SPECIAL CHARACTERISTICS OF THE BREAKUP OF LIQUID DROPS WITH A HIGH GAS PRESSURE

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In a majority of power plants, the conversion of a liquid fuel into combustion products takes place at high pressure and with a high velocity of the motion of the gas. It is natural that in the choice of the working scheme of the process account must be taken of the effect of possible changes in the characteristics of the atomization process of a liquid fuel, connected with a change in the density of the gas. Of particular importance is the effect of perturbations of the pressure and the velocity on the behavior of liquid drops in a high-density gas flow. The number of communications in which such questions are discussed is very limited, since an overwhelming number of experiments were made at atmospheric pressure [1-7]. Only articles [8, 9] give qualitative concepts with respect to the effect of perturbations of the pressure on the breakup of drops with a gas pressure up to 30 atm. From the information given in [8, 9] it is difficult to form a judgment with respect to the change in the critical conditions and the time parameters of the process of the breakup of drops with a rise in the initial pressure (density) of the gas.

1. Experimental Unit and Principal Results

A shock tube was used to establish the characteristics of the process of atomization with a high initial pressure. The initial nitrogen pressure was 1-50 atm. The drop size of the kerosene varied in the interval 0.1-1 mm. Figure 1 shows recordings in a shock wave and in a compression wave, obtained using a pickup with a natural frequency of 30 kHz. On beams 1, 2 of the oscillograph, there are recorded the readings of pickups arranged at a distance of 345 mm apart. The time scale (along the horizontal) is 250 msec/scale division. To beam 3 of the oscillograph there is fed the output signal of a photoelement, recording the moment of the flashing of the pulsed lamp of a strobotron. The pressure scale on the oscillograms of Fig. 1a on beams 1, 2 is 1.1 atm, and on Fig. 1b, 0.52 and 0.83 atm/division of the vertical scale.

One of the problems of the investigations consisted in finding the conditions of the start of the breakup of drops in a high-density gas flow. As with a pressure p_0 = 1 atm, the critical conditions for breakup are described the the value of the Weber number, calculated using the relationship $W=\rho(w-u)^2 d_0(2\psi)^{-1}$, where ρ is the density of the unperturbed gas; w is the velocity of the gas; u is the velocity of the drops; d_0 is the initial drop size; ψ is the surface tension of the liquid. The critical Weber number was found from the greatest dimension of drops which retain their integrity in a flow of gas behind a wave with a profile of the pressure like that of Fig. 1a. The value of the Weber number was calculated from the parameters of the gas at the shock front. The accuracy in determination of the critical Weber number was 40%.

As experiments have shown, the value of the critical Weber number, characterizing the appearance of the atomization of the drops, within the limits of the above accuracy, does not depend on the pressure in the interval 1-50 atm. The critical Weber number is close to $W^* \approx 5$. With an increase in the pressure in a steady-state gas flow, there is no breakup

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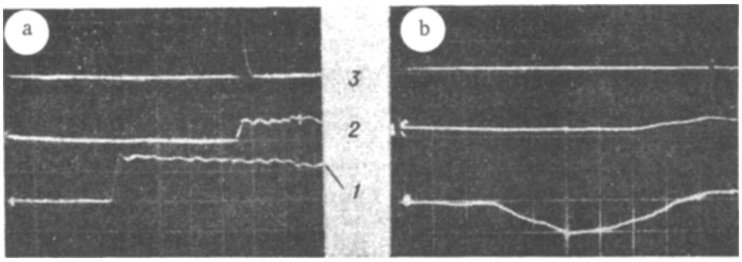

Fig. 1

Fig. 2

of drops of the "parachute" type. Even with a small supercritical Weber number $W \approx 1.2W^*$ the breakup of the drops has a chaotic character. At atmospheric pressure, atomization of the "parachute" type is appreciable in the interval of Weber numbers up to $2W^*$ [2]. With chaotic breakup, individual particles break away from a drop in a random manner.

The moving-picture photo shown in Fig. 2 corresponds to atomization with ordered breakaway of the surface layer of liquid. The drop diameter was 900 μ, and the initial pressure of the gas was 30 atm. The velocity u of the gas behind a wave with an intensity $\delta p p_0^{-1} = 0.1$ is equal to 20 m/sec. Here δ_p is the pressure drop at the shock front. The Weber and Reynolds numbers are equal, respectively, to 283 and 38,500. The Reynolds number is found from the relationship $\mathrm{Re} = \rho(w - u)d_0\mu^{-1}$, where μ is the viscosity of the gas. The photographs were taken at the moments of the time 0, 0.84, 346, and 688 μsec after the encounter between the wave and the drops. Qualitatively, the picture of the breakup does not change in comparison with what was observed with p_0 = 1 atm. During the course of a determined interval of time, the drop is merely deformed in the flow of gas. Breakup sets in with a deformation of the drop $d^* = dd_0^{-1} \approx 2$–$3$ (d is the instantaneous value of the cross section of the drop). Breakaway of the surface layer of liquid is noted with Weber numbers $W \geqslant A(p_0)\mathrm{Re}^{0.5}$. The value of the coefficient $A(p_0)$ with p_0 = 1 atm is about 0.8, and with p_0 = 5 atm, about 0.3.

With a rise in the pressure of the gas, the time required for complete breakup of the drops decreases, but, as at atmospheric pressure, is close to the value $t_5 \simeq 5d_0(w - u)^{-1}(\rho_f\rho^{-1})^{0.5}$ (ρ_f is the density of the liquid). The value of the induction time is lowered (Fig. 3). Along the axis of ordinates there is plotted the value of the ratio of the induction time τ_i to the value of $t = d_0(w - u)^{-1}(\rho_f\rho^{-1})^{0.5}$, i.e., $T^* = \tau_i t^{-1}$. The induction time on the moving-picture photo corresponds to a recording time of 84 μsec, and the time required for complete breakup to the moment of recording, 688 μsec.

Let us examine the picture of the same drop (d_0 = 0.9 mm) in a compression wave (see Fig. 2b). The initial pressure of the gas p_0 = 12 atm. The Weber and Reynolds numbers, W = 159, Re = 17,000 correspond to the moment of the greatest pressure in the compression wave. The character of the change in the pressure with time is shown in Fig. 4. The velocity of the gas at the antinode of the pressure is 25 m/sec. The moments of photography (the first photo shows the drop ahead of the wave) are marked by the arrows on the pressure–time curve. There is (although incomplete) breakup, with breakaway of the boundary of liquid, which is not observed with p_0 = 1 atm.

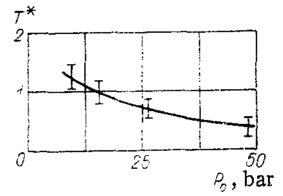

Fig. 3

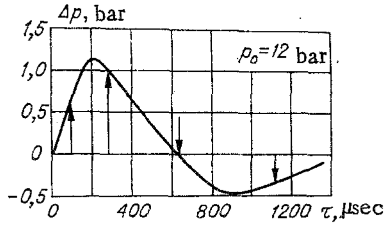

Fig. 4

Let us examine the state of a drop with the dimension 0.2 mm in the same compression wave (see Fig. 2c). From the series of photos, made at times of 0, 120, 190, 250 μsec, it can be seen that the drop breaks up completely in the compression phase. We introduce the parameter of the dimensionless residence time of the drop in the compression wave $\Delta t^* = \Delta t t^{-1}$. The value of the residence time t of the drop in the compression wave corresponds to the greatest value of the density and velocity of the gas (Δt is the duration of the positive phase of compression). The dimensionless atomization time is calculated using the relationship $\tau^* = \tau t^{-1}$. Breakup of drops in the shock wave started at the moment of time $\tau^* \approx 2$ and ended at the moment of time $\tau^* \approx 6$—7 . The residence time of a drop with a diameter of 0.9 mm in a compression wave is close to the time of the start of the breakup of the drop, and the residence time of a drop with a diameter of 0.2 mm is close to the time of complete breakup. Breakaway of the surface layer of liquid from the drops was observed only in cases where $W_1 > Re_1^{0.5}$. Here the Reynolds Re_1 and Weber W_1 numbers were calculated from the maximal values of the velocity and density of the gas in the compression wave. If the Weber number was $W_1 \approx 10 - 25$, then the starting drop decomposed into several equal parts in the rarefaction behind the compression wave.

2. Discussion of Experimental Results

The process of the breakup of drops with a high initial pressure of the gas has a number of special characteristics. In a high-density gas flow only two varieties of the atomization process can be clearly distinguished: chaotic breakup and breakup with breakaway of the surface layer of liquid. Breakup of the "parachute" type was not observed, although this phenomenon is possible in a narrow region of Weber numbers near the critical value W* = 5. With a rise in the pressure there is a decrease in the time of the start of breakup of the drops, and a broadening of the region of parameters in which the drops split up with breakaway of the surface layer of liquid. Atomization with breakaway of the surface layer in a dense gas flow takes place only in compression waves.

Figure 5 gives plots of the values of the perturbations required for the breakup of drops with p_0 = 1 atm (curves 1, 3) and 10 atm (curves 2, 4). Curves 3, 4 were plotted using the dependence W* = 5, and curves 1, 2 using the relationship $W = A(p)Re^{0.5}$. With a 10-fold increase in the pressure (density) of the gas, the intensity of the perturbations $\delta_p = \Delta p p_0^{-1}$ drops by almost three times.

The changes observed in the atomization process are explained by the effect of the pressure and density of the gas on the character of the flow of the gas stream around the drops. It is well known [3-11] that breakup of the drops takes place under the action of a number of simultaneous processes (deformation of a drop, vortical motion of the gas behind the drops, formation of a boundary layer of liquid on the windward side of a drop, motion of the liquid inside a drop, excitation of Rayleigh—Lamb—Taylor instability at the gas–liquid interface). All the above-listed processes have characteristic times and scale parameters, from which a judgement can be formed as to the possibility of the development of one process or another under actual conditions. Schematically, the atomization of a drop can be represented in the following manner. During the course of a short period of time after a drop enters the zone behind a shock wave, some distribution of the pressure is established at the surface of the drop. The time required for establishment of the pressure field is approximately $\tau_1 \approx d_0 u^{-1}$, i.e., with $d_0 \approx 10^{-3}$ m and u $\approx 10^2$ m/sec, $\tau_1 = 10^{-5}$ sec. Under the action of the forces of friction, the drop is flattened-out into an ellipsoid of revolution. With the flattening of a drop, the zone of breakaway of the gas flow is shifted toward its equator, and its whole windward surface is subjected to the action of gas eddies.

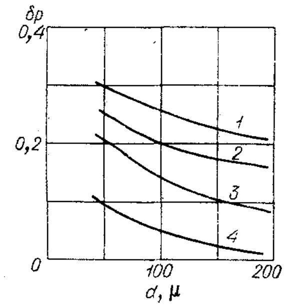

Fig. 5

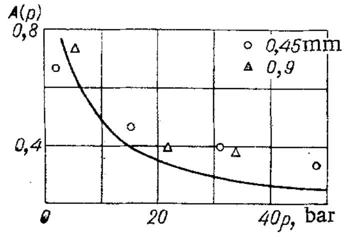

Fig. 6

The liquid at the surface of the drop undergoes the action of the friction forces of the gas and moves away from the center of the drop toward the edges. The thickness of the boundary layer rises from $\delta = 0$ at the stagnation point to $\delta = \delta_{max}$ at the equator of the drop, where part of the liquid is entrained by the gas.

At the surface from $\delta = 0$ to $\delta = \delta_{max}$, the value of $Ap/dx < 0$ (x is the distance along the windward surface). Beyond the equator of the drop, the value of $dp/dx > 0$ and the rise in the thickness of the boundary layer ceases. Eddy flow of the gas behind the drops can also bring about stagnation of the motion of the liquid in them, and perturbation of vortical flow inside a drop is not excluded. Acceleration of a drop leads to the development of waves at the surface of the liquid. The amplitude of the waves rises, and the drops divide into several small pieces. The atomization ends with the breakup of the secondary drops in the flow of gas.

The phenomena of deformation of the drops, development of a boundary layer, and the instability of an accelerating phase interface have been better investigated than the others. We characterize the degree of deformation of a drop by the quantity $d^* = dd_0^{-1}$, the boundary layer of the liquid by the limiting thickness at the equator of a drop $\delta^* = 2\delta_{max}d_0^{-1}$, and the instability of the surface by the wavelength $\lambda^* = \lambda d_0^{-1}$. Here d is the instantaneous transverse dimension of a drop; δ_{max} is the thickness of the boundary layer, defined by the relationship [5]:

$$\delta_{max} = 3.44 d_0 (\mathrm{Re}\, \mu_f \mu^{-1})^{0.5} (\rho \rho_f^{-1})^{0.5};$$

λ is the wavelength, equal to $\lambda = 4.1 d_0 W^{0.5} (1 - \rho\rho_f^{-1})^{0.5}$. Let us consider the identity $W = 0.5\,\mathrm{Re}^2 L^{-1} \rho\rho_f^{-1} (\mu_f \mu^{-1})^{0.5}$ ($L = d_0 \rho_f \sigma \mu_f^{-2}$ is the Laplace number). With all other parameters being unchanged, let a stream of gas flow around a drop, with a pressure p_0 and p_1, so that $W(p_0) = W(p_1)$. Then the Reynolds numbers of the gas flow differ by $\rho(p_1)^{0.5}|\rho(p_0)|^{-0.5}$ times. This means that, with exactly the same Weber number, the conditions of the flow of gas around a drop differ considerably. With a rise in the Reynolds number, the intensity of the eddy formation increases, which is reflected in the distribution of the pressure around the drop. With small supercritical Weber numbers, the breakaway of the eddies takes on a chaotic character and promotes the early development of breakup of the drops.

In the general case, the breakup time is made up of the breakaway time of the boundary from the drops τ_i and the time of the penetration of the drops by waves of instability Δt_i. With a rise in the pressure of the gas, the development of Rayleigh–Lamb–Taylor instability becomes difficult. There is a rise in the limiting Weber number, starting with which instability is impossible. Thus, with a pressure $p_1 > p_0$, the limiting Weber number increases by $(\rho_f - \rho_0)(\rho_f - \rho_1)^{-1}$ times. In the case under consideration, a rise in the Weber number by 1.1 times is possible. With the density of the gas, there is a rise in the length of the unstable waves on the surface of the liquid and, along with it, in the time required to attain the same value of the amplitude of the waves. Then, with a rise in the pressure of the gas, the penetration time of a drop by waves of instability must increase.

An increase in the initial pressure of the gas promotes a rise in the friction forces at the gas–liquid interface. If ρ_1 and ρ is the density of the gas with a pressure $p_1 > p_0$, then the friction force with a pressure of p_1 is $(\rho_1\rho_0^{-1})^{0.25}$ times greater. An increase in the friction force leads to a decrease in the thickness of the boundary layer of the liquid and to a decrease in its formation time. The rise in the friction forces makes possible the breakaway of the boundary layer of liquid, even in weak shock waves and in compression waves. According to Mayer [10], the friction force can be evaluated by the quantity $0.5\beta\,(u-w)^2\,\Delta f$ where β is the coefficient of the wind resistance ($\beta \approx 0.2$). Equating the friction to the force of surface tension, maintaining the boundary layer on a drop, $\psi\delta^{-1}\Delta f$, we obtain the breakaway condition in the form

$$W \geqslant 1.5\,(\rho_f\rho^{-1})^{0.25}\,(\mu\mu_f^{-1})^{0.5}\,\mathrm{Re}^{0.5}.$$

Consequently, the coefficient of proportionality in the relationship $W \geqslant A(p)\,\mathrm{Re}^{0.5}$ is determined by the expression

$$A(p) = 1.5\,(\rho_f\rho^{-1})^{0.25}\,(\mu\mu_f^{-1})^{0.5}.$$

Figure 6 gives a comparison of calculated and experimental values of A(p).

Thus, qualitatively, the picture of the breakup of drops with an increase in the pressure up to 50 atm remains the same as at 1 atm. The observed changes in the quantitative parameters are connected with an increase in the friction forces at the phase interface. An increase in the friction force promotes an acceleration of the process of bringing the liquid into motion and shortens the period of time required for breakaway of the liquid from the drop.

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