RESULTS OF A STUDY OF THE EFFECT OF DROP FRAGMENTATION ON THE STRUCTURE OF SHOCK WAVES IN GAS–DROP MIXTURES

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A mathematical model was proposed in [1] to describe the flow of a two-phase gas–drop mixture with allowance for the effect of drop fragmentation. The study presented examples of calculation of the structures of stationary shock waves (SW) in the presence of drop fragmentation. It was established that fragmentation by the mechanism of stripping of the surface layer of the drop has a significant effect on flow in the SW relaxation zones. In particular, fragmentation of the drops leads to a substantial (by one order or more) reduction in the characteristic lengths of these zones. Investigators observed a nonmonotonic change in the corrected density of coarse drops in the wave relaxation zone.

Here, we undertake a detailed analysis of the results of a study of the effect of the governing parameters (wave intensity, mass content of drops in front of the wave, drop diameter) and different factors on the structure of shock waves in gas–drop mixtures in the presence of drop fragmentation.

1. Basic Assumptions. We will employ the assumptions normally used to describe the flow of a gas suspension. Furthermore, we assume that the drop fragmentation occurs under certain conditions and that it takes place by the stripping mechanism (it was noted in [2] that in experiments with shock waves of moderate intensity, drop fragmentation usually occurs in the surface-layer stripping regime). Here, fine drops (droplets) break away from the surface of coarse drops, the former being much smaller than the latter; some of the droplets vaporize when they enter the hot gas flow (the vaporization is an equilibrium process). If the conditions for drop fragmentation do not come about, then the coarse drops also begin to vaporize (as their surface layer is heated); the mixture of the gas and the droplets with their vapor is regarded as a one-velocity, one-temperature continuum (an "effective gas") with its own unique thermophysical properties.

Within the framework of the above assumptions, the authors of [1] examined the equations of motion of a gas–drop mixture and the closing relations (equations of state, laws of phase interaction, etc.). They did not consider nonsteady effects (the Basse effect, buoyancy, etc.) which delay establishment of stationary velocity and temperature distributions in the neighborhood of the drops (since they could be ignored in the ranges of the governing parameters investigated [3]).

2. Basic Formulas Connected with the Effect of Drop Fragmentation and the Results Needed for Further Analysis. Experiments show [2, 4] that drops in a gas flow begin to be stripped only when the Weber number We_{12} reaches the critical value We_c. The law of drop fragmentation was assigned with allowance for this fact [1]

$$j = \begin{cases} 0, & We_{12} < We_c, \\ j_*, & We_{12} \geqslant We_c, \end{cases} \quad We_{12} = \rho_1^0 d |v_1 - v_2|^2/\sigma.$$

Here, ρ_1^0 is the true density of the gas; d and σ are the diameter and surface tension of the drop; v_1 and v_2 are the velocities of the gas and drop. The intensity of stripping of the surface layer of the drop j_* was determined from the following formula [5], which agrees satisfactorily with the experimental data [5, 6]: $j_* = k(\rho_1^0)^{1/6}(d/2)^{3/2}|v_1 - v_2|^{1/2}$, $k \cong 1.3 - 2$ $kg^{5/6}/(m^{3/2} \cdot sec^{1/2})$.

To calculate We_c, we used the relation [7]

$$We_c = 0.5\, Re_{12}^{0.5}, \quad Re_{12} = \rho_1^0 d |v_1 - v_2|/\mu_1 \tag{2.1}$$

(Re_{12} is the Reynolds number for flow about the drop, μ_1 is the absolute viscosity of the gas) and the formula [2]

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$$\mathrm{We}_c = 60. \tag{2.2}$$

In determining the rate of phase transformations between the droplets and the vapor, it was assumed that they occur on the saturation line (i.e., in equilibrium) [1]. The rate of vaporization of the drops was found from the condition of heat balance on their surface. Here, a surface Σ-phase was recognized as being present; the temperature of this phase differs from the mean temperatures of the gas and drop.

The drop drag coefficient C_d was calculated from the formula [2, 4]

$$C_d = \begin{cases} 27\,\mathrm{Re}_{12}^{-0.84}, & \mathrm{Re}_{12} < 80, \\ 0.27\,\mathrm{Re}_{12}^{0.217}, & 80 \leqslant \mathrm{Re}_{12} < 10^4, \\ 2, & 10^4 \leqslant \mathrm{Re}_{12}. \end{cases} \tag{2.3}$$

It should be noted that the drag coefficient of a drop undergoing deformation and fragmentation differs appreciably from the drag coefficient of solid particles. For comparison with (2.3), we present the form of C_d most commonly used for solid particles [2]:

$$C_d = 24/\mathrm{Re}_{12} + 4.4/\mathrm{Re}_{12}^{0.5} + 0.42. \tag{2.4}$$

Experiments [3] show that even if $\mathrm{We}_{12} \geq \mathrm{We}_c$, drop fragmentation does not occur instantaneously. It becomes appreciable after a certain induction period t_i during which the gas flow acts on the drop. The literature contains several recommendations for calculating t_i. Here, we used the recommendations in [2, 7]

$$t_i = 1.5\,(\lg \mathrm{We}_{12})^{-0.25} t_*, \quad t_* = d_0\,(\rho_2^0/\rho_1^0)^{0.5}/|v_1 - v_2|, \quad 10 < \mathrm{We}_{12} < 10^4, \tag{2.5}$$

where t_* is the characteristic fragmentation time; ρ_2^0, d_0 are the true density and initial diameter of the drop.

In the presence of stripping of the surface layer, it makes sense to introduce the characteristic length L_m associated with the change in the mass of the drop. For example, the characteristic length over which the mass of the drop decreases (due to stripping of its surface layer) by the factor e = 2.71 [1]

$$L_m \cong \rho_2^0 d_0^{3/2} v_{10}^{1/2} / [k\,(\rho_{10}^0)^{1/6}] \tag{2.6}$$

(the subscript 0 pertains to the parameters of the gas and the drops in front of the SW). For comparison, we write the characteristic length L_v^N associated with relaxation of the velocity of a drop with a constant diameter d_0 (in the Newtonian flow regime, when $\mathrm{Re}_{12} \gg 1$):

$$L_v^N \cong 2.6 \rho_2^0 d_0 / \rho_{10}^0. \tag{2.7}$$

Estimates [1] have shown that in the ranges $10^2 \lesssim \mathrm{Re}_0 \lesssim 10^5$ and $0.7 \leq M \leq 3$, the following relations are satisfied between the characteristic lengths associated with velocity relaxation L_v^N and surface stripping L_m

$$\frac{L_m}{L_v^N} \begin{cases} \ll 1, & 10^2 \leqslant \mathrm{Re}_0 \leqslant 10^3, \\ \sim 1, & 10^3 < \mathrm{Re}_0 < 10^5, \end{cases} \quad \mathrm{Re}_0 = \frac{\rho_{10}^0 d_0 v_{10}}{\mu_1}. \tag{2.8}$$

Here, the expression for L_v^N (2.7) was obtained without allowance for the reduction in drop diameter due to stripping. Thus, the estimates (2.8) are mainly of a methodological character.

3. Formulation of the Problem. Let a shock wave propagate at the velocity v_{10} in an infinite space filled with a gas–drop mixture. If $v_{10} > a_0^f$, a_0^e (a_0^f and a_0^e are the frozen and equilibrium sonic velocities in the mixture ahead of the shock wave [8, 9]), then the SW is preceded in the gas by a discontinuity on which the parameters of the gas satisfy the Rankine–Hugoniot relations, while the parameters of the drops remain nearly constant. Thus, we have the following boundary conditions on the discontinuity:

$$\frac{\rho_{1f}}{\rho_{10}} = \frac{(\gamma+1)\,M}{2+(\gamma-1)\,M^2}, \quad \frac{v_{1f}}{a_0^f} = \frac{2}{\gamma+1}\left(\frac{\gamma-1}{2}M + \frac{1}{M}\right),$$

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

Here, the subscripts 0 and f denote parameters ahead of and behind the discontinuity, respectively; γ is the adiabatic exponent of the gas. The parameters ρ_{1f}, ρ_{2f}, v_{1f}, v_{2f}, p_f, T_{1f}, and T_{2f}

determine the boundary conditions at the point $x = x_f$, corresponding to the position of the shock wave, and they make it possible to calculate the structure of the relaxation zone in the region $x > x_f$.

When $a_0^e < v_{10} < a_0^f$, the SW is not preceded by a discontinuity, i.e., the parameters of the mixture in the shock wave change continuously from an equilibrium state ahead of the wave to an equilibrium state behind the wave [8]. In this case, the boundary conditions can be formulated by using the linear solution of the equations of motion in the region of the initial state ahead of the wave. Thus, we have the boundary conditions to calculate the structure of a fully eroded shock wave:

$$x = x_f: \begin{cases} \rho_{1f} = \rho_{10} + \rho_1', \ v_{1f} = v_{10} + v_1', \ p_f = p_0 + p', \ T_{1f} = T_{10} + T_1', \\ \rho_{2f} = \rho_{20} + \rho_2', \ v_{2f} = v_{20} + v_2', \ T_{2f} = T_{20} + T_2' \end{cases}$$

($\rho_1', v_1', p', T_1', \rho_2', v_2', T_2'$ are small perturbations of the parameters of the mixture; they are found from the solution of the linearized system of motion equations).

Analysis of the conditions of SW structures [1] has shown that in the presence of drop fragmentation (by the mechanism of surface-layer stripping), the main similarity criteria will be six dimensionless parameters: γ, $M = v_{10}/a_0^f$, $m = \rho_{20}/\rho_{10}$, k_1, We_{0s}, We_c ($We_{0s} = \rho_{10}^0 d_0 \times (a_0^f)^2/\sigma$, $k_1 = k/[(\rho_{10}^0)^{1/2}\mu_1^{1/3}]$) (m and We_{0S} are the relative mass content of the drops and the characteristic Weber number, calculated from the frozen sonic velocity in the mixture ahead of the wave).

4. Analysis of the Results. We studied the structure of shock waves in a mixture of water drops and air with an initial pressure $p_0 = 0.1$ MPa. We investigated the effect of the principal governing parameters (wave intensity, mass content of drops, drop diameter) and certain other factors on the character and length of the wave relaxation zone in the presence of drop fragmentation (the effect of drop fragmentation on SW structure was examined in detail in [1]). We examined waves with Mach numbers from 0.85 to 3. The relative mass content $m = \rho_{20}/\rho_{10}$ and diameter d_0 of the drops ranged from 0.2 to 5 and from 60 to 600 μm, respectively. Estimates showed that in the presence of drop fragmentation by the stripping mechanism, a temperature wave does not succeed in penetrating inside the layer of liquid being stripped from the drop because the rate of removal of mass from the drop surface (as a result of stripping) is much greater than the velocity of the temperature wave inside the drop. Thus, we assumed in the calculations that, in the presence of stripping, there is no heat exchange between the gas and the drops.

Depending on the dimensions of the droplets torn from the drops, the drops may then either be located in a flow of pure gas – in which case the droplets do not affect the interaction between the gas and the drops – or they may be surrounded by the effective gas – in which case the droplets affect the phase interaction. Thus, in the expressions for the interphase force and stripping rate, we used either the density of the pure gas or the density of the entire carrier phase, together with the droplets. Calculations showed that the distribution of the parameters of the mixture in the relaxation zone of the wave is affected little by the increase which occurs in the density of the gas due to the presence of the droplets. In light of this, we henceforth assumed that the effect of the droplets on the mechanical interaction of the phases and the rate of stripping of the drops could be ignored.

It is interesting to follow the change in We_{12} for drops in an SW. The characteristic rules of the change in W_{12} of a drop in the relaxation zones of waves at $M = 1.5$ and different values of m are shown in Fig. 1 (curves 1). The solid lines correspond to $m = 2$, while the dashed lines correspond to $m = 0.2$ (the curves of We_c in the two cases nearly coincide). The dashed curve corresponds to a constant value of $We_c = 60$ [Eq. (2.2)]. It is evident that if $m = 2$, $d_0 = 200$ μm, then W_{12} changes nonmonotonically: it first increases due to an increase in the difference of the velocities of the phases; then, when this difference decreases, We_{12} also decreases. At $m = 0.2$, $d_0 = 200$ μm, We_{12} decreases monotonically. At a certain distance from the leading discontinuity, We_{12} becomes less than We_c: at these points, drop fragmentation ceases. At $m = 2$, this distance is equal to about 0.05 m, while it is about 0.1 m at $m = 0.2$.

For comparison, Fig. 1 shows the law of change in the Weber number in a shock wave at $M = 0.95$, $m = 2$, and $d_0 = 200$ μm (curve 2). It is evident that in the case of a diffuse (continuous) wave (in contrast to a shock wave with a discontinuity, when droplets begin to be stripped from drops immediately behind the wave front), stripping of the drops begins at a

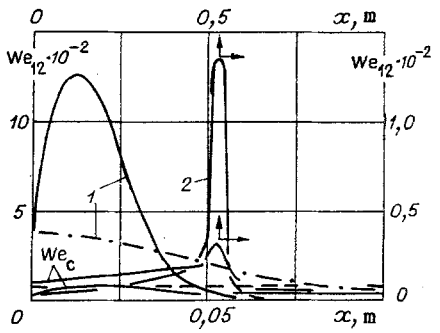

Fig. 1

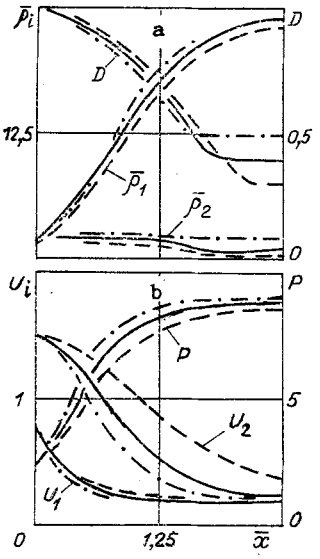

Fig. 2

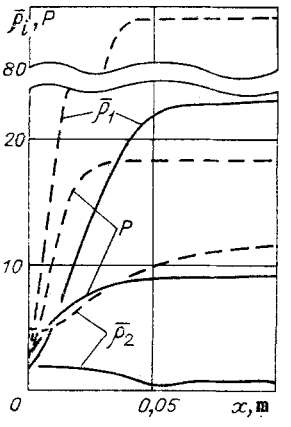

Fig. 3

distance of about 0.45 m from the beginning of the wave (the characteristic point where the perturbations of the parameters amount to approximately 1%) and ends at a distance of about 0.57 m. In the figure, these distances are determined by the points of intersection of the curves of We_{12} and We_c. It should be noted that the length of the region over which stripping occurs is considerably greater in a fully diffuse wave than in a shock wave with a frontal discontinuity (it is roughly twice as great in the variant examined here).

The literature contains different recommendations regarding the criterion of the initiation of fragmentation. Thus, it is desirable to examine how this use of a given criterion affects flow in the relaxation zone. With this in mind, we calculated the structures of waves with two different formulas for We_c, (2.1) and (2.2). The calculations showed that these formulas yield nearly the same results in regard to determination of the beginning of drop fragmentation.

It is interesting to study the effect of variation of the drag coefficient of the drops on flow in the relaxation zone of an SW. With this as a goal, we performed calculations with different relations for the drag coefficient C_d, (2.3) and (2.4). It was found that the arbitrariness in the determination of C_d mainly affects only the parameters of the drops. It has little effect on the parameters of the carrier phase.

It was noted in Part 2 that drop fragmentation does not take place immediately in experiments (even if $We_{12} > We_c$). Instead, it becomes noticeable after the elapse of a certain induction period t_i during which the gas flow acts on the drops. To study the effect of this factor on the relaxation zone, the wave structure was calculated with allowance for the lag in the fragmentation process. The induction time t_i was calculated from empirical equation (2.5). The results of the calculations showed that allowing for the induction period leads to only a slight increase in the length of the relaxation zone and has almost no effect on the behavior of the parameters of the phases.

It is evident from the calculations that in the ranges of the governing parameters investigated, gas temperature decreases substantially in the relaxation zone of the wave because a considerable portion of the thermal energy of the gas is expended on heating the large quantity of droplets torn from drops. Entering the gas flow, many of the droplets are not vaporized. Thus, the effective gas contains a large amount of liquid in the form of droplets, which in turn signficantly increase the corrected density $\bar{\rho}_1$ of the effective gas (Figs. 2 and 3). The substantial reduction in the temperature of the gas in the relaxation zone leads to a situation whereby the drops (after stripping has ceased) also remain liquid. Thus, in the ranges of the governing parameters considered here, phase-transition processes have almost no effect on the formation of the SW structure.

Let us examine the question of the similarity of SW structures in mixtures with different initial drop diameters. We will represent the distributions of the parameters in the waves with different d_0 in the form of dependences on the dimensionless coordinate $\bar{x} = x/L_m$, where L_m is the characteristic drop-stripping length, determined from Eq. (2.6). Figure 2

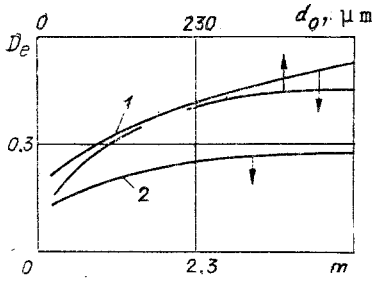

Fig. 4

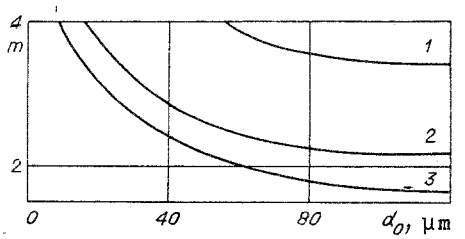

Fig. 5

shows the distribution of the densities ($\bar{\rho}_i = \rho_i/\rho_{10}$) and velocities ($U_i = v_i/a_0^f$) of the phases, as well as the distribution of pressure in the gas ($P = p/p_0$) and drop diameter ($D = d/d_0$) with respect to the dimensionless coordinate in the relaxation zone of an SW at M = 1.5 and m = 2. The dashed, solid, and dot–dash curves correspond to 60, 200, and 600 μm. It is evident that a difference in the initial diameter of the drops has a significant effect only on the parameters of the drops. It has little effect on the parameters of the effective gas. Thus, we can conclude that there is approximate similarity between SW structures in mixtures with different initial drop sizes when their diameter ranges within d_0 = 60-600 μm.

It is important to examine the effect of the mass content of drops in a mixture on the structure of the wave. Figure 3 shows distributions of the parameters of the effective gas and drops in the relaxation zone of an SW with M = 1.5 and d_0 = 200 μm and different m. The solid curves correspond to m = 2, while the dashed curves correspond to m = 5. The parameters of the mixture in the wave are heavily dependent on the initial mass content of drops. For example, the equilibrium density of the effective gas is nearly four times greater at m = 5 than at m = 2, while pressure is almost twice as great. We point out the qualitatively different behavior of drop density in these cases: at m = 2, due to stripping, the equilibrium value of drop density behind the wave becomes less than the initial value in front of the wave. At m = 5, despite stripping, drop density increases and the equilibrium density becomes greater than the initial value. This is related to the fact that a larger mass content of drops leads to more intensive deceleration of the drops behind the wavefront and to an increase in the concentration per unit volume of the mixture. Thus, it is possible to have a situation in which, despite stripping, the corrected density of the drops in the relaxation zone might increase due to an increase in drop concentration.

Figure 4 shows the dependence of the final drop diameter D_e after the cessation of stripping on m and d_0 (lines 1 and 2 correspond to d_0 = 200 and 60 μm) for waves with M = 1.5. It is evident that D_e increases with an increase in m. This is attributable to the fact that an increase in the mass content of drops (given a fixed drop diameter) is accompanied by an increase in the intensity of mechanical interaction of the phases. This accelerates the process of equalization of the phase velocities, which in turn leads to rapid cessation of drop fragmentation ($We_{12} < We_c$). An increase in d_0 also leads to an increase in D_e [in the figure the relation $D_e(d_0)$ corresponds to m = 2]. This is connected with the fact that an increase in d_0 is accompanied by a decrease in the area of the phase boundary, where stripping takes place. Thus, stripping decreases at large d_0.

Regarding the case of a fully diffuse wave without a frontal discontinuity, it is interesting to determine the values of M, m, and d_0 at which drops are fragmented and the values of same at which no fragmentation occurs over the entire wave ($We_{12} < We_c$). Figure 5 shows curves depicting the boundary between these regions in the plane (d_0, m). Lines 1-3 were constructed for M = 0.85, 0.95, and 0.99. The region above each curve corresponds to the presence of fragmentation, while the region below corresponds to its absence. It is evident that an increase in M is accompanied by a decrease in the region of d_0 and m in which drops do not undergo fragmentation.

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STRUCTURE OF A FLOW OF BINARY MIXTURES OF SOLID PARTICLES UNDER CONDITIONS OF TWO-DIMENSIONAL SHOCK-WAVE LOADING

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Study of the behavior of mixtures of dissimilar particles during shock-wave loading is interesting in connection with problems concerning the explosive compaction of powder composites, the generation of physicochemical changes in powder mixtures, etc. Currently, one of the most common sources of information on processes taking place in the shock compression of powdered materials is investigation of the structure of specimens which remain intact after loading. However, this method has a serious shortcoming: the data obtained generally do not permit unambiguous interpretation, and the subsequent analysis represents only one of several possible approaches to explanation of the causes and mechanisms of the phenomena in question. A more objective conclusion can be obtained on the basis of direct observation of the dynamical flow pattern of the substance, particularly by the method of impulsive x-ray diffraction analysis.

Here, we use this method for the first time in experiments to directly observe the structure of the flow of mixtures of dissimilar solid particles during their shock loading under conditions simulating their practical application.

The objects of our study were two-component systems consisting of particles of a lightweight material ("transparent" to x-rays) and intervening particles of a heavier ("opaque") material. The sizes of the particles of each component were roughly the same and amounted to 0.5-1.0 mm. The ratio of the volume fractions of the light and heavy components was much greater than unity, so we will henceforth refer to the heavy component as the impurity component and the light component as the main component. We used particles of aluminum, graphite, sand, and sodium chloride as the main component. The impurity particles used were granules made from an alloy of tungsten with molybdenum, sintered tungsten powder, and lead. The granules were close to spherical.

Shock-wave loading was done in a two-dimensional formulation (Fig. 1). The particles of the main component were arranged in the form of a layer 5 of uniform thickness on a massive steel base 6. The thickness of the layer was 15-20 mm, while the mean density was 30-50% of the density of the material of the particles. Lead-foil "control samples" 20 μm thick (numbered 4 in Fig. 1) were placed inside the layer at certain depths. The foil surfaces were parallel to the surface of the base. We used only two foils located at different depths in one test. The particles of the impurity component 3 were located on top of the lead foil in one row and were in direct contact with the foil. The distance between the particles was 5-10 particle diameters. A plane charge of explosive 1 was placed on the top surface of the layer. The charge was detonated from one end, so that we generated an oblique shock wave (SW) OA in the system. The cumulative interaction of the wave with the surface of the base in turn produced a reflected wave OB. This method of loading is a good approximation of the conditions under which powders are explosively compacted.

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