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HYDRODYNAMICS OF VAPOR-LIQUID FLOWS IN CURVILINED CHANNELS OF SEPARATION DEVICES OF POWER PLANTS

The main factor that affects the efficiency of the separation process is the lack of contact with the surface of the shutter when moving in the flow of small droplets of wet steam. This process depends on the physical and chemical properties of the wet vapor, the dispersion of the droplets, the parameters of the movement of the two-phase medium, adhesion and edge angle, and the geometry of the channel.

Purpose. Determination of the limit modes of operation of separation shutter devices depending on the dispersion and quantity of droplet liquid, flow parameters and geometric characteristics of curved channels.

Methodology. The methodology is based on the analysis of the physical model of the movement of a two-phase medium under the action of mass and gravitational forces in a curved horizontal channel.

Findings. A mathematical model is presented for determining the trajectory of a liquid droplet in a curvilinear corrugation channel of the louvered package of a separator-superheater. The main conditions of film destruction and dynamic droplet breakup are defined. A method for expanding the range of stable operation of separation devices is proposed. Based on the obtained correlations, the design of the blind package is optimized.

Originality. Based on the analysis of the physical model of the movement of a two-phase medium in a curved horizontal channel, a mathematical model was developed and the limit of capture of the dispersed phase was determined.

Practical value. The presented results allow optimization of separation devices of boiler drums, horizontal steam generators and steam superheater separators of the II circuit of VVER-1000, fuel preparation systems of GTU.

Keywords: *two-phase medium, shutter separator, curvilinear movement of a drop, hydraulic mal distribution*

Introduction. Modern TPP and NPP power units are the complex technical systems with a large number of the interconnected main and auxiliary technological equipment which ensures the production of electrical and thermal energy according to the load schedule. Such systems are characterized by multi-parameters, the complex structural and functional connection of parameters, the presence of restrictions on the change of parameters and connections, functioning under the impact of random factors, the complexity of physicochemical processes. To analyse the process of separating the liquid drops from a two-phase medium, a typical design of a steam superheater separator (SSS) was chosen.

The last stages of a steam turbine operate in the area of wet steam whose parameters are related to the processes of forming, transforming and transferring the liquid in the area of a two-phase medium. Decreasing the moisture content allows reducing both mechanical losses from humidity and erosive wear of equipment elements.

During the process of long-term operation, a certain deviation of parameters of the operating medium after the steam superheater separator has been found, namely, decreasing the temperature of the vapor by $\Delta t = (3–5)$ °C. As a result of such processes, there occur deteriorating the operating conditions of the last stages of the low-pressure cylinder (LPC) of turbine and decreasing technical and economic characteristics of the turbine. Based on the above, it is possible to conclude about the relevance of the analysing and researching the processes taking place at the SSS.

The efficiency of the drying process in the steam turbine plant cycle. A lot of studies [1, 2] are dedicated to improving the design of the LPC, which consider the problems of optimizing the operation of low-pressure stages, choosing the places of steam extraction and its consumption, erosive damage of the blade apparatus. The last stage is an important element of the flow and exhaust part of the turbine, which determines its power. The requirements for operating the stage and exhaust are quite various and are related to economy, power, reliability, resource, and manufacturability. At the periphery of the blade device due to flow separation, especially in variable modes, there is not only decrease in efficiency, but also increase in disturbances acting on the blades vanes and, as a result, their reliability decreases [3].

The physical basis of forming the drop liquid at the flow part of the LPC is related to the thermodynamics of the cycle according to which the steam turbine unit of the two-circuit VVER-1000 reactor plant operates. Analyzing the efficiency and selecting the parameters at characteristic points of a steam turbine with intermediate moisture separation and steam overheating are performed in the articles [4, 5]. Applying the separation devices in the technological scheme for removing moisture between the high-pressure cylinder (HPC) and the LPC allows reaching the final humidity $(1 - x) = 14.3\,\%$. As is known, the intermediate overheating of the working fluid increases the thermal efficiency of the cycle by $\Delta h_{0i} = (3–6)\,\%$. For steam turbines of the NPP power units operating on wet water vapor, the amount of superheat is $\Delta t_{im\,ss} = t_0 - (15–40)\,^{\circ}C$. Such amount of intermediate overheating will not provide a significant increase in Δh_t, but it will significantly improve the operating conditions of the last stages of the LPC because the steam humidity will decrease to the value $(1 - x) = 10.6\,\%$. Thus, the intermediate superheating of water vapor (steam) with separation in saturated steam cycles is used to reduce steam humidity at the turbine exhaust.

For the VVER-1000 power unit the installation of two SSS-1000 type devices with two-stage steam superheating is provided. In principle, the designs of all SSSs are similar [5]: at the cylindrical body the louver-type separation blocks are sequentially located at the upper part, and two stages of the intermediate superheater are at the lower part.

The efficiency of the SSS separation devices. The separation device consists of the following main elements: the inlet chamber, the inlet collector, the louver blocks, the outlet collector, and the drainage system. The SSS efficiency mostly depends on processes of separating the drop liquid from wet vapor, which takes place at the separation units. Like any hydraulic system which consists of a certain number of elements (separation blocks) connected in parallel, it depends on the uniformity of distributing the operating fluid on each of them. It is possible to evaluate the perfection of the design of the inlet chamber by the value of the hydraulic maldistribution [6]

$$\rho_{0h\,in\,cham}=\frac{(\rho w)_{in\,cham}}{\left(\overline{\rho w}\right)_{in\,cham}},$$

where $(\rho w)_{in\,cham}$ and $\left(\overline{\rho w}\right)_{in\,cham}$ are actual and average mass flow rates of the operating medium at the inlet chamber, $(kg/m^2 \cdot s)$.

The amount of hydraulic maldistribution of the steam flow is slightly reduced due to the design of the inlet collector, which, in turn, also affected the uniformity of the distribution of saturated steam across the separation blocks. The amount of maldistribution can be determined as

$$\rho_{0h\,in\,col}=\frac{(\rho w)_{in\,col}}{\left(\overline{\rho w}\right)_{in\,col}},$$

where $(\rho w)_{in\,col}$ and $\left(\overline{\rho w}\right)_{in\,col}$ are actual and average mass flow rates of the operating medium at the inlet collector, $(kg/m^2 \cdot s)$.

It should be noted that the fraction of the captured drop liquid at the inlet collector mostly depends on the vapor flow rate. When the speed at the entrance to the louver blocks increased from 1 to 5 m/s, the part of the trapped liquid at the inlet collector decreased by 1.52 times. The total amount of hydraulic maldistribution of the inlet chamber and inlet collector was

$$\rho_{0h}=\rho_{0h\,in\,col}\cdot\rho_{0h\,in\,cham}=2.2\text{–}2.6.$$

In such conditions the efficiency of separation units is significantly deteriorated.

From the inlet collector, a wet vapor enters the louvered packages, in which the main part of the drop liquid is removed. The vapor flow passes through the louvered packages in the horizontal direction. The limited allowable velocities of moving the vapor liquid film are determined by two processes [7]:

- lack of contact with the louver surface when moving the small drops in the wet vapor flow;
- secondary removal of the liquid drops from the wave surface of the film.

Let us consider the movement of the two-phase medium at the channel of the louvered package. The kinematic, dynamic and energy characteristics of the two-phase medium can be determined both by the actual values at the selected space-time point and by the averaged values. Taking into consideration the configuration of the channel, it is possible to assume that the two-phase medium within one corrugation moves along a part of the circle which is connected to the geometrically similar part of another circle, but with the opposite twist of the flow. Under the action of centrifugal forces, the movement vector of the liquid drop is deviated from the movement vector of a vapor flow and, when the momentum of the drop's movement outweighs the action of mass forces and the time of staying within the half wave of the corrugation will be sufficient, it will contact the surface.

Given that the wet vapor is a two-phase medium, it is necessary to analyse the forces that affect the movement of drops.

Hydrodynamic features of moving the two-phase medium in a curvilinear channel. Primary removing the liquid drops. A small number of experimental works are devoted to studying the processes of hydrodynamics of two-phase flows in curved channels. The main purpose of the research [8] was to develop and to study a separation device which is structurally made as a system of combined impact tees, and which is capable to separate gas and liquid in a wide range of changes in mode parameters. Limiting modes for complete separating of the two-phase flows were determined. Based on the results of the research, the map of modes was built, by which it is difficult to assess the influence of dispersing the drop liquid on the boundary coordinates of the characteristic zones.

Designing the separation devices assumes the availability of reliable information on the local distribution of individual components of the two-phase flow at the cross-section of the device. The article [9] presents the results of studies on the distribution of the two-phase flow in foamed and annular flows by using the conductivity sensor which made it possible to determine the dynamic profile of the flow, the interphase velocity, sizes of drops and bubbles. According to the results of researching, it was found that the velocity profile is like the parabolic one, and the maximum part of gas at the axis can reach 95 %. Furthermore, it was determined that the statistical distribution of drops by size does not depend on the radial position. This conclusion needs additional confirmation.

Uneven distribution of the operating medium along the system of parallel channels usually leads to decreasing the equipment efficiency. Article [10] presents the results of experimental studying of the hydrodynamics of the flows of the two-phase medium at the system of parallel channels united by the collector in the projectile mode of the flow. In accordance with the research results, the model was developed considering the impact on the characteristics of the distribution of the input reduced velocities and forces affecting the flow. In fact, it is possible to determine the value of hydraulic maldistributions by the research result.

An important factor, which must be considered when modelling the processes in inertial separation devices, is the curvature of the channels through which the two-phase flow moves. The complexity of the physical phenomenon, especially as to two-phase flows, determines the limited number of experimental works in which the results of research are given. The articles [11, 12] give the results of studying the hydrodynamics of single-phase and two-phase flows during moving in branches of 180° rectangular cross-section. The correlation for determining the pressure loss in channels with a high curvature coefficient was obtained.

It should be pointed out that according to the results from [13], the impact of orientation on flow regimes disappears for horizontal microchannels.

The solution of the problem of moving the sphere in a real viscous liquid was obtained for the case of slow flow around the liquid at Re ≤ 1 [14]. It was considered that inertial forces are not significant compared to viscous forces, and non-linear terms of the Navier-Stokes equation, concerning the speed, can be ignored.

When a viscous liquid flows around a drop, the direction of the resultant of pressure forces coincides with the velocity vector of the liquid. The resultant of normal stresses is determined by the following expression

$$F_i=F_p=\int_n^{\pi}(p_{r_0}\cdot\cos\theta)\cdot 2\cdot\pi\cdot r_0^2\cdot\sin\theta\,d\theta=2\cdot\pi\cdot r_0\cdot\mu\cdot u_\infty.$$

In the case of axisymmetric motion on the sphere surface, the tangential stress $\tau_{r\theta}$ in spherical coordinates is determined as follows

$$(\tau_{r\theta})_{r=r_0}=\left(\frac{\partial u_0}{\partial r}\right)_{r=r_0}=-\frac{3\cdot\mu\cdot u_\infty}{2\cdot r_0}\sin\theta.$$

The resultant of friction forces can be found by integrating over the surface of a drop

$$F_\tau=\int_n^{\pi}(-\tau_{r\theta}\cdot\sin\theta)\cdot 2\cdot\pi\cdot r_0^2\cdot\sin\theta\,d\theta=4\cdot\pi\cdot r_0\cdot\mu\cdot u_\infty.$$

The total resistance force for a spherical drop is determined as

$$F_c=6\cdot\pi\ r_0\cdot\mu\cdot u_\infty. \tag{1}$$

The Stokes formula (1) allows us to calculate the speed of free fall at a stationary mode if the force of gravity is balanced by the force of resistance

$$F_g=\frac{4}{3}\cdot\pi\cdot r_0^3\cdot(\rho'-\rho'').$$

For convenience, we use the resistance coefficient C_d in dimensionless form as a function of the Re number

$$C_d=\frac{6\cdot\pi\cdot r_0\cdot\mu\cdot u_\infty}{\frac{1}{2}\cdot\rho'\cdot u_\infty^2\cdot\pi\cdot r_0^2}=\frac{24}{\mathrm{Re}}. \tag{2}$$

The solutions obtained are valid only for spherical particles of sufficiently small sizes (less than 0.1 mm in diameter). The analysis of the Stokes solution given in [14] made it possible to increase the accuracy of calculations due to inertial terms of the equation of motion. The dependence for determining the resistance coefficient was obtained as a result

$$C_d = \frac{24}{\mathrm{Re}}\cdot\left(1+\frac{3}{16}\cdot\mathrm{Re}\right). \tag{3}$$

It is important that dependence (3) is much more accurate than dependence (2); furthermore, it can be applied for $\mathrm{Re} \le 5$.

Thus, taking into consideration the movement of a single liquid drop in a curvilinear channel in the flow of wet vapor, it is possible to determine the conditions of its probable contact with the surface of the corrugation. Let us assume that the drop moves along the channel axis at the entrance to the curvilinear part of the channel. The average drop residence time at the corrugated channel at $0 \le \varphi \le \pi/2$ within one wave is

$$\tau = \frac{s_{odr}}{w_0},$$

where s_{odr} is the way covered by a drop in the case of its movement along the axis of the channel, m; w_0 is the average speed of the movement of the vapor-liquid mixture at the channel, m/s.

Before contacting the surface of the corrugation, a drop must overcome a distance at the initial cross-section, which is perpendicular to the axis of the flow direction, half the distance between the walls of the corrugations (Fig. 1). The actual way that a drop will overcome while constant deceleration movement takes place with the initial speed w_0 in time τ, is determined by

$$s_{dr} = w_0\cdot\tau - \frac{\dot{a}\cdot\tau^2}{2}.$$

The kinetic energy of a drop is spent on the work that needs to be done to overcome the resistance when moving in the direction perpendicular to the movement the flow of wet vapor. So, the acceleration when a drop slows down is defined as

$$a = 2\cdot\frac{w_0}{\tau^2}\cdot\left(\tau-\frac{m}{2\cdot F_c}\right),$$

where m is mass of a drop, kg.

Accordingly, the acceleration with which the moving drop is slowed down is determined as

$$F_{\tilde{n}} = \frac{\pi}{2}\cdot\rho''^{\cdot w_0^2\cdot r_0^2}\cdot C_d. \tag{4}$$

The resistance coefficient C_d in equation (4) is determined by formula (3).

Researching the process of separating the drop liquid from wet vapor was performed based on the given model. Generalising the research results was carried out by using the similarity theory. The equation form must consider both the thermophysical properties of the liquid and vapor, as well as the mode parameters and geometric characteristics of the system. In the general case, the similarity equation is as follows

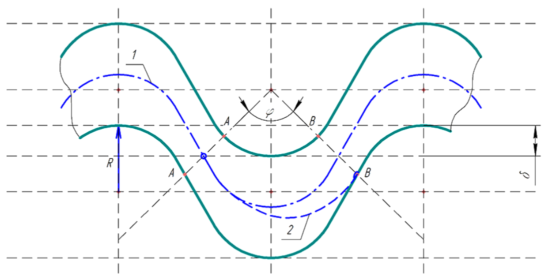

Fig. 1. Scheme of a drop movement between the walls of the corrugations

$$\mathrm{Re} = \mathrm{Re}\left(Bo, We, \frac{\mu'}{\mu''}\right). \tag{5}$$

Only surface tension forces try to give the shape of a sphere to a drop among all forces that significantly affect the hydrodynamics of two-phase systems. Therefore, in the general case, the inequalities must be followed

$$Bo = \frac{4\cdot g\cdot(\rho'-\rho'')\cdot r_0^2}{\sigma} \le 1;$$
$$We = \frac{2\cdot\rho'\cdot w^2\cdot r_0}{\sigma} \le 1; \tag{6}$$
$$\frac{\mu'}{\mu''} \le 1.$$

We can consider the inequalities (6) as conditions for saving the sphericity of a drop. Otherwise, we do not recommend using the equations (3 and 4). The first inequality is typical for hydrostatics problems, and the last one – for drops that move [14].

Fig. 2 presents the results of studying the hydrodynamics of the drop movement within the wet vapor at $P = 7.64$ MPa and t_s = 170 °C. The mode, in which the initial speed of a drop was determined at the drop size changes under the contact with the surface of the corrugation, was chosen as the determining one. Considering equation (5), we obtained the following correlation

$$\mathrm{Re}_0 = 6.4764\cdot Bo^{0.25}\cdot We^{0.5}\left(\frac{\mu'}{\mu''}\right)^{0.15}. \tag{7}$$

The equation (7) is valid in the range of change

$$6.22785\cdot10^{-7} \le Bo \le 9.7989\cdot10^{-5};$$
$$1.025\cdot10^{-9} \le We \le 4.48\cdot10^{-4}.$$

The analysis of the results obtained determines the conditions of contact of liquid drops with the surface of the corrugations of the louvered separator when the condition of a drop sphericity is performed in the entire range of changes in the mode parameters of the wet vapor and the geometric characteristics of the system.

We would like to point out, considering the process of the drop movement under the influence of gravity is no less important than simulating the movement of a liquid drop at the horizontal plane of the curvilinear channel of the corrugation of the louvered package. The monography [14] considers in sufficient detail the features of hydrodynamics of moving a single drop or bubble in a stationary medium, having different densities. The speed of falling liquid drops in a gas can be calculated with sufficient accuracy considering the assumption as to the constancy of the resistance coefficient.

$$w_\infty = \sqrt{\frac{8\cdot r_0\cdot g\cdot\Delta\rho}{3\cdot C_d\cdot\rho''}},$$

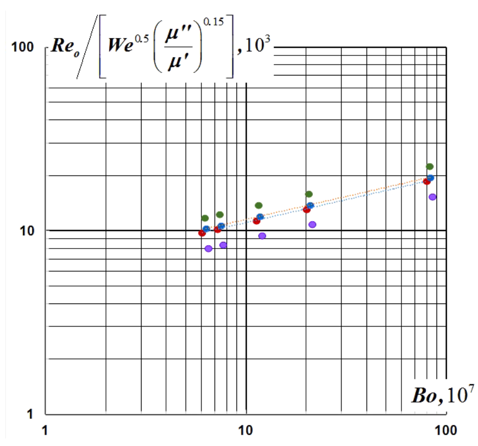

Fig. 2. Hydrodynamics of the drop movement in wet vapor

where $\Delta\rho = \rho' - \rho''$.

The common solution of the equations of the given model will allow determining the trajectory of the drop liquid movement at the curvilinear channel of the corrugation of the louvered package of the steam superheater separator.

The limit mode of breaking the film stability. Secondary removal of liquid drops. The liquid, caught in the separation process, forms a liquid film on the surface of the channel. The film parameters: its thickness and a stream mode depend on the amount of a trapped liquid, a surface tension and boundary wetting angle, as well as on the balance of forces. The description of the hydrodynamics of moving the vapor flow and liquid film consists of differential equations of moving and continuity for the liquid and vapor phases. The tangential and normal components of the stresses from the vapor on the surface of the liquid film can be expressed by the dependence due to deviating the surface of phase separation from the area $\delta = \delta_0$, which corresponds to the surface of the liquid film undisturbed by the waves.

The mode, under which the stability of the stream of the two-phase flow is disturbed under a defined thickness of a liquid film and under increasing the speed of the vapor or gas flow, is the mode characterized by the beginning of drop removal. During formatting the drops by the breaking off a liquid from the ridges of the film surface which is formed on the walls of the louver because of depositing under the action of inertial forces, an important problem is the certainty of the results of a physical experiment, namely, determining the mode of violation of the stability of the film stream. Two methods are used to identify such modes in practice.

When determining the limit modes, R. Nigmatulin and V. Nikolaev [14] measured the temperature, pressure, and flow rates of the components of the steam-water or air-water mixture at the entrance to the measuring section

$$D = D_v + D_{dr},$$

where D is the total mass flow rate of the steam-water mixture, kg/s; D_v is mass flow of wet vapor, kg/s; D_{dr} is mass flow rate of the drop liquid, kg/s.

The liquid flow rate in the film D_{dr} and changing the pressure at in separate sections ΔP were determined along the measuring section by the suction method. The tangential stress on the pipe wall τ_{w1} and on the surface of the film τ_{f1} was determined by changing the pressure at the measuring section. At the specified flow rate at the entrance to the experimental area, a salt solution was supplied to the wall area, and D_{dr} was determined by the salt concentration in the liquid samples that were suctioned.

The studies by S. Kutateladze, Yu. Sorokin and M. Bezrodny [14] accepted the vapor flow speed with the smallest value of the Reynolds number Re at the correlation curve of the hydraulic resistance coefficient, as the critical speed which determined the beginning of the choking process.

Unlike the heat and mass exchange devices, where the vapor-liquid flow can move vertically counter-currently or in one direction, at the channels of shutter separators the generated liquid film is affected by the forces of gravity, friction and tangential stress which is caused by moving the flow of wet vapor. As a result, the liquid moves in the film along the complex trajectory: from top to bottom and from the entrance to the shutter channel to its exit. A significant flow of the film enters the drainage collector and is evacuated from the SSS, but a part of it is collected at the outlet edge of the channel plate as a spindle-shaped stream.

If the vapor-liquid system is in the equilibration conditions, then the equations of hydrostatics are performed in each of the interacting phases

$$p = p_0 + gh.$$

And, the Laplace formula will be solved for each point of the section surface, which is determined by the radius vector r

$$p_1 - p_2 = 2H.$$

By these equations, it is possible to obtain the basic equation of the hydrostatic equilibration of the vapor-liquid system

$$2\sigma H(r) = (\rho' - \rho'') \cdot F(r) + C, \quad (8)$$

where ρ' and ρ'' are the density of liquid and vapor; $F(r)$ is the potential of mass forces.

Considering the fact that the curvature H is a differential operator, then formula (8) is a differential equation whose integral determines the form of the phase separation. The equation (8) takes the following form in the system that is under tranquillity conditions $F(r) = g \cdot z$

$$2\sigma H(r) = \pm(\rho' - \rho'') \cdot g \cdot z + C_1.$$

The constant in the equilibration equation determines the pressure drop at the "zero" position of the level

$$C_1 = 2\sigma H(0) = \frac{2\sigma}{R_0}.$$

The numerical solution of general problems of hydrostatics [14] for capillaries of a small radius $\tilde{r}_k = \frac{r_k}{b} \le 0.5,$ (where b is a capillary constant) made it possible to obtain the equation of the pre-detaching equivalent drop radius

$$R_* = \sqrt[3]{\frac{3 \cdot r_k \cdot \sigma}{2 \cdot g \cdot (\rho' - \rho'')}}.$$

The monography [14] proposes to use the Fritz correlation to determine the pre-breaking off drop diameter for "capillary wall – liquid" systems with boundary wetting angles $\theta_* = 60–140°$

$$D_* = 2 \cdot R_* = 0.0207 \cdot \theta_* \sqrt[3]{\frac{\sigma}{g \cdot (\rho' - \rho'')}}. \quad (9)$$

The process of dynamic removal of drops is characterized by interacting the pulsations, surface tension forces, viscosity forces and inertial forces. The physical experiment made it possible to determine the fact that removing the drops occurred only from the crests of large wave sizes. At relatively low velocities of the vapor flow, the waves are deformed and destroyed followed by the removal of liquid drops from the crests.

The conditions for destructing the film or dynamically plucking the drops are determined by processes associated with the Kelvin–Helmholtz instability. It is possible to conclude that analytically similar problems cannot be solved, and the results of experimental work do not always provide full answers for specific problems. In addition to affection of the capillary, dynamic and viscous forces on the liquid, the gravity force significantly affects the conditions for the beginning of the dynamic removal of drops from the film. In general, the criterion Weber number, which determines the beginning of dynamic plucking of the drops, functionally depends on the process parameters as follows

$$We_{13^*} = f\left(Lp_l, Lp_v, \frac{\rho_v}{\rho_l}, \frac{g \cdot \rho_l \cdot \delta^2}{\sigma}, \mathrm{Re}_\delta \right).$$

The monography [14] performed the important analysis of the research by many authors, along with bringing their results to the conditions of compliance. Fig. 3 presents the experimental values of dimensionless parameters at the very beginning of dynamic removal. Corresponding correlations were obtained for the laminar film ($\mathrm{Re}_\delta \le 290$). Taking into account the humidity of the steam entering the SSS, the amount, geometric dimensions of the louvered packages and the flow rate parameters, the liquid film will be formed on the surface, which will move in the laminar-wave mode.

We would like to note that some questions arise when analysing the research results from Fig. 3. Namely, why the upper limit of laminar–wave movement of the film is limited by the film Reynolds number $\mathrm{Re}_\delta \le 290$, and not by $\mathrm{Re}_\delta \le 400$. as generally accepted in the classical literature. In addition, there is no argument as to the self-similarity of the process of the beginning of the dynamic removal of drops from the film Reynolds number Re_{δ}. The monography [14] suggests using the following correlation in this area

$$We_{13^*} = 8.5 \cdot \mu_l \cdot \left(\frac{g}{\rho_l \cdot \sigma^3} \right)^{0.25}. \quad (10)$$

Correlation (10) meets the mode of changing film Reynolds number in the range in accordance with the results of the correlation research. A significant deviation of the research results from correlation (11) is observed before and after this range. To increase the accuracy of the calculations, the authors propose to determine the beginning of a drop removal in the laminar–wave mode of the film flow at $Re_{\delta} \le 400$ in accordance with the following correlation

$$We_{13^*} = 3.3205 \cdot Re_{\delta}^{0.2022} \cdot \mu_l \cdot \left(\frac{g}{\rho_l \cdot \sigma^3} \right)^{0.25}. \quad (11)$$

The size of drops upon breaking off is recommended to be approximately determined by the Fritz correlation (9), where the thickness of a plate of the louvered package is used as the determinative size instead of the capillary diameter. The overall dispersion of the drop diameter varies in a wide range. Drops of a much smaller size make up a significant part in addition to the drops formed because of secondary removal. Such drops do not have the opportunity to contact the surface due to their geometric dimensions, the speed of the vapor movement and the geometric characteristics of the louver corrugations, and they fly through the volume of the separation package. The size of such drops is determined by correlation (7).

The research was performed using a capillary-porous structure on the surface of the channel wall to determine possible methods, the purpose of which is to expand the range of stable operation of separation packages. It is generally known that using the capillary-porous structures contributes to intensifying the processes of heat and mass exchange during the processes of boiling and evaporation. In addition, the presence of such structure on the contact surface can fully change the hydrodynamics of the film flow. The geometric characteristics of the capillary-porous structure, the channel dimensions, the

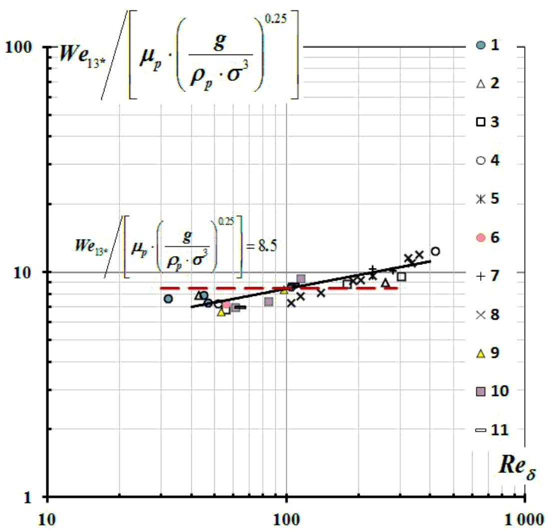

Fig. 3. Results of experimental data processing at the beginning of dynamic removal:

1 – p = 0.28 MPa, D = 9.5 mm, air-water, lifting motion; 2–5 – p = 0.49–4.41 MPa, D = 25 mm, steam-water, downward motion; 6 – p = 2.9 MPa, D = 13 mm, steam-water, lifting motion; 7 – p = = 0.1 MPa, D = 26 mm, air-water, horizontal flow; 8–11 – p = = 0.1–0.45 MPa, D = 13 and 31.5 mm, air-water, upward flow

flow parameters of the two-phase medium and its thermophysical properties significantly affect the process.

During the research, a hydrodynamic feature of the film stream on surfaces with a mesh capillary-porous coating was founded, depending on the density of spraying. The modes were divided into two ranges as to the film thickness: the film, when the spray density changed, did not go beyond the upper limit of the layer of mesh capillary-porous coating; and the layer of mesh capillary-porous coating was flooded by the liquid. The method from [14] was used to determine the limit modes of the beginning of drop removal.

The following type of function was chosen to generalize the experimental research as to determining the limit of violation of the hydrodynamics of the movement associated with the beginning of the removal of liquid drops from the film

$$K = f(Fr_{\delta}, We_{dr}),$$

where $K = \frac{w''_{dr} \cdot (\rho'')^{0.5}}{(g^2 \cdot \sigma \cdot (\rho' - \rho''))^{0.25}}$ is the Kutateladze number; $Fr_{\delta} = \frac{Q_m \cdot (\rho' - \rho'')^{3/4}}{g^{0.5} \cdot \sigma^{3/4}}$ is the Froude number; $We_{dr} = \frac{\sigma}{(\rho' - \rho'') \cdot D^2}$ is the Weber number.

The results of experimental research of violation of the hydrodynamics of the movement of the two-phase flow in a channel with smooth and mesh capillary-porous structure on the wall are presented in Fig. 4.

The obtained results of the critical parameters of the two-phase flow in channels with a flooded mesh capillary-porous structure agree reasonably well with the results of determining for channels with smooth walls [14] and have higher values under condition, if the film does not go beyond the limits of the upper layer of the coating. The ratio of the balance of mass flow rate of the liquid film and the gas flow, which determines the lower choking process limit which depends on the density of spraying, the geometric characteristics of the channel, the size of the mesh capillary-porous coating and the physical properties of the liquid and gas, is generalized by correlations with an error of ±7 %:

- in the range of spray densities, if the film does not go beyond the limits of the mesh capillary-porous coating

$$K = 0.106 \cdot Fr_{\delta}^{0.6821} \cdot We_{dr}^{1.25};$$

- in the range of spray densities, if the mesh capillary-porous coating is in a flooded state

$$K = 0.0331 \cdot Fr_{\delta}^{0.5517} \cdot We_{dr}^{1.25}.$$

The obtained correlations completes the mathematical description of the hydrodynamics of moving the two-phase medium at the curvilinear channels of the louvered packages of the separation blocks of the power and chemical equipment.

Conclusions. Deteriorating operating conditions of the last stages of the LPP and reducing technical and economic characteristics of the turbine are largely due to the processes which take place at the SSS. The SSS efficiency largely depends on the processes of breaking off the drop liquid from wet vapor, which takes place at separation blocks and depends on many factors. The most significant factors are the irregularity of distributing the wet steam on the individual louvered packages, which is estimated by the amount of hydraulic maldistribution of the inlet chamber and inlet collector, and by the process of catching the drops at corrugated channels.

The main factor that affects the separation process is the lack of contact with the surface of the louver if the small drops move in the flow of wet vapor. This process largely depends on the physical-chemical properties of the wet steam, dispersion and parameters of the two-phase medium movement, wettability, and channel geometry.

The physical features of the two-phase medium movement in curved channels were analysed. Modelling the process of separat-

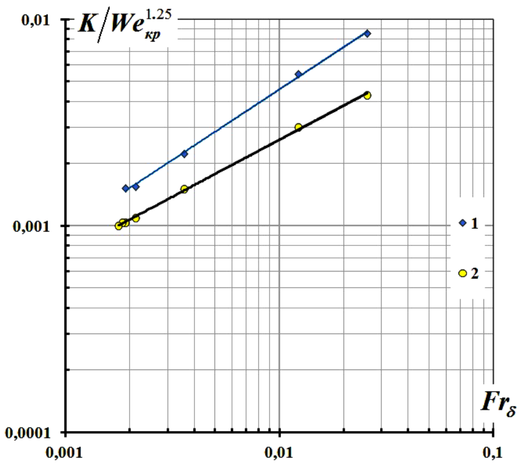

Fig. 4. Stability of gravitational film flow during counter-current movement of liquid and gas:
1 – capillary-porous structure; 2 – flooded pipe

ing the drop liquid from wet vapor was performed, the research results were summarised, and the correlation was obtained. The process of moving a drop under the force of gravity was considered. The joint solution of the equations of the above model will allow determining the trajectory of moving a liquid drop at the curvilinear channel of the corrugation of the louver package of the steam superheater separator and to optimize its design.

The main conditions for the destructing the film and the dynamically breaking off the drops, which are related to the Kelvin–Helmholtz instability, were determined. Not only the capillary, dynamic and viscosity forces, but also the gravity force acts on the liquid, which significantly affects the conditions of the beginning of dynamic removing the drops from the film.

A method to expand the range of stable operation of separation packages by using a capillary-porous structure on the surface of the channel wall was proposed.

The obtained results of the critical parameters of the two-phase flow at the channels with a flooded mesh capillary-porous structure agree reasonably well with the results of determining for the channels with smooth walls [14]. The critical parameters have higher values at the channels with a mesh capillary–porous structure, if the film did not go beyond the limits of the upper layer of the coating.

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Гідродинаміка пароріднинних потоків у криволінійних каналах сепараційних пристроїв енергетичних установок

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Основним чинником, що впливає на ефективність процесу сепарації є відсутність контакту з поверхнею жалюзі при русі в потоці вологої пари крапель малого розміру. Цей процес залежить від фізико-хімічних властивостей вологої пари, дисперсності крапель, параметрів руху двофазного середовища, адгезії та крайового кута, геометрії каналу.

Мета. Визначення граничних режимів роботи сепараційних жалюзійних пристроїв у залежності від дисперсності й кількості крапельної рідини, параметрів потоку та геометричних характеристик криволінійних каналів.

Методика. Методологія заснована на аналізі фізичної моделі руху двофазного середовища під дією масових і гравітаційних сил у криволінійному горизонтальному каналі.

Результати. Представлена математична модель для визначення траєкторії руху краплі рідини у криволінійному каналі гофри жалюзійного пакету сепаратора-пароперегрівача. Визначені основні умови руйнування плівки й динамічного зриву крапель. Запропоновано метод розширення діапазону стабільної роботи сепараційних пристроїв. На підставі отриманих кореляцій виконана оптимізація конструкції жалюзійного пакету.

Наукова новизна. На основі аналізу фізичної моделі руху двофазного середовища у криволінійному горизонтальному каналі розроблена математична модель і визначена границя уловлення дисперсної фази.

Практична значимість. Представлені результати дозволяють виконати оптимізацію сепараційних пристроїв барабанів котлів, горизонтальних парогенераторів і сепараторів-пароперегрівачів II контуру ВВЕР-1000, систем паливоприготування ГТУ.

Ключові слова: *двофазне середовище, жалюзійний сепаратор, криволінійний рух краплі, гідравлічна розвірка*

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