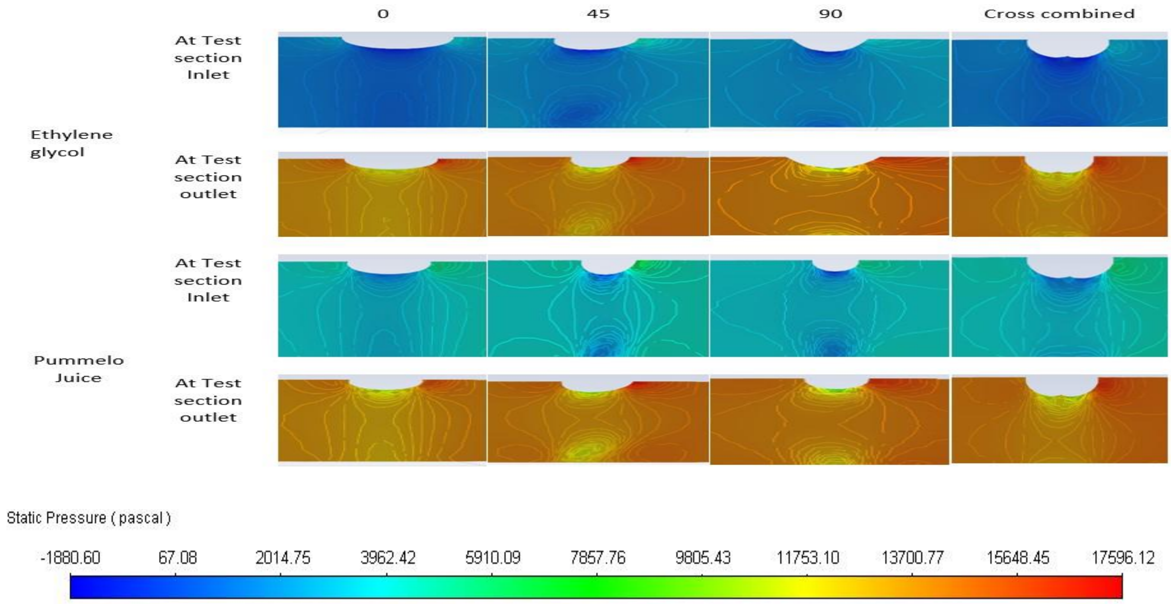


Fig 16. Pressure Distribution for Dimple Angles of 0°, 45°, and 90°, Cross-Combined Dimples at p = 30 mm, Re = 5000

The data presented in Fig. 16 shows that the maximum pressure drop occurs in a cross-combined dimpled tube configuration, specifically at a PL of 10 mm and a Re of 8000. The measured pressure drop is 105538.4 pascal for ethylene glycol and 107210.1 pascals for pummelo juice. The relationship between surface area and Nusselt number implies that incorporating dimples on the tube surface, which increases the surface area, can lead to an enhancement in the Nusselt number, leading to higher Nusselt numbers. A higher Nusselt number indicates more effective convective heat transfer. Technically, it is possible that adding dimples to the tube's exterior can boost heat transmission from the surface to the fluid, resulting in improved convective heat transfer. This is because of the link between surface area and Nusselt number. This is because the dimples' increased surface area, compared to a tube that is smooth, encourages more effective heat transfer. Moreover, the data also shows that a shorter pitch length (10 mm in this case) leads to a higher pressure drop. Pressure drop is the resistance encountered by the fluid as it flows through a conduit or channel. In this case, a shorter pitch length means that the dimples are closer together, which increases the obstruction to the flow and results in a higher pressure drop. This indicates that a decrease in pitch length leads to increased flow resistance, requiring higher pressure to overcome the hindrance posed by the dimples.

3.2.2 Influence of Dimple Pitch Length on Outcomes

The frequency of disrupted flow zones rises as the pitch length is reduced, leading Simply put, adding more dimples along the length of a tube can improve its heat transfer performance. The increased number of dimples provides additional surface area, leading to more efficient convective heat transfer compared to a tube with fewer dimples. as reflected in the increase in the average Nu. The connection between PL and Nu vs Re for the ellipsoidal angle and dimple pitch length is shown in Fig. 11. Thus, modifying the pitch length of a tube can significantly impact the efficiency of heat transmission and flow characteristics. When examining temperature contours using the radial cross-section in Figs. 8 and 9, four distinct zones can be distinguished. Beyond the dimple section, the temperature gradient reduces toward the centre of the cross-section, but it drastically alters closer to the wall. Moreover, as the fluid changes from laminar flow to turbulence, the temperature gradient is somewhat higher at z = 0 mm than at z = 1000 mm. Simply put, the smooth sections of the tube are located at the entrance and exit extensions, while the dimple section exhibits periodic variation along the tube's length. The change in Nusselt number (Nu) is relatively small in the smooth sections but significant in the dimple sections. The three sections' average Nu values are 69.73, 82.95, and 139.278, respectively. In conclusion, the performance of heat transfer is significantly improved by the presence of dimples on the tube surface. The friction factor results for various ellipsoidal angles, pitch lengths, and an 8 mm dimple diameter demonstrate a significant increase in friction factor with increasing ellipsoidal angle. As the pitch length decreases, the average pressure drop along a tube increases because dimples have a more substantial effect on flow blockage. The friction factor distribution is shown in Fig. 15 as a function of the Re, PL, and ellipsoidal angle. The findings show that the friction factor rises with increasing ellipsoidal angles and decreasing pitch lengths. When the dimple diameter is 8 mm, the ellipsoidal angle is cross-combined, the PL is 10 mm, and the Re is 3000, representing the maximum flow resistance, the friction factor reaches its highest value.

4. Conclusions

In conclusion, the research findings show that having dimples on the tube greatly affects how temperature is distributed across the tube's cross-section. The dimple section exhibits a larger temperature gradient compared to the smooth section. This suggests that adding dimples can increase a heat exchanger's available surface area for heat transmission, therefore improving heat transfer efficiency. Furthermore, the use of cross-combined dimple tubes has been demonstrated to considerably enhance heat transfer efficiency, with an average enhancement of 25.6% and a range of improvement between 12.2% and 36.38% when compared to traditional single ellipsoidal dimple tubes. Specifically, the highest Nusselt number was achieved with a tube of 8 mm diameter ratio, a twist angle of 90°, and a PL of 10 mm at a Re of 8000. Additionally, the lowest friction factor (f) was observed for a tube with a Dd of 8 mm, cross-combined with a PL of 10, and a Re of 3000 for both working fluids. These findings highlight the potential of cross-combined dimple tubes as an effective means to enhance heat transfer performance in various applications.

Author contributions

M. Gangadhar Rao: Conceptualization, Supervision

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Declaration of Competing Interest

The authors guarantee adherence to ethical standards while upholding objectivity and transparency in their work by disclosing that they have no competing interests in the research.

Nomenclature

D diameter of the tube in millimeters

f An ellipsoidal dimple tube friction factor

f_0 friction factor of a smooth tube

h dimple height in millimeters

h typical convective heat transfer coefficient [W/m2 K]

L tube length for test section in millimeter

Nu Nusselt number of ellipsoidal dimple tubes

Nu_0 Smooth tubes consists of Nusselt number

P pressure in Pascals

ΔP pressure drop Pascals

Q constant heat flux [W/m2]

T temperature [K]

V velocity magnitude [m/s]

Z millimeters of distance in the z direction

PL pitch length [mm]

Re Reynolds number

Greek characters

ρ Density of working fluid [kg/m3]

α Ellipsoidal dimple angle [°]

μ Dynamic viscosity of fluid [kg/m-s]

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