Thermal and hydraulic efficiency of the corridor tube bundle in conditions of pulsating flow of fluid

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Abstract. The method of determining the thermal and hydraulic efficiency $\eta$ of tube bundles with a pulsating flow is given in the paper. Based on numerical simulation, the effect of the Reynolds number $Re$ of the dimensionless pulsation amplitude $\beta$ and the Strouhal number $Sh$ on the thermal and hydraulic efficiency $\eta$ of the corridor tube bundles was investigated. The optimum pulsation regimes corresponding to the maximum $\eta$ are found.

Tube bundles are the main elements of heat transfer devices which are widely used in various industries. Therefore, nowadays, there are many works devoted to the study of heat transfer and hydrodynamics in tube bundles in order to improve the efficiency of heat transfer equipment. [1-10]

In work [2], the heat transfer of an oscillating cylinder in a fluid flow was studied numerically. The dimensionless maximum frequency of the oscillation velocity of the cylinder lies in the range $0.5 \leq V_m \leq 1$, where $V_m = v_m/u_0$, here $v_m$ and $u_0$ maximum speed of oscillation of the cylinder, m/sec and velocity of fluid flow, m/sec, the range of Reynolds numbers was $100 \leq Re \leq 500$. It is noted that as the $V_m$ increases, the heat transfer intensification increases, and with increasing $Re$ decreases. When $Re = 200$, $V_m = 0.25$, $V_m = 0.5$, $V_m = 1$ the increase in heat transfer were 10.2 $\%$, 13.3 $\%$, and 21.9 $\%$. When $V_m = 1$, $Re = 100$, $Re = 200$ and $Re = 500$ the increase in heat transfer were 17 $\%$, 21.9 $\%$, и 28.7 $\%$. The maximum local increase in heat transfer along the perimeter of the cylinder was observed at the bottom of the cylinder.

In [3], an experimental method was used to study heat transfer in the case of a transverse flow past a cylinder in a pulsating air flow. The Strouhal numbers $Sh$ were in the range $0.18 \leq Sh \leq 2.8$, Reynolds numbers $Re$ $205 \leq Re \leq 822$, amplitude of pressures $40 \leq p \leq 276$, Pa. An increase in the heat transfer coefficient by 2.1 times was registered. It is established that with increasing numbers of $Re$ and $Sh$, the intensification of heat transfer decreases, and with increasing pressure amplitudes, $p$ increases in intensification.

The authors of [4] used numerical methods to study the heat transfer of a semicircular cylinder placed in a horizontal channel under forced fluctuations in the flow of liquid. The pulsations were sinusoidal, water with Prandtl number $Pr = 7$ was used as the working fluid, Reynolds number $Re$ lay in the range $10 \leq Re \leq 100$, Strouhal number $0 \leq Sh \leq 2$, amplitude of vibration $0 \leq A \leq 0.6$. The maximum increase in the dimensionless coefficient of drag of the form (total drag coefficient) was
22%, Nusselt number was 10%. It is noted that the maximum increase in heat transfer irrespective of Re is observed at Sh = 1.

In [5, 6], an experimental method was used to study heat transfer in a corridor bundle of tubes under conditions of a pulsating flow of a liquid. Flow pulsations were asymmetrical. As a working range $100 \leq Re \leq 500$, the ripple frequency is $0.125 \leq f \leq 0.5$ Hz, the amplitude of the oscillation is $1.25 \leq A/D \leq 4.5$. The maximum increase in heat transfer by 90% was observed at $Re = 500$, $f = 0.5$ Hz, $A/D = 4.5$. It is shown that with increasing Re, the heat transfer decreases, and with increasing $f$ and $A/D$, heat transfer increases.

In pulsating currents, the effect of pulsations on heat transfer is mainly considered or the effect of pulsations on the shape resistance coefficient is investigated, but the thermal and hydraulic efficiency of heat exchange elements is not considered. Although the efficiency of the heat exchange equipment depends on the values of the hydraulic resistance and the heat transfer coefficients of the heat exchange elements, which in turn affect the final metal capacity of the heat exchanger and the necessary power of the pumps required for pumping the heat carriers. In this paper, we propose a technique for determining the thermal and hydraulic efficiency of heat exchange elements in pulsating flows.

To assess the effectiveness of methods of intensification in stationary flows, the coefficient of thermal and hydraulic efficiency of Kirpichev [7]

$$ E = q / N, \tag{1} $$

where $q$ – specific heat sink, W/m$^2$; $N$ – specific coolant flow rate, W/m$^2$

$$ N = \Delta p \cdot v = \frac{\rho \cdot v^2}{2} \cdot \frac{v}{\xi} = \frac{\rho \cdot v^3}{2}, $$

Here $\Delta p$ – pressure drop in the tube bundles, Pa; $v$ – Average fluid velocity in the bundle, m/sec; $\rho$ – Fluid density, kg/m$^3$; $\xi$ – coefficient of hydraulic resistance.

The power for pumping a coolant in a bundle of tubes with a pulsating current is averaged over a period of pulsation $T_p$,

$$ N_p = \frac{1}{T_p} \int_0^{T_p} \Delta p_p(t) v_p(t) dt. \tag{2} $$

Here $\Delta p_p(t)$ – instantaneous values of the pressure drop during pulsating flow in a bundle of tubes, Pa; $v_p(t)$ – instantaneous velocities with a pulsating flow, m/sec; $t$ – time, sec.

The effectiveness of the method of intensification can also be estimated with the help of the specific coefficient of thermal and hydraulic efficiency under the condition $Re_p = Re_{st}$ (Reynolds analogy factor) [1] in the form

$$ \eta = E_p / E_{st} = (Nu_p / Nu_{st}) / (\xi_p / \xi_{st}), \tag{3} $$

where $Re_{st}$, $E_{st}$, $Nu_{st}$, $\xi_{st}$ – Reynolds number, Kirpichev efficiency coefficient, Nusselt number and hydraulic resistance in a steady-state channel, $Re_p$, $E_p$, $Nu_p$, $\xi_p$ – the average for the period of pulsations of the Reynolds number, the Kirpichev efficiency coefficient, the Nusselt number and the equivalent hydraulic resistance in the channel for pulsating flow.

Reynolds for steady-state $Re_{st}$ and pulsed flow is calculated as follows $Re_p$: 

$$ Re_p = ... $
where \( D \) – diameter of tube bundle, m; \( \nu \) – Kinematic viscosity, m\(^2\)/sec; \( \nu_{st} \) – The average flow velocity for stationary flow along the narrowest section in the bundle, m/sec; \( \nu_p \) – The velocity during pulsed flow was averaged over the period of pulsation \( T_p \)

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

For steady flow in a tube bundle, the coefficient of hydraulic resistance was determined as follows

\[
\xi_{st} = \frac{\Delta \nu_{st} \cdot 2}{\rho \nu_{st}^2}.
\]

where \( \nu_{st} \) – average flow velocity for stationary flow, m/sec.

For a pulsating flow, the equivalent coefficient of hydraulic resistance \( \xi_p \) (coefficient of hydraulic resistance of the channel with equivalent energy (power) expenditure for pumping the coolant with superposition of pulsations) was determined as follows

\[
\xi_p = \frac{N_p \cdot 2}{\rho \nu_p^3}.
\]

According to the authors of [8, 9], it is more rational from a practical point of view to evaluate the effectiveness of methods of heat exchange intensification from the value of heat removal from a unit surface at equal specific powers spent on overcoming the hydraulic losses \( N_{st} = N_p \)

\[
E_N = \frac{E_p}{E_{st}} \mid _{N_{st} = N_p} = \frac{\text{Nu}_{st}}{\text{Nu}_p} \mid _{N_{crit} = N_p} = \frac{\text{Nu}_p / \text{Nu}_{st}}{\left( \xi_p / \xi_{st} \right)^{\frac{m}{3}}} \mid _{\text{Re}_{st}}.
\]

Where \( m \) – the exponent with the number \( \text{Re} \) in the criterial equation for the calculation of heat transfer in pulsating flow (equation (10)). Thus, the expressions for the efficiency coefficient at equal specific powers \( E_N \) will be calculated as follows

\[
E_N = \frac{\text{Nu}_p / \text{Nu}_{st}}{\left( \xi_p / \xi_{st} \right)^{\frac{m}{3}}}.
\]

Heat transfer in a corridor bundle of tubes with pulsating flow can be found from the following relationship [10]

\[
\text{Nu}_p = 3,05 \cdot \text{Re}_{st}^{0,42} \cdot (\beta \text{Sh})^{0,2}.
\]

Here Strouhal number
Sh = \frac{fD}{v_{st}},

where the ripple frequency f

f = \frac{1}{T_p}, \text{ Hz; } T_p = T_1 + T_2, c,

where \( T_p \) – the period of pulsation, which consists of the sum of two half-cycles \( T_1 \) – half-period of the pulse delivery into the shell space of the tube bundle, \( T_1 = 0.5 \) (const) и \( T_2 \) – half-life pressure relief, \( T_2 \) – is set depending on \( f \). The dimensionless amplitude of pulsations \( \beta = A/D \), here \( A \) return of fluid in a tube bundle, m.

Equation (10) is valid for the following conditions \( 100 \leq \text{Re} \leq 1000, \quad 0.026 \leq (\beta \text{Sh}) \leq 2.6, \quad 2.6 \leq \text{Re}(\beta \text{Sh}) \leq 260, \quad 1.25 \leq \beta \leq 4.5 \). At the relative longitudinal and transverse step of the tubes bundle \( s_1/D = 1.3, \quad s_2/D = 1.3 \) and \( \text{Pr} \approx 5.5 \). The coefficient of determination is \( (R^2 = 0.84) \).

On Fig. 1–8 there are shown the dependencies \( \text{Re, } \beta, \text{ Sh, } f \) from \( \eta \) and \( E_N \) calculated by according to equations (3) and (9), respectively, for data obtained in numerical simulation. \[10\] On Fig. 1–3 there are shown \( \text{Re from } \eta \) and \( E_N \) for different \( \beta \) and \( f \). On Fig. 1–3 it could be seen that as the numbers \( \text{Re} \) increase, the coefficient \( \eta \) grows independently of \( \beta \) and \( f \), and the different influence of \( \text{Re on } E_N \). When \( f = 0.5 \) Hz with an increase in \( \text{Re} \) from 100 to 300, an increase in the index \( E_N \) from 1.09 to 1.32 is observed, with a further increase in \( \text{Re} \), a decrease \( E_N \) to 1.21 occurs. At \( f = 0.25 \) Hz and 0.1666 Hz, the maximum \( E_N \) for various \( \beta \) is observed in the \( \text{Re} \) range from 500 to 900.

In Fig. 4 shows the dependences of \( \text{Nu}_p/\text{Nu}_st \) and \( \xi_p/\xi_{st} \) on \( \beta \text{Sh}, \) which show that with increasing product \( \beta \text{Sh}, \) heat transfer and hydraulic resistance increase in non-stationary flow as compared to stationary flow. In the entire range of \( \beta \text{Sh} \) and \( \text{Re} \) numbers, the growth of \( \xi_p/\xi_{st} \) exceeds \( \text{Nu}_p/\text{Nu}_st \) (Fig. 5). The maximum value of the thermohydraulic efficiency \( \eta = 0.62 \) is observed at minimum \( \text{Re} = 100 \) and \( \beta \text{Sh} = 0.026 \).

\( \beta \) and \( f \) differently affect the indicator \( E_N \) (Fig. 6, 7). If the decrease in the pulsation amplitude \( \beta \) (Fig. 6) \( E_N \) occurs, then an increase in the ripple frequency \( f \) (Fig. 7) leads to an increase \( E_N \). A similar trend is observed for all the \( \text{Re} \) numbers studied (Fig. 8). The maximum value \( E_N = 1.32 \) is observed for \( \text{Re} = 300 \) and \( \text{Sh}/\beta = 0.15 \).
Fig. 2. Dependence Re from $\eta$ and $E_N$ for $f = 0.25$ Hz

Fig. 3. Dependence Re from $\eta$ and $E_N$ for $f = 0.1666$ Hz

Fig. 4. Dependence $\frac{Nu_p}{Nu_{st}}$ and $\frac{\xi_p}{\xi_{st}}$ from $\beta_{Sh}$
Fig. 5. Dependence $\eta$ from $\beta_{Sh}$

Fig. 6. Dependence $E_N$ from $\beta$ for $Re = 100$ and 500

Fig. 7. Dependence $E_N$ from $f$ for $Re = 100$ and 500
A technique is proposed for evaluating the effectiveness of pulsations in order to increase the heat transfer of heat exchange elements.

The parameters of the specific coefficient of thermal efficiency $\eta$ and hydraulic efficiency are given under the condition and the efficiency factor at equal specific powers spent for pumping the heat carrier $E_N$ for external heat transfer in the corridor bundle in pulsating currents.

It is shown that with an increase in $Re$ there is an increase in $\eta$, for $E_N$ maximum regimes are observed at $Re$ about 300 and 500.

With an increase in the frequency $Sh$ and the amplitude $\beta$ of pulsations, a decrease $\eta$ occurs. The increase in $Sh$ and $\beta$ influences differently on $E_N$, the increase in $Sh$ leads to an increase $E_N$, and the increase $\beta$, on the contrary, to a decrease $E_N$.

The maximum value is $\eta = 0.62$ for $Re = 100$ and $\beta Sh = 0.026$. The maximum value $E_N = 1.32$ is observed at $Re = 300$ and $Sh / \beta = 0.15$.

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