NUMERICAL INVESTIGATION OF THERMOHYDRAULIC PERFORMANCE OF TRIPLE CONCENTRIC-TUBE HEAT EXCHANGER WITH LONGITUDINAL FINS

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Abstract

In this work, a triple concentric-tube heat exchanger (TCTH) with or without the application of longitudinal fins is numerically studied concerning its thermohydraulic performance. The computational fluid dynamics (CFD) program, Ansys FLUENT was used to perform the simulations to study the heat transfer enhancement using three different types of hot fluids, i.e. Crude oil, engine oil, and light diesel oil. The validated numerical model was first employed to investigate the heat transfer performance of unfinned TCTHE. Then, longitudinal fins were modeled and investigated for comparative analyses of the thermohydraulic performances of both constructions. To predict the heat exchanger performance, key parameters such as heat flux and temperature field distribution were evaluated. Results revealed that modifying the heat exchanger with longitudinal fins on the tube surface dramatically improves its heat transfer rate. Therefore, this research is designed to keep in view further exploring the potential of longitudinal fins in obtaining an improved performance from these types of heat exchanger devices. The results showed that the crude oil fluid has high heat transfer rate than the other two fluids light diesel oil and

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engine oil. With the application of fins on the tubes’ surfaces, a significant heat transfer exchange among the fluids streams is observed.

**Keywords**: TCTHE, Longitudinal fin, Heat transfer rate, Temperature field distribution.

**I. Introduction**

Heat exchangers are used in vast engineering applications [VII]. Depending on the type of fluid, construction, flowing fluids directions, and mode of contact between them, the heat exchangers are termed as counter-flow, parallel flow, and cross-flow; double or triple concentric tube heat exchangers (TCTHE). The TCTHE is an advanced version of the double concentric tube heat exchanger with an additional intermediate tube. Due to the larger heat transfer area, TCTHE has a higher heat transfer rate than that of the double tube heat exchanger [II]. In the open literature, a variety of techniques have been adopted and explored to improve the performance of these devices. Some commonly used techniques include geometric modifications of the pipes, dimpling on the pipe surfaces, and fouling reduction. However, the modifications on the tube surfaces may increase the pressure drop of the flowing fluid. The investigations highlighted that the geometric modification in a heat exchanger has the promising potential of greater heat transfer enhancement. The most common modifications with the pipe surfaces are ribs, fins, or protrusions [X, XVI-XVIII, XX-XXIII]. In a study performed using numerical and experimental methods [XXV, III], investigated the performance of TCTHE under different flow arrangements and adiabatic and non-adiabatic conditions. The fluids considered in that study were hot water, cold water, and normal tap water. The results presented as the dimensionless temperature variations of the studied fluids along the flow path at different flow rates. The findings of the study revealed a close validation of the numerical predictions with the experimental data [XXIX] used both Computational Fluid Dynamics (CFD) and experimental techniques to investigate the impact of dimple protrusion on the heat transfer enhancement and compared the results with the plain tube heat exchanger. The results showed a significant temperature difference and flow velocity with the dimpled tube compared to the plain tube, however, the pressure across the tube is increased due to the uneven surface [XI] conducted a numerical test on the sizing of the triple tube heat exchanger. During the comparison of triple and double tube heat exchangers, they found that triple tube heat exchangers provided better heat transfer efficiencies.

The improvement in heat transfer rate was occurred due to an increase in heat transfer area per unit length of the heat exchanger. Also, it reduces the space requirement. Considering the reviewed literature, this study aimed to compare the
heat transfer rate and temperature distributions of TCTHE using different fluids with or without the application of longitudinal fins.

**Figure 1.** Schematic illustration of triple concentric-tube heat exchanger with counterflow arrangement

### II. Numerical Methodology

This section discusses the preliminary numerical simulation methods for heat transfer through a finned/unfinned triple concentric tube heat exchanger. Initially, the series of simulations were carried out for unfinned TTCHE of length 1.193m. The temperature and heat flux at inlets and outlets of the tubes were recorded. Later, the simulations were extended after constructing the longitudinal fins on the outer surfaces of inner and intermediate tubes. The collected data from unfinned TCTHE was then compared with the data predicted by finned TCTHE. The length of the tube was kept constant for both types of construction for better comparison. The installation of fins on the tube surfaces may offer enhancement in heat transfer through TTCHE. In the subsequent simulations, the values for the heat transfer rate of three different hot fluids were recorded and compared. In doing so, the effect of varying geometry (fins) and type of fluid on the thermohydraulic performance of a triple concentric-tube heat exchanger is studied.

**Computational domain**

Figure 2 presented the triple concentric-tube heat exchanger and its computational domain with or without the installation of longitudinal fins. The TCTHE includes three tubes, namely inner, intermediate and outer. The fluid flows in these tubes in a way that the cold fluid flows through the inner annulus whereas the hot fluid flows through the inner tube and outer annulus in the opposite direction of the cold fluid, thus make the arrangement counterflow. For cold fluid, pure water is used, whereas engine oil, crude oil, and light diesel oil were used as the hot fluid in the series of simulations. The detailed geometrical description of the investigated heat exchanger is given in Table 1.
Conservation equations of mass, momentum, and energy were used to determine the flow and heat transfer from the hot fluid moving in the inner tube and outer annulus. Heat transfer between the hot and cold fluids occurs across the walls separating them. The generic model of the basic governing equations including continuity, momentum, and energy equations as well as turbulence model can be expressed in tensor notation as follows

\[ \nabla \cdot (\rho \mathbf{V} k)_{nf} = \nabla \cdot (\Gamma_\phi \nabla \phi) + (S_\phi) \]  
(1)

Where \( S_\phi \) and \( \Gamma_\phi \) terms represent the appropriate source and diffusion, respectively. For detailed background theory, the given reference can be referred. The k-\( \varepsilon \) turbulence model contains two additional equations; namely, turbulent kinetic energy (k) and rate of dissipation (\( \varepsilon \)).

\[ \nabla \cdot (\rho \mathbf{V} k)_{nf} = \nabla \cdot \left( \frac{\mu_{t,m}}{\sigma_k} \nabla k \right)_{nf} + (G_m + \rho_m \varepsilon)_{nf} \]  
(2)

\[ \nabla \cdot (\rho \mathbf{V} \varepsilon)_{nf} = \nabla \cdot \left( \frac{\mu_{t,m}}{\sigma_\varepsilon} \nabla \varepsilon \right)_{nf} + \frac{\varepsilon}{k} (C_1 G_m + C_2 \rho_m \varepsilon)_{nf} \]  
(3)

where \( G_m \) represents the generation of turbulent kinetic energy due to mean velocity gradients; \( \sigma_k \) and \( \sigma_\varepsilon \) are effective Prandtl numbers for turbulent kinetic energy and rate of dissipation. \( C_1 \) and \( C_2 \) are effective Prandtl numbers for turbulent kinetic energy and rate of dissipation, respectively; \( C_1 \) with value 1.44 and \( C_2 \) with value 1.92 are constants. \( \mu_{t,m} \) is the eddy viscosity and is modeled as follows.

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\[ \mu_{t,m} = \left( \rho_m C_m \frac{k^2}{\varepsilon} \right) \] \hspace{1cm} (4)

In this study, a most validated and reliable turbulence model, the Realizable k-\(\varepsilon\) model is employed in the simulation. This model was found more accurate for a large flow application than the standard k-\(\varepsilon\) model. The above-mentioned governing equations were solved using proper boundary conditions to obtain the performance parameters of the heat exchanger. The complete details of the boundary conditions chosen are mentioned in Table 1.

**Table 1. TCTHE geometric description and simulation boundary conditions**

| Geometry               | Inner tube | Inner annulus | Outer annulus |
|------------------------|------------|---------------|---------------|
| Inner diameter (m)     | 0.012      | 0.026         | 0.040         |
| Outer diameter (m)     | 0.014      | 0.028         | 0.042         |
| Thickness (m)          | 0.001      | 0.001         | 0.001         |
| Fins, Size (m)/Nos.    | 0.0045 (height) | ------         | 0.0045 (height) | 6 numbers |
|                        | 0.0004 (thickness) | ------         | 0.0004 (thickness) | 6 numbers |
| Length (m)             | 1.193      | 1.193         | 1.193         |

**Boundary Conditions**

| Inlet Temperature/Mass flow rate | Outlet Temperature/Mass flow rate |
|----------------------------------|-----------------------------------|
| Cold fluid (Water)               | Pressure outlet                    |
| (Crude oil)                      | 283.38K / 0.58kg/s                | Pressure outlet                    |
| 325.26 K / 0.58kg/s [inner tube] |                                   | Pressure outlet                    |
| 325.26 K / 0.58kg/s [outer tube] |                                   | Pressure outlet                    |
| Hot fluid                        | Pressure outlet                    |
| (Engine oil)                     | 325.26 K / 0.58kg/s [inner tube]  | Pressure outlet                    |
| 325.26 K / 0.58kg/s [outer tube] |                                   | Pressure outlet                    |
| (Light diesel oil)               | Pressure outlet                    |
| 325.26 K / 0.58kg/s [inner tube] |                                   | Pressure outlet                    |
| 325.26 K / 0.58kg/s [outer tube] |                                   | Pressure outlet                    |
| Fluid-wall interface            | Coupled /conjugate heat transfer  |
| Outer wall                      | No-slip condition and Insulated   |

**Solution procedure**

The commercially available CFD code, ANSYS Fluent v20.0 was used to simulate the cases in the present study. A second-order upwind scheme with a SIMPLE algorithm was applied to solve the numerical terms. Convergence criteria

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for all equations were set at 10^{-3} except energy which was set at 10^{-6}, as recommended in reference.

IV. Grid sensitivity analyses

For the simulation study, structured meshes with quadrilateral elements were generated. Nine different grid sizes were used in the grid sensitivity analyses. The details of the grids produced can be referred to in Table 2. The volumetric mean of the temperature of fluids at inner, intermediate, and outer tubes are recorded for parametric analyses of the grid independence test. These values were closely compared by varying the number of elements in the studied domain. Figures 3(a), (b), and (c) show the grid independence of the generated meshes. It can be seen that at 1.3 million elements or onward the temperature values at inner, intermediate, or outer tubes do not change significantly, thus confirms the grid independence at 1.3 million elements. Following the grid independence test, the selected element size is used in the simulation for the Finned type TCTHE to find the best results in terms of computational time and accuracy.
V. Results and Discussion

In this section, results of the heat transfer performance of TCTHE with fins or without fins on the inner and intermediate tubes using different hot fluids have been presented. The comparison is also done to validate the effectiveness of fins on the tube surfaces. Limited by length only the contours of the intermediate tube (cold fluid) at inlet and outlet are compared in a subsequent section.

Temperature Field

The effects of longitudinal fins on the temperature distribution across tube surfaces can be seen in Figure 4. Color-filled contours on similar temperature scales are used to compare the results of different TCTHE models, i.e. finned/unfinned. The temperature at the cold fluid outlet in the case with longitudinal fins is substantially higher than the temperature of unfinned TCTHE. Because the cold fluid has a larger surface area for heat exchange, it absorbs more heat from the hot fluid going in and out. Furthermore, the heat loss by the fluid in the inner tube

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was found significantly larger than the heat loss for outer tube fluid stream. It may be due to the fins installation at inner and intermediate tube surfaces. Thus, to exchange more heat among the fluids, the optimum use of surfaces for the fins construction is considered. In other words, the temperature distribution of finned TCTHE improves more significantly with the inner tube than the outer tube.

**Heat transfer rate (Heat flux)**

A similar pattern was also seen with the heat transfer rate between cold and hot fluid streams with all the types of hot fluids. The heat flux contours of the intermediate tube at inlet and outlet boundaries in the case of crude oil are shown in Figure 5. A very large amount of heat transfer rate is seen at the outlet boundary of intermediate fluid (cold fluid). The high heat transfer rate confirmed the effectiveness of fins on the tube surfaces. However, further study is still needed to investigate the optimum thickness and quantity of fins along with the varying thickness of the tubes in TCTHE for improved performance.

![Heat flux contours](image-url)
Figure 4. Temperature field distribution at the cold fluid domain (intermediate tube)
(a) Inlet (b) Outlet
VI. Conclusions

In this work, the thermohydraulic performance of triple concentric-tube heat exchangers with or without longitudinal fins was investigated using a numerical model employing CFD code, Ansys Fluent. The heat transfer rate and temperature distribution across the tubes' surfaces were simulated and compared for the TCTHE with or without the application of longitudinal fins. By comparing the contours of the selected parameters at the inlet and outlet of both types of TCTHE constructions, the influence of fins on thermohydraulic performance was also investigated. The following conclusions can be drawn from the findings of this study.

- The heat transfer rate of crude oil as a hot fluid was higher than engine oil or light diesel oil at the same mass flow rate.
- The longitudinal fin configuration is found with the highest thermal enhancement coefficient and hence delivers the best thermohydraulic performance under the scope of this study.
- Other fin types, such as triangular, helical, and twisted tape, should be considered if the highest heat transfer rate in applications where pressure drop is not a limiting factor and a high heat transfer capability is required.
- Even on a single surface, the thermohydraulic performance of triple concentric-tube heat exchangers with fins is superior to that of without fins.

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Finally, the longitudinal fin configuration for triple concentric-tube heat exchangers has been shown to improve the heat transmission and thermohydraulic performance of the triple tube concentric heat exchanger. Other key geometric configurations of fins, height, and top-to-base ratio could be a future research direction for a more in-depth investigation in these types of heat exchangers.

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Conflict of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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