A STUDY CONCERNING THE CHARACTERISTIC OF CAPILLARY-POROUS WICKS FOR LOW-TEMPERATURE HEAT PIPES

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A method is described and results are shown of measuring the characteristics of capillary-porous wicks for heat pipes on a single test stand.

Many studies have been made recently which show the effectiveness of using heat pipes as a solution to various problems in heat transmission, thermostatization, thermal protection, etc., but nevertheless there has been no reliable theory developed yet for the design of heat pipes. The description of heat and mass transfer in some known theories is concerned mainly with the wick characteristics, which indicate the limitations on the heat transmitting capability of a heat pipe.

Such characteristics of porous materials used for wicks are: a) the size (radius) distribution of pores: the integral w(r) and the differential dw/dr, b) the total porosity Π, c) the maximum height of feed h_{max}, d) the permeability as a function of the moisture content K(U), and e) the total permeability of a specimen K.

These characteristics are usually determined experimentally only, by means of various special test devices.

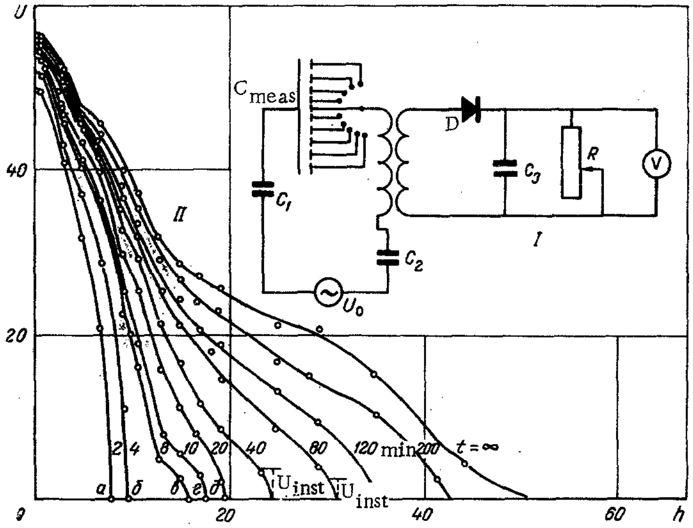

Fig. 1. Schematic diagram of the electrical apparatus for the capacitance method of measuring the moisture content (I); moisture content in a wick as a function of the height, at various instants of time (II).

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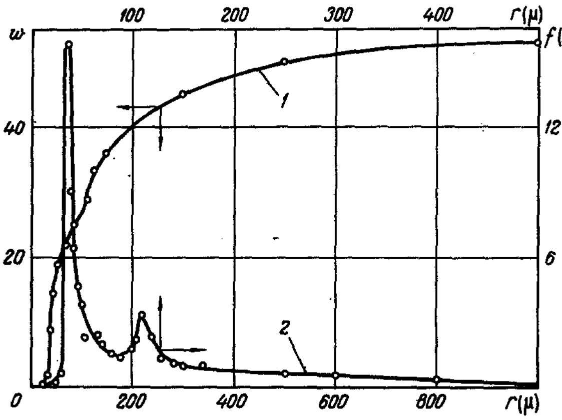

Fig. 2

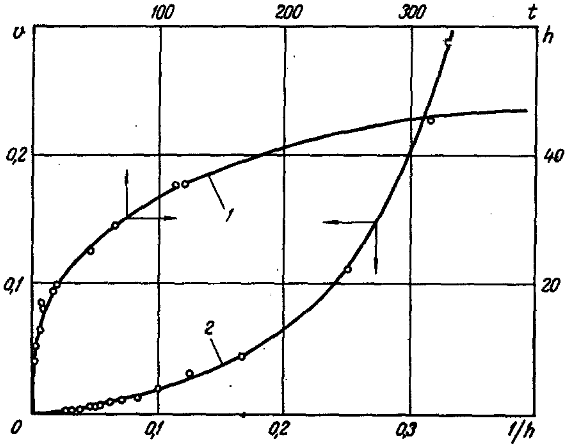

Fig. 3

Fig. 2. Integral (1) and differential (2) size (radius) distribution of pores, w (%).

Fig. 3. Kinetics of the feed front in the capillary-porous wick (1) and velocity of the feed front as a function of the height in this wick (2). Velocity v (cm/sec), time t (min), 1/h (cm^{-1}).

In this article the authors outline a method of calculating the characteristics of capillary-porous wicks from the curves of feed kinetics which have been measured on a single test stand.

The feed kinetics in a capillary-porous wick will be understood here to mean the time variation of the longitudinal moisture-content profile in a wick U(h, t).

The feed kinetics are measured by various methods on the basis of: superhigh-frequency γ-radiation, change in the electrical resistance with changing moisture content, or change in the electrical capacitance with changing moisture content. Our procedure for determining the feed kinetics was based on the use of the electrical capacitance as the measure of the moisture-content field, analogous to the procedure in [1], but with the following modifications. It was not feasible to use two frequencies, because the rate of capillary feed action was especially high at the start. For this reason, the calibration curves were plotted not by calculation, as in [1], but experimentally, somewhat complicating the test series routine but also reducing the error. The calibration was done by drying a porous specimen.

The apparatus is shown schematically in Fig. 1, I. The moisture-content field in porous glass fiber was measured with 18 capacitors, with the specimen in a vertical position. The common plate of all capacitors was a metal cylinder on which glass fiber has been wound. Wire rings (1 mm thick) retaining the glass fiber served also as the second capacitor plates. Such a structure of a porous specimen is analogous to the structure of wicks used for heat pipes and, therefore, this is then a direct method of determining the characteristics of such wicks nondestructively.

The electric circuit (Fig. 1, I) contained capacitors C_1 and C_2, by which the uniformity of the electric field between the plates of each capacitor could be gaged. In order to eliminate the mutual interference between the fields of the capacitors, the high-frequency signal was sent sequentially to each capacitor alone through a stepper switch.

The method of calculating the characteristics of capillary-porous wicks for low-temperature heat pipes is illustrated on the feed kinetics of a grade ASST-b-2 wick (7 layers in 3 mm), measured as shown here.

The U(h, t) curves of feed kinetics for this wick have been plotted in Fig. 1, II.

From the curve which represents the moisture-content profile after the end of the feed process $U(h)_{t=\infty}$ (Fig. 1, II), and by calculation according to the formula in [2]

$$w = U\frac{\gamma_0}{\gamma_*}, \qquad (1)$$

we obtain both the integral and the differential distribution of pores in the capillary-porous wick in a heat pipe (Fig. 2), and these yield the data about the minimum pore radius $r_{min} = 28.4\,\mu$, the mean or the predominant pore radius $r_m = 30\,\mu$, and the porosity $\Pi = 53\%$.

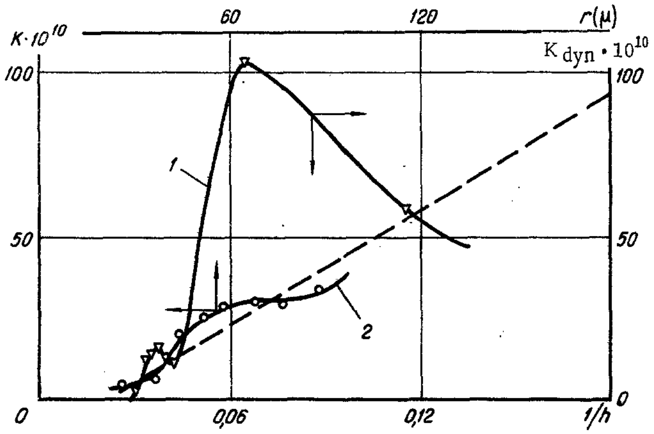

Fig. 4. 1) Dynamic permeability of wick K_{dyn} as a function of the pore radius during feed action; 2) total (integral) permeability $K \cdot 10^{10}$ cm^2 as a function of the pore radius.

The maximum height of capillary feed, according to measurements on the basis of the moisture-content profile (Fig. 1, II), was 52 cm.

Curves representing the kinetics of the feed front in the porous specimen are shown in Fig. 3, plotted from the values of the front height h and the corresponding values of time t in Fig. 1 at points a, b, c, d, etc., and also the rate of front rise as a function of the height. It is to be noted that the $v = f(1/h)$ relation cannot be approximated by a straight line, as is usually done for determining the maximum feed height. The reason for this is that porous specimens of glass fiber have a polycapillary structure.

On the basis of the moisture-content fields (Fig. 1, II) one can determine the dynamic permeability K_{dyn} – an important wick property – which is related to the total permeability K somewhat like the differential size (radius) distribution of pores to the porosity Π. Since we are dealing with feed action here, the dynamic permeability must be treated as the permeability of the base of capillaries which at a given instant of time participate in forming the feed front. On the other hand, K_{dyn} represents a modified version of the capillary conductivity $\varkappa_{\psi}$, which appears in the equation of liquid flow during free feed action [2]:

$$i = \varkappa_{\psi} \nabla \psi. \tag{2}$$

From Darcy's Law one obtains the following equation of liquid flow during free feed action:

$$v = K_{\text{dyn}} \frac{\gamma_*}{\gamma_0} \frac{\frac{2\sigma \cos\theta}{r_{\min}} - h}{\mu h U_{\text{inst}}}, \tag{3}$$

where coefficient K_{dyn} is a function of the height h.

The quantity U_{inst}, the moisture content at height h of the feed front, corresponds to the initial value of each piecewise-constant approximated moisture-content profile in Fig. 1, II. Since the radius of intaking capillaries and the fraction of such capillaries vary according to the size (radius) distribution of pores, hence the relation $K_{dyn} = f(h)$ may have a few maxima. With the aid of Eq. (3), one can then determine this relation.

In Fig. 4 is shown a portion of this curve for our porous specimen.

The application of Darcy's Law to our case is justified on the basis of data available in the technical literature concerning the validity of this law to transient processes [3].

The integral permeability of the specimen can be calculated by graphical integration of the $K_{dyn}(r)$ curve according to the formula

$$K(r) = \frac{1}{r - r_{\min}} \int_{r_{\min}}^{r} K_{\text{dyn}}(r)\, dr. \tag{4}$$

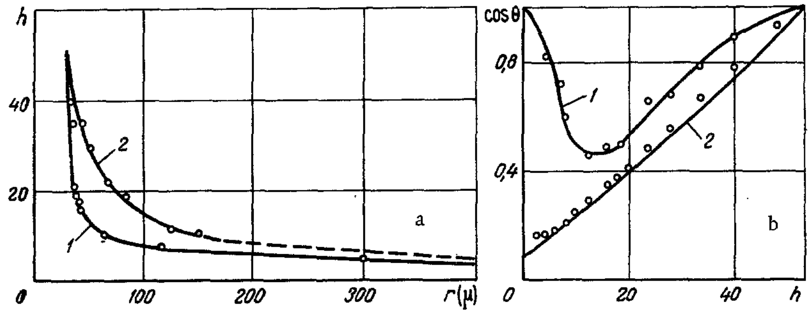

Fig. 5. a) Pore radius as a function of the height, according to the Jourene formula (1); radius of pores forming the feed front, as a function of the height (2). b) Cosine of the wetting angle cos θ as a function of the height during feed action, for a wick of glass fiber (1), according to the formula in [5] (2). Height h (cm).

The shape of this integral permeability curve K(r), a portion of which is shown in Fig. 4, should be analogous to the shape of the curve representing the size (radius) distribution of pores, i.e., $K(r) \to K$ as $r \to r_{max}$, where K denotes the total permeability of a specimen.

In formula (3) there appears the radius r, which is related uniquely to the velocity of the feed front, the radius of the base of capillaries which form the feed front. The relation between such a capillary radius and the front height is shown in Fig. 5a (curve 2), which has been calculated from the same curves of feed kinetics in U(h, t) coordinates (Fig. 1, II).

With the integral pore distribution curve and the final instantaneous moisture content $U_{inst}(h) = N\pi r^2 \Delta h$, one can rather easily determine the radius of capillaries with a given instantaneous moisture content. The characteristic, shown in Fig. 5a (curve 2), is also of interest because it gives some indication about the magnitude of the inrush angle.

Data in the technical literature [4] indicates that the dynamic wetting angle decreases during feed action, i.e., that the cosine of this angle increases. According to calculations in [5], the $\cos\theta = f(h)$ curve is a straight line similar to curve 2 in Fig. 5b. The calculations in [5] are based on the simplified Navier–Stokes equation for capillaries:

$$\cos\theta = \frac{4\mu h}{r(h)\sigma} \cdot \frac{dh}{dt} + \frac{r(h)\, g h \gamma_*}{2\sigma}, \tag{5}$$

with r_{min} in the place of r(h).

Actually, the base radii of capillaries participating in the formation of the feed front vary according to curve 2 in Fig. 5a. Therefore, inserting r(h) into (5) will yield the relation represented by curve 1 in Fig. 5b. Such a trend of the curve is explained by the diversity of pore sizes in a porous body. In capillaries with a large radius the feed velocity is rather high while the feed height is low and, therefore, at the start of feed action the menisci in capillaries forming the feed front are close in shape to those of static menisci.

It is to be noted, in conclusion, that the method shown here is well suited for the determination of necessary characteristics of porous wicks for heat pipes. The characteristics thus obtained can then be used for calculating the heat transmitting capability of a heat pipe.

NOTATION

w	is the volume of pores per unit volume of porous body;
Π	is the porosity;
r	is the radius of pores;
K	is the permeability;
U	is the moisture content;
x	is the space coordinate;
t	is the time;
h	is the height;
γ_0	is the density of dry porous specimen;

γ_*	is the density of the liquid;
μ	is the viscosity;
i	is the mass flow rate;
ψ	is the capillary potential;
v	is the velocity of the feed front;
U_{inst}	is the moisture content (step) at the boundary of the feed front.

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