STABILITY OF THE PROCESS OF EVAPORATION FROM A POROUS STRUCTURE DURING DISPLACEMENT OF THE LIQUID BY CAPILLARY FORCES

V. I. Khvostov and S. K. Marinichenko

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It is demonstrated that evaporation can be stable when the driving capillary pressure head varies across the thickness of a porous plate. Expressions are proposed which describe the effect of structural features and process conditions on the stability characteristics of this process.

Evaporation of liquids in porous structures is a subject of growing interest, because of the application of this process in various heat-transmitting devices (heat pipes, heat exchangers [1, 2]) and in thermal protection systems (two-phase transpiration cooling [3-8]).

In thermal protection systems as well as in evaporation-type heat exchangers built with porous structures, the heat and the coolant in the porous structure flow opposite to each other. In most studies published on this subject [9], note is taken of the fact that evaporation cooling becomes extremely difficult to attain under such conditions, owing to the instability of this process. Instability has been more than once established experimentally [3, 10, 11]. In other studies [6, 7] the stability of transpiration cooling was treated analytically with many simplifying assumptions, making it possible to reveal some fundamental conditions for stability.

It was pointed out in another report [9] that certain earlier experimental and theoretical investigations had been performed on the assumption of a constant pressure drop within the porous structure, this pressure drop being a forced one and stipulated under conditions of a negligibly small (relative to the hydraulic drag in the porous structure) capillary pressure drop. As materials for porous plates cermets were used, usually suitable for service under heavy heat loads such as those occurring in thermal protection systems. The theoretical stability analysis [6, 7] was based essentially on the same assumptions.

In [8] and several other studies there was proposed a method of quenching the instability of two-phase transpiration cooling, viz., by artifically increasing the hydraulic drag in the liquid-carrying part of the porous structure (through use of a double-layer plate). Application of this method to various technically important situations has already been theoretically analyzed in great detail [5, 8, 12]. Of practical interest with regard to several technical applications of the evaporation process in a porous structure is the case where the capillary potential serves as the driving head. Inasmuch as the then available pressure drop is relatively small, preinsertion of a plate with a large hydraulic drag cannot be justified.

We will demonstrate here that with capillary forces at the vapor—liquid interface throughout the thickness of the porous material utilized for realization of the driving head, it is under certain conditions possible to achieve a stable evaporation mode without preinsertion of extra hydraulic drag. We will demonstrate this on the simplest model accounting for only the most strongly influencing factors, just as was done in [4], e.g., in the analysis of transpiration cooling with forced feed of the coolant.

The physical model and the thermal part of the problem will be analogous to those in [6], with the exception that the internal hydraulic drag within the liquid zone and the vapor zone of the plate are assumed to be overcome by the capillary pressure drop. The physical properties of the liquid and the vapor are assumed to remain constant and determined at the saturation level. The flow of liquid through pores is assumed to obey Darcy's law. The liquid and the solid skeleton are also assumed to be at the same temperature in every section. With

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all these assumptions, the process can now be described by the system of differential equations:

equation of continuity

$$\frac{dG}{dy} = 0, \tag{1}$$

equation of motion (Darcy)

$$-\frac{dp}{dy} = \frac{\nu_i}{k} G, \tag{2}$$

equation of energy balance

$$\frac{d^2t}{dy^2} - \frac{c_{p_i} G}{\lambda_i} \frac{dt}{dy} = 0. \tag{3}$$

The boundary conditions are: given the temperature of the coolant and the thermal flux at the plate surface, on the liquid side and on the vapor side, respectively; pressure of the liquid at both the entrance to and the exit from the plate equal to the ambient pressure; pressure drop produced by capillary forces at the evaporation front for overcoming the hydraulic drag of the plate

at y = 0

$$t = t_0; \quad p = p_0; \tag{4}$$

at y = δ,

$$\lambda_2 \frac{dt}{dy} = q; \ p = p_0; \tag{5}$$

at $y = y_s$

$$t = t_s; \ \lambda_2 \frac{dt}{dy}\Big|_{y_s+0} - \lambda_1 \frac{dt}{dy}\Big|_{y_s-0} = Gr; \tag{6}$$

$$\Delta p_\sigma = \frac{2\sigma}{R} = \Delta p_1 + \Delta p_2. \tag{7}$$

The system of equations for this problem is closed by the condition of thermodynamic equilibrium at the phase transition line

$$t_s = f(p_s). \tag{8}$$

The solution to system of equations (1)-(3) yields the hydraulic characteristic and the thermal characteristic of the process, each, respectively, describing the dependence of the hydraulic drag in the porous structure and of the permissible thermal flux at the heated surface on the flow rate of coolant and on the coordinate of the evaporation front:

$$\Delta p_c = G \frac{\delta}{k} [\nu' l + \nu'' (1 - l)] \tag{9}$$

and

$$q = G(i'' - i_0) \exp \frac{G(1-l) c_p'' \delta}{\lambda_2}. \tag{10}$$

The location of the evaporation front is described by the relation

$$l = 1 - \frac{\lambda_2}{G c_p'' \delta} \ln \frac{q}{G(i'' - i_0)}. \tag{11}$$

Upon simultaneous solution of Eqs. (9) and (10), we obtain the net internal hydraulic characteristic of the system

$$\Delta p_c = G \frac{\nu' \delta}{k} + \frac{\nu'' \lambda_2}{c_p'' k} \left(1 - \frac{\nu'}{\nu''}\right) \ln \frac{q}{G(i'' - i_0)}, \tag{12}$$

where the independent variables are quantities either directly stipulated or experimentally determined through measurement: the flow rate and the heat load.

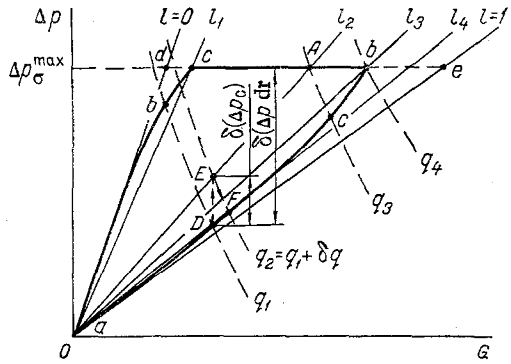


Fig. 1. Hydraulic characteristics of the evaporation process in a capillary-porous plate: q_4) limiting heat load.

Following the established procedure [6, 7], we use the stability condition in the form of relations

$$\Delta p_c = \Delta p_{dr} \tag{13}$$

and

$$\left[\frac{\partial (\Delta p_c)}{\partial G}\right]_q > \left[\frac{\partial (\Delta p_{dr})}{\partial G}\right]_q. \tag{14}$$

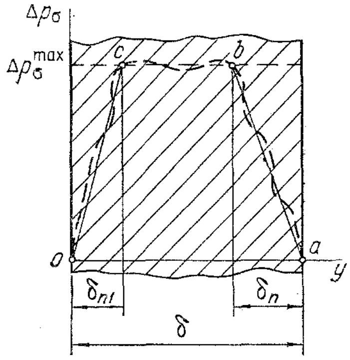
Calculations indicate that in the case of ceramic and fibrous porous materials with a thermal conductivity of 0.1-1 W/m•K and a permeability of 10^{-14}-10^{-16} m^2 under heat loads from 10^3 to 10^6 W/m^2, typical ranges of values for these materials under service conditions in evaporators, the internal characteristic according to Eq. (12) is depicted by a family of steeply dropping q = const lines, just as in the case of thermal protection devices with such materials [6, 7, 13] (Fig. 1).

The external hydraulic characteristic of the system with forced feed of coolant under a constant head is the horizontal line de. Assuming that the capillarity parameters of the porous structure (effective pore radius, wetting angle, surface tension) are precisely constant over the plate thickness, we will find that the external characteristic is a horizontal line even when displacement of the liquid by capillary forces occurs. This means that with a real combination of parameters the process is clearly unstable (point A). Experimental observations have revealed, however, that under certain conditions the process of evaporation from porous structures (with capillary feed of the coolant) is quite stable. A typical example is the operation of heat pipes. This can be explained in accordance with the existing theory of stability [6, 7], if into account is also taken the changing of the capillary pressure drop, characteristic of all porous materials, as the evaporation front moves across the thickness of the plate.

The capillary pressure drop, determined by the radius of pores within the meniscus zone, is maximum when the meniscus (evaporation front) is located deep in the plate and decreases to zero as the vapor—liquid interface reaches the surface (upon inundation or complete desiccation of the plate). The variation of the curvature of a meniscus from the minimum radius with the evaporation front deep in the plate to an infinitely large radius occurs within some boundary layer. The thickness of this layer as well as the law according to which the capillary pressure drop changes depend on the size of particles or fibers and on the porosity, also other geometrical characteristics of the porous structure, determined among others by the technology of producing the plate.

The existence of a boundary layer within which the capillary pressure drop decreases to zero at the surface fundamentally alters the trend of the external hydraulic characteristic of a porous plate. The line *a*bc0 in Fig. 2 schematically depicts the dependence of the capillary pressure drop on the location of the front of menisci deep in a hypothetical plate. The first approximation of this relation with straight lines yields for the segment *a*b

$$\Delta p_\sigma = \Delta p_\sigma^{\max} \frac{1-l}{n}, \tag{15}$$



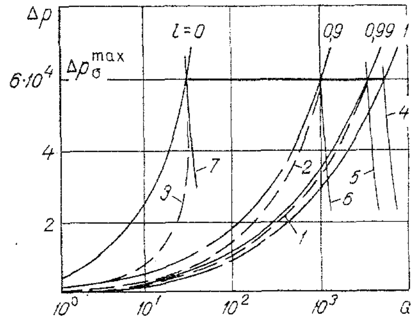


Fig. 2 Fig. 3

Fig. 2. Variation of the capillary pressure drop across the thickness of a porous plate.

Fig. 3. Hydraulic characteristics of a porous plate with various thicknesses of the end layer n: 1) 0.01, 2) 0.1, 3) 1; and q: 4) $6.4 \cdot 10^5$, 5) $3.8 \cdot 10^5$, 6) $0.84 \cdot 10^5$, 7) $0.096 \cdot 10^5$; G, 10^{-4}.

where δ_n denotes the thickness of the boundary layer on the heated side of the plate.

Along segment bc the pressure drop is maximum and remains constant. On the wetted side of the plate one must also assume the existence of a boundary layer, of thickness δ_{n1}. As will be demonstrated subsequently, the stability characteristics are determined by the layer δ_n and do not depend on the layer δ_{n1}.

The hydrodynamic characteristics of a plate, taking into account the boundary layer, are shown in Fig. 1. In contrast to the hydraulic drag, the capillary pressure drop depends only on the location of the evaporation front so that the external characteristic, accordingly, is in this case depicted by a single line $a$bc0. According to the graph in Fig. 1, for any heat load lower than q_4 there are two locations of the evaporation front and correspondingly two flow rates at which Eqs. (10) and (13) are satisfied. The process modes corresponding to points C and D are stable (with the external characteristic $a$bc0 as plotted here on the basis of changes in the capillary pressure drop along lines ab and 0c in Fig. 2). Indeed, a small increment of heat load $\delta q = q_2 - q_1$ (without change in the flow rate) causes the operating point to shift to location E and the driving (capillary) pressure head to rise by $\delta(\Delta p_{dr})$. The hydraulic drag then increases by $\delta(\Delta p_c)$, less than the driving pressure head. This in turn results in a higher coolant flow rate and (at the new level of heat load) in a shift of the operating point to F, where equation (13) is restored. Analogous conclusions are arrived at in consideration of small perturbations of the flow rate or the front location.

In order to obtain an analytical expression for the stability conditions, we transform inequality (14) taking into account that the driving head depends only on the location of the evaporation front:

$$\left[\frac{\partial(\Delta p_{dr})}{\partial G}\right]_q = \left[\frac{\partial(\Delta p_{dr})}{\partial l}\right]_q \left[\frac{\partial l}{\partial G}\right]_q = \frac{d(\Delta p_{dr})}{dl}\left(\frac{\partial l}{\partial G}\right)_q. \tag{16}$$

Then inequality (14) can be rewritten as

$$\left[\frac{\partial(\Delta p_c)}{\partial G}\right]_q > \frac{d(\Delta p_{dr})}{dl}\left(\frac{\partial l}{\partial G}\right)_q. \tag{17}$$

Quite evidently, the stability condition includes the capillary characteristics of a plate $d(\Delta p_{dr})/dl$ as well as its thermal and hydrodynamic characteristics which determine the values of the derivative $(\partial l/\partial G)_q$.

Having found the derivatives in inequality (17), we obtain from expressions (12), (15), and (11) the stability condition in the form

$$K = \frac{\dfrac{Gv'}{k}\left[\dfrac{v'' - v'}{v'} - \dfrac{\delta c_p'' G}{\lambda_2}\right]}{\dfrac{\Delta p_\sigma^{\max}}{\sigma n}\left[1 + \ln\dfrac{q}{G(i'' - i_0)}\right]} < 1. \tag{18}$$

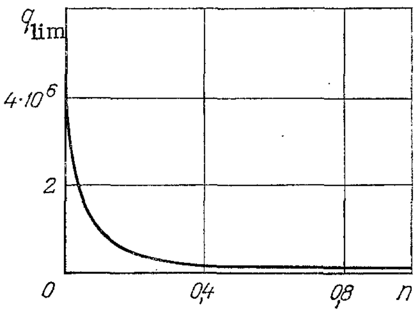


Fig. 4. Dependence of the limiting heat load on the dimensionless thickness of the boundary layer.

This expression yields estimates of the relations between parameters necessary for stable evaporation from a porous structure during displacement of the liquid by capillary forces. The method described here is, of course, applicable also in the case of a more intricate (rather than linear) variation of the capillary pressure drop within the boundary layer.

The limiting heat load, under which a given porous structure will still retain its capability of stable operation, is determined according to relation (10), into which the expression for the limiting flow rate according to relation (9) and under the condition $\Delta p_c = \Delta p_\sigma^{max}$ must be inserted, also $l = 1 - n$,

$$G_{lim} = \frac{\Delta p_\sigma^{max} k}{\delta [\nu'(1-n) + \nu'' n]}; \tag{19}$$

$$q_{lim} = G_{lim}(i'' - i_0) \exp\left(G_{lim} \frac{c_p'' \delta}{\lambda_2} n \right). \tag{20}$$

The quantitative relation between the stability characteristics and the thickness n of the boundary layer, as expressed by relations (18), (19), and (20), depends on the specific values of thermophysical, geometrical, and process parameters appearing in those expressions. The dependence of the external hydraulic characteristic of a 1.75-mm-thick porous plate of kaolin cardboard on the thickness n of the boundary layer is shown in Fig. 3 for the case of water evaporation under atmospheric pressure ($\lambda_2 = 1.88$ W/m•K, $k = 1.35\cdot 10^{-15}$ m^2, $\Delta p_\sigma^{max} = 0.6\cdot 10^5$ Pa). Evidently, even with an insignificantly small thickness of the end layer ($l = 0.99$ corresponds to $\delta_n = 17$ μm and thus to only a few fiber diameters) the limiting heat load decreases far below the level attainable with the full capillary pressure drop developed in the plate. For this case is also shown, in Fig. 4, the limiting heat load as a function of thickness n as the latter varies from zero to full plate thickness. It is noteworthy that a boundary layer of a thickness not more than 50-60% of the plate thickness lowers the limiting heat load by a factor of 30-50, while a further increase of the layer thickness will continue lowering it at a much slower rate.

NOTATION

G, mass flow rate, kg/m^2•sec; y, space coordinate, m; p, pressure, Pa; ν, kinematic viscosity, m^2/sec; δ, plate thickness, m; k, permeability factor, m^2; t, temperature, K; c_p, specific heat, J/kg•K; λ, effective thermal conductivity, W/m•K; q, thermal flux density (heat load), W/m^2; r, latent heat of evaporation, J/kg; σ, surface tension, N/m; R, conventional capillary radius, m; i, enthalpy, J/kg; l, dimensionless coordinate of the evaporation front; n, dimensionless thickness of the boundary layer; subscripts: 0, cold plate surface; s, saturation; 1, liquid layer; 2, vapor layer; σ, capillary pressure drop; c, hydraulic drag; dr, driving head; lim, limiting heat load or flow rate; superscripts: ', liquid at the saturation line, and ", vapor at the saturation line.

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PERMEABILITY OF MOIST POROUS MATERIALS

P. A. Novikov and V. S. Yalovets

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Results of an experimental study are presented pertaining to the dependence of the permeability of porous materials on their moisture content during moisturization and desiccation.

Development of a new technology has recently stimulated interest in studies pertaining to filtration of gases through moist porous systems. Interesting is that pulverulent microparticles of the filtered gas are more effectively precipitated in and retained by moist than by dry porous materials. This applies above all to porous filters protecting the environment against contamination by aggressive substances, also to technological processes involving impregnation of porous materials with various fluids and their desiccation by scavenging with warm air. Filtration of gases through porous materials and the permeability of such materials have been studied by many authors. These studies included, e.g., the dependence of the permeability of porous bodies on the hydrodynamic characteristics of the gas flow through the pores [1, 2]. The study of filtration through moist porous materials has only begun [3]. As far as these authors know, the dependence of the permeability of porous materials on their moisture content has not yet been analyzed.

For a study of this dependence there was assembled the experimental apparatus shown in Fig. 1. The cover plate 1 pressed a porous plate 2 tightly against the beaker 3. The rim of the porous plate was coated with an adhesive, to ensure hermetic sealing. Air was fed from a tank 9 through valve 8, manometer 7, and rotameter 4 to one of the beakers fitting under the porous plate. The air was then drained through the porous plate into the atmosphere. The excess pressure under the porous plate was measured with both a water manometer 6 and a reference manometer 5. The rotameter had been precalibrated against the mass flow rate of air. Atmospheric pressure was measured with a barometer. The apparatus was periodically checked for hermeticity.

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 39, No. 5, pp. 877-881, November, 1980. Original article submitted November 29, 1979.

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