CONTACT ANGLES OF WICKS FOR LOW-TEMPERATURE HEAT PIPES

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The results of an experimental investigation of the contact angles of high-porosity copper wicks for heat pipes in water and organic liquids are given. Recommendations for better wetting of the porous wick structure by the heat-transfer agent are offered.

Heat pipes are now being used to an ever increasing extent in power engineering, electronics, chemical machine construction, and other branches of industry. The development and the design of heat pipes require careful investigation of certain physicochemical processes which characterize the operation of such devices. A more thorough understanding of these processes and the ability to control them would make it possible to improve the basic characteristic of heat pipes — the capacity to trasmit the maximum possible thermal flux.

The capacity of the wick to ensure the required mass flow velocity of the liquid heat-transfer agent is one of the factors limiting the maximum heat flux through the pipe. The capillary head, which causes the liquid to move in the porous wick, is determined from the Laplace equation in the following form:

$$\Delta p_c = \frac{4\sigma}{D_{\mathrm{me}}} \cos\theta. \qquad (1)$$

The contact angle in wetting is an important characteristic of the material–liquid pair acting as the wick and the heat-transfer agent in a heat pipe.

The wetting of a solid surface by a liquid involves a complex physicochemical process, which takes place in a heterogeneous system. The contact angle can be considered as a perfectly determinate physical

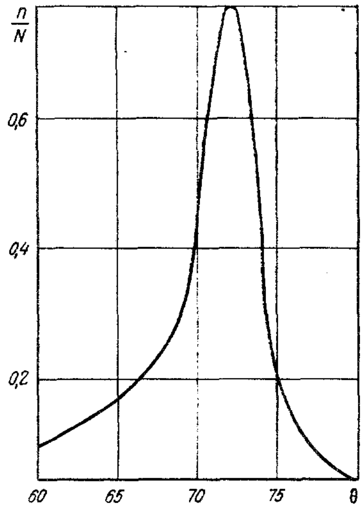

Fig. 1. Distribution of contact angle of a copper surface with water: n/N, dimensionless; θ, deg.

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parameter only for systems that have reached thermodynamic equilibrium. In this case, it is determined by the surface characteristics of the liquid and the equilibrium adsorption layer. The thermodynamic characteristics of the adsorption layer, in turn, are determined by the force field of the solid surface. The presently available analytical methods for determining the surface energy are applicable only to the ideal case of a regular monocrystal in a vacuum. It is difficult to calculate the contact angle for an actual system because of the indeterminacy in averaging the free surface energies. Therefore, experimental data obtained from contact angle investigations have practical importance.

TABLE 1. Results of Contact-Angle Measurements Based on the Resting-Drop Method

Liquid	Contact angle for copper surface, $\theta°$
Water	72 ± 2
Acetone	0
Ethyl alcohol	15 ± 5
Methyl alcohol	0
Methylal	0
Freon-11	0

The contact-angle values given by different authors for the same solid–liquid pair differ from each other for the most part because of the chemical and microgeometric surface nonuniformities of the specimens and the effect of experimental conditions. Thus, the contact angle determined with respect to the parameters of a small drop of doubly distilled water on a copper filament was equal to 44 ± 2° in [1]. The experiments were performed at the temperature $t = 17.8°C$. The contact angle in the wetting of copper by water, determined by means of the inclined-plate method, was in the 51-65° range [2]. The contact angle values for copper and water obtained in [3, 4] by using the resting-drop method were equal to 60° and 76° (at $t = 20°C$). The capillary-rise method, which was used in [5], yielded $\theta = 73°$ (at $t = 25°C$) for water and a porous copper wick.

This brief survey of the investigation results emphasizes the need for a thorough study of the wetting process by using a broader program and considering the operation of the wetted material as a heat-pipe wick. This was the aim of our work. We investigated the wetting of copper by distilled water, acetone, methyl and ethyl alcohols, methylal, and Freon-11.

The contact angle was measured by using the resting-drop method and the capillary-rise method.

In determining θ according to the resting-drop method, the flat surface of the copper specimen was placed in a strictly horizontal position before the objective of the optical instrument. The dependence of the contact angle on the roughness of the metal surface was taken into account [3]; the surfaces of all specimens had a class-7 to class-8 finish. The specimen surface was thoroughly degreased before each experiment.

The contact angle was determined with respect to: 1) the projection of the liquid drop on a screen, where the angle between the copper surface and the tangent to the drop contour at the point of intersection between the contour and the surface was measured; 2) the drop image on photographic plates which were placed under a microscope with a goniometric ocular.

Figure 1 shows one of the contact-angle distribution curves. The relative recurrence frequencies of individual angle values are laid off on the axis of ordinates.

The results obtained in measuring the contact angle according to the resting-drop method at $t = 20°C$ are given in Table 1.

Determination of the contact angle by means of the capillary-rise method is based on the fact that the liquid wetting the porous structure rises along the vertical wick until the capillary forces are balanced by the force of gravity. From the equation of equilibrium, we obtain

$$\cos\theta = \frac{\rho g H D_{\mathrm{me}}}{4\sigma}. \tag{2}$$

The rise height of the liquid in wick specimens made of high-porosity (60-95%) fibrous copper materials with the length-to-diameter ratios of fibers $l_f/d_f = 45;\ 75;\ 150$ was determined experimentally.

The specimens were placed in a vertical glass tube with a length of 510 mm and an inside diameter of 87 mm. All specimens, which had a length of 500 mm, a width of 45 mm, and a thickness of 2 mm, were suspended by means of clamps from the plug closing the upper part of the tube. The lower part of the tube was placed in a tank containing the liquid. The entire system was thoroughly insulated from the ambient. Before each experiment, the atmosphere inside the tube was saturated with vapor of the tested liquid over a period of 1-2 h in order to minimize evaporation of the liquid from the wick surface. Indicator paper strips 3 mm wide were clamped to the wick surface at a spacing of 10 mm from each other by

TABLE 2. Results of Experiments Based on the Capillary-Rise Method

Liquid	Structural characteristics of wick			Rise height $H \cdot 10^3$, m		$\cos\theta$		$\theta°$	
	$\frac{l_f}{d_f}$	P, %	$D_{me} \cdot 10^{-6}$,	oxidized wick	un-oxidized wick	oxidized wick	un-oxidized wick	oxidized wick	un-oxidized wick
1	2	3	4	5	6	7	8	9	10
Acetone	45	61,2	60,0	220	165	≈1,0	0,75	0	41±2
		70,0	81,0	165	125	≈1,0	0,757		
		79,2	107,0	120	90	≈1,0	0,75		
Acetone	75	70,0	60,0	210	160	≈1,0	0,762	0	41±2
		79,4	83,0	145	105	0,98	0,725		
		88,5	108,5	75	55	0,66	0,734		
Acetone	150	79,0	63,0	210	160	≈1,0	0,762	0	41±2
		90,0	93,0	110	85	0,84	0,773		
		95,0	110,0	55	40	0,5	0,727		
Ethyl alcohol	45	61,2	60,0	220	150	≈1,0	0,71	0	45±1
	75	70,0	60,0	200	140	0,99	0,693		
	150	79,0	63,0	200	140	0,99	0,693		
Methyl alcohol	45	61,2	60,0	210	160	1,0	0,764	0	40±1
	75	70,0	60,0	210	155	≈1,0	0,775		
	150	79,0	63,0	205	150	≈1,0	0,75		
Water	45	61,2	60,0	>480	—	—	—	—	—
		70,0	81,0	420	—	≈1,0	—	0	—
		79,2	107,0	290	—	0,995	—	6	—
Water	75	70,0	60,0	>480	—	—	—	—	—
		79,4	83,0	355	—	≈1,0	—	0	—
		88,5	108,5	180	—	0,99	—	8	—
Water	150	79,0	63,0	>480	—	—	—	—	—
		90,0	93,0	270	—	≈1,0	—	0	—
		95,0	110,0	130	—	0,975	—	13	—

means of clamps connected through a multipoint switch to one terminal of an ohmmeter. The top clamp, which was in direct contact with the wick surface, was connected to the other terminal. The infinite resistance of the dry paper strips dropped sharply as they became soaked when the liquid front approached individual sections. In order to ensure the maximum liquid rise along the wick, each experiment was performed over a period of 1 to 3 days. The rise height was determined to an accuracy of 5% for most specimens.

The mean (effective) pore diameter in the wick was calculated with respect to two experimental characteristics of the material — open porosity and gas permeability. The experimental specimens, which had a cylindrical shape, were fastened in a rubber yoke and were blown through with argon. The pressure drop on the specimens was measured by means of a differential pressure gauge, while the argon discharge was measured by means of a flowmeter. For determining the mean pore diameter the obtained dependences of the discharge on the pressure drop were processed according to the method described in [6]. Improvement of wetting of the wick material by the liquid, which results in a higher capillary head, can be achieved by increasing the work of adhesion. One of the methods consists in heating the metal in air, which produces a surface oxide film. The higher work of adhesion of an oxidized metal surface is obviously the result of changes in its chemical characteristics and roughness.

Considering the effect of oxidation, we performed experiments on the same porous copper wicks, which were first oxidized at 300°C over a period of 2 h.

In contrast to unoxidized specimens, the movement of the liquid front was observed visually for all the investigated oxidized specimens and liquids.

The contact angles for oxidized copper wicks and acetone, calculated by means of (2), were close to zero. Specimens with maximum porosity were an exception, which is explained by the considerable nonuniformity of their capillary structure. Thus, assuming that $\cos\theta = 1$ for oxidized copper wicks and acetone, we can determine the contact angle of the same wick (oxidized or unoxidized), wetted by any other liquid, by eliminating D_{me} from the equilibrium equation composed for each pair:

$$\cos\theta = \frac{H}{H'}\cdot\frac{\sigma_a}{\sigma}\cdot\frac{\rho}{\rho_a}\,. \tag{3}$$

The results of the experiments (at t = 20°C) and calculations are given in Table 2. The reason for the absence of experimental results for unoxidized wicks and water is that, in spite of the several cleansing procedures carried out (treatment with acetone, methyl alchohol, and dilute nitric acid, roasting in hydrogen at t = 1000°C, etc.), the authors could not bring about the wetting of dry, unoxidized copper wicks by water.

The contact-angle values determined by means of the capillary-rise method were larger than those obtained by means of the resting-drop method. This discrepancy is probably due to the effect of capillary hysteresis, which occurs in the impregnation of porous materials. The wetting of oxidized wick surfaces by water and organic liquids was almost ideal. Oxidation improves the wetting of not only copper, but also of other metals (stainless steel, nickel, etc.). However, there is an optimum set of temperature and exposure time conditions for the oxidation of any particular metal.

The actual conditions of the process in a heat pipe differ considerably from the conditions in experiments based on the capillary-rise method (a higher temperature, the occurrence of heat and mass exchange, and a wick previously impregnated by the liquid). An analysis of these factors has shown that they only improve wetting [4, 7].

The results of our experiments suggest that metal wicks for low-temperature heat pipes should be oxidized. The characteristics of heat pipes should be calculated on the basis of contact-angle values determined by means of the capillary-rise method, which approaches most closely the actual conditions of the process.

NOTATION

Δp_c	is the capillary head;
σ	is the surface-tension coefficient of the liquid;
θ	is the contact angle of the material wetted by the liquid;
D_{me}	is the mean (effective) diameter of pores in the wick;
H	is the rise height of the liquid along the wick;
H/H'	is the ratio of the rise height for the investigated wick–liquid pair to the rise height of acetone in the same, but oxidized, wick;
σ_a/σ	is the ratio of the surface tension of acetone to the surface tension of the investigated liquid;
ρ/ρ_a	is the ratio of densities of the investigated liquid and acetone;
g	is the acceleration due to gravity.

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