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Heat Transfer in the Heating Zone of Low-Temperature Heat Pipes

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Reported here are results of an experimental study on the heat-transfer characteristics of liquid evaporation from capillary structures. Thirty-five types of wicks typical for low-temperature heat pipes have been studied. It has been found that at high heat flux densities, there is no liquid boiling in wick structures. Heat is removed by evaporation from a meniscus-free surface and is accompanied by the entrainment of drops of the heat-transfer medium. Critical conditions of capillary structures filled with liquid are studied. It is shown that under the conditions of heat transfer, a complicated deformation of the meniscus profile takes place in capillary structure cells.

Nomenclature

c = constant
d = cell diameter
p = pressure
q = heat flux density
q_L = limiting heat flux density
R = half-width of the cell
R_m = meniscus radius
r = wire radius
ΔT = temperature difference between surface and liquid
Θ = contact angle
φ = angle determining the meniscus location at the wire

Introduction

The mechanism of evaporation and characteristics of heat transfer in wicks of low-temperature heat pipes, including water heat pipes, have not been finally clarified up to now. While considering the mechanism of heat transfer in such pipes (unlike liquid-metal ones) it is assumed that besides evaporation from a meniscus-free surface, the process of the liquid boiling in the wick is possible at high heat flux densities. That is why the first critical heat flux in boiling is accepted as limiting for heat removal in low-temperature heat pipes by analogy with pool boiling.[1,2]

The character of heat-transfer coefficient dependence on heat flux density is considered as an indirect confirmation of the existence of boiling in wicks of low-temperature heat pipes, because the dependence is similar to that for heat-transfer coefficients in nucleate boiling on pure heating surfaces.[3,4]

Experimental Apparatus

This paper presents experimental study results on the mechanism of evaporation and heat-transfer characteristics for wicks of capillary-porous structure in low-temperature heat pipes.

The tests have been carried out on an experimental apparatus with the copper thermal wedge as the test element, simulating the zone of evaporation in the heat pipe (Fig. 1). The wedge end (28-mm diam.) served as a heat-transfer surface to which the capillary structure under study was tightly pressed. The liquid level in the chamber was maintained at 1-2 mm below the heat-transfer surface level, the boundary contour of the wick being completely flooded by the liquid. Thus the cooling liquid was supplied to the heating surface by capillary forces.

The liquid temperature corresponded to that of saturation at the given pressure. Heat flux density and heat-transfer surface temperature have been determined by the temperature gradient along the wedge body. Heat flux density at the wedge end could reach 1500 kW/m^2. The experimental vessel was provided with sight windows with double quartz glasses for visual observations, filming, and photographing. (Hot air was supplied into the gap between the glasses to avoid misting.) The tests were made with distilled water within the pressure range 0.05-0.4 MPa, and with butanol, n-heptane, benzole, and acetone at atmospheric pressure.

The capillary structures in the form of a metallic mesh with a cell size 0.04-1.8 mm, perforated plates, and copper felt (35 wick types) were studied. Characteristics of some types of structures are shown in Table 1. Further in the text only the structure number according to Table 1 will be mentioned. The wire meshes were annealed before the test and then etched with nitric acid to remove the oxide film and create artificial microroughness on the wire surface which improves the structure wettability.

It should be noted that using a cylindrical geometry for the heater introduces certain peculiarities into the heat-transfer

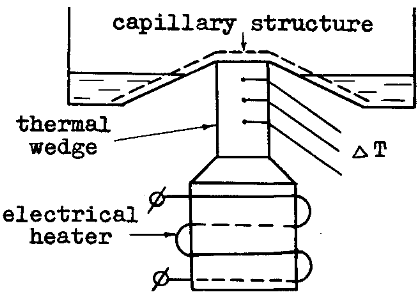

Fig. 1 Experimental apparatus.

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Table 1 Characteristics of capillary structures

Structure No.	Material	Inside size of cell, mm	Wire diam. or thickness of plate, mm	Surface porosity	Notes
1	Brass	0.08×0.08	0.05	0.38	Wire mesh
2	Brass	0.20×0.21	0.125	0.385	"
3	Nickel	0.20×0.24	0.1	0.48	"
4	Steel	0.36×0.41	0.19	0.45	"
5	Brass	0.40×0.40	0.15	0.53	"
6	Stainless steel	0.49×0.42	0.25	0.415	"
7	Brass	0.51×0.54	0.22	0.50	"
8	Brass	0.58×0.58	0.14	0.65	"
9	Brass	0.82×0.82	0.30	0.53	"
10	Brass	1×1	0.30	0.59	"
11	Steel	1.8×1.8	0.33	0.71	"
12	Copper	d=0.085	0.04	0.80	Copper felt 0.5 mm thick
13	Nickel	d=0.5	0.05	0.48	Perforated plate laid with a clearance of 0.2 mm from the heating surface
14	Nickel	d=0.7	0.05	0.575	"

process with regard to real heat pipes. It is evident, however, that the qualitative trends of the results obtained apply to them as well.

Results and Discussion

Direct visual observations of the heat removal process from the porous sample surfaces have shown that there is no boiling in the pores of capillary structures, but there is only liquid evaporation in capillaries from meniscus surfaces. Thus, even at a pressure of 0.02 MPa and a heat flux density of 600 kW/m^2, vapor bubbles are not formed at the wick surface (naturally on those wicks where this heat flux density can be achieved). Boiling was not observed either in the case of mesh structures or those made of copper felt or perforated plates.

This fact can be explained by the following reasons:

1) Formation of very thin, indestructible (due to the stabilizing action of surface tension forces) liquid films in the middle part of the meniscus and the resulting high intensity of heat removal.

2) Large temperature gradient in the thermal boundary-layer of the liquid in the zone of evaporating meniscus which hampers activation of nucleation sites.

3) High effective thermal conductivity of the system liquid-metallic framework of the structure (for instance, the coefficient of effective thermal conductivity as calculated in accordance with Ref. 5 is 27 W/mK for wire mesh No. 10) which facilitates intensive heat removal from the heating surface to the structure framework components and then to the adjacent liquid layers.

Heat is removed from the heating surface not only at the expense of thermal conduction through the liquid film but also by convection caused by the liquid motion in the cell.

At low heat flux densities due to the small evaporating liquid flow rate, there is practically no deepening of the phase interface in the capillary structure cell and no chance for microlayer formation. In multilayer network structures, the microlayer formation is also hampered by the considerable thickness of the wick and, therefore, is possible only under the conditions of upper-layer dryout. Thus, under similar conditions, the liquid film thickness in capillaries can be large enough so that conditions for the activation of individual nucelation sites can arise. This phenomenon can, in particular, explain the fact that with the wick thickness growth the limiting heat flux density decreases sharply, which obviously can be attributed to the boiling of the liquid.

Figures 2 and 3 present the results of our experiments on heat transfer in capillary structures saturated with water and organic liquids. It is evident from Fig. 2 that the mean heat removal intensity at evaporation from the wicks differs from that observed in pool boiling on the surface without capillary coating.

Heat transfer in boiling is realized mainly by evaporation into vapor bubbles disposed randomly at the heating surface. The integral intensity of heat transfer in this case is described by the exponential function of the form $q=C\Delta T^n$, where $n=3.3$. For heat removal from the heating surface by liquid evaporation in the wick, all elementary cells of the capillary structure operate under stable conditions forming a continuous system of evaporating menisci. It is known that temperature gradients at the liquid-vapor interface are small during evaporation and depend weakly on heat flux density. Consequently, the power exponent n in this case should be larger than in nucleate boiling. Indeed, experiments have shown that the value of n at evaporation from the wicks is 3.3 ± 1.0 depending on the structure type, the kind of liquid, and pressure (Figs. 2 and 3).

The decrease in heat-transfer intensity can be caused, in some cases, by two reasons. When insufficient cooling liquid is supplied to the structure cells (deficiency of useful capillary head), and at certain values of heat flux density, a heat-transfer intensity decrease takes place which can be attributed to denuding the most remote central cells. A dry spot appears in the center of the the thermal wedge and grows with the further increase of heat load (the moment of dry spot occurrence is indicated by arrows (↘) in Figs. 2 and 3). By increasing the liquid inflow at the expense of decrease of the structure hydraulic resistance (creation of larger arterial gaps), one can retard the onset of the lowering of the heat-transfer coefficient to higher heat loads. In this case, however, the possibility of liquid flashing in arteries, i.e., earlier occurrence of crisis phenomena should be taken into account. Hence the correct choice of these gap sizes defines, in a certain respect, the effectivenss of heat pipe operation.

For wicks with a larger useful capillary head, i.e., with no capillary limitations, some decrease of heat transfer before the crisis is observed. In this case it is connected with the fact that at some points the wick is insufficiently pressed tightly to the heat-transfer surface. At these points, zones with poor heat transfer appear at lower heat loads than for the whole structure which causes a decrease of mean heat-transfer intensity with respect to the surface.

Formation and size increase with heat load growth of the local zones with poor heat transfer can lead to the fact that the degree of q dependence on ΔT would prove to be below 3.3. This ought to be especially pronounced in cases of an

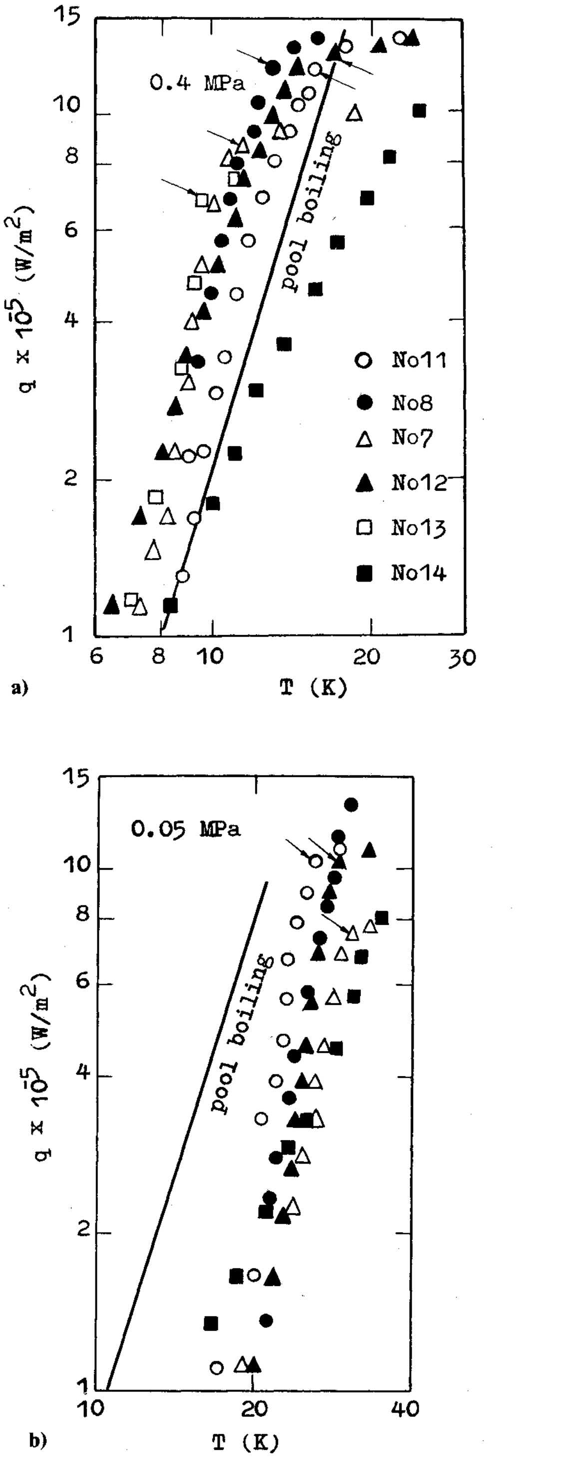

Fig. 2 Heat transfer by water evaporation from single-layer capillary structure.

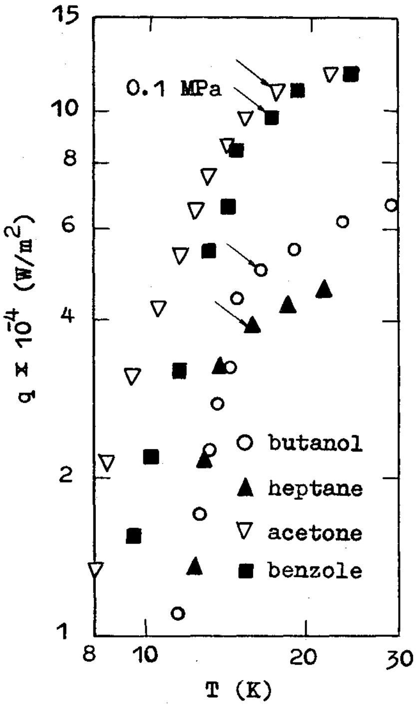

Fig. 3 Heat transfer by organic liquid evaporation from a capillary structure made of a single layer of no. 1 wire mesh.

evaporator with large dimensions. A similar effect can be observed in our tests (Fig. 2).

As to their absolute values, heat-transfer intensities at evaporation are close to those in boiling, only at a pressure of 0.2 MPa. They are lower in vacuum and, at pressures above 0.2 MPa, higher than in boiling.

It has been found in our experiments that the process of evaporation from meniscus-free surfaces in capillary structures is accompanied by liquid drop removal. Under these conditions, liquid removal is attributed to the irregularity of thermal and hydrodynamic conditions at the heating surface (the mechanism of this effect is described in detail in Ref. 6).

In the case of intensive liquid spraying, the evaporation process looks like boiling, especially for multilayer wire net wicks. Some of the drops thrown out fall back from the stream flow, deposit on the wick surface, and form a liquid film over the meniscus surface due to which bubble formation can be observed in these locations over the wick external surface. After the destruction of these bubbles, new ones can appear, sometimes at the same points but at arbitrary (sometimes greater) time intervals. Here it should be pointed out that the dimensions of such bubbles are almost independent of pressure within the range under study. However, even for the most intensive spraying, when due to the abundance of liquid thrown away and then falling back from the stream flow, a small, moving vapor-liquid pimple can appear at the meniscus surface, the cells with free menisci can still be observed.

While studying the process of liquid spraying, it has been established that it decreases with pressure growth and is practically absent already at $p=0.4$ MPa. Visually, the evaporation process is hardly like boiling. This confirms once more that there is no boiling in capillary structure pores, since pressure growth would, otherwise, be accompanied by increasing the number of active nucleation sites and hence the spraying intensity connected with vapor bubble breakdown.

Liquid-drop removal causes liquid deficiency in the wick, i.e., earlier occurrence of dry spots in proportion to the average heat-transfer intensity with respect to the surface.

The dependence of the limiting heat flux density on pressure for some wick types is shown in Fig. 4. The dependence of critical heat flux density in boiling on a pure (without capillary coating) heating surface is also plotted. It is seen from the figure that with increasing pressure, q_L decreases, unlike the behavior of critical heat flux density in pool boiling.

While carrying out the tests with water for some wire mesh and metal fiber structures, limiting heat flux densities have not been achieved since they proved to be higher than the value of maximum heat load achieved by the apparatus used. However, for these structures the deficiency of useful capillary head for cooling liquid transport into the heating zone at large heat flux densities is characteristic. This

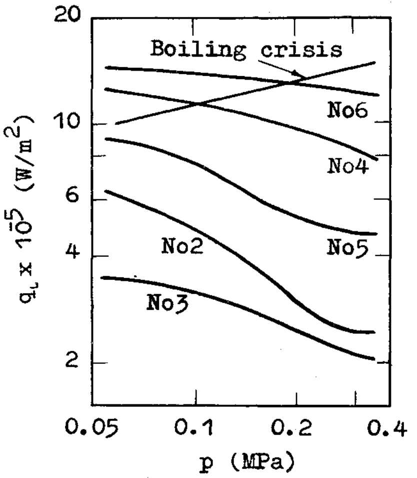

Fig. 4 Limiting heat flux density vs pressure for water-saturated structures.

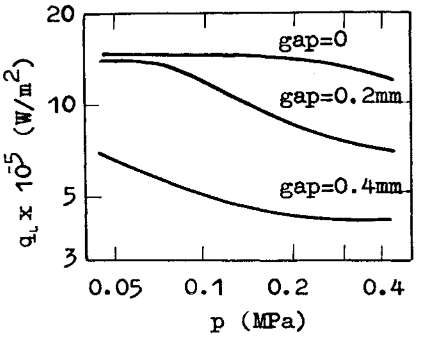

Fig. 5 Limiting heat flux density vs the value of the gap between heat-transfer surface and no. 8 wire mesh.

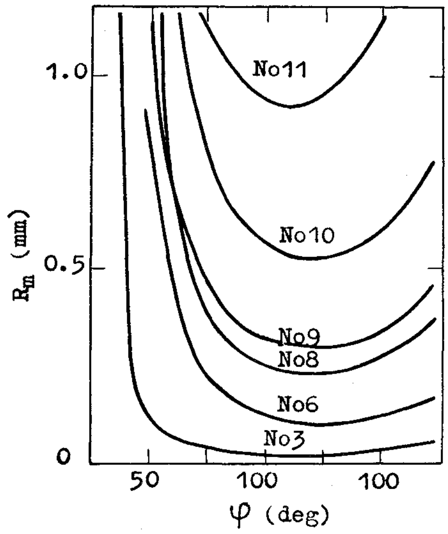

Fig. 6 Meniscus radius vs angle φ.

deficiency manifests itself in the drying of central cells which are most remote from the location of liquid supply. The dry-spot occurrence, as it has been pointed out previously, is accompanied by the decrease of average heat-transfer intensity (Fig. 2), which allows determination with sufficient accuracy of the limit of capillary receptivity of the studied structure under the working conditions. For the organic liquids having been investigated, the limiting heat flux is usually restricted by the capillary head due to small values of surface tension and low latent heat of evaporation.

It has been found that an increase of arterial gap between the heat-transfer surface and the capillary structure for cooling liquid passage results in the decrease of limiting heat flux densities which is illustrated in Fig. 5.

Liquid-drop removal brings about the fact that a part of the useful capillary head, created by the structure, is consumed for transport of the liquid which is then thrown away from the wick without evaporation. Thus the occurrence of spraying is equivalent to the decrease of the heat flux being transferred, i.e., at the expense of intensive liquid-drop removal, such conditions may be created where the wick would be dried out with pressure decrease earlier than at greater pressures, in spite of the capillary head growth because of the surface tension increase. This effect could be observed in a number of experiments; however, for most of the capillary structures saturated with water, q_L increases with pressure decrease or at least depends weakly on the latter (Fig. 4).

It is known that for liquid-metallic heat pipes, the limiting heat flux density increase with pressure growth is characteristic,[7] which can be explained by intensive liquid drop removal in the low pressures of saturation, i.e., in the region where they operate.

While designing actual heat pipes, it should be taken into account that due to liquid-drop removal, the limiting heat flux density can be influenced by spatial orientation of the heat pipe evaporator.

To find out the reasons for the drying of heat pipe wicks, it is necessary to consider the character of mensicus radius changes. As has been shown in Ref. 6, the meniscus radius depends not only on the structure geometry, the liquid physical properties, and the heating surface, but also on the degree of deepening of the meniscus into the cell (i.e., on φ angle):

$$R_m = \frac{R + r(1 - \sin\varphi)}{\sin(\varphi - \Theta)} \tag{1}$$

Depending on the angle φ value, the meniscus surface under the isothermal conditions can, generally speaking, be convex ($\varphi < \Theta$), flat ($\varphi = \Theta$), or concave ($\varphi > \Theta$). Under the actual conditions, the upper part of the wire is bare. For the meniscus surface to be convex, fluid head at the wick periphery is required. Dependence of the meniscus radius on angle φ for some types of network wicks is presented in Fig. 6 as calculated by Eq. (1).

Under the conditions of heat transfer, the meniscus begins to deepen into the cell due to liquid deficiency as the heat flux density increases. The meniscus radius is decreasing while the capillary head is growing. Increased inflow of the cooling liquid is taking place which compensates for heat flux density growth. Thus, a certain value of R_m would correspond to a certain value of q. At further q growth (hence, angle φ growth), there ensues a moment when the meniscus radius is the least, after which q growth is accompanied by R_m growth and then by capillary head decrease. This eventually leads to drying out the wick cells because of insufficient capillary head. This is one of the reasons for crisis phenomena in the wicks and the destruction of heat pipes (the other reason is, as has been mentioned previously, heat transfer medium flashing in the structures).

Generally speaking, Eq. (1) in the pure form is applicable only for toroidal pores and, to a certain extent, for perforated plates where the hole edges are rounded due to technological requirements. In the simplest network structures, the meniscus profile is more complicated and its mathematical description is rather difficult. For this reason, Eq. (1) is applied only for qualitative description.

There is also a considerable uncertainty in determining the cross section of arterial channels supplying the cooling liquid for calculating hydraulic resistance of the structure. The cross

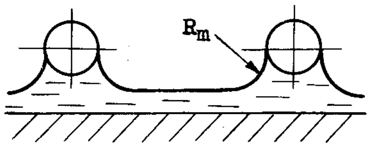

Fig. 7 Meniscus profile in the capillary structure cell.

section of the channel formed by the liquid near the wires depends not only on the wire diameter but also on the meniscus radius. This cross section decreases with the approach of the wires to the heat-transfer surface at the weave node. For multilayer wire mesh structures, this uncertainty is not so significant. But multilayer wicks should operate in the regime of upper-layer drying, otherwise, boiling of the heat-transfer medium would take place in them.

In wicks, deepening of the meniscus into the pore can lead to the fact that at some moment it will touch the heat-transfer surface. Approximate calculation based on Eq. (1) has shown that for wicks with a cell size more than 0.5 mm, the meniscus should touch the surface before it reaches its minimum radius. However at the weave nodes this touching would take place even earlier. At the moment of touching, the capillary head developed by the structure is lower than that necessary for the cooling liquid transport at certain heat flux densities achieved in these wicks.

On the basis of the experimental data obtained, one can suppose that, in the pore of the capillary structure, the meniscus is of the form shown in Fig. 7. The thin film in the middle part of the meniscus is stabilized by the surface tension forces. It is seen from the figure that the meniscus radius creating the capillary structure is less in this case than the pore size and depends substantially on the warp wire diameter.

Wire meshes with greater cell size are ineffective since they have a very low useful capillary head because of high hydraulic resistance to the liquid flow. If the wire mesh is laid on the surface with a gap or in several layers then the useful head grows but there are no conditions for forming a thin film at the cell bottom, hence, the liquid will boil in such wicks. This would immediately lead to their drying out. Proceeding from the above, it becomes clear why it was impossible to remove large heat flux densities in modern low-temperature heat pipes with multilayer wicks made from fine wire mesh.

Conclusions

In conclusion it may be said that:

1) Heat removal in heat pipes is realized by way of liquid evaporation from menisci-free surfaces formed in capillary structure cells.

2) Evaporation from the meniscus-free surface is accompanied by liquid-drop removal.

3) The meniscus radius formed in capillary structure cells depends not only on wick geometry, liquid physical properties, and the warp material, but also on heat flux density.

4) Crisis phenomena in heat pipe wicks are connected with the boiling of liquid or with the meniscus radius transition through its minimum value during heat flux density increase.

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