Research of the heat transfer crisis and limit state of the heat exchange surface covered by capillary porous medium

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Abstract. Model of the vapour bubbles formed at the solid surface in porous structures and steam generating wall (base) was developed. The model is based on filming and photography by high-speed camcorder SKS-1M. Heat flow extraction (up to 2.10⁶ Wm⁻²) is ensured by the joint action of capillary and mass forces with application of intensifier. The analytical model is based on the theory of thermoelectricity. Limit state of the poor conductive porous coating and metal base are determined. Heat flows were calculated from the time of spontaneous birth of vapour bubble (10⁻⁸) to the material destruction time (10²⁻¹⁰⁻³ s), i.e. the time interval was described from the relaxation process to macro process (destruction). The size of pulled particles at the moment of porous coating destruction in model gave a good match with trial at the optic stand.

1. Introduction
The internal characteristics of the liquid boiling process in capillary porous structures were assessed with high speed filming and photography from birth of steam phase [1] to its destruction. That helped develop models and mechanisms of the heat transfer, and obtain single dependencies for different modes of boiling up to the critical state [2]. Heat exchanges were controlled by the joint action of capillary and mass forces. Visualization of heat influence was also performed by holography, which helped research the limit state of good and poor conductive materials in form of porous structures and steam generating surface. Control of heat exchange in porous structures was ensured by influence upon the internal boiling characteristics and the integral values [1, 8-9].

It is required to give a comparative analysis to the newly proposed capillary porous cooling system that applies a joint action of capillary and mass forces with the traditional systems such as boiling in large volume with the help of thin-filmed evaporators and heat pipes [3-7]. Authors [3] perform a comparative analysis of the calculation methods of heat transfer as per the water boiling along with subcooling in vertical channels, calculating corrosion cases as analogy of the capillary porous structure [4, 5]. However, research of heat exchange on the regular structured surface was not conducted; also, the role of speed and subcooling of liquid towards the boiling crisis in porous surfaces is yet not clear.

In the authors’ opinion [6, 7] the surface boiling on porous surfaces could cause or intensify corrosion, and possible erosion, as well as the surface strength when vapour bubbles collapse in the subcooled liquid. Therefore, heat exchange shall be examined in field of mass and capillary forces, taking into account the excessive liquid.

There is a series of experimental devices that allow to research the integral heat transfer characteristics: specific heat flows q, consumption of liquid and steam m, m, distribution of the temperature field as per height and length of the heat exchanged surface. Methods of holography [8],
summarizing similar [9] and identical cases [1, 2] are applied to research the heat exchange mechanism.

It is interesting to provide comparison to intensity of heat transfer and the surface limit state (boiling crisis) with heat pipes [10, 11], as well as make assessment of the fracture mechanics of heated (cooled) surfaces, coated by capillary porous structures applicable to strength, resource and justification of safe operation of the heat mechanical equipment of power plants [12, 13]. This problem arose a long time ago due to the upgrade and extension of the service life of the steam turbine power plant.

2. Trial units for research of the heat exchange crisis and the surface limit state

We developed and studied the trial units to determine the integral (average) heat exchange characteristics of the capillary porous cooling system; the operational diagram and methodology of measurement were established, as well as the cooling element device with pipe arteries, perforated spring and micro arteries. The different factors were studied, such as height of heat exchange surface, pressure in the cooling system up to the wall burning-off (Figures 1 and 2).

![Figure 1](image1.png)

**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.

Power supply to the main heater is maintained by the welding transformer TSD-1000, output voltage values are as follows: 2.5; 5; 7.5 and 10. Current that feeds the heater is measured as per diagram with universal transformer UТТ-6М2 cl. 0.2. Secondary current is up to 5 A, primary is 100-2000 A. Voltage drop at heater is measured by voltmeter D523 cl. 0.5. The maximum admissible tolerance when measuring current is ± 0.6%, voltage drop is ± 1%, capacity is ± 1.6%. Power at the guarding heater is supplied from the voltage controller RNO.
Fig. 2. Scheme for the study of the heat-release surface orientation:
a, b – liquid is supplied by the artery; c, d – the “siphon” liquid supply; β is the angle between the cooling surface and the gravitational force.

Current transformer TSD-1000 is used when studying the beginning of liquid boiling and critical loads with output no-load voltage 71 V. Current rate varies within (200÷1200)A. Temperature of liquid and environment are measured by mercury thermometers TL – 4 with scale of (0…50)°C and (50…100)°C and pressure 0.1°C. Temperature of the drained liquid and steam are measured by chromel-alumel thermocouples made of wire of diameter 0.1·10⁻³ m. Diameter of the thermocouple head is 0.4·10⁻³ m. Thermocouple electrodes are isolated by dual straws of diameter 1·10⁻³ m, which are fixed by glue BF-2 inside injection needles of diameter 1,2·10⁻³ m. To measure temperature, the electrode, walls of diameter 0,2·10⁻³ m, are welded with arc welding formed during discharge of condensers. For this purpose, surface of wall with thickness 2·10⁻³ m is drilled at a depth of 1,9·10⁻³ m of diameter 1,2·10⁻³ with precision ± 0,05·10⁻³ m. The thermocouple electrodes are isolated by porcelain straw of diameter 1,2·10⁻³ m and are placed at the wall surface between two layers of mica with thickness 0.05·10⁻³ m, glued to the heater surface. Cold ends of thermocouple are thermostated in the melting ice. Electrodes of thermocouple are jointed with two dihexagonal switches PP-63 cl. 0,05. In order to avoid the induced ground current upon readings of thermocouples, the device and tools are grounded. Consumption of the cooling and circulating liquid is measured by the electric flow meters RED with secondary electric tool KSDZ 43 cl.1, calibrated volumetric method. Consumption of the drained liquid and condensate are measured by tank with pressure rate 0.5·10⁻³, and time of filling is measured by stopwatch S-P-1b with graduation 0,1 second. The maximum admissible tolerance when measuring liquid consumption by flow meters is ± 3%, and by volumetric method is ± 2%. Imbalance of heat supplied by power and heat discharged by circulating and excessive water with Q shall not exceed ± 12%, and for heat supplied by steam in condenser and heat discharged by circulating water is ± 11%. The discrepancy of balance between consumption of cooling liquid, discharge and condensate is not more than ± 10%.

3. Model of the capillary porous structure of cooling system
Growth of the vapour bubble of radius R was reviewed as separate cell structure. The assumption was that the heat flow \( q \), that determines growth of vapour bubble supplied from the heat surface \( q_1 \) with
“dry” spot through the micro layer of liquid located underneath the vapour bubble, and part of heat $q_c$ is extracted from the overheated liquid that surrounds a growing bubble since value of the overheated liquid in porous structure could reach larger values, and increases reserve of enthalpy of the adjacent layers of liquid. The cooled liquid is transported due to the joint action of capillary and mass forces $\Delta P_{gs}$. The “dry” spot in the bubble centre is described by radius $r$, which at the breakaway torque is proportional to $R_{ds} = k \cdot R$, whereas micro layer of liquid underneath bubble forms an angle $\alpha'$ with sides $\delta'_o$ and $\delta_o$.

Vapour bubble was introduced in volume of the sphere segment, where truncated cone should be deducted, formed by micro layer. Thickness of micro layer $\delta_o$, feeding a vapour bubble due to its evaporation during the growth of bubble will be a constant value as the capillary and gravity forces ensure leaking of fresh portions of cooling liquid to the bubble centre. In model of the vapour bubble growth there is direct transfer from the developed bubble boiling to the possible crisis occurrence, when the imbalance of forces occurs and thickness of micro layer goes to zero ($\delta_o \rightarrow 0$), which is very important to study the limit state of system.

The interphase surface and steam generating wall form an average dynamic angle $\theta$ during growth of vapour bubble. Since task refers to not so low pressures, the dynamic processes at the initial stage of growth of vapour bubble are not under review. Then viscosity forces and superficial tension will also be comparable to the inertia forces and may not be reviewed. The boiling crisis is related to the active growth of “dry” spot size in the bubble centre.

4. Calculation of the boiling crisis

Calculation of value $q_{cr}$ applicable to the described model could be performed in terms of subcooling and flow speed as per equations [1], which means that subcooling of liquid help extend the heat transfer possibilities in the porous system of cooling. Because the heat transfer processes occur in the thin porous structures, then even insignificant excess of the free flowing film along the outer side of structure determined with parameter $\bar{m}$, at this hydrostatic pressure $\Delta P_s$ and relative permeability factor $K_s$, forms a liquid core as a source of the permanent supply to under-heated cooler because of difference of temperature and capillary forces.

Excessive liquid in the porous system creates directional movement of flow that leads to deformation of vapour bubbles in structure, reduction of its diameter, rising frequency of bubble birth. The increased flow speed results in the increased energy that is allocated for liquid displacement from the wall boundary layer, and therefore leads to the increased speed of steam generation $V_{cr}$ and value $q_{cr}$. Although, at some value of the liquid flow speed which is determined by parameter $\bar{m}_{cr}$, of energy, allocated for liquid displacement from the two-phase wall layer is not sufficient that leads to the heat transfer crisis. Certainly, increase of $q_{cr}$ will be reached at major liquid rates which results in the increased energy rate for the drive of supply machines. When a certain value of the moisture content $\bar{\varphi}_{cr}$ is reached, the flow speed will not increase value $q_{cr}$, and in some cases could even decrease value $q_{cr}$, because of the complicated steam extraction from the wall layer. The increased speed of liquid film adjacent to wall due to the parameter $\bar{m}$, begins to give way to the dominant effect of decreased moisture content $\varphi$ in that zone, which primarily impact upon value $q_{cr}$, even minimizing it. Therefore, in each separate case it is required to set a favourable rate of the excessive liquid $\bar{m}$ due to the type of porous structure. For porous systems of cooling mostly for all mode and geometric parameters under the bubble boiling of water the depth of permeability for temperature wave is $h_w < \delta_o$, so thickness of wall $\delta_o$ is not input into the design ratio for $q_{cr}$ in works [1, 8-9].

The design equation for $q_{cr}$ in case when $P \geq 0.1$ MPa, a $b_g > 0.28 \cdot 10^{-3}$ m is as follows:

$$q_{cr} = 0.0347 \bar{\varphi} [g(\rho_v - \rho_s) \bar{\rho}, D_{cr \_ bub}] 0.5(b_g / b_i)^{0.3} (\delta_i / \delta_j)^{1.5} (1 + \cos \beta)^{0.6}$$  (1)
where: \( \bar{T} \) – heat of vaporization; \( \bar{D}_{br, bub} \) – average size of a steam conglomerate that meets the condition \( \Delta T = \Delta T_{cr} \), determined by the formula of work [2]; \( b_{cr} = 0.14 \cdot 10^{-3} \) m; \( \delta_f \) - structure thickness; \( \delta_{w} = 0.18 \cdot 10^{-3} \) m.

It follows from equation (1) that \( q_{cr} = \bar{D}_{br, bub}^{0.5} \) (\( p \geq 0.1 \) MPa) and \( q_{cr} = \bar{f}^{0.5} \) (\( p < 0.1 \) MPa).

Quantity \( \bar{D}_{br, bub} \) and \( \bar{f} \) depend on the thermophysical properties of the heat-dissipating surface:

\[
\bar{D}_{br, bub} = K_w^{-1}, \quad \bar{f} = K_w^2,
\]

where \( K_w = 1 + [(pc\lambda)/(pc\lambda)_w]^{0.5} \). Then for surfaces made of copper and stainless steel and covered with mesh structures, we have the following: \( q_{cr} = 1.07 \) (\( p \geq 0.1 \) MPa), \( \bar{q}_{cr} = 1.15 \) (\( p < 0.1 \) MPa).

The wall material affects value \( q_{cr} \) by set \( (pc\lambda)_w \), where \( c, \lambda \) – the wall heat capacity and heat conductivity. However, it is not appropriate to make a firm statement because practically it is impossible to retain equal conditions for clarity of processing and micro structure.

When designing a combustion chamber and a nozzle in particular, it is required to take into consideration some reserve for thickness of the heated surface. The boiling crisis previously occurs at “thin” heaters since at the pre-crisis boiling area a size of “dry” spot will increase in the bubble centre, the heat exchange process will abruptly worsen, and wall temperature will increase. Surfaces, that have larger thickness will require more time for their heating. For surfaces with porous coating it is very critical as inside them a time of bubble growth is ten times less, hydrodynamic conditions of liquid supply are sharply changed, and therefore time of steam at wall may extend, which avoids contact of liquid with the heat exchanged surface despite the excessive liquid \( \bar{m} \).

The described process is a pre-history of the boiling crisis development. Further “destiny” of the process at other equal conditions is determined by the heat accumulating capacity \( (pc\lambda)_w \). When large value is selected, there is possibility of delaying the boiling crisis, the heat extension along the heat surface increases, and again the favourable conditions are established for contact of liquid phase and wall. Only wall thickness increased ten times increases value \( q_{cr} \), a few times whereas this situation is more distinctive for highly conductive materials and at greater atmospheric pressure.

As shown by calculations, during time \( \tau \leq 5 \) s heat flows reach values \( \sim 8 \cdot 10^7 \) Wm\(^{-2}\) for copper and \( 1.3 \cdot 10^8 \) Wm\(^{-2}\) – for stainless steel. Although, they will be screened by melting curves through \( \sim 0.01 \) s. High heat tension stresses occur as a result of abrupt increase of gradients in wall. The impact of different materials and wall thickness at time of beginning destruction at the boiling crisis was studied. With methods of holography and photo elasticity the most hazardous place was determined at the moment of destruction for porous surface [1, 9].

Cases of the liquid discharge from cell of porous structure [1, 2] deteriorate intensity of heat exchange at movement of some boundary heat flow. By selecting an appropriate type of structure this case could be minimized. The smallest discharge is obtained for the single layer meshes with cells more than \( 0.28 \cdot 10^{-3} \) m. The rising deteriorated modes as per their mechanism are identical to processes that exist under movement of the steam-water mixture in pipes that have no porous coating. These modes are characterized by the resistance crisis when friction resistance is getting reduced at the heated area. This is related to the fact that due to the major discharge of drops the liquid consumption is reduced. At the initial stage of the discharge process liquid drops tubulise process, then at the critical discharge quantity of liquid becomes insufficient for watering the heat exchange wall (Fig. 3).
Figure 3. Influence of the heat flow density upon wall overheating in relation to water steam temperature ($p = 0.1$ MPa): 1 – boiling in large volume at surface w/o coating [3-6]; 2 – Operational area of heat pipes [7, 10, 11]; 3 – operational area of thin filmed evaporators [3]; 4 – researched porous cooling system [1, 2].

Shaded area refers to application of intensifier in porous system. As shown in Figure 3, it is a comparative analysis of the system research (4) with curve in large volume (area 1), by thin-filmed evaporators (area 3) and area of the heat pipes (2). The system (4) extends a limit for discharge of heat loads approaching the liquid boiling in large volume, and in case of applying intensifiers could also discharge large heat flows (shaded part of area 4). As the heat exchange intensifiers the following was studied: wave porous elements with gas-and-liquid dispersoids and the upgraded capillary porous structure, vibrated high heat conductive t-offs and flexible turbulizer.

### 5. Conclusions

Model of the steam generating bubbles at solid surface with porous coating contains filming and photography observations over the internal characteristics of liquid boiling. High boosting of heat transfer is maintained by the joint action of capillary and mass forces. For such model a thermoelasticity problem is solved and the limit state of system was determined: good and poor conductive materials (porous coating at metal base). Heat flows were calculated from explosive birth of vapor bubble ($10^{-8}$s), i.e. from relaxation time to the time of macro process. There is interrelation during destruction process only by compression stress, either by melting or tension stress. Sizes of pulled particles are confirmed by high-speed filming and photography. Comparative analysis was provided for the studied capillary porous system along with boiling in large volume by thin-filmed evaporators and heat pipes applying the heat transfer intensifiers. In future, it is required to expand researches for the other mineral medium.

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