CAPILLARY-POROUS HEAT EXCHANGERS FOR COOLING OF MELTING UNITS

by

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The model of development of a vapor phase in porous structures of heat exchangers for cooling of melting units on the basis of cinema observations which explains the mechanism of nucleation, development, and death of steam bubbles is created. In case of crisis of heat exchange, there are the limiting conditions of a surface of a porous coating and metal substrate. The process of destroying can come from melting, or from heat stresses of compression and stretching. The reliability of a cooling system of melting units is defined by the combined action of capillary and mass forces.

Key words: *capillary-porous system, cooling system, caisson, heat exchangers, heat flux*

Introduction

In the metallurgical units, parts and assemblies operate in highly heat-loaded conditions and require intensive cooling. For ensuring explosion-proof work of the installations containing molten metals and a melt it is offered to use the porous cooling system containing very trace amount of liquid which, having got to a melt, will not lead to explosion. Such installations are used in industrial furnaces. In turn, such a system, being highly efficient, is capable of removing powerful specific heat fluxes. It increases the reliability and mobility of the unit without complicating and additional energy costs.

The capillary-porous system has a number of new advantages when cooling the caissons: the multiple reductions of liquid quantity in cooling system and especially in the caissons, which ensures the explosion safety of the melting units; self-regulation of the heat transfer process in a porous layer, which is important for variable operating modes; high uniformity of the temperature field in the wall; economic effect through pumping less fluid quantity.

It is necessary to investigate the capillary-porous structure, made from natural materials and metals. Such surfaces are being used in large-scale production of power installations and metallurgical engineering. Investigation of the limiting condition of metallic wall and its capillary-porous coating is important. The limiting condition of structure can be studied by solution of thermal elasticity problem.

A model of the nucleation of steam bubbles in the cells of the capillary-porous structure is developed in our study. The model of development of a vapor phase in the porous coat-

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ing of heat exchangers for cooling of melting units makes it possible to explain the mechanism of nucleation of the bubble, its growth up to the point of destruction. The analytical model is obtained on the basis of the solution of the thermoelasticity problem. The functional dependences of the destroying heat fluxes from time of heat supply, the size of the destroyed particles and a depth of penetration of a temperature wave in metal surfaces are revealed.

The analysis of scientific publications shows a trend of increasing use of capillary structures in heat exchangers. Due to the wide area of use of heat exchanges a significant amount of data is presented in the literature related to the study of heat exchange characteristics of the particular devices. Special attention is paid in the modeling of heat transfer in porous material, evaporation, thermal resistance, and thermal conductivity. The following references prove the urgency of the problem [1-10].

In the forced devices of melting furnaces, flow cooling is used. There are various types of flow cooling such as air, liquid, evaporative and gas-liquid cooling. Air cooling is widely used when specific heat fluxes through cooled surfaces increases up to 2000 W/m^2. But the low heat capacity of the air and the low heat transfer coefficient for air cooling make it unsuitable for more powerful heat loads. Methods for cooling of high temperature elements in metallurgy are known, cooling is carried out by technical water, when cold water passes through the cooled surface, taking away the heat.

Small heating of water requires its high consumption and construction of powerful water intake devices, equipment for cleaning, pumping and cooling water in the case of a reverse water supply system. The salt content led to the deposition of sludge, scale and frequent burnout of the cooling elements.

It is proposed for cooling elements of furnaces to use evaporative cooling. The shortcomings of the evaporative cooling system are the possibility of emergence of crisis phenomena, constructive complexity. Uneven distribution of thermal loads between structural elements, their change in time, violates the stability of circulation, causes the temperature jumps in the metal wall and the appearance of fatigue cracks. All this reduces the reliability of the cooling surfaces of heating.

At heat protection by heat-resistant coatings, the selection of materials withstanding high heat without damage with a low thermal conductivity is necessary. With the development of ceramic, plastic and fiberglass materials, a number of compositions have appeared, suitable for use as a heat-resistant coating. However, these materials require thorough testing for compatibility. When selecting the appropriate thickness of the ablating or heat-resistant inert coating, it would be possible to completely eliminate external cooling.

In this way, it was necessary to develop a new system that could meet the requirements for explosion safety of melting furnaces, and also be used for other purposes in metallurgical production. Such a system was capillary-porous, which represents a new class of heat-removing systems where with the capillary potential acts a mass potential.

Capillary-porous structures were studied to reduce the thermal stresses in the walls of the desuperheaters and boilers of the boilers. Drops of liquid, falling on a porous structure, are distributed in it by capillary force, which excludes their interaction with the enclosing walls. The level of maximum cyclic stresses can decrease in several times, and their double decrease increases the longevity of structures in 10 times.

At cooling the caissons, the capillary-porous system has a number of new positive advantages: reduction in dozens of times of cooling liquid volume in the system and especially in the caissons, which ensures the explosion safety of the melting units; self-regulation of the heat transfer process in a porous layer, which is important for variable operating modes;

high uniformity of temperature field in the wall; some economic effect due to the transfer of less liquid.

Modern systems of caisson for lining and the blast-furnace cooler do not solve the problems of explosiveness. Therefore, to ensure the explosion-proof operation of installations containing liquid metals and melt. It is proposed to use a porous cooling system containing a very small amount of liquid that, if trapped in a melt, does not lead to an explosion. Such plants are used in industrial furnaces. In turn, such a system, being highly efficient, is capable of removing powerful specific heat fluxes. It increases the reliability and mobility of the unit without complicating and additional energy costs compared to the most economical evaporative cooling.

In fig. 1 the option of design of the cooling elements is shown. The device consists of a housing – 1, and a removable cover – 2, hermetically bolted on perimeter – 3. The internal surface of a wall – 4, is covered with the capillary-porous structure – 5, pressed by perforated plates – 6. Arteries – 7, are connected to top ends of structure through the end face of which to the cooled surface liquid is supplied by mass and capillary forces. The lower ends of structure are usually free and immersed in baskets – 8, where liquid accumulates due to leaks, droplet entrainment or the excess. Plates – 6, are attached either by clamping bars or by spot welding. On a surface of plates, the recesses with openings – 9, are stamped which provide a steam-out from structure in channel – 10, and also serve as catchers of the drops which are thrown out from structure and the flowing-down excess liquid on an external surface of a plate – 6. This provides a more rational use of the cooling fluid by returning it to the structure, which improves fluid hydrodynamics, intensifying heat transfer. The artery – 7, is connected to a branch pipe – 11, with the distributing pipes – 12, and a collector – 13. The excess of cooling liquid accumulates in the bottom of a caisson and a siphon – 14, is removed in the lower collector – 15, and further in the store for return to system. For the purpose of facilitation of a design and preservation of sufficient rigidity, the caissons are provided with the spacers – 16, made in the form of Z-shaped perforated plates or stiffeners. Ribs may be located outside or inside the body and a cover of a caisson. On a cover, in her upper part, branch pipes – 17, with flanges for connection with a steam line are welded. The size and shape of the porous structure – 5, are determined by the size of the caisson and its design, fig. 1. The structure can be extended in the vertical or horizontal direction, the upper or lower ends of which

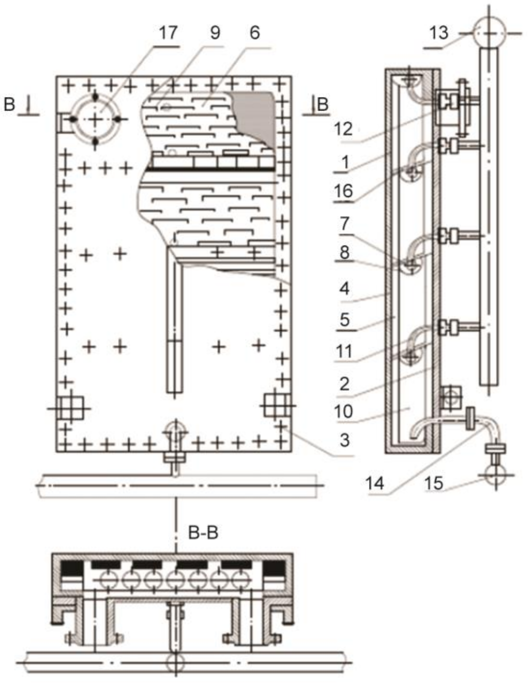

Figure 1. The scheme for cooling the caisson with a porous system with stiffening plates: *1 – housing, 2 – cover, 3 – bolt, 4 – wall, 5 – capillary-porous structure, 6 – plate, 7 – artery, 8 – basket, 9 – opening, 10 – channel, 11, 17 – branch pipe, 12 – pipe, 13, 15 – collector, 14 – siphon, 16 – stiffening plates*

(or both) are connected to an artery – 7. The perforated plates – 6, are made in a form and the sizes according to structure. The stamped and perforated openings in them can have the form of the truncated cone or longitudinal slots with openings facing upwards.

The described cooling system, keeping the advantages of evaporative cooling, has a number of new positive factors: reduction (in tens of times) of cooling liquid consumption in system and especially in caissons that provides explosion safety of units; reduction of financial investments and operational expenses due to sharp decrease of liquid amount in external and internal contours of circulation; the self-regulation of heat exchange process in a thin porous layer allowing to reduce sharply variable cyclic breaking stresses in a wall; some economic and ecological effects due to transfer of significantly smaller amount of liquid; increase in forcing and intensification of heat transfer.

Model and development mechanism of steam phase in porous coatings

The model of the development of a steam phase, the description of the mechanism of processes, and the resulting settlement dependences, are defined, as follows from photo-cinematographic and holographic observations [11-15], from the fact that dynamics of a vapor phase after spontaneous (explosive) nucleation of a bubble of the critical R_{cr} size, fig. 2, proceeds with participation of the evaporating microlayer which is under a steam bubble and under some conditions replacement of a fluid film in the center of a steam bubble with the subsequent development of a *dry* spot begins.

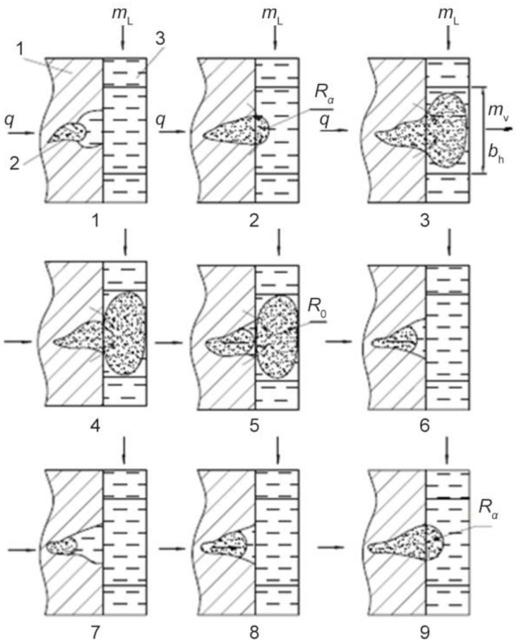

Figure 2. Illustration of the process of nucleation, development, and separation of a vapor bubble in the active pore of the steam generating wall covered with a porous structure: *1 – wall, 2 – pour, 3 – porous structure, q – heat load; m_L – liquid consumption, m_v – vapor consumption, b_h – hydraulic diameter of a pore structure*

The separation or destruction of steam bubbles occurs with diameters, several times smaller, than at pool boiling on a smooth surface. The value of $\overline{D}_0 = 2R_0$ is calculated by a formula of papers [16, 17].

After the separation (destruction) of bubble, under the influence of gravitational and capillary forces, relatively cold liquid portions are sucked into the system. After a period of *silence* in the center of generation, a new critical sized bubble is spontaneously created, and the growth of the coolant controlled flow m_{L} (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 and from heat-conductive mesh skeleton.

The incommensurability of the time of *silence* with the period of growth also indicates a constantly existing overheated pulsating microlayer which fluid stability is expanded as a result of combined action of the gravitational and capillary potentials.

When liquid boiling in large volume the stage of growth of a bubble was

$\sim (10\text{-}100)\cdot 10^{-3}$ seconds, and in porous system this value could be ten times less. Stages of origin and bubble separation are negligible in both systems and have character of explosion. The *silence* time in a periodic cycle of generation of a bubble when boiling in large volume could make ~0.1 seconds and can be commensurable with time of growth of a bubble. The emergence of a bubble of a critical size, R_{cr}, in a cell of structure results from the fast expansion of a bubble in a hollow in liquid, fig. 2.

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 transferred, mainly through a liquid microlayer under the steam bubble, which has a cone-shaped form with a *dry* spot in the center 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 from the opposite side relative to the wall.

The microlayer's thickness and the radius of the *dry* spots in the bubble growth change insignificantly 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 of 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 separation of the bubble is determined by surface tension and hydro-resistance and affects the excess of liquid, which is created by subcooling and also the flux velocity of the flowing liquid.

In a case when the steam bubble does not reach a detachable diameter, and its upper bound concerns an external surface of porous structure, the bubble is destroyed. The mechanism of destruction of a bubble in a thin film of a porous structure is presented in papers [11, 17].

When the boundary of the bubble occurs the level of the liquid at the point of contact, an opening appears through which the vapor flows from the bubble to the steam volume. In the vicinity of this point, the generating lines of a certain curvature appear, which begin to contract to a point, reducing the free surface under the action of surface tension, and the opening in the vapor cavity will continue to expand into the vapor volume. On the surface of the liquid the wave will begin to spread. The described process proceeds during time of $(10^{-7}\text{-}10^{-6})$ seconds, *i. e.* has explosive wave character, the same with regard to the appearance of a steam bubble. This phenomenon was useful for carrying out an analogy to explosive processes in elliptic systems.

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 equalize the temperature of vapor and liquid at the interface of contact, fig. 2. In the case where the parameter of excess fluid $\tilde{m} = m_{\text{L}}/m_{\text{V}}$ is great, the entire vapor 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 the wall temperature below it, the evaporation n stages on microfilm and heating cold liquid will change significantly, which explains the high intensity of heat transfer.

The model of the development of the vapor phase in porous structures makes it possible to receive settlement dependences of heat exchange for various parts and units of heat power stations [18-24].

Model of a capillary-porous coating for the limiting state of the heating surface

The solution of the problem of thermoelasticity makes it possible to determine the limiting state of the media for the capillary coatings of the rock and the metal vapor generating surface [12].

We consider a plate, free in all its sides, and of $2h$ thickness. To the surface $z = +h$, since the moment of $\tau = 0$, a constant specific heat flow of q is brought. The bottom surface and lateral edges of a plate are considered as heat-insulated.

The heat conduction equation with boundary and initial conditions will register as:

$$a_{\mathrm{w}} \frac{\partial^2 T}{\partial z^2} = \frac{\partial T}{\partial \tau}, \quad T = 0, \quad \tau < 0 \tag{1}$$

$$\lambda_{\mathrm{w}} \frac{\partial T}{\partial z} = q \quad z = +h, \quad \lambda_{\mathrm{w}} \frac{\partial T}{\partial z} = 0 \quad z = -h \tag{2}$$

where a_{w} and λ_{w} are the thermal diffusivity coefficient and heat conduction coefficient of the wall, respectively, T is the temperature, and τ – the time.

The solution of eqs. (1) and (2) will be as (3). Temperature distribution on thickness depends on the heat-physical properties of a material, the value of a heat flux and the time of its appearance [12]:

$$T\left(\frac{z}{h};\tau\right) = q\left\{ \begin{array}{l} \dfrac{\mu}{2(c\rho\lambda)_{\mathrm{w}}}\tau + \dfrac{\dfrac{3z^2}{h^2} + \dfrac{6z}{h-1}}{12\mu} - \dfrac{4}{\pi^2 \mu}\cdot \\ \cdot\displaystyle\sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} \exp\left[-\left(n^2 \frac{2\pi^2\mu^2}{4(c\rho\lambda)_{\mathrm{w}}}\tau\right)\right] \cos\left[\frac{n\pi}{2}\left(\frac{z}{h}+1\right)\right] \end{array} \right\} \tag{3}$$

Having been informed about the temperature distribution in a plate, it is possible to calculate the thermal stress of stretching and the compression, appearing at some moment τ at various depth from a surface $\delta_i = h - z_i$ at this value of a heat flow of $q = c$.

The plate with a variable on thickness, temperature is in the plainly stressed state. The tension, σ, is defined with accordance to the following equation (The equation is given in [25]):

$$\sigma_{xx} = \sigma_{yy} = -\frac{\alpha' E}{1-\nu} T\left(\frac{z}{h};\tau\right) + \frac{1}{(1-\nu)2h} \int_{-h}^{+h} \alpha' E T\left(\frac{z}{h};\tau\right) \mathrm{d}z \tag{4}$$

where the first term is the component of the compressive stress and the second member is the stretching component, α' is the coefficient of linear expansion, E – the Young's module, and ν – the Poisson's coefficient.

Product ($\alpha' E$) does not depend on temperature, therefore the expression of tension by stretching becomes simpler.

Calculation of the limiting state of the heat transfer surface

Assuming the limiting values of the compressive stress, stretching for porous coating and metal, a functional dependence on time and penetration depth of the heat flow, q_i, demanded for destruction is obtained.

Besides, when equating plate surface temperatures to temperature of melting for both the coating and the metal, the values of the specific heat fluxes, necessary for the melting of the top layer in various period of their action, are determined. Thus, in each specific case present are functional dependences of a heat flux from the time of its influence on the covering and metal surface:

– melting of a plate surface at a temperature T_M:

$$q_1 = \frac{T_\mathrm{M}}{\dfrac{\mu}{2(c\rho\lambda)_\mathrm{w}}\tau + \dfrac{2}{3\mu} - \dfrac{4}{\pi^2\mu}\sum_{n=1}^{\infty}\dfrac{(-1)^n}{n^2}\exp\left[\dfrac{-(n\pi\mu)^2\tau}{4(c\rho\lambda)_\mathrm{w}}\right]\cos n\pi} \tag{5}$$

– creation of limit compressive stresses σ_comp:

$$q_2 = \frac{\dfrac{(1-\nu)\sigma_\mathrm{comp}}{\alpha' E}}{\left\{\begin{array}{l}\dfrac{\mu}{2(c\rho\lambda)_\mathrm{w}}\tau + \dfrac{\dfrac{3z^2}{h^2}+\dfrac{6z}{h-1}}{12\mu} - \dfrac{4}{\pi^2\mu}\cdot \\ \cdot\displaystyle\sum_{n=1}^{\infty}\dfrac{(-1)^n}{n^2}\exp\left[-(n\pi\mu)^2\dfrac{\tau}{4(c\rho\lambda)_\mathrm{w}}\right]\cos\left[\dfrac{n\pi}{2}\left(\dfrac{z}{h}+1\right)\right]\end{array}\right\}} \tag{6}$$

– creation of limit stresses of stretching σ_str:

$$q_3 = \frac{\dfrac{(1-\nu)\sigma_\mathrm{str}}{\alpha' E}}{\dfrac{\mu}{2(c\rho\lambda)_\mathrm{w}}\tau} \tag{7}$$

where σ_comp is the limit compressive stresses, σ_str – the limit stresses of stretching, α'– the coefficient of linear expansion, E – the Young’s module, and ν– the Poisson's coefficient.

Analysis of calculation results of the limiting state of the heat transfer surface

For the plates made of quartz, granite, teschenit and metallic (copper and stainless steel) coverings, functional dependences of q_1, q_2, and q_3 are calculated. Thermomechanical characteristics of coatings and metals are presented in [12]. The results of calculations for the teschenite coating are shown in figs. 3 and 4. Figure 3 shows the dependence of the heat fluxes causing compression stress of a teschenite coating, depending on action time, τ, for various thickness of the coming-off particles δ: I – stretching tension, sufficient for destruction, II – melting surface curve, III – thermal stresses of compression, sufficient for destruction, melting curves for copper and stainless steel almost coincide with a curve of I in the area of $\tau = (0.01 - 0.1)$ seconds.

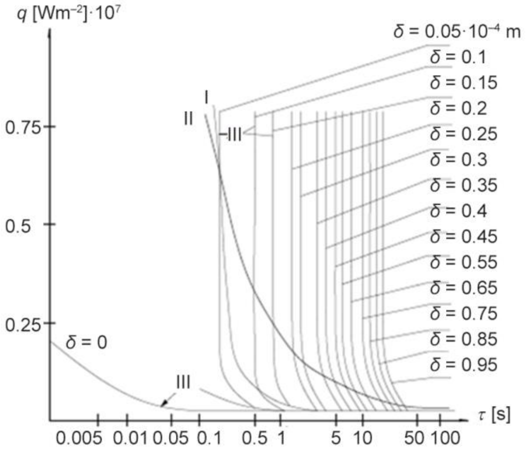

Figure 3. Dependence of the heat fluxes causing compression stress of a teschenite coating, depending on action time, τ, for various thickness of the coming-off particles

Relationship of compressive and tensile stresses can be seen in fig. 4, which represents the stress distribution inside the plate of teschenit coating for various time intervals from the start of the process. At the time of action approximately $t \sim 10^{-1}$ seconds, there are only compressive stresses. Since $t \sim 1$ seconds, in a region of $\Delta(h - z_i)$ to $0.3 \cdot 10^{-2}$ m the compressive stresses become the tensile stresses in a very short period of time, and to different intervals they are located at different depths from the surface of the plate. In the region of transition from compressive stress to the tensile stress, probably the greatest shear stresses of layers of rock surface will be observed. In time dependence, the shear stresses reach its limit values after destructive compressive stresses and, obviously, before the maximum values of tensile stresses.

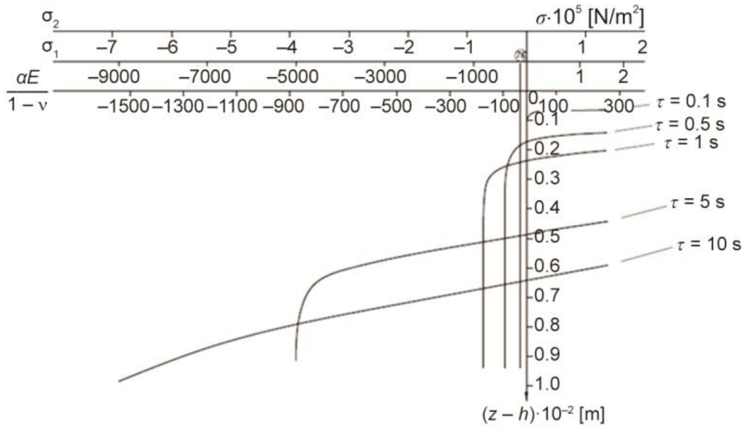

Figure 4. Diagrams of stresses in thickness for plate of teschenite coating at different q and τ: $q_1 = 6.6 \cdot 10^6$ W/m², $q_2 = 1 \cdot 10^4$ W/m², 76 – limit of tensile strength

In figs. 5 and 6 calculation of a specific heat flux necessary to destroy of unit volume of the teschenite coating is presented. Depending on thickness, δ, of the detached particles, specific energy of destruction of Q is defined. Curves have obviously expressed minima.

Experimental studies carried out by the SKS-1M high-speed movie camera made it possible to measure the dimensions of the detachable particles of the porous coating, δ, for a fixed value of q and time. Figure 7 shows the record (kinogram) of the flight of a collapsed teschenite coating, the dimensions of which agree well with the theoretical, see figs. 5 and 6.

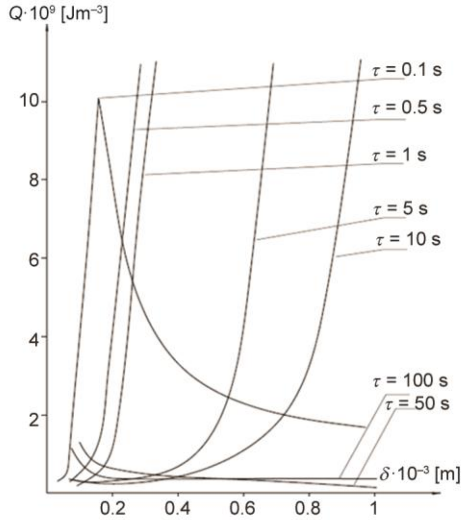

Figure 5. Variation in specific energy of destruction of the coating from a teschenite depending on δ for various τ; $Q = q\tau/\delta$

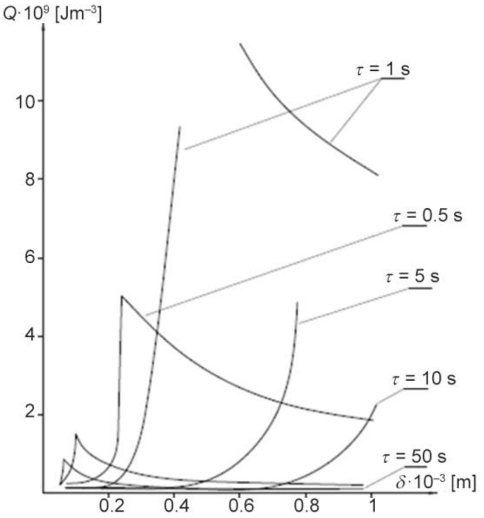

Figure 6. Variation in specific energy of destruction of the coating from a teschenite depending on δ for various τ at $\sigma_{\text{comp}}/\sigma_{\text{str}} = 2$; $Q = q\tau/\delta$

Figure 7 represents the filming of husk flight with size $2.5\cdot 10^{-3}$ m at the destruction of teshenite coating when exposed to torch of a rocket burner ($q = 1.2\cdot 10^6$ W/m^2; $\tau = 2.2$ s): 1 – area of cover destruction, 2 – flying particles, 3 – nozzle of fiery-jet burner, and 4 – capillary-porous covering. Time separation of particles from the teshenite coating defined by high-speed filming [12] is less than 0.5 seconds, depending on the supplied of heat flow. It is agreed with the data given in fig. 7 at $t_{\min} \geq 0.1$ seconds. The maximum thickness of the particles separated under the action of compression for teschenite coating is $(0.25\text{-}0.3)\cdot 10^{-2}$ m.

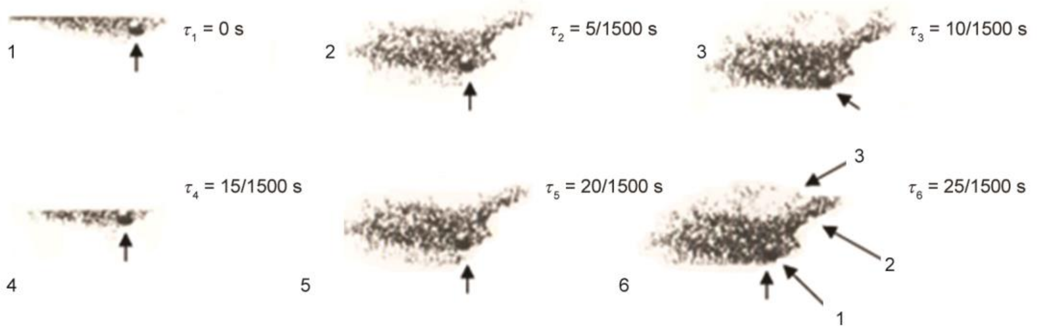

Figure 7. Record of flight of a particle (shelushka) with size $2.5\cdot 10^{-3}$ m at destruction of a teschenite coating by a torch of rocket type (q =$1.2\cdot 10^6$ W/m^2), *1 – particle, 2 – burner torch, 3 – porous coating*

Conclusions

New capillary-porous cooling system operating in the field of mass and capillary forces was investigated. It is considered the possibility of using capillary-porous cooling systems for explosion-proof melting units. The model of development of a vapor phase in the porous coating of heat exchangers for cooling of melting units makes it possible to explain the mechanism of nucleation of the bubble, its growth up to the point of destruction. The limiting state of a porous surface and metal substrate can be characterized by melting, destruction from heat stresses of compression and stretching.

Calculations were made, based on the solution of a problem of a thermoelasticity, and confirmed by visual observation by means of the SKS-1M camera. The functional dependences of the destroying heat fluxes from time of heat supply, the size of the destroyed particles and a depth of penetration of a temperature wave in metal surfaces are revealed. The reliability of the cooling system is determined by the combined action of capillary and mass forces, and the limiting state of the porous coatings depends on the value of the heat load, the time of its supply, and the depth of penetration of the thermal wave.

Nomenclature

a_w – thermal conductivity factor, [m^{2}s^{-1}]
b_h – hydraulic diameter of a pore
c – wall heat capacity, [kJkg^{-1}K^{-1}]
D_0 – tear bubble diameter, (= $2R_0$), [m]
E – Young's modulus (elasticity modulus), [Pa]
h – cooling depth, [m]
q – specific heat flux, [Wm^{-2}]
R_0 – bubble radius, [m]
T_M – melting temperature, [K]
T_W – wall temperature, [K]
z – co-ordinate, [m]

Greek symbols

α' – coefficient of linear expansion
δ – thickness, [m]
δ_{pl} – plate thickness, [m]
λ – thermal conductivity of the wall, [Wm^{-1}K^{-1}]
ν – Poisson's coefficient
ρ – wall density, [kgm^{-3}]
τ – time, [s]
σ – stress

Subscripts

cr – critical cross-section
h – hydraulic
L – liquid
M – melting
v – vapor
w – wall

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