RESULTS OF INVESTIGATING THE MECHANISM OF VAPOR-FORMING PROCESSES RELATING TO WICKS OF LOW-TEMPERATURE HEAT PIPES

V. A. Antonenko and G. R. Kudritskii

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The authors have studied the laws of the heat transfer mechanism in boiling in mesh heat pipe wicks. It is shown that at high heat flux density in the precrisis regime one can stop bubble boiling with transition to evaporation from the surfaces of the menisci.

This paper presents results of an experimental study of the mechanism of the vapor forming process in conditions typical of the wicks of the heating zone of low-temperature heat pipes. As test wicks we chose mesh structures, since they are at present more widely used in industry for heat pipe manufacture. This is due not only to the high technology of mesh wicks, but also to their considerable uniformity, which ensures constancy of heat transfer characteristics of heat pipes in each series. Wicks based on other methods find very limited use (mainly in special purpose heat pipes).

The concept of evaporating a liquid from the free surface of menisci formed in the pores of wicks, as the governing mechanism in the heater zone of liquid—metal heat pipes is conventional [1]. In regard to low-temperature heat pipes opinions vary: the view is expressed that bubble boiling may occur in their wicks right up to the critical heat flux. The correctness of this approach is not self-evident since vapor formation in capillary structures has a number of special features which sometimes present its being considered as bubble boiling in the usual concept of the process. Observations at high heat flux density in [2], and, what is particularly important, at pressures below atmospheric (in a region typical of heat pipe operation) indicate the existence of a purely evaporative regime of vapor formation, not only at low, but also at high heat flux density in the precrisis regime.

The aim of the present paper is to improve our knowledge of the mechanism of the vapor generation process in the wicks of low-temperature heat pipes. The investigation is based on the generally known fact that there are characteristic temperature fluctuations of the heater surface under the action of vapor-generating centers in liquid boiling [3].

To analyze the processes occurring in vapor formation in heat pipe wicks it is appropriate to compare curves of heater surface temperature fluctuations in boiling with analogous curves under the cells of wicks of the heater zone of a heat pipe, taking account of a visual picture of the process. This has determined the method and the experimental technique, to accomplish which we have introduced:

— recording to heater surface temperature fluctuations under one cell of the wick mesh and comparison with temperature fluctuations of the same surface filled with liquid and without the mesh cover;

— taking data on heat transfer intensity and critical heat flux under conditions typical of an individual cell of the mesh wick;

— visual observations of the behavior of the liquid with vapor generation in an individual cell of the mesh wick.

To accomplish the required temperature measurements and duration of visual observation we used the method of local heating of part of the surface directly under one wick cell.

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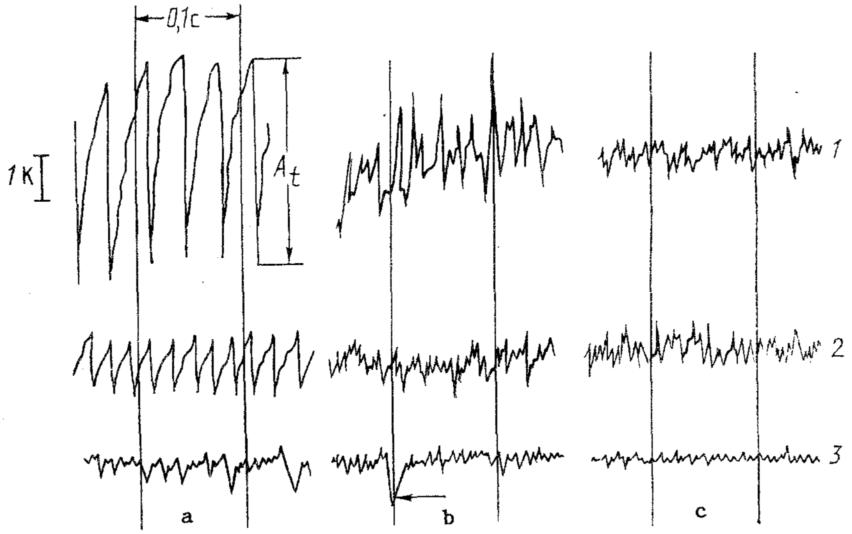

Fig. 1. Oscillograms of heater surface temperature fluctuations under a wick made of 1 mesh layer with $a = 1$ mm (water, pressure 0.1 MN/m^2) (1) free surface, 2) immersed mesh; 3) capillary make-up), for heat liberation densities referred to the transverse section of the heat supply unit: a) 470 kW/m^2; b) 1500; c) 4200.

The tests were carried out on an equipment whose working section is a thermal wedge with a heat supply diameter (a copel rod) equal to that of the mesh cell or somewhat larger. The copel rod was attached by contact welding to a permalloy membrane of thickness 0.03-0.05 mm, sealing the inner volume of the working chamber (a detailed description of the equipment was given in [4]). The construction of the equipment allowed recording to the temperature fluctuations of the heater surface. The mesh was positioned on the membrane surface such that the center of one cell contacted the center of the heat supply unit.

As working liquids we used: distilled water in the pressure range $p = 0.02\text{-}0.2$ MN/m^2, and acetone and ethanol at a pressure of 0.1 N/m^2. The wicks were made of one, two or three layers of metal mesh (brass and stainless steel) with a cell inside dimension a of from 0.2 to 2.5 mm (type GOST 3584-74).

The tests began with an investigation of the laws of flow of the process of vapor formation on a surface free from mesh covering (called a free surface in the text below), positioned in a large volume of liquid. Then on this same surface we laid a mesh wick (called an immersed mesh wick in the text) and the tests were conducted with a large volume of liquid. Thereafter the liquid level in the chamber was decreased and the tests were conducted under conditions of capillary make-up of the mesh wick (called capillary make-up in the text below).

Figure 1 shows typical oscillograms of heat surface temperature fluctuations. On the free surface (Fig. 1, *1*) we observed temperature fluctuations typical of boiling, associated with growth and separation of vapor bubbles and analogous to those observed earlier [5-7]. The temperature fluctuations of the immersed mesh (Fig. 1, *2*) have the same shape as those typical of boiling, but are of smaller magnitude (the causes of reduced magnitude of surface temperature fluctuations in these conditions were explained in [8]).

The heater surface temperature fluctuations for capillary make-up at low heat flux densities resemble those typical for the free surface case (Fig. 1, *3*, *a*). However, with increase of heat flux density the picture changes appreciably: the amplitude of the fluctuations drops sharply, and their frequency increases. For heat flux densities on the order of 2 MW/m^2 the fluctuations are so small that they do not exceed the noise due to the thermocouple amplifier used in our tests (the amplifier noise is on the order of 0.2 K). One should at once stress that in the regime where a single wick cell is heated the critical heat flux densities considerably exceed the levels observed when all the wick cells were heated. The reasons for this were explained in [7]. Thus, one may only qualitatively transfer the results obtained to real extended surfaces.

On the whole, as the tests have shown, under the capillary make-up conditions of the mesh wick five vapor-generation regimes can exist in stable manner.

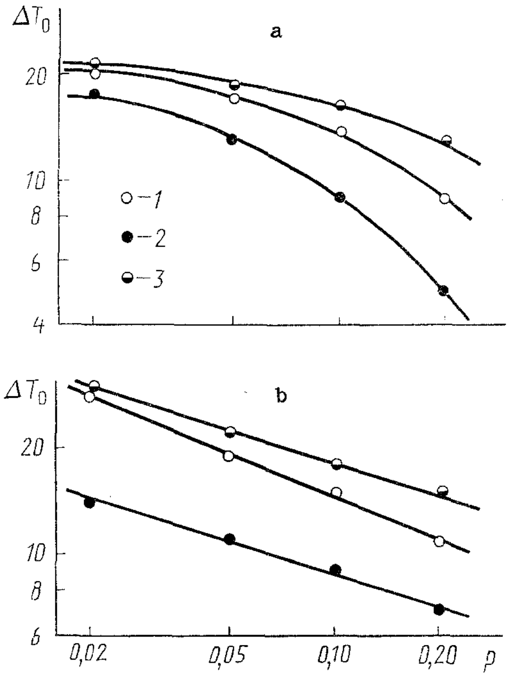

Fig. 2. Dependence of the temperature head at the onset of boiling of (a) water and (b) ethanol on pressure: 1) free surface, (2) immersed wick, 1 mesh layer $a = 1$ mm; 3) capillary make-up, 1 layer of mesh $a = 1$ mm. The quantity ΔT_0 is in K, and p is in MN/m^2.

Regime I is observed at low values of heat flux density and is characterized by the absence of boiling. The heat from the heater surface is transferred via a layer of liquid at the bottom part of the meniscus. Evaporation of the heat transfer agent occurs from the meniscus surface.

The intensity of heat transfer in this regime exceeds that for the immersed surfaces both with the mesh layer and without it. This is due to the small thermal resistance of the thin liquid layer at the bottom part of the meniscus and to an increase of the evaporation surface (due to the meniscus surface being covered by surface tension forces).

Regime II is characterized by the presence of bubble boiling in the cell of the mesh wick, confirmed both by visual observations and by the nature of the temperature fluctuations of the heater surface, analogous to the fluctuations in the free surface case. As was shown by the tests (Fig. 2) for capillary make-up the temperature heads ΔT_0^b corresponding to the start of liquid boiling for thin mesh wicks (thickness up to three layers) considerably exceed the values ΔT_0 observed for the free surface case. However, for the immersed wicks (Fig. 2) there is a sharp decrease of ΔT_0 compared with the free surface case. While the latter result agrees well with conventional ideas [9, 10] and was analyzed in [8], the first result requires explanation.

In the bottom part of the meniscus there is a thin cell of liquid whose thickness depends on three parameters: the wick thickness δ, the geometric dimensions of the cell of the mesh itself a and d, and the height of the capillary rise of liquid H along the wick. It is known [3] that because of the specific conditions for forming the thermal boundary layer, boiling in thin liquid films can begin at larger values of ΔT_0 and q_0 than in a large volume. Thus, delay of the time of the onset of boiling in thin wicks can be explained by formation of thin liquid films at the bottom part of the meniscus.

An increase of the liquid film thickness at the bottom part of the meniscus, due both to thickening of the wick and increased mesh size, causes thickening of the thermal boundary layer and a consequent decrease of ΔT_0^b [3] (Fig. 3, I and II). An increase of the height of the capillary liquid rise along the wick leads to thinning of the liquid film at the bottom part of the meniscus (the menisci in the cell deepen, accompanied by an increase of the capillary head [10]), and consequently, to an increase of ΔT_0^b (Fig. 3, III).

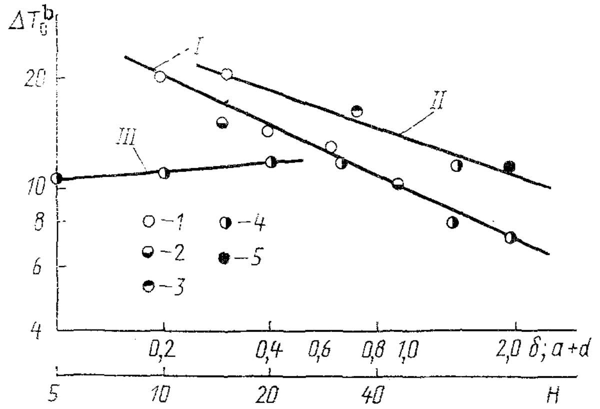

Fig. 3. Influence of wick thickness (I), size of the mesh cell (II), and height of the capillary rise (III) on $\Delta T_0{}^b$ (water, pressure 0.1 MN/m^2): I) 1-3 mesh layers; II, III) 1 mesh layer; 1) $a = 0.2$ mm; 2) 0.4; 3) 0.5; 4) 1; 5) 1.5 mm. $\Delta T_0{}^b$, K; δ, $a + d$, H, mm.

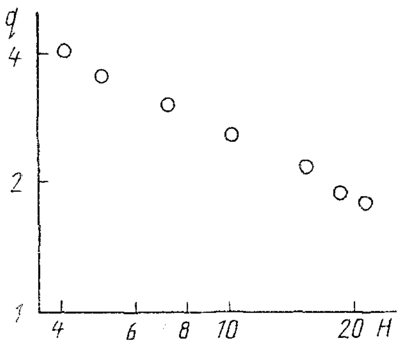

Fig. 4

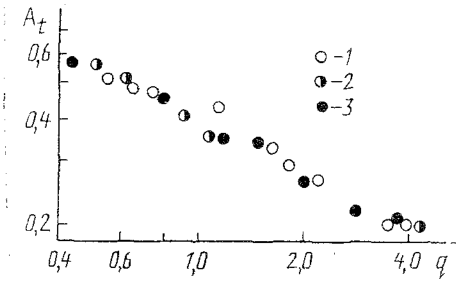

Fig. 5

Fig. 4. Influence of capillary rise height of water along the wick, made of 1 layer of mesh with $a = 1$ mm, on the heat flux corresponding to the start of regime III of vapor generation (pressure is 0.1 MN/m^2). The quantity q is in MW/m^2.

Fig. 5. Influence of roughness of the heater surface under the wick (1 mesh layer, with $a = 1$ mm) on the quantity A_t (water, pressure of 0.1 MN/m^2): 1) surface polished with GOI paste; 2) surface formed by coarse emery paper; 3) surface with artificial vapor generating centers formed by needle pricks. A_t is in K.

A characteristic special feature of boiling in conditions of capillary make-up of the wick is the independence of $\Delta T_0{}^b$ of processing of the heater surface (the difference of $\Delta T_0{}^b$ for two extreme cases, polished and pitted surfaces is only tenths of a degree). This confirms again the conclusions of [3, 12] that activation of vapor-generating centers in thin films depends to a lesser degree on the heater surface roughness than in large volume conditions.

The onset of regime III is characterized by the disappearance of the vapor bubbles above the heated wick cell, i.e., essentially a halt to bubble boiling. In this regime there is constantly a dry spot at the center of the cell, and liquid drops are thrown out from its boundaries. The dry spot was observed clearly with the aid of a dioptric tube giving 12-fold magnification of the observed object.

As the height of the capillary rise H of liquid along the wick increases the third regime sets in, with decreasing heat flux (Fig. 4). In a number of cases (for large H) the second regime may be missing (e.g., for a mesh $a = 0.5$ mm with $H = 20$ mm bubble boiling was not seen in the wick, although it occurred for $H = 5$ mm). This effect is associated with the generally known that when the liquid film thickness decreases, the thin film separates and a dry spot forms within it, leading to a decrease of heat flux density (as was noted above, the film thickness at the bottom part of the meniscus is inversely proportional to H).

In regime III we observe intense ejection of liquid drops from the wick cells, due to causes other than breakdown of vapor bubbles (in contrast with regime II).

The liquid flows to the dry spot at the cell center (according to the scheme described in [11]), and as a result the vapor flux formed removes liquid drops from the edge of the flowing film. There is practically always ejection of liquid drops in this regime from the central part of the cell, as indicated by the visual observations made with the aid of the magnifier. The increase of heat flux leads to an increased intensity of ejection of liquid drops and their contraction due to the increased speed of vapor in the cell. However, an increase of q is accompanied also by thinning of the liquid film at the bottom part of the meniscus [11], and this makes it difficult to remove drops from the edge of the flowing film. Under specific conditions (depending on the properties of the liquid and the wick geometry) a second factor begins to predominate, and consequently for certain values of q the removal of drops ceases, as was noted earlier in [11, 13].

Regime IV, usually observed at high heat flux density, exceeding the heat transfer crisis, is of great interest. In this regime the dry spot at the cell center vanishes, the ejection of drops decreases to a minimum (at pressures above 0.1 MN/m^2 it vanishes completely), and heat transfer is accomplished by evaporation of liquid from the meniscus surface.

It should be noted that both effects accompanying regime four were established earlier on extended surfaces: cessation of drop removal in [11, 13, 14], and wetting of the dry spot, in [15].

The reason for the dry spot at the cell center vanishing is not yet clear, since at the moment of transition to regime IV we did not notice any significant qualitative changes on the oscilloscope screen in the nature of the heater surface temperature fluctuations.

If we assume that at the moment the dry spot vanishes the film thickness at the bottom of the cell for all the liquids investigated is less than 10 μm (these thicknesses are calculated, averaged over the surface, and equal to the ratio of the thermal conductivity of the liquid to the heat transfer coefficient), then the hypothesis is fully justified that wetting of the dry spot is promoted by intermolecular interaction forces, which become very considerable for such film thicknesses [16].

Besides the two main signs (absence of visible bubble boiling in the thin film at the bottom of the cell, and absence of drop removal) regime IV is characterized also by a number of special features. The heater surface temperature fluctuations in this regime differ in character and magnitude from those observed in bubble boiling (see Fig. 1). They practically cannot be distinguished from the noise created by the thermocouple amplifier.

It is known [3] that in the case of bubble boiling the magnitude of the heater surface temperature fluctuations A_t depends strongly on the heater surface processing, which is associated with change of the geometric dimensions of the indentations — the vapor generating centers. With capillary make-up and large heat flux density the value of A_t does not depend on the heater surface roughness (Fig. 5).

It was also noted that this regime is characterized by absence of scale on the heater surface even when conducting water is used as a heat transfer agent. After the equipment was operated for 30 h there was no scale coating, while for lesser heat flux, corresponding to regime II (and also on a surface without a mesh layer), a dense layer of scale was formed even after 3-5 h of operation with conducting water.

All the above mentioned facts indicate that there is no boiling in the cells of wicks with mesh at large heat flux density (the fourth vapor-generating regime), that heat from the heater surface is removed by heat conduction through a thin film of liquid at the bottom of the cell, and then due to evaporation from its surface.

Of course, one should expect roughly similar values and similar nature of heater surface temperature fluctuations in the case of a sharp increase of the number of active vapor-generating centers. However, from the standpoint of contemporary ideas of the physics of boiling one cannot explain the cause of this excess activation of vapor-generating centers in difficult thermal conditions (because of the high heat transfer intensity the surface temperature is lower, and the thermal boundary layer is thinner than on a surface without a mesh covering). Here one should exclude from consideration the special conditions which can arise in places where the base wires are interwoven. Tests conducted both with heated and unheated interwoven nodes (this was achieved by varying the diameter of the heat supply unit) did not establish any substantial difference in the flow of the vapor generation process. In addition, the sharp activation of the excess number of vapor generating centers does not explain the remaining special features in the flow of the vapor formation process in regime IV.

Regime V of vapor generation is characterized by complete drying out of the wick cells and is accompanied by a sharp increase of the heater surface temperature. The onset of this regime is assumed to be linked to the heat removal crisis on surfaces with a porous covering, although from the physical standpoint this crisis differs from that which occurs on an immersed surface without a covering and is due to the lack of a capillary head [11].

It should be noted that the limiting heat flux densities achieved in the tests with heating of only one wick cell exceeded 5-6 MW/m^2, which is significantly greater (by a factor of 2-3) than those observed on extended surfaces with analogous mesh coverings. This kind of increase of the limiting fluxes is evidently due to the fact that in this case the conditions for making up the liquid of the evaporating meniscus are facilitated to the maximum extent (at any heat flux density the adjoining unheated cells are practically fully immersed in liquid). Thus, the heat fluxes obtained under conditions with only one cell heated are the limiting values attainable with porous structures. In this work limiting heat fluxes were not studied specially, since at heat flux densities on the order of 6 MW/m^2 there is melting of the working section heater.

Thus, the results of this investigation indicate that under conditions characteristic for the wicks of heat pipes at large heat flux density (in the pre-crisis regime) bubble boiling ceases, and heat from the heater surface is transferred by evaporation at the free surface of the menisci.

NOTATION

A_t, amplitude of heater surface temperature fluctuations; a, inside dimension of a cell; d, diameter of the mesh wire; q, heat flux density; q_0, heat flux density at which boiling begins on a smooth surface; H, height of liquid rise on the wick; ΔT_0, $\Delta T_0{}^b$, temperature head at which boiling beings, respectively, on a smooth surface located in a large volume of liquid, and in conditions of capillary make-up.

LITERATURE CITED

1. M. N. Ivanovskii, V. P. Sorokin, and I. V. Yagodkin, Physical Fundamentals of Heat Pipes [in Russian], Moscow (1978).
2. V. I. Tolubinskii, V. A. Antonenko, Yu. I. Ostrovskii, and E. N. Shevchuk, Izv. Akad. Nauk SSSR, Énergetika i Transport, No. 1, 141-148 (1979).
3. V. I. Tolubinskii, Heat Transfer in Boiling [in Russian], Kiev (1980).
4. G. R. Kudritskii, "Intensification of heat transfer processes with vapor-generation from surfaces with capillary-porous coverings" Author's Abstract of Candidate Dissertation, Technical Sciences, Kiev (1985).
5. T. F. Rogers and R. B. Mesler, AIChEJ, 10, No. 5, 656-660 (1964).
6. M. G. Cooper and A. J. Lloyd, Proc. 3rd Int. Heat Transf. Conf., New York, 1966. Vol. 3, 193-203.
7. V. I. Tolubinskii, A. A. Kriveshko, and Yu. N. Ostrovskii, Heat Transfer and Hydrodynamics [in Russian], Leningrad (1977), pp. 47-54.
8. V. I. Tolubinskii, V. A. Antonenko, G. R. Kudritskii, and Yu. N. Ostrovskii, Promyshl. Teplotekh., 6, No. 3, 3-11 (1984).
9. L. L. Vasil'ev, A. N. Abramenko, and L. E. Kanonchik, Inzh.-Fiz. Zh., 34, No. 4, 741-761 (1978).
10. Yu. K. Gontarev, Yu. V. Navruzov, N. A. Nosach, and V. F. Prisnyakov, Problems of High Temperature Technology [in Russian], Dnepropetrovsk (1981), pp. 76-84.
11. V. A. Antonenko, "Investigation of heat transfer with boiling and evaporation of liquid in thin films," Author's Abstract of Candidate Dissertation, Technical Sciences, Kiev (1978).
12. Kasuda Nisikava, Nikon Kikai Gakkai Rombunsyu, 34, No. 261 (1968) (Translation of VINITI No. 82792/0 (1970)).
13. B. A. Afanas'ev, "Investigation of the process of vapor-generation in mesh capillary-porous structures," Author's Abstract of Candidate Dissertation, Technical Sciences, Odessa (1981).
14. A. A. Shapoval, "Heat transfer with boiling of water and acetone on surfaces with metal wire capillary-porous coverings," Author's Abstract of Candidate Dissertation, Technical Sciences, Kiev (1985).
15. A. N. Abramenko and L. E. Kanonchik, Heat and Mass Transfer in Systems with Porous Elements [in Russian], Minsk (1981), pp. 13-19.
16. B. V. Deryagin, N. V. Churaev, and V. M. Muller, Surface Forces [in Russian], Moscow (1985).