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INVESTIGATION OF THE COOLANT EDGE WETTING ANGLE FOR MESH HEAT PIPE WICKS

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Results are presented of an experimental investigation of the edge wetting angle of Freon-22, ethane, and ammonia for mesh wicks in the 20-115, 6-115, and 20-60°C temperature ranges, respectively.

The effective units produced recently for heat transmission, namely, heat pipes [1, 2], are being utilized all the more extensively in engineering, including even in the 150-273°K temperature range, because of a number of their inherent properties: the transmission of considerable heat fluxes at low temperature drops, the capability of producing isothermal conditions in relatively large areas, the possibility of transforming a heat load, the negligible weight, the absence of moving parts and the requirement of pumps, and the total autonomy.

A heat pipe transmits heat flux from the heating to the cooling zone by means of evaporation and condensation of the intermediate heat carrier. Reverse motion of the liquid from the condenser section to the heat supply zone is accomplished because of the capillary forces by means of a capillary-porous structure (wick) located on the inner heat pipe surface.

One of the most widespread wick materials for heat pipes is a metal mesh. In order to develop reliable methods of computing and designing heat pipes with mesh wicks, more complete knowledge of the capillary properties of the metal mesh structures is needed. The wick structure in any case of heat pipe utilization should assure delivery of the surface being cooled by the heat carrier. The physical processes occurring in heat pipes impose a number of constraints on their heat-transmitting capability, which are associated, in particular, with the greatest achievable capillary head, which is determined by the Laplace equation for a structure with cylindrical pores

$$\Delta p_c = 2\sigma \cos\theta \left(\frac{1}{R_1} - \frac{1}{R_2}\right). \quad (1)$$

It follows from (1) that the edge wetting angle θ substantially influences the quantity Δp_c.

A number of papers devoted to the investigation of the hydrodynamic and structural characteristics of different classes of porous materials used as heat pipe wicks has recently been published in the literature [3-6].

However, the angle θ is often assumed to be 0° [7-8] in computations of the transport properties of wicks although wetting of the wick structure is far from ideal in the majority of cases, and different working liquids wet the capillary-porous structure with a specific edge wetting angle θ in every case. The edge wetting angle is an important characteristic of the metal–liquid combination which can be used as a wick and heat carrier of a specific heat pipe. Because of the complexity of the analytical computation of values of θ, experimental values of the edge angle are of practical value.

Information about the edge angles is quite scarce in the literature and practically absent for liquids in the temperature range of cryogenic and low-temperature heat pipe operation [9-11].

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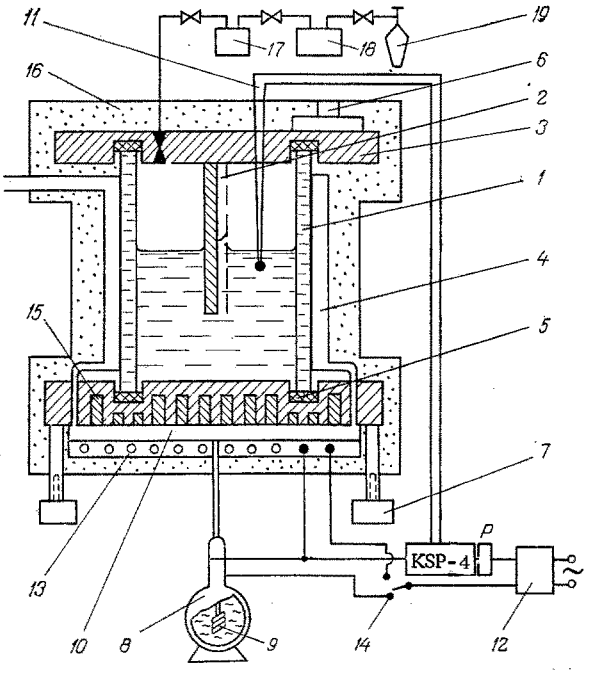

Fig. 1. Diagram of the experimental setup.

The purpose of this paper is to determine the effective edge wetting angle for a mesh capillary structure by Freon-22, ammonia, and ethane in the 150-295°K temperature band. The working section with a capillary structure simulated a heat pipe [12] fabricated from the stainless steel Kh18N10T with a nickel twill mesh 80/270 (the mesh warp is 0.052-mm-diameter wire, and the woof is 0.035-mm-diameter wire). The method of measuring the height of the heat carrier rise in a vertical capillary in the form of a slot formed by the surfaces mentioned [13] was used to determine the wetting angle.

The experiments were performed on the apparatus whose diagram is shown in Fig. 1. The working part of the apparatus is the bucket 1 in which a 30-mm-long capillary 2 is placed and which is rigidly fixed vertically in the upper flange 3. The bucket is a cylinder of 70-mm height with a 36-mm inner diameter and 2-mm wall thickness. The bucket material is molybdenum glass (for Freon-22 and ammonia) or organic glass (for ethane). The bucket is inserted compactly into the cooler 4, which is a double-walled copper cylinder. The upper and lower flanges are fabricated from Kh18N10T stainless steel. By using four tightening pins (not shown in Fig. 1), the bucket is squeezed compactly to the flanges through fluoroplastic (vacuum) gaskets 5, where the upper flange is connected to a heat carrier evacuation and filling system. The working section is mounted horizontally by the level 6 by using the screws 7.

The coolant temperature is lowered by the influx of liquid nitrogen from the nitrogen feeder 8 into the cavity 10 and the cooler. The nitrogen supply is a Dewar vessel with a Nichrome heater 9 inside. The temperature of the coolant liquid phase is measured by the copper – Constantan thermocouple 11 within the stainless $\varnothing 5 \times 0.5$-mm pipe sleeve, and by a KSP-4 electronic potentiometer. The coolant liquid-phase temperature, set by the temperature sensor in the KSP-4, is maintained as follows. A voltage is supplied to the heater 9 from the voltage regulator 12 (RNO-250-2) through the relay P, and the liquid nitrogen starts to flow into the cooling system under the pressure of the intrinsic vapors. The change in thermocouple emf results in displacement of the potentiometer pointer. Activation of the regulating unit of the instrument occurs when the given temperature is reached, and the relay P disconnects the voltage supply in the nitrogen feeder. Nitrogen ceases to flow into the cooling system. The Nichrome heater 13, to which a voltage is supplied from the regulator 12 through the switch 14, raises the coolant temperature.

To improve the quality of the temperature regulation, to diminish the liquid nitrogen discharge, and to shorten the time of emergence at the given temperature, copper inserts 15 are pressed into the lower flange, and the bucket with the coolant is heat-insulated by the plastic foam 16. To avoid excessive overcooling of the coolant during the influx of the liquid nitrogen into the cooler, its volume is made negligible ($V_0 = 45$ cm^3) [14]. The given temperature is set in the cryostat in 10-15 min with a thermostat accuracy of ±1.5°C.

TABLE 1. Impurity Content in the Liquids Being Investigated

Freon-22		Ammonia		Ethane	
impurity	content,%	impurity	content, %	impurity	content,%
Air	$5 \cdot 10^{-3}$	Water	60	Oxygen	$1 \cdot 10^{-6}$
Water	$1{,}2 \cdot 10^{-3}$	Oil	0,57	Nitrogen	$1 \cdot 10^{-6}$
		Iron	0,12		
Nonvolatile residue	$1 \cdot 10^{-3}$			Hydrogen sulfide	$1{,}9 \cdot 10^{-3}$
Freon-12	$1 \cdot 10^{-3}$				
Freon-23	$5 \cdot 10^{-3}$			Propane	$1 \cdot 10^{-3}$
Hexaflouropropene	$1 \cdot 10^{-2}$				

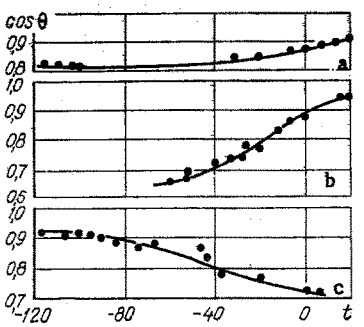

Fig. 2. Dependence of the quantity $\cos\theta$ on the temperature t for Freon-22 (a), ammonia (b), and ethane (c). t, °C.

The filling system includes a module 18 to cleanse the coolant of impurities, to check on the impurity content, and a doser 17.

The height of the liquid rise in the capillary was measured by a KM-6 cathetometer by using an illuminator with ±0.01-mm accuracy. To do this, grooves were made in the heat insulation and cooler, and the apparatus described in [15] was used to prevent freezing of the bucket. The magnitude of the capillary gap was checked by a BMI-1 instrument microscope with ±0.005-mm measurement accuracy.

The capillary was cleaned in a UN1-0.4-VI ultrasonic bath by a mixture of ethanol and gasoline (1:3) at a 19.5-kHz frequency for 15 min prior to being mounted in the bucket. Before the test started, the working part of the apparatus was rinsed carefully by acetone and ethanol, dried in air at room temperature, and evacuated to a residual pressure not greater than $5 \cdot 10^{-5}$ mm Hg.

The coolant being investigated goes from the tank 19 (Fig. 1) to the cleansing module, is checked for the impurity content (the purity of the coolants used in the tests is presented in the table) and is transmitted to the doser, and is then condensed in the bucket when the nitrogen feeder is switched in, until the capillary turns out to be submerged 1-2 mm in the liquid. The thermocouple measuring the temperature of the coolant liquid phase hence turns out to be submerged to a 2-3-mm depth in the liquid. Measurements were carried out only in stationary temperature modes. The rate of change of the liquid temperature during the experiment was approximately 1 deg/h [16].

The effective edge wetting angle of the capillary structure under consideration was computed by means of the known dependence for a rectangular slot

$$\cos\theta = \frac{h(\rho' - \rho'')\delta g}{2\sigma}. \qquad (2)$$

The maximum error of a single measurement of the angle θ is estimated at 1.5-2%. Graphs of the temperature dependence of the cosine of the effective edge wetting angle by Freon-22, ammonia, and ethane, on a capillary structure are represented in Fig. 2. As should have been expected, the organic heat carriers (ethane

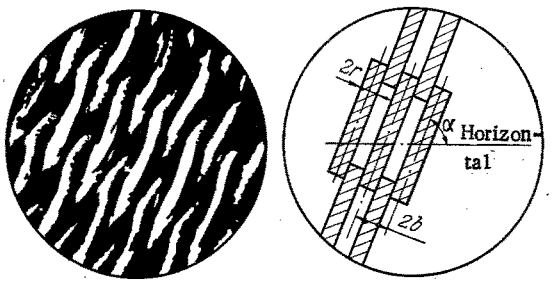

Fig. 3. Twill braided mesh surface and its model.

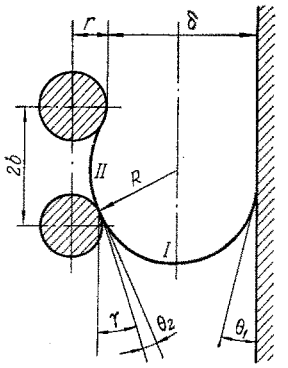

Fig. 4. On the problem of determining the height of the liquid rise in the gap between a plane wall and a mesh.

and Freon-22) wet the capillary structure better than the inorganic (ammonia). Thus, the effective edge wetting angle is θ = 28-34° and θ = 44-23°, respectively, for Freon-22 and ethane when the temperature changes from 0 to −115°C, while the angle θ varies between 25 and 49° for ammonia in the t = 0 to −60°C temperature band. The nature of the dependence $\cos\theta = f(t)$ hence turns out to be different for all three heat carriers, as the working temperature in the heat pipe is lowered, ammonia and Freon-22 wet the structure worse, while ethane on the other hand improves its wetting characteristic.

The effective edge wetting angles obtained refer to conditions when the capillary walls are executed from different materials and are a solid wall (Kh18N10T stainless steel) on the one hand, and a twill braid mesh (nickel NP2) on the other. Let us examine the influence of replacing the solid capillary wall by a mesh on the height of the liquid rise.

The surface of a twill braided mesh is modeled well by a plane layer of cylinders in parallel, whose axes make a certain angle α with the horizontal (Fig. 3). It is easy to conceive that a change in the magnitude of the angle α will result in a change in the effective radius of the cylinders and the spacing between them. Hence, we limit ourselves to a consideration of the case $\alpha = 0°$. Under these conditions, the phenomena of the so-called capillary hysteresis is manifest in full measure, when the capillary system has two stable filling levels: the heights of the rise and the retention. Only the retention level evidently corresponds to the true values of the edge wetting angles.

We provisionally separate the liquid free-surface line into two sections (see sections I and II in Fig. 4) and we solve the ordinary geometric problem. We consequently obtain the following system of equations which is needed to determine the height of the liquid rise:

$$h = \frac{2\sigma}{g(\rho' - \rho'')R},$$
$$R = \frac{\delta + r(1 - \cos\gamma)}{\cos\theta_1 + \cos(\theta_2 + \gamma)}, \qquad (3)$$

$$\sin\gamma = \frac{\sin\theta_2 \sqrt{1+\frac{2r\cos\theta_2}{R}+\frac{r^2-b^2}{R^2}}+\frac{b}{R}\left(\frac{r}{R}+\cos\theta_2\right)}{1+\frac{2r\cos\theta_2}{R}\,\frac{r^2}{R^2}}.$$

An analysis of (3) shows that the height of the liquid rise in the gap between a flat wall and a twill mesh for small values of the edge wetting angle (less than 20°) does not differ in practice from the height of the rise in a gap between two flat walls. The differences can be noticeable for edge wetting angles $\theta > 20°$.

The investigations performed permit extension of the amount of information needed to compute and rationally construct low-temperature heat pipes.

NOTATION

t	is the temperature,
Δp_c	is the capillary head;
θ	is the effective edge wetting angle;
θ_1, θ_2	are the edge wetting angles for a flat wall and mesh;
σ	is the liquid surface tension coefficient;
ρ', ρ''	are the fluid and vapor densities;
g	is the free-fall acceleration;
h	is the height of the capillary rise;
R	is the radius of curvature of the liquid free surface in the capillary;
R_1, R_2	are the least radius of curvature of the meniscus in the heat zone and the greatest radius of curvature of the meniscus in the condensation zone;
r	is the cylinder radius;
b	is half the spacing between the centers of the nearest cylinders;
α	is the slope of the cylinder axis to the horizontal;
γ	is the angle between the tangent to the cylinder and the axis of symmetry;
L	is the cylinder length;
δ	is the gap width between the wall and the mesh.

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COMPRESSIBILITY OF A BINARY MIXTURE OF ARGON AND NITROGEN AT DIFFERENT CONCENTRATIONS IN THE 59-590 BAR PRESSURE RANGE

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UDC 533.21

The compressibility of an argon–nitrogen mixture is measured by a variable volume piezometer. It is shown that the constant in the formula for the binary mixture compressibility depends on the pressure.

The investigation of the compressibility of gas mixtures, which is of great practical value, is associated with the problem of obtaining sufficiently exact and confident semiempirical equations of state. As is known [1], a measure of the cohesive force in the equations of state of a real gas with two parameters which were applied to mixtures is the constant a, which is related to analogous constants for pure gases a_1 and a_2, as well as the constant a_{12} characterizing the collisions between diverse molecules, by the relationship

$$a_M = a_1 x_1^2 + a_2 x_2^2 + 2a_{12} x_1 x_2. \quad (1)$$

Krichevskii and Kazarnovskii [2] proposed an equation of state for binary mixtures which agrees outwardly with (1):

$$Z(T, V) = x_1^2 Z_1(T, V) + x_2^2 Z_2(T, V) + 2x_1 x_2 Z_{12}(T, V), \quad (2)$$

in which Z_{12} is independent of the composition ([3] is devoted to an analysis of this equation).

It is interesting to extend (2) to the compressibility of mixtures

$$Z_M = x_1^2 Z_1 + x_2^2 Z_2 + 2x_1 x_2 Z_{12}, \quad (3)$$

but to consider the quantity Z_{12} as an empirical constant without relating it to some analytical dependence with virial coefficients.

This paper is devoted to the measurement of the compressibility of an argon–nitrogen mixture for different compositions, pressures, and temperatures and to the verification of the possibility of using the relationship (3) to describe mixture compressibility.

The compressibility was measured by a pressure-unloaded piezometer of variable volume with a mercury level search by a gamma radiometer. The mass was measured by directly weighing a definite batch of gas transferred in special stainless steel ampoules with microvalves.

The diagram of the apparatus is shown in Figure 1. The inner tube (D = 14, d = 12 mm) is fabricated from stainless steel and submerged in a thick-walled vessel 2 with mercury. The tube 3 (D = 22.2, d = 15.5 mm) welded to the vessel 2 carries the load under pressure. The thermostatic jacket 4 is heat-insulated by the foam plastic half-rings 5. The inlet for the platinum resistance thermometer 6 is arranged up against the tube 3 in the expanded part of the thermostatic jacket.

The system component to seek the mercury level is constructed as follows. The support slab 7 in the form of a disk is fastened to the outer thick-walled tube 4 of the piezometer at a given height by using bolts not

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