Journal of Engineering Physics and Thermophysics, Vol. 73, No. 3, 2000

# MATHEMATICAL MODELING OF MASS TRANSFER AND REMOVAL OF DROPLET-FILM MOISTURE IN INERTIA-GRAVITY SEPARATORS OF MOIST VAPOR

**A. V. Lagerev**

UDC 532.529

*Hydro- and gasdynamic models of the kinematics of droplet-film moisture in vertical separators with tangential supply of moist vapor are developed. The efficiency of equipping the separators with additional moisture-removing slots is shown, and a technique of their optimum arrangement is suggested, proceeding from the possibility of maximum suppression of secondary mass-transfer processes.*

**Introduction.** Vertical separators with tangential supply of moist vapor, outflow of the gas phase in the upper part of the body, and removal of the caught liquid droplet phase through the lower part are, structurally, the simplest separating devices. They realize the principles of inertia separation of particles of the denser phase (droplets) from a twisted gas flow and gravity motion of a film of precipitated moisture along the separator wall. Various structural types of these separators are used in power engineering as intradrum and discharge cyclones of vapor boilers of thermal electric power plants, systems for cleaning geothermal vapor of geothermal electric power plants, vapor generators of nuclear power plants, etc. [1, 2]. Intense processes of mass exchange between droplet and film (pellicular) moisture, which are caused by stalling phenomena on the wave interface and the three-dimensional structure of the velocity field of the gas phase including the vortex zone and the zone of reciprocal vapor flow in the central part of the separator, are typical of their operation. As a result, with a high precipitability of separators which is characterized by a coefficient of primary precipitation of droplet moisture of 0.98-0.99 and higher [3], the separating ability turns out to be noticeably lower. This indicates insufficiently effective operation of the used system of gravity removal of film moisture and the possibility of its improvement on the basis of purposeful action on the intensity of secondary mass exchange. The organization of an optimum system of removing moisture must rest on the analysis of the kinematics of droplet-film moisture based on mathematical modeling of the processes of precipitation, formation, motion, and removal of the film of precipitated moisture.

**Gasdynamic Model of the Kinematics and Precipitation of Droplet Moisture.** This model deals with a stationary motion of a two-phase heat-transfer agent at the inlet to and inside the separator and primary inertia precipitation of polydisperse droplets of moisture onto the separator wall. The approach resting on spatial and fractional discretization of the distribution of droplet moisture in the volume of the heat-transfer agent is used as the basis for the model. The model makes it possible to estimate flow rate and kinematic parameters of the precipitated moisture and their distribution over the wall of the separator.

According to the spatial discretization, the droplet flow is divided into $N$ parts depending on the place of passing through the outlet section of the input pipe. For this purpose, the outlet section is regularly divided into $N = n_1 n_2$ subregions $S_{ij}$ (rectangular or in the form of annular segments) with an area $f_{ij}$, which are characterized by a center point $M_{ij}$ and four angular points $M_{ij}^{(1)}$, ..., $M_{ij}^{(4)}$ (Fig. 1). As the discreteness of flow separation decreases, the calculated values of the flow rate parameters of precipitated moisture tend to steady-state values. As preliminary calculations showed, when $n_1 \ge 3$ and $n_2 \ge 3$, the change in the coefficient of primary precipitation of moisture associated with various discreteness of the representation of the process appears to be virtually negligible. The size distribution of the mass of droplet moisture in the $ij$th part of the flow can be considered to be normal, proceeding from a normal law of moisture distribution throughout the volume of the heat-transfer agent [4] and the property of superposition of this type of statistical distribution. In this case,

Bryansk State Technical University, Bryansk, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 73, No. 3, pp. 501-509, May–June, 2000. Original article submitted December 3, 1998.

 1062-0125/00/7303-0486$25.00 

the modal radius of the droplets is related to the maximum one $r_{\max,ij}$, which is calculated by the critical Weber number with account for the processes of coagulation and crushing, by the relation $r_{ij} = 0.5 r_{\max,ij}$.

In accordance with the fractional discretization, the droplet flow of each $ij$th part, which has a polydisperse structure with the range of droplet radii $r_d \in (0; r_{\max,ij}]$, is divided into $K_f$ fractions by uniform division of the entire range of sizes into intervals $\Delta r_{ij} = r_{\max,ij}/K_f$. The set of polydisperse droplets $r_d \in ((\nu - 1)\Delta r_{ij}; \nu\Delta r_{ij}]$ composing the $\nu$th fraction is replaced by $n_{ij\nu}$ monodisperse droplets of a mean-fraction radius $r_{ij\nu} = (\nu - 0.5)\Delta r_{ij}$, proceeding from the condition of invariability of the mass flow rate of fraction moisture

$$g'_{ij\nu} = \rho y_{\text{inp}}(M_{ij})\, C_{\text{inp}}(M_{ij}) f_{ij} \int\limits_{r_{ij\nu}-\Delta r_{ij}/2}^{r_{ij\nu}+\Delta r_{ij}/2} \left\{ \exp\left[-\pi\,(2r_d/r_{\max,ij} - 1)^2\right] dr_d \right\} \times$$

$$\times \left( \int\limits_0^{r_{\max,ij}} \exp\left[-\pi\,(2r_d/r_{\max,ij} - 1)^2\right] dr_d \right)^{-1} = 4\pi\rho' n_{ij\nu}\, r_{ij\nu}^3/3\,.$$

The kinematics and primary precipitation of the moisture supplied to the separator are analyzed on the basis of individual calculations of the kinematics and precipitation of all $NK_f$ groups of droplets formed as a result of spatial and fractional discretization of the flow. The motion of a droplet of mean-fraction radius $r_{ij\nu}$ which has passed through the center point $M_{ij}$ of the outlet section of the input pipe gives insight into the motion of the droplets of the $ij\nu$th group. At the parameters of vapor typical of power plants, the droplets move under the predominant action of inertia and gravity forces and aerodynamic resistance on the source side of the gas phase [4], where the velocity distribution along the radius of the separator approaches the law of rotation of a solid body [2]. Therefore, calculation of the trajectory and parameters of the kinematics of a spherical droplet is reduced to integration of the differential equation of motion (in projections on the axis related to the shell of the cylindrical coordinate system $r\varphi z$)

$$(dC'_r)_{ij\nu}/d\tau = (C'_\varphi)^2_{ij\nu}/r - 0.375\,(\rho/\rho')\, C_a \nu r^{-1}_{ij\nu}\, (C'_r)_{ij\nu}\,;$$

$$(dC'_z)_{ij\nu}/d\tau = 0.375\,(\rho/\rho')\, C_a \nu r^{-1}_{ij\nu}\, [G/\pi\rho R_s^2 - (C'_z)_{ij\nu}] - g\,;$$

$$(dC'_\varphi)_{ij\nu}/d\tau = -\,(C'_r)_{ij\nu}\,(C'_\varphi)_{ij\nu} +$$

$$+\, 0.375\,(\rho/\rho')C_a \nu r^{-1}_{ij} \left[ rG/\rho t_p x_p \left( R_s - \frac{x_p}{2} \right) - (C'_\varphi)_{ij\nu} \right] \tag{1}$$

with the initial conditions at the point $M_{ij}(x_{ij}, t_{ij})$

$$(C'_r)_{ij\nu} = (C'_z)_{ij\nu} = 0\,; \quad (C'_\varphi)_{ij\nu} = \Theta_{ij\nu}\, C_{\text{inp}}(M_{ij})\,.$$

In constructing the curve of the distribution of specific (per unit area) mass flow rate of primarily precipitated moisture over the separator wall, use is made of spatial discretization of the shell surface (Fig. 1), according to which the continuous curve $q'(\varphi, z)$ is approximated by two-dimensional spline-functions with respect to the set of its values $q'_{nm}$ at uniformly located reference points $L_{nm}(n \in [1; N];\ m \in [1; M])$. For each $ij\nu$th group of droplets which passed through the angular points $M_{ij}^{(1)}, \ldots, M_{ij}^{(4)}$ of the subregion $S_{ij}$, the position of the corresponding angular points $N_{ij}^{(1)}, \ldots, N_{ij}^{(4)}$ of the zone of precipitation $T_{ij\nu}$ of droplets of size $r_{ij\nu}$ on the shell surface is determined in turn by integration of the equation of motion. Provided that on the $\mu$th step of integration the radial coordinate of the moving droplet becomes $r_\mu \geq R_s$, the coordinates of these points in the surface system $\varphi 0 z$ are

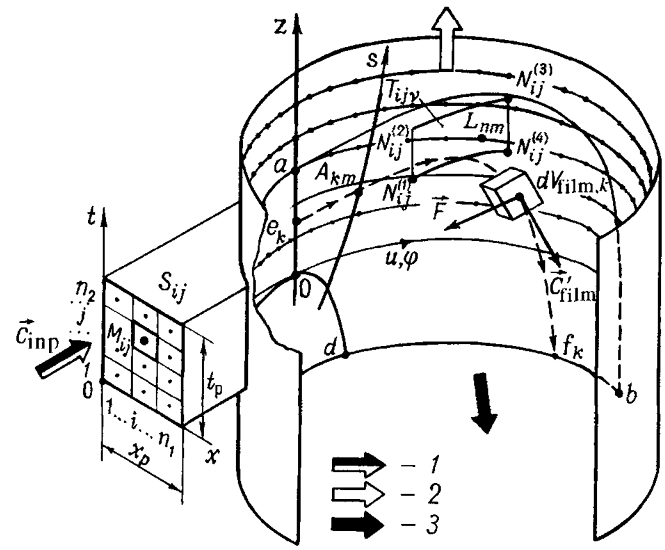


Fig. 1. Computational scheme of the motions in the separator of: 1, 2) two-phase and purified heat-transfer agents; 3) moisture.

$$\varphi\,(N_{ij}^{(k)}) = \varphi_{\mu-1} + [(C'_{\varphi})_{\mu-1}/(C'_{r})_{\mu-1}]\,(R_s - r_{\mu-1})\,,$$

$$z\,(N_{ij}^{(k)}) = z_{\mu-1} + [(C'_{z})_{\mu-1}/(C'_{r})_{\mu-1}]\,(R_s - r_{\mu-1})\,.$$

The specific flow rate of the primarily precipitated moisture for an arbitrary point $L_{nm}$ is the sum of flow rates of all groups of droplets, the precipitation zones of which involve this point:

$$q'_{nm} = \sum_{ij} \sum_{\nu} (g'_{ij\nu}/T_{ij\nu})\,.$$

**Hydrodynamic Model of the Kinematics, Separation, and Secondary Mass Transfer of Film Moisture.** This model considers stationary gravity flow of a liquid film along the wall of the separator with account for the processes of precipitation–entrainment and removal of moisture from the film. The approach which rests on spatial discretization of the film by a finite set of volume elements and trajectories of their motion by a set of liquid-jet elements is used as the basis for the model. The model makes it possible to estimate flow rate and kinematic parameters of the moisture film and their distribution over the separator wall.

In accordance with spatial discretization, at the separator inlet, the liquid film, incoming via the walls of the input pipe, is divided into $K$ volume elements $dV_{\text{film},k}$ ($k \in [1; K]$). For this purpose, in the section $\varphi = 0$ of the surface coordinate system the film is uniformly frontally divided into $K$ parts over the shell height (Fig. 1). The film flow is analyzed on the basis of individual calculations of the kinematics of all volumes $dV_{\text{film},k}$ which passed through the $k$th part of the inlet section. In this case, the positions of the jet elements on the shell surface and variations in the film parameters are determined.

Figure 1 shows the computational scheme of the motion of the film element $dV_{\text{film},k}$ of thickness $\delta_{\text{film}}$ and an area $dS_{\text{film}}$ under the effect of the principle vector of forces $\vec{F}$ between the points of the shell surface $e_k$ and $f_k$. According to the kinematic d'Alembert principle, the equation of motion of the film element in vector form is

$$\delta_{\text{film}}\,\rho'\,(d\vec{C}'_{\text{film}}/d\tau)\,dS_{\text{film}} = \vec{F} = \vec{F}_{\text{mot}} + \vec{F}_{\text{res}} + \sum_{m=1}^{n_{\text{sl}}} \vec{F}_{\text{sl},m}\,\delta\,(A_{km})\,. \tag{2}$$

The motive forces which are allowed for in the hydrodynamic model in the formation of the vector $\vec{F}_{\text{mot}}$ involve

the gravity force

$$\vec{F}_{\text{G}} = \rho' \delta_{\text{film}} \vec{g} \, dS_{\text{film}} ;$$

the reactive force due to a change in the mass of the element upon primary precipitation of droplet moisture onto its surface

$$\vec{F}_{\text{R1}} = dS_{\text{film}} \sum_{ij} \sum_{\nu} \vec{C}'_{\text{prec}ij\nu} \, q'_{ij\nu} ;$$

the friction force at the film–gas interface

$$\vec{F}_{\text{F1}} = f_1 \, (\vec{C} - k_{\text{ph}} \, \vec{C}'_{\text{film}}) \, dS_{\text{film}} .$$

The forces of resistance which are allowed for in the hydrodynamic model in the formation of the vector $\vec{F}_{\text{res}}$ involve

the Archimedes force

$$\vec{F}_{\text{A}} = - \rho \delta_{\text{film}} \vec{g} \, dS_{\text{film}} ;$$

the friction force at the film–wall interface

$$\vec{F}_{\text{F2}} = f_2 \, \vec{C}'_{\text{film}} \, dS_{\text{film}} ;$$

the reactive force due to a change in the mass of the element upon entrainment of moisture from the crests of waves [5]

$$\vec{F}_{\text{R2}} = k_{\text{entr}} \, \psi \, dS_{\text{film}} \left( \sum_{ij} \sum_{\nu} q'_{ij\nu} \right) \vec{C}'_{\text{film}} ;$$

the reactive force due to a change in the mass of the element upon splashing of the film as a result of impact and reflection of primarily precipitating droplets [5]

$$\vec{F}_{\text{R3}} = 1.5 \, dS_{\text{film}} \sum_{ij} \sum_{\nu} A_{ij\nu} \, (C'_{\text{prec}ij\nu})_{\text{norm}} \, q'_{ij\nu} \, \vec{C}'_{\text{prec}ij\nu} ;$$

the reactive forces due to separation of the liquid from the film by the moisture-removing slots (locally acting at the points $A_{km}$) [6]

$$\vec{F}_{\text{sl}} = - [(n+2)/(n+1)] \, \psi_{\text{sl}} \, \rho' \delta_{\text{film}} C'_{\text{film}} \vec{C}'_{\text{film}} \, dS_{\text{film}} .$$

In the determination of forces affecting the liquid film in the separator, it appears most difficult to correctly estimate quantitative parameters of the processes of secondary mass exchange of moisture between the film and the streamlining gas flow and accordingly the reactive forces $\vec{F}_{\text{R2}}$ and $\vec{F}_{\text{R3}}$. At present, only statistical processing of the limited body of known experimental results can serve as a basis for determining them. Analysis of the data on splashing of liquid films upon collision with droplets of moisture in flow parts of turbines of saturated vapor [7] gives the following estimate of the empirical coefficient in the expression for $\vec{F}_{\text{R3}}$:

$$A_{ij\nu} = 75 \, (r_{ij\nu} - 1.5 \cdot 10^{-5}) + 0.04 .$$

Processing of the data on entrainment of moisture from the film surface in a vertical tube by a descending gas flow [8] allows one to suggest the regression relation for calculating the coefficient of entrainment in the expression for $\vec{F}_{R2}$

$$\psi = 0.075 + 3.2 \cdot 10^{-4} C - 5.28 \cdot 10^{-4} C^2 + 1.65 \cdot 10^{-5} C^3 +$$

$$+ (2.72 \cdot 10^{-3} - 3.58 \cdot 10^{-4} C + 1.50 \cdot 10^{-5} C^2 - 1.89 \cdot 10^{-7} C^3) \mathrm{Re}_{\mathrm{film}} .$$

Finally, the calculation of the trajectory of the film element is reduced to integration of the vector differential equation of motion (2) with account for the expressions of acting forces

$$d\vec{C}'_{\mathrm{film}}/d\tau = [f_1 \vec{C} + (k_{\mathrm{ph}} f_1 + f_2 + k_{\mathrm{entr}} \psi \times$$

$$\times \sum_{ij} \sum_{\nu} q'_{ij\nu}) \vec{C}'_{\mathrm{film}} + \delta_{\mathrm{film}} (\rho' - \rho) \vec{g} + \sum_{ij} \sum_{\nu} [1 - 1.5 A_{ij\nu} (C'_{\mathrm{prec}ij\nu})_{\mathrm{norm}}] \, q'_{ij\nu} \vec{C}_{\mathrm{prec}ij\nu} +$$

$$+ [(n + 2)/(n + 1)] \, \rho' \sum_{m=1}^{n_{\mathrm{sl}}} \psi_{\mathrm{sl},m} \, \delta_{\mathrm{film},m} \, C'_{\mathrm{film},m} \vec{C}'_{\mathrm{film},m} \, \delta (A_{km})] / \delta_{\mathrm{film}} \, \rho'$$

with the initial conditions at the inlet to the separator (at $u = 0$ and $z \in [0; t_{\mathrm{p}}]$)

$$\vec{C}'_{\mathrm{film}} (0) = (\vec{C}'_{\mathrm{film}})_{\mathrm{cr}} ; \quad \delta_{\mathrm{film}} (0) = (\delta_{\mathrm{film}})_{\mathrm{cr}} .$$

Integration of this equation for a set $K$ of the elements $dV_{\mathrm{film},k}$, which differ in the axial coordinate of the reference point $z(0) = z(e_k) \in [0, t_{\mathrm{p}}]_{u(0)=0}$ (Fig. 1), makes it possible to construct the trajectories of their motion along the separator wall $(e_k f_k)$ and the limiting trajectories $0d$ (at $z(0) = 0$ and at $z(0) = t_{\mathrm{p}}$), which outline the wettest zone of the film with the main fraction of the flow rate of film moisture, and to find the curves of variation in the velocity $C'_{\mathrm{film}}(s)$, the Reynolds number $\mathrm{Re}_{\mathrm{film}}(s)$, and the thickness $\delta_{\mathrm{film}}(s)$ along the trajectory $s$. The thickness of the film at an arbitrary instant of time $\tau_{\mu+1}$ (at the point of the trajectory with the current coordinate $s_{\mu+1}$) of step-by-step integration of Eq. (2) is found by proceeding from the balance of the flow rates of moisture in the jet element:

$$\delta_{\mathrm{film}} (s_{\mu+1}) = [C'_{\mathrm{film},\mu} \, k_{\mathrm{j},\mu} / C'_{\mathrm{film},\mu+1} k_{\mathrm{j},\mu+1}] [(1 - \Delta\tau \, \psi_{\mu}) \, \delta_{\mathrm{film}} (s_{\mu}) + \bar{q}' (s_{\mu+1}) \, \Delta\tau \, (1 - \psi_{\mu}) / \rho'] .$$

The parameters of the film at the point of intersection of the jet with a moisture-removing slot undergo abrupt changes due to removal of the liquid of the near-wall layers. With account for the power-law character of the curve of change in the velocity of the liquid over the film thickness, the expressions relating the parameters of the film in front of the slot and behind it (in the sections $j$ and $j$+1, respectively) have the form

$$\delta_{\mathrm{film},j+1} = (1 - \psi_{\mathrm{sl}}^{n/(n+1)}) \, \delta_{\mathrm{film},j} ; \quad \mathrm{Re}_{\mathrm{film},j+1} = (1 - \psi_{\mathrm{sl}}) \, \mathrm{Re}_{\mathrm{film},j} ;$$

$$C'_{\mathrm{film},j+1} = [(1 - \psi_{\mathrm{sl}})/(1 - \psi_{\mathrm{sl}}^{n/(n+1)})] \, C'_{\mathrm{film},j} .$$

For an arbitrary $k$th jet of the film, the processes of mass transfer are characterized by the mass flow rates (per unit width) of the flows of droplet-film moisture (these flows form the film):

entered the separator via the wall of the pipe

$$q'_{\mathrm{inp},k} = \rho' \, (C'_{\mathrm{film}})_{\mathrm{cr}} \, (\delta_{\mathrm{film}})_{\mathrm{cr}} ,$$

primarily precipitated onto the wall of the separator

$$q'_{\mathrm{prec},k} = \int_{e_k f_k} k_{\mathrm{j}}(s) \sum_{ij} \sum_{\nu} q'_{ij\nu}(s)\, ds\,,$$

removed through moisture-removing slots

$$q'_{\mathrm{sl},k} = \rho' \sum_{m=1}^{n_{\mathrm{sl}}} \psi_m\, k_{\mathrm{j},m}\, C'_{\mathrm{film},m}\, \delta_{\mathrm{film},m} \cos \alpha_m\,,$$

entered the tray of the separator at the point $f_k$

$$q'_{\mathrm{tr},k} = \rho' \left(C_{\mathrm{film}}\, \delta_{\mathrm{film}}\, k_{\mathrm{j}}\right)\big|_{f_k}\,,$$

entrained during the process of secondary mass transfer

$$q'_{\mathrm{entr},k} = q'_{\mathrm{inp},k} + q'_{\mathrm{prec},k} - q'_{\mathrm{tr},k} - q'_{\mathrm{sl},k}\,.$$

The local coefficient of separation for the $k$th jet (from the balance of flow rates) is

$$\eta_k = (q'_{\mathrm{tr},k} + q'_{\mathrm{sl},k})/(q'_{\mathrm{inp},k} + q'_{\mathrm{prec},k})\,.$$

The integral coefficient of separation for the entire set $K$ of jet elements which defines the efficiency of moisture removal within the wettest zone $0abd$ of an area $S_{0abd}$ on the separator wall is

$$\eta = \left[ \int_{u_d}^{u_b} (C'_{\mathrm{film}} \delta_{\mathrm{film}})\big|_{\mathrm{at}\, z=-z_{\mathrm{tr}}} du + \sum_{m=1}^{n_{\mathrm{sl}}} \psi_m \int_{T_m} C'_{\mathrm{film}}(t)\, \delta_{\mathrm{film}}(t) \cos \alpha_m\, dt \right] \times$$

$$\times \left[ (\rho')^{-1} \iint_{S_{0abd}} q'_{\mathrm{prec}} df + \int_0^{t_{\mathrm{p}}} (C'_{\mathrm{film}}\, \delta_{\mathrm{film}})\big|_{\mathrm{at}\, u=0} dz \right]^{-1}. \qquad (3)$$

**Optimization Model of Film Moisture Separation.** This model allows one to determine an optimum location of a specified number of intermediate moisture-removing slots, which provide maximum efficiency of moisture removal, on the separator wall. The approach resting on spatial discretization of each slot by a finite set of points on the wall of the separator is used as the basis for the model. The locus of these points defines the position, configuration, and dimensions of the slot.

The flow rate of entrained moisture $q'_{\mathrm{entr},k}$ and the local coefficient of separation $\eta_k$ depend on the position of the sites of moisture removal from the film along the length of the $k$th jet. With one moisture-removing slot, the dependences $q'_{\mathrm{entr},k}(s_{\mathrm{sl}})$ and $\eta_k(s_{\mathrm{sl}})$ are polyextremum functions of the coordinate $s_{\mathrm{sl}}$. The location of the slot at the point of the minimum of $q'_{\mathrm{entr},k}(s_{\mathrm{sl}})$ provides maximum removal of moisture from the $k$th jet. With this in view, the optimization model stipulates minimization of the flow rate of moisture, which takes part in secondary mass transfer, on the basis of the solution of the problem of sequential independent conventional minimization of the set of $K$ nonlinear objective functions $n_{\mathrm{sl}}$ of variables of the form

$$U_k(s_{\mathrm{sl},1,k}, \ldots, s_{\mathrm{sl},n_{\mathrm{sl}},k}) = q'_{\mathrm{entr},k}(s_{\mathrm{sl},1,k}, \ldots, s_{\mathrm{sl},n_{\mathrm{sl}},k}) \to \min$$

with limitations by the inequalities $s_{\mathrm{sl},1,k} > 0$ and $s_{\mathrm{sl},m+1,k} - s_{\mathrm{sl},m,k} > 0$ at $m \in [1;\, n_{\mathrm{sl}} - 1]$ and $k \in [1;\, K]$.

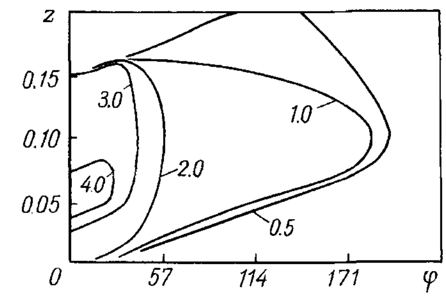


Fig. 2. Distribution of the specific mass flow rate of precipitated moisture over the separator wall. Figures at the curves: $q'$, kg/(sec·m$^2$). $z$, m; φ, deg.

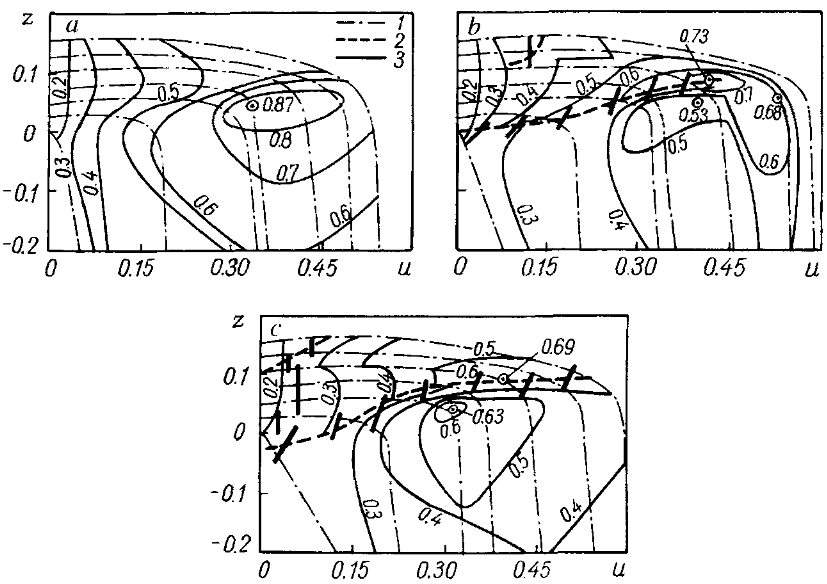

Fig. 3. Lines of equal thickness of the film, trajectories of motion of liquid jets (1) and the optimum arrangement of continuous (2) and discrete (3) slots on the separator wall: a) without a slot; b) single slot; c) two slots. Figure at the curves: $\delta_{\text{film}}$, mm. $z$, $u$, m.

Each $m$th set of optimum values of the variable parameters $s_{\text{sl},m,1}$, ..., $s_{\text{sl},m,k}$ characterizes the optimum arrangement of the $m$th moisture-removing slot on the separator wall.

**Results of Numerical Calculations.** The presented models were realized in the PLENKA computational complex, which is oriented to the use of IBM PC-compatible computers and intended for analysis of the processes of mass transfer and separation of moisture in inertia-gravity separators.

Calculations were made as applied to the separator of the system of preparation of vapor of geothermal power plants with the parameters of heat-transfer agents typical of geothermal deposits of the Far East of Russia: pressure 0.8 MPa and mass humidity 0.8. The parameters of the separator are vapor flow rate $G$ = 0.6 kg/sec, structural dimensions $R_s = t_p$ = 0.15 m, and ratio of mean flow rate values of the inlet and outlet velocities 6.3. This ratio is close to the minimally advisable one, which is equal to 5, i.e., without additional removal of moisture this separator possesses a low separating ability.

According to the gasdynamic model of the process, the calculations of primary precipitation of droplet moisture show its predominant precipitation in a $t_p$-wide band inclined at an angle of $\gamma <$ arctan $(t_p x_p/\pi R_s^2)$ = 3–7° with a pronounced zone of the largest specific flow rates and their maximum at $\varphi >$ arccos $(1 - x_p/2R_s)$ (Fig. 2). Beyond the limits of this zone the intensity of precipitation decreases sharply, since the curve $q'(\varphi,z)$

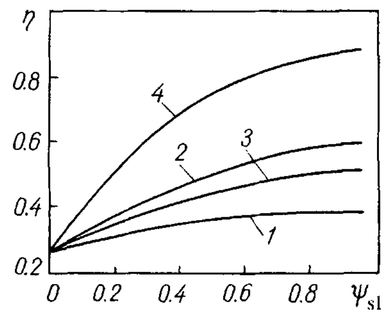

Fig. 4. Coefficient of moisture separation from the 0*abd* zone as a function of the coefficient of separation of the slot: 1) one continuous slot; 2) one discrete slot; 3) two continuous slots; 4) two discrete slots.

is formed due to the most finely dispersed droplets, which constitute a small mass fraction of the total flow rate of moisture.

Within the limits of the wettest zone 0*abd* in the absence of moisture-removing slots, the calculations of the kinematics of film moisture indicate a pronounced nonuniformity of the moisture distribution over the separator wall (Fig. 3a). The positions of the maxima of $\delta_{film}$ and $Re_{film}$ are close and lie in a circumferential direction behind the zone of the maximum specific flow rates of precipitating droplet moisture. The extremum character of these curves is associated with the fact that on the initial portions of the trajectories of motion of film elements the rate of primary precipitation exceeds the rate of entrainment; however, as the rate of precipitation decreases further, secondary mass transfer becomes prevailing. This is confirmed by an analysis of similar curves constructed without regard for secondary entrainment which have no extremum character [5]. The presence of moisture-removing slots increases the nonuniformity of the distribution of film parameters $\delta_{film}$, $C_{film}$, and $Re_{film}$ over the separator wall (Fig. 3b and c). Its thickness and the Reynolds numbers in the zones of maximum values decrease, thus causing suppression of the processes of secondary mass transfer. Efficiency of moisture removal increases with the coefficients of separation of the slots $\psi_{sl}$, although their optimum position turns out to be stable within a wide range of the values $\psi_{sl} = 0.1$–$0.9$. This is a positive feature, allowing for the possibility of variability of the operating regimes of the slots in exploitation of the separator. According to (3), the efficiency of moisture removal also depends on the orientation of the slots. It reaches a maximum with a normal arrangement of the slot front relative to the jet elements of the liquid (i.e., when $\cos \alpha \to 1$). Structurally this condition is provided by discrete slots formed by a set of separate parts with an approximately normal orientation with respect to the direction of film flow at the site of their arrangement (Fig. 3b and c). As follows from Fig. 4, for the considered separator with a solitary continuous or discrete slot the coefficient of separation $\eta$ can be increased by about 10 and 30% (absolute), respectively, with two slots – by 25 and 60% compared to a value of $\eta$ for the separator without intermediary removal of moisture.

**Conclusion.** The data presented indicate the practical expediency of equipping the inertia-gravity separators of moist vapor of power plants with a system of intermediary removal of moisture on the basis of moisture-removing slots, which is optimally designed in accordance with the developed mathematical models of the kinematics and mass transfer of droplet-film moisture.

## NOTATION

$A_{km}$, point of intersection of the *k*th jet with the *m*th slot; $A_{ijv}$, empirical coefficient; $C$, velocity of the gas flow; $C_{inp}$ and $y_{inp}$, curves of the distribution of the velocity and the mass flow rate degree of humidity of the heat-transfer agent in the outlet section of the input pipe; $C_a$, coefficient of aerothermodynamic resistance; $C'_{film}$, mean flow rate of the film; $(C'_{film})_{cr}$ and $(\delta_{film})_{cr}$, velocity and thickness of the film which correspond to the critical flow rate of the liquid [4]; $\vec{C}_{prec\,ijv}$, vector of the rate of primary precipitation of droplets of the *ijv*th group; $(C'_{prec\,ijv})_{norm}$, velocity component $\vec{C}_{prec\,ijv}$ normal to the surface of the wall; $(C'_r)_{ijv}$, $(C'_z)_{ijv}$, and $(C'_\varphi)_{ij\nu}$, projections of the velocity of the droplet of the $\nu$th fraction, which passed through $S_{ij}$, on the axes of the coordinate system $r\varphi z$; $dS_{\rm film}$, area of the film element; $dV_{{\rm film},k}$, volume element of the liquid film; $e_k$ and $f_k$, initial and final points of motion of the $k$th element of the film; $f_1$ and $f_2$, coefficients of friction at the film–gas and film–wall interfaces; $f_{ij}$, area of the subregion $S_{ij}$; $\vec{F}$, principal vector of forces; $\vec{F}_{\rm mot}$ and $\vec{F}_{\rm res}$, vectors of motive forces and forces of resistance; $\vec{F}_{{\rm sl},m}$, reactive force due to separation of the liquid from the film through the $m$th slot, which acts locally at the point $A_{km}(u_{{\rm sl},k,m}; z_{{\rm sl},k,m})$ of its intersection with the $k$th jet element; $\vec{g}$, free-fall acceleration; $g'_{ij\nu}$, mass flow rate of droplets of the $\nu$th fraction through $S_{ij}$; $G$, mass flow rate of the vapor; $k_{\rm j}$, coefficient of expansion of the jet; $k_{\rm entr}$, ratio of the velocity of motion of the center of masses of the entrained moisture to the velocity of the film; $k_{\rm ph}$, coefficient of the excess of the phase velocity of the film over the mean-flow rate velocity $C'_{\rm film}$; $K$, number of volume elements of film division at the inlet to the separator; $K_{\rm f}$, number of fractions of the droplets; $L_{nm}$, reference point on the surface of the shell in constructing the curve $q'$; $M_{ij}$ and $M_{ij}^{(k)}$, central and $k$th angular points of the subregion $S_{ij}$; $n$, exponent of the law of variation in the velocity over the film thickness; $n_{ij\nu}$, number of droplets of the $\nu$th fraction which pass through the subregion $S_{ij}$ per unit time; $n_{\rm sl}$, number of intermediary moisture-removing slots on the surface of the shell; $N$, number of subregions $S'_{ij}$; $N_{ij}^{(k)}$, $k$th angular point of the precipitation zone $T_{ij\nu}$; $q'$, curve of the distribution of the specific mass flow rate of primarily precipitated moisture; $\bar{q}'$, averaged specific mass flow rate of moisture received by the element between the points $s_\mu$ and $s_{\mu+1}$ of the trajectory; $q'_{\rm inp}$, specific mass flow rate of moisture which entered the separator; $q'_{nm}$, specific mass flow rate of moisture primarily precipitated at the point $L_{nm}$; $q'_{ij\nu}$, specific mass flow rate of primary precipitated droplets of radius $r_{ij\nu}$; $q_{\rm prec}$, specific mass flow rate of primarily precipitated moisture; $q'_{\rm tr}$, specific mass flow rate of moisture which entered the tray; $q'_{\rm entr}$, specific mass flow rate of entrained moisture; $q'_{\rm sl}$, specific mass flow rate of moisture removed by the slot; $r_{\rm d}$, droplet radius; $r_{{\rm max},ij}$ and $r_{ij}$, maximum and modal radii of the droplets which passed through $S_{ij}$; $r_{ij\nu}$, fraction-mean radius of droplets of the $\nu$th fraction; $R_{\rm s}$, radius of the shell of the separator; ${\rm Re}_{\rm film}$, Reynolds number for the film; $s$, coordinate along the trajectory of motion of the film element; $s_{\rm sl}$, coordinate of position of the slot along the length of the liquid jet; $S_{ij}$, subregion of the division of the outlet section of the input pipe; $S_{0abd}$, area of the wettest zone; $T_{ij\nu}$, zone of precipitation of droplets of radius $r_{ij\nu}$; $u_b$ and $u_d$, coordinates of the points $b$ and $d$ of the zone $0abd$ in the coordinate system $u0z$; $U$, objective function; $v$, modulus of the difference of the velocities of phases; $x_{\rm p}$ and $t_{\rm p}$, width and height of the input pipe; $z_{\rm tr}$, distance to the tray of the separator; $\alpha_m$, angle between the tangent to the trajectory of the film element at the point $A_{km}$ and the front of the $m$th slot; $\delta(A_{km})$, delta-function equal to 1.0 at the point $A_{km}$; $\Delta r_{ij}$, width of the range of radii of droplets of the fraction in the subregion $S_{ij}$; $\Delta\tau$, time step of integration; $\eta_k$, local coefficient of separation from the $k$th jet; $\eta$, coefficient of separation; $\Theta_{ij\nu}$, coefficient of sliding of the droplet $r_{ij\nu}$; $\mu$, step of integration of the equations of motion; $\rho$ and $\rho'$, densities of the heat-transfer agent and the droplet; $\tau$, time; $\psi$, coefficient of entrainment; $\psi_{\rm sl}$, coefficient of separation of the moisture-removing slot. Subscripts: A, Archimedes; G, gravity; a, aerodynamic; n, normal; mot; motive; cr, critical; prec, precipitation; tr, tray; film, film; R, reactive; j, jet; res, resistance; F, friction; entr, entrainment; ph, phase; d, droplet; inp, input; f, fraction; max, maximum; p, pipe; s, separator.

## REFERENCES


1. A. G. Ageev, V. B. Karasev, I. T. Severov, and V. F. Titov, *Separation Devices of Nuclear Power Plants* [in Russian], Moscow (1982).
2. E. F. Buznikov, *Cyclone Separators in Steam Boilers* [in Russian], Moscow (1969).
3. A. V. Lagerev and E. A. Lagereva, *Computational-Theoretical Analysis of the Kinematics of Moisture in the Vertical Cyclone with Side Input of Moist Vapor* [in Russian], Bryansk (1995). Dep. VINITI 17.11.95, No. 3048-V95.
4. G. A. Filippov, O. A. Povarov, and V. V. Pryakhin, *Study and Calculations of Turbines of Moist Vapor* [in Russian], Moscow (1973).

5. A. V. Lagerev and É. A. Lagereva, *Izv. Vyssh. Uchebn. Zaved., Yadern. Énergetika*, No. 3, 68-72 (1997).
6. A. V. Lagerev and É. A. Lagereva, *Izv. Vyssh. Uchebn. Zaved., Yadern. Énergetika*, No. 6, 30-34 (1997).
7. G. A. Filippov and O. A. Povarov, *Separation of Moisture in Turbines of Nuclear Power Plants* [in Russian], Moscow (1979).
8. G. Wallis, *One-Dimensional Two-Phase Flows* [Russian translation], Moscow (1972).