HEAT TRANSFER CRISIS IN THE CAPILLARY-POROUS COOLING SYSTEM OF ELEMENTS OF HEAT AND POWER INSTALLATIONS

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Abstract. It was shown that liquid boiling processes occur in the porous cooling systems of the elements of the heat and power installations and crisis situation of heat exchange wall overheating may occur at high thermal conditions. Experimental installation was assembled whose schematic and conditions of experimentation were represented in the paper studying the crisis. A crisis mechanism was developed. The gravitational potential aids in the destruction of steam conglomerates in a porous structure, facilitating the transport of an underheated liquid. A surplus of liquid in the porous system creates a directional movement of the flow, which leads to deformation of steam bubbles in the structure, a decrease in diameter, an increase in the frequency of the formation of bubbles. As the flow velocity increases, the energy consumed for displacement of liquid from the wall boundary layer increases, and, consequently, the rate of steam generation and the value of the critical flow increases. An increase of critical load will be achieved at a high flow velocity of the liquid, which will lead to an increase of consumption of energy that is used to power the pressure units. Equations are proposed for computing the hydrodynamic crisis, taking into account the combined actions of gravitational and capillary forces, creating surplus of liquid, underheating and additional velocity to the flow. Theoretical models are confirmed by experiments for a wide range of pressure changes in the system, the parameters of the capillary-porous structure and its orientation in a gravitational field.
Key words: heat transfer crisis; capillary-porous structure; heat and power installations; steam bubble; capillary forces; mass forces; heat transfer control; permeability.

1. INTRODUCTION

The application of porous materials in boiler-and-turbine technology has attracted many researchers to create various devices. The intensity of the heat-eliminating systems and boosting of the processes occurring in them increased [1-3]. The application of porous materials in addition to cooling systems allowed to create units in which issues of explosion safety, work safety and durability were addressed [4-6]. This was facilitated by the ability to control the processes of steam formation due to surplus of liquid in the porous and capillary structures created by the combined actions of capillary and mass forces [7-9]. In heat and power installations (HPI), capillary-porous materials are used to cool highly-boosted detonation burner devices [3], to create steam coolers in steam boilers [9], oil coolers preventing intrusion of oil to cooling water and of water to a bearing system [10], labyrinth seals [11] and in other devices [10]. We protected the main areas of application of capillary-porous systems by patents and inventor's certificates. Integration of equipment and technological processes in the energy sector should be carried out primarily from the ecological and economic terms. Proposed inventions will facilitate the implementation of processes, significantly improving and protecting the environment [3,5,8-11].

The authors [12] carry out a comparative analysis of methods of heat transfer computation for

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water boiling with underheating in vertical channels, wherein they count focal corrosion of fuel-element cladding of fission reactor as analogy of capillary-porous structure [13,14]. However, no studies of heat transfer through a regular structured surface have been carried out. According to the authors [15,16], surface boiling on porous surfaces can affect the development of corrosion due to the erosive action on heat exchange surface when bubbles of steam collapse in an underheated liquid. Therefore, it is required to investigate steam formation of liquid in capillary-porous structures in the field of capillary and mass forces, taking into account the velocity and underheating, which are created by liquid surplus.

Evaluation of the heat exchange intensity for boiling of liquid for large volume and thin films on a smooth surface showed their equal possibilities [12-14] at high heat flows and higher heat transfer parameters than systems with a capillary-porous coating [15-16]. It is required to carry out studies of heat transfer capabilities of coatings operating in the field of capillary and mass forces, and to establish the values of critical loads leading to overburning of heat exchange heating surfaces. A technique for studying of capillary-porous systems was developed in relation to various elements of power installations. Systems differ in the fact that they have predominantly a gravitational liquid supply and in terms of the intensity of heat transfer occupy an intermediate position between thin-film and porous estimators with a predominantly capillary liquid supply (heat pipes). Therefore, such systems should be identified as a separate class of heat-eliminating systems. A generalization of the experimental results and technique of computing heat and mass transfer in capillary-porous systems in accordance with the developed technique are presented in [17-21].

2. EXPERIMENTAL STUDY OF HEAT TRANSFER CRISIS IN CAPILLARY-POROUS COOLING SYSTEM

Experimental installations that allow for the study of integral parameters of heat transfer: heat consumption q, liquid and steam consumption m_l, m_s allocation of temperature field by height and length of the heat exchange surface. A study is carried out in capillary-porous cooling system, which can operate on principle of a closed or open vaporizing-condensation circuit design. Varied conditions of the heat exchange are studied: the method of the coolant supply; structure degree of pressing; ability of the additional makeup from micro-arteries by the height of heat exchange surface to structure; orientation of surface relative to gravitational forces; flat, tubular and bent cooling surfaces; the geometry: the effect of pressure up to the crisis phenomena with the overburning of wall.

Holography methods are engaged for investigating the mechanism of heat exchange, the generalization of the similar and analogous phenomena [1,3,11,20,21]. Control of heat exchange is carried out by means of elliptic systems, through combined action of capillary and mass forces [1,3]. The study of heat transfer is practical, it is designed to create various heating power installations: porous housing elements for pipes, steam boiler steam cooler, porous surfaces made of heat non-conductive material, seals in steam turbines and a number of other power installations [1,3,7,10,19].

In Fig.1 operation scheme of porous cooling system, the technique of the measurement of heating surface temperature t_{st} and liquid consumption: m^t_l, m_1, m_2, m_{dr}, m_c, $m_{c.w}$, m_{air} and steam m_s are shown. Accepted codes: t - tank, d -discharge, c - condensate, c.w. – condensing water, a – air. Temperatures of liquid t_l^t , t_l^{dr} , t_l^{out}, t_l^{in}, steam t_s, electrical insulation $t_{el}^i = t_{dif}$.

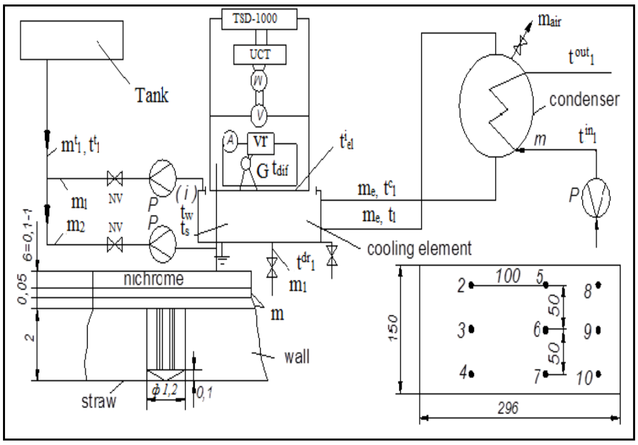

Fig.1. Operation scheme of a porous system and measurement technique: TSD-1000 - welding transformer; UCT - universal current transformer; W - power meter; V-voltmeter; A - ammeter; VR - voltage regulator; G - galvanometer; R - rotameter; NV - needle valve.

A cooling element with a capillary-porous structure is presented in Fig. 2. It allows for the study of the liquid supply scheme from tubular arteries 3, influence of heat exchange surface h, structure degree of pressing using a perforated plate 10 and the intensity distribution of the coolant by micro arteries 11.

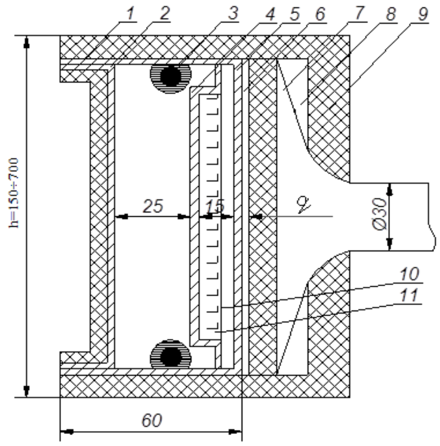

Fig.2. Cooling element with the capillary-porous structure: 1 – housing, 2 – cover, 3 – tubular artery, 4 – plug, 5 – capillary-porous structure, 6 – electroinsulation (mica), 7 – main heater, 8 – guarding heater, 9 – heat insulation, 10 – perforated pressure plate, 11 – micro artery.

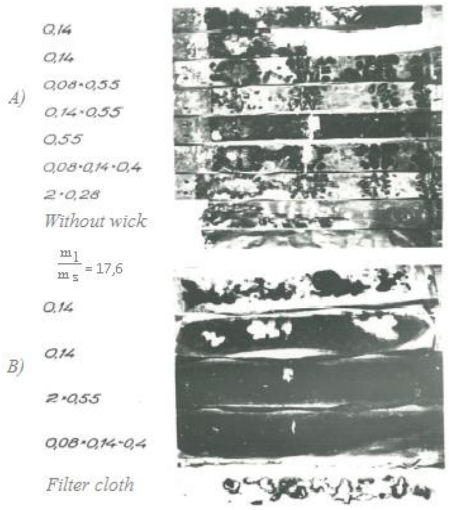

Fig.3. Burned heaters (A) and capillary-porous structures (B) wicks.
Surplus of liquid changed m_l/m_s = from 1 to 17,6.

Heat transfer studies were carried out prior to the occurrence of a boiling crisis with surface and a capillary-porous structure overheating (Fig.3 A, B), wherein surplus of liquid m_l/m_s = from 1 to 17,6.

3. EXPERIMENTAL CONDITIONS

The supply of electrical energy to the main heater is carried out from a TSD-1000 type welding transformer, the output voltage of which has following fixed values: 2,5; 5; 7,5 and 10 (see Fig. 1). Electric current powering the heater is measured according to the scheme with UTT-6M2 type cl. 0,2 universal transformer. Secondary current is up to 5 A, primary current is 100 ... 2000 A. Heater voltage drop is measured by a D523 cl 0,5 voltmeter. Maximum possible error for current measurement is ± 0,6%, ± 1% for voltage drop measurement, ± 1,6% for power measurement. Electric energy is supplied to the guarding heater from a RNO type voltage regulator. TSD-1000 type current transformer, with 71 V no load output voltage, is used in studies at the start of liquid boiling and critical loads. Current strength is regulated within limits of 200…1200 A. The measurements of liquid and environment temperatures are made by TL–4 mercury thermometers with 0…50^0 C and 50…100^0 C scale and division value of $0,1^0$C. The temperatures of the drainage liquid and steam are measured by the Chromel-Copel thermocouples, made of wire with $0,1x10^{-3}$m diameter. The head diameter of thermocouple junction is $0,4.10^{-3}$ m. Thermocouple electrodes are isolated with dual channel straws with diameter of $1x10^{-3}$ m, that are attached with BF-2 glue inside the injection needles with diameter of $1,2.10^{-3}$ m. Electrodes of the thermocouples with a diameter of $0,2.10^{-3}$ m are welded to the wall by the electric arc, which is formed during discharge of capacitors, to measure the temperature of wall. In order to do that drilling of the wall orthogonal to a surface with 2.10^{-3} m thickness is carried out for $1,9.10^{-3}$ m depth with the accuracy of ± $0,05.10^{-3}$ m. Electrodes of the thermocouple are isolated with porcelain straws with $1,2.10^{-3}$ m diameter and come out to the surface of the wall between two layers of mica with thickness of $0,05.10^{-3}$ m attached to the surface of the heater. Cold ends of thermocouples are thermostated in melting ice. Electrodes of the thermocouple are connected with two PP-63 cl. 0,05 twelve point switches. Installation and instruments are grounded to prevent the effect of induced wandering currents on indicated values of the thermocouple. The consumption of cooling and circulating liquid is determined by electric RED type rotameters with secondary electronic CSDH 43 cl. 1 type instrument, calibrated with volumetric method. The consumption of drained liquid and condensate are captured using a test measure with $0,5.10^{-3}$ *l* pressure scale, and filling time with S-P-1b type stopwatch type with a 0,1 second division value. [22]

Maximum possible error when determining liquid consumption by rotameters does not exceed ± 3%, and by the volumetric method it is ± 2%. The conditional permeance coefficient is further studied in [3]. Spread of K_c value when integrating experimental data does not exceed ± 16%. The imbalance between heat supplied by current and heat, extracted by circulating and surplus water taking into account Q_m, does not exceed ± 12%, and between heat supplied by steam in condensing unit and heat, extracted by the circulating water does not exceed ± 11%. The discrepancy of material balance between the consumption of cooling liquid, consumption of drain and condensate is not more than ± 10%. Measurements and processing of experimental data technique is published in the works [2-4].

4. MODEL OF THE CAPILLARY-POROUS STRUCTURE OF THE COOLING SYSTEM

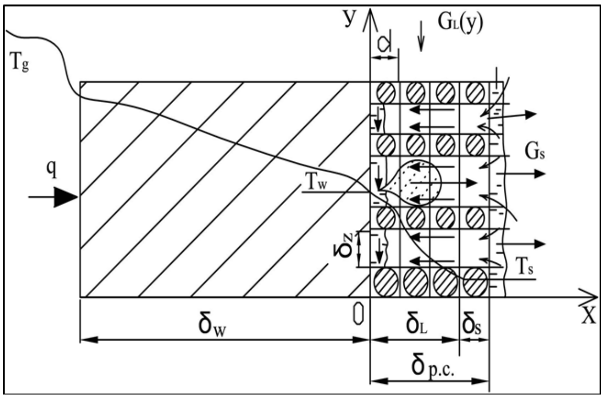

Fig. 4. Physical model of heat and mass transfer in a porous structure covering the coolable surface: Straight lines – fluid movement: q – thermal flow, T_g, T_w, T_s–temperatures of gases, walls and saturation; G_l (y), G_s – liquid and steam flow rates; δ_w, $\delta_{p.c.}$, δ_l, δ_s – steam-generating surface, porous coating, liquid and vapor thicknesses, b_z, d–width of porous coating cells and grain diameter.

Figure 4 shows the model of a capillary-porous coating applied to the coolable surface of a heat-loaded element of power plants. At the onset of the boiling crisis, the critical state of the heating surface arises, and the latter is destroyed along with the coatings. Such a scheme allows to make a model of fissures of brittle coatings and plastic porous structures.

5. MODEL OF CRISIS OF HEAT TRANSFER IN A POROUS COOLING SYSTEM

A rocket burner, which contains a combustion chamber and supersonic nozzle [3] together with the heat supply by electric current (see Fig.2) was used to study critical rates of heat transfer. Cooling system of combustion chamber and nozzle set is one of the important elements of power installation. Let us write over equations of continuity and movement, taking into account the combined action of gravity and capillary forces wherein forces of gravity generate surplus of liquid $\tilde{m} = m_l/m_s$ to determine the maximum heat flow extracted by porous cooling system:

$$\frac{dV_y}{dy} = -\frac{\rho_s}{\rho_l}\cdot\frac{L}{\varepsilon.F_f}.V_z\cdot\left(\frac{m_s}{m_l}+1\right), \qquad (1)$$

$$V_y.\frac{dV_y}{dy} = g.\cos\beta + \frac{2.\sigma}{\rho_l}\cdot\frac{d\left(\frac{1}{R[y]}\right)}{dy} - \frac{\varepsilon.\upsilon_l.V_y}{K}, \qquad (2)$$

We obtain the following by inserting equation (1) into equation (2) taking into account values $V_y = \frac{G_l[y]}{\rho_l}$, $V_z = \frac{q_{cr}}{r.\rho_s}$, and after integrating the obtained equation anywhere from c_1=0 to c_2=H and from $R_0=\infty$ to $R_h=b_h/2$:

$$3.q_{cr}^2.h^2.\frac{m_s/m_l}{2}.\left(r.\varepsilon.\delta_f\,\rho_l\right)^2.\varphi'_{cr} - \frac{3.q_{cr}.h^2.\upsilon_l}{2.r.\delta_f.\rho_l.K.\varphi'_{cr}} + \left(gh\cos\beta + \frac{2.\sigma}{\rho_l.R_h}\right) = 0. \qquad (3)$$

Solution of the quadratic equation is an expression (3) which determines the first critical heat flow of the weakly-underheated and saturated liquid ($\tilde{m}\rightarrow 1$):

$$q_{cr} = \frac{\left[B \pm \left(B^2 - 4.A.C\right)^{0,5}\right]}{2.A}, \qquad (4)$$

where q_{cr} - critical (maximum) heat flow; φ'_{cr} - critical flow humidity rate

$$A = \frac{3.h^2.(m_s/m_l+1)}{2.\left(r.e.d_f.r_l\right)^2.j'_{cr}},\quad B = \frac{3.h^2.\upsilon_l}{2.r.\delta_f.\rho_l.K.\varphi'_{cr}},\quad C = g.H.\cos\beta + \frac{2.\sigma}{\rho_l.R_h}.$$

6. ANALYSIS OF THE HYDRODYNAMIC CRISIS OF HEAT TRANSFER

Let us determine the maximum height of heat exchange surface h, at which hydrodynamic crisis of heat exchange will begin from equation (4). Let us take δ_f, K, b_h, H, P. values in place of variables. We inspect two extreme cases, that occurred in experiments: δ_{f1}=1,5.10^{-3} m and δ_{f2}= 0,15.10^{-3} m. For δ_{f1} we will obtain:

$$\frac{j'_{cr}}{h^2} = \frac{140,4}{\left(9,81.H + 0,447\right)}, \qquad (5)$$

where $K=5,8.10^{-10}$ m^2, $b_h=0,55.10^{-3}$v, P=0,1 MPa. Since H and δ_f values correlate by the formula:

$H\delta_f=15.10^{-3}$ m, then 10 m ≤ H ≤100 m.

When H=10 m; $j'_{cr}=0,1$; $h=h_{max}=0,26$ m. For the δ_{f2} value the equation is as follows:

$$\frac{j'_{cr}}{h^2}=\frac{1386}{(9,81.H+1,76)} \quad (6)$$

When H=100 m, $j'_{cr}=0,1$we obtain close value of the height of the heat exchange surface (h_{max}= 0,266). Inspected cases relate to the case, when the entire cooling liquid moves in the clear opening of porous structure ($K=K_{hp}$). Equations (5) and (6) connect hydrostatic head with the height of the heat exchange surface. Let us solve equation (4) relative to $\frac{j'_{cr}}{h^2}$ value for the case, when the part of the liquid due to its surplus can flow over the surface of the porous body, i.e., coefficient $K=K_c$. In this case, insignificant external pressure generated by the height of the column of liquid H will be required, and capillary potential will substantially exceed the gravitational potential: $\frac{\rho_l \cdot g.H.2.\sigma}{R_h}$. Then H and δ_f values do correlate among themselves. In this case the solution of equation (4) is:
for $\delta_{f1}=1,5.10^{-3}$ m:

$$\frac{\varphi'_{cr}}{h^2}=0,126.(9,81.H+0,447) \quad (7)$$

for $\delta_{f2}=0,15.10^{-3}$ m:

$$\frac{\varphi'_{cr}}{h^2}=17,4.(9,81.H+1,76). \quad (8)$$

We will obtain the values of the heights of heating surface of h_{max1}= 2,86 m, $h_{мах2}$ = 0,758 m at H =10 m, $\frac{j'_{cr}}{h^2}$ =0,1 values, i.e., for thin structures the crisis of boiling will occur at smaller values of h. The solution of equation (4) requires a high accuracy of computation, whereas, after dropping the first term of equation, it is possible to solve this equation with practically the same degree of accuracy. Equation (4) will then be as follows:

$$q_{cr}=\frac{C}{B}=\frac{2.\varphi'_{cr}.r.\delta_f.\rho_l.K.\left(g.H.\cos\beta+\frac{2\sigma}{\rho_l.R_h}\right)}{3.h^2.\upsilon_l} \quad (9)$$

In the equation (9) there is no explicit relation m_l/m_s, however it is considered through the values of φ_{cr} and K. When $\varphi_{cr}\to 0$, the value of $q_{cr}\to 0$, i.e. in the boundary layer of porous structure almost the entire moisture will evaporate and the crisis of boiling will occur.

The solution of equation (9) relative to the height of the column of liquid is of interest for both cases of hydrodynamics of the liquid: $K=K_{hp}$, $K=K_c$. When all liquid moves in the clear opening of the porous structure ($K= K_{hp}$) it is required to create a sufficiently high pressure. Value H equals to tens of meters of the water column for studied cooling system, when h = (0,1...0,7), δ_f = (0,15...1,5).10^{-3}m, b_h = (0,08…1).10^{-3} m, at φ'_{cr} = 0,1. In the second case, when surplus of liquid is generated when liquid flows freely over the external surface of the porous structure ($K=_i$), exceeding the column of liquid is equal to several tens of millimeters. Condition $\rho_z gH«2\sigma/R_h$ can occur not only at horizontal arrangement of cooling systems, but also when the part of the liquid flows over the external surface of the porous structure ($K=K_c$). It does not follow from the formula (9) that by infinitely increasing the hydrostatic head $\rho_{z.}g.H$, it is possible to also increase q_k value, since in this case value K can lose its physical sense of permeability, since the main liquid consumption will lie outside of the clear opening of structure, freely flowing over the porous material. In addition, when q≤6.10^4 W/m^2 redistribution of heat drawn by steam generation and convection will occur, up to degeneration of boiling process. When value $q \to q_{cr}$, in spite of large amount of liquid $G_l=F[H]$, crisis phenomena will occur, which will lead to overburning and destruction of the heat exchange surface (see Fig.3). In this case in the equation (9) $\rho_l gH » 2\sigma/R_h$ inequality will be realized and it will be necessary to introduce K/K_c coefficient. In the case, when $\rho_z gH \approx 2\sigma/R_h$, the value of $\Delta P_{c+m}=(1,5...2)\ 2\sigma/R_h$, and the value of H equals to several tens of millimeters depending on the thickness of structure. Let us establish a relation h = f [H]. Let us also assume that the value of $K = K_{hp}=5,8.10^{-10}\ m^2$. We will obtain the following from the equation (5) for $\delta_{f1}=1,5.10^{-3}$ m:

$$h= (0,32...1)\ \ (0,0699.H+3,18.10^{-3})^{0,5}. \quad (10)$$

We obtain the following for the value $\delta_{f2}=0,15.10^{-3}$ m from the equation (6):

$$h= (0,32...1)\ (7,1.10^{-3}H + 1,27.10^{-3})^{0,5}. \quad (11)$$

At this time it is expected that the mass moisture content can vary from the moment of the boiling occurrence ($\varphi' \to 1$) to the crisis of boiling ($\varphi=\varphi'_{cr} \to 0,1$) [3]. Analysis allows to determine the height of the heat exchange surface, the thickness of the porous structure, which correspond to critical heat load. Taking account of the boiling point in the porous body is carried out with the consumption moisture content φ' and the parameter $\widetilde{m}$, which creates a directed flow of the underheated liquid with insignificant velocity and allows to ensure the stability of the two-phase flow in the boundary pulsating layer of the liquid. Let us cite the experimental and computed values of q_{cr} (equation 4) and the corresponding to them values ΔT_{cr} for different pressures. Due to physical concepts, in equation (4) we keep the sign "-" (Table 1).

Table 1. Critical heat loads and temperature headers

	P, MPa			
	0,01	0,1	8	20
1. q_{cr}, W/m^2 a) $K = K_{hp}$	$2,95.10^4$	6.10^5	$6,9.10^5$	$1,66.10^5$
b) $K = K_c$	3.10^5	6.10^5	$2,5.10^5$	$5,8.10^3$
2. ΔT_{cr}, K	14,2	60	55,2	7,75

Initial computed data were: H = 10 m, cosβ = 1, $R_h= 0,275.10^{-3}$ m, h = 0,27 m, $\varphi'_{cr} = 0,1$, $\delta_f = 1,5.10^{-3}$ m, $K = 5,8.10^{-10}\ m^2$.

Estimation of the temperature split in the porous structure is necessary for ensuring a stable operation of the cooling system. This estimation is rather complicated, which is related to the difficulty of determining the effective heat conductivity coefficient at the time of the boiling crisis, dependent on many factors, the main of which are the presence of a steam-water mixture in the boundary layer, contact resistance between the structure carcass and the wall and between the elements of the carcass itself, which can change from the degree of compression of the structure to the wall and from a change of temperature level of the operation, which leads to a heat expansion of the wire of the grid. In addition, in a crisis mode, the thickness of the liquid layer is a quantity that is not determined. Therefore, the computation of the ΔT_{cr} value cannot be carried out on analytical basis and was the subject of experimental studies (see Table 1).

Computation assumes that the coolant fills the entire clear opening of the structure and does not flow over the porous body. Structurally this is realized by creating a channel and installing it inside a porous structure. If a surplus of liquid $\tilde{m}$ is created and part of it can freely flow over the external surface of the porous body, it is necessary to introduce a conditional permeability coefficient K_c. Comparing the data presented in Table 1, we see that in the case of (δ) for high pressures, a stronger effect of the value of P on the value of q_{cr} is observed, since the rapid decrease of the coefficient σ begins to take effect. Thus, by implicating the gravitational potential, it is possible to deepen the value q_{cr} and stabilize the dependence q_{cr}=f[p] for a wide range of pressure changes (0,01 ... 20 MPa), which is especially important when the system operates under high pressure. The moisture content φ affects the value of q_{cr} through relation, besides the value φ'_{cr}= (0,1...0,15). Equation (4) is obtained on the basis of hydrodynamic analysis of heat exchange processes, where local restrictions of the heat flow are not taken into account when contact of the liquid film with the surface is impossible because of strong overheating of this surface during the growth of the steam bubble.

7. MECHANISM AND COMPUTATION OF THE HEAT EXCHANGE CRISIS IN A POROUS COOLING SYSTEM

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≥0,1 MPa, and b_h> $0,28.10^{-3}$ m:

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

It follows from equation (12) that $q_{cr} \sim \overline{D}^{0.5}_{c.cr}$ (p ≥ 0,1 MPa) and $q_{cr} \sim \bar{f}^{0.5}$ (p <0,1 MPa).

Figure 5 presents experimental results in the form of points. A comparison is also made between the results of the calculation formulas (4 and 12) with the experimental ones. Since the presented computational results of formulas (4 and 12) differ by ± 10%, they are shown in a curve line.

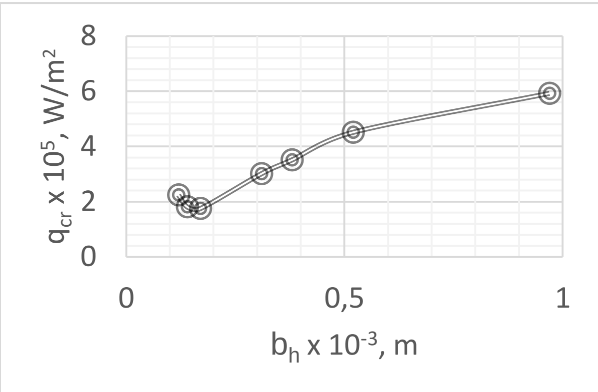

Fig. 5. Effect of the cell width of the grid structure on critical heat flow during water boiling. The computation is carried out using equations (4, 12). The grid and the wall are made of stainless steel. The experiments were carried out for the following conditions: h = 0.27 m; $\tilde{m}$=optimal; P= 0.1 MPa; β =0 deg. Structures of the following type are studied: 1 – 0,08x0,14; 2 – 0,08x0,14x0,28; 3- 3x0,14; 4 - 2x0,28; 5 – 0,4; 6 – 0,55; 7 - 1x1

The value of $\overline{D}_{o.cr}$, $\bar{f}$ depends on the thermophysical properties of the heat-release surface: $\overline{D}_{c.cr} \sim K_w^{-1}$, $\bar{f}_{cr}^{-1} \sim K_w^{2}$, 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 ≥ 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.

As the computations [10] have shown, for time $\tau \leq 5$ s, the heat flows reach values of ~ 8.10^7 W/m^2 for copper and $1,3.10^8$ 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 $0,28.10^{-3}$ 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. 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 (see Table 1).

For water boiling in a large volume at atmospheric pressure, the critical wavelength λ_{cr} between the steam columns is $(15...25).10^{-3}$ 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 ΔT_{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, ΔT_{cr} = 60 K, $\bar{D}_{o.cr}$ = 0,5.10^{-3}, $\tilde{\bar{m}}$ = 1,1, $\bar{n}$ = 5.10^{6} m^{-2}, is provided by the following:

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

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 0,4.10^{-3} m, per 1 m^2, is 2,78.10^6 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 = $\frac{\bar{\pi}}{16}$, i.e. 2,5 times less. When the value of $K_{min} \rightarrow 1$, the ratio $F_s/F \rightarrow 1$. 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)).

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} (see Fig. 4). 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 0,4.10^{-3} m, as steam conglomerates occur in such cells, similar to boiling on a technical surface without a porous coating.

8. Conclusion

The crisis of heat transfer in capillary-porous structures in the cooling system of elements of heat and power installations is studied. Heat exchange crisis is presented on the basis of hydrodynamic conditions at the combined effect of gravitational and capillary forces. The suggested model of crisis, obtained with a system of differential equations that describe one-dimensional flow of single-phase liquid, reflects the physical phenomenon of the process by means of input of viscous element to a total pressure gradient and taking account of the member of the actual velocity of the liquid in the porous structure using a consumption moisture component which allowed to obtain the computing formula. Critical values of height of the heat exchange surface and thickness of the structure for the two regimes of liquid hydrodynamics are estimated, which correspond to the minimum value of the hydrostatic head, creating an optimal surplus ratio depending on the geometric parameters. We proved that the experimental installation with the supply of heat by electric current is effective, as well as conducted experiments with another heat source - with a supersonic torch of a flame-jet burner. The experiments were carried out for grid structures and in the future it is required to carry out numerous experiments with other porous coatings in the form of natural mineral medias, which will allow to expand the results of the study and facilitate their application.

Nomenclature

b_h, δ_w – hydraulic pore size and wick thickness, [m]

C – heat capacity, [J/kg K]

$\overline{D}_{o.cr}$ – the size of the steam conglomerate corresponding to the condition of $\Delta T = \Delta T_{cr}$, [m]

E – porosity

F, F_s – heating (cooling) surface and the surface covered with steam, [m^2]

F_w – section of the porous structure (wick), [m^2]

$\bar{f}$ – rate of steam bubbles generation, [s^{-1}]

G_l [y] – specific liquid consumption, [kg/m^2s]

g – acceleration of gravity, [m/s^2]

h, L – height and the length of the heating surface, [m]

K – coefficient of permeability, [m^2]

K_c – conditional coefficient of permeability, [m^2]

$K_{hp.}$ – permeability coefficient of the wicks of heat pipes (h.p.), [m^2]

m^t_l, m_1, m_2, m_{dr}, m_c, $m_{c.w.}$, m_{air}, m_s – liquid consumption in the tank, at the inlet to the upper and lower mains, condensate, circulating water, air, steam, [kg/s]

$m=m_l/m_s$ – surplus of liquid

$\bar{n}$ – average density of the centers of steam formation, [m^{-2}]

P – pressure, [Pa]

ΔP_{m+c} – the total acting head (mass and capillary), [Pa]

q_{cr} – critical heat flow, [W/m^2]

R [y] – radius (of meniscus) liquid, [m]

$R_{d.s.}$ – radius of the "dry" spot, [m]

r – heat of steam generation, [J/kg]

T_s – saturation temperature, [K]

t_w, t^t_l, t^{dr}_l, t^{out}_l, t^{in}_l, t_s, t^s_{el}, t_{dif} – wall temperature, liquids in the tank, draining liquid, liquid at the outlet and inlet, steam, electrical insulation, differential temperature, [^{0}C]

ΔT_{cr} – critical temperature head, [K]

$\Delta T = T_w - T_s$ – temperature head, [K (^{0}C)]

U_{cr} – critical velocity of steam, [m/s]

V – velocity, [m/s]

y, z – coordinates of direction of liquid and steam(z) motion, [m]

Greek symbol

β – angle of the slope of cooling system to the vertical line, [deg]

δ – thickness, [m]

λ_l , λ_{ef} – coefficients of heat conductivity of liquid and efficiency, [W/mK]

λ_{cr} – critical wavelength between the steam pillars, [m]

ν_l – coefficient of kinetic viscosity of the liquid, [m^2/s]

ρ – density [kg/m^3]

σ – coefficient of surface tension, [N/m]

τ – time, [s]

φ'_k – critical consumption liquid content

Indexes

c – conditional

cr – critical (crisis)

c.w. – circulating water

dr – draining

diff – differential

d.s. – "dry" spot

ef – effective

el – electric

h – hydrodynamic

h.p. – heat pipe

i – insulation

in. out. – input, output

l, s – liquid, steam

m+c – mass and capillary

o.r. – tear - off size at the time of crisis

s - saturation

t – tank

w - wick

w – wall

References

[1] Polyaev, 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, USA, 1995, Vol. 10, pp. 273-286
[2] Polyaev, V.M., Genbach A.A., Heat Transfer in a Porous System in the Presence of Both Capillary and Gravity Forces, *Thermal Engineering*, 40 (1993), 7, pp. 551-554
[3] Polyaev, V.M., Genbach A.N., Genbach A.A. A Limit Condition of a Surface at Thermal Influence (in Russian), *Teplofizika Vysokikh Temperatur*, 29 (1991), 5, pp. 923-934
[4] Polyaev, V.M., Genbach A.A., Control of Heat Transfer in a Porous Cooling System. Proceedings, 2^{nd} World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, *Dubrovnik*, Yugoslavia, 1991, pp. 639-644
[5] Polyaev, V.M., Genbach A.N., Genbach A.A. Processec in the Porous Elliptic Heat Exchanger (in Russian), *Isvestiya Vuzov, Mashinostroyenie*, (1991), 4-6, pp. 73-77
[6] Genbach A.A., Bakhytzhanov I.B., Protection Against Earthquakes TPP Bases with the Help of Porous Geo Screens (in Russian), *Poisk, MES of RK*, (2012), 1, pp. 289-298
[7] Genbach A.A., Danilchenko I., Porous Desuperheater Steam Boilers (in Russian), *Promyshlennost Kazakhstana*, 70 (2012), 1, pp. 72-75
[8] Genbach A.A., Olzhabayeva K.S., Visualization of Thermal Impact on Porous Material in Thermal Energy Installations of Power Plants, *Bulletin of the National RK Engineering Academy*, 45 (2012), 3, pp. 63-67
[9] Genbach A.A., Islamov F.A., Research of the Nozzle Fillets in Electrical Installations (in Russian), *Vestnik KazNTU*, 97 (2013), 3, pp. 245-248
[10] Genbach A.A., Islamov F.A., Modeling Process Grazing Turbine (in Russian), *Vestnik KazNTU*, 100, (2013), 6, pp. 235-240
[11] Polyaev, V.M., Genbach A.A., Control of Heat Transfer in Porous Structures (in Russian), Proceedings, Russian Academy of Sciences, *Power Engineering and Transport*, 38 (1992), 6, pp. 105-110
[12] Jamialahmadi M., et al., Experimental and Theoretical Studies on Subcooled Flow Boiling of Pure Liquids and Multicomponent Mixtures, Intern. J *Heat Mass Transfer*. 51 (2008), 9-10, pp. 2482-2493
[13] Ose Y., Kunugi T., Numerical Study on Subcooled Pool Boiling, *Progr. In Nucl. Sci. and Technology 2*, (2011), pp. 125-129
[14] Krepper E., et al., CFD Modeling Subcooled Boiling-Concept, Validation and Application to Fuel Assembly Design, *Nucl. Eng. and Design*, 237 (2007), 7, pp. 716-731
[15] Ovsyanik A.V., Modelling of Processes of Heat Exchange at Boiling Liquids (in Russian), *Gomel State Technical University named after P.O., Sukhoy, Gomel*, Belarus, 2012
[16] Alekseik, O.S., Kravets V.Yu., Physical Model of Boiling on Porous Structure in the Limited Space, *Eastern-European Journal of Enterprise Technologies*, 64 (2013), 4/8, pp. 26-31
[17] Polyaev, V.M., Genbach A.A., Analysis of Laws for Friction and Heat Exchange in the Porous Structure (in Russian), Bulletin of MGTU, *Mechanical Engineering Series*, (1991), 4, pp. 86-96
[18] Polyaev, V.M., Genbach A.N., Genbach A.A. The Influence of Pressure on the Intensity of Heat Transfer in a Porous System (in Russian*), Isvestiya Vuzov, Mashinostroyenie*, (1992), 4-6, pp. 68-72
[19] Polyaev, V.M., Genbach A.A., Field of Application of Porous System (in Russian), *Isvestiya Vuzov, Energetika*, (1991), 12, pp. 97-101
[20] Genbach A.A., Jamankylova N.O., Bakic Vukman V. The processes of Vaporization in the Porous Structures Working With The Excess of Liquid, *Thermal Science: Year 2017*, Vol 21, №1A, pp. 363-373
[21] Genbach A.A., Olzhabayeva K.S., Iliev I.K., Boiling Process in oil Coolers on Porous Elements, *Thermal Science: Year 2016*, Vol. 20.№ 5, pp. 1777-1789
[22] Genbach A.A., Bondartsev D.Iu., Iliev I.K., Equipment for study of various heat exchange conditions in capillary-porous structures of power equipment, *Proc. 6^{th} Int. Conf. on Thermal Equipment, Renewable Energy and Rural Development TE-RE-RD, 2017*, Moieciu de Sus – Romania, 8 – 10 June, pp. 37-42