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Research Article

Heat Transfer Investigation Inside Heated Pipes of Different Cross-sections

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ABSTRACT

This research examines the thermal transfer efficiency in pipes including various cross-sectional geometries, such as circular, square, and triangular shapes. A computational fluid dynamics (CFD) methodology was used to model flow conditions and examine heat transfer and turbulence intensities under consistent boundary conditions. The results indicate substantial variations in thermal and flow characteristics across the geometries. Circular pipes provide greater convective heat transfer efficiency and minimum temperature gradients, but square and triangular pipes show more turbulence accompanied by a higher pressure drop. These insights may guide the design of efficient piping systems for many technical applications, including HVAC, chemical processing, and renewable energy systems.

1. INTRODUCTION

Energy production, chemical processing, and heating, ventilation, and air conditioning (HVAC) systems are just a few of the many technical domains that rely on heat transfer in pipe systems. Pipe cross-sectional shape has a major impact on system performance, pressure drop, and heat transfer efficiency [1-2]. Although circular pipes are widely utilized because of their simplicity and long-standing design principles, non-circular geometries including elliptical, rectangular, and triangular cross-sections are becoming more popular because of their ability to improve heat transfer [3-5]. The mechanics and uses of various geometrical configurations are explored in this review, which digs into the numerous research that have examined the impact of pipe cross-section on heat transfer [6].

Circular pipes serve as the standard for evaluating heat transfer owing to their isotropic shape, which guarantees uniform flow distribution and consistent performance. Zhang et al. [7] demonstrate that circular pipes are ideal for systems emphasizing minimal pressure drop and manufacturing simplicity. Moreover, the and turbulent heat transfer properties in circular pipes have been well defined, with empirical correlations such as the Dittus-Boelter equation often used. Liu et al. [8] investigated the influence of aspect ratios on heat transfer, finding that flatter ellipses enhance heat transfer owing to increased surface areas orientated perpendicular to the flow. Karmakar and Debnath [9] examined the thermal performance of rectangular ducts and found considerable improvement in heat transfer with higher aspect ratios, however this was accompanied by a corresponding increase in pressure drop. Yang and Sun [10] conducted a research indicating that triangle cross-sections may attain superior thermal performance in flows, since sharp corners facilitate the thinning of the thermal boundary layer. A research by M. Patel et al. [11] shown that flows in triangular and trapezoidal pipes displayed improved conduction-driven heat transfer owing to the fluid's closeness to the pipe walls.

Research by Kumar et al. [12] noted that introducing roughness or turbulators in non-circular pipes disrupted the boundary layer, significantly increasing the Nusselt number but at the cost of increased energy consumption. Chen et al.[13] emphasized that CFD models capture intricate flow and heat transfer patterns in non-circular pipes, particularly for applications in microchannels. The trapezoidal pipes analyzed by Huang et al. [14] shown improved heat transfer in hybrid cooling systems, with asymmetric designs minimizing thermal resistance. Wu and Chen [15] investigated serpentine microchannels with varying cross-sectional shapes, finding that trapezoidal microchannels offered the best thermal-hydraulic performance.

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The main objective of the present work is to investigate the effect of cross section of the pipe on the convective heat transfer with the flowing air. Also, the effect of the cross section on the turbulence intensity is tested

2. PHYSICAL MODEL

This study examines several receiver geometries, including circular, square and triangular configurations, as seen in Figure (1). The surface area is maintained for all receivers by using the same perimeter and length. Table (2) presents the dimensions of the various tube.

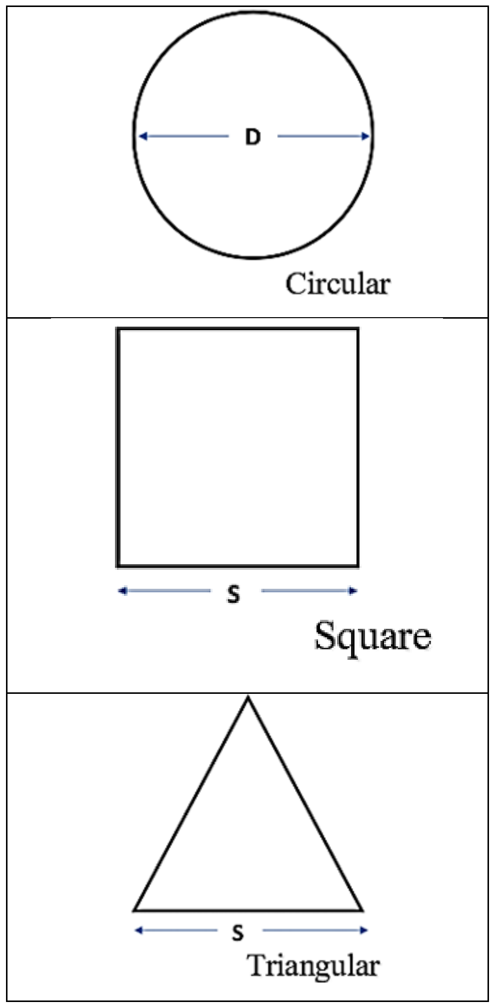

Fig.1. Different receivers' geometries

TABLE I. DIMENSIONS OF THE DIFFERENT RECEIVERS

Shape	**Dimension(mm)**	**Length(mm)**
Circular	D= 26	1000
Square	S= 20.85	1000
Triangular	S=27.7	1000

3. MESH CREATION

Non-structural and structured meshing is employed to mesh the domain. Hexagonal inflated elements are employed to create the mesh near walls while the core of the domain is meshed with tetrahedron elements. The number of components has a substantial impact on the simulation results. In this study, the element number is crucial primarily in the test region, which encompasses fluid flow and heat transfer. To reduce the computational cost , suitable number of mesh elements must be determined carefully. Table (1) present the variation of the Nusselt number (Nu_{av}) inside the test section with element number. It can be seen the variation of the $\mathbf{Nu_{av}}$ is insignificant for all the tested elements number. The elements number is chosen to be 786,361. Figure 2 depicts the meshed domain.

TABLE II. ELEMENTS NUMBER EFFECT ON THE AVERAGE NUSSELT NUMBER

Elements number	$\mathbf{Nu_{av}}$
120,350	9.52
356,564	9.88
529,985	10.68
786,361	10.99
958,874	10.99

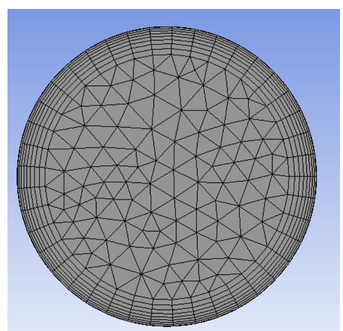

Fig. 2. Cross section of t he meshed domain

4. GOVERNING EQUATIONS

This study utilizes flow to simulate turbulent fluid flow and heat transfer in the proposed simulation, with the governing equations outlined as follows [13] :

Continuity Equation

$$\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial y} + \frac{\partial \overline{w}}{\partial z} = 0 \tag{1}$$

Momentum Equation

$$\frac{\partial}{\partial x_i}(\rho \overline{u_i u}) = \frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\mu\left(\frac{\partial \overline{u_i}}{\partial \overline{x_j}} + \frac{\partial \overline{u_j}}{\partial \overline{x_i}} - \frac{2}{3}\delta_{ij}\frac{\partial \overline{u_l}}{\partial x_l}\right)\right) - B_i - \frac{\partial}{\partial x_i}\left(\overline{\rho u_i' u_j'}\right) \tag{2}$$

Energy Equation

$$\rho\frac{\partial h}{\partial t} = K_s\left(\frac{\partial^2 T}{\partial n^2}\right) + S_h \tag{3}$$

5. BOUNDARY CONDITIONS

The Governing equations are solved by utilizing the following boundary conditions as in Figure (3):

- Left face: mass flow rate.
- Right face: pressure outlet.
- Other walls: heat flux

6. RESULTS

This study quantitatively examined air flow and heat transfer inside three pipe with different cross-section include: circular, square , and triangular. The mass flow rate and temperature are fixed at 0.0004 kg/s and 25 ºC respectively for all cases. The heat flux is set as 300 W/m^2.

Figure (3) presents the surface temperature of the pipe for the tested cases. The data reveals a considerable difference in thermal behaviour across the three pipe designs. The circular pipe attains the lowest maximum surface temperature of 382 K, in contrast to the square pipe at 403 K and the triangular pipe at 442 K. This suggests that the circular cross-section may be more efficient in heat dissipation or possess a reduced heat absorption capacity, thus rendering it beneficial for situations where thermal regulation is essential. In contrast, the triangular pipe's peak temperature of 442 K indicates a greater thermal concentration, presumably attributable to its acute edges and less surface area for heat dissipation. It may also provide issues with material stress and durability at elevated temperatures.

The circular pipe has the least temperature spread (difference between maximum and minimum) 82 K, indicating a more consistent temperature distribution over its surface. This consistency may reduce heat stresses, thereby prolonging the pipe's lifetime and improving its structural integrity. The triangular pipe has the greatest temperature spread 143 K, indicating substantial thermal gradients that might elevate the risks of material fatigue or failure over time. The square pipe achieves equilibrium between these extremes, exhibiting a maximum temperature of 403 K and a spread of 104 K. Its intermediate performance renders it a flexible choice for renewable energy systems, especially in solar thermal applications where compactness and moderate thermal gradients are essential design factors.

Figure (4) presents Average Nusselt number for the tested pipes. The circular pipe has the greatest average Nusselt number among the three designs, signifying the most effective convective heat transfer. This outcome aligns with existing research, since circular pipes are extensively used for their superior flow dynamics and reduced flow resistance, resulting in well-defined temperature and velocity boundary layers. The square pipe has a somewhat reduced Nusselt number in comparison to the circular pipe. The existence of corners in square cross-sections might interfere with flow patterns, resulting in areas with decreased heat transfer efficiency. Nonetheless, square pipes maintain an equilibrium between the improvement of heat transfer and practical manufacturability in tiny heat exchangers. The triangular pipe demonstrates the lowest Nusselt number among the three shapes. Acute angles in triangle conduits may result in localised stagnation areas and diminished convective heat transfer. Nonetheless, triangular pipes may remain advantageous in scenarios when spatial limitations are paramount, and thermal transfer efficiency is of lesser importance.

Figure (5) demonstrate the turbulence intensity. Turbulence intensity in the circular pipe is reasonably consistent, starting low in the centre and increasing towards the walls. This uniform distribution is due to symmetrical shape, which encourages smooth and predictable flow. Although the circular pipe has lower turbulence intensity than other geometries, its streamlined shape maintains effective boundary layer growth and heat transfer. The square pipe's turbulence intensity is highest in the corners. Sharp edges hinder flow and increase turbulence. Regions that boost mixing might also increase pressure drop. The square pipe's intermediate heat transfer performance is due to increased turbulence than the circular pipe. Triangular pipes have the most turbulence around sharp corners.

Sharp triangular angles disturb flow, causing considerable turbulence in certain places. Pressure drop and flow resistance may rise as mixing improves. Due to decreased mixing in the pipe centre, uneven turbulence intensity reduces heat transfer compared to circular and square pipes.

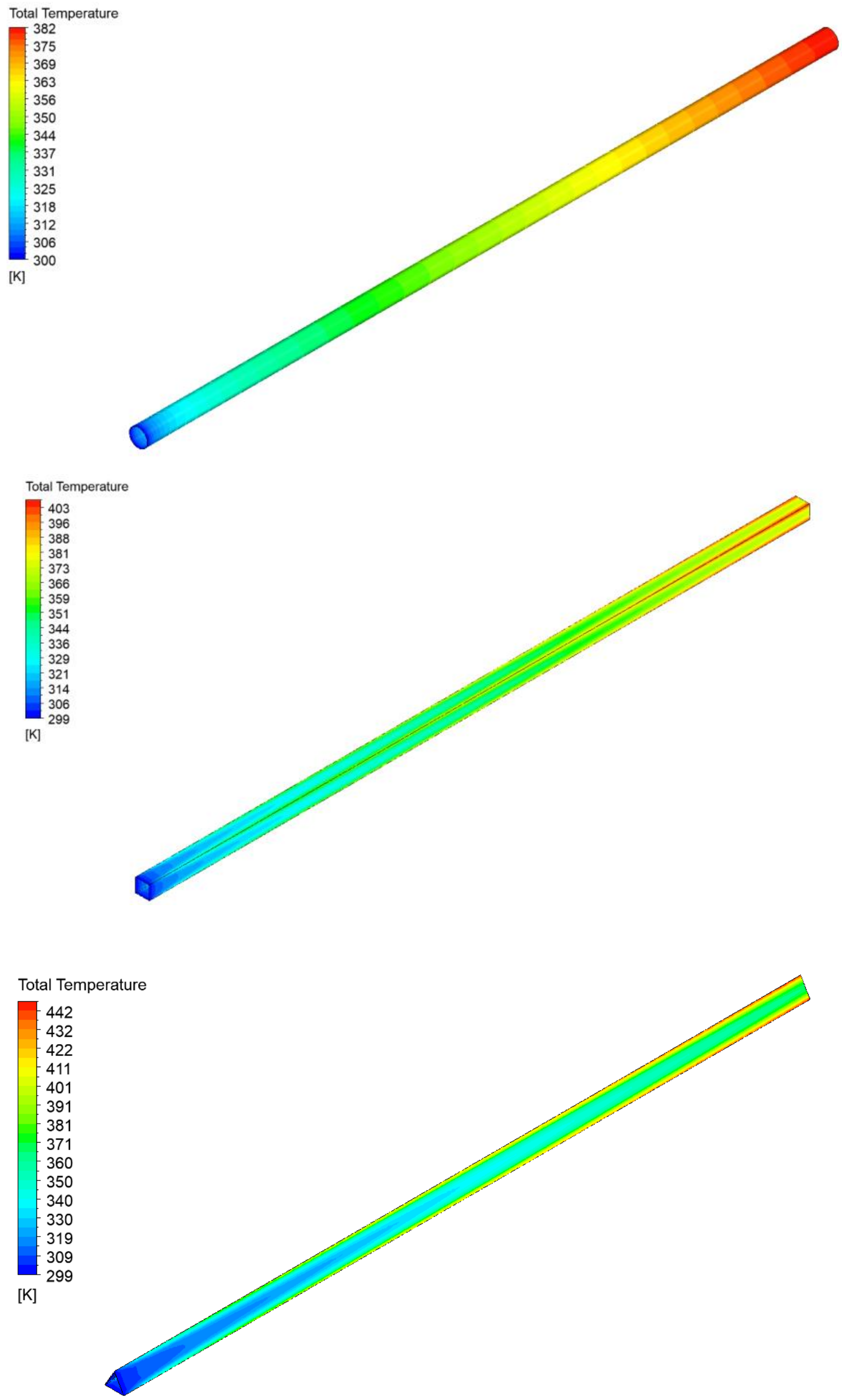

Fig. 3. Temperture distributino for the tested designs.

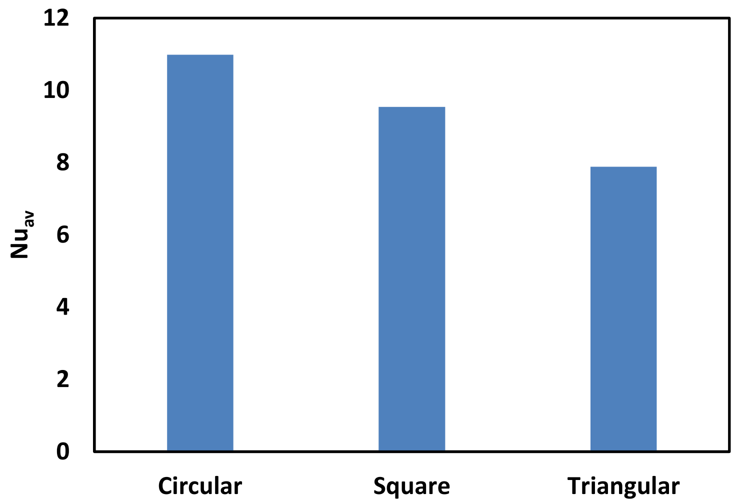

Fig. 4. Average Nusselt number for the tested designs.

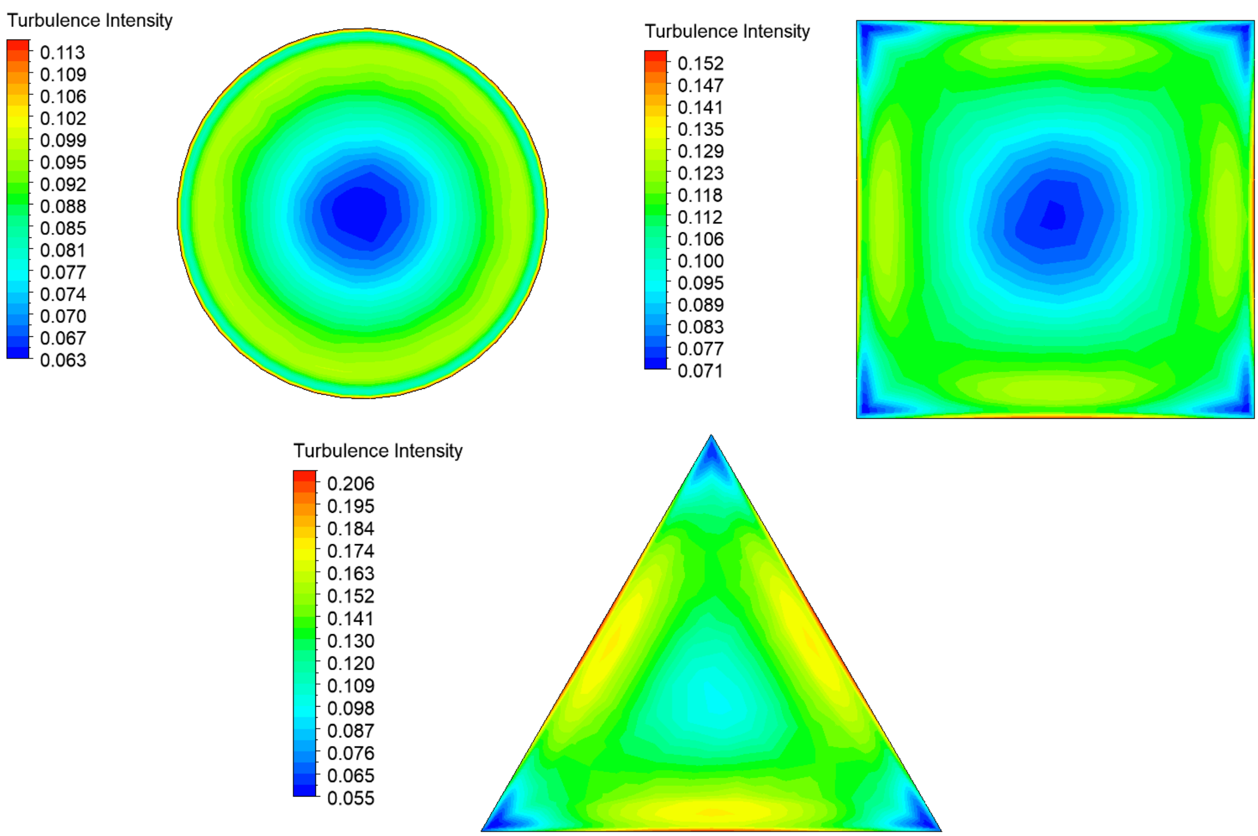

Fig. 5. demonstrate the turbulence intensity

6. CONCLUSIONS

This research examines how well pipes with various cross-sectional geometries, such as circular, square, and triangular shapes, perform in terms of heat transfer. The mains finding are :

- Circular pipes had superior thermal performance, shown by the greatest average Nusselt number and minimal temperature gradients. This renders them optimal for applications that emphasise consistent temperature distribution and thermal efficiency.
- The turbulence distribution in square and triangular pipes demonstrated elevated turbulence intensities attributed to their sharp edges, which facilitated mixing but also heightened the likelihood of pressure decreases and material fatigue over time.
- Design Trade-offs: Square pipes provide a compromise between enhanced thermal efficiency and manufacturability, making them appropriate for small systems. Conversely, triangular pipes, while less effective in heat transfer, may be beneficial in situations with limited space where a smaller pipe diameter is essential.
- The research highlights the need of choosing suitable pipe geometries according to application-specific criteria, weighing the trade-offs among thermal performance, turbulence intensity, and structural design.

Conflicts Of Interest

The author's paper explicitly states that there are no conflicts of interest to be disclosed.

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