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ДОКЛАДЫ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
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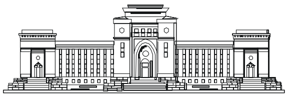

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MODEL OF LIQUID BOILING IN THE ACTUAL POROUS STRUCTURE AT THE NEAR-CRITICAL AREA WITH FURTHER TRANSFER TO THE LIMIT STATE OF COATING

Abstract: modelling of capillary porous coatings and analogy of their processes could help reveal a mechanism of heat transfer during evaporation of liquids, and determine zones for occurrence and development of fatigue fractures in the activation centers of vapour nucleus, research the natural deposits (saline deposits, scales) and artificial porous coatings on metal barriers (bases) up to the limit state of materials. Coatings were made of the poor conductive mineral medium (quartz, granite, teschenite) with low porosity (3÷30%). Heat was supplied from flame of the rocket burner and electric current. Stability of heat transfer is ensured by excessive cooler at the joint action of capillaryand mass forces. Solution of the thermoelastic problem has led to connection between the heat flows that destroy heat stress and fracture energy and time of the heat supply, as well as size of the pulled coating particles. The areas for relaxation, micro and macro destructive processes were determined, which point out the causes for occurrence and development of fatigue fractures of the heat-and-power equipment at stress concentrator along with erosion processes and relation between the limit state of compression and tension and unit. The conducted research refers to the transition operational modes of boiler turbine equipment, as well as formation of the capillary porous cooling system.

Key words: porous coatings, cooling system, heat exchange.

The burners development [1-3] refers to research of the porous cooling system for the rocket burners [4-9]. At heat influence upon the mineral poor heat conductive porous coating by burner, after a certain time a part of coating gets heated at some certain temperature, and the initial temperature remains at the other parts. Therefore, inside the porous coating a temperature gradient arises, which results in uneven extension. The surrounding non-heated layers do resist such extension. As a result, heat stresses occur both in the heated part, and in the surrounding non-heated part including base. These stresses could reach destructive values. In works [2,3] there are solutions for heat stress for idealized processes. The normal compressive stress played the dominant role in destructive process. Destruction of the porous coating takes place as a result of loss of stability in thin layer adjacent to free surface. Thus the stressed condition of upper layer was reviewed, its thickness depends on the heat emission factor and coating structure and base (metal steam generating surface).

In the irradiated coating a density of vacancies rises vigorously that quickly joint in cavities since the intensity of the vacancy joining process is proportional to quadrat of their density. If cavities of vacancies could transmit into dislocations, then the irradiated coating have plastic properties and is not destructed under influence of burner. All metals are like that. Some mineral rocks such as tuff, marble and limestone have this property.

If dislocations are missing in coating, then the growing cavities of vacancies have stresses focused on their edges and lead to destruction. Meanwhile, yet heat stresses in coating do not reach a limit of plastic flow. The brittle heat destruction occurs.

For cooling of heat exchange surfaces of power units up to the critical heat flows(~106 W/m2) as based on reference there are apparent imaginary contradictions in forming a process of heat exchange in porous structures when it is discussed which medium was beside the wall such as liquid, steam or steam-water mixture. In our works it is specified that all models do not contradict each other, and describe different modes of boiling [4-9].

Based on the experimental and theoretic research, the dynamic models of heat exchange enhancement are formed at boiling on porous surface. The developed surfaces contain the interrelated internal cavities in form of rectangular channels and small pores that join channels with volume of liquid.

Relation of latent heat flow $(\frac{\pi}{6}\bar{D}3\text{огрп}\bar{n}\bar{f})$ towards heat flow for the developed surface could have been (2…5) times more than for a single surface at specific heat flow up to 1x104 W/m2. At large heat flows this relation is reduced. Deviation of some data from the designed data reached 300%. The following symbols are specified in formula as: $\bar{D}$3о – average departure diameter of bubbles in porous structure; r – specific heat of steam generation; ρп – steam density; $\bar{n}$ - average density of nucleation core; $\bar{f}$–average frequency of vapour bubble generation.

We develop a physical model of transfer of specific heat flow q through the steam generating surface (wall or base), which is covered by capillary porous structure (Fig.1).

Heat-and-mass transfer processes in porous coating are carried out with excessive liquid $\tilde{m}$=mж/mп because of the pressure potential action that is created by capillary and mass forces ΔPкап+g.

The studied heat and hydraulic (internal) properties of boiling [5,6] help reveal a mechanism, describe a physical picture of the heat-and-mass transfer process in the researched mesh porous structures [4,7], working in field of gravity forces, and obtain calculation equations in order to determine the discharged heat flow [3,7,9].

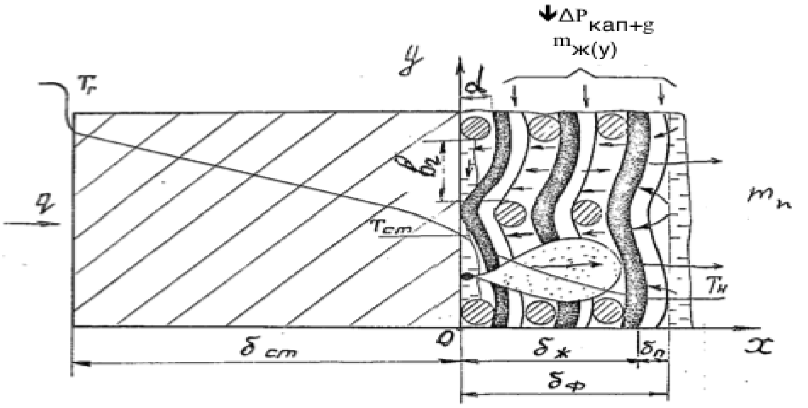

Fig.1 - Physical model of process for the heat and mass transfer in the actual porous structure of coatings that work with excessive liquid: straight lines – movement of liquid; wave lines – movement of steam: q – specific heat flow, W/m2; Tг,Tст, Tн – temperature of gas, wall (base) and saturation, 0C; δст, δж, δп, δф – thickness of wall, liquid, steam, wick, m; mж(y), mп – rate of liquid and steam, kg/f; ΔPкап+g – acting capillary and mass pressure, H/m2; d–size of grain, m; вг – width of the porous material cell, m

In the researched cooling system at minor heat flows the heat transfer is carried out due to the conductive heat exchange. The higher its value the larger is efficiency of heat conductivity of structure soaked in liquid, and heat conductivity of body. The liquid flows in a smooth manner, and there are no vapor bubbles on the liquid surface and related disturbance processes. Liquid is intensively evaporated from capillarity at minor excess of heat agent and the more excessive liquid grows the more evaporation begins from surface of falling films [7].

At some heat flow the lower parameter $\tilde{m}$=mж/mп, leads to disturbance of the smooth wave flow of the liquid film, and occurrence of separate vapor bubbles. The permanently acting generation centres are considered some active structure cells. The beginning of liquid boiling ΔTн.з. depends on many mode and constructive parameters and is determined by proper equation for this process ΔTн.з., which corresponds to heat flow qн.з. The reduced rate of cooling liquid mж(y) or either increase of heat flow q lead to a vigorous growth of steam generation centres $\bar{n}$.

Intensity of each centre operation at the initial mode of boiling is different, some areas of the heated surface are slightly touched by rising centres. In case of increased rate of the circulated heat agent mж(y) time of 'life' of some vapor bubbles gets extended, and part of active pores stop their operations, the extensive breaks between birth of bubbles take place, up to exclusion of such centre from the actively generating centre. The increased excess of liquid $\tilde{m}$leads the other active generation centres to slowliness and unviability.

Zone of the transition section is not so large towards the developed bubble boiling due to the high rate of growth of active steam generation centres $\bar{n}$. Further growth of heat load q leads to a stable operation of great number of active centres of bubble generation, their even distribution on all steam generating surface. However, on some critical condition a boiling crisis and surface overburning occur. Therefore, carrying out analogy in processes of deliberate destruction of fragile materials and boiling crisis would allow to make modelling and reveal a mechanism of such processes.

Some tests were performed in order to reveal a mechanism of destruction using methods of photoelasticity and holography [1].

Assessment of the stressed condition of models in similar time periods was performed with the help of photographic recording of isochromes and calculation of line sequence n at different points of the assessed directions.

Solution of the thermoelastic problem could help determine the limit state of medium for porous coating and metal steam generating surface [2,3,9].

Under heat destruction of poorly heat conductive low porous coatings and metal wall (base) it is required to detect the impact of specific heat flow value q and time of its impact τ for forming destructive stresses σ, grain size composition of husks (size of pulled particles), and for metal is a depth of permeability of temperature perturbation δ.

At rising value q during a very short time τ the dynamic effects become quite significant, compression stress σ reach big values, often they exceed the limit of material strength to compression a few times. Thus it is required to take into account these stresses in mechanism of the material heat destruction. It is required to determine which type of stress σi reach earlier its limit values.

Let’s review a plate 2h thick. The permanent specific heat flow q is being supplied to surface z=+h starting from time τ = 0. The lower surface z=-h and side edges of plate are heat insulated.

Heat conduction equation with boundary and initial conditions is written in form of:

$$d_{\text{ст}}\frac{\partial^2 T}{\partial z^2}=\frac{\partial T}{\partial \tau}, T = 0\ \tau < 0;$$

$$\lambda_{\text{ст}}\frac{\partial T}{\partial z}=q, \qquad z=+h\,;\lambda_{\text{ст}}\frac{\partial T}{\partial z}=0, z=-h\,,$$

Where $d_{\text{ст}}$,$\lambda_{\text{ст}}$–rates of temperature conductivity and heat conductivity of wall (base) [10].

Temperature distribution as per thickness depends on heat physical properties of material, value of heat flow and time of supply [2,3].

Having known the temperature distribution in plate it is possible to calculate heat stresses of compression and extension, arising at certain time τat a different depth from surface δi(h=zi) at value of heat flow q, since plate with variable temperature as per thickness is located in flat stressful condition [2].

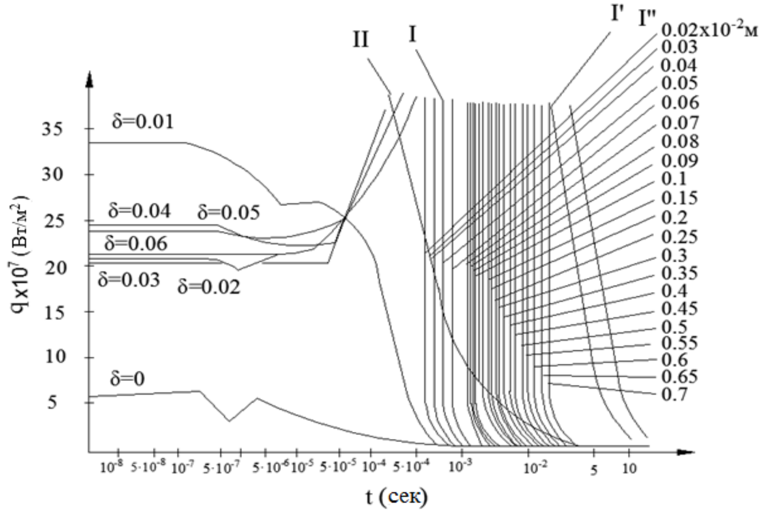

Fig.2 - Dependency of heat flows qi, that cause compession stress III of the quartz coating due to the action time τ for different thickness δ of pulled particles: I – tension stress sufficient for destruction; I1, I11 – copper and stainless steel, h = 0,1x10-3 m; II – surface burning-off. Curves II1, II11 for copper and steel almost match curve I in area τ = (0,01…0,1) s

Setting the limit values of compression stress σпр.сж. and tension σпр.раст for coating and metal, we obtain a functional dependency of heat flow q required for destruction,from time of supply τ and depth of permeabilityδ. Besides, equaling temperature on the plate surface to the melting temperature Тпл. of coating and metal,we find values of specific heat flows required for melting the coating layer for various time of its action q1,i.e. in each case we have functional dependencies of heat flow upon its rock and metal surface [3].

In case of quartz plate (coating) heat flows qi are calculated for extensive time interval - 10-8…103 s. The low limit of this interval (10-8 s.) is a time of relaxation. As shown at Fig.2, for time intervals 10-8…103 scorrelation for value q1 and q2 lose a physical sense. Since heat destruction is a macroprocess, we accept it for time 5x10-3…103 s.

On condition of coating destruction by compression only we obtain a series of curves, each of them correspond to a certain thickness of pulled particles that for teschenite is 0,25…0,3x10-2m, which is confirmed by trial obtained as a result of high-speed filming and photography by camcorder СКС-IM.

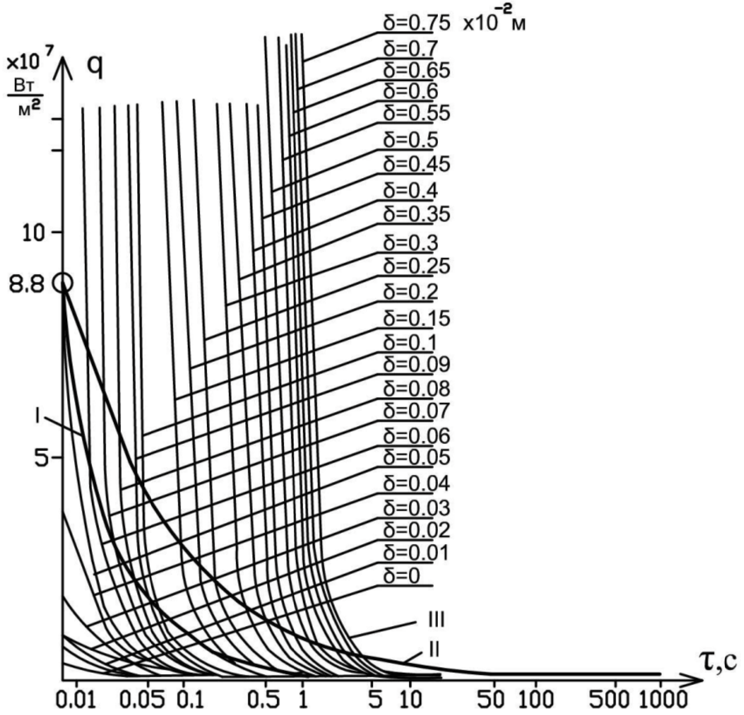

Fig.3 - Dependency of heat flows qi, that cause compession stress III of the quartz coating due to the action time τ for different thickness δ of pulled particles: I – tension stress sufficient for destruction; II – surface burning-off; curves II1 – copper, δ = 0,1x10-3 and II11 – stainless steel, δ = 0,1x10-3 m, almost match curve I in area (0,01…0,1) s

Sections of compression curves that determine pulling of particles with thicknessδ > 0,3x10-2 mfor big values q and small values τ, are screened by melting curve II, and in case of small heat flows and significant time intervals by tension curve I. The melting curve of the quartz coating is much higher than the teschenite coating that substantiates its stable fragiledestruction (see Fig.2,3).

Causes of destruction of the boiler turbine parts depend on prehistory of the fracture origin in the stress concentrator (relaxation zone) (see Fig.2). Countdown should be from time of the rise of bubble nucleation (time interval from 10-8 s to 10-3 s). Energy of spontaneous appearance of the bubble nucleation is considered a value close to the permanent value (invariant) as per the its growing time. It is allocated for maintaining nucleation with radius Rкр. and prevents its collapse(q could reach up to 108 W/m2). Within this time interval a thermodynamic equilibrium is set for further transition from microprocess (micro particles and clusters with radius (10-7÷10-8) m (nanoparticles) of separate (single) individual bubbles to processes described by behavior of great number of bubbles, i.e with integral characteristics ($\overline{q}, \overline{\alpha}$, $\overline{\Delta \mathrm{T}}$, $\overline{\Delta \mathrm{P}}$, $\overline{w}$), where $\overline{\alpha}$, $\overline{\Delta \mathrm{T}}$, $\overline{\Delta \mathrm{P}}$, $\overline{w}$ - average value of the heat transfer rate, temperature and hydro-gas-dynamic pressure and flow speed).

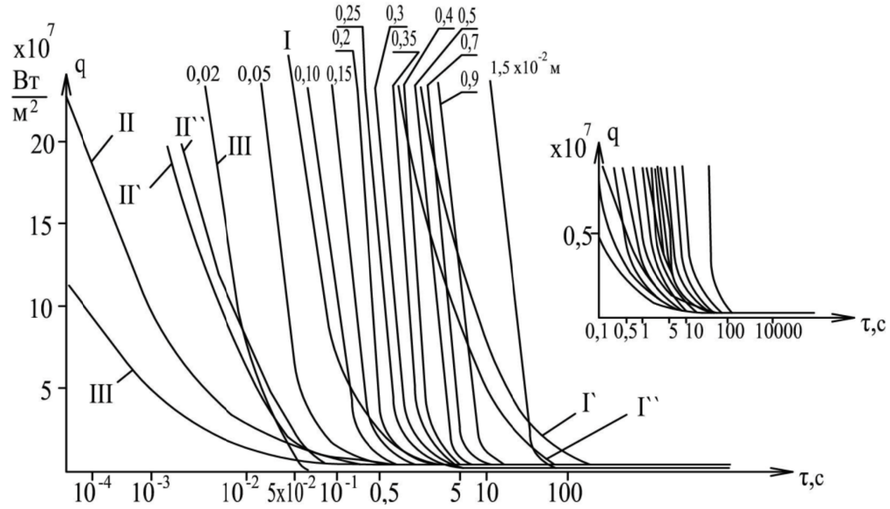

Fig.4 - Dependency of heat flows qi that cause compession stress III of the granite coating due to the action time τ for different thickness δ of pulled particles: I – tension stress sufficient for destruction (I`, I`` - copper and stainless steel, h = 0,1x10-3m); II – surface burning-off (II`,II`` - copper and stainless steel, h = 0,1x10-3m)

Availability of the stress concentrator where the active bubble phase is being born, significantly reduces relation σпр.сж./ σпр.раст and this value could be from (1÷2) including power steels. Also another available stress concentrators are to be considered, as well as cycle of loads during launch-stop operational modes of equipment that lead to fatigue fractures (stresses).

For example, for turbine steel a tensile strength is σв≈(400÷1000) MPa. Yield strength at operating temperature – (400÷550)0C is reduced to (200÷900) MPa at deformation 0,2%. Long-term tensile strength is reduced to (70÷260) MPa at deformation 10÷20%. Value of the temporary heat stress is reduced substantially to (40÷120) MPa. The main fatigue stress is only up to 0,45 from σв.

Therefore, there is a high probability that σпр.раст ≈ σпр.сж., and σпр.раст can reach up to 10 MPa and become of one order for the porous coatings.

Death processes as well as birth of bubbles also have explosive behavior (τ = 10-8÷10-6 s) that result in appearance of cumulative cases, which along with corrosive and electric processes destroy the stress concentrator (active generation centre of the erosion process that turns its size into size of critical fracture. In case of immediate vapor condensation in cavity, its volume immediately disappears and a powerful cumulative effect is formed (cavitation),whereas explosion waves are distributed deep inside parts, fractures are developed where oxygen is supplied.

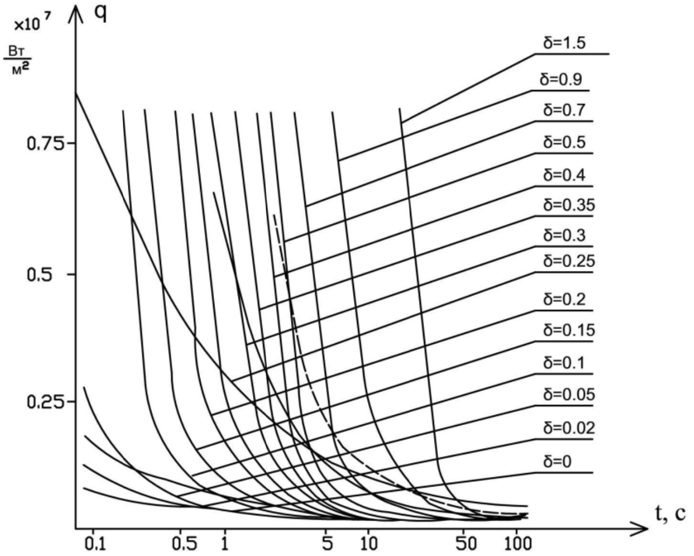

Fig.5 - Dependency qi = f (τ) shown on Fig.5 in range of q = (0,25…0,75)x107 W/m2

When bubble or drop is born, value α is up to 1x105 W/m2K at steam temperature (500÷565)0C value ΔT reaches to 5000C, and q acting in the centre of bubble (zone of 'dry' spot) up to 5x107 W/m2. Taking into account that the individual vapor bubble generates q 10 times more than its integral value [3,4], then total q is 5x108 W/m2, as shown at figures $q=q(\tau, \delta)$. The deeper permeability of heat wave δ (or pulled particle from porous coating), the more time is required for destruction of parts (as per q see Fig.2-6).

Interrelation of compression and tension stresses is introduced as diagrams of stresses inside plate (coating) for different time intervals from the beginning of the reviewed process. At small values τ of 10-2 s, there are only compression stresses. Staring from τ – 10-1 s, in some area Δ(h-zi) compression stress transfers to tension stress, whereas for different time intervals they are located at different depth from the plate surface.

Destruction of surface and metal under influence of compression forces at times occurs prior to tension forces. Intervals of heat flow within limits when destruction takes place are as follows: for quartz coatings – qmax = 7x107 W/m2, qmin = 8x104 W/m2, for granite coating – qmax = 1x107 W/m2, qmin = 21x104 W/m2, for metal (base) - qmax = 2x106 W/m2 (boiling crisis in porous system); qmin = 1x104 W/m2 (without cooling).

With increase of q in the heated layer, and thus with reduced heating time τ, the role of compression stress is growing. Despite high resistivity to compression, destruction from the compressive heat stresses happens immediately in more favorable conditions and in small volumes.

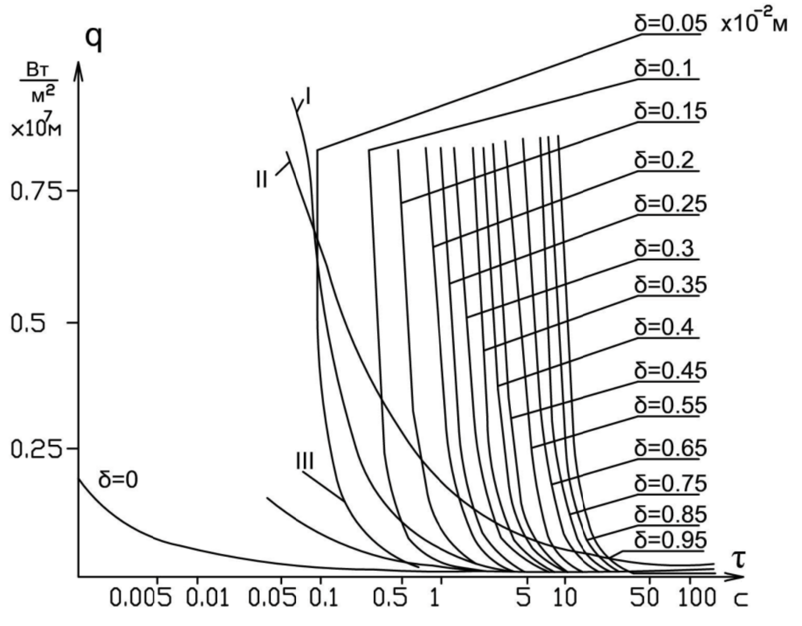

Fig.6 - Dependency of heat flows qi, that cause compression stress of teschenite coating depending on time of action τ for different thickness δi of pulled particles: I – tension stress sufficient for destruction; II – surface burning-off; III – destructive heat stresses of compression. Curves II` and II`` for copper and stainless steel almost match curve I in interval τ = (0,1…1) s; metal thickness δпл = h = 0,1x10-3 m

As shown at Fig. (2-6) there are curves for steam generating surfaces of heatwhen changing the boiling mode the film boiling is established and the temperature on surface up to value Tплis abruptly increased.

Calculation of specific energy Q of the quartz, granite and tescnenite coatings in terms of thickness δ of pulled particles demonstrate that curves have some distinctive minimums.

For quartz coating the minimum destruction power capacity equals Q≅0,5x103 Joule/m3, for τ = (0,1÷1) s, δi = (0,1÷0,25)x10-2m.

For granite coating: Q≅2,5x109 Joule/m3, for τ = (0,1÷5) s, δi = (0,1÷0,3)x10-2 m. For q≅0,1x107 W/m2 and δ = (0,2÷1,5)x10-2 m , Q = 2,5x109 Joule/m3

For teschenite coating: Q≅0,5x109 Joule/m3, for τ = (0,1÷5) s, δi = (0,1÷0,4)x10-2 m, whereas relation of the limit normal compression and tension stresses was changed from 20 to 30. The available micro fractures in the coating monolith reduce its strength for compression around fracture and that the compression strength could be two times bigger that the tension strength.

Curves Q=f(q) with their minimums with growth δi are reduced q, and for heat destruction of fragile coatings a smaller power capacity Q is required.

Therefore, there is a high risk of probable limit heat stresses at the launching and stopping of boiler-turbine equipment of power plants. These stresses occur first of all at locations of concrentrators, which are the birth centers of the active vapor phase or centers of forming condensate drops. Capillary porous structure could be both of natural origin (saline deposits, scales), and of artificial origin with good and poor heat conductive materials in the wide porosity limits from 3% to 90% (permeability). The structures may play a modelling role, and act as highly intensive and enhanced cooling system. For example, the teschenite porous coatings serve as the modelling material that have 5 times higher rate of line extension, and have 10 times smaller of heat supply rate and approximately identical temperature of melting in comparison with power steels. They are the most viscous with porosity up to 30% (see Fig.6)

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