Numerical modelling of heat transfer and hydrodynamics for drop-shaped tubes bundle

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Abstract. A numerical study has been conducted to clarify the flow and heat transfer characteristics of a cross-flow heat exchanger with drop-shaped tubes (6-rows of single/ double tubes) at zero angle of attack. The study is performed for the Reynolds number $Re_a = 1.38 \times 10^3 \sim 9.36 \times 10^3$. A mathematical and numerical model in software package ANSYS for numerical evaluation of heat transfer and flow field of a bundle of drop-shaped tubes, with taking into account the strain caused by different pressures inside and outside the tubes has been developed. Correlations of the average Nusselt number $\text{Nu}_{av}$ and a friction factor $f$ in terms of $Re_D, \max$ and $Pr$ for the studied bundles were presented. The result of the numerical simulation indicates the pressure drop coefficient of the studied drop-shaped tube bundles is about $9.86 \sim 10.88$ times smaller than the circular one.

1. Introduction

Circular tubes bundles are widely used in heat exchange equipment because of the ease of production and its capability of withstanding a high pressure. In contrast to the circular tubes which cause severe separation and a large vortex zone to produce high pressure drops, non-circular tubes of streamlined shapes offer very low hydraulic resistance.

In recent decades, several studies of non-circular tubes have been considered as heat transfer elements in cross-flow heat exchangers Lavasani \cite{1} experimentally investigated the flow around cam shaped tube bank with inline arrangement for both longitudinal pitch ratios 1.5 and 2. It was noted that by increasing longitudinal pitch ratios from 1.5 to 2, heat transfer increases about 7-14%. The effects of angles of attack on the heat transfer characteristics and the drag coefficient for staggered drop-shaped tubes were experimentally and numerically investigated by Sayed Ahmed et al. \cite{2}. They found that the average Nu values at zero angle of attack ($\theta = 0$) was higher by about 76% compared to elliptical tubes bundle with the same heat transfer surface. Deeb and Sidenkov \cite{3-5} numerically studied hydrodynamics and heat transfer characteristics of a drop-shaped tubes bundle of various configurations. Their results indicate that the hydrodynamic resistance of the drop-shaped tubes bundles was better than the circular ones at angles of attack of $0^\circ, 180^\circ$. They proposed a correlation for heat transfer in terms of Re and $\theta$ with taking into account the stress-strain state of the tubes. They developed a numerical method of calculation of the elementary, local and average radiation view factors for staggered bundle of drop-shaped tubes. Deeb \cite{6} numerically investigated the effect of the longitudinal spacing on the flow and heat transfer characteristics of
for a staggered drop-shaped tubes bundle at zero angle of attack in crossflow. The results indicate that a drop-shaped tubes bundle with $S_L=46.25$ mm has more intense heat transfer with less hydrodynamic resistance as compared to a bundle with $S_L=46.25$ mm. The thermal–hydraulic performance of the studied drop-shaped tube bundle is about $18.1 \sim 43.7$ times greater than the circular one.

The purpose of this study is to investigate the heat transfer and hydrodynamics characteristics for staggered drop-shaped tubes bundle (six rows of single/ double tubes) in crossflow using Ansys package with taking into account the effect of deformation caused by pressure drop inside and outside the tubes.

2. Problem definition and boundary conditions

2.1. Geometrical description of the study

Using Ansys, a numerical study of heat transfer and hydrodynamics of the cross-section of the drop-shaped tube is carried out for comparison with circular tubes (figure 1a, b, c). Drop-shaped tubes are located in a square cross-section channel, a side of the square cross-section is 305 mm with the following dimensions: the large radius is 5.8 mm, the small radius is 2.9 mm, the equivalent diameter ($D_{eq}$) is 22.5 mm (figure 1d). the longitudinal and transverse spacing of the tubes in the bundle are the same and are equal to 37 mm.

![Figure 1](image)

Figure 1. Test tube bundles: a) drop-shaped “single tubes”; b) drop-shaped “double tubes”; c) circular tubes, d) Drop-shaped tube cross-section dimensions.

2.2. Problem description and boundary conditions

The forced convection problem has been solved using Ansys Fluent [7] in a two-dimensional stationary formulation assuming a viscous incompressible flow with constant thermophysical properties, with taking into account the possibility of turbulence generation but without heat exchange by radiation. The system of differential conservation equations includes the continuity equation, two momentum equations and the energy equation:

$$\frac{\partial}{\partial x_i}(p U_j) = 0$$  \hspace{1cm} (1)

$$\frac{\partial}{\partial x_j}(p U_i U_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$  \hspace{1cm} (2)

$$\frac{\partial}{\partial x_i}[U_i (p E + p)] = \frac{\partial}{\partial x_i} \left( \frac{p}{\gamma-1} \frac{\partial T}{\partial x_i} \right)$$  \hspace{1cm} (3)
where i-tensor indicating 1 and 2; U - the air velocity; ρ - the air density; P - air pressure; \(\tau_{ij}\) - the viscous stress tensor; \(\lambda\) - the fluid effective thermal conductivity and T - temperature of the liquid.

The modeling process is carried out in two stages. Firstly, the stress-strain state modeling has been performed using Ansys Static Structural, the deformations caused by different pressures inside (14 bar) and outside the tubes (1 bar) have been determined. Figure 2 illustrates the cross section of the drop-shaped tube after deformation.

Figure 2. Stress-strain state.

In the second stage, similar to [2,4], the RNG k-ε model with “Enhanced wall Treatment” function [7-8] is used in the present study. As an external flow, the air flow is used, the initial velocity of the air at the channel’s entrance region varied \(u = 1.33 \sim 7\) m/s, which corresponds to Reynolds numbers \(Re_a = 1.38 \times 10^3 \sim 9.36 \times 10^3\), at a temperature of 56.5 °C and atmospheric pressure (figure 1,a).

2.3. Numerical results verification and mesh generation

The developed mathematical and numerical model has been validated in previously published work [4]. The working fluid domain is meshed similarly to [4].

The mesh-sensitivity analysis was carried out mainly to check for a mesh independent solution. The number of nodes varied from 13508 to 347766. It is seen from figure 3 that the computational Nu of a single-drop-shaped tubes bundle becomes independent from the mesh for the mesh of about 225456 nodes for all studied cases of longitudinal spacing. Hence, the mesh of 225456 nodes is considered here-onwards to optimize the time and the accuracy of the solution.

3. Results and discussion

3.1. Heat transfer characteristics over the tubes bundle

The temperature of the tube surface increases by gaining the heat from the incoming air. As the air velocity increases, the turbulence area behind the tubes, gradually increases, which contributes to a further improvement in heat transfer (Fig. 4).

Figure 4. Distribution of temperature (a-b) circular tubes; (c-d) single-drop-shaped tubes; (e-f) double-drop-shaped tubes.
The heat transfer is affected by the development of the hydrodynamic boundary layer over the surface of the tube. It is clear that there are three zones of significant changes in the local hydrodynamic characteristics of the air flowing across the drop-shaped tubes lead to changes in the local values of heat transfer: two at the lateral and one at the rear surfaces of the tubes.

Fig. 5 shows the heat transfer coefficient averaged over whole surface of the tubes bundle for the air velocity in range of 1.33 ~ 7 m/s. The average Nusselt number of a bundle was determined from the computational experiment results as:

\[ Nu_{av} = \frac{\bar{\alpha}D}{\lambda} \]  

where, \( \bar{\alpha} = \frac{1}{F} \int_0^F \alpha.dF \) is the heat transfer coefficient averaged over whole surface of tubes bundle. The values of the heat transfer coefficient were obtained from the results of the computational experiment using ANSYS program.

![Figure 5. Average Nusselt number Vs air velocity](image)

It is seen from the figure 5 that the average Nusselt number increases with the increase in the air velocity and for the studied cases. The values of \( Nu_{av} \) of a circular tubes bundle are about 1.35 ~ 1.26 and 1.39 ~ 1.2 times greater than those obtained for single-drop-shaped and double-drop-shaped tubes, respectively.

Correlation for the average non-dimensional Nusselt number for the studied bundles based on the computational experiment obtained for various Reynolds numbers was predicted by equation (5):

\[ Nu_{av} = a.Re_{D, max}^{1/3}.Pr^{b/3} \]  

where the thermo-physical properties are calculated for the average temperature of the incoming flow.

The coefficients “a”, “b” and “c” for equation (5) were computed in MathCad package using least square technique (Table 1). Reynolds number \( Re_{D, max} = (U_{av}.D_{eq})/\nu \) has been calculated by the average flow velocity in the minimum free cross section \( U_{av} \).

| Type of tubes bundle   | a        | b       | \( Re_{D, max} \)          | Pr   |
|-----------------------|----------|---------|---------------------------|------|
| Circular              | 0.4556   | 0.5954  | 1.74x10^3 ~ 9.18x10^3     | ≃ 0.7|
| Single-drop-shaped    | 0.1521   | 0.6496  | 3.18x10^3 ~ 1.628 x10^4   |      |
| Double-drop-shaped    | 0.1153   | 0.6945  | 2.7x10^3 ~ 1.38x10^4      |      |

3.2. Friction factor

Figure 6 shows the static pressuredistribution for circular and drop-shaped tubes bundles for two cases of the longitudinal spacing and the air velocity. For all studied cases, it can be seen that the pressure has the highest value at the stagnation point on the front of the tube, this is because of the flow velocity at this point being the highest.
point tends to zero (figure 7). When the flow passes over the surface of the tube, the pressure decreases to the lowest value on the lateral surface.

\[ f = \frac{\Delta P}{0.5 \rho U^2_\text{avg} N_L} \]  

where \( \Delta P \) - pressure drop across the bundle, Pa; \( U_\text{avg} \) - number of transverse rows.

Figure 8 indicates the friction factor for circular and drop-shaped tubes bundles. The friction factor for the fluid decreases, with an increase in the air velocity. This is usually due to the dominant pressure force, which reduces the friction. It is also clear that the friction factor for the circular tubes is 22.84 ~ 24.77 and 19.84 ~ 21.98 times greater than those obtained for single-drop-shaped and double-drop-shaped tubes, respectively.

The friction factor data can be correlated using a dimensionless relation of the form:

\[ f = a \cdot \text{Re}^{-b} \]  

The coefficients “a” and “b” for the above correlation were computed by MathCad program (Table 2).
4. Conclusions
The thermal and fluid flow behaviour in case of a circular, single and double drop-shaped tube bundles with staggered arrangement have been studied numerically for $Re_a = 1.38 \times 10^3 \sim 9.36 \times 10^3$. Mathematical and numerical model has been developed to calculate the heat transfer and friction factor of studied bundles using the Ansys package, with taking into account the stress-strain state of the drop-shaped tubes.

The distributions of flow velocity, pressure, temperature, and the average Nusselt number of all tube configurations were obtained in computational experiments.

Comparison the results of this study with heat transfer characteristics of a cross-flow heat exchanger employing circular tubes which have the same equivalent diameter did not reveal advantages for heat transfer of the drop-shaped tubes bundles, while the hydrodynamic resistance of the drop-shaped tubes bundles was better than the circular ones.

As the air velocity increases, the friction factor decreases. The highest and lowest values of $f$ were obtained for circular, double and single-drop-shaped tubes, respectively.

Correlations were developed from the computational experiment results for the bundles of circular and drop-shaped tubes to give the average Nusselt number and friction factor in terms of $Re_D, max$ and $Pr$.

The results obtained will serve as a base for further studies of the heat transfer and hydrodynamic characteristics of drop-shaped tubes bundle.

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6. References
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