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INVESTIGATION OF THE HEAT EXCHANGE CRISIS IN POROUS STRUCTURES FOR HIGH PRESSURES

Abstract. The crisis of heat exchange in the boiling of water in porous structures is studied. The study relates to heat power plants of power stations. The experiments were carried out on a rocket type burner. The combustion chambers and supersonic nozzles were cooled with various porous structures. The mechanism of the heat exchange processes is described and optimal cell sizes of the porous structures are determined, and the design equation of the critical heat flux for high pressures is obtained.

Keywords: crisis of boiling, capillary-porous structures, cooling systems, the mechanism of heat exchange crisis.

The main task in power plants of power stationsis the creation of a cooling system for high-voltages and nodes. These include furnace screens of high-power boiler units, combustion chambers, nozzles and blades of gas turbine units [8].

In cooling systems, bubble fluid (water) bubbles proceed. At high thermal loads, the onset of a crisis situation with possible overheating of the heat exchange wall is not ruled out. To study the boiling crisis, weas sembled an experimental setup, the scheme of which and the experimental conditions are presented in [6, 7].

Calculation of the value of qcr with respect to the investigated porous system can be performed depending on the underheating and the flow velocity according to the equations of work [2], from which it follows that underheating of the liquid allows several expansion of the heat transfer capabilities in a porous cooling system. Since heat transfer processes take place in thin porous structures, even an insignificant excess of free flowing film on the outside of the structure, determined by the parameter m, at a given hydrostatic pressure ΔPd and a conditional coefficient of permeability Ku, creates a liquid core from which the underheated cooler will be continuously sucked temperature differences and capillary forces.

In addition, the gravitational potential promotes the destruction of steam conglomerates in a porous structure, facilitating the transport of an underheated liquid. The heat flow will be spent additionally on heating of leaking relatively cold portions of liquid.

Excess fluid in the porous system creates a directional movement to the flow, which leads to deformation of the vapor bubbles in the structure, a decrease in their diameter, an increase in the frequency of the formation of bubbles [3]. As the flow velocity increases, the energy expended in displacing liquid from the wall boundary layer increases, and consequently, the generation rate of the vapor V_{cr} and the quantity q_{cr} increase. However, at a certain value of the fluid flow rate determined by the parameter $\widetilde{m}_{cr}$, the energy expended for extruding liquid from the two-phase wall layer will not be enough, and a heat transfer crisis occurs. Of course, an increase in $q_{cr,\ v}$ will be achieved with a large flow of liquid, which will lead to an increase in energy costs for the drive of the injection machines.

Upon reaching a certain value of the water content $\bar{\varphi}^{1}_{\kappa r}$, the flow rate will not contribute to an increase in the q_{cr} value, and in some cases may even lead to a decrease in the q_{cr} value, since vapor evacuation from the wall zone is difficult. The increase in the velocity of the liquid film adjacent to the wall, due to the parameter $\tilde{m}$, begins to give way to the dominant influence of the fall in the moisture content $\bar{\varphi}^{1}_{\kappa r}$ in the same zone, which will have a greater effect on the q_{cr} value, even decreasing it. Therefore, it is required in each individual case to establish an optimal ratio of the excess liquid $\tilde{m}$ depending on the type of the porous structure.

The hydrodynamic model of the liquid boiling crisis in a large volume on the technical surface does not reflect the effect of the thermophysical properties of the wall, although it does occur, which can be explained by the vibrational motion of the vapor-liquid interface. This leads to a wavy movement of the heating surface. Therefore, in some places of such a surface, resonance phenomena should be expected, when the wall temperature will decrease due to a large selection of vapor, which means that the higher the thermal properties of the wall, the more intensive the withdrawal of the quantity «q» will occur.

For porous cooling systems, for practically all regimes and geometric parameters at bubble water boiling, the depth of penetration of the temperature wave is $h_m<\delta_w$, therefore in the computation ratios for q_{cr} the wall thickness δ_w is not introduced [3].

The equation for computing q_{cr} in the case when $P\geq0.1$MPa, and $b_g > 0{,}28\cdot10^{-3}$ m:

$$q_{cr} = 0{,}0347.r.\left[g.(\rho_l-\rho_s).\rho_s.\bar{D}_{c.cr}\right]^{0,5}.\left(\frac{b_h}{b_0}\right)^{0,3}.\left(\frac{\delta_f}{\delta_0}\right)^{0,5}.(1+\cos\beta)^{0,6}, \qquad (12)$$

It follows from equation (12) that

$$q_{cr} \sim \bar{D}^{0.5}{}_{c.cr}\ (p \geq 0{,}1\ \text{MPa})\ \text{and}\ q_{cr} \sim \bar{f}^{0.5}\ (p < 0{,}1\ \text{MPa}).$$

The value of $\bar{D}_{o.cr}$b $\bar{f}$ depends on the thermophysical properties of the heat-release surface: $\bar{D}_{c.cr} \sim K_w^{-1}$, $\bar{f}_{cr}^{-1} \sim K_w^2$, where K_w = I $[(\rho c\lambda)_l/(\rho c\lambda)_w]^{0,5}$. Then for surfaces made of copper and stainless steel and covered with grid structures, we have: $\tilde{q}_{cr} = 1{,}07$ ($p \geq 0{,}1$ MPa), $\tilde{q}_{cr} = 1{,}15$ ($p < 0{,}1$ MPa).

The wall material influences the value of q_{cr} through the complex $(\rho c\lambda)_w$, where ρ, c, λ are density, heat capacity and heat conductivity of the wall respectively, but it is hardly right to state this unequivocally, since it is practically impossible to keep the same conditions for cleanliness of processing and microstructure. When designing the combustion chamber and especially the nozzle, it is necessary to take into account a certain margin for the thickness of the heating surface. Occurrence of boiling crisis will occur earlier on "thin" heaters, since the "dry" spot in the bubble base will start to increase in pre-crisis boiling area, the heat exchange process will drastically worsen, wall temperature will increase. Surfaces having a larger thickness will require more time for their heating.

For surfaces with porous coating this issue is particularly topical, because the bubble growth time is ten times less in them, the hydrodynamic conditions of the liquid supply change drastically and, consequently, the residence time of the steam near the wall can increase, which eliminates the contact of the liquid with the heat exchange surface, despite the large surplus of liquid $\tilde{m}$ [3].

The described process is the prehistory of the development of the boiling crisis. The further "fate" of the process, under otherwise equal conditions, is determined by the heat storage capacity of heating $(\rho c\lambda)_w$. When the size of the complex is chosen to be large, the probability of prolonging the boiling crisis increases, the heat flows along the heating surface will increase, and favorable conditions for the contact of the liquid phase with the wall will be created again. Increasing only the wall thickness by a tenth will increase the value of q_{cr} by just a few percent, besides this phenomenon is more noticeable for high heat conductive materials and at a pressure greater than atmospheric pressure.

The one-dimensional equation of nonstationary heat conductivity, describing the dynamics of the temperature field in a steam-generating wall proved to be useful for the study of the limit state of a surface at a boiling crisis when a "dry" spot of critical size is established on the wall below the steam bubbles. Up to this point, a developed bubble process of boiling, and at the base of the steam bubbles there was a "dry" spot with a radius of $R_{s.p.}$.

As the computations [10] have shown, for time $\tau \leq 5$ s, the heat flows reach values of ~ $8\cdot10^7$ W/m^2 for copper and $1.3\cdot10^8$ W/m^2 – for stainless steel. However, they will be shielded with melting lines in ~ 0,01 s. High heat tensile stresses occur as a result of a drastic increase of temperature gradients in the wall. The effect of various materials and wall thicknesses on the time of the onset of surface destruction at the time of the boiling crisis was studied. With the help of holography and photoelasticity methods, the most dangerous place at the moment of destruction of the porous surface was determined [20, 21].

The phenomena of ejection of liquid drops from the cells of a porous structure [20] deteriorate the intensity of heat exchange when a certain boundary heat flow is reached. By choosing the type of structure, this phenomenon can be minimized. The smallest ejection was obtained for single-layer grids with cells more than $0.28\cdot10^{-3}$ m. The resulting degraded regimes are similar by their mechanism to the processes occurring when the steam-water mixture moves in pipes that do not have a porous coating. These regimes are characterized by a critical region of Reynolds numbers, when the friction head begins to decrease on the heated area. This is due to the fact that due to the violent drop ejection, the liquid consumption is reduced. In the initial stage of the discharge process, the drops turbulize the process, then at a critical ejection the amount of liquid becomes insufficient to irrigate the heat exchange walls.

As the intense drop drift disturbs the smooth flow of liquid along the external surface of the grid, a film break is observed, which also worsens the inflow of fresh portions of relatively cold liquid to the wall two-phase boundary layer. The experimentally chosen porous structures practically eliminated the drop ejection at a given heat flow that occurs due to the balancing of the frictional forces of the liquid in grids and on the surface of the grids with drops and the steam flow in the grids and near-grid space [7].

As a result of the imbalance of operating forces, the amount of incoming liquid becomes insufficient, dry spots occur on the heating surface, the wall temperature gradually increases to a certain value and the process proceeds at temperature headers (60–80) K. The pulsating regime of supplying the wall with liquid does not lead to overheating of the surface, although the intensity of heat transfer decreases. However, pulsations of the wall temperature and the associated with them heat braking stress occur, shortening the service life of the surface. Therefore, it is important to correctly optimize the type of the porous structure and not to allow high overheating of the wall relative to the liquid temperature.

The crisis boiling is characterized by loss of stability of the pulsating liquid film and blocking of the cells of the structure by steam formations. Despite a sufficient amount of liquid, a sharp increase in the heat resistance of the boundary layer is observed, a deterioration of the effect of swirl due to the hindered removal of steam from the cells of the porous structure.

In case of a boiling crisis, as holographic interferometry and high-speed filming have shown [3], the transferred heat flow gains limiting values q_{cr}, the bubbles of steam start to penetrate into adjacent cells of the structure before their departure, merge into conglomerates and form focal zones of steam films. Liquid films under steam conglomerates dry out and, in spite of the large amount of liquid present in the porous structure and on its surface, the coolant cannot penetrate to the wall.

The temperature head comes to a limit value relative to the saturation temperature T_s, $\Delta T_{cr} = T_{cr} - T_s$, where the value of T_{cr} corresponds to the value q_{cr}. At$\Delta T \geq \Delta T_{cr}$, which is more likely for porous structures at $p < 0{,}1$ MPa, when the lowest values of the critical overheating of the wall takes place, or for grids with cells less than $0{,}14.10^{-3}$ m, the microlayer of liquid steams under the steam bubble, or its conglomerate, the wall temperature near the "dry" spot drastically increases, excluding contact of the existing portion of the liquid with the wall.

A study of the boiling of a liquid without a porous structure shows that when the heat flow reaches $\sim 1\cdot10^5$ W/m^2, the number of centers of steam formation drastically increases and the liquid film "swells". Steam bubbles begin to interact with each other, breaking over at smaller sizes. The main portion of the heat is consumed on boiling of the liquid into bubbles. Upon occurrence of the critical regime, the liquid film breaks over into spheroidal drops and does not wet the heating surface. The temperature of the wall starts to increase drastically, up to its burnout. This increase of liquid consumption does not lead to positive results. The crisis occurs at time when the rate of boiling of the liquid exceeds the rate of its spreading over the surface. The film dries out on the periphery of the heating surface, shrinking towards the center.

Since the pore sizes of the studied grid structures can be considered as identical, the outflow of steam will be equally probable. Steam pillars can be generated in much larger cells than, for example, in powder materials, and spaced from each other at shorter distances, and even in cells closely adjacent to each other. For water boiling in a large volume at atmospheric pressure, the critical wavelength λ_{cr} between the steam columns is $(15–25)\cdot10^{-3}$ m, then for a powder porous coating it is (5–15) times smaller. If the value of $q_{cr} \sim U_{cr} \sim \lambda_{cr}^{-0.5}$, then the value of q_{cr} for powder materials turned out to be twice as high, but at a temperature head ΔT= (600–800) K. For grid structures operating in the field of gravitational forces, in spite of an even smaller value of λ_{cr}, the value of q_{cr} was similar to the values achieved at boiling in a large volume on the technical surface, but at a value of $\Delta T_{cr} = 60$ K [3], U_{cr} – critical velocity of steam.

Therefore, the hydrodynamic situation in the volume and on the surface of the grids, which, in turn, depends on the type of structure and organization of the liquid supply,should be considered as the determining factor of the boiling crisis. Due to a slight surplus of liquid (low underheating and flow velocity), as visual observations showed, it became possible to control the steam front in the volume of the structure and, above all, to destroy the accumulating steam formations.

An assessment for crisis state of the fraction of the surface occupied by the steam for p = 0,1 MPa, $\Delta T_{cr} = 60$ K, $\bar{D}_{o.cr} = 0{,}5.10^{-3}$, $\tilde{m} = 1{,}1$, $\bar{n} = 5.10^{6}$ m^{-2}, is provided by the following:

$$\frac{F_s}{F} \geq \frac{\pi.\overline{D}_{0,cr}^{\,2}.\bar{n}.K_{\min}}{4.1} \geq \frac{2{,}5.\pi}{16},$$

Where K_{min} – coefficient, taking into account the presence of a "dry" spot under the steam bubble. At the time of the crisis, the value of $K_{min} \geq 0{,}5$; F, F_n - the total heat exchange surface occupied by steam.

The number of cells for the structure of $0.4 \cdot 10^{-3}$ m, per 1 m^2, is $2.78 \cdot 10^{6}$ pcs. i.e. at the time of the crisis there may be two steam bubbles in each cell. When the liquid is boiling in a large volume for a horizontal heater with a technical surface in the theory of hydrodynamic crisis, the ratio is $F_s / F = \frac{\tilde{\pi}}{16}$, i.e. 2.5 times less. When the value of $K_{min} \to 1$, the ratio $F_s / F \to 1$.

Geometric dimensions that significantly affect redistribution of the capillary and gravitational potentials affect the value $q_{cr}$and thus require optimization. The maximum value of $q_{cr}$was obtained for vertical surfaces with large cell sizes (β =0 deg), where β is the angle of inclination of the surface to the vertical line (see formulas (4) and (12)).

In grid porous structures, the phenomenon of the heat transfer crisis runs more smoothly than on a smooth surface, which is analogous to the vapotron effect, when a certain relief is created on the heating surface with protrusions and recesses. In a crisis situation, the film boiling region starts to shift from the base of the edges to their apexes, increasing the intensity of heat transfer and the value of q_{cr}. This allows to stretch the boiling crisis on a non-isothermal surface. In the porous cooling system, the presence of pores and capillaries on the heat exchange surface creates an artificial roughness, which in this case will play the role of edges. In addition, account must be taken of the stabilizing effect of capillary forces leveling liquid distribution on the heat exchange surface.

Thus, the essential dependence of the heat transfer ability of the studied system from the width of grid (dozens of times), as it takes place in the heat pipes, was not observed. This can be explained by the fact that at small sizes of cells in the presence of gravitational forces, high hydraulic resistance limits consumption to a lesser extent, which can partially flow over for grid surface. At the same time, increased cell size does not lead to a significant decrease of transfer capacity. However, the width of a grid cell in the system under study affects the dynamics of the steam bubbles' development and hence the intensity of the heat exchange and the value of the q_{cr}. The behaviour of bubble formation in individual cells (isolated) as was the case in system under study prevents premature fusion of steam bubbles and the formation of a solid steam film. The presence of large cells allows to improve the ejection of the light phase from the steam-generating surface. However, it is not advisable to increase the cells' size starting from a width of $0{,}4 \cdot 10^{-3}$ m, as steam conglomerates occur in such cells, similar to boiling on a technical surface without a porous coating.

Conclusion. Studies of the heat transfer crisis were performed depending on underheating and flow velocity, thermal properties of the heating surface, and ejection of liquid droplets from the porous structure. The principles of designing combustion chambers and nozzles and calculation of the critical heat flux are determined. The studies have practical significance in the field of the limiting state of the steam generating surface, which is protected by cooling from overheating.

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ЖОҒАРЫ ҚЫСЫМҒА АРНАЛҒАН ҚУАТТЫ ҚҰРЫЛЫМДАРДАҒЫ ЖЫЛУ АЛМАСУ ДАҒДАРЫСЫН ЗЕРТТЕУ

Аннотация. Кеуекті құрылымдардағы суды қайнату кезінде жылу алмасу дағдарысы зерттеледі. Зерттеу электр станцияларының жылу электр станцияларына жатады. Эксперименттер зымыран тозаңдатқыштарында жүргізілді. Жану камералары мен дыбыстан шашатын саңылаулар түрлі кеуекті құрылымдармен салқындатылды. Жылулық алмасу процестерінің механизмі сипатталған және кеуекті құрылымдардың оңтайлы ұяшық мөлшері анықталып, жоғары қысымдар үшін есептелген жылу ағыны теңдеуі алынды.

Түйін сөздер: қайнау дағдарысы, капиллярлы-кеуекті құрылымдар, салқындату жүйелері, жылу дағдарысы механизмі.

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ИССЛЕДОВАНИЕ КРИЗИСА ТЕПЛООБМЕНА В ПОРИСТЫХ СТРУКТУРАХ ДЛЯ ВЫСОКИХ ДАВЛЕНИЙ

Аннотация. Исследован кризис теплообмена при кипении воды в пористых структурах. Изучение относится к тепловым энергетическим установкам электростанций. Эксперименты проводились на горелке ракетного типа. Охлаждались камеры сгорания и сверхзвуковые сопла различными пористыми структурами. Описан механизм процессов теплообмена и определены оптимальные размеры ячеек пористых структур, получено расчетное уравнение критического теплового потока для высоких давлений.

Ключевые слова: кризис кипения, капиллярно-пористые структуры, системы охлаждения, механизм кризиса теплообмена.

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