HEAT-TRANSFER RATE IN BOILING AT A SURFACE WITH POROUS COATINGS IN CONDITIONS OF FREE MOTION

V. K. Zaripov, M. G. Semena, A. A. Shapoval,
and A. I. Levterov

UDC 536.423.1:621.59

Experimental results for the boiling of water, nitrogen, acetone, and ethyl alcohol at heated surfaces with metal-fiber capillary-porous coatings are described, and a dependence is proposed for the calculation of the heat-transfer coefficient.

Heat transfer with boiling at a surface with porous coatings is currently under intensive investigation, both in the Soviet Union and elsewhere. However, as results in this field accumulate, the picture becomes increasingly unclear. For example, according to some researchers, the heat-transfer rate increases with increase in coating thickness δ, in conditions of free motion; according to others, it increases with decrease in δ; and according to still others, it does not depend on the coating thickness at all. The power n to which the heat-flux density is raised in the dependence $\alpha = f(q)$ has been assigned the following values in different studies: 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7. A number of researchers assert that the heat-transfer rate at a surface with a coating is increased by a factor of 7-10 in comparison with a surface with no coating; according to others, this factor is 1.5-2.

The significant discrepancy, and contradiction, between the data of different experimenters is usually attributed to the use of different types of porous coatings, experimental apparatus, and procedures, experimental errors, etc. All this is true but, in our view, the fundamental reason for the discrepancies is the partial, simplified character of the investigations, which are performed on two or three samples, as a rule, in narrow ranges of parameter variation, without taking account of all the basic characteristics determining the heat-transfer rate and their mutual influence, etc. Nevertheless, these investigations are often taken as the basis for broad generalizations and conclusions that are not always true.

The aim of the present work is a comprehensive complex investigation of the influence of the geometric, thermophysical, and structural characteristics of porous coatings, the thermophysical and physical properties of the working liquid and the heating surface, and the operating parameters of the process on the heat-transfer rate in boiling in free-motion conditions.

In six series of experiments on an apparatus whose working portions were described in [1, 2], 79 samples are investigated; the samples are prepared from substrates baked with porous coatings. (Substrate diameter 30 mm; thickness 3.5 mm; material: copper, stainless steel). The coatings investigated are metal-fiber capillary structures baked from discrete fibers of copper, nickel, or stainless steel (fiber diameter 20-70 μm; length 3 and 9 mm). Coating parameter ranges: porosity 40-93%; thickness 0.1-10 mm; effective pore diameter 20-300 μm; liquid permeability 10^{-12}-10^{-9} m^2; frame thermal conductivity 0.066-100 W/m·K. The working liquid is water, nitrogen, acetone, or ethyl alcohol. Experiments are performed at atmospheric and reduced (water, acetone) saturation pressures with heat-flux density 1-200 W/cm^2.

In the first series of experiments, the influence of the heat-flux density on the heat-transfer rate is determined. On analyzing the experimental data, it is found that the power n is not constant, but depends on the coating thickness, decreasing with increase in thickness (except for coatings of great thickness). The other characteristics and properties of the coatings, the heating surface, and the liquid have no marked influence on n.

Kiev Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 2, pp. 181-186, August, 1989. Original article submitted February 8, 1988.

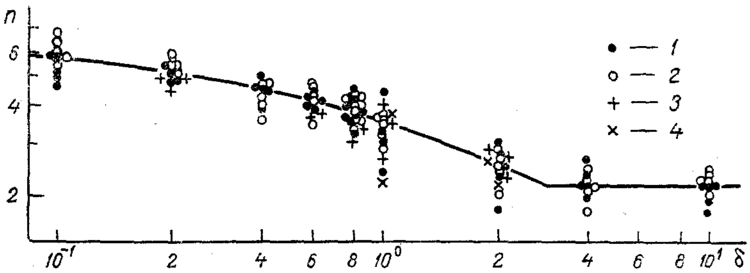

Fig. 1. Dependence of n on the coating thickness: 1) water; 2) nitrogen; 3) acetone; 4) ethyl alcohol. Curve) calculation from Eq. (1). δ, mm.

Experimental data and calculation results for n are shown in Fig. 1; the calculations are based on the generalizing dependence

$$n = 5\delta^{0,7}\,\mathrm{cth}\,(0{,}0035 + 104\delta + 7\cdot 10^{5}\delta^{2,7}),\ 0{,}1\cdot 10^{-3} \leqslant \delta \leqslant 3\cdot 10^{-3}\ \mathrm{m};$$
$$n = 0{,}21432,\ 3\cdot 10^{-3} < \delta \leqslant 10\cdot 10^{-3}\ \mathrm{m}, \tag{1}$$

which is valid as long as q does not exceed the critical heat-flux density q_{cr}^{in}, values of which may be found in [1, 2]. The results obtained allow the factors underlying the discrepancy in different authors' values of n to be largely explained.

In the second series of experiments, the influence of the coating thickness on the heat-transfer rate is investigated. Analysis of the experimental data, taking account of Eq. (1), shows that

$$\alpha \sim \delta^{1,5},\ 0{,}1\cdot 10^{-3} \leqslant \delta \leqslant \delta_{bo}\ \text{and}\ \alpha \sim \delta^{-0,25},\ \delta_{bo} < \delta \leqslant 10\cdot 10^{-3}\ \mathrm{m}, \tag{2}$$

i.e., other parameters and conditions being equal, increase in coating thickness is accompanied first by sharp increase in the heat-transfer coefficient to some boundary value δ_{bo}, and then by reduction in δ; δ_{bo} = 3 mm and 1.3 mm for water and nitrogen, respectively. However, this considerable direct influence of the coating thickness on α ($\delta \leq \delta_{bo}$) is compensated by the above-noted variation in n with heat-flux density, which leads finally to weakening of the dependence of the heat-transfer rate on the thickness δ, especially at large q (Fig. 2).

The results obtained, some of which are shown in Fig. 2, indicate a complex ambiguous dependence of the heat-transfer coefficient on the thickness of the porous coating; this allows the three different viewpoints in the literature – that the heat-transfer rate increases, decreases, and remains constant with increase in δ – to be reconciled.

The influence of the structural characteristics on the heat-transfer rate is investigated in the third series of experiments, by varying the porosity of the coatings, the size of the discrete fibers and pores, and the nonuniformity, i.e., the size distribution of the pores, while the other parameters of the coating remain unchanged, or almost so. Analysis of the experimental data reveals significant influence of the degree of nonuniformity of the coating. The porosity and the pore and fiber size exert a pronounced direct influence on the heat-transfer rate (their influence is expressed through the size distribution of the pores and the thermal conductivity of the coating).

For metal-fiber capillary structures, differential size distributions of the pores were not given in [3] but, because of the unwieldiness of the formulas and the difficulty of determining some parameters, it is simpler to use the ratio $(1 - \Pi_{li})/(1 - \Pi)$ in the present case; this ratio [4] characterizes the nonuniformity of the coating, the degree to which its structure resembles that of a coating of limiting porosity Π_{li} with the same fiber dimensions. The dependence of the heat-transfer coefficient on this ratio takes the form

$$\alpha \sim [(1 - \Pi_{li})/(1 - \Pi)]^{0,4},\ \Pi_{li} = \exp\left(-6\,\frac{d_F}{l_F}\right),\ 10^{-6} \leqslant \left(\frac{d_F}{l_F}\right) \leqslant 10^{-4}. \tag{3}$$

In the fourth series of experiments, the influence of the frame λ_f and effective λ_{ef} thermal conductivities of the coating on the heat-transfer rate is determined. As established in the experiments, the heat-transfer coefficient increases significantly on boiling

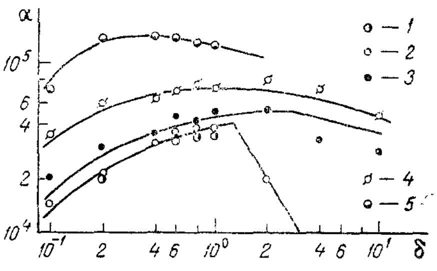

Fig. 2

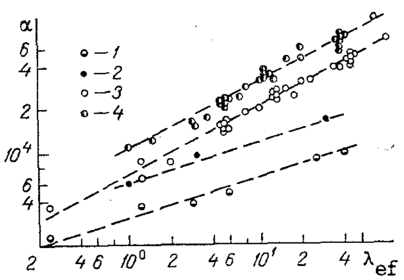

Fig. 3

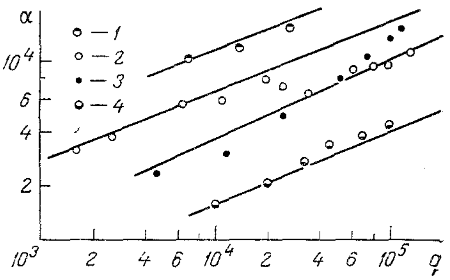

Fig. 4

Fig. 2. Characteristic dependences of the heat-transfer coefficient on the coating thickness. Porosity 60%. Liquid: 1) acetone; 2) nitrogen; 3-5) water. Heat-flux density ($\cdot 10^4$, W/m^2): 1-3) 5; 4) 20; 5) 100. Curves) calculation according to Eq. (4). α, W/m$^2\cdot$K; δ, mm.

Fig. 3. Dependence of the heat-transfer coefficient on the effective thermal conductivity of the coating. Coating thickness 0.8 mm; porosity 40-93%. Liquid: 1, 3) nitrogen; 2, 4) water. Substrate material: 1, 2) stainless steel; 3, 4) copper. Heat flux density ($\cdot 10^4$, W/m^2): 1, 3) 5.66; 2, 4) 10. α, W/m$^2\cdot$K; λ_{ef}, W/m$\cdot$K.

Fig. 4. Dependence of the heat-transfer coefficient on the heat flux density. Sample of copper fibers (1) with Π = 76%; δ = 0.8 mm, λ_{ef} = 15.9 W/m$\cdot$K, $B^{0.4}$ = 0.413 (present data); nickel fibers with 80%, 0.74 mm, 2.34 W/m$\cdot$K [5], assuming that $B^{0.4}$ = 0.5 (2) and with 80%, 0.46 mm [7], assuming that λ_{ef} = 2.34 W/m$\cdot$K and $B^{0.4}$ = 0.5 (3); stainless-steel fibers (4) with 90%, 0.7 mm [6] (samples prepared at Kiev Polytechnic Institute), λ_{ef} = 0.17 W/m$\cdot$K, $B^{0.4}$ = 0.75. Substrate material: 1, 2) copper; 3) layer of nickel on copper; 4) stainless steel. Heat carrier: 1) nitrogen; 2, 3) water; 4) Freon-113. Saturation pressure: 1, 2, 4) 98 kPa; 3) 35 kPa. Curves) calculation according to Eq. (4). q, W/m^2.

with increase in thermal conductivity of the coating. In the range $10 < \lambda_f \leq 100$ W/m$\cdot$K, the frame and effective thermal conductivities are similar in magnitude and have practically the same influence on α; at low λ_f (especially when $\lambda_f < \lambda_L$), their influence is different, the dependence on the effective thermal conductivity $\alpha \sim \lambda_{ef}^p$ being more clearly logical. The index p in this dependence, as established in the analysis of experimental data taking account of Eq. (3), is determined by the material of the heating surface: p = 0.5 and 0.3 for copper and stainless-steel substrates, respectively (Fig. 3).

The influence of the heating-surface material on the heat-transfer rate is investigated in the fifth series of experiments, using pairs of samples with identical or similar parameters but different substrates: copper and stainless steel. As a result, it is found that the thermophysical and physical properties of the heating surface have a pronounced influence on the heat-transfer rate. For example, in the boiling of water at porous coatings with a copper substrate, the heat-transfer coefficients are double those for the same coatings with a stainless-steel substrate; in the boiling of nitrogen, they are almost three times higher. Analysis of the experimental data using the heat accumulation coefficient of the heating-surface material $A_{hs} = \sqrt{\lambda c \rho}$ shows that $\alpha \sim A_{hs}^{0.5}$.

In the sixth series of experiments, the influence of the thermophysical and physical properties of the working liquid on the heat-transfer rate at atmospheric and reduced saturation pressures is investigated. Analysis of the experimental data indicates that the influence of the working-liquid properties on the heat-transfer coefficient, which depends on a known complex of liquid properties $\lambda_L^2/\nu_L \sigma T_{sat}$, the vapor density, and the heat of vaporization, is weaker than for boiling at a smooth surface.

Comparison of the results obtained with data on boiling at a smooth engineering heating surface indicates that, depending on the thickness, thermal conductivity, and porosity of the coating and the incoming heat-flux density, the heat-transfer rate may be higher, for example, by a factor of 10 (when using coatings with $\Pi = 40\%$, $\delta = 0.8$ mm, $q = 5$ W/cm², water), 7, 5, 2, or no more than 1.5 (for example, $\Pi = 80\%$, $\delta = 0.1$ mm) than for a smooth surface with no coating, equal to this value (some coatings at high q), or even lower than this value (coatings of low conductivity; high q).

Even further confusion in the results of such comparisons, often undertaken by different researchers, is introduced by failure to take account of the contact thermal resistance R_{co} between the porous coating and the heating surface, which may lead to severalfold variation in the heat-transfer rate. Thus, in the present experiments on coatings clamped to the heating surface ($R_{co} = 0.0002$-0.001 m²·K/W), the heat-transfer coefficients at small heat flux density ($q < 5 \cdot 10^4$ W/m²) is higher by a factor of 1.1-1.5, and those at $q > 5 \cdot 10^4$ W/m² are lower by a factor of 1.5-4, than the values of α obtained with the same coatings which have been baked with the heating surface ($R_{co} \approx 0$).

The results of all the series of experiments on the heat-transfer rate at a heating surface baked with metal-fiber porous coatings in the boiling of liquid in free-motion conditions may be approximated by a dependence generalizing 95% of the experimental data with an error of no more than ±35%

$$\alpha = kq^n \delta^m \lambda_{ef}^p B^{0.4} A_{hs}^{0.5} N, \tag{4}$$

where $n = 5\delta^{0.7} \operatorname{cth}(0.0035 + 104\delta + 7 \cdot 10^5 \delta^{2.7})$, $0.1 \le \delta \le 3$ mm; $n = 0.21432$, $3 < \delta \le 10$ mm; $m = 1.5$, $k = 6500$, $0.1 \le \delta \le \delta_{bo}$; $m = -0.25$, $\delta_{bo} < \delta \le 10$ mm (water: $\delta_{bo} = 3$ mm, $k = 0.25$; nitrogen: $\delta_{bo} = 1.3$ mm, $k = 0.0578$); $B = (1 - \Pi_{1i})/(1 - \Pi)$; $\Pi_{1i} = \exp(-6d_F/\ell_F)$, $10^{-6} \le (d_F/\ell_F) \le 10^{-4}$; $A_{hs} = \sqrt{\lambda c \rho}$; $N = \rho_v^{0.05} r^{0.12} (\lambda_L^2/\nu_L \sigma T_{sat})^{0.05}$; the effective thermal conductivity λ_{ef} is determined from Eq. (2.40) of [4], and $p = 0.5$ ($k = 6500$) and 0.3 ($k = 8400$) for copper and stainless-steel heating surfaces, respectively. The thermophysical and physical properties of the heating-surface material, fibers, and working liquid are determined from the saturation temperature.

The theoretical and experimental data for boiling at surfaces with metal-fiber porous coatings are compared in Fig. 4; satisfactory agreement is seen.

It is of interest to compare the present results obtained in conditions of free liquid motion with the data of [8], obtained at surfaces with the same porous structures in conditions of capillary transport, and to identify the general and distinctive laws. Common to boiling in both sets of conditions is the direct influence of the geometric parameters of the coating on the rate. Thus, with increase in coating thickness to some boundary value δ_{bo}, the heat-transfer coefficient α increases, but with further increase in thickness δ decreases (the value of δ_{bo} and the degree m of influence of δ on α are different in magnitude in the two cases). The thermophysical and physical properties of the heating surface have almost the same influence on the heat transfer rate. In both cases, the heat transfer coefficients depend significantly on the thermal constant resistance between the porous coating and the heating surface.

There are also a series of fundamental differences between the rate of boiling in free motion and in capillary transport of the liquid. For example, in the first case, the thermophysical and structural characteristics of the porous fiber have a strong influence on the heat-transfer rate, whereas in the second case this influence is slight. In free-motion conditions, the degree to which the heat flux density influences the heat-transfer coefficient depends on the coating thickness over a fairly broad range of thickness variation, whereas in conditions of capillary transport n is a constant (0.6). Overall, the dependence of the heat-transfer rate on the operational parameters and the thermophysical and physical properties of the liquid in the first case is more weakly expressed than in the second case. In contrast to capillary-transport conditions, in which there are two boiling zones with a boundary defined by Eq. (2) of [8], in free-motion conditions there is a single boiling zone extending right up to the critical heat flux density corresponding to the maximum heat-transfer coefficient.

NOTATION

α, heat-transfer coefficient; q, heat flux density; δ, coating thickness; Π, porosity of coating; λ, thermal conductivity; d, diameter; ℓ, length; c, specific heat; ρ, density; r, heat of vaporization; ν, kinematic viscosity; σ, surface tension; T, temperature. Indices: F, fiber; bo, boundary; L, liquid; sat, saturation; v, vapor; hs, heating surface; li, limiting; ef, effective.

LITERATURE CITED

1. A. A. Shapoval, V. K. Zaripov, and M. G. Semena, Teploénerg., No. 12, 65-67 (1983).
2. A. I. Levterov, M. G. Semena, and V. K. Zaripov, Teploénerg., No. 4, 66-69 (1982).
3. A. P. Nishchik and M. G. Semena, Inzh.-Fiz. Zh., 53, No. 4, 671-672 (1987).
4. M. G. Semena, A. N. Gershuni, and V. K. Zaripov, Thermal Tubes with Metal-Fiber Capillary Structures [in Russian], Kiev (1984).
5. A. Abkhat and R. A. Seban, Teplopered., No. 3, 74-82 (1974).
6. A. V. Tikhonov and O. Ě. Zaporozhchenko, in: Cryogenic Engineering and Conditioning. Investigation and Refinement of Processes and Equipment [in Russian], Leningrad (1984), pp. 104-109.
7. J. C. Corman and G. E. Walmet, ASME Paper No. HT-35 (1971), pp. 1-8.
8. M. G. Semena, V. K. Zaripov, and A. A. Shapoval, Inzh.-Fiz. Zh., 52, No. 4, 592-597 (1987).

TWO-PHASE FLOW SINGULARITIES IN THE CRITICAL STATE DOMAIN

I. I. Novikov and T. I. Novikova

UDC 530.1:543.31:536

An analytical proof is presented of the possibility of rarefaction shockwave formation for a two-phase flow in states near the critical point. Results of a theoretical analysis are compared with experimental data available in the literature.

A two-phase flow, that in the simplest case is a moving pair with fluid drops of the same substance contained therein, should possess quite interesting features when the stream temperature and pressure are near the critical parameters T_c, p_c of the moving substance. It will be shown below that the formation of rarefaction shockwaves becomes possible in the stream in this case.

As is known, the entropy increment in a shock wave is according to Jouget

$$S_2 - S_1 = \frac{T}{12}\left(\frac{\partial^2 V}{\partial p^2}\right)_S (p_2 - p_1)^3. \quad (1)$$

From this it is seen that the difference $p_2 - p_1$ should be positive for $(\partial^2 V/\partial p^2)_S > 0$ because of the condition $S_2 > S_1$, i.e., a compression shock is formed, while for $(\partial^2 V/\partial p^2)_S < 0$ the difference is $p_2 - p_1 < 0$, and therefore, formation of a rarefaction shock is possible. In both cases the conditions

$$w_1 > c_1;\ w_2 < c_2, \quad (2)$$

A. A. Baikov Metallurgy Institute, Academy of Sciences of the USSR, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 57, No. 2, pp. 186-189, August, 1989. Original article submitted March 28, 1988.

0022-0841/89/5702-0863$12.50