THE PROCESSES OF VAPORIZATION IN THE POROUS STRUCTURES WORKING WITH THE EXCESS OF LIQUID

by

Alexander A. GENBACH[a], Nellya O. JAMANKULOVA[a*], and Vukman V. BAKIĆ[b]

[a] Almaty University of Power Engineering & Telecommunications, Almaty, Kazakhstan,
[b] Laboratory for Thermal Engineering and Energy, Vinča Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

Original scientific paper
DOI:10.2298/TSCI160326313G

The processes of vaporization in porous structures, working with the excess of liquid are investigated. With regard to the thermal power plants new porous cooling system is proposed and investigated, in which the supply of coolant is conducted by the combined action of gravity and capillary forces. The cooling surface is made of stainless steel, brass, copper, bronze, nickel, alundum, and glass, with wall thickness of $0.05 \cdot 10^{-3}$-$2 \cdot 10^{-3}$ *m. Visualizations of the processes of vaporization were carried out using holographic interferometry with the laser system and high speed camera. The operating conditions of the experiments were: water pressures 0.01-10 MPa, the temperature difference of subcooling 0-20* ⁰C*, an excess of liquid 1-14 of the steam flow, the heat load* $1 \cdot 10^4$-$60 \cdot 10^4$ W/m^2*, the temperature difference 1-60* ⁰C*, and orientation of the system ±0-±90 degrees. Studies have revealed three areas of liquid vaporization process (transitional, developed, and crisis). The impact of operating and design parameters on the integrated and thermal hydraulic characteristics was defined. The optimum (minimum) flow rate of cooling fluid and the most effective type of mesh porous structure were also defined.*

Key words: *vaporization, porous structure, liquid excess, holography, visualization*

Introduction

Studies of porous systems have allowed us to develop a series of new technical solutions for efficient cooling of the thermal loaded elements of power installations, burners, to carry out the cleaning of microscopic dust and gas in the foam boiling stream and to control the energy of wave and gases which have ecological value [1-4].

Control of rapid processes in elliptical porous systems allows to carry out the modeling, similarity, and analogy of processes of boiling, of bubbling and foam generation, and catching of gas and dust [1, 5]. As a result of generalization of these and similar processes calculated criteria dependencies were obtained up to the limiting (critical) state of heat exchange surface [3] depending on a large number of operating and design factors.

The division of the total energy on wave energy of the stress and energy of gases [1] made it possible to develop geological and thermodynamic screens protecting turbine foundations of power stations from the seismic waves [6]. Porous de-superheaters of steam boilers [7], nozzle fillets and grooved porous labyrinths in turbomachinery [8-10], and many other

* Corresponding author, e-mail: dnellya@mail.ru

elements of the power thermal installations were created and studied in which due to control of heat transfer process during vaporization in the porous structures, the high intensity and forcing of heat transfer process are achieved in removing of high heat loads [11].

The comparative analysis of the heat transfer calculation methods was conducted using experimental data on boiling of water with subcooling in vertical channels [12]. This problem is in connection with the influence of surface boiling on the intensity of the focal corrosion of fuel claddings of nuclear installations [13, 14], and this corrosion is an analogue of the capillary-porous structure. However, heat transfer studies on a regular structured surface were not carried out. According to the papers [12-16] the surface boiling on porous surfaces can affect the development of corrosion due to the effects of erosion on the wall due to the collapse of vapor bubbles in the sub cooled liquid. Therefore, it is required to investigate the liquid evaporation in porous structures in the field of mass and capillary forces with considering that a speed and subcooling were produced by an excess of fluid.

Experimental installation and the method of carrying out of heat exchange

For highly accelerated and effective conducting of processes in the described apparatus, a new porous cooling system has developed, in which the heat exchange processes are implemented by the vaporization of the liquid in porous structures and the coolant supply is produced by the combined action of capillary and gravitational potentials, fig. 1. Deliberately created the fluid excess in the cross-section of the porous structure allows conducting the process of evaporation in a forced fluid flow with subcooling to saturated steam temperature. The enclosure of the device – 1, the cover – 2 and the insert – 4 were made from stainless steel. The insert – 4 with width of $15\cdot10^{-3}$ m serves to form the channels through which the steam was directed to the condenser. Water is supplied to the porous mesh structure – 5 over Cu arteries – 3. Pressing of a structure to a cooled wall was carried out by using a perforated brass flexible plate – 10 or the structure which was welded to a wall by spot welding. The flocked excess fluid is captured by microarteries – 11 and redirected to the porous structure – 5, while the visor of microarteries prevented the intensive production of the liquid.

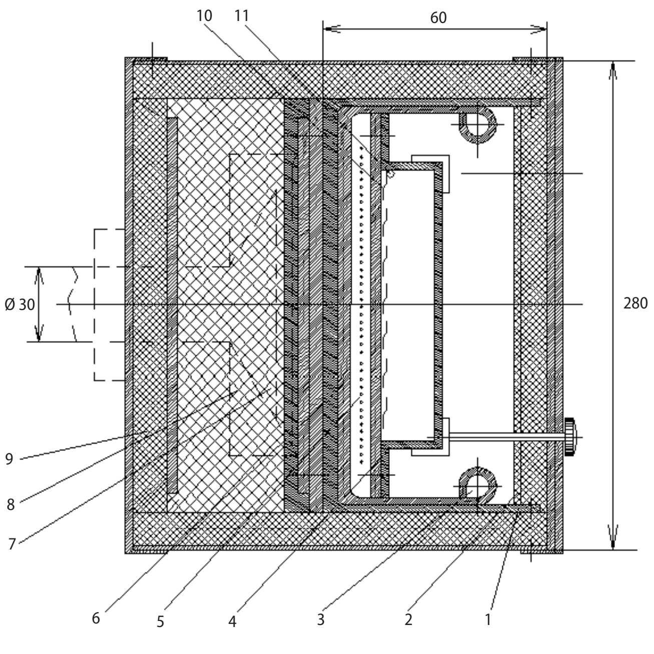

Figure 1. The apparatus for porous cooling (cross-sectional);
1 – enclosure, 2 – cover, 3 – tubular artery, 4 – insert, 5 – porous mesh structure, 6 – electro isolation, 7 – main heater, 8 – protective heater, 9 – thermal insulation, 10 – perforated pressure plate, 11 – microartery

In order to reduce the heat losses of the entire movement path of steam, cooling element and condenser are thermally insulated with asbestos, a thickness of $15\cdot10^{-3}$ m, wrapped in a fiberglass of VPR-10 brand. The Cu electrodes were surrounded by porcelain tubes coated with asbestos insulation.

The heater – 7 was made from NiCr foil with thicknesses of (0.05, 0.1, 0.3, 0.5, 0.7)$\cdot 10^{-3}$ m, and stainless plate – $1\cdot 10^{-3}$ and $2\cdot 10^{-3}$ m. The heater length was changed between 0.05-0.3 m, with the height between 0.15-0.7 m. An electric current is supplied via Cu electrodes with a diameter of $30\cdot 10^{-3}$ m. For the electro isolation between the wall and NiCr foil (stainless plate), mica with thickness of $0.05\cdot 10^{-3}$ m is used. The radiant and the direct heating of the surface by passing an alternating electrical current through the wall and adjacent the mesh porous structure were applied. The porous mesh structures – 5 were made from stainless steel mesh, with simple twill weave, and consisted of one, two, and three layers. To study the beginning of the boiling liquid, the number of layers in the mesh reached nine. The wall is constructed of stainless steel 321 and 304 (US standards AISI) or EN10088-2 (European analog), of brass C 24 000 (US standards ASTM) or CW503L EN, copper C12500 (US standards ASTM), bronze, nickel, alundum, and glass. The wall thickness varied in terms of value (0.05, 0.1, 0.3, 0.5, 0.7, 1)$\cdot 10^{-3}$ and $2\cdot 10^{-3}$ m.

Visual observations of the evaporation processes were produced by using holographic interferometry, fig. 2, and high-speed filming. The helium-neon laser system LG-38 with a power of 60 mV and high speed camera SCS-1M for filming at a frequency of 4000 per second were used. The experimental installation, the conditions and methods of experimental data processing are described in [2-4, 8]. The wall and the porous structures were degreased.

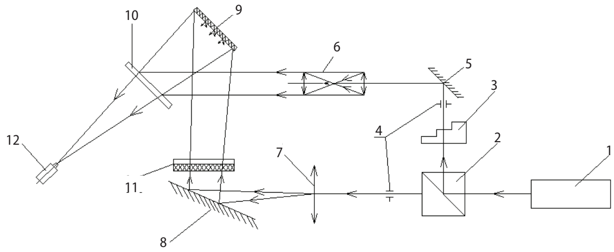

Figure 2 - Scheme of the stand for holographic interferograms; *1 – LG-38 laser, 2 – beam splitter cube, 3 – light filter, 4 – diaphragm, 5 – mirror, 6 – collimator, 7 – lens, 8 – mirror, 9 – diffusion screen, 10 – hologram plane, 11 – cooling element, 12 – registered camera RFK 5M*

These observations have allowed to describe the physical picture and the mechanism of the processes and to generalize the experimental data on the internal characteristics and the diverting heat flows with an accuracy of ±20%, depending on the thermophysical properties of the fluid, the wall, the temperature differential, the excess of coolant, the type of porous structure and the shape of the heat exchange wall.

Results and discussion

Figure 3 shows the impact of thermal load on the wall temperature, depending on type of porous structure and the excess of cooling liquid and the dotted curves define the interval where data are within the standard deviation. The characteristics of capillary structures of experimental samples are performed on fig. 3. The mesh 0.14 presents the size of the mesh pore, $0.14\cdot 10^{-3}$ m, and the structure $3\cdot 0.14$ presents three layers

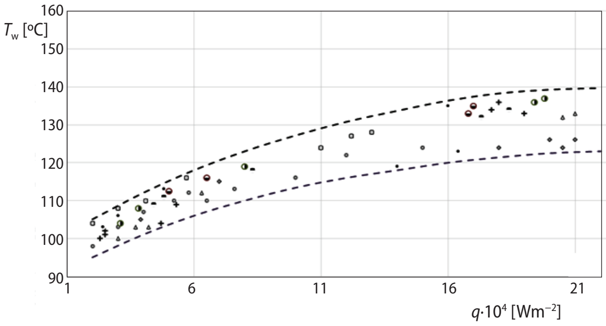

Figure 3. Dependence of wall temperature on the heat flux for P = 0.1 MPa, m_{liq} = (1-7.5)m_v

of mesh with pore size $0.14 \cdot 10^{-3}$ m. Detailed explanation of mesh dimensions and structures and their symbols, as indicated in fig.3, are given on the tab. 1. The mesh and the wall are made from stainless steel.

Table 1. The mesh dimensions, structures, and their symbols

Mesh size [10^{-3} m]	Porous structure consisting of number of mesh layers × mesh size	Symbols
0.14	1 × 0.14	⊙
0.28	1 × 0.28	⟐
0.14	3 × 0.14	◬
0.28	3 × 0.28	⊡
0.08	–	–
0.08, 0.14, 0.14	0.08, 0.14, 0.14 (3 layers from different mesh size)	"+"
0.08, 0.28, 0.28	0.08×0.28×0.28 (3 layers from different mesh size)	●
0.4	1·0.4	◓
0.4	2·0.4	◑
0.55	2·0.55	◑

Analysis of experimental data has proven that for $q = 1\text{-}8 \cdot 10^4$ W/m^2, the boiling mode was transitional. In this mode, we found a significant impact of coolant flow rate, m_{liq}, and type of porous structure. It is especially seen in meshes with large cell size. According to its characteristics, they are close to the thin film evaporator. A later boiling of liquid compared to the heat pipes is caused by the redistribution of the heat fluxes for convection and boiling. Some reduction in heat transfer coefficient, α, with increasing values of, q, associated with the emerging of steam bubbles, when the bubbles reach a certain size, they increase the thermal resistance of the boundary layer.

The influence of liquid flow rate revealed through the excess of liquid within $m_{liq} = (1\text{-}7.5) \cdot m_v$ is insignificant, therefore, it isn't shown in fig. 3. For $q = 1 \cdot 10^4\text{-}8 \cdot 10^4$ W/m^2, the boiling mode was transitional, so the influence of liquid flow rate is insignificant, but area of developed nucleate boiling ($q > 8 \cdot 10^4$ W/m^2) up to critical heat loads with the destruction of the wall did not reveal a significant effect of fluid flow rate within its changes $m_{liq} = 1 \cdot m_v\text{-}7.5 \cdot m_v$. The influence of the liquid flow rate expressed in terms of liquid excess $\tilde{m} = m_{liq}/m_v$

The heat transfer capacity reduction of the system in different size of cells of structure as in the heat pipes [2] was not observed, neither the increased hydraulic resistance of the structure. The decrease of capillary absorption did not restrict of fluid flow rate supply.

An effective structure is a single-layer of 1·0.14 or two-layer of 2·0.4 and 2·0.55 structure, but it should be expected the more overheating of the wall. Large size of cells affect the decreasing of the requirement for liquid purification and reduces gas-and-hydrodynamical resistance.

The illustrated structures having invariable pore size along a normal, showed high efficiency when acting in the field of gravitational forces as opposed to the heat pipes, in which the emergency mode of operation had taken place. During the maximal q_{max} the advantages of anisotropic over isotropic mesh structures were not observed, as it was in the heat pipes. This is related to the improved circulation of liquid and vapor in the structure created by the excess of liquid. There are other possible contributions to the mechanism of processes: the presence of inertial effect and partial condensation of vapor bubbles.

In the area of nucleate boiling the influence of fluid flow rate on the value of α is insignificant. However, at relatively low liquid flow rate, a reliable heat removal is provided by maintaining the stability of the pulsating liquid film, what favorably distinguishes the system from thin-film evaporators [17], in which the falling films are broken and there is a need to a significant increase of liquid flow rate (in 100-1000 times).

Discussion of experimental data of the boiling process in porous structures

Excess of liquid provides:

- establish the structure of small thickness, which increases the heat transfer coefficient for 80%,
- remove the higher values of q due to intensive destruction and removal of steam formations from the heating zone, and
- apply the mesh structure with the increased size of the cell and the heat removal is 3-4 times greater than by the heat pipes even without the use of intensifiers with the heat transfer coefficient, the value of which is higher by 30-40%.

Significantly increasing the flow of coolant is inexpedient, because there is a redistribution of heat flux for convection and boiling streams, that raises the price of the system. Therefore, it is advisable to introduce the concept of an optimum (minimum) excess of fluid, at which a uniform temperature field is established on the height and length of the heat exchange surface.

The minimum (optimal) coolant flow rate is defined: for value of $q \le 100$ kW/m^2 the consumption is maintained close to the mode of operation of heat pipes with $b_g = 0.28 \cdot 10^{-3}$ m and on 30% more for the value $b_g > 0.28 \cdot 10^{-3}$ m; at the values of $q > 100$ kW/m^2 the exceeding of liquid in 1.3-2 times for the value of $b_g \le 0.28 \cdot 10^{-3}$ m allows to expand the withdrawal range of flow q in (2-3) times in comparison with the heat pipes [11].

Estimation of the studied system with the heat pipes, the thin-film evaporators and the boiling in a large volume on a smooth surface showed the extension of limiting value of q, approaching to the pool boiling. There is the influence on the liquid film thickness for value of $q \le 80$ kW/m^2. At capillary liquid supplying, the thickness is smaller, that intensifies the heat exchange. Large values of heat transfer coefficients for a porous system are explained by more intense boiling process due to rapid overheating of thin liquid layer and a higher density of vaporization centers.

The thickness of the liquid film in the porous structure has less effect for value of $q > 8 \cdot 10^4$ W/m^2, and has effects on the deterioration of heat exchange due to the achievement of a certain intensity of vaporization in the pores. The steam accumulation in these volumes causes the limitation of the supply of fresh portions of liquid to the heating surface. In this case the improved heat transfer characteristics are explained by gravity. There is a turbulence intensification of pulsating boundary layer near the wall by improving the circulation of the liquid and vapor, in the structure at intense removal of steam volumes while maintaining high stability of pulsating fluid film and active filling the structure cells by fresh portions of the incoming coolant.

Thermal and hydraulic stability of the boundary layer are determined by the presence of a pulsating liquid film under the steam bubbles through which heat is transferred to bubbles by conduction and by the heat spent to vaporization. The boundary layer turbulence increased due the increasing bursting steam bubbles. The increasing of the boundary layer turbulence and the stability of the pulsating liquid film lead to an increase value of heat transfer coefficient and expansion of limits of heat transfer capabilities of the system.

These have an effect on the hydrodynamic impact of fluid flow on the mechanism of the evaporation process, facilitating separation of steam bubbles before they reach the value of separation diameter. The relatively *cold* liquid portion of the core of the flowing stream, rushing to the wall, replaced the two-phase mixture, reducing its thickness and the thermal resistance. There are a loss of stability of wall pulsating layer, locking the mesh cells by steam bubbles and termination of fluid access to the heated area when reached the certain liquid overheating. The sharp rise of thermal resistance leads to overheating of the wall until it is burnout.

The intensity of the heat exchange in porous system is inferior to pool boiling on a smooth surface. Boiling on a smooth surface is the boiling on the surface without any porous structure. The smooth surface is treated with high accuracy, the 7th class of accuracy, it is brought for comparison purposes with boiling in porous structures. Based on the theory of microinterlayer evaporation the main share of heat is supplied to the base of the steam bubbles and is spent by vaporization into bubbles. In a porous system this value is proportional to $\sim\Delta T^2$. A convectional component of heat transfer is negligible, and this leads to reduce the growth of heat flux rate. The convective component of the heat flux appears only in the transition area and is not found in the areas of developed and crisis boiling.

Cooled elements for energy devices may be arranged obliquely in a gravitational field. Therefore, the effect of surface orientation on a heat exchange was studied. The angle varies from 0 to ±90°, where the sign "–" means the exit of steam against the direction of gravity. We study the structures with maximum 0.08 × 0.14 × 0.4 and minimum 3 × 0.4 capillary potential. The maximum intensity of heat exchange was obtained at an inclination angle $\beta = 0°$ (vertical position). At the same time, significant differences were found in heat exchange intensity at inclination angles up to ±45° for all structures. When the inclination angles are ±75°, the effect of orientation is very weak, as in the boiling liquid in a large volume, except for the horizontal plate facing downwards, it is explained by the lightweight emergence of additional secondary flows in the boundary layer due to mass forces, which destroys the steam conglomerates.

For angles of inclination greater than ±75° the dependencies are clearly expressed naturally, especially for structures with small capillary potential, because the forces of gravity are the main transport forces and the capillary forces used for uniform distribution of the liquid through the pores and capillaries of the structure. The capillary structure with greater potential has more uniform temperature distribution in the wall for different q.

Comparison of heat exchange in the heat pipes [2, 17] for $q > 100$ kW/m^2 indicates that the intensity of heat exchange in the heat pipes is below for about 40%, or heat pipes do not operate (work). For $q < 20$ kW/m^2 the heat pipes have a high intensity of heat exchange. There is a satisfactory agreement between the experimental data [2, 17] when q changes between $2\cdot10^4$-$10\cdot10^4$ W/m^2.

An analysis of criteria equations of boiling processes in porous structures

Discussion of criteria equations has revealed as follows [2, 4, 11, 17].

- For the studied porous system there is no steep dependence of $\alpha = f(b_g, h, L)$, as is the case in the heat pipes.
- The function $q = f(\Delta T)$ is more *strong* than for the heat pipes that is explained by the excess of liquid.
- Excess fluid flow rate through which reflected the impact of the speed and the subcooling of the liquid has an insignificant effect on the value of q, but its presence considerably expands the boundaries of system operation (q_{cr}).
- The inclination of the system reduces q.
- The increased size of the cells and the large thickness of structures decrease q.
- Increasing of pressure influences on the small increase of q, than in case of boiling in a large volume [18], since the limiting factor is the presence of capillary potential.
- The growth of accumulating capacity of the wall increases q [2].
- The frequency of generation and the density of centers have great values because of the greater and more uniform boundary layer overheating and the separation diameters are smaller than at boiling in a large volume [11].

An analysis of the holographic interfero-grams and filming of boiling processes in porous structures

An analysis of the holographic interfero-grams and their interpretation revealed that for q = constant value. The stable concentration of interference fringes, during the quasi-stationary boiling process were obtained, fig. 4(a). However, some deformation of fringes with increasing q, figs. 4(b)-(e) associated with the pulsating mode of the boiling process and the presence periodically changing centers of vaporization in the cells of the structure, while in the area near of mesh the drops of liquid are ejected, fig. 5.

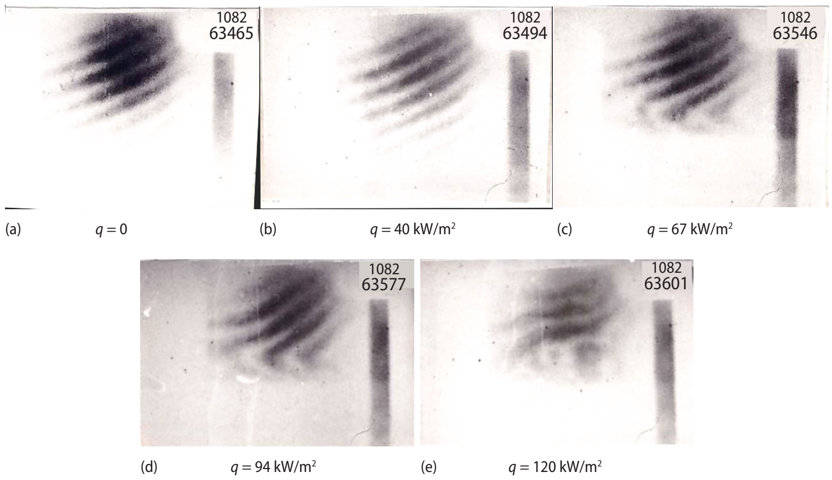

Figure 4. Holographic interfero-grams of vaporization process in porous mesh structure type 1 × 0.4 at q = var; $\tilde{m} = m_{liq}/m_v = 1.1$ optimum (min.)

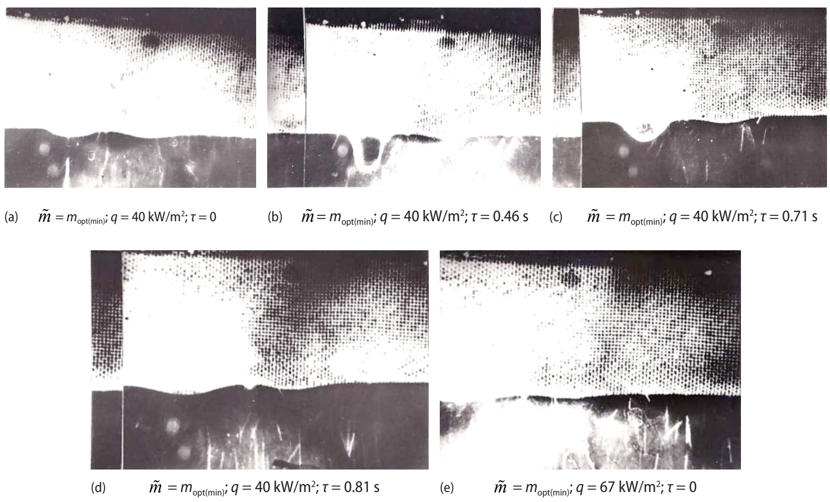

Figure 5. Picture of phenomenon ejection of liquid droplets in the process of evaporation from a porous mesh structure of type 0.14 × 0.4 at $\tilde{m} = m_{opt(min)}$, for the fixed heat load q and the transitional regime (τ = var); (a), (b), (c), (d) for q = 40 kW/m^2; (e) for q = 67 kW/m^2

For different values of q, based on the degree of shape deformation and density of the interference fringes, the thermal and hydrodynamic state of the heat and mass transfer processes were estimated. It becomes possible to consider the micro and some local processes, such as fluctuation phenomena, droplet productions, the temperature of microrelief, *etc*. The more intensive process, the clearest picture is expressed. Some differential pictures are clearly expressed at intensive process and can not be detected by other means except holographic interfero-grams.

In the space above the mesh the active processes occur within $4\cdot10^{-3}$ m for $q = 40$ kW/m^2 and $7\cdot10^{-3}$ m for $q = 120$ kW/m^2, fig. 4.

For small values of q, the homogeneity zones are more enlarged, which indicates stability processes in a certain local area, or even at a considerable part of the surface. For high values of q the zones are concentrated up to the size of the structure of individual cells. Consequently, it is possible to investigate the nature of the boiling liquid in one or more cells.

The interferometric patterns were obtained for variable modes of operation. When the flow rate of liquid was reduced to zero [3, 8], they revealed the state which corresponds to the optimal operation mode with the critical heat transfer conditions, fig. 4.

The optical uniformity changes for high values of q or for small values of $m_{\mathrm{liq}}/m_{\mathrm{v}}$ indicate the concentration changes of a steam-water mixture in the bottom (top) shapes, depending on the top (bottom) way of the liquid supply. One can see the concentration changes (the optical uniformity changes) of a steam-water mixture in the bottom if the liquid supply from the top and vice versa.

High-speed filming [11, 19] revealed the thermal and hydrodynamic conditions in the structure during the time of *life* of excess liquid drop for different parameters (q , τ) at $\tilde{m} = m_{\mathrm{opt(min)}}$, fig. 5. Results are presented for $\tilde{m} = m_{\mathrm{opt(min)}}$, for each heat load: $q = 40$ kW/m^2 and $q = 67$ kW/m^2, and optimum value $\tilde{m}$ is also a minimal one, that was determined by the constancy of wall temperature of a height (diameter) of heat exchange surface.

The areas of generation of steam and liquid supply for all values of q were highlighted. There is clearly seen movement and destruction of steam formations facilitated by the action of gravity and arising in this pulsating liquid flow. Introducing the core of liquid flow in the wall boundary layer provides the displacement of two-phase mixture, which reduces the thermal resistance of the layer, intensifying the heat transfer, and increasing the values of $q_{\mathrm{cr.}}$

With the increasing of q, increases the number of vaporization centers. Vapor bubbles and their formations obtained by merging the single bubbles are observed. In the presence of a fine mesh near the wall a trend of filling and accumulation of bubbles of steam in mesh cells is shown, which creates a *dry* zones on the wall. Such phenomena are not observed for the mesh with large mesh pour size ($0.4\cdot10^{-3}$ m). Sensitivity of structure is higher, since it has a lower hydraulic resistance and the ability to better remove the bubbles despite of larger size.

The formation of *dry zones* in porous structure was determined from the concentration of the interference fringes in fig. 4 and fig. 5 (visually) when steam conglomerates blocked the inflow of fresh portions of the coolant. The sensitivity of the structure is related to the flow of coolant on removing the heat flux q: this sensitivity is very weak for $\tilde{m} = 1\text{-}1.75$, within the accuracy of the experiment. For small values of q an explosive behavior of two-phase flux is weak.

In multi-layer structures liquid is ejected significantly greater than in monolayer structures because the liquid being absorbed by the lower layers of mesh with smaller size of cells, boils and, leaving the structure, carries away liquid from an external layer.

Dimensions of the droplets departing from the structure are no more than the width of the external layer of the cell. Actively operating centers of drop departures were registered, fig. 5. On the minimum (optimum) fluid flow rate the *life* time of steam bubbles is no more than 1/2500 second and delay time is (0.006-0.014) from the time of *life* for the value of q = 120 kW/m^2 and is twice more for q = 67 kW/m^2. Delay of vapor bubble is a crisis boiling mode occurs under certain q and steam bubbles merge into a single conglomerate, blocking the inflow of fresh portions of the coolant. The observed liquid ejection does not lead to violation of operability of system as to the heat pipes. The first layer of structure has a significant influence on the intensity of heat and mass transfer, which is also confirmed by the salt method. The salt method consists in determining the critical boiling mode by the deposition of salts contained in the coolant, on the heat exchange wall and porous structures adjoining to the wall.

For transitional boiling area the time of *life* of bubbles increases and reaches more than a second, and the bubbles take the shape of the cell. The structure loses the turbulizer property, reducing (impairing) the heat transfer intensity. Liquid ejection is not seen, but the number of vaporization centers is dramatically reduced.

The occurrence of vapor bubbles was found mainly on the heat exchange wall, and partly on the skeleton of the structure. When reaching the upper border of a mesh cell, the bubble *lived* for some time and burst. The growth of the bubble is accompanied by complex oscillatory movements within the cell. The competitive mechanism of the process is displayed. Due to hydrodynamic effects liquid flow bubbles did not reach the size of the mesh cell and *died*, the part of bubbles condensed in a relatively cold liquid flow far away from the wall. These phenomena were observed with negligible value of q or substantial excess of liquid.

The phenomenon of emergence of bubbles from the film, as in the thin-film evaporators, did not occur. At the moment of the destruction the bubble took shape of a circle. The steam bubble has a spherical shape and the projection is seen as a circle. The phenomenon of the drop removal for structure 1·0.4 is occurred very weak.

The growth of q was accompanied by an increase in the density of vaporization centers. When q = 67 kW/m^2, it was equal to 18/144 bubbles/number of cells, and when q = 120 kW/m^2 it was 33/144 bubbles/number of cells.

An increase of the load leads to increase of the frequency of bubble formation, but the size of bursting bubbles still does not exceed the width of the mesh cell. For q = 67 kW/m^2, the time of life τ_{life} is 0.12 second, while for q = 120 kW/m^2, τ_{life} is 0.036 second, for $m_{\text{liq}}/m_{\text{v}}$ = 5.2. The new fact in our study of vaporization centers density is in defining the value of $\overline{n}$ which is much higher than for the pool boiling on a smooth surface and is generalized by the calculated equation for the first time obtained and analyzed in our papers [2, 11].

Consequently, at the optimal liquid flow rate, the frequency of the formation and separation of bubbles is in ten times more than for pool boiling and the same order for liquid boiling films, in the same time dimensions of tear-off bubbles are several times less. At considerable excess of liquid, the frequency of formation and the separation of bubbles are close to the fluid boiling in a large volume. The size of bursting bubbles still does not exceed the width of the cell structure.

For liquid flow rate less than m_{opt} the number of single centers of vaporization is dramatically reduced, the bubbles are merging to form a single seething picture, the frequent micro- explosions and intensive emission of small drops occur. A further reduction of fluid flow rate induces that the steam volumes near the surface block the inflow of fresh coolant portions. There is a microlocal drying of the structure, which leads that the liquid film is broken in some places. *Dry* places of the wall are overheated, and the liquid does not wet the surface. If the fluid flow rate increased again, this leads to the appearance of steam bubbles. The density of vaporization centers. $\overline{n}$, increases to a certain value of fluid flow rate, and then the redistribution of heat fluxes for convection and boiling, significantly increasing the *life* time of steam bubbles and abruptly reducing the rate of growth of $\bar{n}$. Therefore, the boundary of transition, changes the values of $\bar{n}$ and τ_{life}, determines the optimal flow rate of liquid (it was also the minimum flow rate).

Conclusions

In this paper is proposed and studied a new porous cooling system where coolant supply produced by the combined action of capillary and gravitational potential. On the basis of measurements and optical methods, the integrated and internal characteristics of the evaporation process of water in the mesh porous structures were discussed. This explains the physical characteristics of the mechanism of the processes, depending on the thermal properties of the fluid, the wall, the temperature difference, the excess of coolant, the type of porous structure, and the shape of the steam generating surface. The results were obtained using an experimental installation for porous cooling and conducted integrated use of heat exchange (q, T_w, α). These results show the physical nature of the boiling process, and explain the heat exchange mechanism in porous structures from a number of operating and design factors, such as fluid excess, the heat load, the wall material, steam, and structure thermohydraulic characteristics (tear-off diameters of bubbles, the density of generating points, the separation frequency). The proposed cooling system is a new class of heat-removing system, taking an intermediate value between the heat pipes and pool boiling on a smooth surface because of the existence of joint action of capillary and mass forces.

Nomenclature

b – hydraulic diameter of a pore structure, [m]
h – height of a steam generating surface, [m]
L – length of a steam generating surface, [m]
m – flow rate, [kgs^{-1}]
$\bar{n}$ – density centers of the steam generation, [number of centers/number of cells]
P – pressure, [Nm^{-2}]
q – specific heat flow, [Wm^{-2}]
T – temperature, [K]
T_s – saturation temperature, [K]
T_w – wall temperature, [K]
ΔT – temperature difference, [K]

Greek symbol

α – heat transfer coefficient, [Wm^{-2}K^{-1}]
β – inclination angle to vertical cooling, [º]
τ – time, [s]

Indexes

cr – critical (crisis)
g – hydraulic
liq – liquid
s – saturation
v – vapor
w – wall

References

[1] Polyaev, V. M., *et al*., *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., *et al*., 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*, 2nd *World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics,* Dubrovnik, Yugoslavia, 1991, pp. 639-644
[5] Polyaev, V. M., *et al*., Processes 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, 2* (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., *et al*., 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

Paper submitted: March 26, 2016
Paper revised: December 11, 2016
Paper accepted: December 27, 2016