

## INTERACTION EFFECTS IN FILM BOILING ON SPHERICAL PARTICLES

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UDC 536.24

*Consideration is given to the initial stage of the process of thermal and dynamic interaction of a "collective" of melt particles that are in contact with a cooling liquid.*

Problems on perfecting the technology of the production of powders of light alloys require that the processes of interaction between the particles of molten metal and the coolant be studied. The contact of a strongly superheated particle with a liquid is characterized by high rates of heat transfer and can end with thermal explosions of different intensity, which necessitates the prediction of the safety of a number of technological operations in metallurgy.

Experimental works are known where the physical models of thermal interaction between a melt and a coolant are suggested [1, 2]. The authors of the models of the physical mechanism of vapor explosion point to the importance of investigating the initial stage of interaction of a melt particle with a cooling liquid and assume that the dynamics of phase transformations determines further development of the process in either the "normal" direction where the metal is crystallized to form a more or less regular shape or the direction of melt fragmentation that leads to vapor explosion [2, 3].

If an incandescent particle is immersed in a cold liquid, then, owing to the intense heat transfer near the surface of contact, a superheated layer is formed, which boils up after an interval of  $\sim 10^{-6}$  sec [1]. As a consequence of the inertia of the liquid, which prevents expansion of the vapor film, the vapor pressure grows at a high rate. From the experimental results, the characteristic time within which a pressure pulse is observed is  $\sim 10^{-4}$  sec; its amplitude depends on numerous factors and can attain 10–100 MPa [2].

In the case of contact of a set of melt particles with an underheated liquid, an acoustic pulse is formed, whose value is undoubtedly influenced by the effects of the interaction of boiling vapor films.

The problem of evaporation of the condensed phase on the surface of superheated spherical particles, even for an isolated inclusion, is a complicated nonlinear problem and requires that one account for many thermophysical factors [4]. We would like to note, in particular, [4–6], in which mathematical models of dynamic and thermal interaction of a hot particle with a coolant in the stage of film boiling are derived for an isolated particle. The collective effect is evaluated, if at all, on the basis of semiempirical relations. The aim of the present work is to model the behavior of a finite set of superheated spherical particles in their contact with a liquid medium in the initial stage of evaporation.

The model of thermal and dynamic interaction of spherical particles with a cold viscous incompressible fluid is constructed under the assumption that the particles are concentrated in a certain volume of the

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fluid, i.e., a "cloud", which is substantially smaller than the entire volume of the coolant, and the characteristic particle radius is considerably smaller than the characteristic distance between them  $r_{b0} \ll l_0$ .

The spherically symmetric flow of the viscous incompressible fluid initiated by an expanding vapor film is known to be the potential. The velocity potential  $\Phi$  satisfies the Laplace equation

$$\Delta\Phi = 0 \quad (1)$$

and the boundary conditions

$$\left. \frac{\partial\Phi}{\partial r} \right|_{r=R} = v_{fR}, \quad \left. \frac{\partial\Phi}{\partial r} \right|_{r=\infty} = 0. \quad (2)$$

For low concentrations of the particle, we can consider roughly that the potential of the velocity field at an arbitrary point  $M$  is composed of the sum of the potentials of the flows created by individual inclusions [7]:

$$\Phi(M, t) = - \sum_i \frac{v_{fR}^{(i)} R^{(i)^2}{}}{|\mathbf{r}_i|}, \quad (3)$$

where  $\mathbf{r}_i$  is the radius vector drawn from the center of the  $i$ th particle to the point  $M$ .

We consider the potential of the velocity field near the vapor-film surface around the  $i$ th particle after reduction to dimensionless form:

$$\tilde{\Phi}_i = - \frac{\tilde{v}_{fR}^{(i)} \tilde{R}^{(i)^2}}{\tilde{r}_i} - \varepsilon \sum_{j \neq i} \kappa_{ij} \tilde{v}_{fR}^{(j)} \tilde{R}^{(j)^2}, \quad \kappa_{ij} = \sum_{j \neq i} \frac{l_0}{l_{ij}}, \quad \tilde{\Phi}_i = \Phi_i \frac{t_{\text{char}}}{r_{b0}^2}, \quad \tilde{r} = \frac{r}{r_{b0}}, \quad \varepsilon = \frac{r_{b0}}{l_0}. \quad (4)$$

The first summand in (4) corresponds to the velocity potential around the isolated inclusion, while the second term gives a correction of the order of  $\varepsilon$  for the influence of the other melt particles, surrounded by the growing vapor layer as well, on the flow characteristics. Since for the investigated case  $\varepsilon \ll 1$ , the contribution of the potentials created by all external sources is substantially smaller than the value of the self-potential of the  $i$ th particle.

The motion of the vapor film boundary around each particle can be determined with the Lagrange–Cauchy integral using kinematic and dynamic conditions at the interface [8]:

$$\frac{\partial\Phi^{(i)}}{\partial t} + \frac{1}{2} \left( \frac{\partial\Phi^{(i)}}{\partial r} \right)^2 + \frac{1}{\rho_f} \left[ p_v^{(i)} - p_\infty - \frac{2\sigma}{R^{(i)}} - \frac{4\mu_f v_{fR}^{(i)}}{R^{(i)}} + j^{(i)^2} \left( \frac{1}{\rho_{vR}^{(i)}} - \frac{1}{\rho_f} \right) \right] = 0, \quad (5)$$

where  $i = 1, \dots, N$ . The index on the radial coordinate is omitted here and henceforth.

The scheme of the phase transitions is assumed to be equilibrium; the temperatures of the fluid and the vapor on the bubble wall coincide and are equal to the saturation temperature for this pressure:

$$T_f^{(i)} \Big|_{r=R^{(i)}} = T_v^{(i)} \Big|_{r=R^{(i)}} = T_s. \quad (6)$$

The pressure and the temperature of the saturated vapor are related by the Clausius–Clapeyron relation, using which we can obtain

$$\frac{dT_s^{(i)}}{dt} = \frac{B_v T_s^{(i)2}}{L p_v^{(i)}} \frac{dp_v^{(i)}}{dt}. \quad (7)$$

Since the film thickness in the initial stage of evaporation is small,  $\delta \sim 10^{-6}-10^{-4}$  m, for the vapor pressure we can adopt the homobaric hypothesis  $p_v = p_v(t)$  [8]. The assumption of ideality of the vapor makes it possible to obtain the integral of the equation of heat efflux in the vapor film which expresses the rate of change of the pressure as a function of the work of surface forces and of the heat fluxes at both interfaces [8]:

$$\frac{dp_v^{(i)}}{dt} = \frac{3(\gamma-1)}{R^{(i)3} - r_b^{(i)3}} \left[ Z^{(i)} - \frac{\gamma R^{(i)2}}{\gamma-1} \left( p_v^{(i)} \frac{dR^{(i)}}{dt} - j^{(i)} B_v T_s^{(i)} \right) \right], \quad Z^{(i)} = \lambda_v R^{(i)2} \left( \frac{\partial T_v^{(i)}}{\partial r} \right)_{r=R^{(i)}} - \lambda_v r_b^{(i)2} \left( \frac{\partial T_v^{(i)}}{\partial r} \right)_{r=r_b^{(i)}}. \quad (8)$$

The temperature profile in the vapor surrounding the particle is approximated by a hyperbolic function of the form

$$T_v^{(i)}(r, t) = \Psi_1 + \frac{\Psi_2}{r}, \quad \Psi_3 = R^{(i)}/(R^{(i)} - r_b^{(i)}), \quad \Psi_1 = T_m^{(i)} - \Psi_3 (T_m^{(i)} - T_s^{(i)}), \quad \Psi_2 = \Psi_3 r_b^{(i)} (T_m^{(i)} - T_s^{(i)}). \quad (9)$$

Here  $T_m$  is the surface temperature of the melt particle, which is determined from the heat-balance equation

$$\frac{1}{3} r_b^{(i)} \rho_m c_m \frac{dT_m^{(i)}}{dt} = \lambda_v \left( \frac{\partial T_v^{(i)}}{\partial r} \right)_{r=r_b^{(i)}}. \quad (10)$$

The temperature distribution in the fluid is described by the convective heat-transfer equation

$$\rho_f c_{fp} \left[ \frac{\partial T_f^{(i)}}{\partial t} + v_f^{(i)} \frac{\partial T_f^{(i)}}{\partial r} \right] = \frac{1}{r^2} \frac{\partial}{\partial r} \left( \lambda_f r^2 \frac{\partial T_f^{(i)}}{\partial r} \right). \quad (11)$$

The heat balance at the vapor-cooling medium interface is expressed by the relation

$$-\lambda_v \left( \frac{\partial T_v^{(i)}}{\partial r} \right)_{r=R^{(i)}} + \lambda_f \left( \frac{\partial T_f^{(i)}}{\partial r} \right)_{r=R^{(i)}} + \sigma_{\text{rad}} \left( \alpha_m T_m^{(i)4} - \alpha_f T_s^{(i)4} \right) = L j^{(i)}. \quad (12)$$

At the moment of boiling, the following initial conditions are adopted:

$$R^{(i)}(0) = r_b^{(i)} + \delta_0, \quad v_{fR}^{(i)}(0) = 0, \quad T_m(0) = T_{m0}, \quad p^{(i)}(0) = p_\infty, \quad T_f^{(i)}(r, 0) = T_s^{(i)}(0) = T_s(p_\infty) = T_\infty. \quad (13)$$

The formulated system of equations and boundary and initial conditions (1)–(13) was investigated by the small-parameter method. After reduction of the equations to dimensionless form, all the sought quantities were represented in the form of series expansion in  $\varepsilon$ :

$$\begin{aligned} \tilde{R}^{(i)} &= R_{0i} + R_{1i}\varepsilon + R_{2i}\varepsilon^2 + o(\varepsilon^2); \quad \tilde{p}_v^{(i)} = p_{0i} + p_{1i}\varepsilon + p_{2i}\varepsilon^2 + o(\varepsilon^2); \\ \tilde{v}_{fR}^{(i)} &= v_{0i} + v_{1i}\varepsilon + v_{2i}\varepsilon^2 + o(\varepsilon^2); \quad \tilde{j}^{(i)} = j_{0i} + j_{1i}\varepsilon + j_{2i}\varepsilon^2 + o(\varepsilon^2); \end{aligned}$$

$$\tilde{T}_q^{(i)} = T_{q_{0i}} + T_{q_{1i}} \varepsilon + T_{q_{2i}} \varepsilon^2 + o(\varepsilon^2), \quad q = s, f;$$

$$\tilde{v}_{fR} = v_{fR} \frac{t_{\text{char}}}{r_{b0}}; \quad \tilde{p} = \frac{p}{p_\infty}; \quad \tilde{R} = \frac{R}{r_{b0}}; \quad \tilde{T} = \frac{T}{T_\infty}; \quad \tilde{j} = \frac{j}{j_{\text{char}}}; \quad j_{\text{char}} = (\rho_f p_\infty)^{1/2}.$$

The zero approximation ( $\varepsilon^0$ ) for the problem under consideration represents the problem of boiling of a vapor film on an isolated particle. The first approximation ( $\varepsilon^1$ ) and approximations of higher order take into account the collective effect of the interaction of boiling vapor films with simultaneous cooling of a set of particles.

The equation for the fluid velocity at the boundary with the vapor layer in the zero and first approximations is as follows:

$$\dot{v}_{0i} R_{0i} + 2v_{0i} \dot{R}_{0i} - 1/2v_{0i}^2 = t_{\text{rel}}^2 \left[ p_{0i} - 1 - \frac{2\tilde{\sigma}}{R_{0i}} - \frac{4\tilde{\mu}v_{0i}}{R_{0i}} + J_{0i}^2 \left( \tilde{\rho}_f \frac{T_{s_{0i}}}{p_{0i}} - 1 \right) \right],$$

$$t_{\text{rel}} = \frac{t_{\text{char}}}{t_{\text{Ra}}}; \quad t_{\text{Ra}} = r_{b0} \sqrt{\frac{\rho_f}{p_\infty}}; \quad \tilde{\mu} = \frac{\mu_f}{t_{\text{char}} p_\infty}; \quad \tilde{\sigma} = \frac{\sigma}{r_{b0} p_\infty}; \quad \tilde{\rho}_f = \frac{\rho_f}{p_\infty T_\infty};$$

$$\begin{aligned} \dot{v}_{1i} R_{0i} = & -\dot{v}_{0i} R_{1i} - 2v_{1i} \dot{R}_{0i} - 2v_{0i} \dot{R}_{1i} + v_{0i} v_{1i} + \sum_{i \neq j} \kappa_{ij} (\dot{v}_{0j} R_{0j}^2 + 2v_{0j} R_{0j} \dot{R}_{0j}) + \\ & + t_{\text{rel}}^2 \left[ p_{1i} + \frac{2\tilde{\sigma} R_{1i}}{R_{0i}^2} - \frac{4\tilde{\mu}}{R_{0i}} \left( v_{1i} - \frac{v_{0i} R_{1i}}{R_{0i}} \right) - 2j_{0i} j_{1i} \right] + \tilde{\rho}_f \left[ \frac{J_{0i}^2}{p_{0i}} T_{s_{1i}} + \frac{T_{s_{0i}}}{p_{0i}} \left( 2j_{0i} j_{1i} - \frac{J_{0i}^2}{p_{0i}} p_{1i} \right) \right]. \end{aligned}$$

Here and henceforth, the sign  $\sim$  above the dimensionless variables is omitted, while above the constant quantities it is retained. The equations for the vapor-film radius in the zero and first approximations are identical:

$$\dot{R}_{0i} = v_{0i} + \tilde{j}_p j_{0i}, \quad \tilde{j}_p = \frac{j_{\text{char}} t_{\text{char}}}{r_{b0} \rho_f}, \quad \dot{R}_{1i} = v_{1i} + \tilde{j}_p j_{1i}.$$

The equations for the vapor pressure in the zero and first approximations are obtained in the form

$$\begin{aligned} \dot{p}_{0i} = & -\frac{3\gamma R_{0i}^2}{\gamma - 1} \left[ p_{0i} \dot{R}_{0i} - \tilde{j}_p \tilde{\rho}_f j_{0i} T_{s_{0i}} \right], \\ \dot{p}_{1i} = & -\frac{3\gamma}{R_{0i}^3 - b_i^3} \left\{ R_{0i}^2 \dot{R}_{0i} p_{1i} + p_{0i} \left[ R_{0i}^2 \dot{R}_{1i} + \left( 2R_{0i} R_{1i} - \frac{3R_{0i}^4 R_{1i}}{R_{0i}^3 - b_i^3} \right) \dot{R}_{0i} \right] - \right. \\ & \left. - \tilde{j}_p \tilde{\rho}_f \left[ R_{0i}^2 j_{1i} T_{s_{0i}} + j_{0i} \left( R_{0i}^2 T_{s_{1i}} + T_{s_{0i}} \left( 2R_{0i} R_{1i} - \frac{3R_{0i}^4 R_{1i}}{R_{0i}^3 - b_i^3} \right) \right) \right] \right\}, \quad b_i = \frac{r_b^{(i)}}{r_{b0}}. \end{aligned}$$

The saturation temperature in each approximation can be determined from the relations

$$\dot{T}_{s_{0i}} = s_L \frac{T_{s_{0i}}^2}{p_{0i}} \dot{p}_{0i}, \quad s_L = \frac{B_v T_\infty}{L}, \quad \dot{T}_{s_{1i}} = s_L \left[ \frac{T_{s_{0i}}^2}{p_{0i}} \dot{p}_{1i} + \frac{\dot{p}_{0i}}{p_{0i}} \left( 2T_{s_{0i}} T_{s_{1i}} - \frac{T_{s_{0i}}^2}{p_{0i}} p_{1i} \right) \right].$$

The equation for the temperature in the fluid surrounding a particle in the zero approximation is

$$\frac{\partial T_{f_{0i}}}{\partial t} + \frac{v_{0i} R_{0i}^2}{r^2} \frac{\partial T_{f_{0i}}}{\partial r} = \frac{1}{\text{Pe}_f r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T_{f_{0i}}}{\partial r} \right), \quad \text{Pe}_f = \frac{r_{b0}^2}{t_{\text{char}} a_f}, \quad a_f = \frac{\lambda_f}{\rho_f c_{pf}};$$

in the first approximation it is

$$\frac{\partial T_{f_{1i}}}{\partial t} + \frac{1}{r^2} \left[ (v_{1i} R_{0i} + v_{0i} R_{1i}) \frac{\partial T_{f_{0i}}}{\partial r} + v_{0i} R_{0i} \frac{\partial T_{f_{1i}}}{\partial r} \right] = \frac{1}{\text{Pe}_f r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T_{f_{1i}}}{\partial r} \right).$$

The conditions at the boundary of the phase transitions in the zero and first approximations are written in the form

$$\begin{aligned} & -\lambda_{vf} \frac{b_i}{R_{0i}} \frac{T_{s_{0i}}}{R_{0i} - b_i} + \frac{\partial T_{f_{0i}}}{\partial r} \Big|_{r=R_{0i}} + j_r (\alpha_m T_m^4 - \alpha_f T_{s_{0i}}^4) = j_t j_{0i}, \\ & \lambda_{vf} = \lambda_v / \lambda_f, \quad j_r = \frac{\sigma_{\text{rad}} T_\infty^3 r_{b0}}{\lambda_f}, \quad j_t = \frac{L j_{\text{char}} r_{b0}}{\lambda_f T_\infty}; \\ & -\lambda_{vf} \left[ \frac{b_i}{R_{0i}} \frac{T_{s_{1i}}}{R_{0i} - b_i} - \frac{b_i R_{1i}}{R_{0i}^2} \frac{(T_{s_{0i}} - T_m)}{(R_{0i} - b_i)^2} (2R_{0i} - b_i) \right] + \frac{\partial T_{f_{1i}}}{\partial r} \Big|_{r=R_{0i}} + \\ & + R_{1i} \frac{\partial^2 T_{f_{0i}}}{\partial r^2} \Big|_{r=R_{0i}} - 4j_r \alpha_f T_{s_{0i}}^3 T_{s_{1i}} = j_t j_{1i}. \end{aligned}$$

The initial conditions for the first approximation are the zero ones, while for the zero approximation they are as follows:

$$R_{0i} = b_i + \frac{\delta_0}{r_{b0}}, \quad v_{0i} = 0, \quad p_{0i} = 1, \quad T_{s_{0i}} = T_{f_{0i}} = 1, \quad T_m = \frac{T_{m0}}{T_\infty}.$$

The character of change in the parameters of the process in both the first and second approximations can be studied only by numerical methods. In the present work, use is made of the method of straight lines, which reduces a solution of partial differential equations to that of the Cauchy problem for a system of ordinary differential equations. The solution has been obtained by the Runge–Kutta method. To increase the accuracy of approximation of the equation of convective heat transfer, grids nonuniform on the space coordinate were used.

Figures 1–3 present the calculation results illustrating the effect of the collective interaction of vapor films in the initial stage of evaporation of the condensed phase in the case of contact of a group of high-temperature solid metal particles with water. The calculations were carried out for a "cloud" of particles of the same radius  $r_{b0} = 1 \cdot 10^{-4}$  m uniformly distributed throughout the volume at the nodes of a square grid. In this case, for instance, for 5 and 25 particles the contribution made by the remaining inclusions to the value of

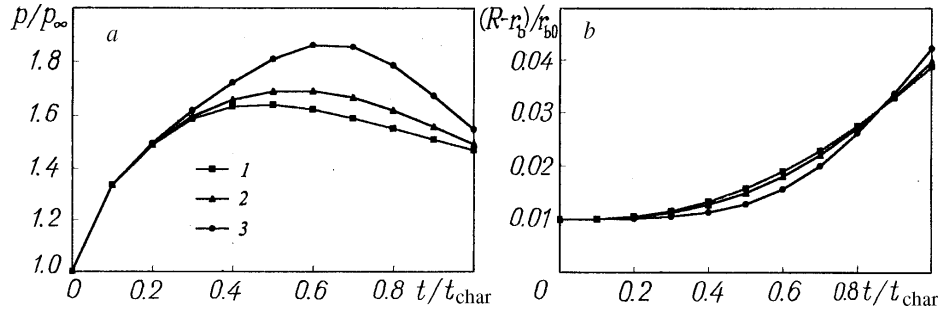


Fig. 1. Time variation in the pressure in the vapor film [a]  $\varepsilon = 0.01$ ] and its thickness [b]  $\varepsilon = 0.05$ ] in relation to the number of particles in the group: 1) 1; 2) 5; 3) 25.

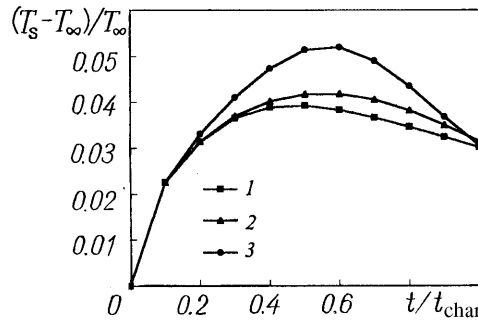


Fig. 2. Influence of the effect of interparticle interaction on the time variation in the temperature of the saturated vapor ( $\varepsilon = 0.01$ ): 1, 2, 3) notation is the same as in Fig. 1.

the potential of the flow field about the central particles is determined by  $\sum_{j=2}^4 \kappa_{1j} = 4$  and  $\sum_{j=2}^{24} \kappa_{1j} = 13.81$ , respectively. By the 1st particle is meant that located at the center of the collective. The ratio of the particle radius to the characteristic distance between the particles  $\varepsilon$  was varied.

The initial width of the vapor layer  $\delta_0 = R_0 - r_{b0}$  was assumed to be equal to  $10^{-6}$  m,  $p_\infty = 10^5$  Pa, and  $T_\infty = 373$  K. For the melt particle  $\rho_m = 8900$  kg/m<sup>3</sup>,  $\lambda_m = 0.683$  W/(m-deg), and  $c_m = 0.39 \cdot 10^3$  J/(kg-deg). The particle temperature was  $T_{m0} = 1073$  K. The parameters of radiative heat transfer were as follows:  $\sigma_{rad} = 5.76 \cdot 10^{-8}$  W/(m<sup>2</sup>·deg<sup>4</sup>),  $\alpha_m = 0.85$ , and  $\alpha_f = 0.15$ . The thermophysical characteristics of the vapor were:  $\lambda_v = 0.0248$  W/(m-deg),  $c_v = 2.034 \cdot 10^3$  J/(kg-deg), and  $\gamma = 1.28$ . The characteristic time of the process was proportional to the time of equalization of the temperature in the vapor:  $t_{char} = (10\delta_0)^2 / r_{b0}$ . The thermal diffusivity of the vapor was evaluated at the initial instant of time and was equal to  $a_v = 2.0 \cdot 10^{-5}$  m<sup>2</sup>/sec. For the chosen conditions,  $t_{char} = 0.2 \cdot 10^{-5}$  sec.

The values of the thermophysical parameters of the fluid (water) were assumed to be as follows:  $\lambda_f = 0.683$  W/(m-deg),  $\mu_f = 0.3 \cdot 10^{-3}$  Pa·sec,  $\delta = 0.062$  N/m,  $\rho_f = 980$  kg/m<sup>3</sup>,  $c_{pf} = 4.2 \cdot 10^3$  J/(kg-deg), and  $L = 2.3 \cdot 10^6$  J/kg. The thermal diffusivity of the fluid was  $a_f = 1.7 \cdot 10^{-7}$  m<sup>2</sup>/sec, and the Péclet number was  $Pe_f = 1.24 \cdot 10^4$ , which testifies to the rather substantial role of convection in this process.

As is seen from Fig. 1c, the interparticle interaction exerts a pronounced influence on the maximum pressure in the vapor. With increase in the number of particles the amplitude of the pressure pulse increases, whereas its duration decreases. Unfortunately, the experimental results available in the literature cannot be used for a quantitative comparison to the calculated values since they do not provide a sufficient amount of data on the thermophysical characteristics of the process and, moreover, the experimental conditions differ

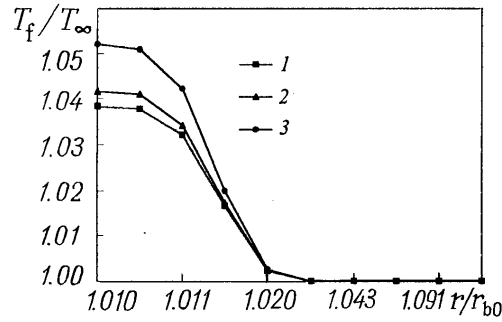


Fig. 3. Temperature distribution in the liquid medium in the radial direction for  $t = 0.6t_{\text{char}}$  ( $\epsilon = 0.01$ ): 1, 2, 3) notation is the same as in Fig. 1.

from those assumed in this model problem. Nonetheless, it is pertinent to note that the order and the qualitative change of the characteristics in the initial stage of vapor explosion coincide. With a collective of particles being present, we can consider that the behavior of the vapor film on an individual particle is similar to its development in a medium with larger inertia.

The calculations show that the expansion of the vapor film on any particle of the "cloud" is slower than in the case of an isolated particle (Fig. 1b). This is associated with the fact that the neighboring particles experience expansion they create extra pressure in the coolant.

With increase in the pressure in the vapor, the temperature of the latter at first increases (Fig. 2) and once the pressure peak has been passed (for  $t \sim 0.6t_{\text{char}}$ ) the interface temperature undergoes a corresponding decrease. The collective effect leads to higher maximum values of the saturation temperature  $T_s$ . As a consequence, a greater temperature drop of the fluid around the vapor interlayer corresponds to a greater amount of inclusions (Fig. 3).

Thus, the calculations carried out for the model of cooling of a collective of particles in a liquid medium have shown the pronounced influence of interaction effects on the thermal and dynamic characteristics of the initial stage of film boiling that develops on inclusions.

This work was carried out with financial support from the Russian Foundation for Basic Research, grant No. 95-02-06075-a.

## NOTATION

$r$ , radial coordinate;  $R$ , radius of the vapor film;  $\delta_0$ , initial thickness of the vapor layer around particles;  $\Phi$ , velocity potential;  $v$ , velocity;  $t$ , time;  $t_{\text{char}}$ , characteristic time of the process;  $t_{\text{Ra}}$ , characteristic time of expansion of a vapor bubble;  $r_b$ , particle radius;  $r_{b0}$ , characteristic radius of particles;  $b$ , dimensionless particle radius;  $l_{ij}$ , distance between the centers of the  $i$ th and  $j$ th particles;  $l_0$ , characteristic distance between particles;  $p$ , pressure;  $\rho$ , density;  $\sigma$ , surface tension of the liquid phase;  $\mu$ , dynamic viscosity of the coolant;  $j$ , density of the vapor-mass flux across the surface of phase transitions;  $T$ , temperature;  $T_{m0}$ , initial temperature of the melt;  $L$ , heat of vaporization;  $B_v$ , individual gas constant;  $\gamma$ , polytropic index;  $\lambda$ , thermal conductivity;  $c_p$  and  $c_v$ , heat capacity at constant pressure and volume;  $\sigma_{\text{rad}}$ , Stefan-Boltzmann constant;  $\alpha_m$  and  $\alpha_f$ , coefficients of radiation and absorption of the vapor layer boundaries;  $\epsilon$ , small parameter;  $a$ , thermal diffusivity;  $Pe$ , Péclet number;  $j_p$ ,  $s_L$ ,  $j_R$ ,  $i_t$ ,  $\lambda_{\text{vf}}$ , and  $t_{\text{rel}}$ , dimensionless combinations. Subscripts and superscripts: 0 and 1, zero and first approximations; v, vapor; f, fluid; m, melt;  $\sim$ , dimensionless values of the variables;  $i$ , number of a particle; s, saturation state; R, fluid-vapor interface;  $\infty$ , values at a distance from a collective of particles; point above the variable, time derivative.

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