STRUCTURE OF SHOCK WAVES IN TWO-PHASE MIXTURES OF A GAS WITH FLUID DROPS

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During propagation of a shock wave (SW) in a gaslike medium (the mixture of a gas with small particles and drops) the strong velocity and temperature phase nonequilibrium features lead to formation of a wave relaxation zone, where mass, momentum, and energy exchange occur between the gas and disperse phases, gradually equating the phase velocities and temperatures. The SW relaxation zone was treated in [1] for gaslike, solid, inert particles. It was noted that the interphase friction process usually affects fundamentally the relaxation zone, while the heat-exchange process affects it much less. The effect of phase transitions (in the absence of drop breakup) on SW structure in gas–drop mixtures was investigated in [2].

In the present study we investigate SW structure in vapor–gas–drop mixtures in the presence of drop breakup processes (by the mechanism of surface layer stripping) and mutual phase transition processes. A mathematical model is suggested, describing the flow of a gas–drop mixture with account of the effect of stripped small drops (with the surface of large-scale drops).

1. Basic Assumptions and Equations. For the mathematical description of the flow of gas–drop mixtures we use the fundamental assumption of mechanics of heterogeneous media: the distances over which the flow parameters change substantially are much larger than the characteristic drop size. It is further assumed that the drops are incompressible and do not collide; viscosity and thermal conductivity effects are important only during phase interaction processes; breakup of large-scale drops occurs under certain conditions by the stripping mechanism, in which case small drops, whose sizes are substantially less than those of the original drops, are stripped in this case from the surface of the large-scale drops; part of the stripped small drops, incident in a warm gas flow, evaporates (with the evaporation process occurring in equilibrium); if the breakup conditions do not apply, the large-scale drops (to the extent that their surface layer starts warming up) also start evaporating.

A mixture of a gas with small drops and their vapor is considered as a single-temperature and single-velocity continuous medium with special thermophysical properties. This medium will be further called an effective gas. Its parameters are denoted by the subscript 1, and the parameters of the large-scale drops – by the subscript 2. The parameters of the gaslike components of the effective gas, corresponding to the gas (the "passive" component, not hindering phase transitions) and the vapor (the "active" component, appearing during evaporation of fluid drops), are denoted by the subscripts 1g and 1v, respectively, and the parameters of the fluid component of the fluid gas (small drops) – by the subscript 12.

Let α_{11} be bulk content of the gaslike phase, and let α_{12}, α_2 be the bulk contents of small and large-scale fluid drops in the mixture. We have $\alpha_{11} = \alpha_{1g} = \alpha_{1v}$, $\alpha_1 = \alpha_{11} + \alpha_{12}$, $\alpha_1 + \alpha_2 = 1$, $\alpha_2 = n\pi d^3/6$, where α_{1g} and α_{1v} are the bulk contents of the gas and the vapor, α_1 is the bulk content of the effective gas, and n and d are the number of large-scale drops in a single mixture and their diameter. The true (denoted by the superscript 0) and reduced (smeared over the volume of the whole mixture) densities of various components of the gas–drop medium under consideration are related by

$$\begin{gathered}\rho_{1g} = \alpha_{11}\rho^0_{1g},\ \rho_{1v} = \alpha_{11}\rho^0_{1v},\ \rho_{12} = \alpha_{12}\rho^0_2,\ \rho_2 = \alpha_2\rho^0_2,\\ \rho_{11} = \rho_{1g} + \rho_{1v} = \alpha_{11}\rho^0_{11},\ \rho_{11} + \rho_{12} = \rho_1.\end{gathered} \tag{1.1}$$

The mass conservation equations of the gas, vapor, small and large-scale drops, as well as the conversation equation of the number of large-scale drops for one-dimensional stationary motion with planar symmetry can be written in the form

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$$\frac{d\rho_{1g}v_1}{dx} = 0,\ \frac{d\rho_{1v}v_1}{dx} = j_{12}^v + nj_2^v,\ \frac{d\rho_{12}v_1}{dx} = nj_2^s - nj_2^v,$$
$$\frac{d\rho_2 v_2}{dx} = -nj_2^s - nj_2^v,\ \frac{dnv_2}{dx} = 0. \tag{1.2}$$

Here v_1 and v_2 are the velocities of the effective gas and of large-scale drops, j_2 is the intensity of mass removal from the surface of an isolated large-scale drop (the superscripts of v and s refer to the evaporation and stripping intensities, respectively), and j_{12}^v the evaporation intensity of small drops. Combining the first three equations (1.2), with account of (1.1) we obtain a mass conversation equation of the thermodynamically equilibrium vapor–gas–drop medium, called above the effective gas:

$$\frac{d\rho_1 v_1}{dx} = nj_2^s + nj_2^v. \tag{1.3}$$

The following mass integral follows from (1.3) and (1.2):

$$\rho_1 v_1 + \rho_2 v_2 = \text{const}. \tag{1.4}$$

The momentum conversation equations for the gas, vapor, and small drop mixture (moving with the same velocity v_1) is written as

$$\rho_1 v_1 \frac{dv_1}{dx} = -\frac{dp}{dx} - nf_{12} - nj_2^s(v_2^s - v_1) + nj_2^v(v_2^v - v_2),$$
$$\rho_2 v_2 \frac{dv_2}{dx} = nf_{12} - nj_2^s(v_2^s - v_2) - nj_2^v(v_2^v - v_2), \tag{1.5}$$

where p is the pressure, f_{12} is the force by the effective gas acting on a single large-scale drop, and v_2^s and v_2^v the characteristic velocities of the stripped and evaporating fluids on the surface of large-scale drops. We further put $v_2^s = v_2^v = v_2$, and therefore Eqs. (1.5) have the simpler form

$$\rho_1 v_1 \frac{dv_1}{dx} = -\frac{dp}{dx} - nf_{12} + (nj_2^s + nj_2^v)(v_2 - v_1),\ \rho_2 v_2 \frac{dv_2}{dx} = nf_{12}. \tag{1.6}$$

The complicated momentum equation (1.5) or (1.6) with (1.3) and (1.2) gives the momentum integral of the mixture

$$\rho_1 v_1^2 + \rho_2 v_2^2 + p = \text{const}. \tag{1.7}$$

The thermal flux equation for large-scale drops and the total energy conversation equation of the whole mixture can be written in the form

$$\rho_2 v_2 \frac{de_2}{dx} = -nq_{2\Sigma} - nj_2^v(i_{2s} - i_2),$$
$$\frac{d}{dx}\{\rho_1 v_1(e_1 + v_1^2/2) + \rho_2 v_2(e_2 + v_2^2/2) + (\alpha_1 v_1 + \alpha_2 v_2)p\} = 0. \tag{1.8}$$

Here e_1, e_2 are the internal energies of the effective gas and of large-scale drops, i_2 is the enthalpy of large-scale drops (the additional subscript s refers to the saturated state), and $q_{2\Sigma}$ is the intensity of thermal flux toward the surface of the large-scale drop from within. From the second of Eq. (1.8) follows the energy integral

$$\rho_1 v_1(e_1 + v_1^2/2) + \rho_2 v_2(e_2 + v_2^2/2) + (\alpha_1 v_1 + \alpha_2 v_2)p = \text{const}. \tag{1.9}$$

We provide the equations of motion of the mixture components. The components of the gaslike phase will be assumed to be calorically a perfect gas, while the condensed phase is treated as an incompressible medium with a constant heat capacity

$$p = (x_{1g}R_g + x_{1v}R_v)\rho_1^0 T_1,\ e_1 = c_{V1}T_1 \tag{1.10}$$
$$(c_{V1} = x_{1g}c_{Vg} + x_{1v}c_{Vv} + x_{12}c_2,\ x_{1g} = \rho_{1g}/\rho_1,\ x_{1v} = \rho_{1v}/\rho_1,\ x_{12} = \rho_{12}/\rho_1);$$
$$\rho_2^0 = \text{const},\ e_2 = c_2 T_2 \quad (R_g, R_v, c_{Vg}, c_{Vv}, c_2 = \text{const}), \tag{1.11}$$

where T_1, T_2 are the temperatures of the effective gas and of large-scale drops; R_g, R_v, c_{Vg}, c_{Vv} are the gas constants and heat capacities at constant volume, c_2 is the heat capacity of the condensed phase, and x_{1g}, x_{1v}, x_{12} mass fractions of the gaslike components, small drops, and effective gas.

2. Specific Laws of Interphase Interaction in the Presence of Drop Breakup. The review [3] of experimental and theoretical studies shows that drop breakup at substantial velocities

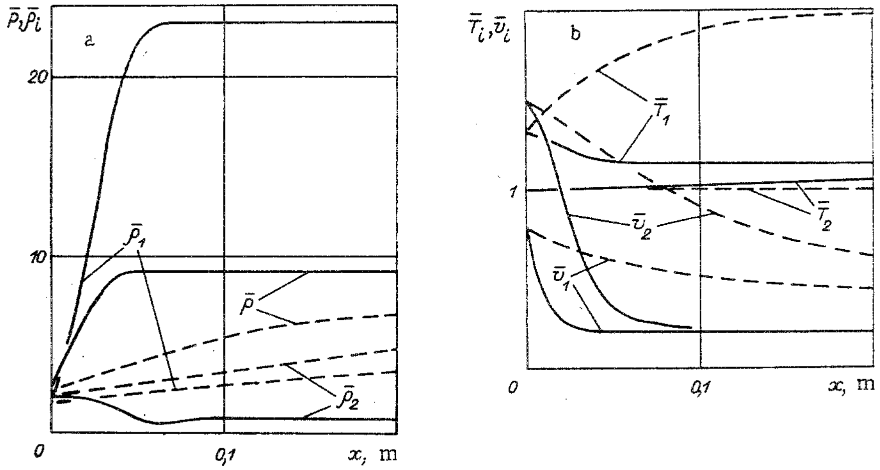

Fig. 1

of relative flow is realized in the regime of their surface layer stripping. An expression for the intensity of mass removal (under the action of gas flow) from the drop surface by a stripping mechanism, satisfying the experimental data described, was obtained in [4, 5]:

$$j^s_{2*} = k\left(\rho^0_1\right)^{1/6}(d/2)^{3/2}\,|v_1 - v_2|^{1/2} \tag{2.1}$$

(k is a constant coefficient). For the mixtures often encountered in practice of air or vapor with water drops k ≈ 1.3-2 $\mathrm{kg}^{5/6}/(\mathrm{m}^{3/2}\cdot\mathrm{sec}^{1/2})$. Analysis of the experimental data makes it possible to draw the conclusion that the fundamental criterion characterizing the realization condition of the stripping mechanism is the Weber number $\mathrm{We}_{12} = \rho^0_1 d\,|v_1 - v_2|^2/\sigma$, where σ is the surface tension coefficient of the drop. In this case the drop in the gas flow starts being stripped only when We_{12} reaches a certain critical value We_c [3, 6]. The stripping intensity is assigned with account of this fact:

$$j^s_2 = \begin{cases} 0, & \mathrm{We}_{12} < \mathrm{We}_c, \\ j^s_{2*}, & \mathrm{We}_{12} \geqslant \mathrm{We}_c \end{cases} \tag{2.2}$$

(j^s_{2*} was determined, for example, according to (2.1)). There exists a number of recommendations on determining the generation conditions of surface layer stripping [3]. We note the recommendation [7]

$$\mathrm{We}_c = 0.5\,\mathrm{Re}^{0.5}_{12},\quad \mathrm{Re}_{12} = \rho^0_1 d\,|v_1 - v_2|/\mu_{11}, \tag{2.3}$$

where Re_{12} is the Reynolds number relative to the drop flow, and μ_{11} is the dynamic viscosity coefficient of the gas.

To determine the intensity of phase transitions between small drops and the vapor it is assumed that they occur along the saturation line $T_1 = T_s$

$$j^v_{12} = \begin{cases} 0, & \rho_{12} = 0, \\ 0, & T_1 < T_s, \\ j^v_{12*}, & \rho_{12} \neq 0; \end{cases} \tag{2.4}$$

$$j^v_{12*} = j^v_{12*}(\partial e_1/\partial x_{12},\ \partial e_1/\partial x_{1g},\ dp/dx,\ dT_s/dp,\ x_{12},\ x_{1g},\ nf_{12},\ nq_{1\Sigma},\ nj^s_2,$$
$$nj^v_2,\ \alpha_1,\ p,\ \rho^0_1,\ v_1,\ v_2,\ i_1,\ i_2,\ i_{1vs}). \tag{2.5}$$

Here T_s is the saturation temperature, $q_{1\Sigma}$ is the intensity of heat flux toward the surface of the large-scale drop from the side of the carrying phase, and i_{1vs} is the vapor enthalpy at the saturation temperature. Due to its awkwardness the expression for j^v_{12} is not provided. For known $f_{12},\ q_{1\Sigma},\ j^s_2,\ j^v_2$ and known dependence $T_s(p)$ Eq. (2.5) can be used to determine j^v_{12} in terms of dp/dx. In the limiting case of absence of large-scale drops, when $j^s_2,\ j^v_2,\ f_{12},\ q_{1\Sigma} \equiv 0$ and there exists only an equilibrium mixture of the vapor with small drops, we obtain

$$j^v_{12*} = -\left[\frac{\partial e_1}{\partial x_{12}}\right]^{-1}\left\{A\frac{dp}{dx}\right\},\quad A = \frac{\alpha_{1v}p}{\rho^0_{1v}v_1} - \rho_{1v}v_1\left(c_{Vv}\frac{dT_s}{dp}\right).$$

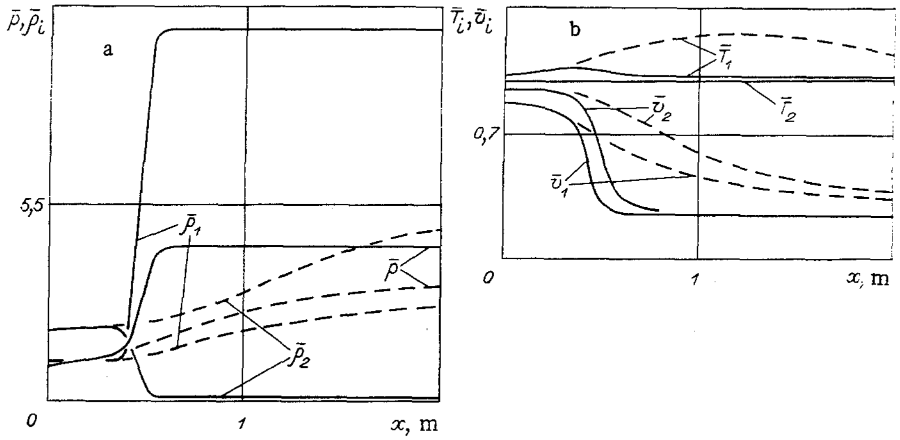

Fig. 2

For a given intensity of phase transitions on the surface of a large-scale drop it is assumed that in the presence of stripping they do not occur:

$$j_2^v = \begin{cases} j_{2*}^v, & j_2^s = 0, \\ 0, & j_2^s \neq 0. \end{cases} \tag{2.6}$$

The intensity of phase transitions j_{2*}^v determined by the thermal balance relation at the drop surface [3, 8]

$$j_{2*}^v = (q_{1\Sigma} + q_{2\Sigma})/l \tag{2.7}$$

(l is the heat of vapor formation).

Experiments show [3, 5] that secondary microdrops, stripped from the surface of large-scale drops, are quite small and flow with the large-scale drop, following the gas flow lines. Therefore, direct collisions between secondary microdrops and the original large-scale drops can be neglected.

The force acting on the large-scale drop from the side of the carrying phase and the intensity of the heat flux toward its surface were assigned in the form

$$\begin{gathered} f_{12} = (\pi d^2/8)\,\rho_1^0 C_d\,|v_1 - v_2|\,(v_1 - v_2), \\ \overset{*}{q}_{1\Sigma} = \pi d \lambda_{11}\,\mathrm{Nu}_1\,(T_1 - T_\Sigma),\ \overset{*}{q}_{2\Sigma} = \pi d \lambda_2\,\mathrm{Nu}_2\,(T_2 - T_\Sigma). \end{gathered} \tag{2.8}$$

Here C_d is the resistance coefficient of the drop, λ_{11}, λ_2 are the thermal conductivity coefficients of the vapor–gas mixture and of the drop, Nu_1, Nu_2 are the external and internal Nusselt numbers, and T_Σ is the surface temperature of the phase separation (usually $T_\Sigma = T_s$ [3, 8]).

In the presence of drop deformation and breakup one can use for C_d the relation [3, 6]

$$C_d = \begin{cases} 27\mathrm{Re}_{12}^{-0.84}, & 0 < \mathrm{Re}_{12} < 80, \\ 0.27\mathrm{Re}_{12}^{0.217}, & 80 \leqslant \mathrm{Re}_{12} < 10^4, \\ 2, & 10^4 \leqslant \mathrm{Re}_{12}. \end{cases} \tag{2.9}$$

The external Nusselt number is found from the ordinary Rance–Marshall equation

$$\mathrm{Nu}_1 = 2 + 0.6\mathrm{Re}_{12}^{0.5}\mathrm{Pr}_1^{0.33}, \quad \mathrm{Pr}_1 = c_{p11}\mu_{11}/\lambda_{11}, \tag{2.10}$$

where Pr_1 is the Prandtl number, and c_{p11} is the heat capacity of the gas phase at constant pressure. In determining the internal Nusselt number of the drop we took into account the nonstationary effect of the enhanced characteristic width of the temperature boundary layer inside the drop:

$$\mathrm{Nu}_2 = \begin{cases} d/\Delta d, & \Delta d \leqslant 0.1d, \\ 10, & \Delta d > 0.1d \end{cases} \quad \left(\Delta d = \sqrt{\nu_2^{(T)} t}\right). \tag{2.11}$$

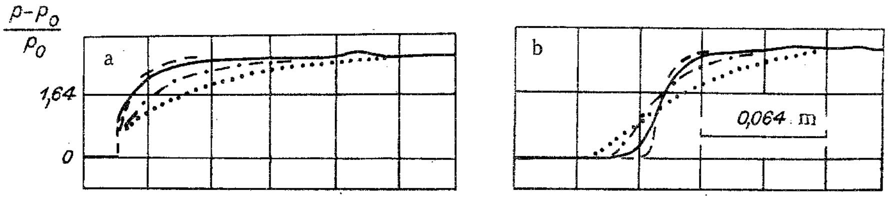

Fig. 3

Here $v_2^{(T)}$ is the temperature conductivity coefficient of the drop, and t is time, referred to the time of drop incidence on the SW front.

Estimates show that the rate of decrease of the drop diameter due to stripping is much higher than the propagation rate of the temperature wave inside the drop. Therefore, in the presence of breakup the drop temperature remains practically constant, since the temperature wave cannot penetrate the limits of the layer of the stripped fluid. For given heat-exchange intensities $q_{1\Sigma}$ and $q_{2\Sigma}$ this fact can be accounted for by putting

$$q_{1\Sigma}=\begin{cases} q^*_{1\Sigma}, & j_2^s=0,\\ 0, & j_2^s\neq 0,\end{cases}\qquad q_{2\Sigma}=\begin{cases} q^*_{2\Sigma}, & j_2^s=0,\\ 0, & j_2^s\neq 0,\end{cases} \tag{2.12}$$

where $q_{1\Sigma}$ and $q_{2\Sigma}$ were determined, for example, according to (2.8).

<u>3. Statement of the Problem.</u> In infinite space, filled by a gas–drop mixture, let there propagate a SW with velocity v_{10} and $v_{10}>a_0^f,\ a_0^e$ (a_0^f and a_0^e are the frozen and equilibrium sound velocities in the mixture ahead of the wave [9, 10]). The SW then undergoes a jump in the gas, on which the gas parameters satisfy the Rankine–Hugoniot relations (the drop effect on the gas parameters directly at the jump can be neglected [2]), while the drop parameters practically do not change. Thus, at the jump we have the following boundary conditions

$$\frac{\rho_{1f}}{\rho_{10}}=\frac{(\gamma_{10}+1)\mathrm{M}}{2+(\gamma_{10}-1)\mathrm{M}},\quad \frac{v_{1f}}{a_0^f}=\frac{2}{\gamma_{10}+1}\left(\frac{\gamma_{10}-1}{2}\mathrm{M}+\frac{1}{\mathrm{M}}\right),$$
$$\frac{p_f}{p_0}=\frac{\gamma_{10}-1}{\gamma_{10}+1}\left(\frac{2\gamma_{10}\mathrm{M}^2}{\gamma_{10}-1}-1\right),\quad \rho_{2f}=\rho_{20},\quad v_{2f}=v_{20},\quad T_{2f}=T_{20},\quad \mathrm{M}=\frac{v_{10}}{a_0^f}. \tag{3.1}$$

Here the additional subscripts 0 and f refer to the parameters ahead and following the jump, the parameters $\rho_{1f},\ \rho_{2f},\ v_{1f},\ v_{2f},\ p_f$ determine the boundary conditions at the point $x = x_f$, corresponding to the position of the jump condensation, and makes it possible to calculate the structure of the relaxation zone in the region $x > x_f$.

Let now $a_0^e<v_{10}<a_0^f$. The SW has than no jump ahead of itself, i.e., the mixture parameters in the condensation wave vary continuously from the equilibrium state ahead of the wave to an equilibrium state behind the wave [9]. In this case, to state boundary conditions one can use the linear solution of Eqs. (1.2)-(1.11) near the initial state in front of the wave. Thus, we have boundary conditions for calculating the structure of a totally diffuse condensation wave:

$$x=x_f:\ \rho_{1f}=\rho_{10}+\rho_1',\quad v_{1f}=v_{10}+v_1',\quad p_f=p_0+p',$$
$$\rho_{2f}=\rho_{20}+\rho_2',\quad v_{2f}=v_{20}+v_2',\quad T_{2f}=T_{20}+T_2', \tag{3.2}$$

where $\rho_1',\ v_1',\ p',\ \rho_2',\ v_2',\ T_2'$ are small perturbation parameters of the mixture, determined by solving the linearized system of equations of motion. We note that drop breakup can be neglected in linearizing (1.2)-(1.11), since the perturbed parameters can be arbitrarily small, so that the breakup conditions do not apply.

<u>4. Estimates of Characteristic Relaxation Times and Analysis of Breakup Conditions.</u> We estimate the characteristic relaxation times of the velocity and temperature of a constant size drop. It is well known that for large Reynolds numbers ($\mathrm{Re}_{12} \gg 1$), when the Newtonian flow conditions concerning drop flow are realized ($C_d \cong 0.44,\ \mathrm{Nu}_1 = 0.6\mathrm{Re}_{12}^{1/2}\mathrm{Pr}_1^{1/3}$), the characteristic relaxation times of the drop velocity τ_v^N and temperature τ_T^N are

$$\tau_v^N \cong \frac{2.6\rho_2^0 d_0}{\rho_{10}^0 v_{10}}, \quad \tau_T^N \cong \frac{\rho_2^0 d_0^2 c_2}{5.1\lambda_{10}(\mathrm{Re}_{0s}\mathrm{M})^{0.5}\,\mathrm{Pr}_{10}^{0.33}}$$
$$(\mathrm{Re}_{0s} = \rho_{10}^0 d_0 a_0^f/\mu_{10}, \quad \mathrm{Pr}_{10} = c_{p10}\mu_{10}/\lambda_{10}). \tag{4.1}$$

Estimates show that $\tau_T^N/\tau_v^N \gg 1$, i.e., for $\mathrm{Re}_{12} >> 1$ the characteristic time of equating the gas and drop temperatures exceeds substantially the characteristic time of equating their velocities.

In the presence of stripping of the surface layer of the drop it makes sense to introduce a characteristic time τ_m of variation in drop mass. It can be shown that the characteristic time, following which the drop mass decreases due to stripping by e ≈ 2.71 times, is

$$\tau_m \cong \rho_2^0 d_0^{3/2}/k(\rho_{10}^0)^{1/6} v_{10}^{1/2}. \tag{4.2}$$

It follows from expressions (4.1) and (4.2) that the following conditions are satisfied in the investigated regions of variation of the decisive parameters $10^2 \leqslant \mathrm{Re}_{0s} < 10^5$, $0.7 > \mathrm{M} < 3$ between the characteristic times τ_v^N and τ_m

$$\frac{\tau_v^N}{\tau_m}\begin{cases} \gg 1, & 10^2 \leqslant \mathrm{Re}_{0s} \leqslant 10^3, \\ \sim 1, & 10^3 < \mathrm{Re}_{0s} < 10^5. \end{cases} \tag{4.3}$$

It is noted in this case that the expression for τ_v^N (4.1) was obtained without account of the effect of decreasing drop diameter due to stripping. Therefore, the comparison carried out between τ_v^N and τ_m (4.3) is of a basic methodological nature.

To analyze the similarity conditions of SW structures we consider three cases.

A. There is no drop breakup during the phase transitions, i.e., $j_2^s, j_2^v = 0$. In this case the basic similarity criteria of the flow are the three dimensionless parameters:

$$\gamma_{10} = c_{p10}/c_{V10}, \quad \mathrm{M} = v_{10}/a_0^f, \quad m = \rho_{20}/\rho_{10} \tag{4.4}$$

(m is the relative mass content of drops ahead of the wave).

B. There is no drop breakup ($j_2^s = 0$), but phase transitions occur on the separation surface ($j_2^v \neq 0$); among the similarity parameters (4.4) we have the dimensionless heat of vapor formation $L = \ell/(a_0^f)^2$.

C. Drop breakup occurs ($j_2^s \neq 0$). The similarity of SW structures is then basically guaranteed by six criteria: γ_{10}, M, m, K, We_{0s}, We_c $(K = k/(\rho_{10}^0)^{1/2}\mu_{10}^{1/3}, \quad \mathrm{We}_{0s} = \rho_{10}^0 d_0 (a_0^f)^2/\sigma)$.

5. Several Calculation Results. The structure of condensation waves was investigated in a mixture of water drop with air. Situations were considered in which ahead of the wave the mixture is in thermodynamic equilibrium ($v_{10} = v_{20}$, $T_{10} = T_{20}$) at pressure 0.1 MPa. The equations of motion given in Sec. 1 for a vapor–gas–drop mixture with the closure relations (2.1)-(2.12) and boundary conditions (3.1), (3.2) were integrated numerically by the modified Euler method. The calculation accuracy was controlled by satisfying the first integrals of mass, momentum, and energy (1.4), (1.7), and (1.9).

We investigated the effect of the drop breakup process, as well as of the decisive parameters (wave intensity, mass content, and drop diameter) and various parameters on the nature of mixture flow in the wave relaxation zone. The calculations were carried out for waves with Mach numbers from 0.7 to 3. The relative drop mass content $m = \rho_{20}/\rho_{10}$ and the drop diameter d_0 were varied, respectively, from 0.2 to 5 and from 60 to 600 μm. Several calculation results are shown in Figs. 1-3. Figure 1 illustrates the effect of drop breakup on the structure of a strong SW (with a front-end jump) for M = 1.5, m = 2, d_0 = 200 μm, the solid lines correspond to presence of breakup, and the dashed – to its absence. It is seen that breakup leads to substantial shortening of the length of the SW relaxation zone. In the presence of drop breakup their reduced intensity $\bar{\rho}_2 = \rho_2/\rho_{10}$ (Fig. 1a) in the wave relaxation zone behaves nonmonotonically: initially it decreases, then it increases, and at the same time it always increases monotonically in the SW in the absence of breakup. This is related to the fact that two substantial factors affect the reduced density of large-scale drops: surface layer stripping of drops, and their damping. Sripping causes a decrease in $\bar{\rho}_2$, and damping, leading to an increase in large-scale drop concentration – to an increase in $\bar{\rho}_2$. Therefore, depending on which of these factors predominates, the reduced density of large-scale drops in the relaxation zone of a condensation wave can either increase or decrease. It is noted that due to heat losses by the gas during the heating of stripped small drops the gas temperature $\overline{T}_1 = T_1/T_{10}$ decreased substantially (Fig. 1b), and small drops could not evaporate. In this connection the effective gas composition included small drops, leading to substantial increase of its reduced density $\overline{\rho}_1 = \rho_1/\rho_{10}$.

Figure 2 shows the effect of drop breakup on the structure of a weak SW (diffuse, i.e., without a front-end jump) for M = 0.95, m = 2, and d_0 = 200 μm (the notations are the same as in Fig. 1). As is seen, the reduced density of large-scale drops behind the weak wave is substantially lower than behind the strong one, i.e., the total effect of stripping in a weak wave can be substantially more clearly manifested in a weak wave than in a strong one.

So far there exist no experimental studies of the effect of drop breakup on SW structure. In this connection it is interesting to compare calculated and experimental wave structures in gaslike solid inert particles. In Fig. 3 we compare typical experimental pressure oscillograms, obtained in [11] (solid lines), with calculations. The experimental oscillogram in Fig. 3a for m = 1.0 corresponds to a SW with a front-end jump (M = 1.16). The oscillogram in Fig. 3b with m = 1.7 corresponds to a totally diffuse wave with M = 0.99. The particle diameter in the mixtures used in the experiments varied from 3 to 9 μm.

Calculations were carried out for monodisperse mixtures of the corresponding mass contents for various particle diameters: 3 (dashed lines), 6 (dashed–dotted), and 9 (dotted) μm. Good agreement is observed between theoretical and experimental structures, while best agreement with experiment is observed for calculations with particle diameter 3 μm. Since there exist no data in [11] on the particle distribution function over size, one may conclude that the mass content of particles with diameter 3 μm predominates in the gaslike structures used.

LITERATURE CITED

1. G. Rudinger, "Some properties of shock relaxation zone in gas flows carrying small particles," Phys. Fluids, 2, No. 5 (1964).
2. R. I. Nigmatulin, "Hydromechanical equations and condensation waves in two-velocity and two-temperature continuous media in the presence of phase transitions," Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 5 (1967).
3. A. I. Iavndaev, A. G. Kutushev, and R. I. Nigmatulin, "Gas dynamics of multiphase media," Itogi Nauki i Tekhniki, Mekh. Zhidk. Gaz., VINITI, Moscow (1981), Vol. 16.
4. O. Engel, "Fragmentation of water drops in the zone behind an air shock," J. Res. Nat. Bur. Stand., 60, No. 5 (1958).
5. A. Ranger and J. Nicholls, "Aerodynamic shattering of liquid drop," AIAA J., 7, No. 2 (1969).
6. A. L. Gonor and V. Ya. Rivkind, "Drop dynamics," Itogi Nauki i Tekhniki, Ser. Mekh. Zhidk. Gaz., VINITI, Moscow (1982), Vol. 17.
7. R. Dickerson and T. Coultas, "Breakup of droplets in an accelerating gas flow," AIAA Paper No. 611 (1966).
8. R. I. Nigmatulin, Foundations of Mechanics of Heterogeneous Media [in Russian], Nauka, Moscow (1978).
9. R. I. Nigmatulin, "Condensation waves in two-phase media," Vestn. Mosk. Gos. Univ., Ser. 1, Mat. Mekh., No. 4 (1969).
10. A. I. Ivandaev, "Propagation of small perturbations in a mixture of water vapor and drops," Akust. Zh., 24, No. 1 (1978).
11. E. Outa, K. Tajima, and H. Morii, "Experiments and analysis on shock waves propagating through a gas-particle mixture," Bull. JSME, 19, No. 130 (1976).