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# Numerical Study of a Shell and Tubes Heat Exchanger: Impact of the Geometrical Change of the Tube Section on the Overall Exchange Coefficient and the Pressure Drop

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**Abstract**: Shell and tube heat exchanger is the most widely used type in industry because of its advantages: solid design, excellent reliability, compact, resistant to fouling fluids, having a very high exchange coefficient...etc. Several studies have highlighted the importance of this configuration. This study consists in the design and the thermo-fluid simulation by COMSOL software of a shell and tube exchanger with two different tubular geometries: i) circular, ii) square, iii) elliptical 90° using segmental baffles at 25% and two working fluids: water-air. The mass flow rates of the two fluids are varied and their influence on the energy performance of the heat exchanger is also examined. The results show that changing the geometry of the tube bundles affects the pressure drop especially on the shell side, the square geometry created a higher pressure drop than the circular tube geometry. A considerable improvement in the overall exchange coefficient was recorded for the exchanger with the circular tube bundle by increasing the fluid velocity.

**Keywords:** Shell and tube heat exchanger, Simulation, Thermo-fluid, Circular tubes, Square tubes , Elliptical 90°.

## Introduction

Heat exchangers play a crucial roler in various industries and engineering field: chemical, petroleum, food processing, nuclear power plant, thermal power plant, electric power plant, .... etc., by the transmission and recovery of energy (Master, Chunangad, & Pushpanathan, 2003). The shell and tube heat exchanger are the most used type in the industry (35% - 40%) (El Maakoul et al., 2016)]due to its advantages: easy to maintain, efficient, compact and resistant. It consists of two main elements: i) tubes, ii) shell. The tubes ensure the transport of aggressive fluids (hot or cold), compressible and incompressible and especially at high pressure. The shell ensures the circulation of fluids at low pressure, it generally includes longitudinal and/or transverse baffles. The implementation of the baffles makes it possible to lengthen the path of the fluid in the shell, accelerate its turbulence and thus increase the exchanged flow. However, they have certain disadvantages, such as a high resistance to flow, vibrations induced by the flow, and dead flow areas on the side of the envelope (Ünverdi, 2022).

In order to improve the performance of the shell and tube type heat exchanger many researchers have conducted a lot of research work. Some of the recent researches are focused on the shell side more precisely the baffles: material type, number, shape, cutting angle......etc. Juan Xiao et al. (2020) studied the effect of geometric variation of baffles on the performance of exchangers, they used baffles: segmental, helical and folded. Ali Akbar Abbasian Arania et al. (2019) examined the combination of disk baffles with other drawn baffles. Another part of the research is studied the tube side, The study of tube side is quite trouble-free with a smaller number of parameters.

The tube arrangement has an influence on the energy performance of tube and shell heat exchangers, Sachin Kallannavar et al. (2020) studied the effect of variation of four types of tube arrangement 30°, 90°,60°and 45°, for a tube and shell heat exchanger with circular tube. Arania & Moradi (2019) segmental baffles and combined segmental-disk baffle with two types of circular and triangular ribbed tube. Matos et al. (2014a, 2014b) compared 12 elliptical and circular tubes at Reynolds numbers between 300 and 800. Elliptical tubes increase the heat transfer with 20% compared to circular tubes. Tao et al (2007) numerically studied a tube and shell heat exchanger with elliptical tubes and found a 30% increase in heat transfer compared to circular tubes.

The objective of this manuscript is to study the effect of varying the different tube cross-sections (square, circular and elliptical tube with 900 attach angle) on the hydro-thermal performance of a tube and shell heat exchanger using numerical software for design, modeling and simulation. A coupling of heat transfer with fluid mechanics was performed based on the Navier - Stokes equations and the k-**ε** turbulence model.

## Methodology

### Feometric Model

The exchanger used in this study belongs to the family of multi-tube exchangers with a bundle of 37 tubes. It has 1 tube side pass and 1 shell side pass with counterflow. The shell has four vertical single segment baffles with a 25% cut. The geometry of this exchanger was drawn in 3D using COMSOL Multiphysics 5.5 software (Figure 1).

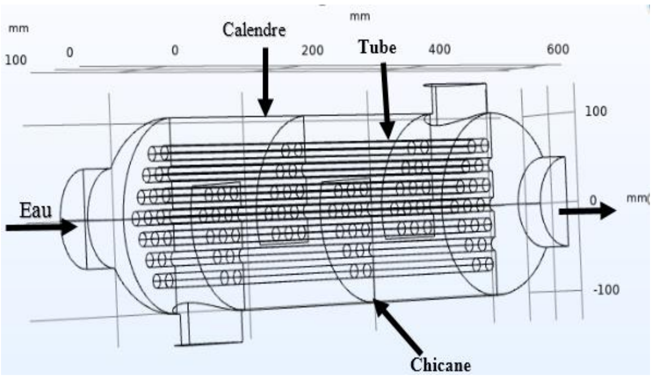


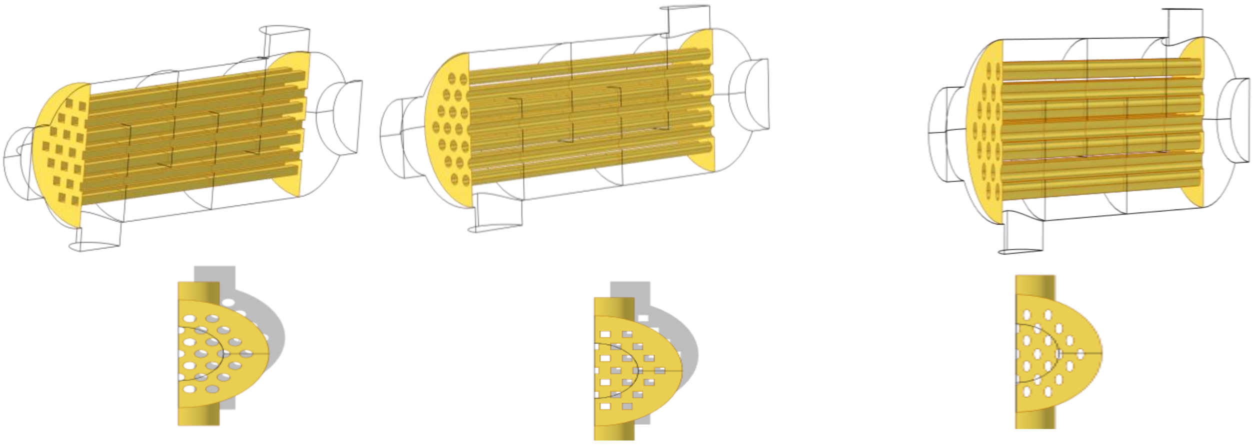

Figure 1 Numerical model of the shell and tube exchanger

The hot fluid (water) enters the shell at of 80°C while the cold fluid (air) enters the tubes with a temperature of 5°C. Table 1 shows the thermo-physical properties of the two fluids.

Table 1. Thermophysical properties of shell and tube heat exchanger

| Properties | Fluid | | |
|---|---|---|---|
| | water | air | unit |
| $T_{inlet}$ | 80 | 5 | °C |
| Thermal conductivity | 0.6562 | 0.02401 | (W/m.K) |
| Density | 971.8 | 1006 | (kg/m$^3$) |
| Specifc heat capacity | 4194 | 1006 | (J/Kg K) |
| Dynamic viscosity | $3.54\times10^{-4}$ | $1.75\times10-^{5}$ | (Pa s) |

The geometry of the exchanger was maintained in the three cases examined only the tubes bundles which was varied (Figure 2), the dimensional specifications of this heat exchangers are presented in the Table 2.



Circular cross section    Sαuare cross section    Elliptical 90° cross section

Figure 2. Cross sectional models of the shell and tube exchanger

Table 2. Size of the heat exchanger

| Propertie | Value | Unit |
|---|---|---|
| Shell diameter | 200 | mm |
| Tube diameter | 15 | mm |
| Length shell /tube | 500 | mm |
| Number of tubes | 37 | |
| Number of baffles | 4 | |

**Mathematical Model**

*Heat Transfer Coefficient*

The overall heat transfer coefcient is calculated by the following equation (Allen & Gosselin, 2008; He et al., 2016):

$$U = \frac{1}{\frac{1}{hi} + \frac{di ln(\frac{de}{di})}{2\lambda} + \frac{1}{he}} \qquad (1)$$

hi : convective transfer coefficients for the tube side, he : convective transfer coefficients for the shell side, k : thermal conducivity of the tube, $d_i$ : inner diameters of the tube, $d_e$: outer diameters of the tube.

*Pressure Drop in Shell Side*

The pressure drop in the shell side can be obtained using the following equation (2) (Allen & Gosselin, 2008; He et al., 2016)

$$\Delta P = f \frac{D_S}{D_e}(N_b + 1)\frac{1}{2}\rho V^2$$
$$f = \exp(0.576 - 0.19 lnR_{es})$$
$$D_e = \frac{4\left(\frac{\sqrt{3}P_t^2}{4} - \frac{\pi d_0^2}{8}\right)}{\frac{\pi d_0}{2}}$$
$$Re_s = \frac{\rho u_m D_e}{\mu} \qquad (2)$$

**ΔP**: pressure drop in shell side $\mathbf{Re_s}$: Reynold's number in shell, **f** = friction factor, $\mathbf{D_s}$ : Sell diameter, $\mathbf{D_e}$: equivalent diameter for the triangular pitch,, $\mathbf{N_b}$ : number of bafe, **ρ**= density of the fluid, **μ**= dynamic viscosity of the fuid, $\mathbf{u_m}$: velocity of the fuid,,**V** : mean fow velocity, $\mathbf{P_t}$: tube pith ,$d_0$: outer diameters of the tube.

*Turbulent Fow k–ε Model*

The turbulent flow model (k - ε) is widely used in the literature to the study the turbulent flows with very high Reynolds numbers. It is a model with two partial differential equations: i) turbulent kinetic energy (k) and ii) dissipation (ε). COMSOL uses the Navier - Stokes equations as the basic equations to solve the fluid flow models (3)

$$\rho(\mu.\nabla)\mu = \nabla.[-PI + (\mu+\mu_T)(\nabla\mu + (\nabla\mu)^T - \frac{2}{3}(\mu+\mu_T)(\nabla.\mu)I - \frac{2}{3}\rho kI] \qquad (3)$$
$$\nabla.(\rho\mu) = 0$$

ρ : density (kg/m$^3$ ) ; μ : Dynamic viscosity (kg/m/s) ; P : fluid pressure (Pa)
k : Turbulent kinetic energy (m²/s²) et $\mu_T$ : turbulent viscosity (Pa.s).

The turbulent kinetic energy is defined as follows (4):

$$\rho(\mu.\nabla)k = \nabla.\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\nabla k\right] + p_k - \rho\varepsilon \qquad (4)$$

$\sigma_k$ : the turbulent Prandtl number; ε : Turbulent dissipation(m²/s²)

Turbulent dissipation is the rate at which velocity fluctuations dissipate. It is defined by the equation (5)

$$\rho(u.\nabla)\varepsilon = \nabla.\left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + C_{e1}\frac{\varepsilon}{k}\,p_k - C_{e2}\,\rho\frac{\varepsilon^2}{k} \qquad (5)$$

*u* : fuid flow velocity,.
For a turbulent flow, the viscosity is defined by the equation (6)

$$\mu_T = \rho C_\mu \frac{k^2}{\varepsilon} \qquad (6)$$

La production d'énergie cinétique turbulente est peut-être exprimée par l'équation (7)

$$P_k = \mu_T\left[\nabla u:(\nabla u + (\nabla u)^T) - \frac{2}{3}(\nabla.u)^2\right] - \frac{2}{3}\rho k\nabla.u \qquad (7)$$

The constants used in the equations for turbulent kinetic energy, turbulent dissipation and turbulent viscosity are: $C_{e1}$=1.44, $C_{e2}$=1.92, $C_\mu$=0.99, $\sigma_k$ = 1, $\sigma_\varepsilon$ =1.3

*Mesh Control*

The computational grid was generated using the COMSOL software. The volume of the shell and tube assembly was discretized using a free unstructured tetrahedral mesh (figure 3). A sensitivity study of the mesh was performed to choose the number and size of the meshes and to minimize the computational cost

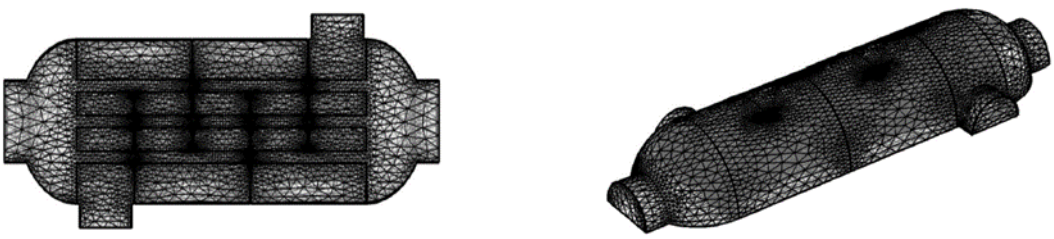


Figure 3. The meshed model used in the numerical calculations of the heat exchangers

## Result and Discussion

### Temperature Evolution

The 3D temperature contours in the heat exchanger for the three geometries are shown in Figure 4. The heat transfer in the shell and tube exchanger is performed by both modes of heat transfer: conduction and convection. The separating walls between the two fluids, namely the tube plate inside the exchanger and the shell wall as well as , the baffles ensure the conductive transfer. The convective transfer is carried out between the cold fluid (air) and the interior faces of the tubes as well as the hot fluid and the exterior faces of the tubes and the interior of the shell. The temperature evolution is uniform along the exchanger, the lowest temperature for the tube bundle corresponds to the outlet temperature of the cold fluid 324.35K, 328.44K and 328.22 corresponds to the 90° elliptical square section respectively. The heat transfer is higher for the exchanger with circular tubular section compared to the square and 90° elliptical geometry. The specification of the square geometry which disadvantages the convective transfer and decreases the heat exchange rate.

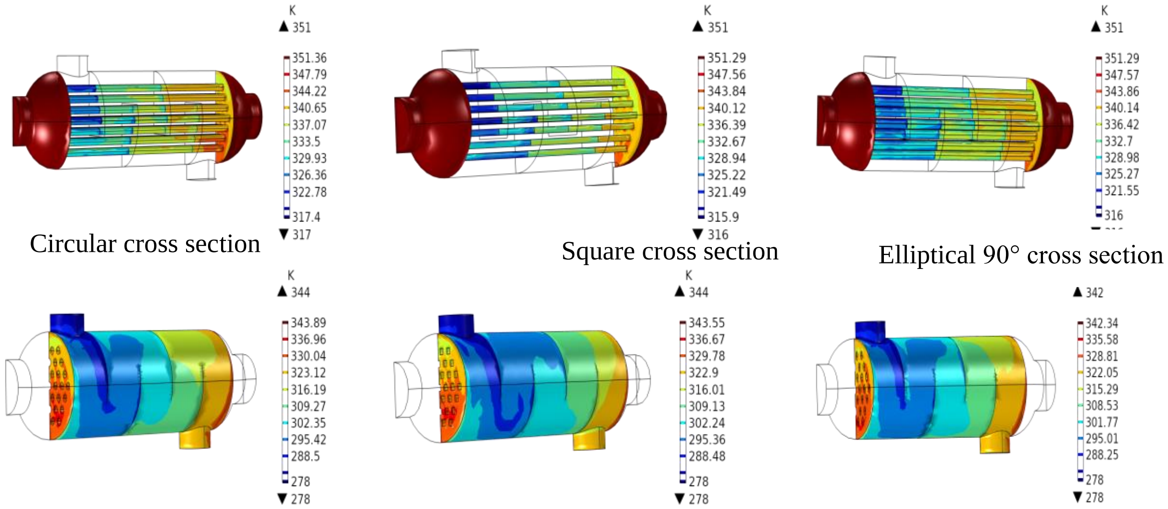



Figure 4. 3D temperature contours for both shell and tube exchanger geometries

### Velocity Evolution

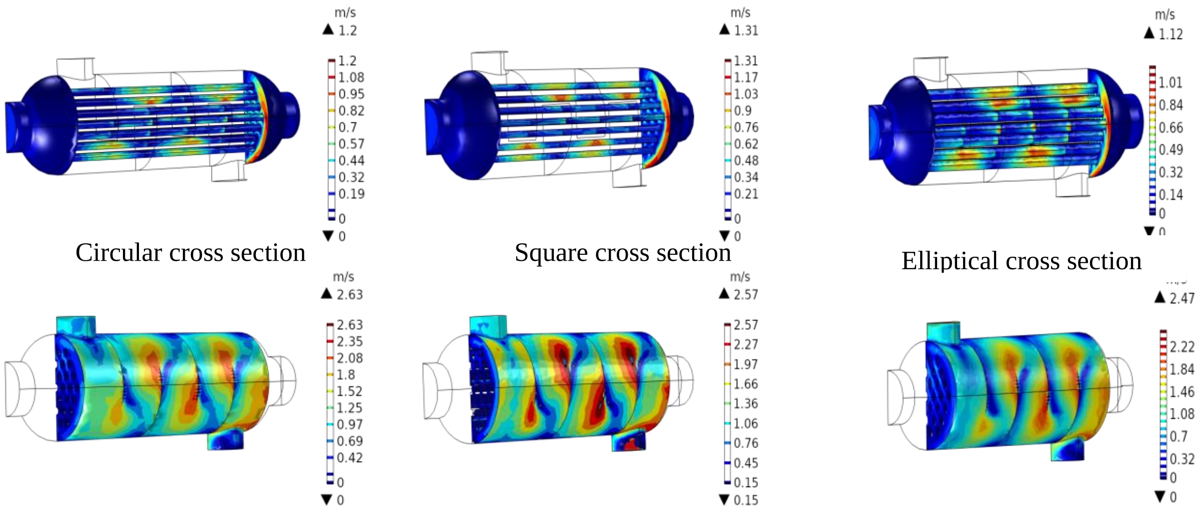



Figure 5. 3D velocity contours for three shell and tube exchanger geometries

The velocity contours across the cross section of the three geometries (square and circular section) are shown in figure 5. The maximum velocity value in the three exchanger geometries (1.31 m/s ,1.2m/sand 1.12 m/s for the square, circular and 90° elliptical section respectively) was in the baffle edge. The restriction of the flow area between the shell and the baffle plates as well as the external shape of the tube bundle induces a flow acceleration on the shell side and has no influence on the tube side.

### Pressure Evolution

The pressure drop is one of the fundamental criteria to be respected in the design of heat exchangers. This parameter has a very important impact on the thermal performance of shell and tube heat exchangers. Figure 6 presents the influence of the variation of the circular, square and elliptical 90° tube section on the pressure drop for a shell and tube heat exchanger. The results show an increase in pressure drop of 1.28% and 1.27% for the square and 90° elliptical tube sections respectively. 1.28% and 1.26% for the square and 90° elliptical geometry on the shell side compared to the circular heat exchanger. The change of cross section in the square configuration causes a sudden expansion and contraction of the fluid and increases the pressure drop (Arani & Uosofvand, 2021). The choc created between the fluid and the shell and the change of the cross section between the shell and the baffles induces a higher creation of the dead zones and increases the pressure drop.

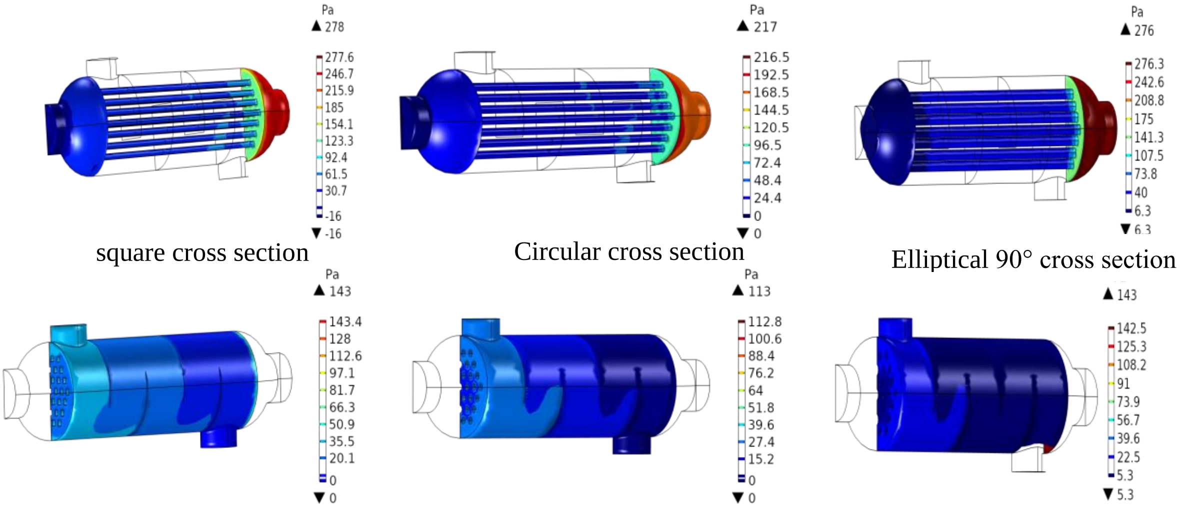



Figure 6. 3D Pressure contours for shell and tube exchanger geometries

### Heat Transfer Coefficient

Figure 7, shows the variation of the global heat transfer coefficient as a function of the Reynolds number for the three geometries of heat exchangers circular, square and elliptical 90 ° The global exchange coefficient varies proportionally with the Reynolds number. The maximum value of Reynolds corresponds to the highest mass flow rate and the largest transfer coefficient. the heat exchangers with circular section presents the highest heat transfer 10. 458 (W/m$^2$.K) compared to the square ( 9.056 (W/m$^2$.K) and 90° elliptical (9.9552 W/m$^2$.K) geometries, due to the decrease of the higher flow section for the circular geometry in the shell side which causes an increase in the flow rate which in turn causes the heat transfer to penetrate the cold fluid at a higher rate.

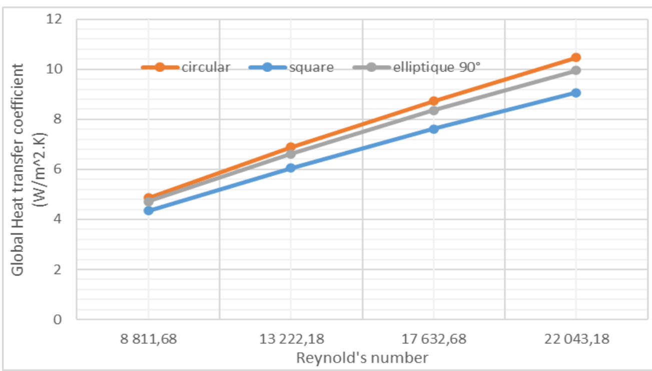



Figure 7. The overall heat transfer coeffcient in the three geometries

**Pressure Drop ın Shell Side**

According to the results presented in figure 8 which represents the variation of the pressure drop in the shell side as a function of the Reynolds number for the three different cross sections, the pressure drop varies proportionally with the Reynolds number. The maximum value of the pressure drop corresponds to shell and tube heat exchanger with the square cross-section, while the circular geometry shows the minimum pressure drop. The variation of the square and 90° elliptical geometry increases the creation of recirculation zone and the friction factor on the shell side then increases the pressure drop.

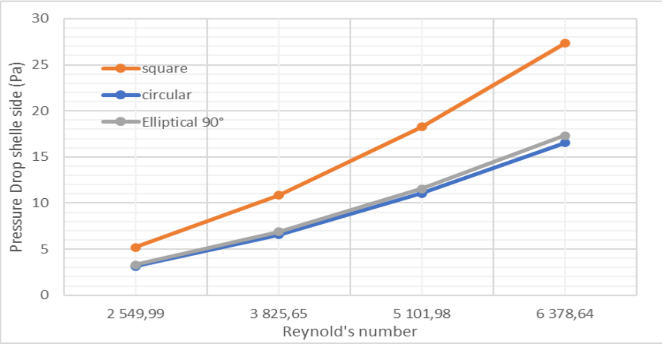



Figure 8. Pressure drop in shell side of three geometries heat exchangers

## Conclusion

The overall heat transfer coefficient and the pressure drop are studied through three different types of tube bundles (circular, square and 90° elliptical) of a water/air shell and tube heat exchanger, in order to determine the influence of the tube geometry on the pressure drop and the heat transfer by varying the mass flow rate. The numerical study was performed with the modeling and simulation software CONSOL Multiphysics 5.5a. The heat exchanger with circular cross section has the highest heat transfer coefficient. The square section increases the pressure drop on the shell side compared to the circular section. Reynolds number varies proportionally with the fluid mass flow rate, the higher the Reynolds number the higher the flow rate. The variation in flow velocity influences the heat transfer in the tube and shell heat exchanger.

## Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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