Rate of Aerodynamic Atomization of Droplets

ROBERT A. DICKERSON* AND MERLIN D. SCHUMAN†
North American Aviation, Inc., Canoga Park, Calif.

Nomenclature

C_D = droplet drag coefficient
D = average diameter, cm
K_1, K_2 = coefficients relating drag coefficient to Reynolds number
$\dot{m}$ = mass loss rate, g/sec
Mn = mass number, $\dot{m}D/S_d\mu_d$
Re = Reynolds number, $DU_r\rho_g/\mu_g$
Re' = modified Reynolds number, $DU_r(\rho_g\rho_d)^{1/2}/\mu_d$
S = surface area, cm^2
U = velocity, cm/sec
We = Weber number, $\rho_g U_r^2 D/\sigma_d$
μ = viscosity, g/cm-sec
ρ = density, g/cm^3
σ = surface tension, dyne/cm

Subscripts

d = droplet
g = gas
r = relative

Introduction

ATOMIZATION of large liquid droplets subjected to high relative gas velocities is of interest to the field of liquid propellant combustion and instability processes, which occur in rocket engines. It is desirable to have quantitative information for the time rate of mass loss from the droplet as a function of the gas stream and droplet characteristics. The aerodynamic atomization process is known to be intimately related to the propagation of capillary waves over the surface of the liquid.[1, 2] The capillary waves originate from some small surface disturbance, are caused to grow in amplitude by aerodynamic forces, and eventually crest and disintegrate into a myriad of microdroplets. Analysis of the capillary wave dynamics for plane liquid surfaces is straightforward,[1, 3] but for droplets, because of the surface curvature, divergent propagation of capillary waves from the forward stagnation point, and the magnitude of deformation that occurs when liquid droplets are subjected to high velocity gas flows, a sound theoretical development would be excessively and perhaps intractably complicated.

This note describes a technique that was used to experimentally measure the rate of mass atomization from liquid droplets that were subjected to a high relative gas velocity. The results are expressed as an equation that empirically relates the mass number (Mn) to the Reynolds number (Re') and Weber number (We) as defined in the Nomenclature.

Experimental Work

A convenient means of subjecting a droplet to a high-speed gas flow is to use the calculable gas flow that occurs for a short period of time behind a shock wave in a shock tube. This was the approach selected to determine the droplet atomization rates. A diagram of the shock tube apparatus used is shown in Fig. 1. The droplet was suspended by surface tension from the end of a length of 0.010-in.-o.d. hypodermic tubing. The hypodermic tubing was an integral part of the the core of an electrical solenoid. Actuation of the solenoid caused the hypodermic tubing to be quickly pulled upward, leaving the droplet temporarily suspended in mid-air. A second solenoid was used to puncture the cellophane diaphragm separating the high-pressure section of the tube from the low-pressure section. Accurate measurement of the various time constants involved in the system, and the use of an electronic time delay generator capable of delay times of a few milliseconds, made it possible to have the droplet suspended in mid-air just prior to the arrival of the shock wave and the subsequent gas flow.

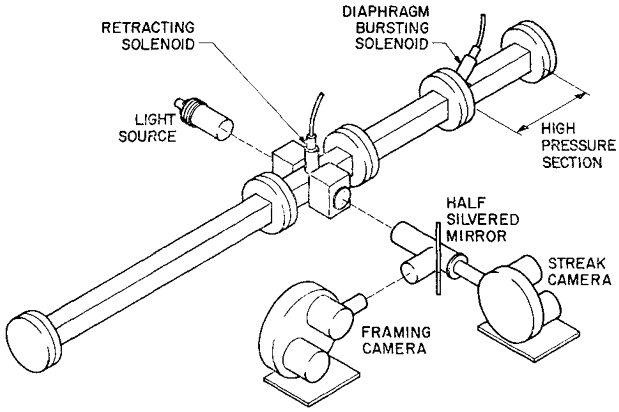

Fig. 1 Schematic diagram of test setup.

The liquid used was a high-grade kerosene (RP-1). Nitrogen was used in both the driver and test sections of the shock tube. Four different conditions of gas flow rate and density were used, but, because of various difficulties, data were extracted for only two of them. The limitation to two sets of flow conditions is actually not a very serious handicap, since the velocity of the gas relative to the droplet varies considerably as the droplet is simultaneously accelerated and atomized.

The tests were simultaneously photographed by a high-speed motion picture camera (14,500 frames/sec) and a high-speed streak camera, using a half-silvered mirror beam-splitting device (Fig. 1). Figure 2 shows the streak-film record (negative reproduction) of a drop being atomized by a 199 fps, 17.35 psia, 578°R flow of gaseous nitrogen. The primary source of data was these streak photographs, which give the

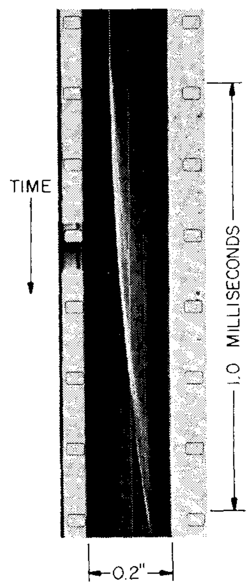

Fig. 2 Streak-film record of droplet being atomized.

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* Research Engineer, Rocketdyne Division.
† Research Engineer, Rocketdyne Division. Member AIAA.

droplet displacement vs time history of the atomizing drops. The major or leading edge portion of the streak gives the position of the large droplet. It is interesting to note that, in the light area behind the major streak, many very fine streaks were observed. These fine streaks are the trajectories of the microdroplets.

Analysis of Data

Droplet ballistics are described by balancing the drag and inertial forces to yield

$$dU_d/dt = 3C_D\rho_g U_r|U_r|/4\rho_d D \tag{1}$$

The drag coefficient C_D for distorted droplets has been found to have the following dependence on Reynolds number[4]:

$$\begin{aligned} C_D &= 27\,Re^{-0.84} & 0 \leq Re \leq 80 \\ C_D &= 0.271\,Re^{0.217} & 80 \leq Re \leq 10^4 \\ C_D &= 2 & Re \geq 10^4 \end{aligned} \tag{2}$$

Therefore, C_D can be replaced by $K_1 Re^{K_2}$, and, using the definition of Re, Eq. (1) becomes

$$D = \frac{3K_1}{4}\frac{\rho_g}{\rho_d}\left(\frac{\rho_g}{\mu_g}\right)^{K_2} U_r|U_r|\left(\frac{dU_d}{dt}\right)^{1/(1-K_2)} \tag{3}$$

In order to determine droplet diameter as a function of time, the droplet velocity and acceleration are required. The rate of mass loss is given as

$$\dot{m} = \rho_d(\pi/2)D^2(dD/dt) \tag{4}$$

Therefore, equations describing the droplet velocity, acceleration, and diameter as a function of time are required in order to find the rate of mass loss. These equations were determined by an IBM 7094 program that reads in streak-film droplet displacement vs time data, curve-fits the displacement data with a seventh-order polynomial equation using the least-squares method, and differentiates with respect to time twice to find droplet velocity and acceleration. The program then uses the droplet diameter [Eq. (3)] to find the diameter of the droplet at certain preselected times. A seventh-order polynomial equation is again used to determine the equations for droplet diameter and the rate change of diameter as functions of time. Mass rate loss is then calculated.

Shown in Fig. 3 are displacement, velocity, and diameter vs time for a test of 199 fps gas flow. Since the leading edge of the droplet was used in calculating displacement, droplet diameters during the first part of the test could not be calculated due to the relative motion between the leading edge and the center of gravity of the droplet. All data used for correlation purposes were taken after the droplet became flattened.

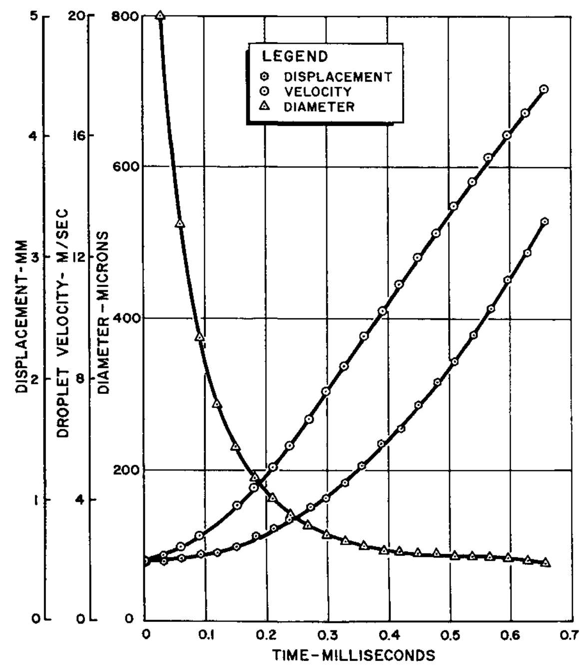

Fig. 3 Droplet history vs time.

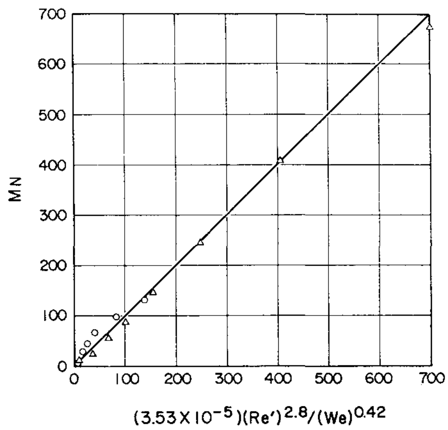

Fig. 4 Correlated test data.

Results

By the method of dimensional analysis, three important dimensionless groups were obtained. These three groups were then used to correlate the experimental data, and the following expression for the atomization rate of liquid droplets resulted:

$$Mn = 3.53 \times 10^{-5}\,(Re')^{2.8}\,We^{-0.42} \tag{5}$$

The diameter and area which are to be used in this expression must be referred to a sphere having the equivalent mass. The area must be the total surface area of the sphere. Figure 4 is a plot of the experimental data and the correlated equation. Only one liquid (RP - 1) was used in the development of Eq. (5); therefore, caution should be used when applying this equation to liquids having physical properties widely different from those of RP-1. The surface tension of the RP-1 sample used was approximately 26 dynes/cm, and the viscosity was 1.71 centipoise at the test conditions.

Equation (5) is assumed to apply to a quasi-steady-state atomization process. For example, the atomization rate from a droplet is zero at the instant it is first intercepted by the gas flow behind a shock wave, and will remain zero until local random disturbances are amplified to capillary waves with sufficient amplitude to crest. Rojec[2] has shown that the duration of the zero atomization rate for a 1000-μ droplet in the presence of a 300 fps, 17 psi, 550°R gas flow is approximately 0.1 msec. This time period is a significant fraction of the time required for essentially complete atomization of the droplet (as may be noted from Fig. 3).

The atomization rate of a droplet is also somewhat dependent on the extent of deformation of the droplet. The droplet represented by the data of Fig. 3 was initially about 1400 μ in diameter; a time period between the initial interception by gas flow and the recording of data was allowed in order to be certain that the quasi-steady-state was reached.

References

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