HEAT EXCHANGE IN THE EVAPORATION REGION OF COOLANT
INSIDE A POROUS FUEL ELEMENT

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The article presents the results of the analytical investigation of the temperature field and of heat exchange in the evaporation zone of coolant inside a porous fuel element, with heat transfer by heat conduction across its boundaries taken into account.

The extremely high intensity of heat exchange upon evaporation of a stream of liquid inside heated porous metals makes it possible to produce smaller heat exchangers by using porous materials in them. Porous fuel elements (FE) ensure the most favorable conditions for investigating this process, smooth change of volumetric heat release in them makes it possible to check its course, to obtain at the outlet a biphase stream with gradually increasing vapor content, and to obtain a notion of the structure of the evaporating stream [1]. In [2] the present authors developed an analytical model on the basis of which they investigated in [3] the temperature state of a porous FE without regard to heat transfer by heat conduction across the boundaries of the evaporation zone, i.e., maintaining adiabatic conditions on them.

Experimental investigation of the process showed that the temperature distribution inside such a FE depends largely on the conditions of coolant outflow (Fig. 1). Variant a corresponds to the outflow of a biphase stream, b corresponds to the outflow of superheated vapor. Whereas in variant a the conditions are adiabatic at the beginning of the evaporation zone (maximum of the temperature T of the porous material for Z = L), and the results obtained in [2, 3] are correct for it, in variant b there takes place monotonic increase of the temperature of the porous material, both at the beginning Z = L, and at the end Z = K of the evaporation zone, and conditions here are not adiabatic. Heat transfer by heat conduction across its boundaries leads here to a substantial change of all the characteristics of the process.

The temperature field of a FE illustrated in Fig. 1b is described by a system of equations including equations for calculating the temperatures of the porous material T_j and of the coolant t_j on the liquid (0 < Z < L, j = 1) and vapor (k < Z < δ, j = 3) sections of single-phase flow:

$$\lambda \frac{d^2 T_j}{dZ^2} + q_v = h_v (T_j - t_j);$$

$$Gc_j \frac{dt_j}{dZ} = h_v (T_j - t_j) \tag{1}$$

and the critical equation for determining the intensity h_v of intraporous convective heat exchange in the motion of a single-phase heat-transfer agent in porous cermets [4]:

$$\mathrm{Nu}_j = 0.004 \mathrm{Re}_j \mathrm{Pr}_j; \quad \mathrm{Nu}_j = \frac{h_v (\beta/\alpha)^2}{\lambda_j}; \quad \mathrm{Re}_j = \frac{G (\beta/\alpha)}{\mu_j}.$$

In the evaporation zone (L < Z < K) the temperature of the vapor phase is equal to the local saturation temperature $t_2 = t_S(P)$, and the temperature distribution of the porous material is determined by the equation
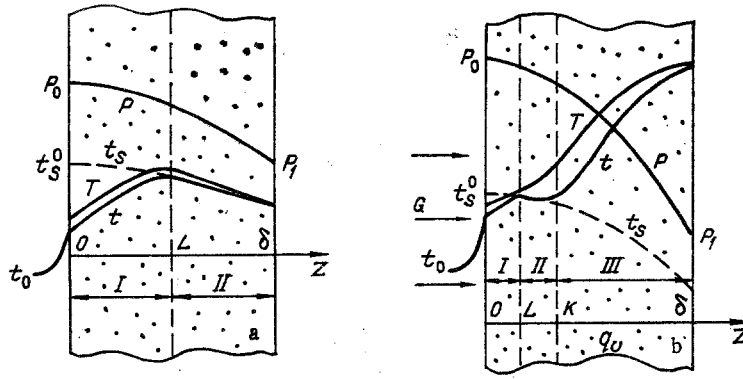
Fig. 1. Experimental and theoretical model of the process of evaporative liquid cooling of a porous fuel element (a) outflow regime of biphase stream; b) outflow regime of superheated vapor). I) liquid region; II) evaporation zone; III) vapor region.

$$\lambda \frac{d^2 T_2}{dZ^2} + q_v = h_v (T_2 - t_s) = G \frac{di}{dZ} . \tag{2}$$

The order of magnitude of the intensity h_v of volumetric heat exchange upon evaporation of a liquid inside a porous material can be estimated with the aid of the following expression that was derived in [5]:

$$\frac{h_v d^2}{\lambda'} = 18 \frac{(1 - \Pi)^2}{\Pi} [1 - (1 - s)^{1/2}]^{-1}. \tag{3}$$

The boundary conditions for the system of equations (1), (2) have the form:

$$Z = 0, \quad Gc(t_1 - t_0) = \alpha (T_1 - t_0); \tag{4}$$

$$Z = L, \quad t_1 = t_2 = t_s; \quad T_1 = T_2; \tag{5}$$

$$\lambda \frac{dT_1}{dZ} = \lambda \frac{dT_2}{dZ} = G(i' - ct_0) - q_v L;$$

$$Z = K, \quad t_2 = t_3 = t_s; \quad T_2 = T_3;$$

$$\lambda \frac{dT_2}{dZ} = \lambda \frac{dT_3}{dZ} = G(i'' - ct_0) - q_v K; \tag{6}$$

$$Z = \delta, \quad \lambda \frac{dT_3}{dZ} = 0. \tag{7}$$

The coordinate Z = L of the beginning of the evaporation zone is determined from the condition of the coolant attaining the state of saturation $t_1 = t_s$, $i = i'$. At the end of the evaporation zone Z = K the enthalpy of the coolant is equal to the enthalpy i'' of saturated vapor. The nucleation of vapor bubbles in motion of water inside porous metals proceeds practically under conditions thermodynamic equilibrium [6], i.e., $T_2 - t_s|_{Z=L} \leqslant 1°C$.

The use of expression (3) for water with s = 0.19, Π = 0.33, and d = 316; 100 μm yields the respective values h_v = 1.63 · 10^9; 1.63 · 10^{10} W/(m^3 · °K). Hence follows that in porous FE with mean particles size d < 300 μm with volumetric heat flux density $q_v < 10^9$ W/m^3 the temperature of the material in the evaporation zone in the regime of outflow of a biphase stream practically does not differ from the temperature t_s of the vapor phase of the mixture: $T_2 - t_s \approx q_v/h_v \approx 1°C$.

If we accept the assumption that the values of t_s, h_v in the evaporation zone are constant, the solution of Eq. (2) with the boundary conditions (5) can be obtained in analytical form:

$$\vartheta_2 = a \exp[\gamma(z - l)] + b \exp[-\gamma(z - l)] + q_v/h_v; \tag{8}$$
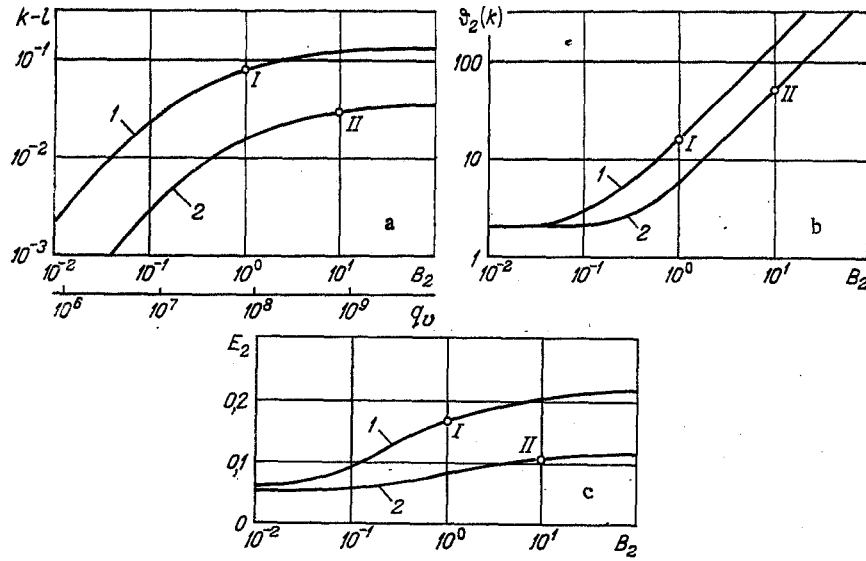
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Fig. 2. Dependence of the relative length $k - l$ of the evaporation zone (a), of the temperature difference $\vartheta_2(k)$ between the porous material and the coolant at the end of the region (b), and of the value of E_2 (formula (14)) (c) on the parameters of the process: 1) $\gamma = 31.6$; 2) 100. q_v, W/m³; $\vartheta_2(k)$, °C.

$$\frac{i(z)-i'}{c'} = \frac{\gamma}{B_2}\{a\exp[\gamma(z-l)] - b\exp[-\gamma(z-l)]\} - N_1(1-E_1) + N_3(z-l); \tag{9}$$

$$x(z) = \frac{i(z)-i'}{c'(N_2-N_1)}; \tag{10}$$

$$a = \frac{1}{2}\left[\vartheta_0 - q_v/h_v + \frac{B_2}{\gamma}N_1(1-E_1)\right];$$

$$b = \frac{1}{2}\left[\vartheta_0 - q_v/h_v - \frac{B_2}{\gamma}N_1(1-E_1)\right]; \tag{11}$$

where

$$\vartheta_2 = T_2 - t_s; \quad \vartheta_0 = T_2 - t_s\big|_{Z=L}; \quad z = Z/\delta;$$

$$l = L/\delta; \quad k = K/\delta; \quad B_2 = G\delta c'/\lambda;$$

$$N_1 = (i'-ct_0)/c'; \quad N_2 = (i''-ct_0)/c'; \quad \gamma = \delta(h_v/\lambda)^{1/2};$$

$$N_3 = (i[t_3(\delta)] - ct_0)/c'; \quad E_1 = q_v\delta l/Gc'(t_s-t_0). \tag{12}$$

The above expressions make it possible to calculate the change of temperature of porous material, of the enthalpy of the coolant, of the discharge mass quantity of vapor of a biphase stream in the evaporation zone. To determine the relative length $k - l$ of the evaporation zone, we use the last of conditions (6) which, taking (8)-(12) into account, may be written as follows:

$$a\exp[\gamma(k-l)] - b\exp[-\gamma(k-l)] - \frac{B_2}{\gamma}\{N_2 - N_3[(k-l)+l]\} = 0. \tag{13}$$
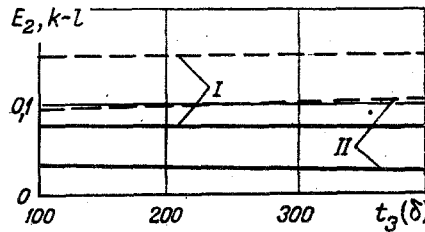
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Fig. 3. Dependence of the length of
the evaporation zone $k - l$ (solid lines)
and of E_2 (dashed lines) on the tem-
perature of superheated vapor flowing
out of the element, with parameters cor-
responding to points I, II in Fig. 2. t_3
(δ), °C.

The obtained expression is the characteristic equation for determining the value of $k - l$ in dependence on the parameters γ, B_2, E_1, l, N_1, N_2, N_3. The solution of this equation is presented in Fig. 2a in the form of the dependence of $k - l$ on B_2 for two values of the parameter γ. N_1, N_2 are calculated by using the physical properties of water and of water vapor in the satura- ted state at atmospheric pressure. In addition, the following was adopted: $\vartheta_0 = 2$°C; $\delta = 10$ mm; $\lambda = 10$ W/(m·°K); $l = 0.052$; $E_1 = 0.5$. Under these conditions the values $h_V = 10^8$; 10^9 W/(m³·°K) correspond to the values of the parameter $\gamma = 31.6$; 100.

The change of the parameter B_2 with fixed values of δ, λ, c' occurs on account of a change in the flow rate of the coolant G. Complete evaporation of this coolant stream and its superheating inside the fuel element to the temperature $t_3(\delta) = 400$°C corresponds to the value of volumetric heat flux density q_V shown on the additional axis of abscissas. It should also be pointed out that with constant temperature $t_3(\delta)$ the value of q_V/h_V can be expressed in the following way: $q_V/h_V = B_2 N_3/\gamma^2$.

Figure 2b shows the values of the excess temperature $\vartheta_2(k) = T_2 - t_S$ (superheating) of the porous material at the end of the evaporation zone under the same conditions as given in Fig. 2a, and Fig. 2c illustrates the change of the magnitude

$$E_2 = \frac{N_3}{N_2} k = \frac{q_v \delta k}{G(i'' - ct_0)}.$$

(14)

The magnitude E_2 represents the ratio of the amount of heat supplied on account of heat release in the liquid region and in the evaporation zone to the amount of heat absorbed here by the coolant. In that case $1 - E_2$ indicates the relative fraction of the heat expended on heating and evaporating the coolant which is supplied by heat conduction from the vapor region to the evaporation zone.

Figure 3 shows the dependence of the length of the evaporation zone $k - l$ and of E_2 on the temperature of the outflowing vapor $t_3(\delta)$ when the parameters have values corresponding to points I, II in Fig. 2.

On the basis of the data presented in Figs. 2, 3 we may conclude that for the conditions under examination, heat transfer by heat conduction from the vapor region to the evaporation zone causes a qualiative change of the nature of the heat exchange. The length of the eva- poration zone decreases greatly in consequence of the increased length of the vapor region, and when the intensity of volumetric heat exchange is $h_V = 10^8$ W/(m³·°K) ($\gamma = 31.6$), the thickness of the evaporation zone does not exceed $k - l = 0.1$ instead of $k - l = 0.67$ when there is no heat supply by heat conduction from the vapor region. It should be noted that when $k - l$ is small, it is correct to assume that t_S is constant in the evaporation zone.

It follows from (8) that the temperature of the porous material in the evaporation zone increases exponentially, and its increase is determined chiefly by the heat flux trans- ferred from the vapor region. The contribution of the component q_V/h_V taking volumetric heat release into account is very small. The existence of a finite temperature difference $T_2 - t_S$ with high intensity of heat exchange enables the evaporating coolant to absorb the heat flux supplied by heat conduction. The proportion of heat E_2 expended on heating and evaporating the coolant, supplied by volumetric heat release in the liquid region and in

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the evaporation zone, is also small (Fig. 2c). The main proportion of heat $(1 - E_2)$ is conducted there by heat conduction from the vapor region.

With increasing temperature of the outflowing superheated vapor and of the porous material in the vapor region, the length of the evaporation zone remains practically unchanged (Fig. 3) but it gradually shifts to the inner surface of the element.

The obtained results enable us to determine the coordinate K of the end of the evaporation zone and the temperature difference $\vartheta_2(k) = T_2 - t_s$ at that place, which are necessary for solving Eqs. (1) with the boundary conditions (6), (7) for finding the temperature field in the vapor region. It should be noted that the common solution for the liquid and vapor regions with the boundary conditions (5), (6) has the same form as the expressions (14), (15) and (29), (30) obtained in [3] under adiabatic conditions at the boundaries of the evaporation zone. However, a change of the boundary conditions leads to a change of the integration constants. In the notation of [3] the integration constants assume the following form for the liquid region:

$$C_0 = E_1/B_1;$$

$$C_1 = \left[(1 - E_1) P - \frac{E_1}{B_1} (P + V \exp D_2)\right](P \exp D_1 - Q \exp D_2)^{-1};$$

$$C_2 = \left[-(1 - E_1) Q + \frac{E_1}{B_1} (Q + V \exp D_1)\right](P \exp D_1 - Q \exp D_2)^{-1};$$

$$P = 1 - St(1 + D_2/A_1); \quad Q = 1 - St(1 + D_1/A_1);$$

$$V = St(1 + B_1/A_1) - 1; \quad St = \alpha/Gc; \quad E_1 < 1 \tag{15}$$

and for the vapor region:

$$C_3 = 1 + E_3\left(\frac{1}{B_3} - 1\right);$$

$$C_4 = \left\{\frac{-E_3}{B_3} + \left[1 + E_3\left(\frac{1}{B_3} - 1\right)\right] \exp D_4\right\}(\exp D_3 - \exp D_4)^{-1}; \tag{16}$$

$$C_5 = -(C_3 + C_4); \quad E_3 > 1.$$

The solution for the liquid region enables us to determine the magnitude of the superheating at its end $T_1 - t_1|_{z=l} = T_2 - t_s|_{z=l}$, which is used as one of the boundary conditions in finding the temperature field of the evaporation zone.

The obtained results in determining the temperature state of the liquid region and of the evaporation zone contain in explicit form the coordinate l of the beginning of the evaporation zone which until now had been taken as independent parameter. The length $k - l$ of the evaporation zone also depends on the coordinate l, and consequently also the coordinate k of its end. The magnitude k in turn determines the temperature field of the vapor region.

The unique value of the magnitude l and the unambiguous solution of the entire problem can be found as a result of subordinating the derived parametric solutions to the last unused boundary condition: the condition of continuity of the temperature of the porous material at the end of the evaporation zone: $T_2 = T_3$ for $z = k$.

NOTATION

G, specific mass flow rate of the coolant; L, K, coordinates of the beginning and end, respectively, of the evaporation zone; Π, porosity; T, temperature of the porous material; Z, coordinate; c, heat capacity of the coolant; d, mean particle size of the porous material; h_v, intensity of the volumetric intrapore heat exchange; i, enthalpy of the coolant; l, k, dimensionless coordinates of the beginning and end, respectively, of the evaporation zone; q_v, density of volumetric heat flux; s, saturation of the porous material with liquid phase; t, temperature of the coolant; x, vapor content of the stream; z, dimensionless coordinate; δ, thickness of the porous element; λ, thermal conductivity; μ, dynamic viscosity. Subscripts: 1, 2, 3, relating to parameters in the liquid region, in the evaporation zone, and

in the vapor region, respectively; ', ", relating to the parameters of the liquid and of the vapor in the state of saturation.

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HYDRODYNAMICS OF RIVULET FLOW ON A VERTICAL SURFACE

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The flow of rivulets on a vertical surface is investigated theoretically and experimentally.

Liquid flow in the form of individual rivulets occurs upon the breakup of a liquid film. Such a regime can occur, for example, in heat-transfer devices where heat is transferred through evaporation—condensation of the heat-transfer agent [1] and in the emergency film cooling of nuclear reactors. It is closely connected with the formation of dry patches on a heated surface [2]. As investigations showed [1, 2], in such a regime rather intense heat removal from the surface occurs without causing a sharp increase in its temperature.

The majority of the research has been devoted to problems of the hydrodynamics and stability of liquid film flow or the stability of rivulet flow [3-6].

The hydrodynamics of rivulet flow has still been inadequately studied. In [7], for example, the connection between the flow rate in a rivulet and its width was obtained on the basis of a solution of the Navier—Stokes equation for rivulet flow, and it was compared with experiment and showed only qualitative agreement. The problem of describing rivulet flow is divided into two parts: the first is to describe the shape of the surface of the rivulet; the second is to find the velocity distribution in the rivulet.

In accordance with [7], we use the following physical model of rivulet flow. The shape of the rivulet is determined only by surface tension; we neglect gravity. The rivulet is represented in the form of a segment of a circle which does not vary during the entire flow. All the physical properties of the liquid remain constant. The rivulet moves uniformly in one direction under the action of gravity. We take the flow as fully developed and steady. Shear stresses at the interface are absent.

The adopted physical model and coordinate system are shown in Fig. 1. Under the adopted assumptions the Navier—Stokes equations take the form