BOILING PROCESS IN OIL COOLERS ON POROUS ELEMENTS

by

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Holography and high-speed filming were used to reveal movements and deformations of the capillary and porous material, allowing to calculate thermo-hydraulic characteristics of boiling liquid in the porous structures. These porous structures work at the joint action of capillary and mass forces, which are generalised in the form of dependences used in the calculation for oil coolers in thermal power plants. Furthermore, the mechanism of the boiling process in porous structures in the field of mass forces is explained.
The development process of water steam formation in the mesh porous structures working at joint action of gravitational and capillary forces is investigated. Certain regularities pertained to the internal characteristics of boiling in cells of porous structure are revealed, by means of a holographic interferometry and high-speed filming. Formulas for calculation of specific thermal streams through thermo-hydraulic characteristics of water steam formation in mesh structures are obtained, in relation to heat engineering of thermal power plants. This is the first calculation of heat flow through the thermal-hydraulic characteristics of the boiling process in a reticulated porous structure obtained by a photo film and holographic observations.

Key words: *oil cooler, capillary porous structure, heat exchange*

Introduction

A literature survey has showed that it is necessary to develop and research installations, which can provide oil cooling in turbo generators, by means of porous elements [1, 2].

The analysis of scientific publications shows a trend of increasing use of capillary structures in heat exchangers [3]. Due to the wide area of use of heat pipes a significant amount of data is presented in the literature related to the study of heat exchange characteristics of the particular devices. [4]

Special attention is paid in modeling the process of heat transfer in porous material [5], heat transfer [6] in the process of evaporation, thermal resistance and thermal conductivity. Studied are also images from the holographic devices used to capture the cellular structures [7].

In papers [8, 9] series of experiments and computational studies have been conducted of the simultaneous processes of heat and mass transfer in porous media using physics modern methods and models. Large attention has been paid on the influence of the parameters of the porous structures, namely the thickness [10-12], the porosity, the particle size of which the cap-

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illary structure is made [13], and the geometry of the capillary structure [14] on the characteristics of boiling. Some of the publications are devoted to study the effect of external conditions on the intensity of heat transfer while boiling, in particular thermo-physical characteristics of the coolant [15], pressure [16] in the system and others [17-19].

The characteristics in surface boiling have been studied in [20]. In the paper they are presented as physical models of the boiling process [21, 23] as well as its mathematical description [21, 24, 25]. However, because of the complexity of stochastic process of boiling, the most important finds are obtained during the experimental research. Among all methods to date in terms of the intensification of heat transfer during boiling is the method associated with the laying of the capillary-porous structure on the heat exchange surface [26]. However, described methodology in [26] is unusable for the examined porous structures in this study, which work in the field of mass forces.

Among the currently used methods for intensification of heat transfer widely used are automated calculations using a software [27, 28]. In paper [29] an experimental study is conducted on a new micro structured surfaces, which allows the prediction and prevention of reaching boiling crisis in industrial apparatus. Along with this of significant interest are the internal processes in porous structures, in particular the intensification of the process of phase transition in the area of the porous structure. In the given work the nature of the influence of boiling capillary structure on the intensity of heat transfer was studied. However, we cannot get data on internal characteristics and should therefore use speed shooting to determine internal features, such as centers of steam, breakout diameter and others.

Some studies [30, 31] have numerically investigated heat and mass transfer with phase transition in porous materials. Experimental studies of the velocity field and the temperature inside the porous environment for some specific applications are also conducted and therefore the findings can be attributed only to those specific cases. Analysed is the impact of the hard limit and inertial forces on the flow and heat transfer in porous media. The results are applicable to the entire field of heat and mass transfer with the phase transition in the porous media. However, in this case mesh structures are used acting as porous structures. That is why in the future porous mesh structures will be used for large-scale power plants, including oil coolers.

This requires the development and research of devices for cooling oil in turbine plants by using porous elements.

The proposed solution provides high thermal performance and eliminates water pollution by oil products and water ingress into the oil. The presence of water in oil drastically reduces the technical quality of the latter, as well as exacerbates the risk of accidents, as emulsified oil has low lubricity and an increased ability to absorb oxygen. Therefore, according to the safety regulations, oil pressure must exceed the pressure of the cooling water [1].

According to their design features, oil coolers of steam turbines are divided into the subsequent categories: shell and tube, finned-tubes, heat exchangers with turbulizer, plate heat exchangers and other special heat exchangers (coiled, twisted, *etc.*). Shell and tube coolers are the most widely used. Cooling water flows in the tubes of the heat exchanger, consisting of brass tubes, and the oil flows outside in the shell around the tube system, in order to transfer the heat efficiently.

The current flow of oil in the cooling circuit of a steam turbine plant does not provide sufficient sealing at the joints. Due to oil leakage, caused by loose sealing, technical water sources can be contaminated.

Unfortunately, in modern thermal power plants a substantial amount of water is discharged containing about 100 ml/l of oil (about 1.5 kg/s per turbine and the same turbine on auxiliary mechanism device). In order to reduce the contamination with oil, coolers are forced to allocate it in a separate closed cooling circuit. Yet again, running water-oil cooling system cannot satisfy the increasing demand for water purity preservation [32, 33].

The offered capillary-porous cooling system eliminate the oil and coolant ingress in water supplies and in the oil supply system respectively. This way a high coefficient of heat transfer of the water is maintained and the one for coolant is increased. The uniformity of the temperature field stabilises the temperature of the oil. The amount of circulating refrigerant is significantly reduced (60-70 times), and prospective solution provides a simple and reliable design-its unification.

At the hot side of the heat pipe the liquid inside transforms into vapour while absorbing the heat from the surface. The vapour then moves along the pipe towards the other side where it condenses back into a liquid, releasing the latent heat. After that the liquid returns back to the hot side of the thermal pipe using several different designs: centrifugal force, gravity or capillary action. The cycle then repeats ensuring continual cooling of the hot side of the pipe, as well as, due to the high heat transfer coefficient for boiling and condensation heat pipes are highly effective heat exchangers

Thus, this scheme allows us to solve the problem of environmental pollution in two aspects: wastewater treatment and soil protection against oil pollution and use of low-grade heat.

The finned tube heat exchangers are well known. It consists of a metal tube having metal plates, joined to the tube, perpendicular to its length. This allows it to transfer heat from the tube to the surrounding air or liquid. The fins of the tubes are carried out by means of a wavy steel tape and a copper wire in the form of low spiral edges. In comparison to smooth tubes, where the design is very similar, such oil coolers have dimensions almost 5 times smaller and 2.7 times decreased expenses of non-ferrous metal.

The described finned tube heat exchange elements are also packed in the shell and tube heat exchangers, where in order to compensate for the tubes' length, the top pipe board is made movable. Membrane seal is applied according to the type of ring, in order to properly seal the pipe board. Nevertheless, even these mostly perfect oil coolers are characterised by an underwhelming complexity of design and have a difficulty in achieving the appropriate tightness, thus it is frequently violated.

Usually oil pressure in coolers is kept higher than the pressure of the cooling water. In case of depressurisation oil mixes with water, polluting both the water basin and the soil, leading to great cooling water expenses. It should be noted that the heat transfer coefficient in the smooth pipe coolers is usually equal 150-180 W/m^{2}K, and the hydraulic resistance on oil $-1\cdot10^4$ to $4\cdot10^4$ and on water is less than 10^4 Pa. We will highlight that in the smooth pipe oil coolers the heat transfer coefficient on the side of the oil is 10-20 times less, in comparison to the one from water, which predetermines their large dimensions and metal consumption for manufacturing.

In the heat exchangers that operate in conditions of excessive pressure of the viscous environment (for example, turbine oil) as a heat exchange element, pipes with unilateral internal fins are used. However, in this case the hydraulic resistance of internal fins of an element is substantial, furthermore the sizes of the coefficients from both parties significantly differ.

The closest technical solution is the heat exchange element [2], including entrance and output branch pipes, a direct round pipe ribbed inside with a corrugated tape. This allows the channels to have the same hydraulic diameter. Such heat exchange element possesses a steady geometrical arrangement of a corrugated tape in a pipe and, therefore, provides stable thermal and hydraulic characteristics.

However, there are a number of essential shortcomings. It is necessary to refer to the complexity of design and manufacturing techniques, as well as the rigidity of the system, excluding bent (serpentine) forms of a pipe, non-demountability, hence complicating the repair and cleaning of these pipes. There are also large expenses of oil cooling liquid, whose heat is not utilised thus a lack of heat waste recovery occurs. A further drawback is the high hydraulic resistance.

It is of great interest to develop an environmentally friendly oil cooler that will be the next step in the future evolution of heat exchangers of a finned tube type, which are widely applied in various branches of equipment, for example, in the lubrication systems of steam and gas turbines [32, 33].

The experiment in this paper is the first that uses holographic interferometry to study the processes of boiling inside the capillary-porous mesh structures [33-35]. The displacements on the surface of the centres of the three heat sources are shown in this paper (fig. 2) and the parallel surface of the centres of these sources (fig. 3) in order to clarify the distribution of thermal stresses inside the porous material.

The thermal stresses to fatigue occur in the centres of the activation of the steam bubbles which are generated in the interior of the porous body on the surface of the pipes of the oil cooler. Destructive cracks of fatigue arise in the centres of activation and managing internal characteristics allows for the reliable operation of a heat exchanger.

For the purposes of an intensification of the heat transfer and the protection of the biosphere against pollution, within the oil pipe a flexible turbulizer is placed, consisting of a cable, along the length on the inside of which branchings are interwoven, with weaved delays from high-heat-conducting metal, resting against the internal walls of the pipes. The branching need to be directed against the stream and they also decreases the internal diameter of the oil pipe by 25-30%. The cooling of the oil is carried out by a porous system.

Methods (experimental installation)

It is of interest to conduct research on the boundary condition of the mineral environment when under certain thermal loads steam bubbles can clog up element pores, reaching a heat transfer crisis. The heated surface will reach thermal breaking points in the place of "dry" spots and it reaches its flashing state. Therefore, it is necessary to thoroughly investigate the nature of deformation at separate points of the material, depending on the arrangement of the warmth sources, and to define the cooling system's capabilities of the source itself [36-39].

Previous research [34, 35] was conducted on various processes with the application of holography when registration of interferograms were made in real time. A study on the boundary conditions of the porous environment is carried out by means of holographic interferometry with application of spiral thermoelements. The margin of error of the capacity does not exceed ±1.6%. The studied model contains one, two or three thermoelements connected in parallel and the ends of spirals are attached to the copper electrodes.

The second method of the experiment in the form of photo-kinematic studies of the dynamics of steam bubbles inside and on the surface of capillary-porous network structures is also first used by us [33, 34, 40] for the new system working in the field and mass of capillary forces. This method helps define the lifetime and density of the centres of steam, the diameter of the separation of steam bubbles. By means of such internal features boiling formulas have been proposed for the calculation of various modes of boiling (formulas (1), (2), (3)). Scientific contribution of the study is new cooling system, proposed by the authors for use on specific heat exchangers. Engineering formulas are derived by the internal characteristics of the boiling with the generalization of experimental data by characteristics of the capillary-porous structures working in the field of mass and capillary forces, see formulas (1)-(3). The novelty of this heat exchanger was published in the works [41].

Applied are samples of different porosity: mesh and ceramic-metal. Openings in the blocks are carried out with a diameter of $5 \cdot 10^{-3}$ m and depth of $10 \cdot 10^{-3}$ m, according to a line, perpendicular to the surface of the larger side. Thus the development is simulated (dynamics) of three steam bubbles on the surface of the warmed up heat exchanger tubes, coated with a capillary – porous structure.

With the help of the power unit and remote control, a range of stable expositions is provided when creating holograms and photography of interferograms, using a RFK chamber 5. The system also supplies the synchronous inclusion of thermoelements and cameras, as well as regulation and control of the energy on the thermoelements.

Registration of holograms is made on plates of BP-L, the exposition for which has to be made in no more than 15 seconds and its size is defined by reflective properties of objects and their illumination in the hologram plane. The intensity of basic and subject bunches is measured by the digital light meter Yu-16 [35].

Helium – the LG neon "Laser-38", supplied with non-standard adaptations, is a source of radiation: holders of optical elements with a micrometric adjustment in three planes, the device for photochemical processing of holograms on the place of exposure, electromagnetically-driven locks, and lastly a stair-like light filter, placed in the supportive bunch.

Plates of BP-L are processed by chemical developer "D-19", a sour fixative, and bleached by solution. Photography of interferograms is carried out by a camera with the lens "Helios-61" at a diaphragm 1:2 and endurance 1/4 s on a film of "KN-3".

At the stages of registration of the holograms and the reconstruction of the holographic image various combinations of light filters allow to receive interferograms for various samples of identical density at the fixed exposition.

Results and analysis

The analysis of the interferograms (fig. 1) has provided us with the subsequent information. An expansion of the capillary-porous sample is observed around the heat source, initially only in the beginning, and later in the whole volume. The deformation of the sample volume depends on the temperature field distribution created by heat sources and the arising thermal tension on surface and in the body's volume.

It is revealed that samples with small porosity (ceramic-metal structures) are in a more intense state in comparison to viscous and porous mesh materials. The increase in thermal stream power leads to the growth of deformations on the surface of ceramic-metal samples by three times, and for the mesh – by one and a half times. The number of interferential strips per unit length is higher at ores with low values of porosity – that means there is large internal thermal tension, which growth rate increases with the growth of thermal loading.

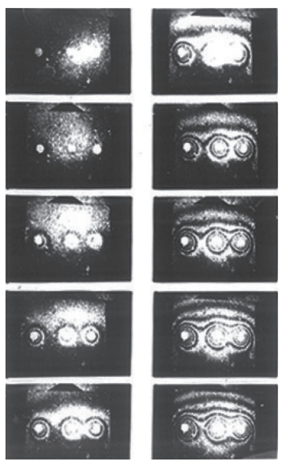


Figure 1. Holographic interferograms of the porous sample executed from mesh structure, the surfaces display a state through every 5 seconds up to a boundary state at a thermal flow of 15 W ($2.1 \cdot 10^6$ W/m^2)

Interferograms allowed to reveal the defects and cracks which cannot be seen otherwise. They are found in the right bottom corner of the ceramic-metal structure. In the sample mesh a large inclusion in the field is recorded, in which lines with equal deformations are broken.

The interpretation of holographic interferograms is accomplished with a particular technique [42]. The direction of vectors of shift $\bar{d}$, whose size, according to the photo of an interferential picture, is defined: $|\bar{d}| = N\lambda/(1+\cos\varphi)$. This interpretation is applied to objects when the direction of vectors of shift is constant at all points of a surface. The corner φ is measured by means of surveying compass (BG-1), established on a support, with an accuracy ±5.

The dependences of movements along the studied surfaces are presented in figs. 2 and 3. The gradient of movement which determines the size of deformations for one thermal source has the greatest value in the field of the heater with a radius up to $10\cdot10^{-3}$ [m], which increases with the increase of time of thermal influence. In case of three heat sources operating all at once (see figs. 2 and 3), each of them creates an independent field of movements that along with the growth of heating time leads to simple superposition on the sample surface. This phenomenon takes place in fields of movements along the plane passing through the centres of sources (fig. 2), and in the planes, remote from them at distance $y = 6\cdot10^{-3}$ m (see fig. 3). The law of distribution of tension in large porous materials states that the probability of emergence of destructive cracks in the design of the heat exchange devices is reduced.

The used method of heating modelled the thermal influence on the capillary – a porous material, imitating heat exchange in a pipe system of turbine plants' oil coolers. It can also be used in other heat power installations: the pipe bundles of boilers cooled by porous materials of the turbines' blades, tubes of heat exchangers (condensers, heaters) [39].

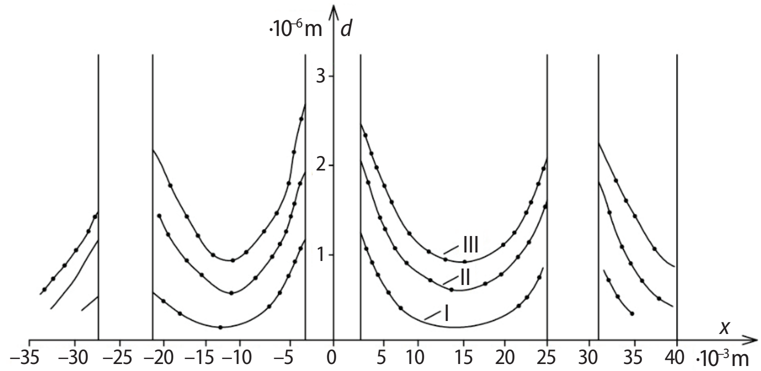


Figure 2. The dependence on the displacement plane of the centres of three heat sources (y = 0) surface of the mesh structure at N = 4.8 W for various thermal effects: I – τ = 15 s; II – τ = 25 s; III – τ = 30 s; angle – $38^0 55'$ ($q = 7\cdot10^5$ W/m^2)*

Thus, studies have shown the effectiveness of the optical method in detecting the possible distribution of thermal stress volumetric capillary – porous material made of mesh and metal structures. There is also an opportunity to analyse interferograms and the ways to reduce the likelihood of destructive cracks in the depth of the porous structure and the steam generating heat exchange wall cooler. The studies have practical value in the boundary condition of steam-generating surfaces, which are protected by means of cooling, as well as experiencing vibrating pulse load.

* Co-ordinates of fig. 2 and fig. 3 are the same. The information from these figures is used to determine the thermal displacement (deformation), and from that – the thermal stresses.

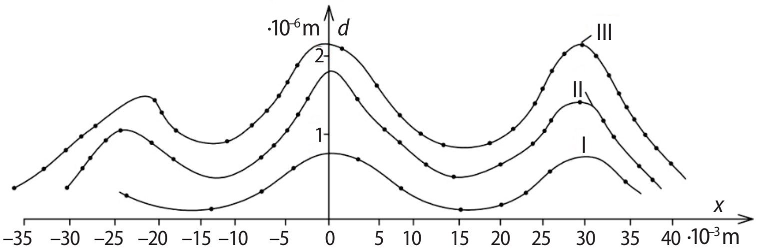


Figure 3. Dependence movements on the plane, parallel plane centres of thermal sources ($y = 6\times10^{-3}$ m), surfaces of mesh structure at N = 4,8 of W for various thermal influence: I – τ =15 s; II – τ =25 s; III – τ = 30 s; a corner – 38^0 55' ($q = 7\cdot10^5$ W/m²)*

Discussion and generalization

As it can be observed on the photo-film and holographic observations [36, 40-43], the dynamics of the vapour phase in the cells of capillary-porous structures, after the spontaneous formation of the bubble with critical size, occurs with the presence of vaporizable liquid microlayer located under steam bubble. Under certain conditions, the liquid film begins to displace itself in the centre of the bubble with the subsequent development of "dry" spot [43]. Detachment or destruction of bubbles occurs in diameters of bubbles several times smaller than boiling in large volume and size of the radius of the detachment rely on formula [40]. After the separation (destruction) of bubbles, under the influence of gravitational and capillary forces, relatively cold liquid portions are sucked into the system. For some "silent period" a new critical sized bubble is spontaneously generated, and the growth of the coolant controlled flow (flow rate and degree of subcooling) is reduced. As a result of this there is a more intensive heat supply from a thin layer of superheated liquid surrounding the bubble inside the porous structure. After a period of "silence" in the centre of generation, a new bubble with critical size is spontaneously created. The time of growth decreases, directly influenced by the cooling liquid's debit. Heat is brought into the system more intensively from the thin overheated liquid layer of the surrounding bubble, from the porous structure's side.

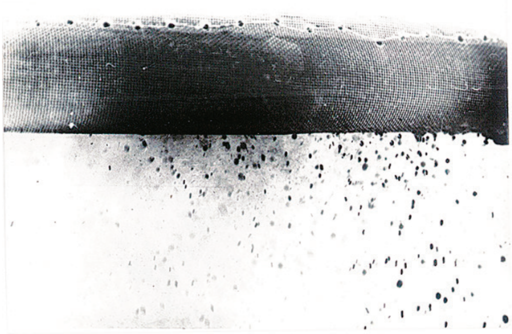
When boiling liquid in large volume the stage of growth of a bubble were $10\cdot10^{-3}$ s to $100\cdot10^{-3}$ s, and in porous system these values could be ten times less. Stages of origin and bubble separation are negligible in both systems and have character of explosion [40]. The silence time in a periodic cycle of formation of a bubble when boiling in large volume could make ~ 0,1 s and can be commensurable with time of growth of a bubble.

The emergence of a bubble of a critical size in a cell of structure results from the fast expansion of a bubble in a hollow in liquid. However, the increasing curvature of the bubble surface slows down the process of its expansion in a hollow, and initially the dynamic forces arising in superheated liquid interfering with the further growth of a bubble are great. Heat is transmitted, mainly through a liquid microlayer under the steam bubble, which has a cone-shaped form with a "dry" spot in the centre of the latter. The main process of evaporation happens on the basis of this "dry" spot. Part of the heat is transferred into the bubble from the superheated liquid present in the volume of the porous structure.

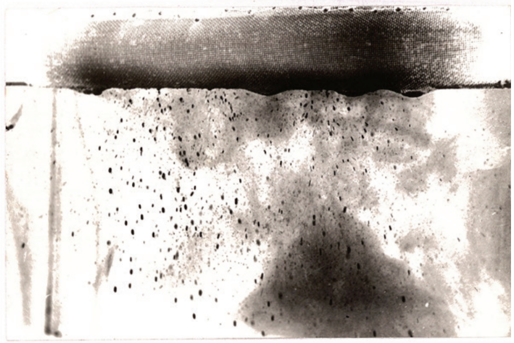
The microlayer's thickness and the radius of the "dry" spots in the bubble growth change insignificantly [40, 43, 44] due to the inflow of fresh portions of the coolant that is conveyed by gravity and capillary forces, and also due to the action of the buoyant forces on the bubble. The forces of inertia are manifested at an early stage of the bladder's development, the front of the margin decreases and the bubble assumes a shape close to spherical, reducing the area of "dry" spots that vary significantly form the microlayer. The disengagement of the bubble is determined by surface tension and hydro-resistance, and affects not only the excess liquid, which is created by subcooling, but also the flow rate of fluid, flowing and implemented by the thermal-hydraulic characteristics.

In a case when the steam bubble doesn't reach a detachable diameter, and its upper bound concerns an external surface of porous structure, the bubble is destroyed. According to literature [40] at the point of contact an opening occurs through which the steam flows out of the bubble into the steam volume. The free surface of the bubble is reduced under the forces of surface tension s, while the volume of the bubble will continue to expand in the direction of the steam channel. As a consequence, the surface of the liquid began to spread wave. The opening in the steam chamber will continue to expand into the steam volume and on the surface of the liquid a wave begins to spread.

The described process proceeds during time of 10^{-7} to 10^{-6} seconds, *i. e.* has explosive wave character, the same with regard to the appearance of a steam bubble, with the light phases' expiration. This phenomenon was useful for carrying out an analogy to explosive processes in elliptic systems, and for the division of power processes into wave and compressed gas energy. The phenomenon was followed by an intensive emission of drops of liquid (fig. 4), however no violation of operability of porous system has been observed.



(a) q = 94 kW/m^2; m_f/m_{st} = 1.4

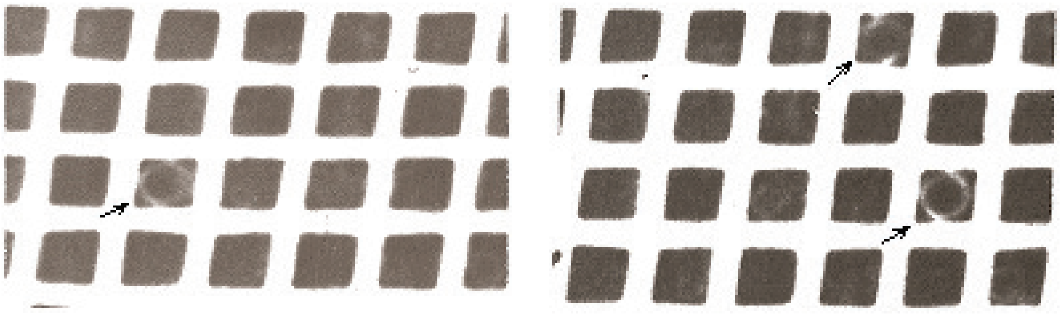


(b) q = 120 kW/m^2; m_f/m_{st} = 1.1

Figure 4. Appearance of droplet ejection liquid (water) from the reticulated pore structure of the form 0.14·0.4 a stainless steel

Into the cavity vacated by the bubble rushes a relatively cold portion of the liquid, and part of the steam is condensed in the cavity, so as to equalise the temperature of vapour and liquid at the interface of contact. In the case where the parameter of excess fluid $\tilde{m}$ is great, all the steam condenses in the cavity, preventing it from forming bubbles. The influx of heat accumulated in the wall leads to a new cycle of initiation steam of critical nucleus size. For one cycle of bubble wall the temperature below the evaporation stages on microfilm and heating cold liquid will change significantly, which explains the high intensity of heat transfer. Reducing the magnitude of the heat flux q at high parameters $\tilde{m}$ (fig. 5) returns the system to its previous state.

The form of the bubble, growing in a cell of the structure, has an odd form between spherical and hemispherical. The spherical type of bubble takes place when boiling water at high pressures ($p < 1$ bar), whilst the hemispherical one – at low pressure ($p \geq 1$ bar). If we factor in the initial moment of separation forces of a superficial tension, the bubble gets a spherical form in the cells.



(a) τ = 28/24 s (b) τ = 33/24 pages

Figure 5. A fragment from a record in an enlarged view, showcasing the process of steam formation of water for mesh structure of the type 0.4 at q = 94 kW/m^2, m_f/m_{st}=1.4; $\bar{\tau}_f$ = 1.58 s, $\bar{n}$ = 0.14 m^{-2} ($\bar{\tau}_f$, $\bar{n}$ – time of life expectancy [s], and density of the steam formation centres [m^{-2}]; the density of the centres of the steam is converted to 1 m^2, *i. e.* the amount of bubbles, referred to 1 m^2, so the dimension would be $\bar{n}$ = (number of bubbles)/m^2, [number m^{-2}])

Rapid growth of the bubble in an initial time point, under the influence of the force of inertia, is defined by a larger uniformity and degree of interface overheating at the fixed value of size q. The described form of the bubble and the model based on it, allowed us to explain the mechanism and to receive settlement dependences for boiling of liquid in cells of porous structure, which are well supported by experience:

– Area of superficial boiling:

$$q = 1.1 \cdot 10^{-3} \lambda_{ef} \left(\alpha_f \text{Ja} \bar{R}_0^{-2} \nu_f^{-1} \right)^{0.5} \Delta T \Phi K_w^{-1} \tag{1}$$

Formula (1) is obtained by building a physical model using the internal characteristics, assuming that the main share of heat in the heat exchange process is carried through effective thermal conductivity. The experimental constant is chosen in such a way that the deviation from the test data does not exceed ±20%.

The function considering orientation of the cooling system, excess of liquid, geometry of structure and a steam-generating surface:

$$\Phi = \left(1 + \cos\beta\right)^{0.57} \tilde{m}^{0.25} \left(\frac{h}{\delta_\Phi} \right)^{0.5} \left(\frac{b_0}{b_r} \right)^{0.27} \tag{2}$$

where $\tilde{m} = m_f/m_{st}$.

For the field of boiling bubble, formula (2), is assumed that the discharge of heat flow is carried out mainly at the expense of steam creation, *i. e.* $q = \bar{w} r \rho_{st} \bar{n}$ where $\bar{w}$ is the average speed of steam creation [ms^{-1}]

This formula is useful for calculating oil coolers of the steam turbines of thermal power plants.

– Area of developed nucleate boiling:

$$q = 0.0862 r \rho_{st} \alpha_f \text{Ja} \sqrt{\bar{n}} \Phi K_w^{-1} \tag{3}$$

For the boiling crisis, formula (3), is assumed that steam is forming conglomerates, at the heart of which lay moving areas of liquid layers and "dry" spots, which did not let the vapor escape through the porous structure. This led to difficulty in liquid movement by capillary and gravitational forces at the heated surface. The thickness of the vapour "cushion" is proportional to the hydraulic diameter of the porous structure, *i. e.*, stability criterion for biphasic mural boundary layer will be:

$$\rho_{st} W_{cr}^2 / 2g(\rho_f - \rho_{st})\bar{D}_0 = \text{const} \tag{4}$$

where $W_{cr} = q_{cr} / r\rho_{st}\varphi$

- φ – a function that takes into account the congestion of the section for vapor discharge in a summary of experimental data with an accuracy of ±20%;
- formulas (1)-(3) describe the experimental data (the influence of pressure, the material, the width of the cell and the thickness of the structure, orientation, and geometry of the surface) to the nearest ±20%, and
- the deviation of the experimental data for computing the values $\bar{\tau}$, $\bar{n}$, R_0, φ did not exceed ±20%.

– Boiling crisis $b_r > 0.28 \cdot 10^{-3}$ m

$$q_{cr} = 0.0347 \cdot r\sqrt{g\left(\rho_f - \rho_{st}\right)\rho_{st}\bar{D}_0}\left(\frac{b_r}{b_0}\right)^{0.3}\left(\frac{\delta_\Phi}{\delta_0}\right)^{0.5}\left(1+\cos\beta\right)^{0.6} \tag{5}$$

$$\bar{D}_0 = 2\bar{R}_0 \tag{6}$$

The analysis of the vapour bubble growth model shows that the presence of steam on the wall should lead to an increase in wall temperature under growth of the bubble and malfunction, however, the sustainability of existing liquid microlayer, driven by gravity and capillary forces, allows a single bubble to absorb several times greater heat flux, compared to the average integral value, which generally lowers the temperature of the wall during the growth of the bubble.

Conclusions

Experimental data for porous structures which can be controlled through a combination of gravitational and capillary forces have been summarised according to their thermos-hydraulic characteristics during the process of boiling. Formulas have been created between dependencies of thermal loading on a temperature pressure, excess of liquid, pressure, thermos-physical properties of a wall, orientation, geometrical characteristics of porous structures and a heat exchange wall are received. Formulas for calculations were obtained, which may be used at the design of heat power installations. The movements (the foremost of which is deformation) of the porous material are also shown, loaded by three thermal sources. The development, dynamics and movements of steam bubbles, and refinement of their form are analysed and describer. The mathematical models dependent on them allow for the explanation of the mechanism, as well as, for the obtainment of dependences for boiling liquid in cells of porous structure, which are well coordinated with experiment. The results acquired allow for further development of oil coolers with a possible solution with regard to the issue of environmental protection in two aspects: sewage treatment and soils affected by oil pollution and the use of low potential heat. The results would also be useful when calculating boundary conditions of power plants.

Nomenclature

b_h – hydraulic pore size structure, [m]
c_{pf} – isobaric heat capacity of liquid, [Jkg^{-1}K^{-1}]
D_0 – tear bubble diameter, ($= 2\bar{R}_0$), [m]
d – displacement points of the deformed body, [mm]
g – acceleration of gravity, [ms^{-1}]
h – height (perimeter) of the heating surface, [m]
Ja – Jacobs number, [$= c_{pf}\rho_f(T_w - T_S)/(r\rho_{st})$], [–]
K_w – coefficient taking into account heat storage capacity of the wall {$= 1+[(\rho c\lambda)_f/(\rho c\lambda)_W]^{0.5}$}, [–]
m_f – flow rate of liquid, [m^{3}s^{-1}]
m_{st} – flow rate of generated steam, [kgs^{-1}]
N – the measured number of strips between the studied point and a strip of a zero order, [–]
$\bar{n}$ – nucleation sites density, [m^{-2}]
$\bar{R}_0$ – tear bubble radius, [m]
r – latent heat of evaporation, [kJ·kg^{-1}]
T_w, T_s, – wall temperature and saturation temperature, [K]

Greek symbols

α_f – temperature coefficient of liquid conductivity, [m^{2}s^{-1}]
β – angle to the vertical cooling, [°]
δ_0 – constant thickness, [m]
δ_Φ – the thickness of the structure, [m]
λ – wavelength, [μm]
λ_{ef} – effective heat conductivity of porous structure, [Wm^{-1}K^{-1}]
ν_f – coefficient of kinematic viscosity, [m^{2}s^{-1}]
ρ_f, ρ_{st} – densities of the liquid and vapour, [kgm^{-3}]
Φ – the function considering orientation of the cooling system, excess of liquid, geometry of structure and a steam-generating surface, [–]
φ – corner between the direction of illumination of the studied point $\vec{r_0}$ and supervision of this point $\vec{r_H}$ on the hologram, *i. e.* $\vec{r_i} \wedge \vec{r}_0$, [–]

Acronyms

BG-1 – name of used apparatus
BP-L – type holographic plates [11]
CN-3 – type photographic film
D-19 – type of chemical developer, [–]
LG-38 – helium-neon laser with a transmission power of 60 mW, at a wavelength of 0.6328 μm
RFK – camera registration;
YU-16 – type digital light meter

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