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Numerical Study of Heat Transfer Characteristics in Shell-and-Tube Heat Exchangers with Different Tube Geometries: A Comparative Analysis

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ABSTRACT
This study presents a comparative analysis of the heat transfer characteristics among shell-and-tube heat exchangers featuring round-shaped tubes, oval-shaped tubes, and twisted tubes, utilizing Computational Fluid Dynamics (CFD) techniques. The primary objective of this research is to enhance the performance of shell-and-tube heat exchangers by integrating twisted and oval-shaped tubes, thereby replacing conventional smooth round tubes. For this investigation, a twisted tube with a pitch length of 135 mm was employed. Different heat transfer characteristics including outlet temperature, pressure drop, and total heat transfer rate were calculated for various mass flow rates (.5 kg/s, 1 kg/s, and 2 kg/s) of water. The CFD model used in this study was validated against existing literature, ensuring the reliability of the results. The findings indicate that the implementation of twisted tubes results in an increase in outlet temperature to 338.72 K compared to the Oval-shaped tube (337.88 K), round-shaped tube (335.86 K), and also a reduction in pressure drop to 1560.1 Pa from the Oval-shaped tube (1718.285 Pa), round-shaped tube (1591.547 Pa) at a consistent mass flow rate of .5 kg/s of water. The research indicates that the innovative design of twisted tubes significantly enhances the thermal efficiency of shell-and-tube heat exchangers. This establishes a promising alternative to traditional round tube designs, particularly in applications where improved heat transfer rates and reduced pressure drops are critical.

Keywords: Twisted Tube, Oval shaped tube, Shell and Tube Heat Exchanger, Heat Transfer, CFD

1. Introduction

The principal components of shell and tube heat exchangers consist of a shell, shell cover, tube, tube cover, baffles, and nozzles. Shell and tube heat exchanger performance can be optimized by changing tube side design, shell side design, tube layout pattern, tube pitch, baffling, etc [1]. Prasad et al. [2] stated that shell and tube heat exchanger has various applications fields such as in boilers, preheaters, condensers, refrigeration, and air conditioning industry. From various possible configurations, the design engineer should choose the optimum design based on the application. According to LIN et al. [3] to enhance the performance of a shell and tube heat exchanger different techniques such as optimizing geometrical configuration, introducing improved thermal property fluid, optimizing baffle configuration, adding inserts in the tube, increasing the thermal conductivity of the fluid, and assembling multiple techniques have been employed. Abd et al. [4] investigated optimizing shell diameter and tube length and found their effect on heat transfer coefficient and pressure drop. The results show that a .05m increase in the shell outer diameter results in a 3% increase in heat transfer coefficient. Additionally, increasing tube length by .61m results in a 2.2% increase in heat transfer coefficient and a 21.9% increase in pressure drop.

From the research of Bichkar et al. [5] showed different types of baffle segments have an effect on the performance of shell and tube heat exchangers. By conducting numerical analysis using single-segmental, double-segmental, and helical baffles decision was made that helical baffles decrease pressure drop which improves the overall performance of the heat exchanger.

Researchers have also been conducted for the enhancement of the performance of a shell and tube heat exchanger by optimizing tube arrangement.

Labbadlia et al. [6] found that the efficiency of the heat exchanger greatly depends upon the flow distribution. Non-uniformity of the flow distribution is not desirable which can be controlled by tube arrangement. 60° by angle tube arrangement shows better uniformity which results in better performance of the heat exchanger.

Saffarian et al. [7] have analyzed different cross-section tube shapes like circular, and elliptical with different attack angles of 90°and 0°. Also, combined models of circular and elliptical tubes have been studied. It was found that the combined model shows better performance than circular and elliptical tubes. Bouselsal et al. [8] investigated different tube shapes like diamond tubes, rectangular tubes, square tubes, and circular tubes. Additionally, added Al_2O_3-MWCNT hybrid nanofluid for performance enhancement. Results show that with increasing nanoparticle concentration the heat transfer characteristics also get enhanced. Diamond shape tubes improve the performance of the heat exchanger most by decreasing entropy than other shape tube.

Zhao et al. [9] have worked on improving the performance of heat exchangers by inserting twisted tubes. Results indicated inserting twisted tubes creates more turbulence in the working fluid hence better mixing occurs. Thus, overall heat transfer performance has been improved.

Another research work by Tan et al [10] studied twisted oval tubes inside the heat exchanger. The effect of twist pitch P, and aspect ratio A/B on the performance of the heat exchanger have been analyzed. Results show that aspect ratio

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A/B is proportional to overall heat transfer performance but with pitch length performance at first increase but then decreases later.

Wang et al [11] have analyzed the performance of a heat exchanger using a three-start twisted tube combined with oval dimples. The results show an increase in thermal performance factor 1.38 times compared to a straight tube.

Ghazanfari et al. [12] compared the performance of a smooth tube with 6 baffle heat exchanger with a twisted tube no baffles heat exchanger. Also, added Al_2O_3 nanoparticles to enhance performance. The research shows that combining the use of nanofluid and twisted tube instead of smooth tube increases the heat transfer coefficient by 8% and also reduces the pressure drop by 40 %.

In another investigation by Ghazanfari et al. [13] optimized the performance of shell and tube heat exchangers by varying the pitch length of the twisted tube also incorporating various nanofluids (Al_2O_3, Cu, CuO, and TiO_2). It was found that a twisted tube with a pitch length of 45mm increased the heat transfer performance by 1.12 times. Also using a twisted tube results significant reduction in pressure drop which is 1.55 times.

Based on previous research works, researchers have been mostly focused on heat transfer enhancement by incorporating nanofluid and optimizing baffle segments. Literature shows that implementing twisted tubes in no-baffle heat exchangers with nanofluid improves heat transfer characteristics. Also altering the tube shape can increase performance. Nevertheless, no research study is available that provides a comparative analysis of heat transfer characteristics using round-shaped, oval-shaped, and twisted tubes with baffle segments. This research work solely focused on improving the performance of shell and tube heat exchangers by changing tube shape. For this purpose, several simulation works have been performed using 3 types of tube at different mass flow rates (.5 kg/s, 1 kg/s, and 2 kg/s) of water and shell outlet temperature, pressure drop, and Total heat transfer rate data have been recorded for comparison.

2. Methodology

2.1 Governing equations

The governing equations are written followed by Ozden and Tari [14]. The model is based on the numerical solution of continuity, momentum, and energy equations.

Conservation of Mass

$$\nabla \cdot (\rho \vec{V}) = 0$$

x-Momentum Equation

$$\nabla \cdot (\rho u \vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \quad (1)$$

y-Momentum Equation

$$\nabla \cdot (\rho v \vec{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho g \quad (2)$$

z-Momentum Equation

$$\nabla \cdot (\rho w \vec{V}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \quad (3)$$

Energy Equation

$$\nabla \cdot (\rho e \vec{V}) = -p \, \nabla \cdot \vec{V} + \nabla \cdot (k \nabla T) + q + \Phi \quad (4)$$

Dissipation Function (Φ)

$$\Phi = \mu\left(\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right) + \kappa\left(\nabla \cdot \vec{V}\right)^2 \quad (5)$$

Properties of water is assigned according to Ghazanfari et al., 2016b [15] shown in Table 1.

Table 1 Properties of water

Fluid	Density, ρ (kg/m^3)	Specific Heat, C_p (J/ kg K)	Thermal Conductivity, k (W/m K)	Dynamic Viscosity, μ (Kg/ms)
water	997.1	4179	0.605	0.001003

2.2 Geometrical Parameters

The geometrical model is done in ANSYS design modeler. For validation purposes later in this paper geometrical specification is considered according to Ozden and Tari [14]. Table 2, Figure 1 shows the geometrical parameters and isometric view of the geometrical model.

Table 2 Geometrical Parameters of the Model

Parameters	**Values**
Shell size	90mm
Tube bundle geometry and pitch	Triangular, 30mm
Number of tubes	7
Heat exchanger length, L	600mm
Baffle cut	36%
Central baffle spacing	86mm
Number of baffles, N	6
Tube outer diameter	20mm

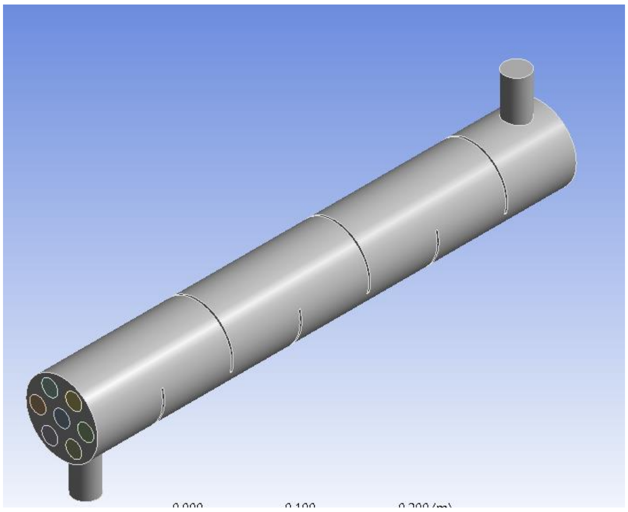

Figure 1 isometric view of the geometrical model.

Table 2 Geometrical parameters of twisted and Oval Tube

Parameters	**Value**
Minor axis (a)	16mm
Major axis (b)	25mm
Pitch length	135mm

According to Ghazanfari et al selecting the parameters of the oval-shaped and twisted tube a=16mm and b =25mm have been selected for acquiring lateral surface area approximately equivalent to a round-shaped tube diameter of 20mm for comparison [13].

Table 2 shows the geometrical parameters of twisted and Oval-Shaped Tube. Figure 2 shows the front view and isometric View of the Round-Shaped, Oval-Shaped, and Twisted Tube respectively.

(a)

(b)

(c)

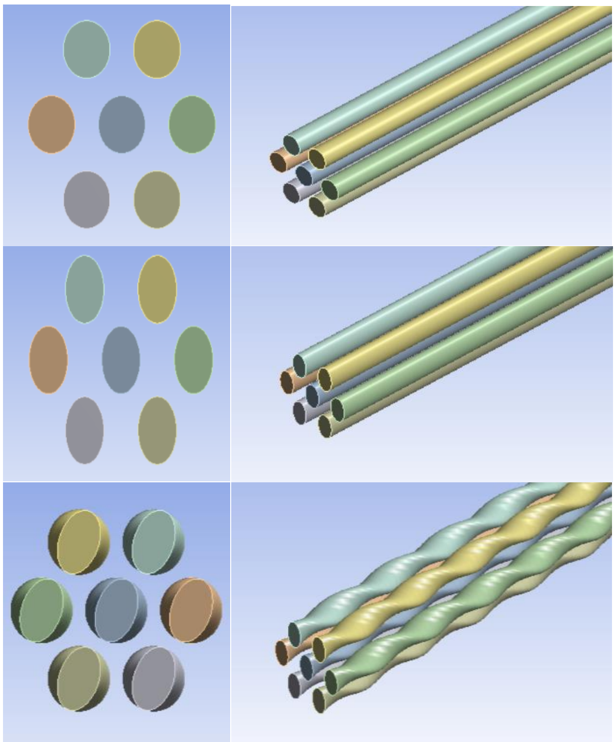

Figure 2 Front and isometric View of the (a) Round-Shaped, (b) Oval-Shaped, and (c) Twisted Tube.

2.3 Meshing

Meshing was created using ANSYS shown in Figure 3. The messing contains the number of mesh elements 3956592 with Orthogonal quantity .89, Skewness .15, and aspect ratio 1.9679. A mesh independency test has been performed shown in Figure 4 for further refinement of the mesh.

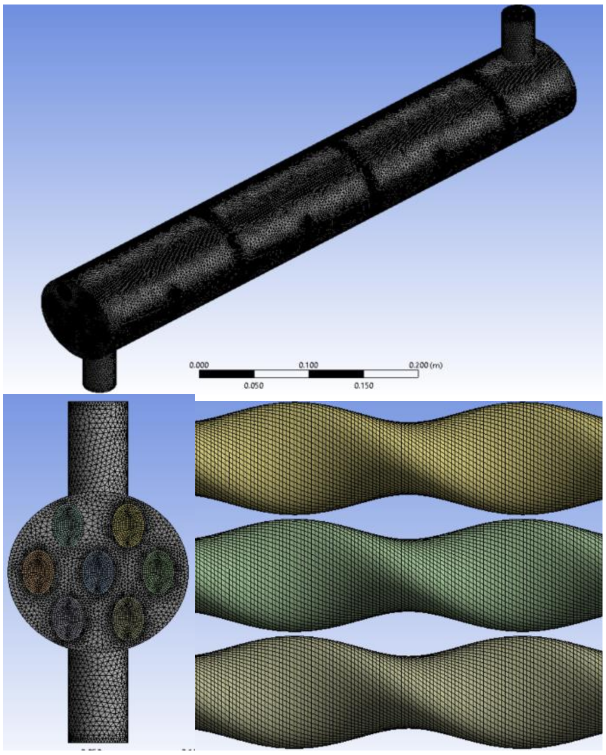

Figure 3 Meshed Geometry of the Model

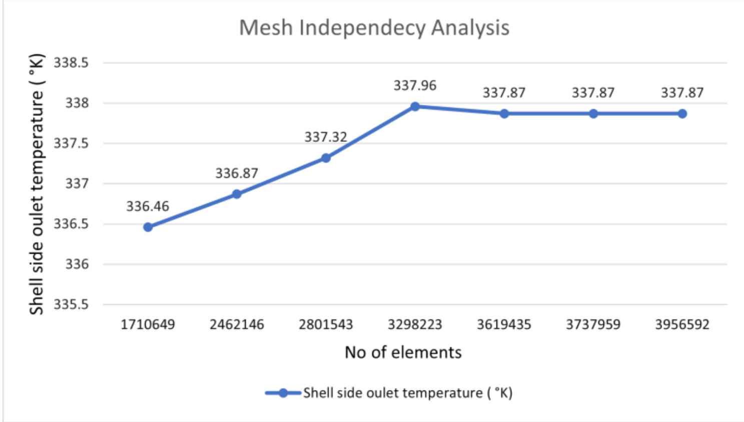

Figure 4 Mesh Dependence Test

In order to verify the mesh independence Figure 4 represents the variation of Shell Side outlet temperature at varying numbers of mesh elements. Since the mesh of elements of 3619435, 3737959, 3956592 shows insignificant variation in shell side outlet temperature. Thus, the number of mesh elements 3956592 is considered for the rest of the analysis.

2.4 Boundary Condition

The boundary condition is set for the present study similar to Ozden and Tari et al [14]. The inlet temperature of the shell's side is set to 300 K, and the shell outside is considered a pressure outlet with zero-gauge pressure. The sell wall is perfectly insulated and set to zero heat flux, and the temperature of the tube wall surface is constant at 450k. No slip condition is attached to all surfaces and inlet velocity is considered uniform. The shell side inlet is a mass flow type inlet with varying mass flow rates (.5 kg/s, 1 kg/s, 2 kg/s).

3. Validation

The present CFD model has been validated by comparing some of the output with the previously published results of Ozden and Tari [14], which were experimentally and theoretically verified. For the validation process, a configuration of seven round-shaped tubes, each with a diameter of 20 mm, arranged within a shell of 90 mm diameter and 600 mm length and 6 baffles has been employed as the reference geometry. Figure 5 and Figure 6 represent a comparative analysis of different outputs of the current study with Ozden and Tari findings at a varying mass flow rate (.5,1,2 kg/s) of water.

Figure 5 shows, the comparison in shell outlet temperature obtained from the present CFD model with the results from the Ozden and Tari [14]. The highest observed deviation in this comparison is 1.33%, which falls within an acceptable range and can be considered negligible. In Figure 6, the shell side's pressure drop has been compared at different mass flow rates and the error obtained is between -4.56% to -2.79. The consistency observed between the results of this study and those of Ozden and Tari provides strong evidence for the validation of the present CFD model. It is important to acknowledge that discrepancies may arise from minor differences in the geometry model due to unspecified details in the model setup. Furthermore, Ozden and Tari [14] considered approximately 1360,000 elements as finer mesh, but the present study employed a finer mesh consisting of 3,956,592 elements. Such differences in meshing can contribute to minor errors, however, mesh independence is tested for the present model. Additionally, the different software versions of Ansys Fluent and the difference in thermophysical properties can cause minor discrepancies.

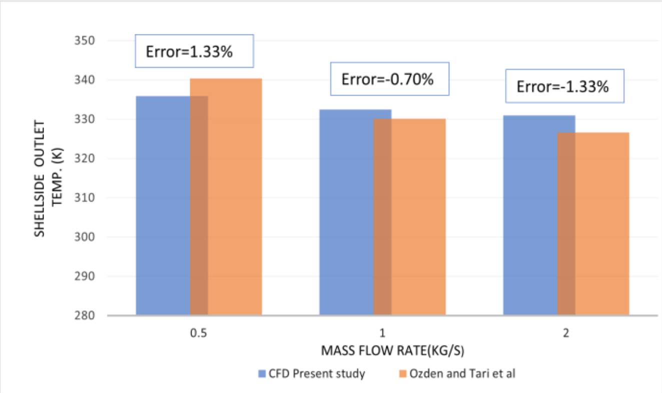

Figure 5 Comparative analysis of outlet temperatures between the current study and a published study

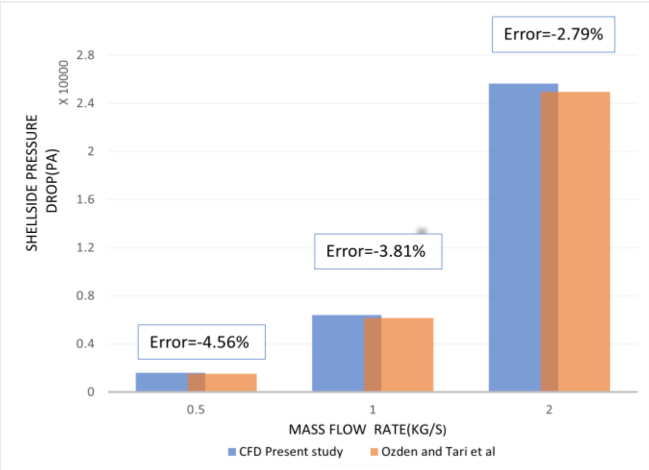

Figure 6 Comparative analysis of pressure drop between the current study and a published study

4. Results and Discussions

Figure 7, Figure 8, and Figure 9 demonstrate a comparative analysis of different output parameters at varying mass flow rates for round-shaped, Oval-shaped, and Twisted tube arrangements.

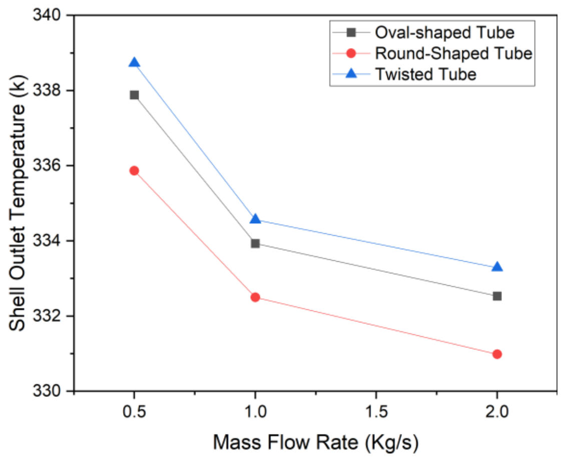

Figure 7 Comparison of outlet temperature for various mass flow rates

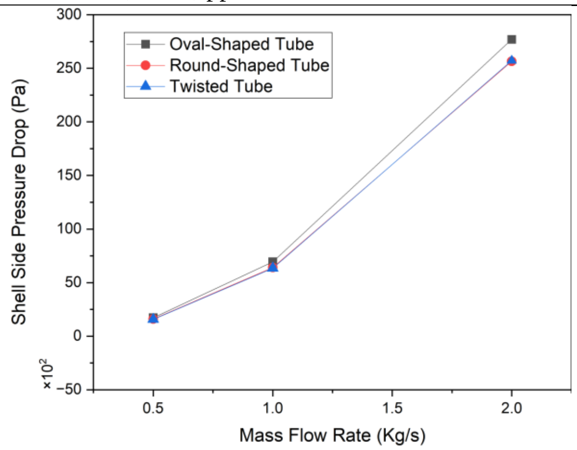

Figure 8 Comparison of pressure drop for various mass flow rates

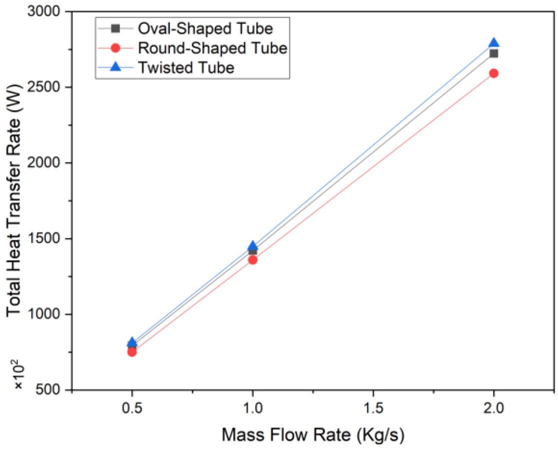

Figure 9 Comparison of total heat transfer rate for various mass flow rates

From Figure 7 the shell outlet temperature is getting decreased to an increasing trend in mass flow rate. For .5 kg/s of water flowing the shell outlet temperature of round-shaped, Oval-shaped, and Twisted tube arrangements are 335.86 K, 337.88 K, and 338.72 K respectively. This means using twisted tubes increases outlet temperature by 2.86 K more than round-shaped tubes and .84 K more than oval-shaped tubes. Similarly for 1 kg/s of water outlet temperature increased by 2.07 K and .63 K more than round-shaped and Oval shaped tubes respectively. This trend continues for the flowing of 2 kg/s of water also.

From Figure 8 the Pressure drop value for .5 kg/s of water in an Oval shaped tube arrangement is 1718.28 Pa but for a round-shaped tube, this value is dropped to 1591.54 Pa and In the twisted tube it is further dropped to 1560.1 Pa. Similarly, for 1 kg/s of water pressure drop value for the twisted tube is 8.63% less than the oval-shaped tube and .90 % less than the round-shaped tube.

Figure 9 illustrates the comparison in total heat transfer rate from different tube arrangements. For .5 kg/s of water twisted tube has 8.13% more heat transfer rate than round shaped tube and 2.14% greater than oval shaped tube. In the case of 2 kg/s of water, this rate is 7.60% and 2.38% higher than round-shaped tubes and oval-shaped tubes respectively.

4.1 Comparison of the contour of the different tube arrangements

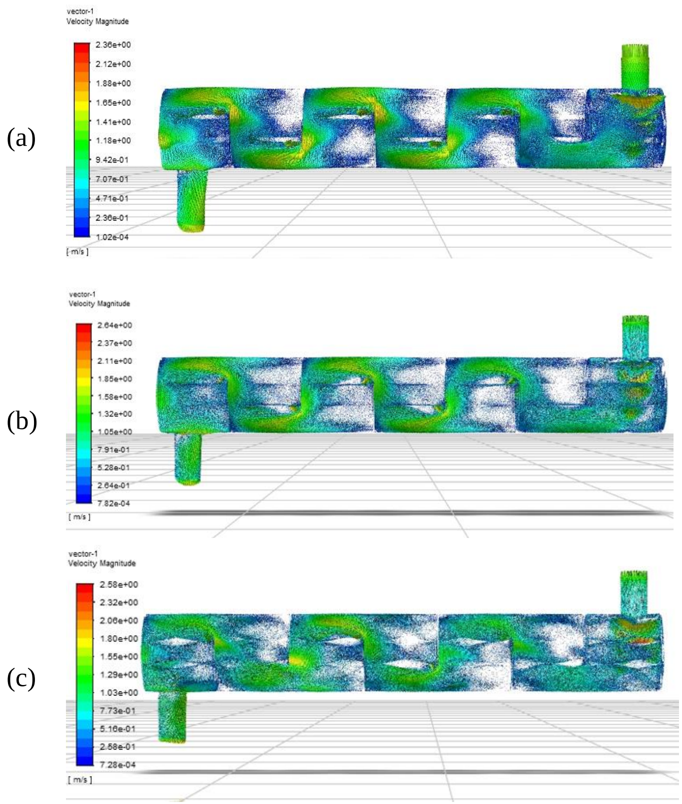

Figure 10 Velocity contour of the (a) Round Shaped tube, (b) Oval Shaped tube, and (c) Twisted tube heat exchanger respectively for 1 kg/s of water

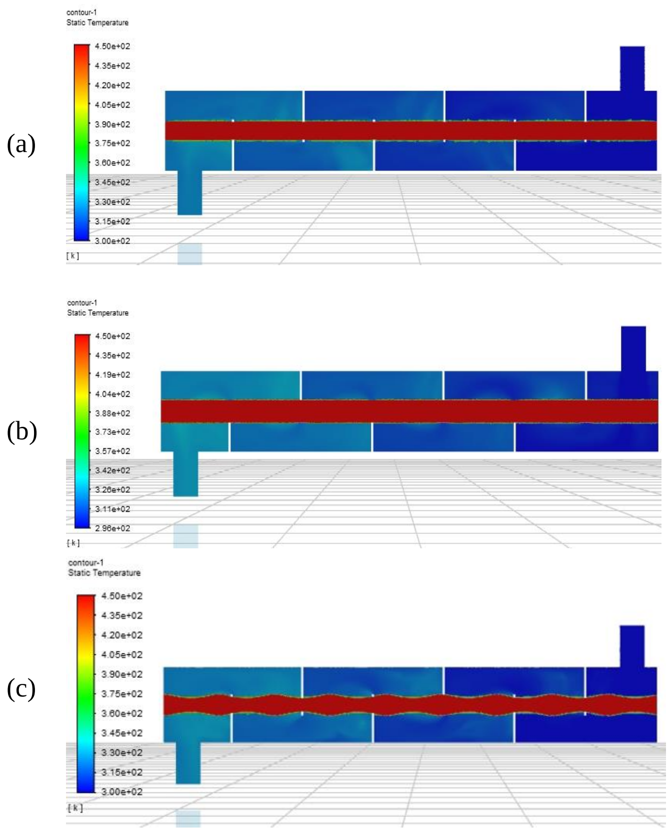

Figure 11 Temperature contour of the (a) Round Shaped tube, (b) Oval Shaped tube, and (c) Twisted tube heat exchanger respectively for 1 kg/s of water

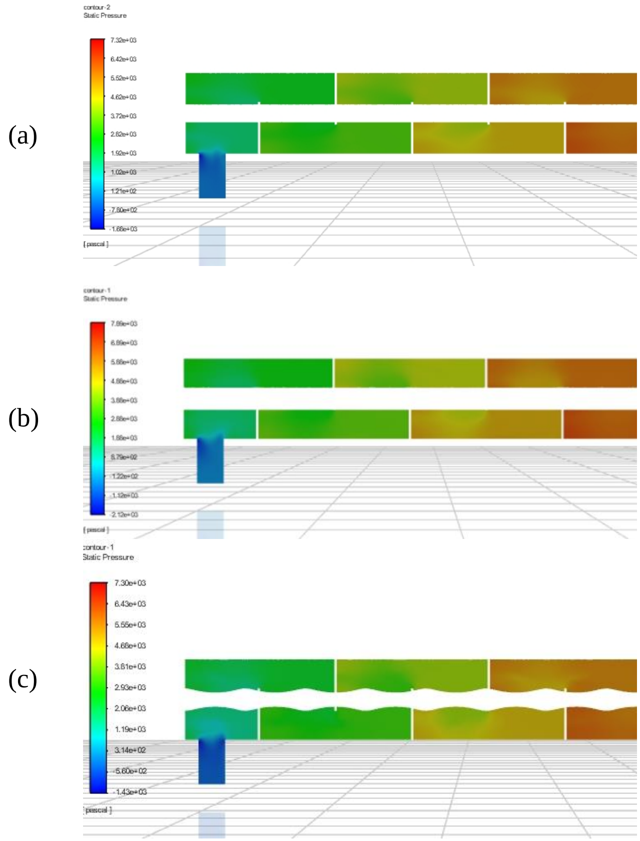

Figure 12 Pressure contour of the (a) Round Shaped tube, (b) Oval Shaped tube, and (c) Twisted tube heat exchanger respectively for 1 kg/s of water

Figure 10 illustrates the velocity variation in different tube arrangements. The greenish and yellowish area represents higher velocity. From the figure in the baffle region, there is a higher velocity which circulates the motion of water. It can be observed in the heat exchanger with (c) Twisted tubes that there is a swirling motion created near the twisted region of the tube which creates better mixing and enhances heat transfer of fluid.
Figure 11 demonstrates the temperature contour of the various types of tubes used in heat exchangers. From Figure 12 it can be observed that in (c) the twisted tube arrangement, the shell outlet temperature is higher than the other two because of the greater circulation of the water and increased area of the tube.
Whereas, Figure 12 represents the pressure contour of the different geometry tube heat exchangers. It shows pressure variation across the shell side of the heat exchanger where the blue area represents lower pressure and the orange area represents higher pressure. From the contour, it can be observed that at (b) Oval Shaped tube pressure variation between the inlet and outlet is maximum whereas in (c) Twisted tube pressure drop is lowest.

5. Conclusion

In this study, our main objective is to find an alternative to the conventional round-shaped tubes used in shell and tube heat exchangers ensuring enhanced heat transfer characteristics. For this purpose, we have conducted a CFD simulation for a shell and tube heat exchanger with 6 baffles and 3 types of tube variation. After a comparative analysis after the implantation of round-shaped tubes, Oval-shaped, and twisted tubes some of the key findings are presented below

- The results from the graph show that using twisted tubes increases the shell outlet temperature by about .85% and the Total heat transfer rate by about 8.13%.
- Additionally, the pressure drop for the twisted tube is 8.63% less than the oval-shaped tube and .90 % less than the round-shaped tube
- Pressure drop is highest for oval-shaped tubes and lowest for the twisted tube arrangements.

So, the findings of this study suggest that twisted tubes represent a promising alternative to traditional round and smooth tubes. This is particularly relevant in industrial applications where high outlet temperatures, enhanced heat transfer rates, and minimized pressure drops are essential. Thus, the implementation of twisted tube design offers significant advantages in these regards, indicating their potential as effective replacements for conventional tube configurations.

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NOMENCLATURE

$\vec{V}$: velocity vector
ρ : density(kg/m^3)
τ : shear stress(N/m^2)
μ : dynamic viscosity (Pa s)
p : pressure, kPa
T : temperature, K
Φ : dissipation function
V : volume, m^3
κ : closure coefficient of transport equations
g : gravitational acceleration(m/s^2)
q : heat flux as a source term(W/m^2)
k : thermal conductivity (W/m K)
C_p : specific heat (J/ kg K)