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INVESTIGATION OF THE HYDRODYNAMIC REGIMES OF A LIQUID IN A SMOOTH-WALLED ROTATING HEAT PIPE. II

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The article deals with the analytical and experimental investigation of the influence of the slope of a rotating heat pipe and of the taper of its inner surface on the hydrodynamics of a liquid.

The heat transfer ability and other characteristics of a rotating heat pipe (RHP) depend largely on the orientation in the gravity field, which is particularly noticeable at relatively low rotational speeds, and on the geometry of the inner surface.

Let us examine the operation of a RHP in the range of slopes of the axis $0 \leqslant \beta < \beta_d$, where β_d is the maximum angle at which the axial component of the centrifugal force cannot ensure transport of the heat carrier from the zone of condensation to the zone of evaporation, i.e., the extreme section of the zone of heat supply begins to dry.

When $\beta > 0$ and the rotational speed ω is low, the liquid is redistributed along the x axis in the groove. If ω is sufficiently large for the liquid to spread over the inner surface without forming a groove, then the redistribution is determined by the ratio of the axial component of the force of gravity to the pressure gradient ΔP in the liquid layer formed on account of the longitudinal thickness gradient δ_x. In either case the mean thickness of the layer over the perimeter $\overline{\delta}_x = S_x/2\pi R$ is a function of the coordinate x. When $\beta = 0$ or $\omega \to \infty$, $\overline{\delta}_x = \delta = \text{const}$. When $\beta > 0$, the number $\text{Re}_x = \omega(\overline{\delta}_x)^2/\nu$, determining, together with the number $\text{Fr}_c = \omega^2 R/g$, the flow regime (see Fig. 1 [1]), is also a function of x as distinct from the horizontal position of the pipe at which the Reynolds number is constant for a specified value of ω.

Thus, when a RHP is inclined, the Reynolds number along the pipe changes, and in consequence a complex hydrodynamic pattern arises in it; this pattern is characterized by the simultaneous existence of different flow regimes described in [1].

We obtain the dependence of $\overline{\delta}_x$ on the coordinate x for two characteristic cases: a) for small values of ω at which there is a groove in the lower part of the pipe; b) for high speeds when the liquid spreads over the entire inner surface.

Taking small values of the angle β, and consequently a very slight longitudinal component of the force of gravity, we assume that with small ω the dependence of $\overline{\delta}_x$ on x with specified amount of liquid and specified geometry of the pipe is determined solely by the slope. This assumption means that in the range of rotational speeds at which there exists a groove, the liquid moves in a plane perpendicular to the longitudinal axis of the pipe, and does not move axially.

The expression for the volume of liquid in a pipe with $\beta > 0$ has the form (Fig. 1):

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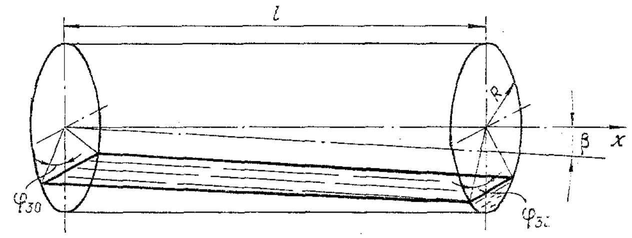

Fig. 1. Distribution of the liquid in the groove of an inclined rotating heat pipe.

$$V = \frac{R^3}{\operatorname{tg}\beta}\left(\sin\varphi_{30} - \frac{\sin^3\varphi_{30}}{3} - \varphi_{30}\cos\varphi_{30} - \sin\varphi_{3l} + \frac{\sin^3\varphi_{3l}}{3} + \varphi_{3l}\cos\varphi_{3l}\right). \tag{1}$$

When the pipe is situated horizontally ($\beta = 0$), the volume of liquid in it is determined by the equation

$$V = Sl = \frac{R^2 l}{2}\left(2\varphi_3^0 - \sin 2\varphi_3^0\right). \tag{2}$$

To simplify Eqs. (1) and (2), bearing in mind that the angles φ_{30}, φ_{3l}, φ_3^0 do not exceed $\pi/4$, it suffices to replace the trigonometric functions by two terms of their Taylor expansion. However, such substitution in (1) has the effect that the terms in parentheses on its right-hand side cancel each other. Therefore, if we confine ourselves to three terms of the series in Eq. (1) and to two terms in Eq. (2), and if we equate their right-hand sides and carry out the corresponding transformations, we obtain

$$\left(\varphi_3^0\right)^3 = \frac{R}{5l\operatorname{tg}\beta}\left(\varphi_{30}^5 - \varphi_{3l}^5\right). \tag{3}$$

From (2) we have

$$\varphi_3^0 = \sqrt[3]{\frac{3V}{2lR^2}} = \sqrt[3]{3\pi\bar{\Delta}}. \tag{4}$$

We express φ_{3x} (the angle in an arbitrary section x) through φ_{30}:

$$\varphi_{3x} = \operatorname{Arccos}\left(\cos\varphi_{30} + \frac{x}{R}\operatorname{tg}\beta\right). \tag{5}$$

If we substitute φ_{3x} from Eq. (5), with x = 1, into (3), we obtain

$$(\varphi_3^0)^3 = \frac{1}{5p\operatorname{tg}\beta}\left[\varphi_{30}^5 - \operatorname{Arccos}^5(\cos\varphi_{30} + p\operatorname{tg}\beta)\right]. \tag{6}$$

The numerical solution of the transcendental equation (6) with respect to φ_{30} in the range of change $\beta = 0°–4°$, $p = 6–24$, $\varphi_3^0 = 0–\pi/4$ is approximated with an accuracy of 2% by the expression

$$\varphi_{30} = \sqrt{3\pi\bar{\Delta}} + 9{,}44\cdot 10^{-2}\left(\frac{p^{1,3}}{\bar{\Delta}^{0,33}}\right)^{0,62}\beta^{0,87}. \tag{7}$$

Using Eq. (4), we determine the value of $\bar{\delta}_x$:

$$\bar{\delta}_x = \frac{S_x}{2\pi R} = \frac{(\varphi_{3x})^3 R}{3\pi}. \tag{8}$$

Thus, by using successively Eqs. (7), (5), and (8), we can determine the longitudinal distribution of an amount of liquid in a pipe rotating at relatively low speed.

In the second case, with high rotational speeds, the dependence of $\overline{\delta}_x$ on x, in addition to the slope, is also affected by the rotational speed. The axial component of the force of gravity, under whose effect the liquid is displaced to one end of the pipe, is balanced by the pressure gradient due to the axial gradient of the thickness of the layer. If we examine the balance of forces in the projection on the x axis, we can write the following equation:

$$\rho\omega^2\left(R-\frac{\delta}{2}\right)\frac{d\delta}{dx}=-\rho g\sin\beta. \tag{9}$$

Taking into account that R >> δ, and integrating it, we obtain

$$\overline{\delta}_x=-\frac{\sin\beta}{\mathrm{Fr_c}}x+c. \tag{10}$$

We determine the integration constant c from the condition

$$\overline{\delta}=\frac{1}{l}\int_0^l\overline{\delta}_x dx. \tag{11}$$

Then

$$c=\overline{\delta}+\frac{\sin\beta}{\mathrm{Fr_c}}\frac{l}{2}. \tag{12}$$

If we substitute the value of c into Eq. (10), we obtain an expression determining the longitudinal distribution of a liquid in an inclined RHP for flow regimes outside the region of the "entrained thin layer":

$$\overline{\delta}_x=\frac{\sin\beta}{\mathrm{Fr_c}}\left(\frac{l}{2}-x\right)+\overline{\delta}. \tag{13}$$

In the region of high rotational speeds it is also easy to take into account the effect of the taper of the inner surface of the RHP on the dependence $\overline{\delta}_x = f(x)$. In this case Eq. (9) will contain an additional term characterizing the magnitude of the taper:

$$\rho\omega^2\left(R_0+x\,\mathrm{tg}\,\alpha\right)\left(\mathrm{tg}\,\alpha-\frac{d\delta}{dx}\right)-\rho g\sin\beta=0. \tag{14}$$

Then the expression for determining $\overline{\delta}_x$ has the form

$$\overline{\delta}_x=\mathrm{tg}\,\alpha\left(x-\frac{l}{2}\right)+\overline{\delta}+\frac{\sin\beta}{\mathrm{Fr_c}}\left[\frac{1+p\,\mathrm{tg}\,\alpha}{p\,\mathrm{tg}\,\alpha}\ln(1+p\,\mathrm{tg}\,\alpha)-\ln\left(1+\frac{x}{R_0}\mathrm{tg}\,\alpha\right)-1\right]\frac{l}{p\,\mathrm{tg}\,\alpha}. \tag{15}$$

If we compare Eqs. (13) and (15), we see that the taper of the inner surface impedes the redistribution of the liquid when the pipe slopes toward the narrowing end, and conversely, promotes redistribution if the pipe slopes toward the widening end.

By using Eqs. (8) and (13), we will examine how the slope affects the distribution of the thickness of the layer over the inner surface of a cylindrical RHP when the rotational speed increases from the limiting low speeds to relatively large values. Figure 2 shows the dependences of the mean thickness of a layer of liquid on the wall of a RHP on the coordinate x and on the speed ω, obtained on the basis of calculations by formula (32) [1] written in dimensional form:

$$\delta_0=2\cdot10^{-2}R^{1,36}\frac{\mathrm{Ca}^{0,68}}{\overline{\delta}_x^{\,0,36}}\exp(11,8\,A), \tag{16}$$

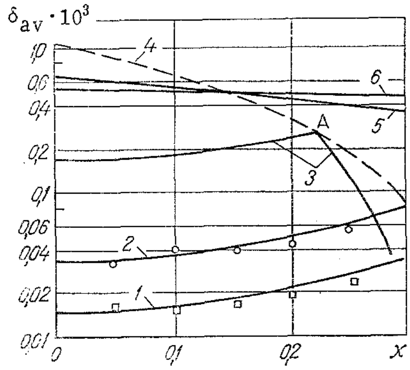

Fig. 2

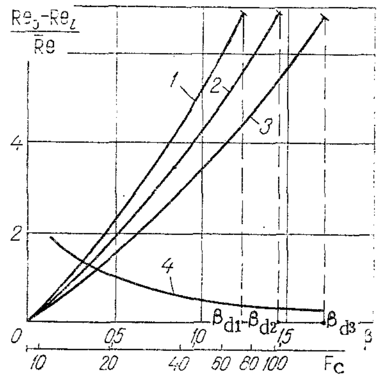

Fig. 3

Fig. 2. Dependence of the mean thickness of the layer of liquid on the coordinate x and on the speed ω: 1) $\omega = 0.314\ \mathrm{sec}^{-1}$; 2) 1.047; 3) 10.47; 5) 83.78; 6) 209.4; 4) the dependence $\delta_{av} = \overline{\delta}_x = f(x)$ according to (8). δ_{av}, m; x, m.

Fig. 3. Dependence of the relative range of change of the Reynolds number on β, p, Fr_c: 1) p = 12; 2) 10; 3) 8; 4) β = 1°, p = 10; $Fr_c = \omega^2 R/g$.

and also by formula (13). Equation (16), in which $\overline{\delta}_x$ is determined from (8), describes the thickness of a liquid layer in the region of the "entrained thin layer," and Eq. (13) describes it in the region of high values of ω, when there is no groove. Here it is assumed that in the former case $\delta_{av} = \delta_0$, and in the latter case $\delta_{av} = \overline{\delta}_x$. Here we present some results of the experimental investigation carried out with the installation [2] equipped with an electric contact sensor for measuring the thickness of layers of liquid. We used water as a working liquid. The object of investigation was a cylindrical stainless steel pipe (D_{in} = 64 mm, l = 300 mm).

With increasing rotational speed, the thickness of the entrained layer (curves 1, 2) increases over the entire length of the pipe. Observations revealed that beginning at some speed ω_H, a zone forms at the extreme section of the pipe where the groove disappears. With increasing speed this zone becomes ever longer until the groove disappears altogether when $\omega = \omega_K$. An illustration of this process is in Fig. 2: the fact that with increasing speed ω the curve characterizing the distribution of the layer entrained by the wall shifts upward. Beginning at ω_H it intersects curve 4, which describes the distribution of the liquid in an inclined pipe in the region of the "entrained thin layer" and is plotted according to Eq. (8). The point of intersection of these curves A corresponds to the coordinate x where the liquid in the given pipe section spreads in an annular layer over the perimeter, and the groove disappears, i.e., the flow regime leaves the region of the "entrained thin layer." With increasing ω, the shift of point A expresses the decrease in length of the groove. Visual observation showed that at the place which is theoretically determined by point A, a transient zone of a thicker turbulized layer of liquid forms; this is in agreement with the behavior of the dependence $\delta_{av} = f(x)$ (curve 3) in Fig. 2. In the interval of the rotational speeds $\omega_H < \omega < \omega_K$ the dependence $\delta_{av} = f(x)$ changes its slope. This is due to the difference in the nature of the distribution of liquid along the longitudinal axis at low speed, when there is a groove, and at high speeds, when the entire liquid is distributed over the inner surface. In the former case the redistribution of the liquid is determined by Eq. (8), and it leads to the formation of a layer with positive thickness gradient; in the latter case it is determined by Eq. (3), and the longitudinal thickness gradient of the layer is negative.

When the inner surface of the RHP is conical, the redistribution of the liquid at high rotational speed is determined by Eq. (15); the thickness gradient of the layer may be either positive of negative, depending on the rotational speed, the taper angles, and the inclination of the pipe.

A quantitative indicator of the complexity of the hydrodynamic pattern in an inclined RHP is the relative magnitude of the range of measurement of the Reynolds number, shown in Fig. 3, in dependence on the slope β and the parameter p for low rotational speeds, and also on the centrifugal Froude number for flow regimes outside the region of the "entrained thin

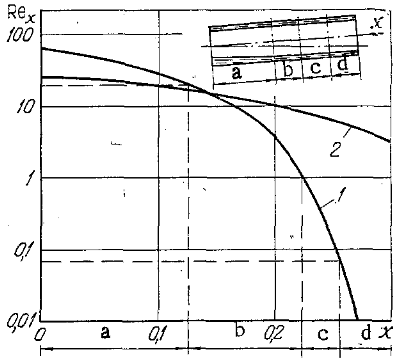

Fig. 4. Dependence of the number Re_x on the coordinate x ($Fr_c = 8$): 1) $\beta = 1.4°$; 2) 0.5°; a) region of "entrained thin layer"; b) of inertial flow; c) of viscous flow; d) "of rotation of a solid," $Re_x = \omega(\overline{\delta}_x)^2/\nu$. x, m.

layer." It can be seen from the figure that the nature of the flow of the heat carrier in a RHP with higher value of p depends to a greater extent on the slope, and the magnitude of the limiting slope β_d, which is determined by the joint solution of Eqs. (5) and (7), then becomes smaller ($\beta_{d1} < \beta_{d2} < \beta_{d3}$). With increasing centrifugal Froude number the range of change of Re outside the region of the "entrained thin layer" decreases rapidly and tends toward zero in the region of "rotation of a solid" ($Fr_c \to \infty$).

In the upper right-hand corner of Fig. 4 there is a diagram of the possible flow distribution of a liquid in a RHP into zones with different regimes. Thus, when the RHP is installed at the angle $\beta = \beta_d$, the Reynolds number in it changes from zero in the extreme cross section $x = l$ to the maximum value in the section x = 0. In consequence it is possible that, depending on the rotational speed, there may simultaneously exist two, three, or even four flow regimes extending in accordance with the Reynolds number that diminishes with increasing x: the region of the "entrained thin layer," region of inertial flow, region of viscous flow, and the region of "rotation of a solid." If the range of change of the Reynolds number is sufficiently large and includes values belonging to both the viscous-flow and inertial-flow regions, then there is a substantial increase if the ratio of the maximum thickness of the layer to the mean thickness, and also a decrease of the magnitude of the angular position of the maximum thickness φ_m with increasing coordinate x.

If we use Eq. (4) for the upper boundary of the emergence of the flow regime from the region of the "entrained thin layer" [1] ($Fr_c = 2.2\ Re^{0.44}$), for the boundary between the regions of viscous and inertial flow (Re = 1), and also for the arbitrary boundary of the region of "rotation of a solid" (for $\xi = 1.01$, see Fig. 1 [1]), we can determine the actual dimensions of the zones. In Fig. 4 we can see the change of the number Re_x along the RHP, and also the dimensions of the zones for a slope $\beta = 1.4°$ (curve 1) that is close to the limit value ($\beta_d = 1.47°$). For $Fr_c = 8$, which was adopted in plotting curves 1 and 2, the above-mentioned boundaries are, respectively: Re = 20, Re = 1, and Re = 0.07, and they are shown in Fig. 4 by horizontal dashed lines. It follows from Fig. 3 that when β decreases, the range of changes of the Reynolds number becomes smaller. This leads to the number of simultaneously existing flow regimes becoming smaller, too. For instance, with $\beta = 0.5$ (curve 2), we find only two regimes in the pipe: the region of the "entrained thin layer" and the region of inertial flow. One of the zones (with the flow regime existing under the given conditions in the horizontal position of the pipe) extends over the entire length of the RHP, superseding the others.

The taper of the inner surface affects the redistribution of the liquid when the rotational speed is high, and, as was shown above, increases or decreases (in dependence on the sign of angle α) the effect of the slope on the regimes of the hydrodynamics of the liquid in a RHP.

NOTATION

β, slope of the pipe; β_d, slope at which the extreme section of the pipe dries; α, taper angle; ω, angular speed of rotation; x, longitudinal coordinate; ρ, density; g, acceleration of gravity; μ, dynamic viscosity; ν, kinematic viscosity; V, volume of liquid in the pipe;

S_x, area of liquid in the section x; R, radius of the inner cylindrical surface; R_0, initial radius of the conical surface; l, length of the pipe; $\varphi_{30}, \varphi_{3l}, \varphi_{3x}, \varphi_3^0$, half-angles of flooding in the sections x = 0, x = l, and in an arbitrary section x, and also for $\beta = 0$, respectively; $\overline{\delta}_x = S_x/2\pi R$, mean thickness of the layer of liquid in the section x; $\overline{\delta} = V/2\pi R l$, mean thickness of the layer of liquid in the pipe; $p = l/R$; $\overline{\Delta} = \overline{\delta}/R$; $A = (\sigma/\rho g R^2)^{1/2}$, dimensionless capillary constant; $\xi = \delta_m/\overline{\delta}$, ratio of the maximum thickness to the mean thickness of the layer; φ_m, angular coordinate of the maximum thickness of the layer; $Re_x = \omega(\overline{\delta}_x)^2/\nu$, Reynolds number in the section x; $Fr_c = \omega^2 R/g$, centrifugal Froude number; $Ca = \omega R\mu/\sigma$, capillarity number; σ, specific surface energy.

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HEAT TRANSFER TO TURBULENT STREAM IN PIPES UNDER SUPERCRITICAL PRESSURES

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Experimental results are presented on heat transfer to several liquid hydrocarbons under supercritical pressures and pseudoboiling conditions. An empirical relation is proposed which generalizes these results.

Much attention has been paid in recent years, in the Soviet Union and abroad, to studies of heat transfer to liquids under supercritical pressures. This interest is being stimulated on the one hand by practical considerations, and on the other hand by the desire of scientists to understand the laws of heat transfer under conditions where the physical properties of liquids vary. Reviews of studies on this subject can be found in articles by B. S. Petukhov [1, 2], W. Hall and J. Jackson [3], and V. M. Eroshenko and L. A. Yaskin [4]. Many of those studies have dealt with heat transfer under supercritical pressures with attendant self-excited thermoacoustic vibrations [3, 5, 6]. The effect of these factors will not be dealt with in this report.

On the basis of the results of such studies, there have been proposed many theoretical methods for calculating the heat transfer (Dreisler, Goldman, Petukhov, Popov, Melik-Pashaev, Eroshenko and Yaskin, etc.), and semiempirical formulas have been proposed (Miropol'skii and Shitsman, Krasnoshchekov and Protopopov, etc.) which agree satisfactorily with experimental data on water, carbon dioxide, helium, and other liquids.

Curves taken from one report [1], depicting the $\alpha/\alpha_0 = f(T_w/T_m)$ relation for carbon dioxide, are shown in Fig. 1. The graph indicates that the intensity of heat transfer decreases with rising temperature of the pipe wall. The trend of this relation is the same here as in the methods proposed by other authors and used for other liquids.

Those methods of calculation assume that the mechanism of heat transfer under supercritical pressures is similar to that of plain heat transfer in a turbulent stream of liquid. The difference between them lies essentially in the way of accounting for the variation of properties of a liquid over the stream section. The attenuation of heat transfer with increasing referred wall temperature T_w/T_m is caused by formation of a gaseous boundary layer with a thermal resistance much higher than that of the liquid. The most significant factor affecting this attenuation of heat transfer with rising wall temperature is the change in density, which follows clearly from the theoretical equation $\alpha/\alpha_0 = (2/\sqrt{\rho_L/\rho_w} + 1)^2$ according to S. S. Kutateladze and A. I. Leont'ev.

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