The shields were used to protect the surfaces of catalytically active detectors (the detector surface was coated with silver, for example) in an apparatus with an electric-arc air heater. It should be noted that at $M \approx 6$, attainable on this apparatus, the zone with Prandtl–Meyer flow comprises 5-7° (if one assumes, by analogy with the results at lower M, that the results of the experiments and calculations will also agree in this case).

The experiments demonstrated the workability of the proposed shields. In the absence of a shield the state of the detector surface varied in the course of one startup ($\tau \approx 10$ sec) — the surface became electrically nonconducting. When shielded, the detector surface became electrically nonconducting after four to five 10-sec startups. Heat-flux measurements with shielded catalytic detectors showed that under the test conditions the heat flux did not depend on the catalytic activity of the surface with the accuracy of the error in the heat-flux measurement. Thus, these experiments made it possible to reveal the character of the flow over shields whose action is based on the use of stream deflection with the realization of Prandtl–Meyer flow and to decrease the deposit of impurities on the detector surface in an apparatus with an electric-arc gas heater.

LITERATURE CITED

1. V. I. Alferov and A. S. Bushmin, "An electric discharge in a supersonic air stream," Zh. Eksp. Teor. Fiz., 44, No. 6, 1775 (1963).
2. McGregor, "The vapour-screen method of flow visualization," Fluid Mech., 12, No. 4 (1961).
3. A. Ferri, Elements of Aerodynamics of Supersonic Flows, Macmillan Co., New York (1949).

BREAKUP OF A LIQUID DROP AGGREGATE IN SHOCK WAVES

B. E. Gel'fand, S. A. Gubin, E. N. Timofeev, and S. M. Sheparnev

UDC 532.529.516

The development of investigations of the dynamics of multiphase flows indicates that the breakup process of a liquid drop has a significant effect on the physical and chemical phenomena in a gas–liquid medium. However, the majority of the available data concerning the breakup of a drop have been obtained by using as an example individual drops or drops remotely spaced from one another [1, 2]. In actual cases, an aggregation of drops in a system is distributed in a random way. As a result, there are still no grounds for assuming that the behavior of the whole aggregate is identical with the behavior of drops taken individually from this aggregate. It is justifiable to expect that for a certain density of the number of drops, a mutual effect of the drops on one another will start. In the modern power installations, using the energy of liquid fuel, the density of the number of drops per unit volume is large and increases with increase of the pressure at which combustion of the fuel occurs. An increase of the volume fraction of liquid in the system up to values exceeding 1% of the gas volume may require the interaction between adjacent drops to be taken into consideration as the distance between drops decreases to a value of $\Delta Z < 10 d_0$, where d_0 is the size of the drop. The appearance of specific breakup properties of the drops in the presence of closely arranged adjacent particles is entirely probable.

One of the causes of the mutual effect of the particles is shown in [3], where a hypothesis is expressed concerning the increase of the speed of breakup in a chain of consecutive drops in consequence of the increase of the two-phase flow density because of the collapse of particles which are higher with respect to the flow than the original. However, this conclusion from [3] is debatable, since it is drawn only on the basis of analysis of the final stage of breakup, when screening of adjacent particles during blowing with gas is not taken into account. The experimental demonstrations of the acceleration of breakup given are not sufficiently convincing.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 6, pp. 43-48, November-December, 1978. Original article submitted December 30, 1977.

 0021-8944/78/1906-0742$07.50

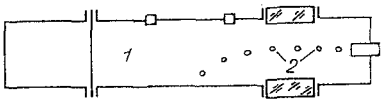

Fig. 1

There is also another probable cause for the variation of the speed of breakup of an aggregate of drops. This cause is induced by a change of the drag coefficient of a group of drops. A relation is given in [4] for calculating the drag coefficient of a group of particles c_1 in the form

$$c_1 = c_0(1 + 6.8\, d_0 \Delta l^{-1}).$$

It follows from this relation that when $\Delta l d_0^{-1} < 10$, the drag coefficient and, consequently, also the acceleration in a group of particles are greater than for an isolated particle c_0.

In order to explain the effect of neighboring drops on the breakup of individual particles in aggregates, a series of experiments was undertaken by the procedure developed in [2, 5]. The investigations were conducted with three aggregates of drops. The first of the aggregates of drops was formed by the collapse of a jet of water flowing out along the axis of a shock tube from an opening with a diameter of 0.8 mm, according to the scheme shown in Fig. 1. In the observation section of the tube 1, as a result of this an almost coaxial chain of drops 2 with a diameter of d_0 = 1.2 to 1.5 mm and with a distance between drops of $(2-3)d_0$ to $(10-15)d_0$ was formed.

The second aggregate of drops was formed by an ordered group of vertical openings arranged along the surface of the tube with a pitch of up to $(10-15)d_0$. The third aggregate of drops was obtained from a single opening, spraying a random cluster of drops of liquid nitrogen with a diameter of 80-100 μm into the tube space. The distance between the particles was established in a random manner and fluctuated over a wide range. The maximum density of the number of particles was limited upward by the resolution of the system, in order to avoid blocking the photographs with an excessive number of images of the disintegrating particles. For convenience of observation, these experiments were conducted with liquid nitrogen. The investigations of the breakup of a cluster of drops were conducted in shock waves with Mach numbers of M = 1.05 to 1.6. The range of Weber numbers $W = \rho_1 u_1^2 d_0 (2\sigma)^{-1}$ amounted to 5 to 10^3. Here ρ_1 and u_1 are the density and velocity of the gas (nitrogen) behind the wave, and σ is the surface tension of the liquid.

Let us consider the experimental results. Figure 2a shows the state of several combinations of water drops from the first aggregate with a diameter of d_0 = 1.5 mm in a wave with M = 1.47, i.e., with a gas flow velocity of u_1 = 220 m/sec and $W \approx 10^3$. The photograph was obtained at the instant t = 500 μsec behind the wave. The characteristic time of the process $\tau = d_0 \rho_f^{0.5} (\rho_1 u_1^2)^{-0.5}$ = 190 μsec, i.e., the dimensionless time for the instant of mapping $t^* = t\tau^{-1} = 2.6$. With this value of t*, an intense breakup of an isolated drop with density ρ_f should occur, for example, as for the leading (to the lift in the photograph) drop of the chain. The breakup of the drop in the chain, obviously, is delayed in time and takes place, like the breakup of an individual particle, at the time $t^* \approx 1.8$. The distance between the drops is $\Delta l \approx 3d_0$. The breakup delay of neighboring drops in the initial stage is marked even with $\Delta l \approx 7d_0$, although when $\Delta l \gg 7d_0$ all the drops in the chain are split up like single drops. The time for the total breakup of all particles in the chain, within the limits of the measurement error of 30-40%, is invariable despite the delay of the early and middle stages. Because the pressure wave successively crosses the individual drops, their times of stay in the floware different and amount to 2.6 for the right-hand particle and 2.9 for the left-hand particle. All the particles belong to one aggregate.

According to [3], with a distance between drops of $\Delta l \approx (3-5)d_0$, the time of breakup of the drops in the coaxial chain should amount to only 30% of the time of breakup of a single particle and, consequently, should be equal to $t^* = 1.5$. The experiment shows that even for $t^* = 2.6$, breakup of the drops is far from its completion.

Figure 2b shows the state of the second aggregate of drops with an average diameter of d_0 = 1.5 mm behind the wave front with M = 1.3 and W = 500 ($\Delta l d_0^{-1} = 7$). It can be seen that the presence of neighboring (along the flow) particles in the case of $\Delta l \geqslant 7d_0$ does not affect the breakup of a particle taken individually in the aggregate, but each drop breaks down like a single drop. The presence of a number of particles arranged transverse to the flow is not

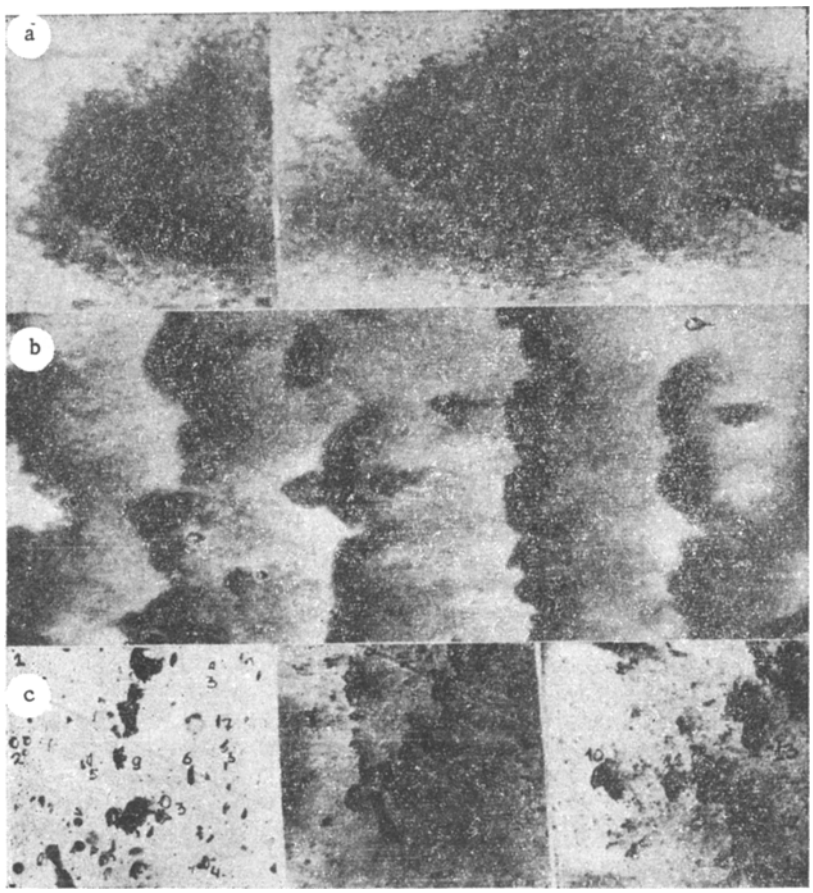

Fig. 2

expressed when $\Delta l d_0^{-1} = 1$. The photograph of the breakup of the random (third) aggregate of drops is of great interest. In Fig. 2c, the photograph was obtained behind the wave with M = 1.05 (dynamic pressure heat of gas $\rho_1 u_1^2 = 2300$ N/m^2) at the instants t = 90, 120, and 170 μsec after the wave. The photographs give the total representation concerning the possible types of disintegration of the drops in a cluster behind the pressure wave. The range of Weber numbers for drops of d_0 = 60-500 μsec amounted to 4-100, and the Reynolds numbers were Re = 10^2-$2 \cdot 10^3$. Very small drops not undergoing disintegration (denoted by the number 1) can be seen; W ≈ 4-5.2 and Re = 100. Drops can be seen breaking up on a type of parachute, W ≈ 7-14 and Re ≈ 250-500, at a different stage from the instant of deploying the parachute (2, 3) up to its disintegration (4, 5). Drops which are deformed to the state of liquid disks (6, 7), W ≈ 20-40, Re ≈ 800-1500, and drops starting to disintegrate with the separation of a boundary layer of liquid (8-10) can be seen. It may be noted that the disintegration of all drops in the random aggregate occurs independently of one another, with the possible exception of particles 11-13, separated from one another by a distance of Δl < (3-4)d_0. Almost nowhere, apart from the last stage of completion of breakup, when it was impossible to carry out the measurements with sufficient reliability, is a marked acceleration of breakup observed, as in [3], which may be due partially to the noncoaxial disposition of the drops.

Analysis of the experiments carried out shows that the effect of neighboring drops can be seen in cases when special measures are taken for an orderly disposition of the drops, close to coaxial along the flow in the wake of each other. Under these conditions, the marked disintegration delay in the initial stages of breakup with Δl < (3-7)d_0 has its cause in the shading of the rear drops, deformed by the leading particle. We recall that the length of the vortex wake behind the deformed drop will be about $\Delta l \approx (3\text{-}5)d$, where d = (2 to 3)$d_0$. Thus, the flow pattern behind the leading drop can be distorted at distances of up to $\Delta l \approx 10 d_0$. In consequence of the disintegration delay in the initial stage in a cluster of orderly disposed drops, the shape of the curve of the decrease of mass of the drop with time may be modified. However, this problem will require a special study. We shall use the data obtained for estimating the conditions for which interactions of neighboring drops can be expected,

and we shall explain the reason for the accelerated disintegration of a cluster of drops in the terminal stage of breakup in shock waves. It is well-known that in a stoichiometric two-phase mixture, drops of liquid hydrocarbon (for example, kerosene) under normal conditions are at distances of $\Delta l \approx (10\text{-}20)d_0$ in oxygen and $\Delta l = (20\text{-}40)d_0$ in air. The volume fraction of liquid kerosene in the gas at an arbitrary pressure $p > p_0 = 1$ bar for oxygen will be $\beta = V_g V_0^{-1} (p\, p_0^{-1}) \cdot 1800^{-1}$. The number of drops per unit volume of gas, for an excess oxidant coefficient α, amounts to

$$n = 6\beta \left[\pi \alpha d_0^3\right]^{-1}.$$

The number of particles N arriving inside a cylinder of length L and diameter $d = 3d_0$ can be established from the quantity n ($N = 2.25\pi n d_0^2 L$), and the distance between drops in the wake behind the deformed drop $\Delta l = LN^{-1}$.

We estimate the composition of the mixture for which the onset of the interaction of neighboring drops can be expected from the value of $\Delta l = \Delta l(\alpha)$, and then the boundary value of α^*, equal to $\Delta l(\alpha^*) = 10d_0$. For $\alpha < \alpha^*$, interaction of the drops is possible in the case of an ordered disposition of the particles. With a random disposition of the particles in space, their interaction is possible when $\alpha_1^* < \alpha^*$. Estimates show that the interaction of coaxially disposed drops in stoichiometric mixtures of kerosene with oxygen and air can develop at pressures of 10 and 50 bar, respectively. With normal conditions, the interaction of neighboring drops starts in mixtures which are significantly overenriched with the liquid fuel component, since $\Delta l = 10d_0$ when $\alpha^* < 0.1$.

When analyzing the pattern of the breakup of an aggregate of drops in shock tubes, attention should be paid to the change of flow parameters, the gas density, and the relative velocity of the gas and drops in the relaxation zone [6]. In consequence of the retardation of the drop relative to the gas and the increase of the gas density because of its retardation with the drops, in the terminal stages of breakup over the range $1.5 < t^* < 4\text{-}5$, the Weber numbers for two-phase flow are increased by comparison with the case of an individual isolated particle, and this can accelerate the disintegration of the drop in the final stage. However, the increase of the Weber number obviously is not so significant. The results of measurements of the particle size after secondary breakup in a smoothly accelerating flow [7] show this. It is shown in [7] that over the range of distances between drops of $\Delta l d_0^{-1} = 6\text{-}13$, no change of size of the broken-up particles is noticed. We shall analyze the causes, on account of which the estimate of the distances where particle interaction in [3] can develop was found to be excessive. One of the reasons consists in that in [3], the velocity of the particles after breakup is assumed to be equal to the gas flow velocity behind the wave. This assumption is true only for particles found at the leading edge of the wake behind a drop but not close to it. It is well known [5] that acceleration of the secondary products of breakup from the velocity of the primary drop to the velocity of the gas takes place within the wake. During a time $0 < t^* \leq 2$, the velocity of the original particle is small in comparison with the velocity of the gas. Because of this, the speed of movement of the two-phase medium within the wake changes from the velocity of the drop to the velocity of the gas. In the expression for the time of breakup, the effect of velocity is more significant than the effect of density, and a reduction of velocity even by 20% can totally compensate the effect of an increase of the gas density by 40%.

The formal introduction of the density of a two-phase mixture into the expression for the characteristic breakup time shows that by the substitution of a gaseous medium by a two-phase medium the pressure differential between the bow and stern parts of the drop increases. There are no experiments whatsoever confirming the validity of this situation. The concept of uniformity of the distribution of liquid within the wake does not coincide with the atomization scheme of the particles. During breakup, the mass of the drop is concentrated within a thin film, curved in the direction of the flow. The bulk of the liquid is carried away from the rim of the particle and is concentrated in an annular region which is gradually expanding because of the turbulence of the gas flow. The nonuniformity of distribution of the mass of the liquid within the wake is particularly significant in the vicinity of the nucleus of the original drop. The concept of the shape of the wake of a drop in the form of a cone, with the base equal to the diameter of the deformed particle, is valid only for a narrow range of characteristic times behind the shock front, $0 < t^* < 1$. It is shown in [2, 5] that the shape of the wake behind the drop during the greater part of the breakup process is considerably different from conical, and the mass of the liquid is distributed in a larger volume of gas than is supposed in [3]. In order to analyze the limiting conditions for which interac-

tion of the drops can be observed generally, there is no necessity to resort to artificial constructions. It is completely sufficient to analyze the experimental data of [5], in order to verify in the absence of the mutual effect of the drops that $\Delta z d_0^{-1} \approx 40\text{-}50$.

The estimates in [3] were carried out partially for a linear model of the coaxial disposition of drops throughout the chain. For cases of practical interest, a coaxial disposition of the drops is a rare occurrence. A deviation from the coaxial disposition of drops makes the expected shortening of the time of breakup according to the model of [3] unrealistic.

Also, it is not possible to agree with the opinion of the authors of [3] concerning the continuous increase of the diameter of a single disintegrating particle during the time interval $0 < t^* < (4\text{-}5)$. It is known from [2, 5] that an increase of the diameter of an isolated drop is observed only for $0 < t^* < 2$. In the case of $2 < t^* < (4\text{-}5)$, the diameter of the drop decreases and it ceases to exist as a single entity. The inclusion of data on the ignition delay of drops in order to demonstrate the diminution of the disintegration process is not valid because during the interaction of the shock wave with the system of drops the temperature of the gas increases. A digression from the enumerated special features of the breakup process led to the fact that the expected shortening of the time according to the model of [3] was not observed in a number of the experiments in [3] and was not corroborated in our experiments.

LITERATURE CITED

1. R. E. Luna and W. A. Klikov, "On the aerodynamic breakup of liquid drops," SC-RR-2716 (1966).
2. B. E. Gel'fand, S. A. Gubin, and S. M. Kogarko, "Varieties of the breakup of drops in shock waves and their characteristics," Inzh.-Fiz. Zh., 27, No. 1, 120-126 (1974).
3. G. E. Fox and E. K. Dabora, "Breakup of liquid drops due to convective flow in shocked sprays," in: Fourteenth International Symposium on Combustion, Combustion Institute (1973), pp. 1365-1373.
4. P. N. Rowe, "Drag forces in a hydraulic model of a fluidized bed," Trans. Inst. Chem. Eng., 39, No. 2, 175-180 (1964).
5. W. G. Reinecke and G. D. Waldman, "An investigation of water drop disintegration in the region behind strong shock waves," AIAA Paper No. 147 (1975).
6. S. M. Kogarko, B. E. Gel'fand, S. A. Gubin, and A. A. Borisov, "Dynamics of the breakup of drops of liquid in a gas flow," Dokl. Akad. Nauk SSSR, 198, No. 1, 71-73 (1971).
7. L. J. Zajac, "Droplet breakup in accelerating gas flows," NASA CR-134479 (1973).