DISTRIBUTION OF HEAT TRANSFER AGENT IN THE CAPILLARY STRUCTURE OF ROTATING HEAT PIPES WITH A DISPLACED AXIS OF ROTATION

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The authors present theoretical and empirical relations describing the influence of centrifugal forces on the filling of the capillary structure by the heat transfer agent.

Of the different constructions one finds for rotating heat pipes (RHP) with a displaced axis of rotation the simplest and quite efficient are the smooth-walled RHP's. However, in some cases, to ensure operation when at rest, or with high heat flux density in the evaporation zone, it is desirable to use a capillary structure (CS). The presence of the centrifugal force field in the normal operating regime of such RHP's will substantially influence the distribution of heat transfer agent in the capillary structure, and will therefore influence the heat transmission characteristics.

In a horizontally located RHP with a displaced axis of rotation the heat transfer agent is drawn out of the capillary structure pores under the influence of centrifugal forces towards the side opposite to the axis of rotation. In a heat pipe at rest or under rather low inertial load, when the capillary forces exceed the centrifugal forces, the heat transfer agent fills the capillary structure completely, but without excess, and the heat pipe operates in the regime typical of heat pipes at rest, a regime that has been quite well studied at present.

With increase of the rotational frequency the heat transfer agent begins to be drawn out of the pores of the capillary structure and consequently there is an increase of the hydrostatic head due to the column of liquid of height $2R_p$ in the field of the mass forces:

$$P_h = \rho\,|g + \omega^2 R_r|\,2R_p. \tag{1}$$

It is assumed in Eq. (1) that the inertia loads are the same for any point of the RHP. The capillary head of the metal-fiber capillary structures considered here is [1]:

$$P_c = \frac{4\sigma\cos\Theta}{D_{ef}}. \tag{2}$$

Evidently liquid will be drawn out of the pores under the condition

$$\rho\,|g + \omega^2 R_r|\,2R_p > \frac{4\sigma\cos\Theta}{D_{ef}}. \tag{3}$$

Here along the perimeter of the heat pipe zones are formed with capillary structure that is dry, or is normally saturated, or is flooded by a stream of liquid.

In this work we investigated the distribution of heat transfer agent in a RHP with displaced axis of rotation (Fig. 1), containing a metal-fiber capillary structure, the aim being to determine the influence of structural, geometrical and regime parameters on the ratio of capillary structure surface areas: dry areas to areas saturated and areas flooded by a stream.

Starting by equating the capillary head to the hydrostatic pressure of an equilibrium liquid column, and neglecting gravity g because it is small, we can determine the height of rise H of heat transfer agent relative to the surface formed by the stream

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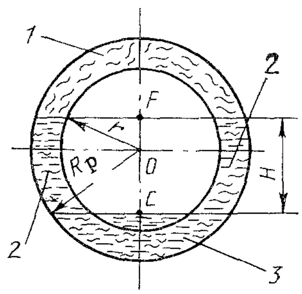

Fig. 1. Distribution of heat transfer agent in the capillary structure when partially dry: 1) dry section; 2) normally saturated section; 3) section flooded by a stream of heat transfer agent.

$$H = \frac{4\sigma \cos\Theta}{\rho\omega^2 R_r D_{ef}}. \tag{4}$$

Saturation of the capillary structure by heat transfer agent is described by the degree of filling Π', equal to

$$\Pi' = \frac{V_{cs}}{V_\ell} = \frac{V_\ell - V_d}{V_\ell} = 1 - \frac{V_s}{V_\ell}. \tag{5}$$

Equating the volume of liquid drawn out from the pores of the capillary structure V_{cs} and the volume of liquid in the stream V_s, as determined from the geometry of the heat pipe and the capillary structure (Fig. 1), we obtain the following transcendental expression:

$$\Pi\left\{\frac{R_p^2}{2}\left[2\arccos\frac{OF}{R_p} - \sin\left(2\arccos\frac{OF}{R_p}\right)\right] - \frac{r^2}{2}\left[2\arccos\frac{OF}{r} - \sin\left(2\arccos\frac{OF}{r}\right)\right]\right\} = \frac{r^2}{2}\left[2\arccos\frac{H-OF}{r} - \sin\left(2\arccos\frac{H-OF}{r}\right)\right], \tag{6}$$

from which we determined by a numerical method the intercept OF and then the volume V_s. Then the degree of filling of the capillary structure will be

$$\Pi' = 1 - \frac{\frac{r^2}{2}\left[2\arccos\frac{H-OF}{r} - \sin\left(2\arccos\frac{H-OF}{r}\right)\right]}{\pi(R_p^2 - r^2)\Pi}. \tag{7}$$

Experimental data on the distribution of heat transfer agent was based on a visual determination of the fraction of the cross section of the pipe occupied by liquid drawn out from the pores of the capillary structure. The tests were conducted on an experimental facility equipped with a stroboscope [2]. We investigated copper heat pipes of internal diameter 16.8 mm and a copper metal-fiber capillary structure of porosity 0.4 to 0.8 and thickness 0.5 to 1 mm. Here the effective diameter of the pores varied in the range 23.5 to 107 μm. As test liquids we used water and ethyl alcohol.

The experimental results showed that at low rotational frequencies, i.e., when condition (3) does not hold, there is no stream in the pipe, and therefore the liquid occupies the entire capillary structure and the filling level is $\Pi' = 1$. With increased rotational frequency, when condition (3) begins to hold, a stream appears. The amount of liquid in the stream increases, and for large enough values of ω it reaches a limit, and the degree of filling reaches its minimum value.

It was also observed that the degree of filling depends on the direction of the process, i.e., on whether drying or filling of the capillary structure is in progress. During drying of the capillary structure the value of Π' is larger than during filling, for the same rotational frequency. This phenomenon of capillary hysteresis is typical of irregular capillary-

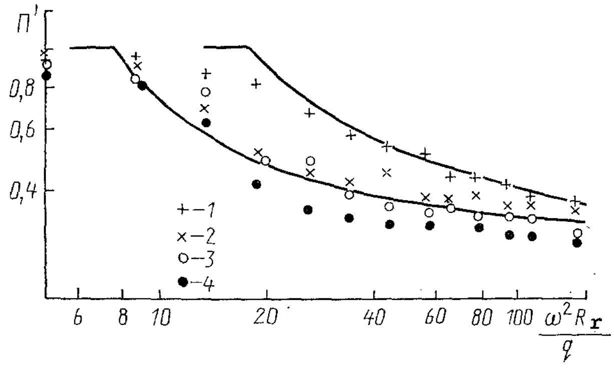

Fig. 2. Dependence of the degree of filling of the capillary structure on the loading. Experimental data: 1) Π = 0.6, δ_{cs} = 1.0 mm, increase of ω; 2) Π = 0.6, δ_{cs} = 1.0, increase of ω; 3) Π = 0.8, δ_{cs} = 1.0, increase of ω; 4) Π = 0.8, δ_{cs} = 1.0 mm, decrease of ω; the solid lines are calculation using Eq. (7).

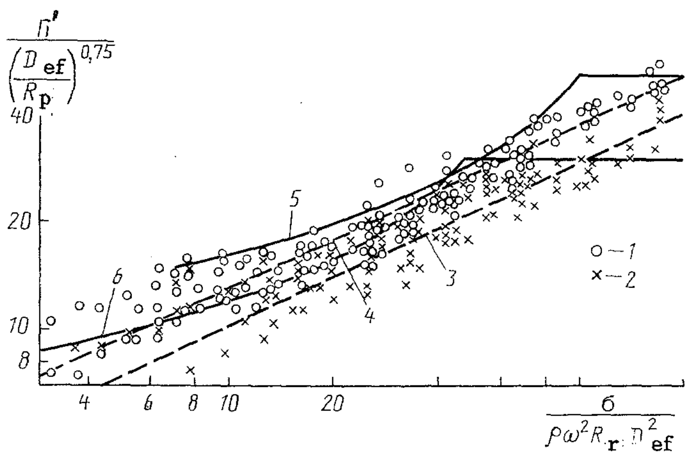

Fig. 3. Generalization of the experimental data to determine the degree of filling of the capillary structure. The experimental data are: 1) increase of ω; 2) decrease of ω; 3) correlation for an increase of ω; 4) correlation for a decrease of ω; theory: 5) Π = 0.6, δ_{cs} = 0.5 mm; 6) Π = 0.8, δ_{cs} = 0.5 mm.

porous structures such as metal-fiber structures. The degree of uniformity of the porous structure is characterized by integral and differential functions of pore size distribution [3]. When heat transfer agent is drawn out of the pores, some of the pores with diameter less than D_{ef} will contain liquid, even located in the drying zone. However, when the capillary structure is filling, some of the pores of diameter less than D_{ef} will not yet be filled, because of the phenomenon of hysteresis, even in an area where the structure should be filled with heat transfer agent.

Using dimensional theory and the method of least squares, we obtain a relation generalizing the experimental data to determine the degree of filling of the capillary structure (Fig. 3):

$$\Pi' = C\left(\frac{\sigma}{\rho\omega^2 R_r D_{ef}}\right)^{0.5}\left(\frac{D_{ef}}{R_p}\right)^{0.75}, \qquad (8)$$

which agrees satisfactorily with the theory, Eq. (7). Here C = 4.0 for an increase of ω and C = 3.3 for a decrease of ω.

Thus, we have obtained a theoretical dependence (7) and an experimental dependence (8) which allow us to determine the ratio of capillary structure surface areas: dry, normally saturated, and flooded with a stream. These results are needed for computing the heat transfer characteristics of rotating heat pipes with a displaced axis of rotation.

NOTATION

Π(porosity; δ_{cs}) thickness of capillary structure; L) lenth of the heat pipe; R_p) internal radius of the heat pipe; r) radius of the vapor space; R_r) radius of rotation; V_ℓ) volume charged with liquid; V_s) volume of liquid in the stream; V_{cs}) volume of liquid in the capillary structure; V_d) volume of liquid drawn out; D_{ef}) effective diameter of the pores; P_h) hydrostatic pressure; P_c) capillary head pressure; ρ) density of heat transfer agent; g) acceleration of free fall; ω) angular velocity of rotation; σ) surface tension; Θ) wetting angle; H) height of rise of heat transfer agent; Π') degree of filling of the capillary structure.

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NUMERICAL STUDY OF THE PROBLEM OF UNSTEADY HEAT TRANSFER IN A CASED-WELL–BED SYSTEM

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A solution is presented for an unsteady axisymmetric heat-conduction problem connected with the development of the theory of the geothermal logging of cased wells. The solution is used as a basis for reaching several practical conclusions regarding the feasibility of conducting geothermal logging in cased wells.

Thermal monitoring techniques employing an active source have recently come into wide use in flaw detection. To optimize measurement conditions and gain a better understanding of the physics of the pertinent phenomena, investigators have solved a number of two- and three-dimensional problems of unsteady heat transfer in nonuniform laminated media. Examples of such problems are those studied in [1, 2]. In the present investigation, we solve a similar problem connected with the theory of geothermal logging. The results may prove useful in refining the theory and optimizing logging conditions. The solution of this problem is also of interest in regard to developing methods of detecting flaws on tubes of heat exchangers and fuel elements in nuclear reactors.

Mathematically modeling the processes which take place in geothermal logging makes it possible to study the effect of the parameters of the probe (power and concentration of the source, velocity and length of the probe), the thermal properties of the fluid and the walls of the well, and geometric factors on the distribution of the temperature field and heat sources in the well–bed system. Here, we study the effect of the casing string and cement ring on unsteady heat transfer in the well–bed system and we evaluate the effect of the velocity and length of the probe on the feasibility of performing geothermal logging in cased wells.

We will examine a cylindrical region (Fig. 1) containing a well of radius R_1 filled with a fluid (liquid or gas) having a thermal conductivity λ_1, heat capacity c_1, and density ρ_1. It is assumed that the well has been cased with a string having the thermal properties λ_2, c_2, and ρ_2. The external radius of the string is R_2. The casing string has been cemented, the cement ring being represented as a hollow cylinder with an external radius R_3

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