

LITERATURE CITED

1. Z. R. Gorbis, Heat Exchange and Hydrodynamics of Disperse Through Flows [in Russian], Énergiya, Moscow (1970).
2. S. Soy, Hydrodynamics of Multiphase Systems [Russian translation], Mir, Moscow (1971).
3. A. V. Fafurin, R. A. Muslimov, and K. R. Shangareev, "Experimental study of transient heat transfer in a two-phase flow on the initial section of a pipe," in: Heat and Mass Transfer in Chemical Engineering [in Russian], Kazan. Khim.-Tekhnol. Inst., Kazan (1978), pp. 52-55.
4. A. V. Fafurin, "Laws of friction and heat transfer in a turbulent boundary layer," in: Heat and Mass Transfer in Aircraft Engines [in Russian], Kazan Aviation Institute (1979), p. 62-69.
5. S. S. Kutateladze and A. I. Leont'ev, Heat and Mass Transfer and Friction in the Turbulent Boundary Layer [in Russian], Énergiya, Moscow (1972).
6. A. V. Fafurin, K. R. Shangareev, and R. A. Muslimov, "Transient heat transfer in a two-phase flow on the initial section of a pipe," in: Heat and Mass Transfer in Chemical Engineering [in Russian], Kazan. Khim.-Tekhnol. Inst. (1979), pp. 46-50.
7. P. N. Romanenko and I. V. Krylov, "Study of the effect of inlet conditions on heat transfer in the initial section of a pipe," Inzh.-Fiz. Zh., No. 4, 8-17 (1964).
8. E. U. Repik, "Experimental study of the structure of a turbulent boundary layer in the presence of a longitudinal pressure gradient," Tr. TsAGI, No. 1218, 19-35 (1970).

EXPERIMENTAL STUDY OF HEAT TRANSFER IN LIQUID BOILING IN HIGH-HEAT-CONDUCTIVITY CAPILLARY STRUCTURES

L. L. Vasil'ev, S. V. Konev,
P. Shtul'ts, and L. Khorvat

UDC 536.423:536.248.2

Results are presented from an experimental study of heat exchange in the boiling of water in copper capillary structures at low saturation vapor pressures.

The current intensive study of boiling processes stems from their heat-transfer coefficients and high maximum (critical) heat fluxes. The principal method of intensifying heat transfer is by using rough and capillary surfaces. For example, in the boiling of water on vapotron surfaces [1], the maximum heat flux reached 10^7 W/m². A value of $3 \cdot 10^7$ W/m² was achieved in heat removal on a capillary surface of the "inverted meniscus" type [2]. Among the shortcomings here, however, are large temperature gradients (vapotron) and small total heat flux (second case).

The most promising method of intensifying heat transfer is arranging for boiling in a capillary structure. The promise of this method owes to the achievement of high critical heat fluxes with small temperature gradients. Development of the method is currently proceeding in three directions: 1) boiling in submerged capillary structures [3]; 2) boiling in nonsubmerged capillary structures [4]; 3) boiling in a fluidized bed of dispersed particles [5]. Analysis of these procedures indicates that boiling in nonsubmerged capillary structures — so-called thin-film evaporators — is the most promising. The boiling mechanism in such evaporators depends significantly on the parameters of the capillary structure.

We investigated heat transfer in the boiling of water in nonsubmerged copper capillary structures, which are most effective at low saturation vapor pressures.

In examining heat transfer in boiling in capillary structures, we do not find an unequivocal answer to the question of the effect of the parameters of the structures on heat

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. State Research Institute of Machine Construction, Czechoslovak Socialist Republic. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 42, No. 6, pp. 893-898, June, 1982. Original article submitted May 8, 1981.

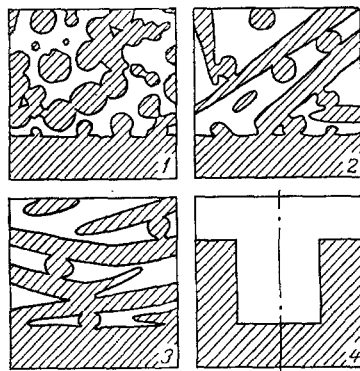


Fig. 1

Fig. 1. Structure of investigated capillary materials: 1) sintered beads; 2) sintered felt; 3) sintered fiber; 4) rectangular channels.

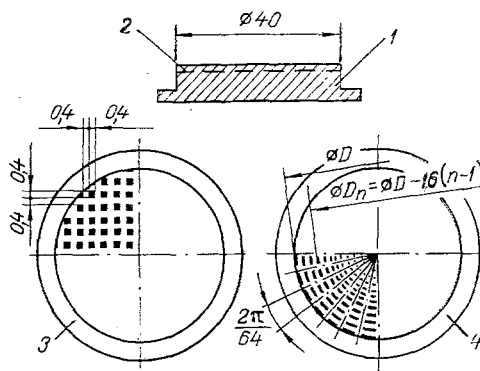


Fig. 2

Fig. 2. Design of experimental specimens: 1) cross section; 2) capillary structure; 3 and 4) top view of specimens with perpendicular-intersecting and radial-concentric channels, respectively.

transfer. This is due to the many factors which affect heat transfer. For example, the dependence of the heat-transfer coefficient on heat flux is of a conservative nature in some cases [6], while in others, $\alpha \sim q^n$, where $n \approx 0.7$ [7]. We will adhere to the second hypothesis. Very little attention has been given to the relation $\alpha = f(\lambda_{ef})$ in current investigations. For example, recommendations were made in [8] on the use of capillary structures with a high effective thermal conductivity, small thickness, and low porosity. Proceeding on this basis, in our experiments we chose three types of capillary-pore structures: sintered from copper beads, fiber, and felt. We also studied rectangular channels in copper. Figure 1 shows the structure of the investigated capillary materials. The parameters of the capillary structures are given in Table 1.

The 0.4-1.5 mm minimum thickness chosen for the capillary structure, high thermal conductivity of the body, and the low heat-transfer resistance of the contact made it possible to obtain higher values of heat-transfer coefficient and critical heat fluxes than normal. Figure 2 shows the setup of the specimens. The porous materials were obtained by sintering a disperse medium 1.5 mm thick directly on a copper disk 40 mm in diameter. The 0.4×0.4 mm channels were made by cutting directly on the disk surface. The disk was chosen for the specimen shape in connection with the fact that end heat delivery is often employed in heat pipes. The experiments were conducted on a unity of the classic type, representing a hermetic volume with a zone for delivering heat to the specimen and a condenser, similar to that described in [9]. The main difference is in the heat-exchange block (Fig. 3). The level of the working fluid (distilled water) in the top section of the capillary structure was accurately maintained using a coordinate system. The liquid was absorbed by the specimen through the lateral surfaces of the capillary structures. The temperature in the heat-exchanger-condenser and the double optical window was maintained by two ultrasonic thermostats.

The temperature transducers were 12 Chromel-Alumel thermocouples. The heater block consisted of a copper thermal wedge with a 40-mm-diameter heat-extraction zone. The maximum power of the heater was 1700 W, and the maximum heat flux in the heat-extraction zone was $1.35 \cdot 10^6$ W/m². The electric heater was made of Nichrome, while the electrical insulation was a thin layer of spray-coated Al₂O₃ powder. The outer surface of the heater was thermally insulated. Thermocouples were embedded in the copper block to measure heat flux. Heat was removed from the copper block to the specimen with a mechanical contact employing a clamp. The contact heat-transfer resistance was reduced by applying a thin layer of heat-conducting paste to the contact surface. The specimen was made tight with a fluoroplastic ring. The temperature transducers were installed on the surface of the evaporator, in the vapor space, and in the liquid. The wetting of the surface by the working fluid was improved by subjecting the specimens to a chemical treatment prior to their installation in the chamber. Air was evacuated from the chamber before the tests. The experiment was conducted in the saturated-vapor pressure range $(0.1-0.2) \cdot 10^5$ N/m². In determining the critical heat flux, we determined the moment of drying from the thermocouple readings and by visual observation.

TABLE 1. Parameters of Capillary Structures Made of Copper

No. of specimens	Type of structure	Thickness of structure	Channel width, mm	Channel depth, mm	Base diameter, mm	Fiber length, mm
	Channels:					
1	radial	0,4	0,4	0,4	—	—
2	perpendicular	0,4	0,4	0,4	—	—
	Sintered:					
3	powder (beads)	1,5	—	—	0,04	—
4	»	1,5	—	—	0,063	—
5	felt	1,5	—	—	0,04	3
6	»	1,5	—	—	0,06	3
7	»	1,5	—	—	0,075	3
8	»	1,5	—	—	0,09	3
9	fiber	1,5	—	—	0,09	—

Discussion of Results

Figure 4 shows the critical heat fluxes q_{ICr} for different capillary structures. Comparison of the data obtained shows that the q_{ICr} for all of the structures is roughly twice as great as the value obtained in boiling on a smooth surface in a large volume. The porosity of the capillary structures is close to 0.4, so their heat conductivity is highest. Specimen 3 has the lowest critical heat flux. This has to do with the fact that the specimen was poorly made and the particles included impurities.

Comparison of the maximum heat fluxes for the perpendicular-intersecting and radial-concentric channels showed that the latter had the advantage due to the shorter liquid transport length and less sinuousness. The sintered fiber has some advantage over the channels, which might be explained by the higher values of effective thermal conductivity. The results obtained for critical heat flux for the well-prepared specimens with sintered particles showed that such capillary structures are to be preferred over those already mentioned. No results for critical heat flux were obtained for the sintered-felt specimens due to the limited power of the heater. Most of the capillary structures work stably at heat fluxes above 10^6 W/m² at a pressure of $0.2 \cdot 10^5$ N/m².

Comparison of the data obtained for critical heat flux with the experimental data published in [10, 11] shows that our data is considerably higher. This is due to the fact that the structures investigated in [10, 11] were made of a material with a moderate thermal conductivity, the cells (pores) were large, and the mechanical clamp did not permit good thermal contact between the thicknesses and layers of the structure.

Visual studies of the boiling process in capillary structures have shown that there is a substantial difference in the way it takes place in a large volume — the boiling in the capillary structures is of a pulsation nature. It is accompanied by vigorous drop entrainment, with the moisture content of the vapor-drop flow increasing with an increase in heat flux. This agrees with the results in [12]. Figure 5 presents results of experimental study of heat transfer in boiling on the investigated specimens compared to published data. It is seen that all of the capillary structures studied have a wall-vapor temperature drop in the 5–10°K range with a change in heat flux of $(10-127) \cdot 10^4$ W/m². These results are adequately described by the relation $q = KAT^3$, characteristic of developed nucleate boiling. Analysis of the data in the form of the dependence of the heat-transfer coefficient on heat flux (points 1–4 in Fig. 5) made it possible to describe the information in the form of the empirical relation $\alpha = 5.68q^{0.7}$, again typical of developed nucleate boiling. High heat-transfer coefficients were seen in our experiment compared to [10] (hatched region II in Fig. 5). Our data does agree well with [4, 7, 13, 14, 16]. Most of the empirical points from these works were taken close to the first critical heat flux, i.e., in the region most characteristic of developed boiling. Individual points (6, 8, 10–15, 18) were obtained at $P = 10^5$ N/m² but agree well with the results (points 1–4) obtained at $P = 2 \cdot 10^4$ N/m². This confirms the proposition of the stabilizing effect of the capillary structure on the boiling process at reduced pressures and the lessening of the effect of pressure on the heat-transfer coefficient.

The study results confirmed that capillary structures in the form of sintered high-heat-conducting particles stabilize boiling on an unsubmerged surface at reduced pressures,

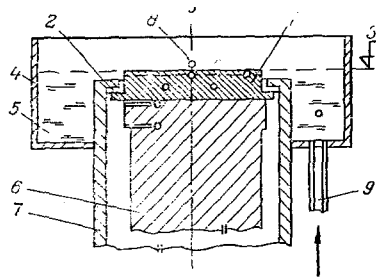


Fig. 3

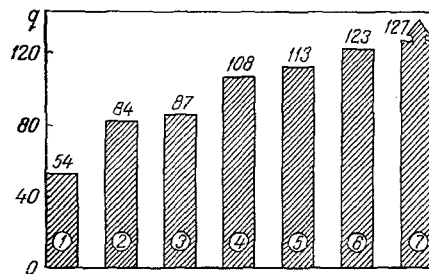


Fig. 4

Fig. 3. Installation of test specimen: 1) specimen; 2) fluoroplastic seal; 3) level of liquid; 4) volume for replenishing specimen with liquid; 5) working liquid; 6) heater block; 7) chamber of heater block; 8) thermocouples; 9) channel for delivering liquid to working chamber.

Fig. 4. Maximum critical heat fluxes for different capillary structures at $P = 0.2 \cdot 10^5 \text{ N/m}^2$: 1) boiling in a large volume [4]; 2) specimen 3; 3) 2; 4) 1; 5) 9; 6) 4; 7) 8; q , W/cm^2 .

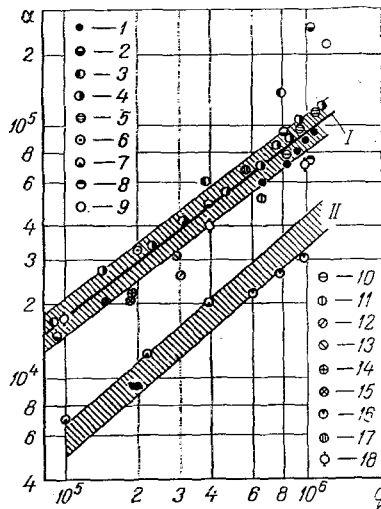


Fig. 5. Dependence of heat-transfer coefficient ($\text{W/m}^2 \cdot \text{K}$) on heat flux (W/m^2) in boiling of water in capillary structures: 1) specimen 1; 2) 9; 3) 2; 4) 4; 5) triangular channels [13]; 6) boiling in a large volume, sintered 0.1-mm spheres of stainless steel, $P = 10^5 \text{ N/m}^2$ [7]; 7) grid; 1st layer 4 μm , 2nd layer 130 μm , clamped, stainless steel, $P = 10^4 \text{ N/m}^2$ [11]; 8) sintered copper powder, pore size 0.01 mm, oxidized, thickness 3.17 mm, $P = 10^5 \text{ N/m}^2$ [14]; 9) sintered copper particles, 0.12-0.25 mm, thickness 1-2 mm (approximate data) [15]; 10-15) triangular channels, $P = 10^5 \text{ N/m}^2$ [16]; 10, 11) copper, spacing 0.3 and 0.5 mm, respectively; 12, 13) steel 20, spacing 0.3 and 0.5 mm, respectively; 14, 15) stainless steel, spacing 0.3 and 0.5 mm; 16) copper, triangular channels, spacing 0.653 mm, $P = 5 \cdot 10^4 \text{ N/m}^2$ [17]; 17) sintered nickel spheres [4]; 18) 4-mm-diam. disk without capillary structure, $P = 10^5 \text{ N/m}^2$ [18]; I) relation $\alpha = 5.68 q^{0.7}$; II) region corresponding to data in [10]. α , $\text{W/m}^2 \cdot \text{K}$; q , W/m^2 .

significantly increase the first critical heat flux (above 10^6 W/m^2), and improve heat transfer during vaporization (the heat-transfer coefficient approaches $10^5 \text{ W/m}^2 \cdot \text{K}$).

LITERATURE CITED

1. S. A. Tiktin, Vapotron Technology [in Russian], Tekhnika, Kiev (1975).
2. R. R. Barthelmy, D. Jacobsen, and D. Rabe, "Heat pipe mirrors for high power lasers," in: A Collection of Technical Papers, Third International Heat Pipe Conference, Palo Alto (1978), pp. 63-70.
3. O. N. Man'kovskii, O. B. Ioffe, L. G. Fridgant, and A. R. Tolchinskii, "Boiling mechanism on submerged surfaces with a capillary-pore coating," Inzh.-Fiz. Zh., 30, No. 2, 310-316 (1976).
4. H. R. Funz, L. S. Langston, B. H. Hilton, and S. S. Wycle, Vapor Chamber Fin Studies, NASA Report CR-812 (1967).
5. G. F. Smirnov, "Heat transfer in liquid boiling in a closed layer of a disperse material," Inzh.-Fiz. Zh., 34, No. 5, 792-798 (1978).
6. A. Abkhat and R. A. Seban, "Boiling and evaporation of water, acetone, and ethyl alcohol in heat-pipe wicks," Teploperedacha, No. 3, 74-82 (1974).
7. S. A. Kovalev and V. A. Len'kov, "Mechanism of the boiling crisis on a porous surface," Teploenergetika, No. 4, 8-11 (1981).
8. G. F. Smirnov, "Approximate theory of heat transfer in boiling on surfaces covered with capillary-pore structures," Teploenergetika, No. 9, 77-80 (1977).
9. L. L. Vasil'ev, A. N. Abramenko, and S. V. Konov, "Heat transfer in liquid evaporation and boiling on capillary and pore surfaces," in: Heat Transfer [in Russian] (1978): Soviet Studies. Nauka, Moscow (1980), pp. 224-235.
10. V. I. Tolubinsky et al., "Heat transfer at liquid evaporation from wicks capillary structure of low temperature heat pipes," in: A Collection of Technical Papers, Third International Heat Pipe Conference, Palo Alto (1978), pp. 140-146.
11. B. A. Afanas'ev, V. V. Zrodnikov, A. L. Koba, et al., "Heat transfer in boiling in channels, capillaries, and capillary-pore structures," in: Heat Transfer and Hydrodynamics in Boiling and Condensation [in Russian], Institute of Thermophysics, Novosibirsk (1978), pp. 86-94.
12. S. V. Konev and V. V. Khrolenok, "Analysis of vapor moisture content in a heat pipe," in: Heat and Mass Transfer [in Russian], Minsk (1980), pp. 87-93.
13. K. Moritz, "Effect of capillary geometry on maximum thermal load in heat pipes," in: Heat Pipes [Russian translation], Mir, Moscow (1972), pp. 33-117.
14. R. A. Freggens, "Experimental determination of wicks properties for heat pipe applications," Proceedings of the Fourth Intersociety Energy Conservation Engineering Conference, Washington (1969), pp. 888-897.
15. W. Fisher and G. Gammel, "Heat pipe with a sintered capillary structure," United States Patent, No. 3.840.069, Oct. 8, 1974.
16. I. G. Shekriladze and D. G. Rusishvili, "Experimental study of heat transfer in vaporization and condensation processes on capillary surfaces," Inzh.-Fiz. Zh., 38, No. 5, 793-799 (1980).
17. K. T. Feldman and M. E. Berger, "Analysis of a high-heat-flux water heat pipe evaporation," Technical Report ME-62(73), ONR-012-2, New Mexico (1973).
18. Yu. Ya. Pechenegov, Yu. I. Serov, A. P. Chelyapin, and O. V. Lopatnikov, "Experimental study of heat transfer in liquid boiling on a small surface," in: Boiling and Condensation [in Russian], Riga Polytechnic Institute (1979), pp. 26-30.