

A.A. Genbach¹, D.Yu. Bondartsev²

¹Genbach A.A., Almaty University of Power Engineering and Telecommunications (AUPET);

²Bondartsev D.Yu., Almaty University of Power Engineering and Telecommunications (AUPET),
JSC «TrestSredazenergomontazh»
d.bondartsev@saem.kz

GENERATION OF STEAM ON SOLID SURFACE IN SEPARATE CELL OF POROUS STRUCTURE

Abstract. A model is developed of the dynamics of vapor bubbles produced on a solid surface in porous structures and a steam-generating wall (substrate). The model is based on the high-speed cinematography SCS-1M. The removal of high heat fluxes is ensured by the combined effect of capillary and mass forces. An analytical model is developed on the basis of the theory of thermoelasticity, when the heat flow is fed to the base of a vapor bubble having a "dry" spot and a microlayer of a truncated cone liquid.

The limiting state of a poorly heat-conducting porous coating and a metal substrate is determined. The heat fluxes were calculated from the time of spontaneous appearance of the steam germ (10-8) up to the time of material destruction (102 + 103 s), i.e. the time interval from the process of relaxation to the macroprocess (destruction) is described. The dimensions of the detachable particles at the moment of destruction of the porous coating, determined in the model, agree well with the experiment at the optical stand.

Keywords: model of the dynamics of steam bubbles, capillary-porous coatings, intervals of heat flows, heat equation with boundary and initial conditions.

The thermohydraulic characteristics of the liquid boiling process in capillary-porous structures were studied using high-speed cinematography from the onset of explosive nucleation of the vapor phase [1] until its destruction. This allowed us to develop models and the mechanism of heat transfer and to obtain simple calculated dependencies for different boiling regimes [2] up to the crisis state [3]. The heat exchange was controlled by the combined effect of capillary and mass forces [4-7] and served as the basis for the creation of various heat exchange devices [5,8,9].

The visualization of the thermal effect was also carried out with the help of holography, which made it possible to study the limiting state of good and poorly heat-conducting materials in the form of porous structures and a steam generating surface [3,8,10-13]. Control of heat exchange in porous structures was carried out by influencing the internal boiling characteristics [14] and integral volumes [2-4].

The growth of a vapor bubble of radius R in a separate cell of the structure was considered (Figure 1). We assume that the heat flux q , which determines the growth of the vapor bubble, comes from the heating surface q_1 with allowance for the "dry" spot through the microlayer of the liquid under the vapor bubble, similar to the D.A theory. And part of the heat q_2 is supplied from the superheated liquid surrounding the growing bubble, since the amount of superheating of the liquid in the porous structure can reach large values, which increases the store of enthalpy of the adjacent layers of the liquid.

The cooling liquid is transported by the combined action of capillary and mass forces $\Delta P_g + \text{cap}$. The "dry" spot at the base of the bubble is described by the radius r , which at the moment of bubble detachment is proportional to $R_{sp} = kR$, where the microlayer of the liquid under the bubble forms an angle α with sides δ_o^l and δ_o .

A steam bubble is represented as a volume of a spherical segment, from which a truncated cone formed by a microlayer should be subtracted. The thickness of the micro-layer δ_0 that feeds the vapor bubble due to its evaporation during the growth of the bubble will be constant, since the capillary and gravitational forces allow the fresh portions of the cooling liquid to leak to the base of the bubble. In the steam bubble growth model, there is a direct transition from the developed bubble boiling to the possible onset of the crisis, when the balance of forces is violated and the thickness of the microlayer tends to zero ($\delta_0 \rightarrow 0$), which is very important for studying the limiting state of the system.

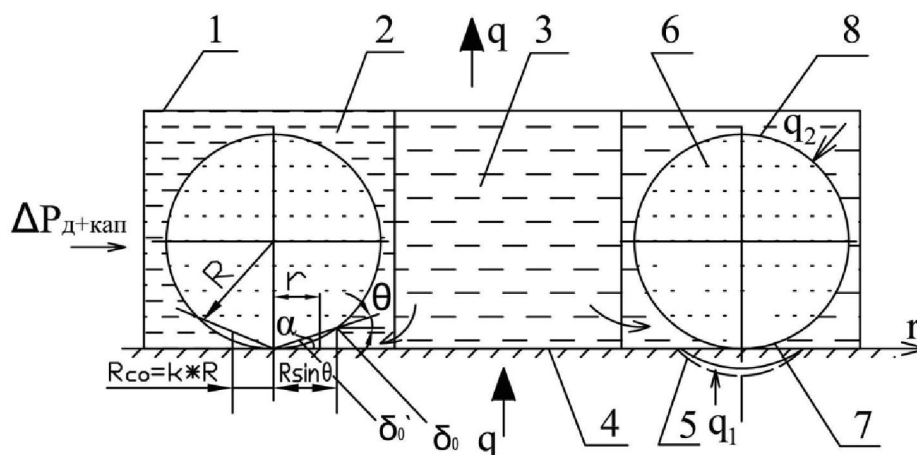


Figure 1 - The model of contact of steam bubbles with the steam generating surface in the cells of steam generation of the porous structure: 1 - the skeleton of the porous structure; 2 - cell for generating steam; 3 - a cell of a supply with a liquid; 4 - steam generating surface; 5 - front of the propagation of the temperature wave in the volume of the heat generating surface (stainless steel and copper (dashed line)); 6 - steam; 7 - "dry" spot; 8 - front of light (vapor) phase propagation.

The interfacial surface 8 and the steam generating wall 4 form a dynamic angle θ average during the time of growth of the steam bubble. Since the problem is solved for not very low pressures, the dynamic processes taking place in the initial stage of the development of the vapor bubble are not considered. Then the forces of viscosity and surface tension will also be commensurable with inertial forces and may not be taken into account.

The volume of the spherical segment is calculated by the formula:

$$W_{\text{cer.}} = \pi(2R - h)^2 \left(R - \frac{2R^2 - h^2}{3} \right) = \frac{\pi}{3} R^3 (1 + \cos\theta)^2 (2 - \cos\theta),$$

$$h^2 = R(1 - \cos\theta).$$

$$dw_{\text{cer}} / d\tau:$$

$$\frac{dw_{\text{cer}}}{d\tau} = \pi R^2 (1 + \cos\theta)^2 (2 - \cos\theta) \frac{dR}{d\tau}$$

The thickness of the microlayer under the vapor bubble is a truncated cone, bounded from the side of the bubble by a "dry" spot 7, will be:

$$\delta_0^I = k R \tan \alpha^I, \quad \delta_0 = R \sin \theta \tan \alpha^I,$$

k – coefficient of proportionality.

For the bubble model according to Fig. 1, we consider the solution of the thermoelasticity problem for determining the limiting state of the medium by the example of a brittle coating from a rock and a metal vapor generating surface of a substrate.

For the thermal destruction of a porous coating, we estimate the influence of the specific heat flux q applied to the surface and the time of its influence on the creation of destructive stresses, the granulometric composition of the husk δ (tearing particles upon destruction), and for the metal, the depth of penetration of the temperature disturbance with the destruction of the surface 5 at Figure 1. In some works the decisive role in the destruction is attributed to the thermal tension of the tension, since the value of the ultimate strength of porous coatings consisting of a furnace x of the rocks for compression is 10 or more times higher than the tensile strength, and in metal - several times. It is possible that tensile stresses cause only cracking of the coating and do not determine its peeling, i. E. they are not decisive for thermal destruction, and the main destructive stresses are shear [3].

In [3, 10, 12], an estimate is made of the magnitude of the compression stress. As the temperature of the porous coating rises in a very short period of time, t dynamic effects become very significant, compressive stresses reach large values, often several times higher than the compressive strength of the material. Therefore, it is necessary to take it into account in the mechanism of thermal destruction of coatings. It is necessary to find out what kind of voltage reaches before its limit values for the heat fluxes q supplied. The destruction mechanism for cyclonic drills changes fundamentally, when the fracture temperature T_p is about 800°C , which is much lower than the melting temperature T_m . This can be achieved by changing the aerodynamic structure of the flow, in which the coefficients of heat transfer are increased by tens of times [13].

A free plate (of arbitrary shape in plan) of thickness $2h$ was considered on all sides. To the surface $z = +h$, starting from the time $t = 0$, a constant specific heat flux $q = \text{const}$ was applied. The lower surface $z = -h$ and the side edges of the plate were considered to be thermally insulated [15].

Knowing the temperature distribution in the plate, we find the thermal stresses of tension and compression arising at a certain time t at different depths from the surface $\delta_i = (h = z_i)$ for a given value of the heat flux $q = \text{const}$. The plate with a variable temperature is in the plane tension state.

Setting the limiting values of the compressive stress $\sigma_{pr.szh.}$ and stretching $\sigma_{pr.rust}$ for each given coating and metal, we obtain the functional dependence of the heat flux q_i , which is necessary for the destruction from the time of delivery and the depth of penetration. In addition, equating the temperatures on the surface of the plate to the melting point of the coating and the metal, we find the values of the specific heat fluxes necessary for melting the surface layer for a different time interval of their action. Thus, in each case, we obtain the functional dependences of the heat flux q_i on the time of its influence on the medium [15].

For a plate made of quartz, granite, teschenite and metal, the functional dependences q_1, q_2, q_3 were calculated on a PC. In the figure (2-5) the following symbols are used: ν - is the coefficient of transverse compression; α - is the coefficient of linear expansion; E - is the modulus of elasticity.

The results of the calculations for the granite coating are shown in the graph (Figure 2-5). In the case of a quartz coating, the heat fluxes were calculated for very wide time intervals ($10^{-8} - 10^{-3}$) s. The lower limit of this interval (10^{-8}) s is the relaxation time.

For time intervals of the order of ($10^{-8} - 10^{-3}$) the relations for q_1 and q_2 representing hyperbolic curves in the (q, t) coordinates lose their physical meaning, since in this problem the heat equation was taken as the basis. To take into account the microprocesses, it is necessary to add to it a term of the type $K^t \frac{\partial^2 T}{\partial t^2}$. Since thermal destruction is a macro process, we take it to take place over time ($5 \times 10^{-3} - 10^3$). The change in heat fluxes q_1, q_2, q_3 versus time on plates made of granite coating is shown in Fig. 2.

Under the condition that the coatings are destroyed only by compression, a series of curves is obtained, each of which corresponds to a certain thickness of the opening particle. For each value of the heat flux and some interval, we obtain particles with thicknesses $\delta_1, \delta_2 \dots, \delta_i$. The maximum thickness of the particles that break away under the action of compression forces for coatings of quartz and granite is $(0.25-0.3) \times 10^{-2} \text{ m}$.

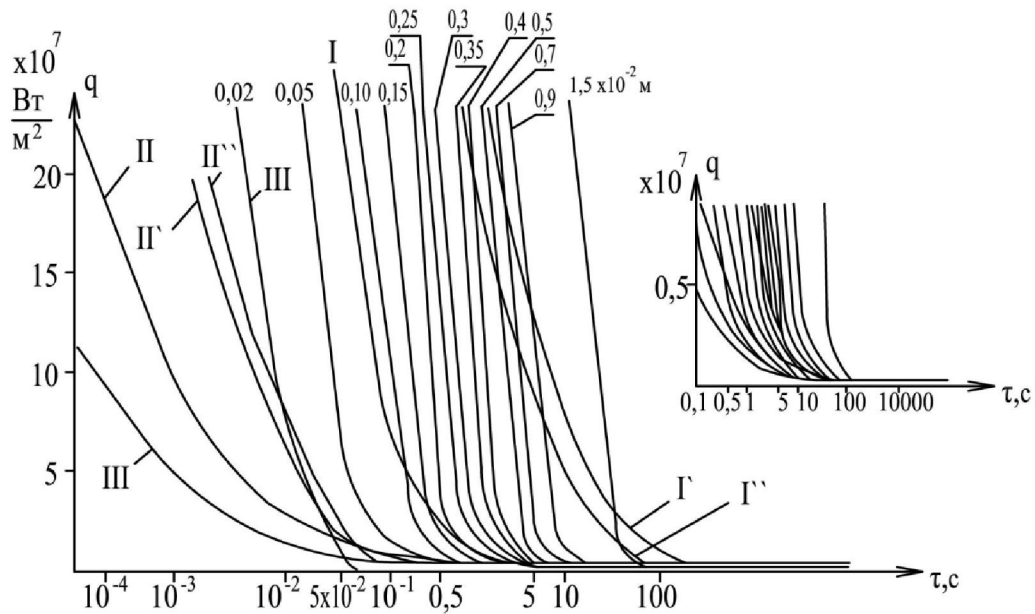


Figure 2 - Dependence of the heat fluxes causing compressive stresses of the porous coating of granite as a function of the time of action for different thicknesses of the detached particles: I - stretching stresses sufficient to destroy (Γ , Γ' - copper and stainless steel, $h = 0.1 \times 10^{-3} \text{ m}$); II - fusion of the surface (Π , Π' - copper and stainless steel, $h = 0.1 \times 10^{-3} \text{ m}$)

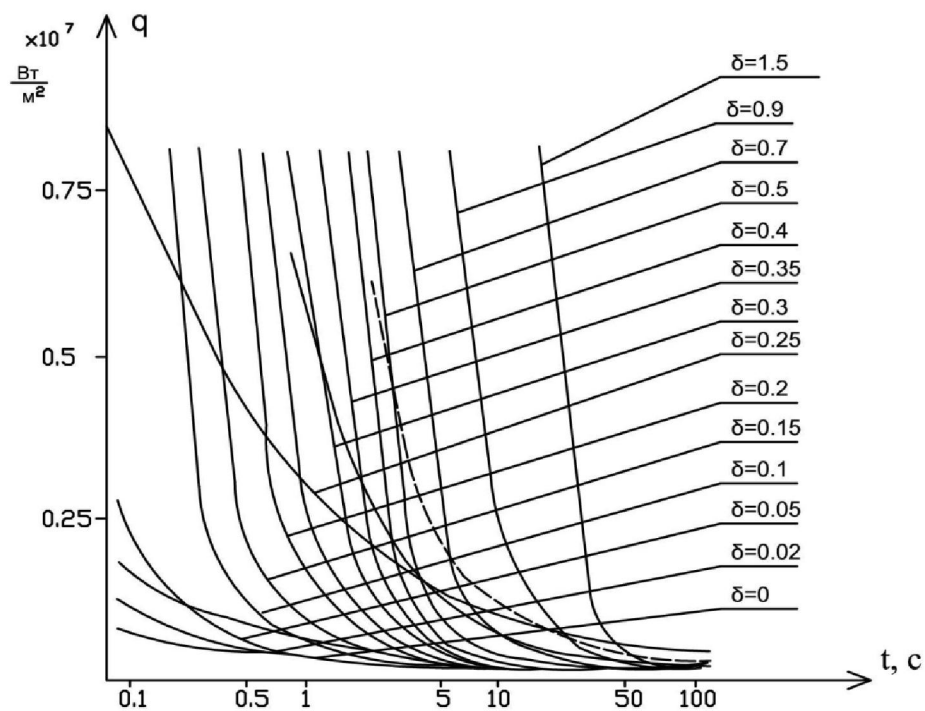


Figure 3 - Dependence of $q = f(t)$, presented in Figure 2. in the range $q = (0.25 \dots 0.75) \times 10^7 \text{ Bt/m}^2$

Sections of compression curves that determine the separation of particles with thicknesses $\delta > 0.3 \times 10^{-2} \text{ m}$ for large heat fluxes and small t are screened by the melting curve II, and in the case of small heat fluxes and significant time intervals, the expansion curve. Moreover, the melting curve of the coating from quartz is much higher than that of granite, which explains its stable brittle fracture.

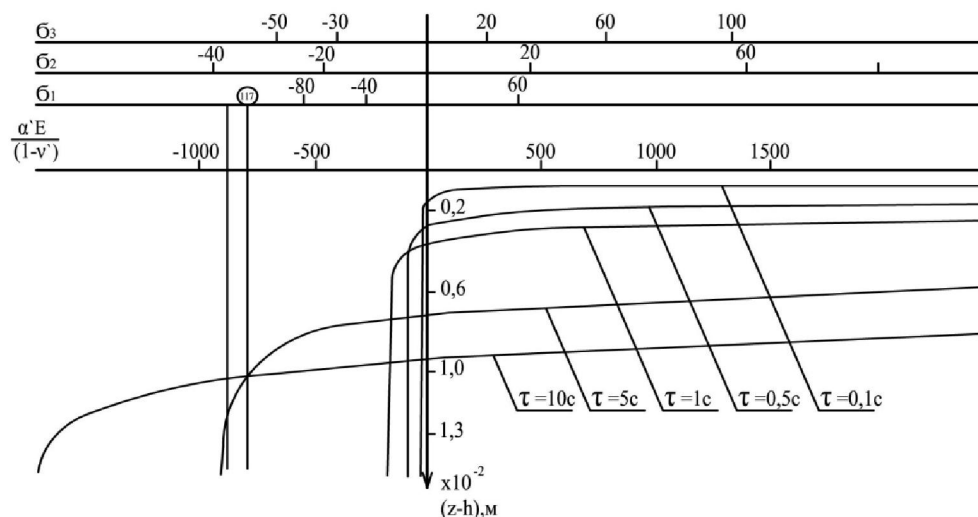


Figure 4 - Stress diagrams for the thickness of the granite plate for different heat flows and the time of their action: $q_1=0.142 \times 10^7 \text{ Bt/m}^2$, $q_2=0.042 \times 10^7 \text{ Bt/m}^2$, $q_3=0.075 \times 10^7 \text{ Bt/m}^2$

The relationship between compressive stresses and tensile stresses (see Figure 4) represents stress plots within the plate for different time intervals from the beginning of the process under consideration. At small t , on the order of 10^{-2} s, only compressive stresses arise. Beginning with $t \approx 10^{-1}$ s, in some region Δ ($h - z_i$), the compression stress turns into a tensile stress, and for different time intervals they are at different depths from the plate surface. In the region of the transition of the compressive stress to the tensile stress, the greatest shear stresses of the coating layers will apparently be observed. In time, the shear stresses reach their ultimate values later than the destructive compressive stresses and, obviously, before the maximum tensile stresses.

Destruction from compression can occur both at a certain depth ($0.3 \times 10^{-2} \text{ m}^2$), and in a small surface layer δ in a very short time t .

The time of detachment of the particles of the coarse coating determined by the high-speed cinematography, the camera SCS-1M [3], is (0.11 ... 0.47) s and agrees well with the data given ($t_{\min} =$ or 0.1s) see Fig. In figure 5, the calculation of the specific energy Q of the unit volume destruction of the granite coating is given. Depending on the thickness δ of the particles being separated, the energy Q is calculated. The curves have pronounced minima.

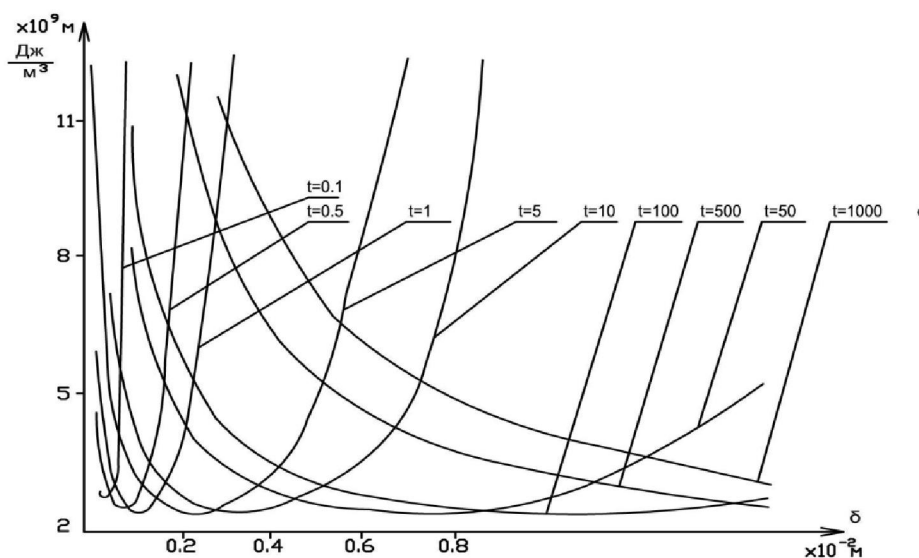


Figure 5 - Change in the specific energy of destruction of the granite coating as a function of δ for various t .

Conclusion. A model for the generation of vapor bubbles on a solid surface with a porous coating is developed, based on film-photogrammetric observations of the internal characteristics of the boiling of the liquid. High forcing of heat transfer is provided by combined action of capillary and mass forces. The steam bubble is represented as a volume of a spherical segment with a microlayer of liquid and a "dry" spot in its base. For such a model, the problem of thermoelasticity is solved and the limiting state of a system of well - and poorly heat-conducting materials (a porous coating on a metal substrate) is determined. The heat fluxes applied to the surface are determined, the time of their action on the creation of destructive stresses, the dimensions of the detached particles and the depth of penetration of the temperature wave into the substrate. The heat fluxes were calculated from the time of the explosive appearance of the first embryo (10-8 s) up to the time of destruction of the materials (102 + 103 s), i.e. from the relaxation time to the time describing the microprocess. The interrelation in the process of destruction is established only by the compression stress, melting or tensile stress. The sizes of the detachable particles are confirmed by the high-speed shooting, each thickness δ_i of the detached particle under the action of compression forces corresponds to its limiting values of heat fluxes, which are within the limits of the reduced integrals.

REFERENCES

- [1] Polyayev V.M., Genbach A.N., Genbach A.A. Methods of monitoring Energy Processes // Experimental thermal and fluid science, International of thermodynamics. Experimental Heat transfer, and Fluid Mechanics. Avenue of the Americas - New York, **1995**. V. 10. April - p. 273-286.
- [2] V.Polyayev. A. Genbach. Heat Transfer in a Porous System in the Presence of Both Capillary and Gravity Forces // Thermal Engineering. - **1993**. Volume 40, number 7, Moscow. - P. 551-554.
- [3] Polyayev V.M Genbach A.A Limit state of the surface by thermal exposure // High Temperature. - **1991**. T.29, number 5. - S. 923-934.
- [4] Polyayev V., Genbach A. Control of Heat Transfer in a porous coating System // Second world conference of experimental heat transfer, fluid mechanics and thermodynamics. - **1991**. - Dubravnik, Yugoslavia, 23 - 28, June. - P. 639-644.
- [5] Polyayev V.M Genbach A.A Minashkin D.V Processes in Porous electric heat exchanger // Proceedings of the universities. Mechanical Engineering. - **1991**. - number 4 - 6 - p. 73-77.
- [6] Polyayev V.M Genbach A.A Analysis of friction and heat transfer laws in the porous structure // Vestnik MSTU, a series of Engineering. - **1991**. - p. 86-96.
- [7] Polyayev V.M Genbach A.A, IN Bocharova The effect of pressure on the rate of heat transfer in a porous system. // Proceedings of the universities. Mechanical Engineering. - **1992**. - number 4 - 6 - C 68 -72.
- [8] Genbach A.A, I.B Bakytzhan protection against earthquakes TPP bases with the help of porous geokranov // Search, MES, number 1 (2), **2012**. - p. 289-297.
- [9] Genbach A.A, Danilchenko I. Porous desuperheater steam boilers // Kazakhstan Industry, № 1 (70), **2012**. - p. 72-75.
- [10] Genbach A.A Olzhabaeva K.S Visualization of the thermal effects on the porous material in the TEU ES // Bulletin of the National Engineering Academy of Kazakhstan, № 3 (45), **2012**. - p. 63 - 67.
- [11] Genbach A.A, F.A Islamov Research prisoplovoy fillet in power plants // Vestnik KazNTU, number 3 (97), **2013**. - p. 245-248.
- [12] Genbach A.A, F.A Islamov Modeling process grazing turbine rotor // Herald of KazNTU, number 6 (100), **2013**. - p. 235-240.
- [13] Polyayev V.M, Genbach A.A Applications porous system // Proceedings of the universities. Energy. - **1991**. № 12. - p. 97 - 101.
- [14] Polyayev V.M., Genbach A.A Management of heat exchange in the porous structure. Transport. – **1992**. T 38.
- [15] Genbach A.A., Bondartsev D.Yu. Model of steam generation on a solid surface, covered with a porous structure for elements of thermal power plants // Bulletin of KazNITU, № 4 (122) **2017**. p. 49-56.

А.А. Генбач¹, Д.Ю. Бондарцев²

¹Генбач А.А., техникалық ғылым докторы, профессор АЭЖБУ;

²Бондарцев Д.Ю., докторант АЭЖБУ, бас инженер, АО «Трест Средаэнергоустановка»

БОҚТЫҢ ҚОЗҒАЛЫСЫНДАҒЫ БІРЛІГІ МАҢЫЗДЫ ҚҰРЫЛЫМЫНЫҢ ЖЕКЕ КЕЗІНДЕ

Аннотация. Кеуекті конструкциялардағы қатты бетке және бу шығаратын қабырғада өндірілген будың көпіршік-тері динамикасының моделі жасалды. Модель SCS-1М кино-фотосемке жылдамдығы жоғары камерасына негізделген. Жоғары жылу ағындарын жою капиллярлық және жаппай күштердің аралас әсерімен қамтамасыз етіледі. Термоэласт-тиктің теориясы негізінде жылу ағыны «құрғақ» нүктесі бар және

буып-соғылған конустық сұйықтық микротолы бар будың көпіршігі негізіне жеткізілетін аналитикалық модель жасалады. Нашар жылу өткізетін кеуекті жабынның және металдың субстратының шектік күйі анықталады. Жылу ағындары бу шығынын (10-8) өздігінен пайда болған уақытынан материалдың бұзылу уақытына дейін (10² + 10³ сек) есептелген. Релаксация процесінен макропроцесске (жойылу) дейін уақыт аралығы сипатталған. Үлгіде анықталған кеуекті қаптаманы жою сәтінде алынбалы бөлшектердің өлшемдері оптикалық стендте экспериментпен жақсы келісіледі.

Тірек сөздер: модель динамикасын бу көпіршіктер, капиллярно-кеуекті жабынды, аралықтары жылу ағындары, жылу өткізгіштік теңдеуі бастап шекаралас және бастапқы шарттары.

УДК 631.344. (088.8)

А.А. Генбач¹, Д.Ю. Бондарцев²

¹Генбач А.А., доктор технических наук, профессор АУЭС;

²Бондарцев Д.Ю., докторант АУЭС, ведущий инженер, АО «Трест Средаэнергомонтаж»

ГЕНЕРАЦИЯ ПАРА НА ТВЕРДОЙ ПОВЕРХНОСТИ В ОТДЕЛЬНОЙ ЯЧЕЙКЕ ПОРИСТОЙ СТРУКТУРЫ

Аннотация. Создана модель динамики паровых пузырей, рождающихся на твердой поверхности в пористых структурах и парогенерирующей стенке (подложке). Модель основана на кино-фотосъемке скоростной камерой СКС-1М. Отвод высоких тепловых потоков обеспечивается совместным действием капиллярных и массовых сил. Составлена аналитическая модель на основе теории термоупругости, когда тепловой поток подводится к основанию парового пузыря, имеющего «сухое» пятно и микрослой жидкости в виде усеченного конуса. Определено предельное состояние плохотеплопроводного пористого покрытия и металлической подложки. Тепловые потоки рассчитывались от времени спонтанного появления парового зародыша (10⁻⁸) до времени разрушения материала (10² + 10³ с), т.е. описан интервал времени от процесса релаксации до макропроцесса (разрушения). Размеры отрывающихся частиц в момент разрушения пористого покрытия, определенные в модели, дают хорошее совпадение с экспериментом на оптическом стенде.

Ключевые слова: модель динамики паровых пузырей, капиллярно-пористые покрытия, интервалы тепловых потоков, уравнения теплопроводности с граничными и начальными условиями.

Information about authors:

¹Genbach A.A. - Almaty University of Power Engineering and Telecommunications (AUPET), Doctor of Engineering Science, Professor;

²Bondartsev D.Yu. - Postdoctoral student AUPET, leading engineer, JS «TrestSredazenergomontazh», d.bondartsev@saem.kz.