INFLUENCE OF THE TWO-PHASE HELIUM FLUX STRUCTURE ON HEAT TRANSFER DYNAMICS

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UDC 536.48

It is established as a result of an experimental investigation that the quantitative and qualitative characteristics of nonstationary heat transfer depend substantially on the two-phase helium flux structure. A simple working model that permits estimation of the influence of the expended mass vapor-content and density of the heat flux on the dynamics of the process for a homogenized phase distribution (bubble and emulsion flow modes) is proposed to describe nonstationary film boiling. The fundamental heat transfer singularities under conditions of a dispersely annular flux structure are noted.

INTRODUCTION

The reliability of superconducting (SC) system operation, cryostabilized by helium, depends to a significant degree on the stability to impulsive heat liberation. Estimation of the thermal stability conditions for immersed systems was performed by Jackson [1], Steward [2], and many others, whereupon extensive material has accumulated. Certain results in application to SC systems, for instance, accelerators cryostatted by underheated or supercritical helium, are presented in [3] and [4], respectively. Recently interest has grown in systems in which forced fluxes of two-phase helium [5-7] are preferred for utilization as cryoagents. However, the authors have not encountered results of an experimental investigation of the heat transfer to two-phase helium under impulsive energy liberation conditions although the singularities assumed for such processes as compared with modifications of the single-phase or static cryoagent flux should be sufficiently substantial.

An attempt is made in this paper to fill in the gap noted by paying special attention to the interrelation between the quantitative characteristics of the thermal processes being investigated and the flow modes of two-phase helium fluxes in horizontal channels.

EXPERIMENTAL EQUIPMENT

Selection of the channel orientation was due to features of the actual structures with superconducting magnets [5-7] being used for cryostabilization of two-phase helium. Typical channels of such systems have a section in the shape of a circle (pipes) or a ring. We investigated the nonstationary heat transfer to helium moving in channels of annular section. The construction of the experimental specimen is displayed schematically in Fig. 1. It is an evacuated ceramic pipe with carbon films of length 4.2 and 57 mm deposited on the outer surface that are simultaneously low-inertia heaters and thermometers (HT). The ceramic pipe is placed in a steel pipe to produce an annular channel with a uniform gap. Hydrodynamic flux stabilization sections are in front of the section with the films and after it. A cryostat with the experimental specimen was installed in a circulation stand [9].

The experiments were performed at the constant pressure P = 129 kPa while the other two-phase helium flux parameters varied in the following ranges: the relative enthalpy x = 0-1, the mass flow rate m = 20-140 kg/(m^2·sec). A step shaped power pulse with not more than 20 μsec leading front duration was delivered to the specimen, where the heat liberation power in the HT after the front was stabilized by a special electronic system. Measurements started 20 μsec after delivery of the power pulse and were performed at 50 μsec intervals or greater. The heat flux density q varied between 0.5 and 50 kW/m^2. A more detailed description of the equipment utilized can be found in [8].

United Institute of Nuclear Investigations, Dubna. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 58, No. 6, pp. 885-892, June, 1990. Original article submitted May 25, 1989.

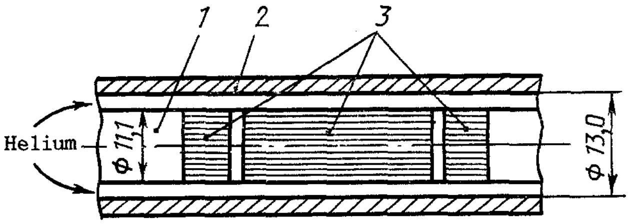

Fig. 1

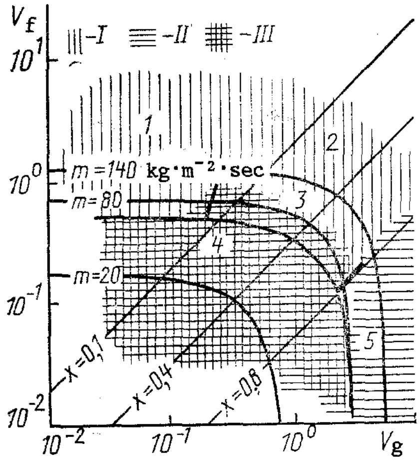

Fig. 2

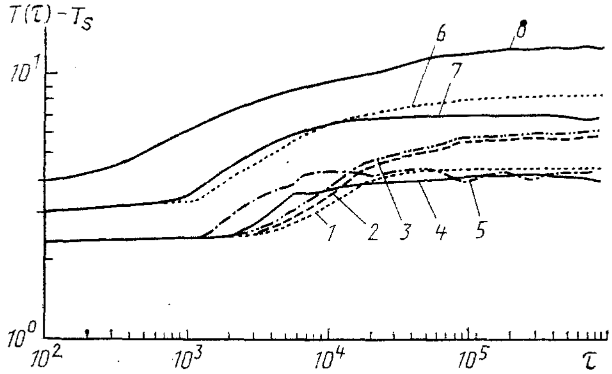

Fig. 3

Fig. 1. Experimental specimen: 1) ceramic pipe; 2) steel pipe; 3) carbon films.

Fig. 2. Two-phase helium flow modes in the horizontal channel of a 30 mm high slot section with Δ = 1 mm gap for P = 0.13 MPa ($V_f = m(1 - x)/\rho_f$, m/sec; $V_g = mx/\rho_g$, m/sec): 1) bubble mode; 2) emulsion; 3) intermittent; 4) stratified; 5) dispersely-annular; domains: I) homogenized phase distribution; II) with symmetric phase distribution relative to the channel axis; III) with phase distribution dependent on the vertical coordinate m is in $kg \cdot m^{-2} \cdot sec^{-1}$.

Fig. 3. Dependences of heating $T(\tau) - T_s$ on time τ after power pulse delivery for a homogenized phase distribution in the flux (P = 0.13 MPa): 1) q = $6.9 \cdot 10^3$ $W \cdot m^{-2}$, x = 0.05, m = 120 $kg \cdot m^{-2} \cdot sec^{-1}$; 2) $6.9 \cdot 10^3$, 0.05 and 42; 3) $6.9 \cdot 10^3$, 0.05 and 25; 4) $6.9 \cdot 10^3$, 0.3 and 120; 5) $6.9 \cdot 10^3$, 0.5 and 120; 6) $1.31 \cdot 10^4$, 0.05 and 120; 7) $1.31 \cdot 10^4$, 0.3 and 120; 8) q = $2.13 \cdot 10^4$ $W \cdot m^{-2}$, x = 0.3, m = 120 $kg \cdot m^{-2} \cdot sec^{-1}$. $T(\tau) - T_s$, K; τ, μsec.

RESULTS AND DISCUSSION

Before discussing the results, it should be noted that the features of the dynamics and the intensity of the heat transfer to a static cryoagent under a step power pulse (the limit case of the process for a forced flow) depend on the time τ, the heat flux density q, and the pressure P [2]. When examining the heat transfer to a moving two-phase cryoagent, it is necessary to take account of at least the expended mass vapor content x and the mass velocity m of the flux, which increases the number of variables and complicates the problem. It can here be expected that the influence of these flux parameters on the dynamics of nonstationary heat transfer is due to the dependence of the flux structure on m and x.

The dependence of the flux structure on its mode parameters is ordinarily displayed in the form of a flow mode chart. Such a chart [9] is shown in Fig. 2 for a horizontal helium flux supplemented by our latest experimental data. As is seen from this figure, the following structures are characteristic for two-phase helium flux in the investigated range of mass flow rates and vapor-contents: bubble, stratified, intermittent, dispersely-annular, emulsion. In connection with the fact that the heater thermometer is a horizontal cylinder

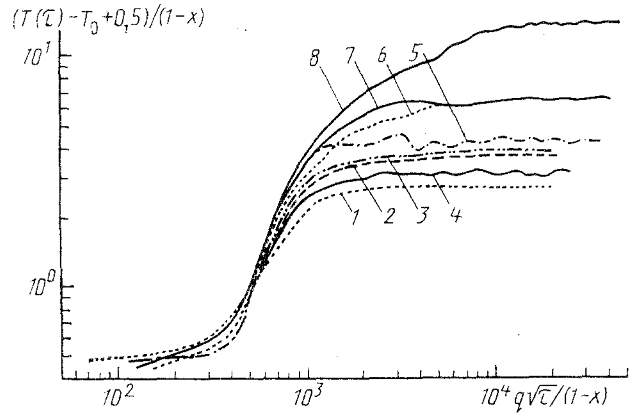

Fig. 4. Dependences of $\Delta T(\tau)$ for a homogenized phase distribution in the coordinates $[T(\tau) - T_0 + 0.5]/(1 - x)$, K, $q\sqrt{\tau}/(1 - x)$, $W \cdot sec^{0.5}/m^2$. Notation the same as in Fig. 3.

around which the flux flows, correct quantitative results can be obtained for the flow modes by using the experimental specimen when the phase distribution is almost homogeneous or has cylindrical symmetry. Consequently, the main attention is paid to the bubble, emulsion, and dispersely annular two-phase helium flow modes.

We start discussion of the results with the case when the phase distribution is comparatively uniform over the channel section, i.e., with the bubble and emulsion modes denoted by the shaded domain vertically in Fig. 2. The characteristic dependences of the heating ΔT of the heat eliminating surface on the time are presented in Fig. 3 curves 1-8 for these structures.* Here and henceforth, features of the processes are considered for a 4.2 mm long HT for magnitudes of q considerably exceeding the critical value and 100 μsec to 1 sec times. In this interval, growth of the vapor film occurs on the heat-eliminating surface. We will later call this process the nonstationary film boiling mode. It is seen from the figure that the mass flow rate and the expended vapor content exert no influence, in practice, on the intensity and dynamics of the heat elimination at the beginning of the thermal pulse action. However, as the time increases this influence appears in that the most rapid temperature rise is observed for greater vapor-contents and smaller mass flow rates. It can also be seen that the vapor-content exerts a greater influence on the heat transfer intensity than does the mass flow rate. As the mass flow rate diminishes and the relative flux enthalpy reduces to zero, the nature of the nonstationary heat transfer to the moving cryoagent becomes similar to the corresponding dependence for nonstationary heat transfer in a large volume. This can be the basis for constructing a model of nonstationary film boiling of a two-phase mixture for the bubble and emulsion flow modes.

As regards the heat transfer to a static cryoagent under nonstationary film boiling conditions, then this process can be stimulated in a first approximation on the basis of the following assumptions: 1) vapor film thickness equals zero and the surface temperature the quantity T_0 at the time τ_{fi} of going over to unsteady film boiling; 2) the temperature of the vapor—fluid boundary of the growing film equals T_0 during the extent of this process; 3) the heat flux through the vapor film boundary with the fluid is expended completely in fluid evaporation; 4) the thermodynamic properties of helium are independent of the temperature and determined on the saturation line.

The formal solution of such a problem can be found in the form of double power series [10]. The temperature of the heat-eliminating surface will here be determined by the following expression

$$T(\tau) = T(0, \tau) = T_0 + \frac{1}{\lambda_g} \sum_{k=1}^{\infty} B_k \frac{[q^2 a_g (\tau - \tau_{fi})]^k}{(a_g h \rho_g)^{2k-1}}. \quad (1)$$

Without examining questions of convergence of the series (1) here, we use this expression just to expose the self-similar variables of the process. After manipulation, we obtain

*Experimental points are not separated on this and subsequent figures since they practically merge.

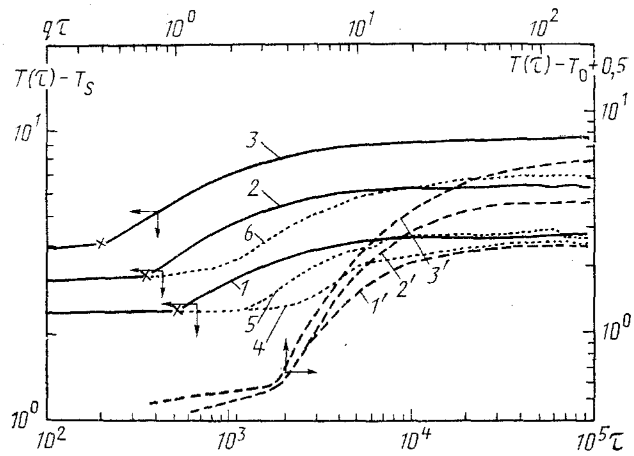

Fig. 5. Dependences of the heating $T(\tau) - T_s$ on the time τ for the dispersely-annular flow mode (curves 1-3) and a homogenized phase distribution (4-6) ($P = 0.13$ MPa, $m = 120\ kg\cdot m^{-2}\cdot sec^{-1}$): 1, 1') $q = 6.9\cdot 10^3\ W\cdot m^{-2}$, $x = 0.8$; 2, 2') $1.31\cdot 10^4$ and 0.8; 3, 3') $2.13\cdot 10^4$ and 0.8; 4) $6.9\cdot 10^3$ and 0.3; 5) $6.9\cdot 10^3$ and 0.5; 6) $q = 1.31\cdot 10^4\ W\cdot m^{-2}$, $x = 0.3$. $q\tau$, J/m^2.

from (1)

$$[T(\tau) - T_0]\frac{c_p}{h} = \sum_{k=1}^{\infty} B_k\left[\frac{q(\tau - \tau_{fi})c_p}{h^2\lambda_g\rho_g}\right]^k. \qquad (2)$$

Therefore, the self-similar variables can be represented in the form $[T(\tau) - T_0]c_p/h$; $q\sqrt{\tau - \tau_{fi}}/h\sqrt{\lambda_g\rho_g/c_p}$. It can also be noted that the quantity τ_{fi} is much less than the characteristic times of the processes under consideration, i.e., $\tau_{fi} \ll \tau$, therefore, $\tau - \tau_{fi} \simeq \tau$. A confirmation utilizing experimental data of [11] showed that such an approach is completely well-founded.

Let us attempt to use these self-similar variables for the case of a two-phase mixture. It seems logical here to introduce a superposition of the liquid and gas phase properties of the flux into (2) instead of the fluid properties, as is completely justified for a homogeneous structure. That is, we use the specific energy needed to evaporate the liquid phase $h_{tp} = (1 - x)h$ instead of the specific heat of evaporation h. Then the possible self-similar variables of the passage over to nonstationary film boiling for a two-phase mixture acquire the form

$$[T(\tau) - T_0]\frac{c_p}{h(1-x)};\quad \frac{q\sqrt{\tau}}{h(1-x)\sqrt{\lambda_g\rho_g/c_p}}.$$

The form of the self-similar variables simplifies somewhat when the pressure is constant:

$$[T(\tau) - T_0]\frac{1}{1-x} = \psi\left(\frac{q\sqrt{\tau}}{1-x}\right). \qquad (3)$$

The operability of the proposed model under bubble and emulsion flow conditions is shown in Fig. 4. Here the curves 1-8 in the coordinates $[T(\tau) - T_0 + 0.5]/(1 - x)$; $q\sqrt{\tau}/(1 - x)$ represent* the initial dependences $\Delta T(\tau)$ displayed in Fig. 3. The HT temperature at the time $\tau = 100$ μsec is taken here as T_0. It is seen from the figure that curves 1-8 practically merge in the time and heating ranges corresponding to the vapor film formation process. This indicates that despite the sufficiently approximate estimates used in the derivation of (3), the

*The value 0.5 is introduced into (3) for convenience in representing the dependences in logarithmic coordinates since for $\tau = 100$ μsec the quantity is $T(\tau) - T_0 = 0$.

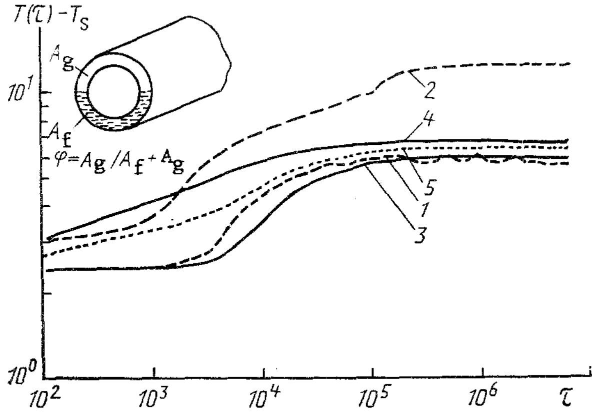

Fig. 6. Dependences of the heating $T(\tau) - T_s$ on the time τ for stratified flow (1, 2) and under conditions of single-phase cryoagent motion (3, 4) (P = 0.13 MPa, m = 25 $kg\cdot m^{-2}\cdot sec^{-1}$); 1) q = $6.9\cdot10^3$ $W\cdot m^{-2}$, x = 0.3; 2) $1.31\cdot10^4$ and 0.3; 3) $6.9\cdot10^3$ and 0; 4) $6.9\cdot10^3$ and 1; 5) computation using the relationship (7).

main factors that influence the dynamics and intensity of the initial nonstationary film boiling process are taken into account sufficiently correctly. However, stratification of the curves as a function of the flux velocity and vapor content is observed with the lapse of time, which is especially characteristic for the bubble mode. This is certainly explained not only by the incompletely homogeneous phase distribution and the influence of the flux velocity on vapor film formation but also by growth of the pressure in the comparatively extended narrow channel during evaporation of the part of the fluid that can be sufficiently significant.

We now turn to an exposition of the experimental results obtained for another phase distribution in the flux. For a vapor-content above 0.75-0.8 and relatively high mass flow rates, a dispersely annular flow mode of a two-phase mixture is realized that corresponds (see Fig. 2) to the horizontally shaded domain. The distinguishing feature of this mode is that the liquid and gas phase distribution is nonuniform over the channel section but is approximately symmetric relative to its axis. We trace how changes in the flux structure are reflected in the nature of the nonstationary heat transfer.

The data $\Delta T(\tau)$ obtained for the dispersely annular (1-3) and emulsion (4-6) flow modes are presented in Fig. 5. This figure shows that in qualitative respects the influence of the expended vapor-content on the nature of the nonstationary heat transfer in the dispersely annular mode is conserved approximately the same as for the homogenized phase distribution, i.e., at the first instants [$\tau \lesssim (2\text{-}5)\cdot10^2$ μsec used for curves 1-3] the relative enthalpy exerts no noticeable influence on the heat transfer intensity but the most rapid growth in the heating (other conditions remaining equal) is observed later for large values of x. This is illustrated by curves 1 and 5, 4, respectively, for the dispersely-annular and emulsion flows. Such a feature of the nonstationary heat transfer as the presence of characteristic breaks in the curves $\Delta T(\tau)$, noted by crosses in Fig. 5, turns attention to itself for the dispersely annular mode. The rate of heating growth increases abruptly after them. Such breaks, indicating a qualitative change in the heat elimination mechanism, are not observed for a homogenized phase distribution. The times τ_{fi} corresponding to a break in the curves of $\Delta T(\tau)$ depend on both the modal parameters of the flux and on the thermal pulse power. Analysis of the experimental data shows that the magnitude of the product $q\tau_{cr}$ is a function of just the parameters z, m, P and is independent of the thermal flux density, i.e.,

$$q\tau_{cr} = C(m,\ x,\ P). \tag{4}$$

This is illustrated by the representation of the data $\Delta T(\tau)$ in the coordinates $[T(\tau) - T_0 + 0.5]$-$q\tau$ by curves 1'-3' in Fig. 5. The dependence (4) between τ_{cr} and q can be explained by drying up of the fluid film on the surface of the heat liberating element. Indeed, if it is considered that all the thermal pulse energy is expended in fluid evaporation, the condition for drying up of a film of thickness δ has the form

$$\int_0^{\tau_{cr}} q(\tau)\, d\tau = h\delta. \quad (5)$$

Under a step power pulse (i.e., for q = const) the relationship (5) converts to the form

$$q\tau_{cr} = h(P)\,\delta(x,\ m,\ P), \quad (6)$$

analogous to (4) in structure. Therefore, the dependences (4) and (6) permit determination of the interrelation between the fluid film thickness on the surface of the heat-liberating element and the characteristics of nonstationary heat elimination for the dispersely annular mode.

Finally, let us consider the nonstationary heat transfer processes for flow modes when the structure of the phase distribution over the channel section changes substantially with the vertical coordinate. Among such modes are the stratified and intermittent, combined in Fig. 2 in the domain shaded by the mesh. It should be noted that construction of the experimental specimen permits only preliminary results to be obtained, which is due to differences in the heat elimination processes for the upper and lower generatrices of the cylindrical HT. Without pretending to completeness of analysis, let us discuss just the stratified mode as the limit case of a nonuniform phase distribution over the vertical. The characteristic dependences $\Delta T(\tau)$ for the stratified flow mode are presented in Fig. 6 as curves 1 and 2. The dependences $\Delta T(\tau)$ corresponding to heat elimination to the pure fluid flux are represented here by curve 3 and to pure vapor by curve 4. It is seen from Fig. 6 that the intensity of heat elimination to the stratified flux at the beginning of power pulse action ($\tau \lesssim 2\cdot10^3$ µsec) is close to the heat elimination intensity to a pure fluid. As time lapses, curve 1 corresponding to a two-phase flux with an x = 0.3 vapor-content occupies an intermediate position between curves 3 (x = 0) and 4 (x = 1).

We attempted to simulate the process to estimate heat-elimination intensity to a stratified flux by using the data of limit cases as $x \to 1$ and $x \to 0$. In a first approximation the heat drain from the upper and lower parts of the thermometer-heater can be considered as heat elimination to a vapor and fluid, respectively, as the insert in Fig. 6 illustrates. In such an approach the mean of film heating over the perimeter is defined as

$$\Delta T(\tau) = \Delta T_{\varphi=1}(\tau)\,\varphi + \Delta T_{\varphi=0}(\tau)\,(1-\varphi), \quad (7)$$

where $\varphi = A_g/(A_g + A_f)$ is the true bulk vapor-content, and $\Delta T_{\varphi=0}(\tau)$, $\Delta T_{\varphi=1}(\tau)$ are dependences of the heating of the heat-eliminating surfaces for the fluid and gas, respectively. An expression from [12] obtained for the stratified modes

$$\varphi(x) = \left[1 + \frac{1-x}{x}\left(\frac{\rho_g}{\rho_f}\right)^{4/7}\left(\frac{\eta_f}{\eta_g}\right)^{1/7}\right]^{-1} \quad (8)$$

can be used as the dependence of the true bulk vapor-content φ on the mass expended vapor-content x for annular horizontal channels. The result of computing $\Delta T(\tau)$ in conformity with (7) and (8) where values of the curves 3 and 4 are utilized as $\Delta T_{\varphi=0}(\tau)$ and $\Delta T_{\varphi=1}(\tau)$ are represented by curve 5 in this same figure. It is seen from the figure that the relationship (7) is valid only for relatively larger times, for $\tau \gtrsim 8\cdot10^3$ µsec under the conditions of this experiment. The real process proceeds more intensely in the initial times than the model predicts. This can be associated with the presence of the thin fluid film that partially or completely covers the upper generatrix of the heat-liberating element, which contributes to intensification of the heat elimination.

A detailed investigation of the heat elimination for flow modes when the mutual phase distribution depends substantially on the vertical coordinate is expediently conducted by using a heat liberating element sectioned along the perimeter.

CONCLUSION

The experimental data obtained and the results of the modeling indicate that the two-phase flow structure substantially influences the dynamics and intensity of nonstationary heat transfer to helium. For a dispersely annular mode the clearly fixed time of transition to the crisis is inversely proportional to the heat flux density, which is explained by the dynamics of film dessication on the heat eliminating surface. The dependences of the heating of the heat-eliminating surface on the time have no characteristic breaks under emulsion and bubble mode conditions, which could be interpreted as a qualitative change in the heat transfer mechanism. The initial nonstationary boiling process is self-similar in the variables $[T(\tau) - T_0]/(1 - x)$; $q\sqrt{\tau}/(1 - x)$ for these flow modes. Formation of a fluid film is possible for stratified flow on the upper heater generator, which intensifies the heat elimination in the initial moments.

NOTATION

x, φ, respectively, the expended mass and true bulk vapor-content; m, mass flow rate; P, pressure; q, heat flux density; δ, fluid film thickness; T, temperature; $\Delta T = T - T_s$, heating relative to the saturation temperature; T_0, temperature of the heat-eliminating surface at the time τ_{fi}; τ, time; τ_{fi}, time corresponding to the transition to nonstationary film boiling; τ_{kp}, time of crisis onset; c_p, gas specific heat; λ, thermal conductivity; ρ, density; a, thermal diffusivity; η, dynamic viscosity; h, specific heat of evaporation; A, transverse section area; V, reduced velocity; C, a constant; B_k, series coefficients. Subscripts: f, fluid; g, gas; tp, two-phase (tp); s, saturated.

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