Evaluation Of Melt-Water Premixture Formation Due To Hydrodynamic Instabilities

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ABSTRACT

The rupture of the heat exchange tube of the steam generator of lead-cooled reactor leads to a high-velocity discharging of a water jet into liquid lead, and a steam film is formed on the interface. As a result of the water discharging in the steam generator, a multiphase mixture is formed, in which a steam explosion is possible. In this work, the process of fragmentation of a water jet under these conditions is theoretically investigated. The problem of the stability of the given hydrodynamic system is solved by the method of linear analysis. A dispersion equation is obtained and it is shown that it reduces to known cases under certain simplifications. The characteristics of the fastest growing disturbance are determined using the dispersion equation. On the basis of these results, the parameters of the forming multiphase mixture were estimated. The water droplets formed are small, making a steam explosion unlikely in this multiphase mixture. However, the small size of the water droplets can cause intense steam generation and large-scale lead displacement and sloshing, what can pose a threat to the integrity of the steam generator.

1 INTRODUCTION

The development of new designs for nuclear power plants and new safety systems is accompanied by an analysis of new situations in which steam explosions can occur. In particular, design-basis accidents with rupture of steam generator tubes can occur in lead-cooled reactors [1]. In this case, high-pressure water is discharged from the rupture into molten lead, as a jet, and conditions are formed for possible steam explosions [2]. The initial state of the explosive melt-water mixture in this case differs from the traditional case when a melt jet is poured into a pool of water. In this case, the melt is a continuous phase, and water is a dispersed phase. To analyze the development of a steam explosion in this system, it is necessary to estimate the parameters of the formed melt-water mixture, first of all, the size of dispersed water droplets.

Dispersed water droplets are formed due to the occurrence and development of instabilities of interface surfaces. The instability of the melt jet, which is poured into water under film boiling condition, was theoretically investigated in the works [3] (plane geometry) and [4] (cylindrical geometry). A stationary parallel flow of three phases (a melt jet, a vapor film around the jet, surrounding water) was considered, and small harmonic disturbances of the interface surfaces were produced. Then, the development of these disturbances was investigated by the method of linear analysis. In the region of parameters providing a stable flow, the initial disturbances disappeared. In the region of parameters at which the flow became unstable, an exponential growth of disturbances occurred (within the framework of linear analysis). In reality, the growth of disturbances is limited by nonlinear effects, and the disturbances of the interface surfaces themselves are transformed into dispersed droplets. Therefore, the linear method is not applicable to the analysis of the entire process of jet breakup into droplets. However linear analysis of the development of small disturbances makes it possible to evaluate the wavelength of the fastest growing disturbance and the characteristic time of development of the disturbance. This information can be used to estimate the size and time of formation of dispersed droplets during jet fragmentation [5].

The present work is aimed at studying the parameters of molten lead-water mixture, which is formed during the discharge of water jet into a vessel filled with molten lead. The study is carried out by linear analysis of the flow of a three-phase system: a water jet, a vapor film surrounding the jet, and molten lead occupying the rest of the space. The response of this system to small harmonic disturbances of the interphase surfaces is studied. The region of flow instability and the parameters of the most rapidly growing disturbance are determined. Based on the results obtained, the characteristics of the "melt-steam-water" multiphase mixture were evaluated.

2 PROBLEM FORMULATION

We consider a stationary flow of a cylindrical water jet with a constant velocity U_1 directed along the z axis. A cylindrical steam film with an inner radius a and an outer radius b separates the water jet from an infinite volume of molten lead. Steam and melt flow at constant velocities U_2 and U_3, parallel to the velocity of the water jet U_1. The densities of water, steam and melt are denoted as ρ_1, ρ_2 and ρ_3. Hereinafter, subscripts 1, 2, 3 refer to water, steam and melt, respectively. Water, steam and melt are considered as ideal fluids.

Let us assume that small harmonic axisymmetric disturbances are superimposed on the water-steam interface r_{12} and steam-melt interface r_{23}:

$$r_{12} = a + \eta_0 exp(ikz - i\omega t), \qquad r_{23} = b + \xi_0 exp(ikz - i\omega t). \tag{1}$$

Here η_0 and ξ_0 are unknown constants; k and ω are wave number and circular frequency of superimposed disturbances; z is axial coordinate; t is time.

We will assume that the flow is potential. Arising small velocity disturbances are expressed in terms of the velocity potential φ:

$$u = \partial\varphi/\partial z, \quad v = \partial\varphi/\partial r, \tag{2}$$

u and v are disturbances of the axial and radial velocity components, r is the radial coordinate.

For potential flows, the continuity equation is reduced to the Laplace equation for the velocity potential:

$$\frac{\partial^2\varphi_j}{\partial r^2} + \frac{1}{r}\frac{\partial\varphi_j}{\partial r} + \frac{\partial^2\varphi_j}{\partial z^2} = 0. \quad (j = 1,2,3) \tag{3}$$

The boundary conditions of the problem are formulated on the axis z $(r = 0\colon \partial\varphi/\partial r = 0)$ and at infinity $(r \to \infty\colon \varphi \to 0)$. They express zero normal velocity on the axis of symmetry and the damping of the velocity potential (and velocity) at infinity.

The solution of equation (3) can be represented in the form:

$$\varphi_j = f_j(r)exp(ikz - i\omega t). \tag{4}$$

Substituting (4) into (3), we obtain

$$\frac{\mathrm{d}^2 f_j}{\mathrm{d}r^2} + \frac{1}{r}\frac{\mathrm{d}f_j}{\mathrm{d}r} - k^2 f_j = 0. \tag{5}$$

Solutions of equation (5) in regions occupied by water, steam, and melt have the form:

$$f_1 = A_1 I_0(kr),\ f_2 = A_2 I_0(kr) + B_2 K_0(kr),\ f_3 = \ A_3 K_0(kr). \tag{6}$$

I_0 и K_0 are modified zero-order Bessel functions of the first and second kind; A_1, A_2, A_3, B_2 are unknown constants.

Pressure is calculated from Cauchy–Lagrange integral:

$$P_j = -\rho_j\,\frac{\partial \varphi_j}{\partial t} - \rho_j \frac{1}{2}\left[\left(U_j + u_j\right)^2 + v_j^2\right] + c_j\,, \tag{7}$$

c_j is unknown constant for phase j.

After linearization of the right side of the equation (7) we obtain

$$P_j = -\rho_j\,\frac{\partial \varphi_j}{\partial t} - \rho_j U_j \frac{\partial \varphi_j}{\partial z} + c_j. \tag{8}$$

The pressure in the water jet is determined by the expression

$$P_1 = -\rho_1\,\frac{\partial \varphi_1}{\partial t} - \rho_1 U_1 \frac{\partial \varphi_1}{\partial z} + c_1. \tag{9}$$

The constant c_1 is determined from the condition that the pressure in the undisturbed jet is P_0. Taking into account (4) and (6) we obtain from (9):

$$P_1 = \rho_1(i\omega - ikU_1)A_1 I_0(kr)exp(ikz - i\omega t) + P_0. \tag{10}$$

The pressure in the steam film is

$$P_2 = -\rho_2\,\frac{\partial \varphi_2}{\partial t} - \rho_2 U_2 \frac{\partial \varphi_2}{\partial z} + c_2. \tag{11}$$

In a stationary flow, the pressure in the steam differs from the pressure in the water jet by the value of the surface pressure. Hence the constant c_2 is $P_0 - \sigma_{12}/a$, σ_{12} is water surface tension coefficient. Taking into account also (4) and (6) we obtain from (11):

$$P_2 = i\rho_2(\omega - kU_2)[A_2 I_0(kr) + B_2 K_0(kr)]exp(ikz - i\omega t) + P_0 - \sigma_{12}/a. \tag{12}$$

The pressure in the melt is determined as follows

$$P_3 = -\rho_3\,\frac{\partial \varphi_3}{\partial t} - \rho_3 U_3 \frac{\partial \varphi_3}{\partial z} + c_3. \tag{13}$$

In a stationary flow, the pressure in the melt differs from the pressure in the steam by the value of the surface pressure, therefore

$$c_3 = P_0 - \sigma_{12}/a - \sigma_{23}/b, \tag{14}$$

σ_{23} is melt surface tension coefficient.

Taking into account (4), (6) and (14) we obtain from (13):

$$P_3 = i\rho_3(\omega - kU_3)A_3 K_0(kr)exp(ikz - i\omega t) + P_0 - \sigma_{12}/a - \sigma_{23}/b. \tag{15}$$

The following dynamic and kinematic conditions must be met at the interface surfaces.

On the inner and outer surfaces of the steam film, the pressure difference must be balanced by the surface tension:

$$r = a:\ \ P_1 = P_2 + \sigma_{12}(1/R_1 + 1/R_2), \tag{16}$$

$$r = b:\ \ P_2 = P_3 + \sigma_{23}(1/R_1' + 1/R_2'). \tag{17}$$

Here $R_1,\ R_2,\ R_1',\ R_2'$ are radii of curvature at a given point on the interface surface. Assuming the disturbances to be small deviations from the cylindrical surface, we will use the approximation formulas for the curvature of the surface in cylindrical coordinates. As a result, (16) and (17) take the form:

$$r = a:\ P_1 = P_2 + \sigma_{12}/a - \sigma_{12}/a^2\ \ (\eta + a^2\, \partial^2\eta/\partial z^2), \tag{18}$$

$$r = b:\ P_2 = P_3 + \sigma_{23}/b - \sigma_{23}/b^2\, (\xi + b^2\, \partial^2\xi/\partial z^2), \tag{19}$$

$$\eta = r_{12} - a, \qquad \xi = r_{23} - b. \tag{20}$$

To conditions (18) and (19), it is necessary to add four more kinematic conditions connecting the velocities of the phases on the interface surfaces with the motions of these surfaces:

$$r = a:\ v_j = \partial\eta/\partial t + U_j\, \partial\eta/\partial z, \quad (j = 1, 2) \tag{21}$$

$$r = b:\ v_k = \partial\xi/\partial t + U_k\, \partial\xi/\partial z. \ \ (k = 2, 3) \tag{22}$$

3 DERIVATION OF THE DISPERSION EQUATION

Substituting the expressions (1), (4), (6), (10), (12), (15) into conditions (18), (19), (21), (22), we obtain a homogeneous system of linear equations with respect to unknown constants $A_1, A_2, A_3, B_2, \eta_0, \xi_0$. This system has a nontrivial solution only with a zero determinant. This condition leads to the dispersion equation:

$$\begin{gathered}[I_{01}(a)\rho_1(\omega - kU_1)^2 - \sigma_{12}k(k^2 - a^{-2})]\{K_{01}(b)[H_1(a) + H_0(b)]\rho_2(\omega - kU_2)^2 \\ +[K_{01}(b)\rho_3(\omega - kU_3)^2 - \sigma_{23}k(k^2 - b^{-2})][H_1(b) - H_1(a)]\} \\ +K_{01}(a)\rho_2(\omega - kU_2)^2\{K_{01}(b)[H_0(b) - H_0(a)]\rho_2(\omega - kU_2)^2 + \\ [K_{01}(b)\rho_3(\omega - kU_3)^2 - \sigma_{23}k(k^2 - b^{-2})][H_0(a) + H_1(b)]\} = 0.\end{gathered} \tag{23}$$

Here $I_{01}(x) = I_0(x)/I_1(x)$, $K_{01}(x) = K_0(x)/K_1(x)$, $H_0(x) = I_0(x)/K_0(x)$, $H_1(x) = I_1(x)/K_1(x)$, where I_1 and K_1 are modified first-order Bessel functions of the first and second kind.

Dispersion equation (23) implicitly determines the dependence of the circular frequency on the wavelength of the disturbance of the interface surfaces $\omega(k)$.

4 LIMITING CASES

Since the dispersion equation (23) is very complicated, we first consider a number of limiting cases, in each of which it is significantly simplified.

Plane case. Let us increase the radius of the jet to infinity ($ka \to \infty,\ kb \to \infty$). In this case, the asymptotic representations of the Bessel functions become valid [6]:

$$x \to \infty:\ I_0(x) \approx I_1(x) \approx exp(x)/\sqrt{2\pi x}, \tag{24}$$

$$x \to \infty:\ K_0(x) \approx K_1(x) \approx exp(-x)/\sqrt{2\pi x}. \tag{25}$$

Taking into account (24) and (25), dispersion equation (23) takes the form

$$\begin{gathered}\rho_2(\omega - kU_2)^2[\rho_1(\omega - kU_1)^2 - \sigma_{12}k^3] \\ + th(k\delta)[\rho_3(\omega - kU_3)^2 - \sigma_{23}k^3][\rho_1(\omega - kU_1)^2 \\ -\sigma_{12}k^3] + \rho_2^2(\omega - kU_2)^4 th(k\delta) + \rho_2(\omega - kU_2)^2[\rho_3(\omega - kU_3)^2 - \sigma_{23}k^3] = 0.\end{gathered} \tag{26}$$

Equation (26) coincides with the dispersion equation for the plane case [3].

Identical properties of phases 2 and 3. Let the phases 2 (steam) and 3 (melt) be indistinguishable $(\rho_2 = \rho_3, \sigma_{23} = 0, U_2 = U_3)$. For simplicity we put $U_2 = U_3 = 0$. Omitting intermediate calculations, we present the final form of dispersion equation (23) in this case:

$$\begin{gathered}\left(\rho_1 I_{01}(a) + \rho_2 K_{01}(a)\right)\omega^2 - 2kU_1\rho_1 I_{01}(a)\omega \\ +\rho_1 k^2 U_1^2 I_{01}(a) - \sigma_{12}k(k^2 - a^{-2}) = 0.\end{gathered} \tag{27}$$

Equation (27) coincides with Rayleigh dispersion equation for this case, given in [5].

Extremely low steam film thickness. Let $b \to a$. Without loss of generality, we will assume that $U_3 = 0$. Then (23) takes the form:

$$I_{01}(a)\rho_1(\omega - kU_1)^2 + K_{01}\rho_3\omega^2 - \sigma_\Sigma k(k^2 - a^{-2}) = 0. \tag{28}$$

Equation (28) is the dispersion equation for the stability problem for a jet with a density ρ_1 flowing at a velocity U_1 in a stationary fluid with a density ρ_3. At the interface surface, the effective surface tension coefficient is $\sigma_\Sigma = \sigma_{12} + \sigma_{23}$.

Extremely high steam film thickness. Consider the case when $a \ll b$. Neglecting small complexes of Bessel functions in (23), we obtain

$$\begin{gathered}[I_{01}(a)\rho_1(\omega - kU_1)^2 + K_{01}(a)\rho_2(\omega - kU_2)^2 - \sigma_{12}k(k^2 - a^{-2})] \\ [I_{01}(b)\rho_2(\omega - kU_2)^2 + K_{01}(b)\rho_3(\omega - kU_3)^2 - \sigma_{23}k(k^2 - b^{-2})] = 0.\end{gathered} \tag{29}$$

Thus, the stability problem for the system under consideration is reduced to two independent problems. In the first (internal) problem, the dynamics of a melt jet in a steam medium is investigated, which corresponds to the fact that the first square bracket in (29) is equal to zero. In the second (external) problem, the stability of a steam jet in the surrounding water is studied (the second square bracket in (29) is equal to zero).

Low steam density. If $\rho_2 \ll \rho_1$ and $\rho_2 \ll \rho_3$, then terms with ρ_2 can be neglected in (23). Then it will be simplified and take the form:

$$\begin{gathered}[I_{01}(a)\rho_1(\omega - kU_1)^2 - \sigma_{12}k(k^2 - a^{-2})] \\ [K_{01}(b)\rho_3(\omega - kU_3)^2 - \sigma_{23}k(k^2 - b^{-2})] = 0.\end{gathered} \tag{30}$$

The problem was reduced to a step-by-step analysis of the stability of the melt jet in vacuum and the stability of the "jet" of vacuum in water.

5 NUMERICAL TECHNIQUE

As mentioned above, parameters of fastest growing disturbance determine the characteristics of the forming melt-water mixture. To determine them, it is necessary to solve the dispersion equation (23). To solve equation (23), the following numerical technique was developed. Firstly, the initial approximate value for the root of the equation was determined. For this purpose, the internal problem was used for the case "*Extremely high steam film thickness*". The problem was preliminarily simplified using the limit transition $k\delta \to \infty$, and a dispersion equation was considered:

$$\rho_1(\omega - kU_1)^2 + \rho_2(\omega - kU_2)^2 - \sigma_{12}k^3 = 0. \tag{31}$$

Equation (31) helps to easy find wave number k_{max} of fastest growing disturbance and its frequency $\omega_0 = \omega_{0,re} + \omega_{0,im}i$, where $\omega_{0,re}$ and $\omega_{0,im}$ are real and imaginary parts of ω_0. The complex number ω_0 was used as an initial approximate value to find the root of the dispersion equation (23).

On the complex plane, a rectangular grid was introduced with the centre at point ω_0, with the number of points 8500 x 1000. After that, the complex number ω is assigned the value of the complex number corresponding to a certain grid point and the module of the right-hand side of equation (23) is calculated. This procedure is performed for all grid points. Thus, the module of the right-hand side of equation (23) is determined at each grid point.

Based on the calculations performed, the point in which the module has the minimum value is determined. This point is taken as a new approximation for the root of equation (23). A new rectangular grid with a reduced step between points is introduced near this point, and the procedure is repeated. The convergence of the solution is achieved after the third grid.

On the basis of this numerical technique, the authors of the paper developed an original calculated code using the FORTRAN-90 programming language for finding the roots of the dispersion equation, which was tested on exact solutions of algebraic equations of the 4th degree and was used in our analysis. In the calculations, the wave number k_{max} was determined at which the fastest growth of the disturbance occurred, which was identified by the maximum of the imaginary part of the angular frequency $Im(\omega_{max})$.

6 RESULTS

The instability of water jet discharging from a rupture of a heat exchange tube of a steam generator of a lead-cooled BREST reactor [7] was considered. An idealized consideration was implemented, which is necessary for the application of linear analysis - an infinitely long water jet surrounded by a steam film in liquid lead. This formulation is justified, since the calculation results showed that the jet breakup occurs at very small distances, which are less than the distance between the steam generator tubes. Pressure in the steam generator is 8 bar, water and steam were considered as saturated ones, and their densities and surface tension coefficient were calculated under such pressure. The density and surface tension coefficient of liquid lead were calculated for lead temperature 800 K.

A single rupture of a heat-exchange tube from a partial rupture to a guillotine one was considered, while the radius of the water jet varied in the range $a = 4 - 20$ mm.

The water discharge from the tube rupture is critical. An estimate of the critical flow rate for various modes of operation of the BREST reactor was made in [8]. Based on these results and taking into account the radius of the water jet, the water jet velocity was set in the range $U_1 = 10 - 35$ m/s. Liquid lead was assumed to be motionless ($U_3 = 0$), the steam velocity was taken $U_2 = (U_1 + U_2)/2$.

The diameter of the formed water droplet d is estimated as half the length of the fastest growing disturbance $d = \pi/k_{max}$ [5]. The characteristic time of droplet formation τ is evaluated by the maximum value of the imaginary part of the circular frequency $\tau = 1/Im(\omega_{max})$ [9]. The jet breakup length L was estimated by the formula $L = U_1\tau$ [9].

The steam film thickness was varied in calculations. The influence of this parameter is shown in Figures 1-3 ($U_1 = 10\,m/s\,, a = 6\,mm$). It is seen that even at $\delta > 1.5\,mm$, the characteristics of jet fragmentation do not depend on the film thickness. This means that the film blocks the influence of liquid lead on the dynamics of the water jet. With a decrease in the thickness of the vapor film, the effect of lead increases, which leads to an intensification of the water jet breakup. Figure 3 shows, that droplets are formed at very short distances after the onset of initial disturbances, which leads to rapid fragmentation of the water jet and the formation of a “water-steam-molten lead” mixture.

The influence of water jet velocity on jet breakup length is demonstrated on Figure 4 ($a = 20\, mm, \delta = 1\, mm$). An increase in the jet velocity causes a decrease in the length of the jet breakup. The forming water droplets also become smaller down to 0.15 mm.

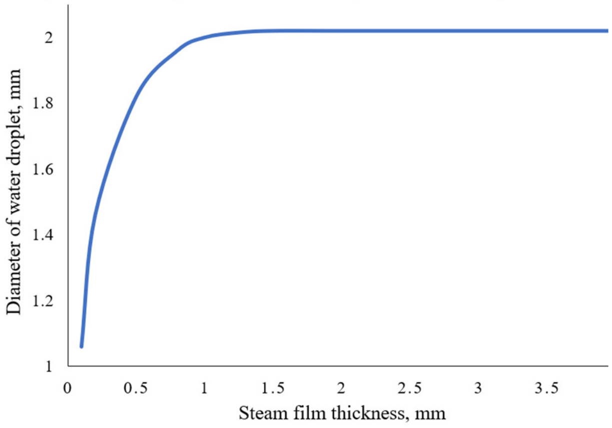

Figure 1. Influence of steam film thickness on water droplet diameter

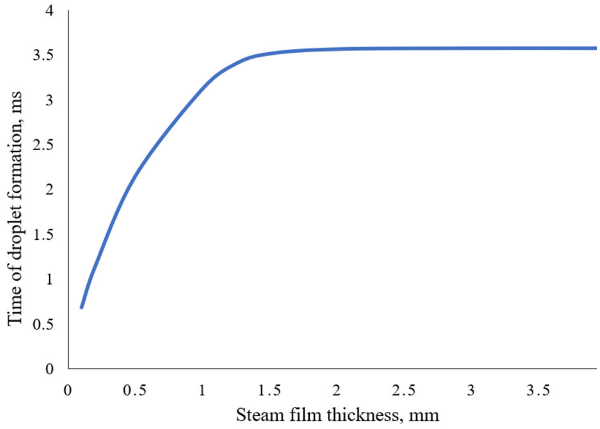

Figure 2. Influence of steam film thickness on droplet formation time

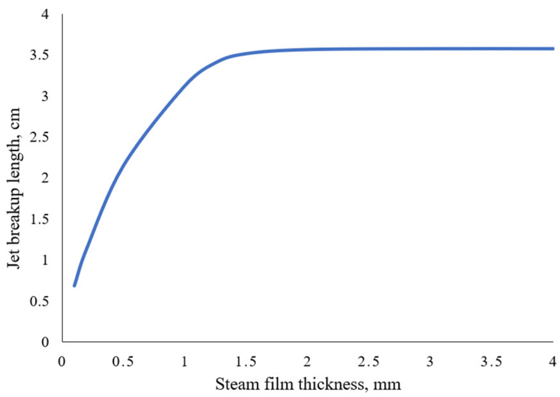

Figure 3. Influence of steam film thickness on jet breakup length

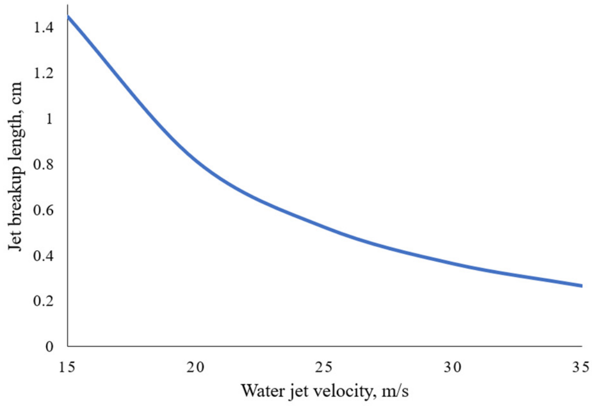

Figure 4. Influence of water jet velocity on jet breakup length

Calculations were carried out in which the water jet velocity was 10 m/s, the thickness of the steam film was 0.5 mm, and the jet radius varied from 4 mm to 8 mm. In all cases, the size of the formed water droplets was about 2 mm, and the jet breakup length was about 2 cm.

Thus, the fragmentation of water jet, which moves at a high velocity in liquid lead, leads to the formation of a multiphase mixture, where water droplets surrounded by steam bubbles are located in continuous liquid lead. Such mixtures were observed in experiments [10]. The size of the formed water droplets is from a few parts of mm to a few mm. The disintegration of the jet begins almost immediately after the rupture and fragmentation of the jet occurs at a distance of several centimeters.

7 CONCLUSION

The problem of the hydrodynamic instability of a water jet surrounded by a steam film moving in liquid lead has been considered. Using the method of linear analysis, a dispersion equation has been derived, which allows one to determine the frequency of the disturbance (the decrement of the disturbance growth) depending on the wave number of this disturbance. It is shown that this dispersion equation is reduced to known cases when the governing parameters tend to some limits.

The sensitivity analysis performed revealed the following trends. An increase in the steam film thickness leads to an increase in the size of the formed water droplets and an increase in the length of the jet breakup. However, when the film thickness becomes more than 1 mm, these parameters no longer increase, the jet disintegration occurs in the same way as in a vapor atmosphere without the presence of a melt.

A decrease in the velocity of the water jet leads to an increase in the size of the formed water droplets and to an increase in the time of their formation, the jet breakup length is also increased. At high jet velocities and at its large radius (about 20 mm), the jet fragments in the atomization mode.

In the investigated range of parameters, the effect of the radius of the jet on its fragmentation was insignificant.

The relatively small size of the water droplets formed during the fragmentation of the jet limits their further fragmentation, which is necessary for a steam explosion. Thus, the realization of a steam explosion in a multiphase mixture formed during the water jet breakup is unlikely.

ACKNOWLEDGMENTS

This research was funded by Russian Science Foundation (RSF) under Grant 21-19-00709.

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