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A. A. Genbach, N. O. Jamankulova

Almaty University of Power Engineering & Telecommunications, Almaty, Kazakhstan.
E-mail: dnellya@mail.ru

CHARACTERISTICS OF THE SINGLE STEAM BUBBLE IN CELLS OF CAPILLARY-POROUS STRUCTURE

Abstract. In this article a physical model for the generation of single (individual) steam bubbles in separate cells of the capillary-porous structure was developed. Individual characteristics of bubbles can significantly (on one-two orders) differ from integral size and that is important for an explanation of emergence and development of cracks of a damage of details and clusters of heat power stations. The solution of a problem on evaporation of a clinoid microlayer under the steam bubble growing in a cell of porous structure covering a metal heating surface (substrate) was used. The task was to determine the time dependence of the film thickness distribution and the distribution of temperature field in the wall in the area of the radius of the "dry" spot. Wall material was copper and stainless steel. The surface was taken as infinite plate (semi-limited solid body). At determination of radius of a "dry" spot, experimentally obtained approximation for the law of the growth of a bubble in a cell of porous structure taking into account the influence of underheating, speed of liquid and thermal properties of liquid and a heating surface was used. It is shown that an excess of fluid in the porous structure reduces the amount of separated diameter of the bubble, which is associated with a decrease in average-mass temperature and overheating of the liquid film.

Keywords: boiling, single steam bubble, capillary-porous structure, clinoid microlayer, "dry" spot, depth of cooling.

Introduction. Not without interest is to obtain characteristics (parameters) of a single steam bubble that characterize its dynamic growth in capillary-porous materials. They may differ significantly from the integrated characteristics and boiling parameters in a large volume without the porous surface coating [1, 2]. However, they allow to qualitatively identify the influence regime and arrangement factors in the process of boiling liquid in the cells of the porous structure [3-12].

The problem is reduced to a certain time τ dependent variables: the thickness δ of the film distribution under the steam bubbles growing on a porous surface, at $0 \le r \le R_{cn}$, considering that at $r = R_{cn}$, it is set liquid film of constant δ_0, evaporation of which is compensated by dribbling of fresh portions of the relatively cold liquid by means of capillary and mass forces $\Delta P_{g+\kappa an}$; fluid temperature distribution in the film θ of thickness δ; the depth of cooling $\bar{h}$, to which the front of temperature perturbation in the steam generating surface is amplified; local heat flux, bled with individual steam bubble. All these quantities will be determined at fixed value of liquid overheating P.

Let us make a record of outlined functions in dimensionless form as in [1, 2]:

$$\bar{\delta} = \frac{\delta}{\delta_0}; \quad \Theta = \frac{(T_0 - T_{X=0})}{(T_0 - T_S)}; \quad \bar{h} = \frac{h\lambda'}{\delta_0 \lambda}; \quad \tilde{q} = \frac{q\delta_0}{\lambda'(T_0 - T_S)} = \frac{q}{q_0}; \qquad (1)$$

q_0 – heat flux, bled by steam bubble; $q = 2q(0,\tau) = 2[T_0 - T(0,\tau)]\frac{\lambda}{h}$ – heat flux at the "liquid film – wall" on the part of the wall.

The argument is the dimensionless time $t = \dfrac{a\tau(\lambda')^2}{(\delta_0\lambda)^2}$.

Fixed amount is liquid overheating $P = \dfrac{4c\rho(T_0 - T_S)\lambda}{3r'\rho'\lambda'}$ (heat parameter).

Agreed notations: r – coordinate of steam generating surface covered with porous structure; R_{cn} – radius of "dry spot" along the coordinate r; $T_0 = T(x,0)$ – liquid temperature at $\tau = 0$ (initial liquid temperature at the wall); T_S – saturation temperature; λ, λ' – thermal conductivity of the wall and the liquid; a – temperature conductivity coefficient; c, ρ, ρ' – wall heat capacity, the wall and the liquid density; r' – heat of evaporation.

The dimensionless time can also be defined as $\tilde{t} = \dfrac{t}{t_P}$, where t_P – time required for complete evaporation of the film at a given parameter value P, i.e t_P= f(P). This dependence is calculated at $\bar{y} = 1(\bar{\delta} = 0)$, where $\bar{y} = 1 - \bar{\delta}$.

The value q on the side of the liquid on the "wall - liquid" boundary

$$q = \frac{\lambda'}{\delta}\left[T(0,\tau) - T_S\right]$$

In the works [13, 14] it is noted the urgency due to the influence of the boiling surface (with subcooling) on the intensity of the focal corrosion of fuel element cladding, which may occur due to the collapse of bubbles in the subcooled liquid.

In studied capillary-porous cooling system the liquid boiling, subcooled to the saturation temperature, takes place inside and on the structure surface, as the massive forces create excess fluid [8.12], but in the works [13, 14] boiling occurs on the surfaces without porous coatings.

Currently, liquid microlayer research at the base of the steam bubble is carried out in many scientific centers of the world [15,16]. However, it is needed further study of single bubbles in the cells of a new class of diverting systems [10-12], especially made of poor thermally conductive brittle coatings. This makes it possible to analyze the development of fatigue cracks in the bubbles activation centers, to apply the theory of thermoelasticity to the limiting state of the heat exchange surface, to draw an analogy between the processes of heat transfer in micro- and macrokinetics of origin and development of bubbles and the processes of thermal destruction of porous coatings. In addition, as noted in the works [13-16], many authors model the boiling process on heat transfer surfaces, that are absolutely smooth (nanoscale surface), which is far from the actual thermal power plants.

The process model of heat transfer. Let us consider the unsteady heat transfer at microlayered evaporation of liquid film under the steam bubble, growing cells of the capillary-porous structure, by the heat supply from the storage volume of the steam generating surface, which is taken as infinite plate with $\delta_{пл}$ thickness (figure 1).

The problem of the evaporation of the liquid film from the solid surface, received by semibounded $(\delta \to \infty)$ for a variety of conditions, is presented in the works [1, 2].

We use a solution of the evaporation problem of the liquid film from the solid surface, considering that the film thickness $\delta_0$is in the cell of capillary-porous structure.

It applies a linear temperature distribution over the film thickness δ:

$$\delta = \delta_0 - \frac{\lambda'}{r'\rho'}\int_0^{\tau}\left(\frac{\partial T}{\partial x}\right)_{x=0} d\tau, \qquad (2)$$

at $x = -\delta_0$, $T = T_S$; $x = 0$, $T = T_0$.

The temperature field in the plate (substrate), which is covered with porous structure, is described by the one-dimensional heat equation:

$$\frac{\partial T}{\partial \tau} = a\frac{\partial^2 T}{\partial x^2}. \qquad (3)$$

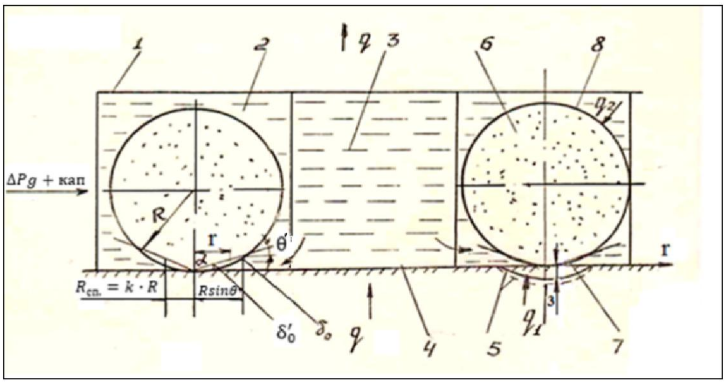

Figure 1 – Model of contact of steam bubbles with steam generating surface in the steam generation cells of the porous structure: 1 – skeleton of the porous structure; 2 – steam generation cell; 3 – cell of liquid power supply; 4 – steam generating surface; 5 – the temperature wave distributing front h in a volume of the heat generating surface made of the stainless steel and copper (dotted line) (the depth of cooling); 6 – steam; 7 – "dry" spot; 8 – distribution front of light (steam) phase

Initial conditions:

$$0 \le x \le \delta_{пл},\ \tau = 0,\ T(x,0) = T_0. \quad (4)$$

Boundary conditions:

$$x = 0,\ \tau \ge 0,\quad \lambda\left(\frac{\partial T}{\partial x}\right)_{x=0} = \lambda'\frac{T(0,\tau)-T_S}{\delta}; \quad (5)$$

$$x = \delta_{пл},\ \tau \ge 0,\ \left(\frac{\partial T}{\partial x}\right)_{x=\delta_{пл}} = 0.$$

To solve this nonlinear unsteady heat conduction problem it is used the integral method to average the heat-transfer equation on the areas $0 < x < h$ at $\tau < \tau_к$ and by the areas $0 < x < \delta_{пл}$ at $\tau > \tau_к$.

Under $\tau_к$ is meant time of complete evaporation of the liquid film, in which the temperature perturbation front, distributing in a solid body, does not reach the plate thickness $\delta_{пл}$ and characterizes the area $0 < x < \delta_{пл}$ with quantity of cooling depth h $(h < \delta_{пл})$, when

$$T = T_0,\ \left(\frac{\partial T}{\partial x}\right)_{x=h} = 0.$$

When $\tau > \tau_к$, front of temperature perturbation in the heating surface resulting from the selection of heat by the individual bubble, in steam generation cell, reaches the border of the plate $h=\delta_{пл}$. Thus, in the case, where $\tau < \tau_к$, plate can be considered as semibounded body, and the plate thickness $\delta_{пл}$ is not included in the calculation dependance [2].

In the case of $\tau < \tau_к$ problem is reduced to a system of differential equations for a semibounded body $(\delta_{пл} \to \infty)$, which is written in dimensionless form [1]

$$\frac{1}{3}\frac{d}{dx}(\bar{h}\theta) = \frac{2\theta}{\bar{h}};\quad \frac{2\theta}{\bar{h}} = \frac{1-\theta}{\bar{\delta}} = \tilde{q}, \quad (6)$$

где $\tilde{q} = \dfrac{2q(0,\tau)}{q_0};\ q(0,\tau) = \dfrac{[T_0 - T(0,\tau)]\lambda}{h};\ q_0 = \dfrac{[T_0 - T_S]\lambda'}{\delta_0};\ \bar{\delta} = 1 - \dfrac{p\theta\bar{h}}{4}.$

The values θ and $\bar{h}$ depending on $\bar{\delta}$ are given by

$$\theta = -\frac{1-\bar{\delta}}{p\bar{\delta}\left[1-\sqrt{1+\dfrac{2p\bar{\delta}}{1-\bar{\delta}}}\right]};\quad \bar{h} = \frac{2(1-\bar{\delta})}{p\sqrt{1+\dfrac{2p\bar{\delta}}{1-\bar{\delta}}}}. \quad (7)$$

Then the differential equation takes the form:

$$\left[2p+(1-2p)\bar{y}+\sqrt{2p\bar{y}}\sqrt{1+\frac{1-2p}{2p}\bar{y}}\right]d\bar{y}=\frac{3}{4}p^2dt, \tag{8}$$

where $\bar{y}=1-\bar{\delta}$.

Determination of boiling parameters, results and discussion. For a capillary-porous system operating in the pressure range (0,1 ... 200) bar having a heating surface made of copper and stainless steel, liquid superheat value $P > 0,5$. Then integrating the differential equation within $\delta_1 = 0$; $\delta_2 = \bar{\delta}$, we obtain a distribution of the film thickness in the range $0 \le r \le R_{cn}$, which is different from the work [1]:

$$2p\bar{y}+\frac{1-2p}{2}\bar{y}^2+0.393\frac{(2p)^2}{(2p-1)^{3/2}}+\frac{\sqrt{2p}}{2}\bar{y}^2\sqrt{\frac{1}{y}-\frac{2p-1}{2p}}-\frac{(2p)^{3/2}}{4(2p-1)}\times$$
$$\times\left[\bar{y}\sqrt{\frac{1}{y}-\frac{2p-1}{2p}}+\sqrt{\frac{2p}{2p-1}}arctg\frac{\sqrt{2p}\sqrt{\frac{1}{\bar{y}}-\frac{2p-1}{2p}}}{\sqrt{2p-1}}\right]=\frac{3}{4}p^2t. \tag{9}$$

Considering the value $\bar{y}=1$ in the resulting equation, we define time τ_0 of complete evaporation of microlayer with thickness δ_0, at which under the bubble in the structure cell the "dry" spot is settled ($r = R_{cn}$):

$$f'(p)=\frac{2p+1}{2}+0.393\frac{(2p)^2}{(2p-1)^{3/2}}+0,5-\frac{(2p)^{1,5}}{4(2p-1)}\times$$
$$\times\left[\sqrt{\frac{1}{2p}}+\sqrt{\frac{2p}{2p-1}}arctg\frac{1}{\sqrt{2p-1}}\right]=\frac{3}{4}p^2\frac{a\tau_0}{\delta_0^2}\left(\frac{\lambda'}{\lambda}\right)^2=\frac{3}{4}p^2\tilde{\tau}_0. \tag{10}$$

Then the radius of the "dry" spots on the base of the steam bubble is given by:

$$R_{cn}=\frac{\delta_0}{tg\alpha}=\frac{\sqrt{3}}{2tg\alpha}\frac{\lambda'}{\sqrt{\rho c\lambda}}\frac{p\sqrt{\tau_0}}{\sqrt{f'(p)}}, \tag{11}$$

where α – the angle between the heating surface and a tapered microlayer located under the bubble with a radius R_{cn}.

For capillary-porous system working in the field of mass forces, we have defined the law of steam bubble growth [3] as

$$R_d = 2\sqrt{54,1a'Ja\tau_0}\left[1+\left(\frac{m_{жс}}{m_n}\right)^{0,1}\right]^{-1}.$$

Then the equation for $R_{сп}$ is converted to the form:

$$R_{cn}=\frac{\sqrt{3}}{2tg\alpha}\frac{\lambda'}{\sqrt{\rho c\lambda}}\frac{p}{\sqrt{f'(p)}}\frac{R_d\left[1+(m_{жс}/m_n)\right]^{0,1}}{2\sqrt{54,1a'Ja}}, \tag{12}$$

where the ratio of $\frac{R_{cn}}{R_d}=K$ represents a coefficient of "dry" spot.

Researches of values $\bar{\delta},\theta,\delta$ of $\tilde{t},P,r,\tau,R_{cn}$ depending on the angle α at fixed values of pressure, temperature difference, thermal properties of the wall are shown in figures (2–5).

Generally speaking, in the studied capillary-porous cooling system the influence of subcooling, liquid velocity and liquid thermal properties and the heating surface can be approximated by the averaged expression of the form:

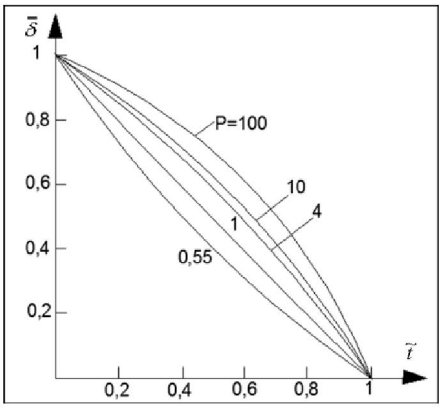

Figure 2 – Changing the thickness $\overline{\delta}$ of the water film through time $\widetilde{t}$ in the base of the steam bubble growing in the structure cells

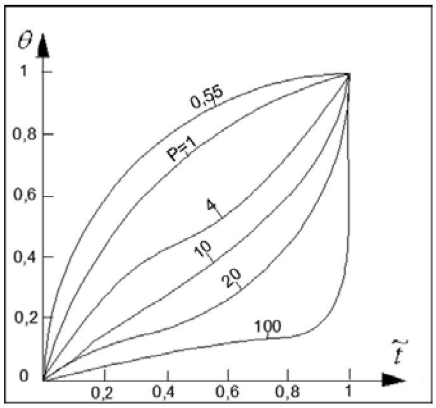

Figure 3 – Temperature field distribution θ through time $\widetilde{t}$ in the steam generating surface, covered by porous structure

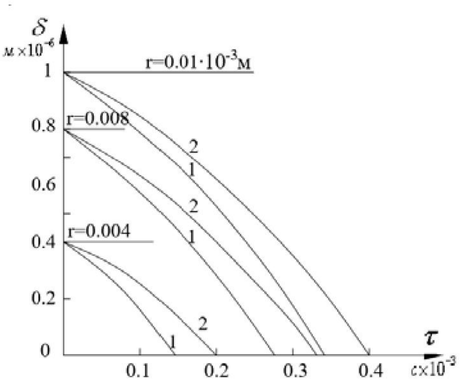

Figure 4 – Dependence of the thickness of the evaporating water film in the steam bubble growing in cells of capillary-porous structure, on time τ in the neighborhood of $0 \le r \le R_{cn}$ for different substrate materials: 1 – copper; 2 – stainless steel

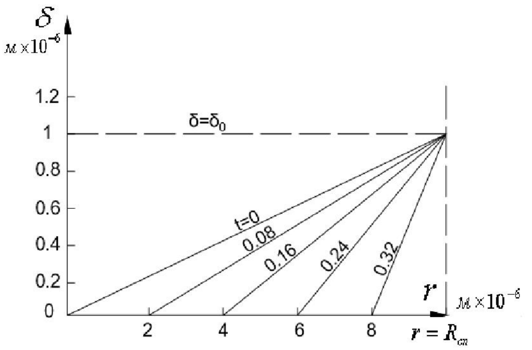

Figure 5 – Changes in the thickness of the evaporating water film δ under the steam bubble growing in the porous structure cells from the coordinates r in the range $0 \le r \le Rsp$ for different time points τ (surface – stainless steel)

$$\overline{R} = \frac{\overline{R}_d}{\overline{R}_0} = 2{,}42\left[k_{жс}k_{CT}\right]^{-1},$$

where $\widetilde{m} = 1 \ldots 14$; $W_0 = (1{,}1\times10^{-3}\ldots0{,}1)$ m/s; $W_0 = \dfrac{m_{жс} l q}{m_n \varepsilon \delta_\varphi r \rho'}$; l – height of the heat exchange surface; ε – porosity of structure; δ_φ – thickness of porous structure; $k_{жс} = 1 + \widetilde{m}^{0,1}$; $k_{CT} = 1 + \left[\dfrac{(\rho c\lambda)'}{(\rho c\lambda)}\right]^{0,5}$ – coefficients taking into account the excess of fluid and heat storage capacity of the wall; $\widetilde{m} = \dfrac{m_{жс}}{m_n}$ – option, taking into account the excess of fluid.

Excess of fluid $\widetilde{m}$ in the cross-section of the porous structure makes a flow with low subcooling and low speed W_0, which reduces the averaged value of the detachable bubble radius $\overline{R}_0$ to the value of $\overline{R}_d$. This is due to a decrease in the average weight temperature, which leads to overheating falling of liquid film surrounding the bubble, and may cause partial condensation of [7].

Dynamic angle of contact in the studies is obtained θ' = 80 degrees. (see. Fig.1); angle α = 5° 30′ ; K = 0,5.

The low of steam bubble growth R takes into account deformation and outline of bubbles due to excess of fluid $m_{жс}$ with in relation to the flow of generated steam m_n. Jakobi number $Ja = \frac{c'_p \Delta T}{r} \frac{\rho'}{\rho''}$;

ΔT = temperature difference; ρ'' – steam density; $\tilde{m} = \frac{m_{жс}}{m_n}$ – excess of fluid.

Time τ_0 of complete evaporation of microlayer with thickness δ_0 , at which under the bubble the "dry" spot is settled ($r = R_{cn}$), is determined from the expression (10).

Conclusion. The physical and mathematical models of the dynamics of steam bubbles growing in the porous structure cells, were studied. Characteristics of heat exchange differ substantially for individual bubbles. It uses the solution of the problem of evaporation of the liquid film in the "dry" spots area under the steam bubble and it was defined the film thickness and the temperature field in the wall (copper and stainless steel). Law of bubble growth in the structure cells was determined experimentally, taking into account the excess of fluid and thermal storage capacity of the walls. Excess of liquid reduces the value of the detachable diameter of bubbles. It was conducted a triple analogy of microprocesses of heat transfer of dynamics of steam bubbles (the first analogy) and macroprocesses of heat exchange surface destruction with the porous brittle coating (second analogy), including the value of cooling of wall and the value of coming off particles at the thermal destruction of coatings (third analogy). The calculation results are confirmed by experiment. We have proved that the temperature perturbation front, distributing in a solid body, does not reach the thickness of the surface, due to the fact that the porous coating contributes to a greater and more uniform thickness of the boundary layer and the low value of temperature fluctuations in the wall. The obtained results can be extended to other porous structures, wherefore needs a further experiment, for example, using metal-fibrous and powder structures.

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А. А. Генбач, Н. О. Джаманкулова

Алматы энергетика және байланыс университеті, Алматы, Қазақстан

КАПИЛЛЯРЛЫҚ-КЕУЕКТІК ҚҰРЫЛЫМНЫҢ ЖӘШІКТЕРІНДЕГІ БІРЛІК БУ КӨПІРШІГІНІҢ СИПАТТАМАЛАРЫ

Аннотация. Капиллярлық-кеуектік құрылымның бөлек жәшіктерінде бірлік бу көпіршіктер өндірісінің физикалық үлгісі жасалған. Көпіршіктердің жеке сипаттамалары интегралдық шамалардан едәуір өзгешеленуі (бір-екі дәрежеге) мүмкін, бұл тетіктер мен жылу энергетикалық құндырғылардың түйіндерінің шаршау жарық шақтарының пайда болуы және өрбуі арқасында бұзылуын түсіндіруге маңызды. Металл құздыру бетін (төсеніштi) жауып тұратын, кеуектік құрылымның жәшігінде өсетін бу көпіршіктерінің астындағы сұйықтың сына тәрізді микроқабатының булануы туралы есептің шешімі қолданылған. Есептің мағынасы үлбірдің үлестірілу қалыңдығының және «құрғақ» дақ радиусы аумағының қабырғадағы температура өрісінің үлестірілуінің уақыттық тәуелділігін анықтау болатын. Қабырға мыс пен тот баспайтын болаттан жасалған. Жазық беті шексіз пластина түрінде қарастырылады (жартылай шектелген қатты дене). «Құрғақ» дақ радиусын анықтауда кезінде шала қыздыруды, сұйықтың жылдамдығын, сұйық пен қыздыру бетінің жылу физикалық қасиеттерін ескергендегі кеуектік құрылымның жәшігінде өсетін бу көпіршігінің ұлғаю заңы бойынша эксперимент жүзінде алынған аппроксимация пайдаланылды. Кеуектік құрылымдағы артық сұйық көпіршіктің үзілу диаметрін кемітетіні көрсетілген, бұл орташамассалық температураның кемуімен және сұйық үлбірінің қызуының төмендеуімен байланысты.

Түйін сөздер: қайнау, бірлік бу көпіршігі, капиллярлық-кеуектік құрылым, сына тәрізді микроқабат, «құрғақ» дақ, салқындату тереңдігі.

А. А. Генбач, Н. О. Джаманкулова

Алматинский университет энергетики и связи, Алматы, Казахстан

ХАРАКТЕРИСТИКИ ОДИНОЧНОГО ПАРОВОГО ПУЗЫРЯ В ЯЧЕЙКАХ КАПИЛЛЯРНО-ПОРИСТОЙ СТРУКТУРЫ

Аннотация. Разработана физическая модель генерации индивидуальных (одиночных) паровых пузырей в отдельных ячейках капиллярно-пористой структуры. Индивидуальные характеристики пузырей могут существенно (на один-два порядка) отличаться от интегральных величин, что важно для объяснения возникновения и развития трещин усталости и разрушения деталей и узлов теплоэнергоустановок. Использовано решение задачи об испарении клиновидного микрослоя жидкости под паровым пузырем, растущим в ячейке пористой структуры, покрывающей металлическую поверхность нагрева (подложку). Задача сводилась к определению временных зависимостей толщины распределения пленки и распределений температурного поля в стенке в области радиуса «сухого» пятна. Поверхность принималась как бесконечная пластина (полуограниченное твердое тело). При определении радиуса «сухого» пятна использована аппроксимация, полученная экспериментально, для закона роста пузыря в ячейке пористой структуры с учетом влияния недогрева, скорости жидкости и теплофизических свойств жидкости и поверхности нагрева. Показано, что избыток жидкости в пористой структуре снижает величину отрывного диаметра пузыря, что связано с уменьшением среднемассовой температуры и падением перегрева пленки жидкости.

Ключевые слова: кипение, одиночный паровой пузырь, капиллярно-пористая структура, клиновидный микрослой, «сухое» пятно, глубина захолаживания.