External heat transfer in corridor and staggered tube bundles of different configuration under the application of low-frequency pulsations

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Abstract. In this paper, the external heat transfer coefficient for cross flow around a tube bundle by a pulsating flow was studied by numerical method. ANSYS Fluent 14.0 program is used for the mathematical modeling. The Reynolds numbers lie in the range $100 \leq Re \leq 1000$, the Prandtl number $215 \leq Pr \leq 363$, the frequency and the dimensionless relative amplitude of the pulsations were in the range $0.2 \leq f \leq 0.5$, Hz, $15 \leq \beta \leq 35$, the pulsation ratio $0.25 \leq \psi \leq 0.5$. The external heat transfer for low-frequency pulsations was studied for 9 configurations of staggered tube bundles and 3 corridor tube bundles. Based on the modeling results, a criteria equation is obtained that allows calculating the external heat transfer in pulsating flows in tube bundles of different configurations. It is established that an increase in Re, Pr, $\psi$ leads to a decrease in heat transfer, and an increase in $f$ and $\beta$ to an increase in heat transfer.

Introduction

Heat transfer in pulsating flows are being studied for several decades. At the moment, there is a huge amount of work devoted to the study of external and internal heat transfer in pulsating flows, specifically the flow of fluid in circular tubes [1], in channels with depressions [2], flowing around a single cylinder [3, 4], a tandem of cylinders [5], various protrusions, blocks and other obstacles [6, 7].

Experimental studies related to the flow structure and heat transfer in the case of a transverse flow past a single cylinder with superimposed pulsations on the air flow were performed by the authors of the paper. [3] The dimensionless pulsation frequency was in the range $St = 0-1.76$, relative ripple amplitude $\beta = 0-0.85$. In the studied range of parameters, the maximum increase in heat transfer was 15%.

In research [5], the heat transfer of a tandem of cylinders in pulsating flow was investigated by an experimental method. Flow pulsations had a symmetrical character. The dimensionless frequency parameter lay in the range of $58.1 < \beta < 451.7$, the Kelegane-Carpenter number was in the range $3.14 < KC < 15.7$. It is established that an increase in the parameter KC leads to an increase in heat transfer.

In research [8], a numerical and experimental method was used to study the heat transfer in the case of a transverse flow past a cylinder with low-frequency pulsations of sinusoidal character in the range $0.2 \leq f \leq 1.1$, Hz and high relative pulsations $10 \leq A/D \leq 38$, and the pulsation number Reynolds was...
in the $40 < \text{Re}_{\text{sat}} < 810$. It is established that with increasing $f$ and $A / D$ it has been occurring an increase in heat transfer.

In most works, flow pulsations have a symmetric sinusoidal character, and in the presence of more papers devoted to flow past a cylinder, studies devoted to heat transfer in pulsating flows in bundles of tubes are extremely small. In this paper, it is planned to investigate heat exchange in tube bundles of various configurations, with symmetrical and asymmetrical pulsations. The heat exchange of a single cylinder in pulsations with different ratio $\psi$ was studied numerically in [9], tube bundles in paper [10]. It is shown that the pulsation ratio $\psi$ influences the heat transfer at constant $\text{Re}$ and frequencies $f$.

**Mathematical model**

The calculated region of the model (Fig. 1) is shown in Fig. 1.

Fig. 1. The estimated area of the model

The flow of an incompressible fluid is described by the system of Navier-Stokes equations (Reynolds averaged Navier–Stokes RANS) averaged by the Reynolds method, which consists of the continuity equation [11]

$$\frac{\partial \bar{u}_j}{\partial x_j} = 0,$$

and equations of transfer for the mean values of quantities randomly pulsating in a turbulent flow using the theory of turbulent viscosity proposed by J. Boussinesque

$$\frac{\partial \rho \bar{u}_i}{\partial t} + \frac{\partial \rho \bar{u}_j \bar{u}_i}{\partial x_j} = - \frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \mu + \mu_t \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right),$$

where $\bar{u}_i$, $\bar{u}_j$ – averaged speed components; $\rho$ – fluid density; $\mu$ – dynamic viscosity; $\bar{\rho}$ – pressure; $\mu_t$ – turbulent viscosity; $(i = 1, 2)$, $(j = 1, 2)$.

Heat transfer is described by the equation of convective heat transfer (Fourier–Kirchhoff)

$$c_p \left( \frac{\partial}{\partial t} \rho T + \frac{\partial}{\partial x_j} (\rho \bar{u}_j T) \right) = \frac{\partial}{\partial x_j} \left( \lambda + \lambda_t \right) \frac{\partial T}{\partial x_j},$$

(3)
where \( c_p \) – heat capacity of a liquid; \( \lambda_t = c_p \mu_t / Pr_t \) – turbulent thermal conductivity; \( Pr_t = 0.85 \) – turbulent Prandtl number; \( t \) – temperature.

For turbulence simulating on the basis of the analysis [12, 13], the Spalart-Allmara model (SA) was chosen in the modified SARC model with correction for curvature of the current line (RC).

\[
\frac{\partial \rho \tilde{v}}{\partial t} + \frac{\partial \rho \tilde{v}_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \frac{\rho (v + \tilde{v})}{\sigma_v} \frac{\partial \tilde{v}}{\partial x_j} \right) + \frac{C_{b2} \rho}{\sigma_v} \frac{\partial \tilde{v}}{\partial x_j} \frac{\partial v}{\partial x_j} + \rho P_v - \rho \varepsilon_v. \tag{4}
\]

where \( P_v \) – the velocity of turbulent viscosity generation, \( \varepsilon_v \) – the velocity of its dissipation, \( \tilde{v} \) - quantity that coincides with turbulent viscosity everywhere except near-wall regions.

The pulsating currents were modeled with the help of the velocity profile (dependence the velocity from time \( u(t) \)) corresponding to the necessary relative amplitudes \( \beta \), frequencies \( f \), \( Re \) and ratio \( \psi \) of pulsations, which was specified at the input by a tube bundle as the boundary condition (Fig. 1). The relative amplitude was calculated as \( \beta = A / D \), where \( A \) – the displacement of the liquid particle back, \( m \) in the narrowest section of the annular space of the beam; \( D \) - the diameter of the beam tube. The numbers \( Re \) were calculated as

\[
Re = \frac{uD}{v}, \tag{5}
\]

where \( v \) – the kinematic viscosity, \( m^2 /sec \); \( u_p \) – fluid velocity, \( m /sec \) for pulsating flow averaged over the pulsation period \( T_p \), was equal to the velocity of stationary flow of \( u_{st} \)

\[
u_{st} = u_p = \frac{1}{T_p} \int_0^{T_p} u_p(t) dt.
\]

The velocity profile is obtained using the mathematical model of the hydraulic system of the pulsator-heat transfer. [14] In this article, numerical simulation was carried out to find out the real velocity profile in the bundles of tubes of heat transfer equipment during the generation of pulsations by means of a pulsating device.

The working fluid was oil. The temperature of \( T_{oil} \) was set at the entrance to the bundle of tubes, depending on the Prandtl numbers \( Pr = \nu / \alpha \), where the thermal diffusivity was \( m^2 /sec \). The thermophysical properties of the oil corresponded to the oil “Turbine oil-T22”. On the wall of the central tube in the beam (Fig. 1) the temperature \( T_{wall} = T_{oil} - 1 \) was set.

Numerical simulation was carried out for Prandtl range \( 215 \leq Pr \leq 363 \), ratio of pulsations \( 0.25 \leq \psi \leq 0.5 \), while \( Re \) numbers and frequencies \( f \) were in the range \( 100 \leq Re \leq 1000, 0.2 \leq f \leq 0.5 \) Hz, relative amplitude \( 15 \leq \beta \leq 35 \). The influence of different bundle configurations on heat transfer during pulsating flows have been studied for 9 configurations of staggered and 3 corridor bundles (Table 1).

Variants of bundles correspond to widely use in heat transfer equipment. [15]

| №  | \( \varphi \) | \( s/D \) | \( D, \text{мм} \) |
|----|-------------|-----------|----------------|
| 1  | 30°         | 1.25      | 16             |
| 2  | 30°         | 1.5       | 16             |
| 3  | 30°         | 1.75      | 16             |
| 4  | 45°         | 1.25      | 16             |

Table 1

Geometrical characteristics of bundles
Numerical simulation was performed in the ANSYS Fluent 14.0 program using the finite volume method (FVM). The optimal grid was calculated according to the procedure given in [13]. When evaluating the simulation results, the Nusselt numbers were calculated as follows

$$\text{Nu} = \alpha \cdot \frac{D}{\lambda},$$

where $\lambda$ – the thermal conductivity, W/(m·K); $\alpha = q/(T_{oil} - T_{wall})$ – heat transfer. Here $q$ – the heat flux, W/m² averaged over the surface of the central tube in the bundle and during the pulsation period. $T_{oil}$ also averaged over the entire design area and during the pulsation period.

### Results and discussion

In Fig. 2 it is shown the dependence $\text{Nu}_p/\text{Nu}_{st}$ from $\text{Re}$ with different $s_1/D$ for $\varphi = 90^\circ$. With the increase of $\text{Re}$ in the range $100 \leq \text{Re} \leq 600$, $\text{Nu}_p/\text{Nu}_{st}$ drastically decreases, regardless of $s_1/D$, compared to the $600 \leq \text{Re} \leq 1000$ range, where the ratio $\text{Nu}_p/\text{Nu}_{st}$ varies insignificantly. An increase in $s_1/D$ results in an increase in $\text{Nu}_p/\text{Nu}_{st}$. Considering the influence of $\psi$ on heat transfer, it can be seen that the intensification is mainly observed in regimes with a smaller $\psi$.

In Fig. 3 it is shown the dependence $\text{Nu}_p/\text{Nu}_{st}$ from $\text{Re}$ for $\text{Pr} = 293$, $\beta = 15$, $f = 0.5$ for different $\varphi$ and $s_1/D$. When $\varphi = 30^\circ$, $s_1/D = 1.25$ (Fig. 3, a), the increase in the heat transfer intensity over the entire range of $100 \leq \text{Re} \leq 600$ decreases with increasing Re. When $s_1/D = 1.5$ and 1.75, the decrease of $\text{Nu}_p/\text{Nu}_{st}$ slows down after $\text{Re} = 600$. The effect $\psi$ on $\text{Nu}_p/\text{Nu}_{st}$ is more appeared for $\text{Re} = 1000$, and $\text{Nu}_p/\text{Nu}_{st}$ is higher at $\psi = 0.25$.

When $\varphi = 45^\circ$ (Fig. 3, b), the effect of Re numbers on $\text{Nu}_p/\text{Nu}_{st}$ is, in general, similar to the tube bundle layout for $\varphi = 45^\circ$ (Fig. 3, a).

At $\varphi = 60^\circ$, $s_1/D = 1.25$ (Fig. 3, b), with an increase in Re in the range $100 \leq \text{Re} \leq 600$, $\text{Nu}_p/\text{Nu}_{st}$ decreases at first, with a further increase in $\text{Re} = 1000$, a slight increase in $\text{Nu}_p/\text{Nu}_{st}$ occurs. Effect $\psi$ on $\text{Nu}_p/\text{Nu}_{st}$ for bundle $\varphi = 60^\circ$ is less compared with bundles at $\varphi = 30^\circ$ and $45^\circ$.

![Fig. 2. Dependence $\text{Nu}_p/\text{Nu}_{st}$ from $\text{Re}$ for $\text{Pr} = 215$, $\beta = 15$, $f = 0.5$ Hz, $\varphi = 90^\circ$](image-url)
In Fig. 4, 5 it is shown the dependence of $\frac{Nu_p}{Nu_{st}}$ from $Pr$ for different $s/D$, at $\varphi = 90^\circ$ and $60^\circ$, by which it is seen that an increase in the $Pr$ number as well as an increase in $Re$ leads to a decrease in heat transfer in the pulsating flow as compared with the stationary one, regardless of $s/D$.

In Fig. 6 it is shown the dependence of $\frac{Nu_p}{Nu_{st}}$ from $\beta$ at $\varphi = 90^\circ$ from which it follows that an increase in $\beta$ and $f$ leads to an increase in heat transfer. When $Re = 600$, $Pr = 293$, $f = 0.2$ (Fig. 6, a), it is noticeable that with increasing $s/D$ the influence of $\psi$ decreases, i.e. the curves $\psi=0.25, 0.4$ and $0.5$ converge.

In pulsation modes with a lower intensity, i.e. at minimum values of $\beta$ and $f$, it is observed $\frac{Nu_p}{Nu_{st}} < 1$, which is mainly occurred when approaching the symmetric nature of pulsations $\psi = 0.5$ and with decreasing $s/D$.

In Fig. 7 it is shown the dependence of $\frac{Nu_p}{Nu_{st}}$ from $f$ for different combinations of staggered bundles at $Re = 600$, $Pr = 215$, $\beta = 35$, by which it is seen that an increase in $f$ leads to an intensification of heat transfer, regardless of the arrangement of the bundles.

The maximum increase in heat transfer is observed for a bundle with $\varphi = 60^\circ$ and $s/D = 1.75$.

In Fig. 8 it is shown the dependence of $\frac{Nu_p}{Nu_{st}}$ from $\beta/(Re \cdot Pr \cdot Fo)$ at $\psi=0.25$ for different $\varphi$ and $s/D$. Here $Fo$ - the Fourier number which is calculated as follows $Fo=a(f \cdot D^2)$, where $a$ – the
thermal diffusivity of the oil, $m^2/sec$. The dimensionless complex $\beta/(Re \cdot Pr \cdot Fo) = Af/ust$ characterizes the ratio of the pulsation velocity to the stationary one, the increase of which leads to the growth of $Nu_p/Nu_{st}$ irrespective of the bundle arrangement and the ratio pulsation $\psi$.

Fig. 4. Dependence of $Nu_p/Nu_{st}$ from $Pr$ at $Re = 100$, $\beta = 25$, $f = 0.2$ Hz, $\varphi = 90^\circ$

Fig. 5. Dependence of $Nu_p/Nu_{st}$ from $Pr$ at $Re = 600$, $\beta = 25$, $f = 0.312$ Hz

Fig. 6. Dependence of $Nu_p/Nu_{st}$ from $\beta$: 

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a) \( \text{Re} = 600, \text{Pr} = 293, f = 0.2, \text{Hz}, \varphi = 90^\circ; \) b) \( \text{Re} = 600, \text{Pr} = 293, f = 0.5, \varphi = 90^\circ; \)

Fig. 7. Dependence of \( \frac{\text{Nu}_p}{\text{Nu}_{st}} \) from \( f \) at \( \text{Re} = 600, \text{Pr} = 215, \beta = 35: \)

a) \( \varphi = 30^\circ; \) b) \( \varphi = 45^\circ; \) c) \( \varphi = 60^\circ; \)
As a result of generalization of numerical modeling data, a criterial equation of the following type

$$\frac{\mathrm{Nu}_p}{\mathrm{Nu}_{st}} = 0.954 \Re^{-0.201} \Pr^{-0.211} \beta^{0.184} \cdot \Fo^{-0.230} \cdot \psi^{-0.053} \cdot \varphi^{0.085} \cdot \frac{s_1}{D}^{0.287}$$

(7)

where $\mathrm{Nu}_{st}$ – the Nusselt number for a stationary flow could be found by the criterion equation

$$\mathrm{Nu}_{st} = 0.354 \cdot \Re^{0.6} \Pr^{0.33} \varphi^{-0.1} \cdot \left(\frac{s_1}{D}\right)^{-0.45} \cdot \left(\frac{\mu_{jk}}{\mu_{ct}}\right)^{0.14}.$$

(8)
Equation (7) is obtained for the ranges $215 \leq Pr \leq 363$, $0.25 \leq \psi \leq 0.5$, $100 \leq Re \leq 1000$, $15 \leq \beta \leq 35$, $5.81 \cdot 10^{-4} \leq Fo \leq 14.53 \cdot 10^{-4}$. Coefficient of determination $R^2 = 0.906$, maximum error of approximation is not more than $\delta_{\text{max}} = 35.7\%$, mean deviation is not more than $\bar{\delta} = 5.5\%$.

Conclusion

A numerical method was used to investigate heat transfer in the case of cross flow around tubes bundles with the imposition of low-frequency pulsations on the flow of liquid. It is shown that, depending on the parameters of pulsations, the heat transfer of $Nu_p/Nu_{st}$ can be increased up to 3 times.

It is established that an increase in $\beta$ and $f$ lead to an increase in $Nu_p/Nu_{st}$, and an increase in $Re$, $Pr$ and $\psi$ lead to a decrease in $Nu_p/Nu_{st}$. It is noted that with an increase in geometric parameters $\varphi$ and $s_l/D$, the $Nu_p/Nu_{st}$ ratio increases.

A criterial equation is obtained for the calculation of heat transfer in tube bundles in pulsating flows. In terms of exponential parameters, it has been found that the minimum effect on $Nu_p/Nu_{st}$ has $\psi$ parameter value of the degree $\psi$ (-0.053), the maximum effect on $Nu_p/Nu_{st}$ has the $s_l/D$ parameter value of the degree (0.287). Comparing the influence of $\beta$ and $Fo$ on $Nu_p/Nu_{st}$, it is noticeable that $Fo$ has a greater influence (the degree of $Fo$ is greater than $\beta$ by 25%).

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