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# Size Distribution and Velocity of Ethanol Drops in a Rocket Combustor Burning Ethanol and Liquid Oxygen

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Single jets of ethanol were studied photomicrographically inside a rocket chamber as they broke up into sprays of drops which underwent simultaneous acceleration and vaporization with chemical reaction occurring in the surrounding combustion gas stream. In each rocket test-firing, liquid oxygen was used as the oxidant. Both drop velocity and drop size distribution data were obtained from photomicrographs of the ethanol drops taken with an ultra-high speed tracking camera developed at NASA, Lewis Research Center.

A JET of liquid fuel injected into a relatively high temperature, high pressure, combustion-gas stream very quickly atomizes and ignites into a spray of burning drops. Knowledge of the size distribution and the velocity of burning fuel drops in a combustor is required in order to determine spray vaporization rates which are generally considered to control the rate of the overall combustion process (1).<sup>2</sup>

The purpose of this investigation was to obtain the size distribution and velocity of ethanol drops in a rocket combustor burning ethanol and liquid oxygen. Other investigations (2) have produced some results in this field by means of photographic technique. From past experience, photographic methods appear to hold the most promise for this type of investigation. For the present study, a high speed tracking camera was developed at NASA, Lewis Research Center [described in (3)] which gave photomicrographs as shown in Fig. 1. A magnification of 15 was used for these pictures.

From the photomicrographs of burning ethanol drops taken at a distance of 4 in. downstream from the injector face, it was possible to determine the size distribution of the drops and analyze the data using the Nukiyama-Tanasawa, log probability, and Rosin-Rammler expressions for size distribution. Also, drop velocities were determined from the speed at which the mirror tracked the drops in stopping their images on the infrared film.

The velocity  $V_d$  of a stopped ethanol drop image (as shown in Fig. 1) was calculated from the expression  $V_d = 4\pi\omega L/M$ , where  $L$  is the distance from the mirror to the film plane,  $M$  is the magnification ( $M = 15$ ), and  $\omega$  is the mirror speed. A semilog plot of the observed drop velocity against the drop diameter, at a distance 4 in. downstream from the injector face, is shown in Fig. 2. The injection velocity for the ethanol jets was approximately 25 fps, whereas drop velocities were found to be approximately 30 and 70 fps for the 344- and 35- $\mu$  diameter drops, respectively, at the camera station.

The volume median drop diameter  $D_{30}$  was found to be 152  $\mu$  as calculated by direct integration of the experimental drop



Fig. 1 Photomicrograph of burning ethanol drops

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<sup>2</sup> Numbers in parentheses indicate References at end of paper.

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size data. This agrees with the value of  $154 \mu$  obtained for  $D_{30}$  from Fig. 3, which shows a plot of the following Nukiyama-Tanasawa expression

$$\frac{dR}{dD} = \frac{b^6}{120} D^5 e^{-bD} \quad [1]$$

which may be rewritten as

$$\log \frac{\Delta R}{(\Delta D) D^5} = -1.7 \frac{D}{D_{30}} + \log \left[ \frac{3.915}{D_{30}} \right]^6 / 120 \quad [2]$$

since integration of Equation [1] gives  $D_{30} = 3.915/b = -1.7/\text{slope}$ .

The drop size data were also plotted, as shown in Fig. 4, using the log probability expression

$$R = \frac{\delta}{\sqrt{\pi}} \int_{-\infty}^{\delta y} e^{-\delta^2 y^2} dy \quad [3]$$

where  $y = \ln(D/D^*)$ . Integration of Equation [3] and the slope of the plot in Fig. 4 gives a value of  $D_{30}$  of  $158 \mu$ , which also agrees fairly well with the value obtained by direct integration of the drop size data.

A plot of the Rosin-Rammler expression

$$1 - R = e^{-(D/D^*)^q} \quad [4]$$

shown in Fig. 5, gives a  $D_{30}$  value of  $116 \mu$ . This is considerably below the value of  $152 \mu$  obtained by direct integration of the drop size data. Thus, the Rosin-Rammler expression appeared to give the poorest results. However, more experimental drop size data for fuel sprays burning in rocket combustors are needed to establish the general applicability of the Nukiyama-Tanasawa and log probability expressions to burning sprays.

## Concluding Remarks

The most difficult problem encountered in photographing the fuel spray was that of providing sufficient light to penetrate the relatively opaque flame without scattering appreciably and still operate on an extremely short time scale (ten billionths of a second for a  $10\text{-}\mu$  diameter drop traveling 100 fps and magnified 15 times). However, with the tracking camera it was possible to have an exposure time of approximately 8 microsec. Also, since long wave length light gave less light scattering, it was found that infrared film used in conjunction with a red filter on the light source gave the best results.

## Nomenclature

- $b$  = constant Equation [1]
- $D$  = drop diameter, cm
- $\bar{D}$  = size parameter in Equation [4], cm
- $D^*$  = drop diameter at  $R = 0.50$ , cm
- $D_{30}$  = volume median drop diameter, defined by the general expression  $(D_{30})^{e-f} = \frac{\sum n D^e}{\sum n D^f}$  which gives

$$D_{30} = \left[ \frac{\sum n D^3}{\sum n} \right]^{1/4}$$

- $e$  = mean diameter notation
- $f$  = mean diameter notation
- $L$  = distance from tracking mirror to film plane, cm
- $M$  = magnification
- $n$  = number of drops
- $q$  = constant Equation [4]
- $R$  = volume fraction of drops having diameters  $< D$
- $\Delta R$  =  $n D^3 / \sum n D^3$
- $V_d$  = drop velocity, fps
- $y$  =  $\ln(D/D^*)$
- $\delta$  = constant Equation [3]
- $\omega$  = tracking mirror speed, rps

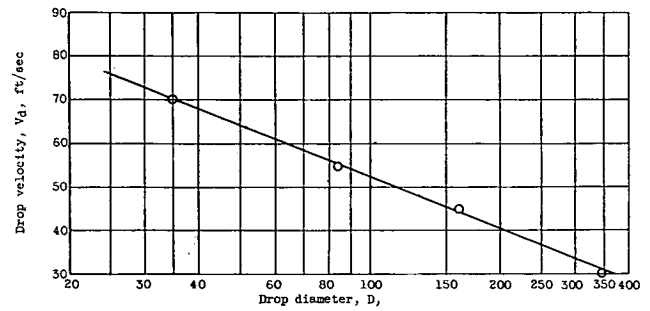


Fig. 2 Drop size and velocity data

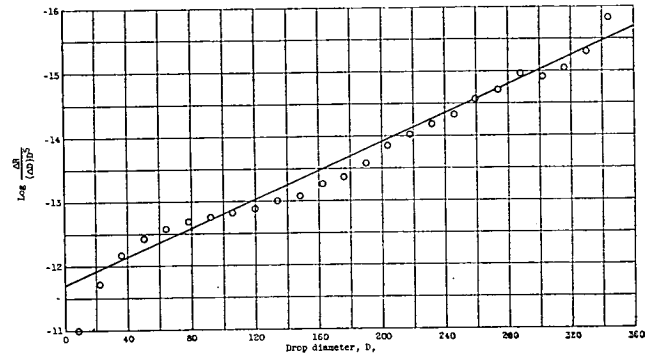


Fig. 3 Nukiyama-Tanasawa analysis of experimental drop size data;  $b = 0.0254$ ,  $D_{30} = 154 \mu$

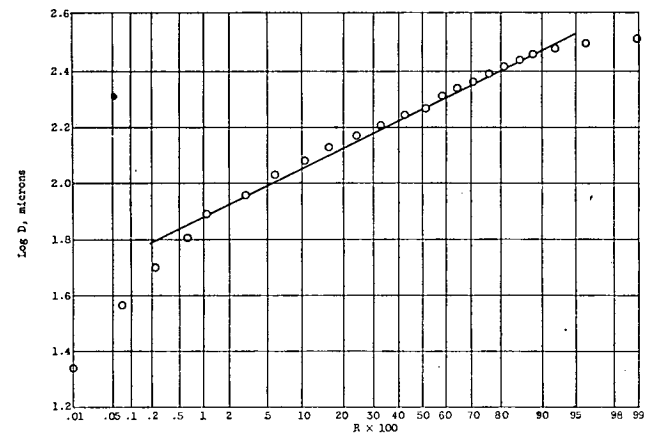


Fig. 4 Log probability analysis;  $D^* = 187 \mu$ ,  $D_{30} = 158 \mu$

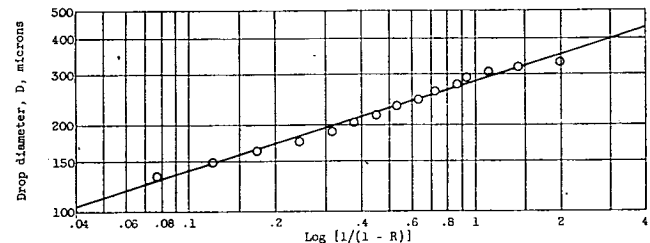


Fig. 5 Rosin-Rammler analysis;  $q = 3.2$ ,  $\bar{D} = 288 \mu$ ,  $D_{30} = 116 \mu$

## References

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