Experimental Investigation of the Aerodynamic Breakup of Liquid Drops

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An experimental investigation was made of the deformation and the mechanism of stripping-type breakup of liquid drops. Experiments were conducted in a 60 × 150 mm cross-sectional shock tube equipped with pulsed laser holographic interferometry. Water drops having diameters of 1030 and 4300 μm were examined for shock wave Mach numbers from 1.3 to 1.5 in atmospheric air. The Weber and Reynolds numbers under these conditions were in the range of 600 to 7600 and 1.38 to 10.4 × 10⁴, respectively. In previous works, the experimental data of the stripping-type breakup were obtained by spark shadowgraphs and streak schlieren methods and high-speed movies. However, in previous works, due to the effect of light scattering through the micromist, the structure of disintegrating drops could not be visualized. The purpose of the present work is, by using holographic interferometry, to re-examine the classical problem of the stripping-type breakup of liquid drops. As a result, a four-stage mechanism of the stripping-type breakup of liquid drops was established.

Nomenclature

Bo	= Bond number = $\rho_2 g r^2/\sigma$
d	= drop diameter
g	= acceleration
M	= Mach number
r	= radius
Re	= Reynolds number, $\rho_2 u_2 d_0/\mu_2$
T	= temperature
t	= time
$\bar{t}$	= dimensionless time, $tu_2(\rho_2/\rho_\ell)^{1/2}/d_0$
t^*	= dimensionless time, $tu_2(\rho_2/\rho_\ell)^{1/2}/r_0$
u	= flow velocity
We	= Weber number, $\rho u^2 d_0/\sigma$
μ	= viscosity
ρ	= density
σ	= surface tension

Subscripts

0	= initial condition
2	= gas state behind shock wave
b	= breakup
c	= critical
ℓ	= liquid
s	= shock wave
md	= maximum diameter
os	= onset of stripping

I. Introduction

THE stripping-type breakup of liquid drops was first observed by Lane[1] in 1951. The first substantial shock-tube investigation was conducted by Engel[2] in 1958.

The stripping-type breakup of liquid drops in a high-speed gas stream has many important scientific and engineering applications, e.g., supersonic flights (rain damage to aircraft structures), space research (ablation), and combustion and detonation of two-phase mixtures (especially rocket engine combustion instability). This is why this phenomenon has been studied extensively for the past 35 years. However, the comprehensive literature survey by Wierzba and Takayama[3] revealed that substantial discrepancies exist among previous works.

There are two main views regarding the mechanism of stripping-type breakup. The first view, which was presented for the first time by Rabin et al.,[4] developed by Ranger[5] and Ranger and Nicholls,[6] and then confirmed by Kauffman and Nicholls,[7] Krauss and Leadon,[8] and Bielenkii and Ievsiev,[9] pointed out that the shattering of liquid drops can be attributed to the boundary-layer separation process. The second view, proposed for the first time by Hinze[10] and later developed and confirmed by Engel[2] (see Refs. 11–25), emphasizes the importance of the formation of surface waves on the windward surface of the drop that was caused by their rapid acceleration when the drops were exposed to the gas stream. It should be mentioned here that two interpretations are given on the role of these surface waves. In the first interpretation proposed by Engel,[2] Buzukov,[11] Rojec,[12] and Dickerson and Coultas,[13] the removal of microdrops from the surface of the original drop was attributed to the capillary surface wave erosion from the broken crests of capillary waves that developed on the drop surface. The second interpretation, by Reinecke and Waldman[14] and Harper et al.,[16] emphasized the unstable rapid growth of the surface waves that finally induces shattering of the remaining part of the drop.

However, even among the works that support the second interpretation, there are large discrepancies regarding the conditions at which surface waves are formed. For example, the first visible evidence of surface waves was reported by Simpkins.[18,19] At $We \approx 1800$, surface wave is formed[18,19] at $We > 100$, while the formation of surface waves is initiated.[20] It should be emphasized that the role of the surface waves is mostly from analytical considerations,[15,16] and the experimental evidence is very poor.

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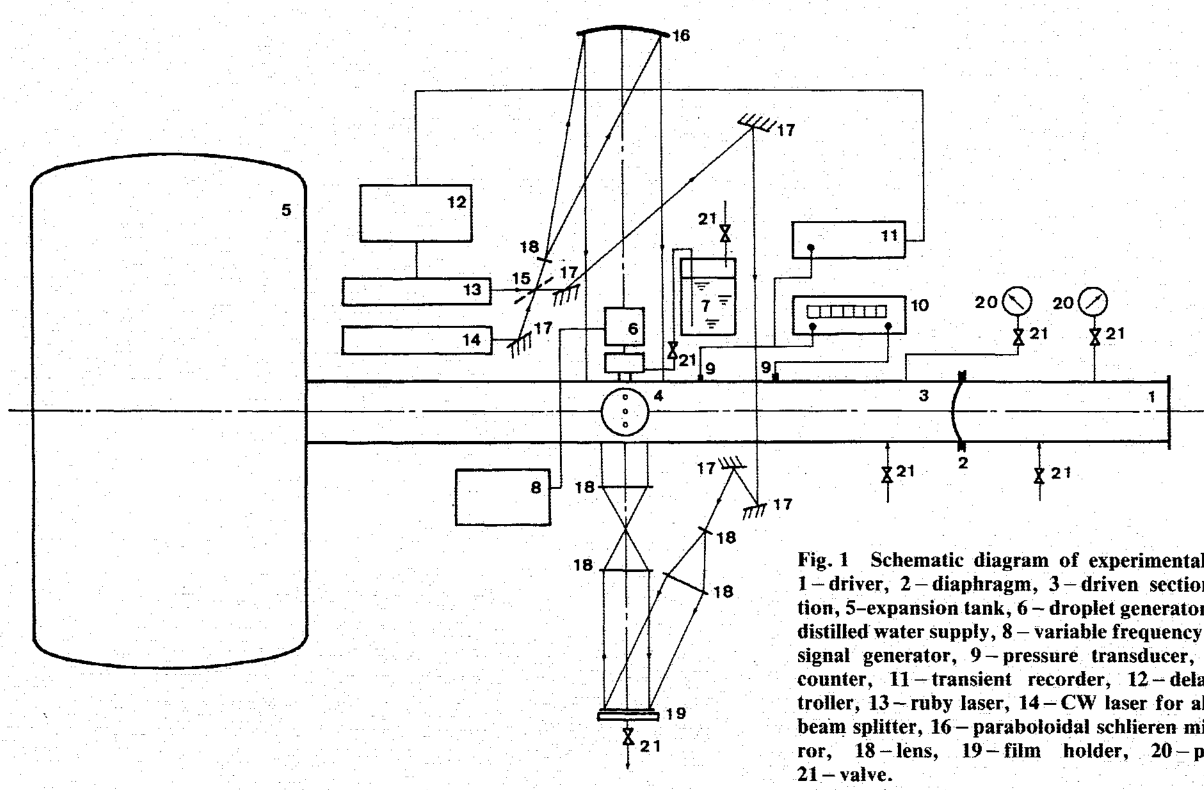

Fig. 1 Schematic diagram of experimental arrangement: 1 – driver, 2 – diaphragm, 3 – driven section, 4 – test section, 5-expansion tank, 6 – droplet generator assembly, 7 – distilled water supply, 8 – variable frequency and amplitude signal generator, 9 – pressure transducer, 10 – electronic counter, 11 – transient recorder, 12 – delay, laser controller, 13 – ruby laser, 14 – CW laser for alignment, 15 – beam splitter, 16 – paraboloidal schlieren mirror, 17 – mirror, 18 – lens, 19 – film holder, 20 – pressure gage, 21 – valve.

Simpkins and Bales[21] investigated the Taylor instability effect that was defined by appearance and growth of surface waves on the windward surface of the drop within a wide range of the Bond number or the Weber number. They did not find any instability until $Bo \approx 10^4$. It is shown that the relationship $t^* = 22Bo^{-1/4}$ indicates the onset of Taylor instability. However, experimentally the role of surface waves to the mechanism of the breakup process was not clarified yet.

In all of the aforementioned works, the proposed models differ substantially in each case. For example, Ranger[5] and Ranger and Nicholls[6] divided the breakup process into two distinct stages. The first stage, called the dynamic stage, covers the period during which drops were deformed. The second stage appears when the actual disintegration takes place. It is characterized by the surface-stripping phenomenon. It is observed[5] that for $M_s = 1.5$ and $d_0 = 900\ \mu m$, the time that is required for the first stage to develop fully is approximately 20% of the entire breakup time, and at lower dynamic pressures the time required for the first stage to develop is equal to the breakup time. Since the $\bar{t}_b$ in their experiments[5] was approximately $\bar{t}_b = 5.0$, it implies that $\bar{t} = 1.0$ for the first stage (deformation) and $\bar{t} = 2.5$ for the second stage (disintegration). It was also indicated that at higher dynamic pressures the two stages took place simultaneously.

Krauss and Leadon[8] also divided the breakup process into two distinct stages of deformation and stripping. It was reported that the second stage was well established at $\bar{t} = 0.2$. They took a crescent shape for the remaining unstripped part of the original drop until the mass of the drop was continuously reduced to approximately 2% of its initial mass at time $\bar{t} = 2.5$ and defined this instant as the breakup time.

In experiments conducted at high shock wave Mach numbers, Reinecke and Waldman[14,23] found a drastically violent breakup at $We > 20{,}000$, which they called the catastrophic-type breakup. They related this type of breakup to the unstable rapid growth of surface waves until their amplitude was comparable to the dimension of the drop. At this moment the drop was shattered before all of its mass could be removed by the stripping.

In Refs. 20 and 24, Gel'fand and co-workers conducted experimental investigations on the breakup of droplets of liquid nitrogen behind a shock wave. In their experiments, the ratio of the ambient temperature to the critical temperature of liquid nitrogen was $T/T_c = 2.23$. They reported the possibility of the observation of the latest stage of droplet breakup due to the rapid evaporation of the microdrops stripped from the parent drop and observed the explosive shattering of the liquid nitrogen drops.

Additionally, Borisov et al.[25] reported that at the critical stage of the droplet deformation ($\bar{t} = 1.0$), its "perforation" by unstable surface waves took place.

It should be noted that previous experimental data of the mechanism of the stripping-type breakup were obtained by spark shadowgraphs and streak schlieren methods as well as high-speed movies. Because of the effect of the parallel light beam that was scattered through the micromist in the wake of the shattering drop, the shattering drop and its wake look like a fireball. Consequently, the structures of the shattering drop and its wake were not observed nor was other important information on the stripping-type breakup such as the breakup time, etc. Somewhat of a subjective and qualitative judgment is required to determine the pattern of shattering drop from such photographs. In order to overcome this difficulty, holographic interferometry is known to be useful,[26] since this method can store the density change of three-dimensional flowfields.

The purpose of the present work is to re-examine the stripping-type breakup of liquid drops by holographic flow visualization. As a result, it is revealed that none of the aforementioned models is confirmed in the present flow visualization study.

II. Experimental Apparatus

The experimental arrangement is shown schematically in Fig. 1. The low-pressure channel of the shock tube has a 60×150 mm cross section and is 5 m long. The high-pressure chamber is 230 mm in diameter and 1.5 m long. There is a smooth transition section between the circular cross section and the rectangular cross section of the shock tube. The diaphragm is a Mylar film of different thickness ranging from 50 to 100 μm. The test gas is air. Helium and nitrogen are used as the driver gases. The shock velocity is measured by using two pressure transducers (Kistler model 603 A) located 250 mm apart just ahead of the test section. Their output signals are connected to a digital counter. The second transducer also triggers a light source after an appropriate time delay.

The water drops are produced by oscillating a thin water jet at the Rayleigh instability frequency. For this purpose, a droplet generator is developed following the technique used by Dabora.[27] The drop is generated through a capillary tube connected to a water reservoir whose top is a thin stainless steel diaphragm. The diaphragm was vibrated by a small Bruel and Kjaer vibrator. The stream of uniform drops falls vertically through the test section of the shock tube into a catch system.

The optical system consists of a beam splitter that can transmit 60% of the light intensity to the object beam formed by parabolic schlieren mirrors of 300 mm diam and 3 m focal length, two lenses of 120 mm diam and 1 m focal length, a collimating lens of 150 mm diam and 1 m focal length, which is used to the reference beam and auxiliary planar mirrors and lenses. A Q-switched ruby laser (Apollo Lasers, Inc., 22HD, 2J/pulse and 30 ns pulse width) is used as a light source (for details see Ref. 28). The magnification of the image in the test section was either 1:1 or 2:1. The film used is an Agfa 10E75, 102 mm × 127 mm sheet film. Reconstruction of the holograms is carried out by using an argon-ion laser (wavelength 514.5 nm).

III. Experimental Results and Discussion

In the present study, the behavior of water drops in a high-speed airstream is examined under conditions that are characteristic of the stripping-type breakup. The water drops having diameters of 1030 and 4300 μm were tested in air at room temperature and atmospheric pressure for shock waves having Mach numbers ranging from 1.3 to 1.5. These experimental conditions resulted in the Weber number We_2 ranging from ~600 to ~7600 and the Reynolds number Re_2 ranging from 1.38 to 10.4×10^4, respectively.

The histories of the shock-loaded water drops were observed using different photographic techniques, namely, shadowgraphs, infinite-fringe double-exposure holographic interferograms, finite-fringe double-exposure interferograms, single-exposure-image holograms, and three-dimensional real-time holograms. It was found that each of these photographic techniques has its own advantages and disadvantages. Their combination sometimes gives better information about the breakup process than is obtained by using a single photographic technique. The three-dimensional real-time hologram provides an entire view of the deforming drops. As for its disadvantage, the images are blurred, and the spatial resolu-

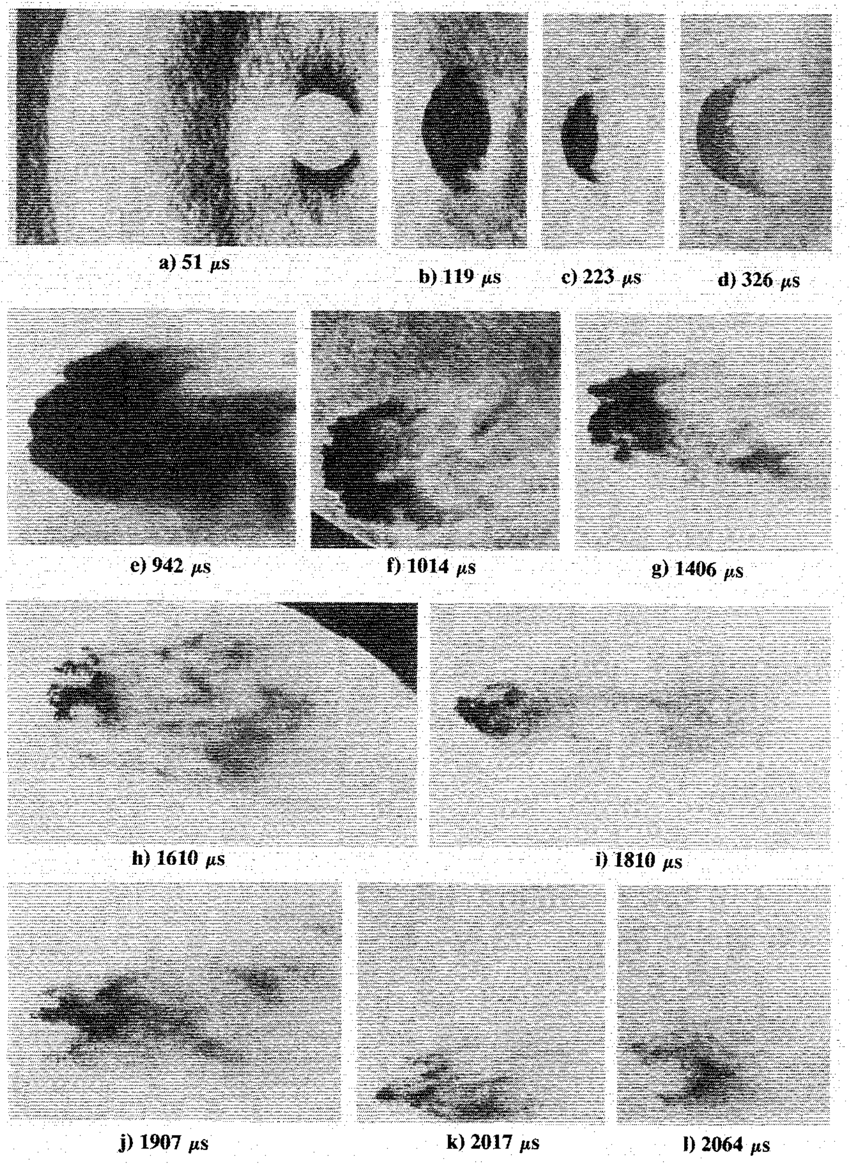

Fig. 2 History of a water drop after its interaction with a shock wave, $M_s = 1.35$, $d_0 = 4300$ μm, $We = 3590$, $Re = 67{,}700$.

tion is not as good as the image hologram. The shadowgraphs referred to here mean the unreconstructed image holograms, which are equivalent to the shadowgraphs. In the present flow visualization study, double-exposure holographic interferometry is found suitable to observe the earlier stage of the shock-drop interaction, since with fringes the reflected shock wave from the liquid drop and other fine-wave interactions are observable. It is noted that these delicate-wave interactions cannot be visualized quantitatively by other methods. However, at the later stage, single-exposure-image holograms are found to be much more useful.

An example of sequential photographs of the dynamic behavior of the water drops exposed to a high-speed airstream is shown in Fig. 2. Here, the time history of the 4300 μm drops is shown after interaction with the incident shock wave of $M_s = 1.35$. The flow direction is from left to right in Fig. 2. It should be noted that photographs were taken at different runs with the identical initial condition but by changing the delay time. The magnification of the drops in Figs. 2a and 2b is 3:1; in Figs. 2c and 2d, 2:1, and in all other photographs, 1:1. Figures 2a and 2b are infinite-fringe double-exposure holographic interferograms; Figure 2e is a conventional shadowgraph, and all others are single-exposure image holograms.

It may be recognized from these holograms that whereas the image of the remaining part of the drop is opaque, the micromist in the wake has a diffusive appearance. It is clear that in the holographic observation, the droplet distribution is measurable, where as in the conventional shadowgraph, as shown in Fig. 2e, the shattering drop and its wake are combined and look like a fireball. If one compares Fig. 2e with Fig. 2f, this trend is clear. Therefore, it is evident that the shadow photograph shown in Fig. 2e fails to determine many important data that are relating to the stripping-type breakup, such as the shape and dimensions of the deformed unstripped part of the drop, the mass loss rate, and the moment of complete breakup, etc.

The lateral deformation of the drop is defined as the ratio between the lateral diameter of the liquid phase of the disintegrating drop and the initial drop diameter. This ratio d/d_0, as determined from the holograms, is given in Fig. 3 as function of the dimensionless time $\bar{t} = (tu_2/d_0)\rho_2/\rho_\ell$. Experimental curves of other authors are also included in Fig. 3. Both Engel's data and Reinecke and Waldman's data are taken from Ref. 23.

As may be seen from Fig. 3, the present data are different from previous experimental data. Large discrepancies exist, especially after the lateral deformation of the drop reaches its maximum. This is because the size of the unstripped part of liquid drops cannot be determined accurately from shadowgraphs. It is to be noted that the Weber number in Engel's experiments[2] and in Reinecke and Waldman's experiments[23] was within the identical Weber number range of the present study.

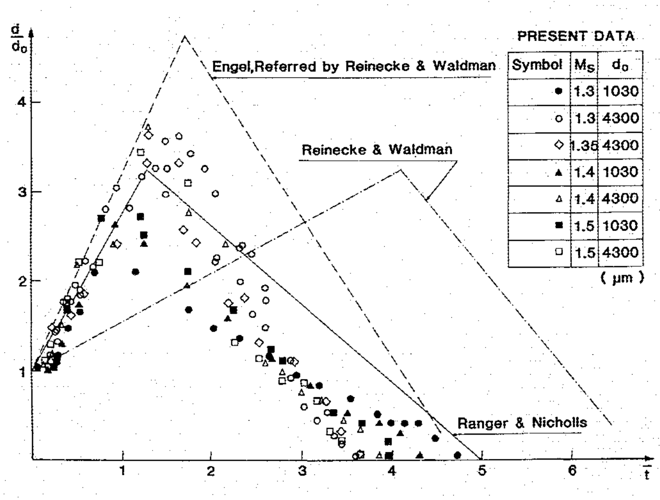

Fig. 3 Drop lateral deformation vs dimensionless time.

Experimental data on the lateral deformation of the drop were reported by Krauss and Leadon[8] and Aeschliman.[29] These results are not given here because these data are within data-scattering range of Ranger and Nicholls,[6] which appears in Fig. 3.

It should also be noted that the lateral deformation of the drop is a maximum $d/d_0 = 3$ at $\bar{t}_{md} = 1.2$–1.5 in Ref. 20, and $d/d_0 = 2.9$ at $\bar{t}_{md} = 1.5$ in Ref. 22.

It is evident from Fig. 3 that larger initial drop diameter (open symbols) results in larger maximum lateral deformation of the drop. The maximum lateral deformation of the 4300-μm-diam drops was in the range 3.5–3.7, whereas for the 1030-μm-diam drops, the maximum lateral deforming was in the range 2.4–2.9. In each group of the data of the lateral deformation, it increases with increasing the shock wave Mach number. Also, the dimensionless time $\bar{t}_{md}$ corresponding to maximum lateral deformation of the drop is larger for larger drops. Under the present experimental conditions, for 4300-μm-diam drops $\bar{t}_{md} \cong 1.5$, whereas for 1030-μm-diam drops $\bar{t}_{md} \cong 1.0$.

The lateral dimension is prominently diminishing in the time-period $\bar{t} = \bar{t}_{md}$ to $0.85\ \bar{t}_b$. It is considerably reduced for $\bar{t} \cong 0.85\ \bar{t}_b$ to $\bar{t}_b$. This is because the size diminishing of the liquid phase and the relative velocity decrease make the breakup process less intensive.

By examining more than 200 holographic interferograms, it becomes apparent that the mechanism of the stripping-type breakup can be divided into four stages. In the first stage, after the shock wave interaction with the drops, the shock-wave-induced flowfield is established around the drop, and the disruption of the liquid drop surface is initiated. During this stage the drop remains spherical. At the end of this stage the formation of the small lip on the leeward surface of the drop appears at the separation point. The formation of this lip, shown in Fig. 2a, takes place at $\bar{t} = 0.16$–0.18 for 1030-μm-diam drops and $\bar{t} = 0.09$–0.1 for 4300-μm-diam drops.

In the second stage the drop deformation takes place. The microdrops are initiated off the drop surface. This deformation, induced by the unsteady pressure distribution around the drop, is shown on the enlarged single-exposure image hologram in Fig. 4. The leeward surface has started to be flattened between the separation points and the dilation of the drop in the direction of the minimum pressure. As shown in Fig. 2b and on the enlarged single-exposure-image hologram in Fig. 5, this stage terminates by the appearance of the stripping of microdrops; the stripping is initiated at the separation point on the leeward surface and by boundary-layer separation on the windward surface. By increasing the shock Mach number from 1.3 to 1.5, the dimensionless time to initiate the separation $\bar{t}_{os}$ was decreasing from 0.21 to 0.18 and from 0.4 to 0.27 for drops having diameters of 4300 μm and 1030 μm, respectively. It should be noted that the relationship between the Weber number and the mode can hold deformation until the breakup is initiated, since the concept of the similarity law by the Weber number is applicable to unbreakup drops.

The third stage is characterized by continuous deformation of the drop and the continuous stripping of microdrops. The microdrops are subsequently entrained in the wake of the original drop. The evolution of the original drop into a plano-convex shape takes place, as shown in Fig. 2c, and thereafter into a crescent-shaped body as shown in Fig. 2d. As observed in Fig. 2d and in the fringe-infinite double-exposure holographic interferogram presented in Fig. 6, the drop disintegration is promoted, and its surface is significantly corrugated. The stripping of microdrops takes place on a substantial area of the windward and leeward surfaces of the drop. It is very intense at the trailing edge of the drop, which

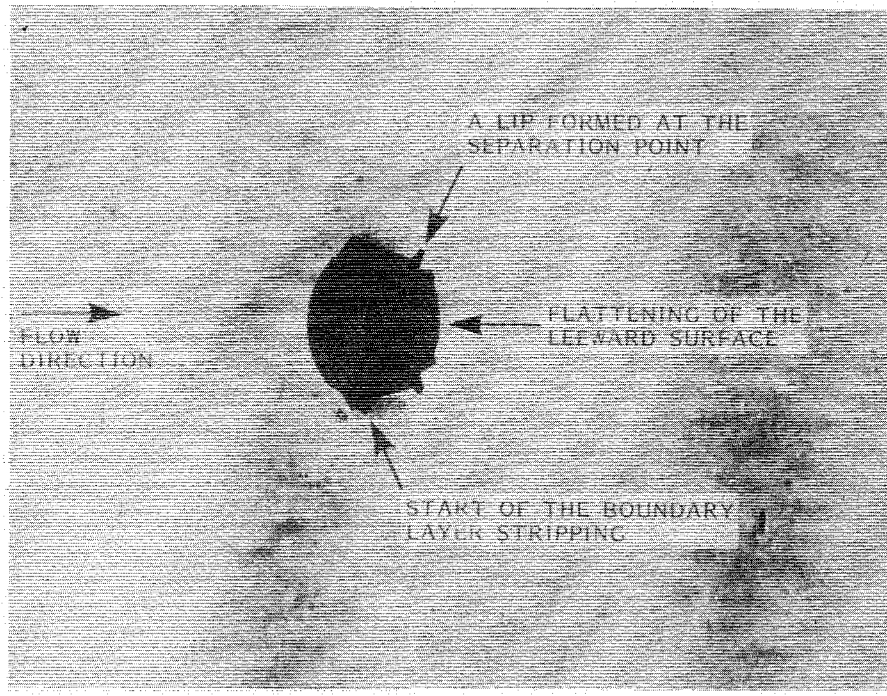

Fig. 4 Infinite-fringe double-exposure holographic interferogram of a water drop after its interaction with a shock wave, $M_s = 1.3$, $d_0 = 4300$ μm, $\bar{t} = 0.204$.

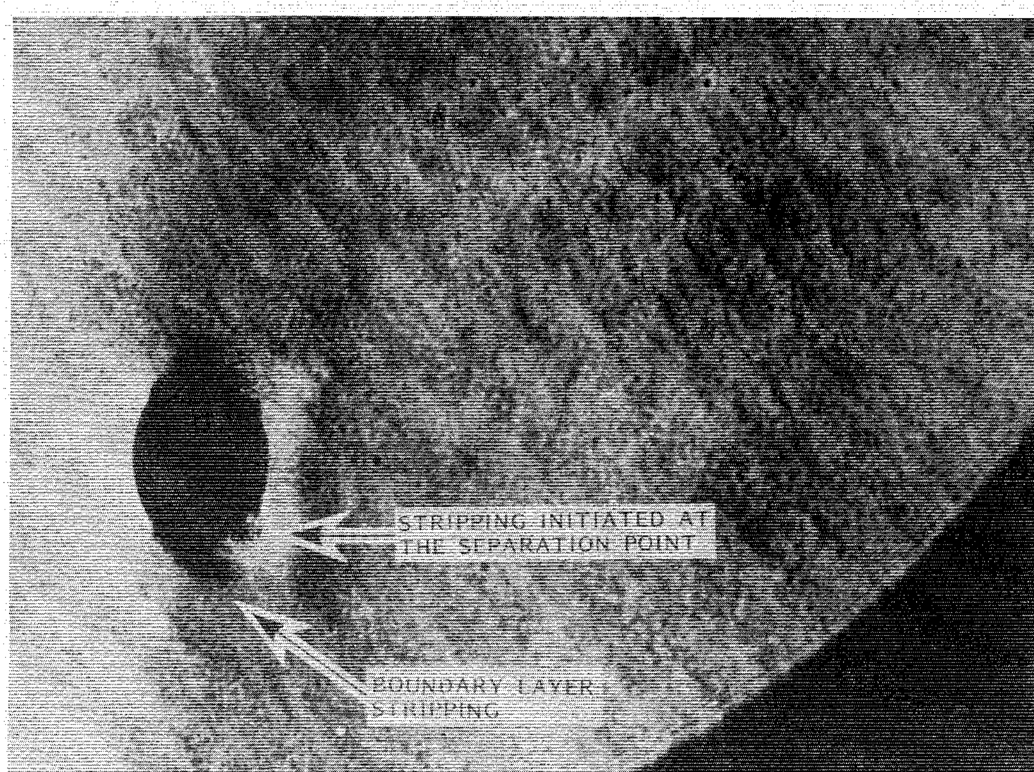

Fig. 5 Infinite-fringe double-exposure holographic interferogram of a water drop after its interaction with a shock wave, $M_s = 1.35$, $d_0 = 4300$ μm, $\bar{t} = 0.214$.

is very jagged. It is worthwhile to note that Fig. 6 is an enlarged infinite-fringe interferogram. The gray region shows the deforming drop. The trend is clearly seen that the micromists are separated from the margin of the deforming drop. The dark fringes in front of and behind the deforming drop indicate a density increase in front of the deforming drop and the density decrease behind it. Since the whole flowfield is three-dimensional, the fringes do not indicate the isopycnics. However, one can immediately recognize the drastic change of density around a deforming drop. It should be again emphasized that in Fig. 6 the deforming drop does not look like a fireball; instead, its fine structure is easily observable. This is a remarkable advantage of holographic interferometry when applied to the shock-drop interaction study.

The conclusion that the stripping process is very intense during this stage agrees well with previous observations, e.g., see Wierzba,[30,31] who stated that during the period of time $\bar{t} \leq 0.4$, after the interaction with shock waves of $M_s \geq 2.1$, the degree of shattering of the fuel drop was sufficient for the combustion detonative mode of the whole mass of fuel contained in the initial drop. At the end of this stage, the lateral deformation of the drop reaches a maximum, and the

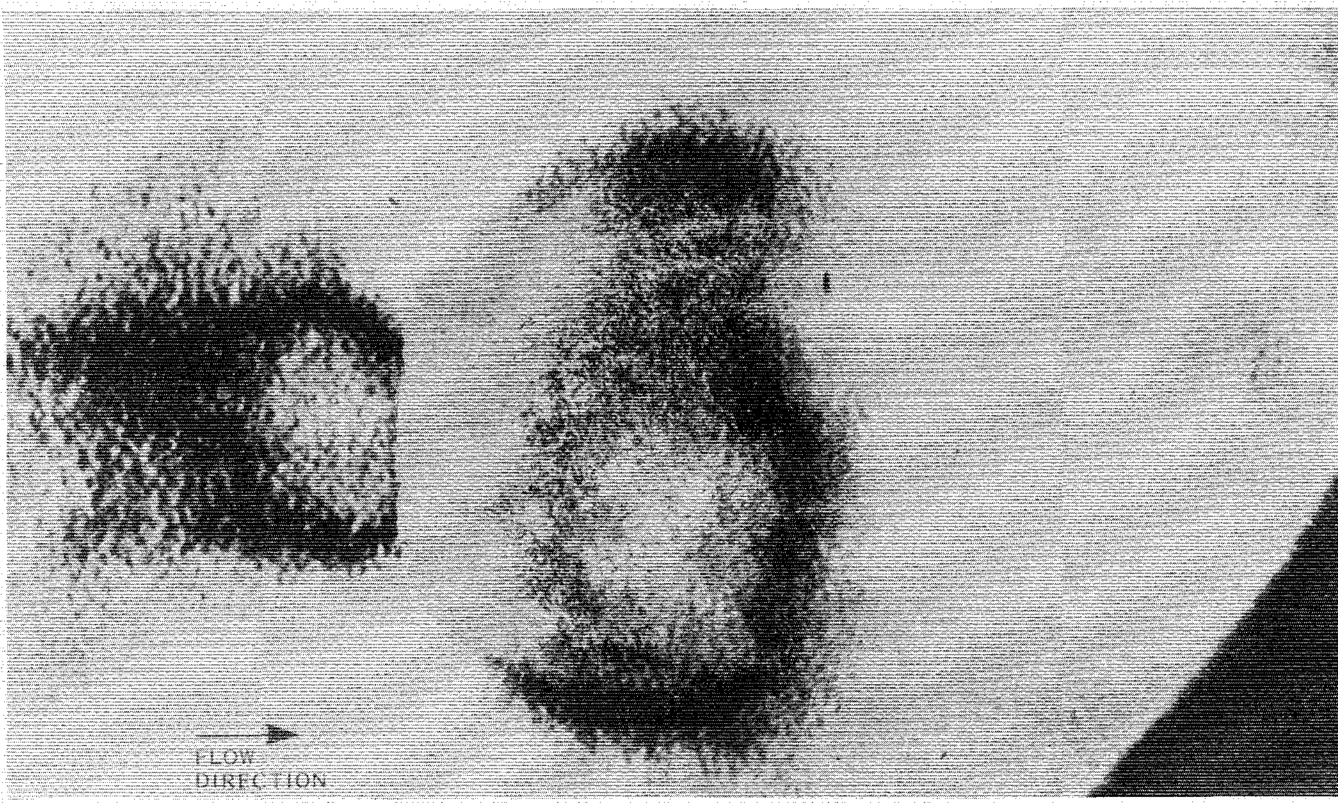

Fig. 6 Infinite-fringe double-exposure holographic interferogram of a water drop after its interaction with a shock wave, $M_s = 1.35$, $d0 = 4300$ μm, $\bar{t} = 0.92$.

remaining part of the drop becomes unstable against the aerodynamic forces and breaks up into comparatively large fragments.

The breakup of this remaining part of the drop usually takes place either by a separation of the tip of a crescent-shaped drop, while a comparatively large central part remains intact, as it is shown in Figs. 2f and 2g, or by a breakup into more uniform fragments as shown in Fig. 2h. As a result, there is a significant data scattering regarding the drops' disintegration in the region behind the drop at maximum lateral deformation.

The fourth stage is stripping of microdrops from the fragments produced by the breakup of the remaining part of the drop. In view of this phenomenon, which was not included in the model developed by Ranger and Nicholls[6] and the approximate nature of the model itself, their calculations should be considered to be reasonable and the proof that the boundary-layer stripping process plays a significant role in the stripping-type breakup. Another proof was given by Fishburn.[17] His calculation is based on the boundary-layer stripping the increased liquid surface area due to fragmentation of the deforming original drop. His result regarding the mass loss rates agrees reasonably with the experimental data of Reinecke and Waldman.[14] The breakup process in the fourth stage is more chaotic than that observed in the third stage. This stripping process may be called as "secondary stripping." This stage of droplet breakup is shown in Figs. 2f–2k. At the end of this stage, the last portion of the unstripped liquid phase loses its opaqueness, as seen on the hologram; this means that all liquid contained in the original drop is converted into the micromist cloud. This corresponds to the breakup time. In Fig. 2k ($t = 2017$ μs, $\bar{t} = 3.63$), a small portion of a liquid drop still exists at the leading edge of the micromist cloud. However, a complete breakup, shown in Fig. 2l, is established only 47 μs later ($t = 2064$, $\bar{t}_b = 3.72$).

IV. Conclusions

The application of holographic interferometry to the experimental investigation of stripping-type breakup of liquid drops revealed new quantitative and qualitative data on this process.

The stripping-type breakup of liquid drops can be divided into four stages. In the first disruption of the liquid surface, manifested by the formation of the small lip on the leeward surface, takes place. During the second stage, drop deformation occurs, and the process of the stripping of microdrops from the surface of parent drop is initiated. The third stage is characterized by continuous stripping of the microdrops and its continuous deformation until its lateral deformation reaches a maximum. At the end of this stage, the remaining part of the drop breaks up into comparatively large fragments. During the fourth stage, the secondary stripping of microdrops from these fragments takes place.

The present data on the lateral deformation of drops are different from previous experimental data. A larger initial drop diameter results in a larger maximum lateral deformation of the drop and in larger dimensionless time corresponding to this deformation.

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