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EXPERIMENTAL METHOD OF INVESTIGATION OF THE HEAT TRANSFER CRISIS IN A CAPILLARY-POROUS COOLING SYSTEM

Abstract. The crisis of heat exchange in grid porous structures at boiling water is studied. The study relates to heat and power installations of power plants. Experiments were carried out on an electric testing bench and on a rocket type burner, in which combustion chambers and supersonic nozzles were cooled with various capillary-porous structures. The model and mechanism of the heat exchange processes are described, the optimal dimensions of the cells of the porous structures are determined, and computational equations for determining the critical heat flow for a wide variation of pressure in the system and the parameters of the porous structures (pore sizes, structure thickness, permeability, geometric dimensions of the cooling surface and its orientation) are obtained. Experimental installations for determining integral (average) heat-exchange parameters in a capillary-porous cooling system are produced: operation scheme and a measurement technique, a cooling element with tubular arteries structure, a perforated clamping plate and micro arteries. Studies were carried out until the wall and the capillary-porous structures were overburnt.

Keywords: heat transfer crisis; capillary-porous structure; heat and power installations; steam bubble; capillary forces; mass forces; heat transfer control; permeability.

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 asurplus 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].

These systems allow to achieve fuel, raw materials, air, water and heat savings; they increase the reliability of cooling and fire and explosion safety of equipment operation; they facilitate highly effective destruction of rocks, concretes, metals, and reduce low-temperature corrosion of surfaces, as well as reduce bio contamination by toxic gases, dust, and heat. Furthermore, the systems facilitate the resolution of food program issues, whilst helping to achieve strong economic and social effects in the area of ecology and a work safety.

The main advantages of such systems are high intensity, high heat transfer ability, reliability, compactness, ease of manufacturing and operation; they improve the performance and technological parameters and have low capital and operating costs.

The authors [12] carry out a comparative analysis of methods of heat transfer computation for water boiling with underheating in vertical channels, wherein they count focal corrosion of fuel-element cladding of fission reactor as ananalogy 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 thesteam 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 theboiling 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.

The studies carried out allow to give recommendations for choosing of heat-transfer medium, taking into account the type of its circulation, determine the geometry and material of heat exchange devices and intensifiers, taking into account the conditions and orientations of the system operation under pressure or under exhaust, the supply and type of energy, and the orientation of the system. 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].

The study of various factors influencing the heat transfer in structures shows that the extreme states of the heating surface are of specific interest when the system is capable of transferring the maximum flow of energy and matter. However, in this case, it is required to know the values of the heat flows and heat stresses in order to ensure a reliable long-term operation of the installation. In this way, it is possible to achieve maximum energy and matter transfer for the following conditions: a clean liquid circulating on a force-feed basis in closed elliptical heat exchangers under pressure in perforated and profiled heating surfaces made of stainless steel is used. The system works with asurplus of liquid, and the presence of mass forces ensures the force-feed flow of the heat transfer medium with underheating. Energy is fed to the vertical surface along the perimeter with asupersonic high-temperature pulsating rotating torch [1, 3, 11, 19].

Experimental study of heat transfer crisis in thecapillary-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 thecapillary-porous cooling system, which can operate on theprinciple 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 in 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 thecombined 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 figure 1 operation scheme of theporous 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 $t_{el}^i = t_{dif}$.

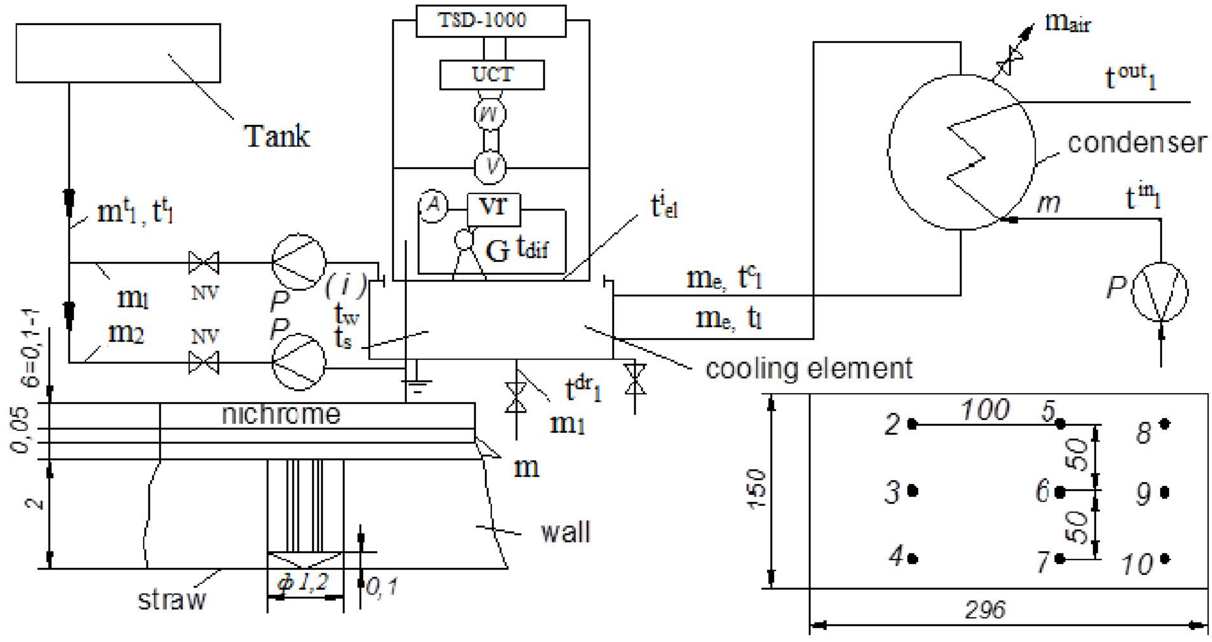

Figure 1 – Operation scheme of a porous system and measurement technique:
TSD-1000 – welding transformer; UCT – universal current transformer; W – power meter; V – voltmeter;
A – ammeter; VR – voltage regulator; G – galvanometer; R – rotameter; NV – needle valve

A cooling element with a capillary-porous structure is presented in figure 2. It allows for the study of the liquid supply scheme from tubular arteries 3, theinfluence 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.

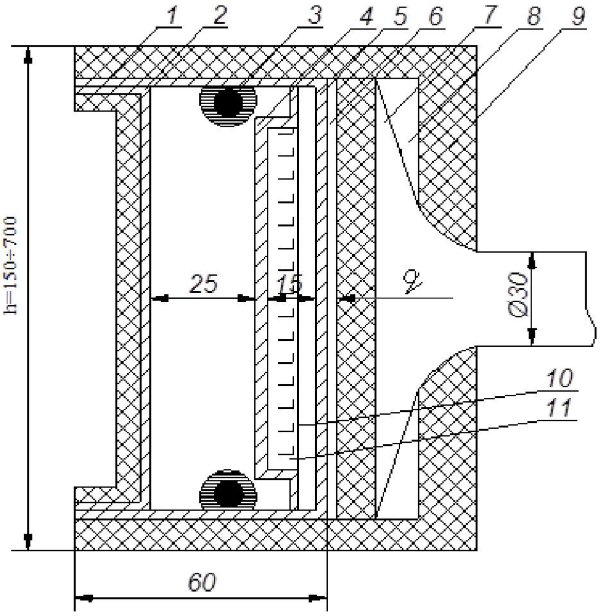

Figure 2 – Cooling element with the capillary-porous structure:
1 – housing, 2 – cover, 3 – tubular artery, 4 – plug, 5 – capillary-porous structure, 6 – electroinsulation (mica),
7 – main heater, 8 – guarding heater, 9 – heat insulation, 10 – perforated pressure plate, 11 – micro artery

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

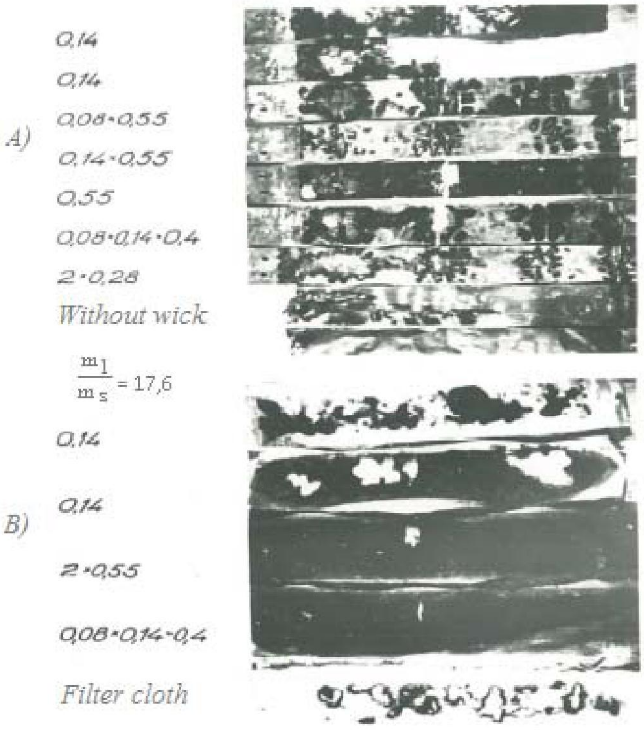

Figure 3 – Burned heaters (A) and capillary-porous structures (B) wicks.
Surplus of liquid changed m_l/m_s = from 1 to 17,6

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 $0.1\cdot10^{-3}$ m diameter. The head diameter of thermocouple junction is $0.4\cdot10^{-3}$ m. Thermocouple electrodes are isolated with dual channel straws with adiameter of $1\cdot10^{-3}$ m, that are attached with BF-2 glue inside the injection needles with adiameter of $1.2\cdot10^{-3}$ m.

Electrodes of the thermocouples with a diameter of $0.2\cdot10^{-3}$ m are welded to the wall by the electric arc, which is formed during discharge of capacitors, to measure the temperature of thewall. In order to do that drilling of the wall orthogonal to a surface with $2\cdot10^{-3}$ m thickness is carried out for $1.9\cdot10^{-3}$ m depth with the accuracy of $\pm\ 0.05\cdot10^{-3}$ m. Electrodes of the thermocouple are isolated with porcelain straws with $1,2\cdot10^{-3}$ m diameter and come out to the surface of the wall between two layers of mica with athickness of $0.05\cdot10^{-3}$ m attached to the surface of the heater. Cold ends of thermocouples are thermostated in melting ice. Electrodes of the thermocouple are connectedwith 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 $0.5\cdot10^{-3}l$ 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%.

Effective heat conductivity of moistened netted structure was determined by the following formula:

$$\lambda_{ef} = \lambda_l . \left[1 + \frac{1}{0,5.a.b + C} \right], W/(m.K)$$

wherea = 8.10^3 m^{-1}, C = 1,35 for grids 12X18H9T: a = $1.8.10^3$ m^{-1}, C = 0.73 for brass grids.

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].

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 theheight 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. Using the system of differential equations describing the one-dimensional flow of a single-phase liquid, in accordance with the Darcy law, the task of determining the critical heat loads in which potential of gravitational forces exerts along with the capillary potential. Studieswere carried out for two cases: liquid moves only in the cross-section of the porous structure and the liquid can freely flow over the surface of the porous body. Consequently, the studied critical moisture content, conditional permeability coefficient and surplus of liquid all take into account the influence of gravitational forces, expressed through the flow velocity of the liquid (directed flow) and possible underheating of the liquid to the saturation temperature. We proved that the experimental installation with the supply of heat by anelectric 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 media, which will allow to expand the results of the study and facilitate their application.

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. Computation of the value of the critical load in relation to the studied porous system can be carried out depending on underheating and flow velocity according to the obtained equations, showing that liquid underheating allows to improve heat transfer capabilities in the porous cooling system. Since the heat transfer processes take place in thin porous structures, even a small surplus of freely flowing film over the external surface of the structure, at a given hydrostatic pressure and conditional permeability coefficient, creates a liquid core from which the underheated cooler will be continuously sucked due to the temperature difference and capillary forces. 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. The heat flow will be consumed additionally on heating of leaking relatively cold portions of 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. However, at a certain value of the liquid flow velocity, the energy consumed for pressing out the liquid from the

two-phase wall layer is not enough, and a heat transfer crisis occurs. 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. Upon reaching a certain amount of consumption moisture content, the flow velocity will not aid in an increase of critical load, since steam evacuation from the wall zone becomes difficult. Increase of velocity of the liquid film adjacent to the wall, due to surplus of liquid, starts to give way to the dominant effect of decrease of moisture content in the same zone, which will have a greater effect on the value of the crisis, even reducing it. Therefore, it is required to establish an optimum ratio of surplus of liquid depending on the type of the porous structure in each individual case. The hydrodynamic model of the liquid boiling crisis in large volume on the technical surface does not reflect the effect of the heat-transfer properties of the wall, although it does occur, which can be explained by the oscillatory motions of the steam-liquid interface. This leads to a wavy motion of the heating surface. Thus, in some areas of such surfaces, a resonance phenomenon should be expected when the wall temperature decreases due to a large extraction of steam, which means that the higher the heat-transfer properties of the wall are, the more intense the critical load extraction will be. 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.

Summary. The crisis of heat exchange in grid porous structures at boiling water is studied. The study relates to heat and power installations of power plants. Experiments were carried out on an electric testing bench and on a rocket type burner, in which combustion chambers and supersonic nozzles were cooled with various capillary-porous structures. The model and mechanism of the heat exchange processes are described, the optimal dimensions of the cells of the porous structures are determined, and computational equations for determining the critical heat flow for a wide variation of pressure in the system and the parameters of the porous structures (pore sizes, structure thickness, permeability, geometric dimensions of the cooling surface and its orientation) are obtained. Experimental installations for determining integral (average) heat-exchange parameters in a capillary-porous cooling system are produced: operation scheme and a measurement technique, a cooling element with tubular arteries structure, a perforated clamping plate and micro arteries. Studies were carried out until the wall and the capillary-porous structures were overburnt.

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Designations:

t_w, $t^t{}_1$, $t^{dr}{}_1$, $t^{out}{}_1$, $t^{in}{}_1$, 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;
$m^t{}_1$, 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;
h, L – height and the length of the heating surface, m;
λ_l , λ_{ef} – coefficients of heat conductivity of liquid and efficiency, W/mK;
V - velocity, m/s;
y, z - coordinates of direction of liquid and steam(z) motion, m;
ρ - density kg/m^3;
E - porosity;
g - acceleration of gravity, m/s^2;
β – angle of the slope of cooling system to the vertical line, deg;
σ – coefficient of surface tension, N/m;
R [y] – radius of (meniscus?) liquid, m;
ν_l - coefficient of kinetic viscosity of the liquid, m^2/s;
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;
F_w - section of the porous structure (wick), m^2;
G_l [y] - specific liquid consumption, kg/m^{2}s;
q_{cr} - critical heat flow, W/m^2;
r – heat of steam generation, J/kg;
φ'_k - critical consumption liquid content
b_h, δ_w - hydraulic pore size and wick thickness, m;
P - pressure, Pa;
ΔP_{m+c}- the total acting head (mass and capillary), Pa;
ΔT_{cr} - critical temperature head, K;
$\bar{D}_{o.cr}$ - the size of the steam conglomerate corresponding to the condition of $\Delta T = \Delta T_{cr}$, m;
$\bar{f}$ - rate of steam bubbles generation, s^{-1};
C – heat capacity, J/kg K;
$R_{d.s.}$ - radius of the "dry" spot, m;
τ – time, s;
T_s - saturation temperature, K;
$\Delta T = T_w – T_s$ - temperature head, K (^{0}C);
U_{cr} - critical velocity of steam, m/s;
λ_{cr} - critical wavelength between the steam pillars, m;
$\bar{n}$ - average density of the centers of steam formation, m^{-2};
F, F_s - heating (cooling) surface and the surface covered with steam, m^2;
$m=m_l/m_s$ – surplus of liquid
δ – thickness, m.

Indexes:

w. - wall; l, s – liquid, steam; t - tank; dr. - draining; in. out. - input, output; i - insulation; el. - electric; diff. - differential; c.w. - circulating water; air - air; ef - effective; c - conditional; h.p.; - heat pipe; w - wick; cr. - critical (crisis); h - hydrodynamic; m+c - mass and capillary; o.r. - tear-off size at the time of crisis; d.s. - "dry" spot; s - saturation.

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ЖЫЛДЫҚ ЕСЕПТІЛІКТІ ДАҒДАРЫСТАНДЫҚТЫҢ КЕЗ КЕЛГЕН ТЕҢІЗДІК ЖҮЙЕСІНІҢ ЗЕРТТЕУ ЖҮЙЕСІ

Аннотация. Терілген појисты құрылымдардағы судың әсерінен термоөндеу. Электр қондырғыларының энергетикалық қондырғыларына деген тәуелділігі. Эксперименттер электрлік стендте және горелке ракеталық типтегі болды, ол камералармен шаншылып, әртүрлі капиллярлық-пористым құрылымдармен жабдықталған. Қапиллярлы-пористтік жүйе салқындатудың интегралдық (орташа) жылу сипаттамаларын анықтауға арналған экспериментальдық қондырғыларды әзірледі: функционирования және әдістерін өлшеу сызбасы, түтікшелі артериялардың элементтері, перфорированной пластиналар және микроартериялар. Қапиллярлық-пористы құрылымды стенкиге дейінгі аралықты зерттеді.

Түйін сөздер: жылу тасымалдау дағдарысы, капиллярлық-кеуекті құрылым, жылуэнергетикалық қондырғылар, будың көпіршігі, капиллярлық күштер, жаппай күштер, жылуды басқару, өткізгіштігі.

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ЭКСПЕРИМЕНТАЛЬНЫЙ МЕТОД ИССЛЕДОВАНИЯ КРИЗИСА ТЕПЛОПЕРЕДАЧИ В КАПИЛЛЯРНО-ПОРИСТОЙ СИСТЕМЕ ОХЛАЖДЕНИЯ

Аннотация. Исследован кризис теплообмена при кипении воды в сетчатых пористых структурах. Изучение относиться к тепловым энергетическим установкам электростанций. Эксперименты проводились на электрическом стенде и на горелке ракетного типа, в которой охлаждались камеры сгорания и сверхзвуковые сопла различными капиллярно-пористыми структурами. Описаны модель и механизм процессов теплообмена, определены оптимальные размеры ячеек пористых структур, получены расчетные уравнения для определения критического теплового потока для широкого изменения давления в системе и характеристик пористых структур (размеры пор, толщины структуры, проницаемости, геометрических размеров поверхности охлаждения и ее ориентации). Разработаны экспериментальные установки для определения интегральных (средних) теплообменных характеристик в капиллярно-пористой системе охлаждения: приведена схема функционирования и методика измерений, устройство охлаждающего элемента с трубчатыми артериями, перфорированной прижимной пластиной и микроартериями. Исследования проводились вплоть до пережога стенки и капиллярно-пористых структур.

Ключевые слова: кризис теплопередачи, капиллярно-пористая структура, тепловые энергоустановки, паровой пузырь, капиллярные силы, массовые силы, управление теплопередачей, проницаемость.

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