EXPERIMENTAL STUDY CONCERNING THE EFFECT OF A LOCAL WHIRL ON THE THERMAL EFFICIENCY OF A PIPE SURFACE

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UDC 536.244

Results are shown of an experimental study concerning the thermal efficiency of a pipe surface, when a local whirl is produced by paddle wheels with different twist angles and different radial variations of the twist angle.

The excellence of power apparatus will depend on further improvements in the thermotechnical characteristics of straight tubular heat exchangers simple in design and easy to manufacture. One method of solving this important problem is to increase the heat transfer rate by means of whirling the stream.

The effect of a local whirl produced by a paddle wheel on the heat transfer and on the hydraulic drag in a pipe under turbulent flow conditions has been studied experimentally in [1]. The paddle wheels were made in the form of bronze rims with an inside diameter 32.5 mm and eight blades of 0.5 mm thick sheet brass welded to the inside surface of each. The radial and the axial dimensions of these blades were equal to half the pipe radius. The blades were profiled along a circular arc. The variation of the blade twist angle was designed according to the power relation

$$ur^n = \text{const.} \tag{1}$$

Tests were performed in a water stream with a Reynolds number $\mathrm{Re}_f = 10{,}000$-$90{,}000$. The results in [1] were used as a basis for calculating the thermal efficiency of cylindrical surfaces with the stream whirled inside at a variable axial pitch.

The thermal efficiency of the heating surface was defined in terms of the energy coefficient E [2], as the ratio of transmitted heat to energy losses due to hydraulic drag during the flow of the heat carrier through the pipe.

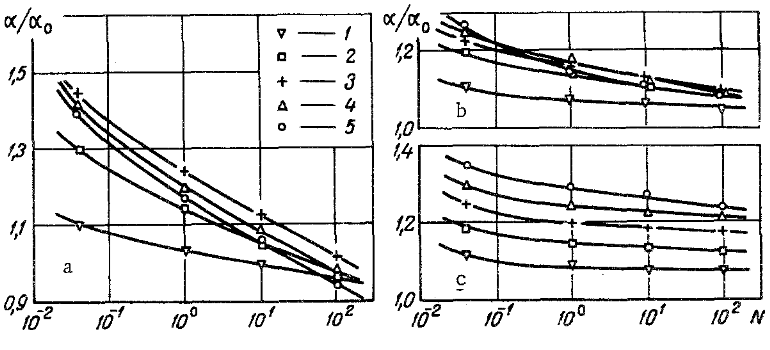

Fig. 1. Comparison between the thermal efficiencies of a surface with a local whirling of the stream by means of a paddle wheel, in terms of the energy coefficient, for $l/d = 5$ (a), 20 (b), 60 (c): $\varphi = 15°$ (1), 30° (2), 45° (3), 60° (4), 75° (5).

Kazansk Institute of Aviation, Kazansk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 23, No. 1, pp. 10-14, July, 1972. Original article submitted October 18, 1971.

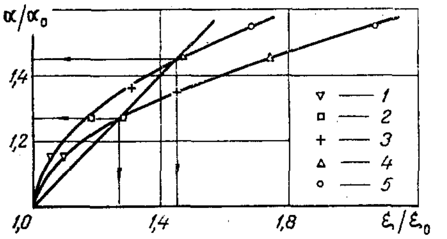

Fig. 2. Relation $\alpha/\alpha_0 = f(\xi/\xi_0)$ for paddle wheels with various blade twist angles (1-5 as in Fig. 1).

If the thermal efficiency of a surface is referred to $\Delta T = 1°C$ and the power lost on moving the heat carrier is referred to a unit area of heat transfer surface, then the heat transfer coefficient α [3] can serve as the criterion for estimating and comparing thermal efficiences. In this case the energy coefficient is defined as the ratio

$$E = \frac{\alpha}{9.81\,\mathrm{Eu}\,\rho w^3} \cdot \frac{F}{f}. \tag{2}$$

A higher value of the energy coefficient, at N = idem, means a more efficient surface in terms of energy losses.

The ratio of respective heat transfer coefficients in a whirled and in a straight stream, as a function of the power loss on moving the heat carrier, is shown in Fig. 1 for five different whirling paddle wheels with different blade twist angles ($n = 0$, $\varphi = 15°, 30°, 45°, 60°, 75°$) and for three different relative pipe lengths ($l/d = 5, 20, 60$).

For $l/d = 60$ (Fig. 1c) the heat transfer coefficients in a whirled stream are 10-34% higher than the respective coefficients in a pipe without whirling but with the same power lost on moving the heat carrier. A larger twist angle corresponds to a higher ratio α/α_0. In comparison with an axial stream, this advantage is gained at much lower velocities of the heat carrier. Thus, at $\varphi = 75°$ the ratio of heat carrier flow rates in a whirled and in a straight stream, with N = idem, is 0.837, when $\mathrm{Re}_f = 10{,}000$ and 0.77 when $\mathrm{Re}_f = 90{,}000$.

As the relative pipe length is decreased, the thermal efficiency of the heat transfer surface changes. For $l/d = 5$ (Fig. 1a) most effective are paddle wheels with the blade twist angle $\varphi = 45°$. When paddle wheels with $\varphi = 60°$ or $75°$ are used for ensuring the same amount of heat extraction as at $\varphi = 45°$, more power is required for pumping the heat carrier.

A comparison between the graphs in Fig. 1 shows that paddle wheels with $\varphi = 75°$ are most effective when $l/d \geq 20$, while paddle wheels with $\varphi = 45°$ are most effective when $l/d < 20$.

For G = idem, the effectiveness of whirled streams in improving the heat transfer can be evaluated from the $\alpha/\alpha_0 = f(\xi/\xi_0)$ graph characterizing the increase in the heat transfer coefficient as a function of the relative increase in the hydraulic drag coefficient. At a given value of ξ/ξ_0 most effective is the paddle wheel which yields a higher α/α_0 ratio.

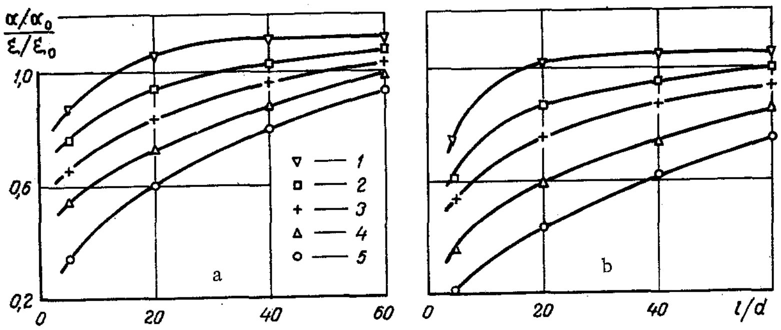

Fig. 3. Variation of the ratio: relative heat transfer coefficient to relative hydraulic drag coefficient along the pipe, for $\mathrm{Re}_f = 10{,}000$ (a), $\mathrm{Re}_f = 90{,}000$ (b) (1-5 same as in Fig. 1).

NOTATION

d is the pipe diameter, m;
Eu is the Euler number;
E is the energy coefficient for the heating surface, 1/deg;
F is the area of the heating surface, m^2;
f is the cross section area of pipe, m^2;
G is the flow rate of liquid, kg/sec;
l is the pipe length, m;
N is the power lost on overcoming the hydraulic drag, W/m^2;
n is the power-law exponent;
Re is the Reynolds number;
r is the radius, m;
T is the temperature, °K;
u is the circular velocity, m/sec;
α is the heat transfer coefficient, $W/m^2 \cdot {}^\circ C$;
ρ is the density, kg/m^3;
w is the mean axial flow velocity, m/sec;
ξ is the hydraulic drag coefficient;
φ is the angle between velocity vector and pipe axis, ang · deg.

Subscript

o denotes axial flow.

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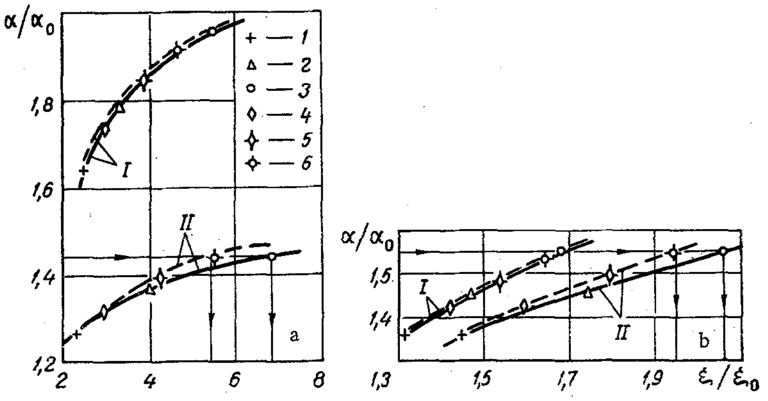

Fig. 4. Relation $\alpha/\alpha_0 = f(\xi/\xi_0)$ for paddle wheels with different twist angles and different radial variations of the twist angle: $l/d = 5$ (a), $l/d = 60$ (b), $Re_f = 10{,}000$ (I), $Re_f = 90{,}000$ (II), $\varphi = 45°$ and $n = 0$ (1), $\varphi = 60°$ and $n = 0$ (2), $\varphi = 75°$ and $n = 0$ (3), $\varphi = 45°$ and $n = 1$ (4), $\varphi = 45°$ and $n = 2$ (5), $\varphi = 45°$ and $n = 3$ (6).

The relation $\alpha/\alpha_0 = f(\xi/\xi_0)$ is shown in Fig. 2 for paddle wheels with $\varphi = 15\text{-}75°$ and for pipes with $l/d = 60$, $Re_f = 10{,}000$ and $Re_f = 90{,}000$. The straight line corresponds to $\alpha/\alpha_0 = \xi/\xi_0$. According to the graphs, as the Reynolds number becomes higher, the region where whirling has a positive effect on improving the heat transfer shifts toward smaller ratios of the hydraulic drag coefficient in a whirled and in a straight stream respectively, i.e., toward smaller twist angles of the stream. Thus, a paddle wheel with $\varphi < 60°$ improves the heat transfer at $Re_f = 10{,}000$ and a paddle wheel with $\varphi < 30°$ improves the heat transfer at $Re_f = 90{,}000$.

The relations which characterize changes in the ratio of heat transfer coefficient to hydraulic drag coefficient in a whirled and in a straight stream respectively along the pipe, under the same conditions, are shown in Fig. 3 for $Re_f = 10{,}000$. According to the graphs, at G = idem, a decrease in the relative pipe length is accompanied, at all twist angles, by a faster increase in the hydraulic drag than in the heat transfer.

In a whirled stream there appear inertia forces which can change the character of the liquid flow. As the circular velocity varies along the radius in accordance with relation (1), the distribution of inertia forces in the system depends on the exponent n. A stability analysis of a whirled stream by the Rayleigh method [4] shows that in an isothermal stream with $n = 1$ there prevails a radial equilibrium in the liquid, which may be disturbed when $n > 1$: the liquid is displaced radially and this brings about an additional increase in the heat transfer rate. When $n < 1$, the inertia forces stabilize the stream. In an anisothermal stream the radial distribution of inertia forces changes somewhat, because of a change in the radial distribution of density (the inertia force per unit volume is equal to the product of density and centrifugal acceleration), but the possibility that secondary current will be produced remains.

Thus, whirling of a stream increases the heat transfer rate on two counts: because the velocity of the liquid relative to the pipe wall increases and because secondary currents are produced. Evidently, the amounts of energy required to achieve these effects may be different.

The relation $\alpha/\alpha_0 = f(\xi/\xi_0)$ for paddle wheels with $\varphi = 45°$, $n = 0\text{-}3$ and with $\varphi = 45\text{-}75°$, $n = 0$ is shown in Fig. 4 for two relative pipe lengths with $Re_f = 10{,}000$ and $Re_f = 90{,}000$ respectively. A comparison between the test values in Fig. 4 shows that, at small values of the Reynolds number ($Re_f = 10{,}000$), the $\alpha/\alpha_0 = f(\xi/\xi_0)$ curves for paddle wheels with $n = 0$ (solid line) and $n > 0$ (dashed line) almost coincide over the entire range of relative pipe length from 5 to 60. At large values of the Reynolds number ($Re_f = 90{,}000$) and equal heat transfer rates, paddle wheels with profiled blades ($n > 0$) are characterized by a lower hydraulic drag than in the case of paddle wheels with $n = 0$. Thus, whirling the stream by means of paddle wheels with $\varphi = 45°$, $n = 3$, and $\varphi = 75°$, $n = 0$ at $Re_f = 90{,}000$ produces the same increase in the heat transfer rate, but in the latter case the hydraulic drag is higher by 7% when $l/d = 60$ and by 25% when $l/d = 5$.