Numerical simulation of the heat transfer of staggered drop-shaped tubes bundle

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Abstract. Tube bundles can be used as a separation heat exchanger in the “organic” Rankine cycle power plants (ORC), while the hot gas passes over the outer surface, and the working substance ORC flows inside the tubes. A numerical study has been conducted to clarify heat transfer and hydrodynamics of a cross-flow heat exchanger with staggered drop-shaped tubes at different flow angles of attack (θ). A mathematical and numerical model in software package ANSYS has been developed 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. The results of numerical simulation of pressure, velocity, temperature distribution in the tube’s bundle had provided the development of equation to determine the average Nusselt number (Nu) in terms of Reynolds number (Re), Prandtl number (Pr) and angle of attack.

1. Introduction
In low-boiling working fluids-based power plants, working on the ORC, one of the main heat exchangers is a separation heat exchanger (figure 1). Tube bundles can be used as a separation heat exchanger: the outer surface of the tubes is washed by a hot gas, and the working substance of ORC flows inside the tubes.

![Figure 1. Schematic view of an ORC.](image-url)
Circular tubes are widely used in heat exchange equipment because of the ease of production and its capability of withstanding a high pressure. However, when the fluid flows across a circular tube, a large vortex zone is developed at the rear of tube, which can lead to large pressure drop losses and strong vibrations. In recent decades, several studies of the drop-shaped tube bundles determined that they have low drag coefficients and high enough Nusselt numbers in comparison with tubes of different shape cross-section with the same perimeter length [1-3].

Sayed Ahmed et al. [1], experimentally and numerically, studied the flow and heat transfer characteristics of a three-row staggered drop-shaped tubes bundle in cross flow. They found that the average Nu values at zero angle of attack (θ=0) was higher by about 76% compared to elliptical tubes bundle with the same heat transfer surface. In [1], the correlations were presented for determining the average values of Nu depending on the Re and θ for the bundle of drop-shaped tubes.

The subject of this study is to evaluate the effect of the deformation of the cross-sectional profile of the drop-shaped tube on the heat exchange and hydrodynamic characteristics of the tubes bundle. Numerical simulations have been conducted using the software package ANSYS to evaluate the heat transfer and hydrodynamics of a bundle of drop-shaped tubes, with taking into account the stress-strain state. The data of [1] are used to verify the numerical model.

2. Problem statement and boundary conditions

2.1. Geometrical description of the study
Using ANSYS, a numerical study of heat transfer and hydrodynamics of a bundle of 22 drop-shaped staggered tubes (figure 2) is carried out. 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 (Deq) is 22.5 mm, the longitudinal and transverse spacing of the tubes in the bundle are the same and are equal to 37 mm. A change in the angle of attack θ is achieved by simultaneously turning all the tubes of the bundle by 0, 45, 135 and 180 degrees clockwise as shown in figure 3.

![Figure 2. Schematic plane of the test section (θ= 0°).](image-url)
2.2. Problem description and boundary conditions
The forced convection problem has been solved using ANSYS Fluent [4] 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:

\[
\frac{\partial}{\partial x_1} \left( \rho U_i \right) = 0
\]

\[
\frac{\partial}{\partial x_j} \left( \rho U_i U_j \right) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}
\]

\[
\frac{\partial}{\partial x_1} \left[ U_i \left( \rho E + p \right) \right] = \frac{\partial}{\partial x_i} \left( \lambda \frac{\partial T}{\partial x_i} \right)
\]

where: i - a tensor indicating 1 and 2; U - the air velocity; ρ - the air density; P - air pressure; τ_{ij} - the viscous stress tensor; λ - the fluid effective thermal conductivity and T - temperature of the liquid.

Similar to [1], the RNG k-ε model [4,5] 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 ~ 7 m/s, which corresponds to Reynolds numbers Re = 1.8x10^3 ~ 9.4 x10^3, at a temperature of 56.5°C and atmospheric pressure. The water pressure inside the tube is 14 bar, with an average wall temperature of 20.8 °C.

The stress-strain state modeling has been performed using ANSYS Static Structural, the deformations caused by different pressures inside and outside the tubes have been determined. Figure 4 illustrates the cross section of the tube after deformation.

"Figure 4. Tube status under the load."

2.3. Numerical results verification
The verification of the developed mathematical and numerical model is carried out using the results obtained in [1] experimentally and numerically (without deformation). Figure 5 shows the average Nusselt numbers corresponded to values of Reynolds numbers calculated as in [1] for the flow velocity and angles
of attack $\theta = 0^\circ$, $45^\circ$, $135^\circ$ and $180^\circ$.

Figure 5. Comparison of heat transfer from the staggered drop-shaped tubes in present work and [1].

Figure 6. Comparison of heat transfer from the staggered drop-shaped tubes for Re calculated by $u_{av}$ and [1].

A good agreement is observed, which allows us to recommend the developed numerical model for calculating the states of such systems. Figure 6 shows Nusselt numbers for the corresponding Reynolds numbers calculated by the average flow velocity in the minimum free cross section ($U_{av}$) from the ANSYS simulation results.

3. Results and discussion
A numerical study is carried out using the software package ANSYS to clarify fluid flow and heat transfer characteristics of a cross-flow heat exchanger employing staggered drop-shaped tubes. Velocity, pressure and temperature distribution are obtained (figures 7-10) for two hydrodynamic regimes and four flow angles of attack after deformation of the cross section of the tubes (figure 4).

Figure 7. Static pressure, velocity and temperature contours at $\theta= 0^\circ$.
Figure 8. Static pressure, velocity and temperature contours at $\theta = 45^\circ$.

Figure 9. Static pressure, velocity and temperature contours at $\theta = 135^\circ$.

Figure 10. Static pressure, velocity and temperature contours at $\theta = 180^\circ$. 

u=1.33 m/s

u=7 m/s
The distributions of the local heat transfer coefficient (the averaged value for each row) along the perimeter of the drop-shaped tubes are given in figure 11.

![Figure 11. The distribution of the local heat transfer coefficient along the perimeter of the drop-shaped tubes at $\theta = 0^\circ$: a) $u=1.33$ m/s; b) $u=7$ m/s.](image)

It is clear that there are three zones of significant changes in the local hydrodynamic characteristics of the air flowing across the tubes lead to changes in the local values of heat transfer: two at the lateral and one at the rear surfaces of the tubes.

The results of the computational experiment are presented in the form of equation (4) for the average non-dimensional heat transfer coefficient at whole tubes bundle surface area as follows:

$$N\bar{u} = a \cdot Re^b \cdot Pr^c \cdot \left(1 + \frac{\theta^\circ}{90^\circ}\right),$$  \hspace{1cm} (4)

where the thermo-physical properties are calculated for the average temperature of the incoming flow. The equivalent diameter $D_{eq}$ is used as a reference length in order to calculate Reynolds number $Re_{\alpha} = (U_{av} \cdot D_{eq})/\nu$. Figure 12 illustrates the relationship between Reynolds number calculated by the average flow velocity in the minimum free cross section $U_{av}$ and the different flow angles of attack $\theta$.

The average Nusselt number of a bundle was determined from the computational experiment results as $N\bar{u} = (\bar{\alpha} \cdot D_{eq})/\lambda$, where $\bar{\alpha} = \frac{1}{F} \int_{0}^{F} \alpha \cdot dF$ is the heat transfer coefficient averaged over whole surface of tubes bundle $W/(m^2K)$.

![Figure 12. The change in the average velocity in the minimum free cross section depending on the angle of attack ($\theta$) and the velocity of the incoming flow ($u$).](image)
The coefficients $a$, $b$ and $c$ for equation (4) were computed in MathCad package using least square technique (Table 1). The obtained equation is applicable for $Re_a=1.8\times10^3 \sim 9.4\times10^3$ and for Prandtl number ($Pr \cong 0.7$).

| $0^\circ \leq \theta \leq 45^\circ$ | $\theta = 135^\circ$ | $\theta = 180^\circ$ |
|-----------------------------------|----------------------|----------------------|
| $a$ | $0.318$ | $0.318$ | $0.318$ |
| $b$ | $0.574$ | $0.574$ | $0.574$ |
| $c$ | $-0.797$ | $-0.336$ | $-0.027$ |

Conclusions

Mathematical and numerical model has been developed to calculate the heat transfer coefficient of the three-row staggered drop-shaped tubes bundle using the ANSYS package, with taking into account the stress-strain state of the tubes.

The verification of the developed mathematical and numerical model was carried out by comparing the computational results of the present study with those obtained by [1] (the deformation effect was not taken into account) experimentally and numerically. A good agreement was observed, which allows to recommend the developed numerical model for calculating the states of such systems.

Comparison the results of this study with heat transfer characteristics of a cross-flow heat exchanger employing circle tubes which have the same equivalent diameter did not reveal advantages for heat transfer of the considered staggered drop-shaped tubes bundle.

The equation for calculation of the staggered drop-shaped tubes bundle’s $\overline{Nu}$ depending on the average flow velocity in the minimum free cross section and the discrete flow angles of attack $\theta = 0^\circ$, $45^\circ$, $135^\circ$ and $180^\circ$ was proposed.

It was shown that the values of $\overline{Nu}$ for the arrangement of $\theta = 45^\circ$ and $135^\circ$ are greater than those for the arrangement of $\theta = 0^\circ$ and $180^\circ$ by about 25-40 %.

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References

[1] Sayed A 2014 Heat and Mass Transfer 50 (8) 1091–102
[2] Nouri-Borujerdi A and Lavasani A 2007 Journal of Heat and Mass Transfer 50 (13) 2605–611
[3] Nouri-Borujerdi A and Lavasani A 2008 Journal of Heat Transfer 130 (12) DOI:10.1115/1.2969259
[4] ANSYS Inc. 2019 Ansys Fluent User’s Guide. In Ansys Aim Student 19.0 19.2.
[5] Yakhot V 1993 International Conference on Near-Wall Turbulent Flows (Arizona: Tempe) pp 1031–406