QUANTITATIVE RELATIONSHIPS GOVERNING THE MOTION OF A LIQUID IN SMOOTH-WALLED ROTATING HEAT TUBES WITH A DISPLACED AXIS OF ROTATION

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We present the results from an experimental investigation into the hydrodynamics of a coolant, and have derived relationships determining the regimes of liquid motion, as well as the characteristics of these regimes.

Rotating heat tubes (RHT) with a displaced axis of rotation are utilized in certain types of electrical equipment [1] and in heat-exchange machinery [2]. However, extensive utilization of such RHT is restrained by the lack of information regarding the processes of hydrodynamics and heat exchange that occurs within such equipment.

The hydrodynamics of the coolant in smooth-walled RHT with a displaced axis of rotation decisively affects the exchange of heat and, consequently, determines the heat-transfer characteristics of these heat tubes.

As a result of experimental studies of the hydrodynamics [3] we have derived and described two characteristic regimes of coolant motion: a) the liquid, in the form of a stream, successively flushes the entire inside surface of the tube, moving nonuniformly (subcritical frequencies of rotation); b) the stream executes oscillations about the generatrix that is most distant from the axis of rotation (supercritical velocities of rotation). The boundary of these regimes is represented by the transitional process that appears in the separation of the stream into two flows, moving along the walls in opposite directions, and then rejoining into a single stream. The critical angular velocity of RHT rotation serves as this boundary. However, in order to study the processes of heat exchange it is essential that we have not only a qualitative picture of the coolant hydrodynamics, but also quantitative characteristics of these regimes. It is the purpose of the present study to derive characteristics which take into consideration the nonuniformity of liquid motion, as well as to generalize the experimental data on the determination of the critical angular velocity ω_{cr} and the magnitude of the flushed RHT surface at supercritical frequencies of rotation.

The results from our study into the nature of the liquid motion [3] demonstrates that the instantaneous values of the angular velocity of coolant motion at subcritical frequencies of rotation may significantly differ from the average angular velocity, equal to the angular velocity ω_t of tube rotation. Such nonuniformity of motion must, obviously, affect the intensity of the heat-exchange processes. Utilization of the average velocity ω_t to generalize heat-exchange data would therefore be incorrect. Bearing this in mind, let us institute some effective velocity of rotation by means of which to take into consideration the nonuniformity of coolant motion:

$$\omega_\ell^A = A\omega_t, \tag{1}$$

where the coefficient A, characterizing the magnitude of the velocity pulsation amplitude, is defined as

$$A = \frac{\overline{|\omega_\ell - \omega_t|} + \omega_t}{\omega_t}. \tag{2}$$

The experimental results demonstrated that a change in viscosity and density over the range of values characteristic for the liquids utilized as coolants exerts no significant influence on the magnitude of liquid velocity pulsations and the coefficient A depends exclusively on the overload η. The numerical value of this coefficient in the overload range η = 0.07-1.0, i.e., corresponding to the immersion into the lower portion of a nonmoving tube of a segment with a central angle ψ = 90-150°, and a tube radius in the range 10 mm < R_t < $R_r/2$, is defined by the relationship (Fig. 1)

$$A = 1{,}52\left(\frac{\omega_t^2 R_r}{g}\right)^{0,15}. \tag{3}$$

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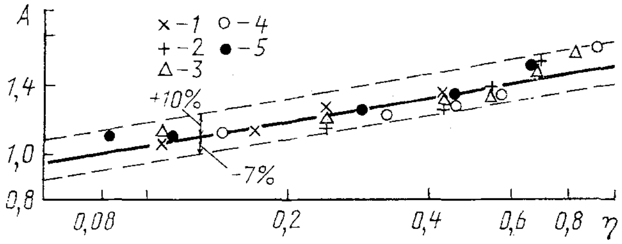

Fig. 1. Experimental data to estimate nonuniformities in the velocity of liquid stream motion relative to the tube wall at subcritical frequencies of rotation: 1) R_t = 5.4 mm, R_r = 60 mm; 2) 6.4 and 60; 3) 8.4 and 60; 4) 8.4 and 80; 5) 8.4 and 40.

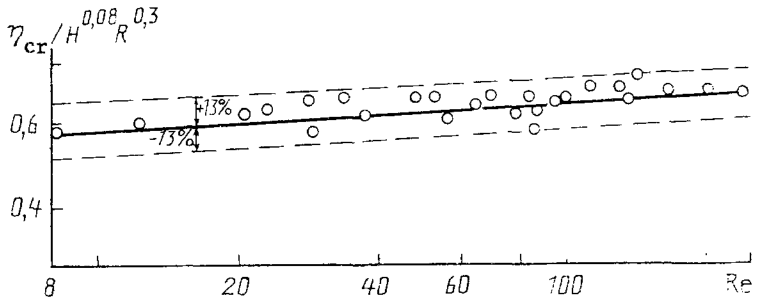

Fig. 2. Generalization of experimental data on the determination of the critical rotational frequency ($\eta_{cr}/H^{0.08}R^{0.23}$).

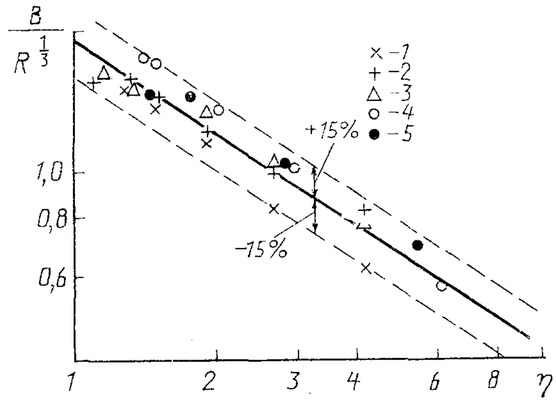

Fig. 3. Experimental data to evaluate nonuniformities in liquid stream velocity of motion relative to the walls of a tube at supercrititical velocities of rotation: 1-5) the same as in Fig. 1. The values of $B/(R_t/R_r)^{1/3}$ are plotted along the ordinate.

In order to determine the critical angular velocity ω_{cr}, corresponding to the boundary of the cited regimes, we will ascertain the parameters which affect that value: R_t, g, R_r, ρ, μ, and h. Using the theory of dimensionalities, we find the form of generalization for the experimental data

$$\eta_{cr} = f(R;\ \mathrm{Re};\ H). \tag{4}$$

Experimental data processed by the method of least squares are generalized by the relationship (Fig. 2)

$$\eta_{cr} = 0{,}53 R^{0,23}\, \mathrm{Re}^{0,06} H^{0,08}, \tag{5}$$

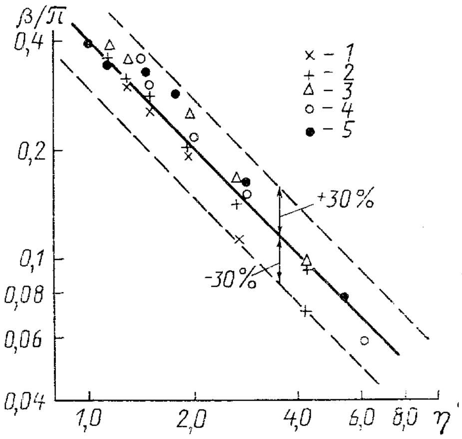

Fig. 4. Experimental data on the determination of the flushed tube surface: 1-5) the same as in Fig. 1.

valid in the range of Re = 6-300, R = 4-16, H = 0.11-0.5. Thus, the critical overload depends primarily on the relationships between the radius of rotation and the radius of the tube. The relationship between the forces of inertia and the forces of viscosity, as well as the dimensionless depth of the stream, exert insignificant influence.

With supercritical rotational frequencies, when the liquid stream executes oscillations about the generatrix most distant from the axis of rotation, the average velocity of the stream relative to the wall of the tube within a given period is equal to 0 and the effective liquid velocity is equal to

$$\omega_{\ell}^{B} = B\omega_{cr}, \tag{6}$$

where $B = |\bar{\omega}_\ell|/\omega_t$ is the coefficient by means of which we take into consideration both the velocity of liquid motion and the magnitude of its pulsations. Analysis of the experimental data showed that when $\eta > 1$, $R_t/R_r = 0.09$-0.22 the coefficient B can be expressed by the following relationship (Fig. 3):

$$B = 1{,}9\left(\frac{\omega_t^2 R_r}{g}\right)^{-\frac{2}{3}}\left(\frac{R_t}{R_r}\right)^{\frac{1}{3}}. \tag{7}$$

From this we can see that with an increase in the overload, the velocity of liquid motion and the amplitude of the oscillations diminish, and given a sufficiently large value of the overload ($\eta >> 1$) the stream becomes immobile relative to the tube.

In addition to the velocity of liquid motion relative to the tube, at a rotational frequency in excess of the critical, the most important characteristic is the size of the surface flushed by the oscillating stream. An analysis of the experimental data has established that the value of the maximum angle through which the normal to the stream surface is deflected from the direction of the centripetal acceleration when $\eta > 1$ can be described by the following function (Fig. 4):

$$\beta = 0{,}4\left(\frac{\omega_t^2 R_r}{g}\right)^{-1}\pi. \tag{8}$$

Then that portion of the tube surface flushed by the stream, as the liquid is introduced to correspond to an immersion angle ψ, is equal to

$$\Delta = 0{,}4\left(\frac{\omega_t^2 R_r}{g}\right)^{-1} + \frac{\psi}{2\pi}. \tag{9}$$

Thus, the effective liquid velocities determined as a result of this research at sub- and supercritical frequencies of rotation reflect the quantitative relationships governing the movement of the coolant in the rotating heat tubes, where the axis of rotation has been displaced, and they can be used in studying the processes of heat exchange in the form of parameters which affect their quantitative characteristics.

The magnitude of the flushed tube surface at supercritical angular velocities is an important characteristic, defining the actual heat-exchange surfaces in both condensation and vaporization zones of a rotating heat tube.

The resulting generalizing relationship applicable to critical overload allows us to determine the values of the angular rotational velocity separating the flow regimes for the coolant in a heat tube.

NOTATION

ω_t, angular rotational velocity of the tube; ω_l, angular velocity of liquid motion; R_r, radius of tube rotation; g, free-fall acceleration; ρ, density; μ and ν, coefficients of dynamic and kinematic viscosity; h, stream depth; $\eta = \omega_t^2 R_r/g$, overload; ω_{cr}, critical angular velocity; ω_l^A and ω_l^B, effective angular velocities of liquid motion for sub- and supercritical frequencies of rotation; A and B, coefficients to account for nonuniformity of liquid motion at sub- and supercritical frequencies of rotation; R_t, tube radius; $R = R_r/R_t$, dimensionless radius of rotation; $\eta_{cr} = \omega_{cr}^2 R_r/g$, critical overload; $Re = \omega_t R_t h/\nu$, Reynolds number; $H = h/R_t$, dimensionless stream depth; β, angle through which normal to the stream surface is deflected; Δ, portion of the tube surface flushed by the stream; ψ, angle of immersion.

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MODEL OF HEAT TRANSFER IN THE LIQUID PHASE DURING AXIAL AND TWISTED TURBULENT MOTION OF LIQUID AND GAS FILMS IN SHORT CHANNELS

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Based on the model of a diffusion boundary layer in conjunction with a given law governing the attenuation of turbulent pulsations in a viscous sublayer, we have derived an equation to calculate the volumetric coefficients of mass transfer based on the experimentally determined hydraulic resistance in a two-phase system.

We know that the transfer of mass in a liquid film is significantly intensified in direct axial, and particularly in twisted, motion of phases in a contact tube. A large number of studies, involving both axial [1-8] and twisted motions [6-10], has been devoted to the study of the hydraulic features and the modeling of mass transfer in dispersed-circular flows. The mathematical models of mass transfer in these studies, as a rule, contain empirical coefficients which require correction as the conditions of phase interaction change, and for this we must use the experimental data related to mass transfer.

Model of Mass Transfer in a Turbulent Film. Let us examine the direct (ascending or descending) turbulent motion of a liquid and gas, when the tangential stress $\tau_{g\text{-}l}$ at the boundary of phase separation considerably exceeds the stress $\tau_w = \rho_l g \delta$ at the wall, the latter generated exclusively by gravitational forces ($\tau_{g\text{-}l} >> \tau_w$). Such a regime is achieved in tubular contact devices at high gas-stream velocities of $W_g > 12\text{-}15$ m/sec.

To describe the processes of transfer in a turbulent film, we will adopt the model of the diffusion boundary layer [11-13], according to which the basic resistance to the transfer of mass is concentrated in the viscous sublayer:

$$\frac{1}{\beta} = \int_0^{\delta_1} \frac{dy}{D + D_t}, \quad (1)$$

where D_t is the coefficient of turbulent diffusion in the viscous sublayer, defined by the law governing the attenuation of turbulent pulsations.

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