The Effect of Droplet Size on The Burning Velocity of Kerosene-Air Sprays

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The burning velocity of open inverted-cone shaped kerosene-air sprays was measured at constant air-fuel ratio and for several degrees of atomization of the spray. The results show that as the degree of atomization in the spray increases, the burning velocity first increases to a maximum value, and then decreases to the burning velocity approaching that of a premixed gas flow.

Introduction

The effect of droplet size on the burning velocity of liquid fuel sprays has been studied by several investigators to date. The experiments of Burgoyne and Cohen [1] using monodisperse tetralin-air sprays showed that the laminar burning velocity in sprays with very small droplets is smaller than the burning velocity in comparable sprays of larger droplets. Moreover, very small droplets appear to vaporize completely upstream of the flame front, thus giving the flame a premixed gas flame appearance, while large drops burn in diffusion flames around the liquid phase, thus giving the flame a "brush" type appearance. Unfortunately, the air-fuel ratio in Burgoyne and Cohen's experiments was not constant over the wide range of droplet diameters required to find a critical diameter for maximum burning velocity at constant air-fuel ratio.

The following mechanism for flame propagation can be used to qualitatively interpret the experimental results: In sprays of large droplets the flame propagation is in relatively vapor-free space with a relay process across the diffusion flames surrounding each droplet. Heterogeneous combustion around the droplets takes place in the optimum air-fuel ratio, and the droplets act as high temperature heat sources for the ignition of adjacent droplets, thus resulting in flame propagation with pockets of cool air remaining between the droplets. In addition, the thermal expansion of the gas around the burning droplets intensifies the transport process, and accelerates the burning velocity. At constant air-fuel ratio, beginning with relatively large droplets, an initial reduction in a droplet size results in a more closely spaced suspension, a higher volumetric heat release rate, and consequently an increase in burning velocity. However, further decrease in droplet size eventually results in significant amounts of fuel evaporating ahead of the flame and mixing with the air between the droplets. Burning of this lean homogeneous fuel-air mixture requires high temperatures, or a relatively large amount of heat transferred ahead of the flame for ignition. As a result, for the relay flame transfer associated with heterogeneous combustion around the droplets, an increase in the amount of fuel evaporated before ignition will also decelerate the burning velocity. Thus, increasing the droplet size in such a spray may result in increasing the burning velocity. Although this was not confirmed by previous experimental investigations, an interesting conclusion of the previous results is that there is a range of droplet diameters for maximum burning velocity in a spray, and that very fine atomization may not always be desirable in combustion applications.

A quantitative interpretation of the transition from heterogeneous to homogeneous combustion in a spray, and of the accompanying influence on burning velocity, must take into account the relative magnitudes of the characteristic ignition delay and burning times for individual droplets and for

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a premixed gas. According to William's [2] approximate analysis, it is expected to have both increases and decreases in burning velocity upon transition from heterogeneous to homogeneous combustion in a spray depending on the properties of different fuel oxidizer systems. Reference [3], using several different ignition delay times for the droplets, shows how this transition process can result in a maximum value for the calculated burning velocity as the droplet diameter decreases at constant air-fuel ratio. References [4] and [5] include discussions of a possible decrease in air-fuel ratio as the spray particle size decreases in the lean limit for flame propagation.

Mizutani and Nakajima [6] used an open inverted-cone-flame burner, and measured the local rate of flame spread in turbulent kerosene-mist-propane-air mixtures. The normal rate of flame spread, S_u, into the mixture was defined in terms of the expression $S_u = \overline{V} \sin \overline{\theta}$, where $\overline{V}$ is the local mean flow speed, and $\overline{\theta}$ is the angle between the mean position of the flame front and of tracks from every small droplet in the flow.

The measurements in [6] were carried out in a region of relatively constant average gas speed and turbulence intensity. It is therefore assumed that flame elements reach their "equilibrium" speed of propagation in that region so that the measured value of S_u is the burning velocity of the mixture. Data in [6] show that for the same upstream conditions and overall air-fuel ratio, addition of kerosene spray to a propane-air flame may increase the burning velocity, while addition of kerosene mist consisting of very fine droplets may produce the opposite effect. It was concluded that the measured changes in burning velocity as the kerosene is added in relatively large droplet or fine mist form are a consequence of the change of the system from a gas phase mixture into a gas-liquid two phase mixture and not of the different physicochemical properties of kerosene and propane vapor. Thus, this conclusion is also in support of the previous qualitative description of the effect of droplet size on the burning velocity.

The present work is an experimental investigation of the effect of droplet size on the burning velocity of polydisperse kerosene-air sprays. The experiments were similar to those in [6] and [7], and the normal rate of flame spread into the combustible mixture, measured in a region of relatively constant mean flow speed and turbulent intensity, will be identified as the burning velocity of the mixture for the turbulence level present in the apparatus. No rigorous justification for this assumption is attempted here. However, from schlieren photographs it appears that the flame front is flat in that region, suggesting a constant speed of flame propagation.

Experimental Apparatus and Procedure

The experimental apparatus was similar to that used in [6] and is shown schematically on Fig. 1. It consisted of a vertical stainless steel tube 25 mm i.d. and 1 m long with kerosene-air spray flowing upwards and discharging into the ambient atmosphere. A small acetylene pilot flame, with a 3 mm o.d. burner, was located at the exit of the tube and was used to ignite the spray. The resulting inverted cone flame was photographed using a schlieren system. The primary air supply was metered using a rotometer, and a second rotometer was used for measuring the air supply to an ultrasonic atomizing nozzle operating at 35,000 cps, which was employed for atomizing the liquid fuel. The fuel was supplied to the nozzle through a variable flow rate rotary pump, and the air-fuel

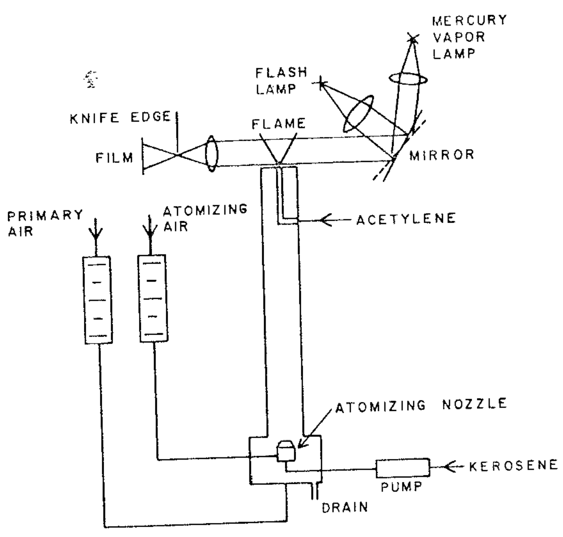


Fig. 1. Schematic diagram of experimental apparatus.

ratio, as well as the droplet size distribution, were set by adjusting the pump exit pressure, and the primary and atomizing air flow rates. The air-fuel ratio was calculated from the rotometer readings, and by weighing the mixture collected at the tube exit using a plastic bag. The kerosene and air flow rates were constant for all the experimental runs, and the air-fuel ratio was 18.

Figure 2 shows the distribution along the tube radius of mean velocity and rms velocity fluctuations upstream from the flame front measured using hot wire anemometry. These measurements were carried out with no combustion and no spray present. In addition, the different atomizing and primary air flow rates that were employed during testing resulted in mean velocity and rms velocity fluctuation profiles that differed by a negligible amount from those shown on Fig. 2. The flow Reynolds number based on the tube diameter was 2700. The rms fluctuations shown are average values including turbulent bursts due to the transitional flow regime.

Droplet diameters were measured from photographs of the spray obtained using an instantaneous light source with a flash duration of approximately 5 μ sec. The optical system was similar to that used by Ingebo [8], and produced a magnification of X8 on the film with a depth of field of approximately 1 mm. To avoid excessive attenuation of the light passing through the fine spray, a 10 mm wide slit was placed perpendicular to the light beam over the tube exit when photographing the droplets. Photographs were taken only at one position corresponding to a distance of half a tube radius from the tube centerline and from the tube exit. Droplet sizes were measured after magnifying the negatives about 3 times. About 300-650 droplets were counted using several negatives for each run. The droplet sizes measured with this method are subject to uncertainty because of (a) personal interpretation of the position of the droplet boundaries, as well as of the droplets that are out of focus and (b) the effect of film developing time on the image size of the very small droplets. The counting and film developing were carried out by the same person to minimize differences in interpretation and developing technique. The resulting droplet size counts were used to qualitatively describe the relative extent of atomization between different sprays. This was accomplished by comparing the liquid volume in each droplet size group for the sprays tested. Droplets that appeared smaller than 30 μ in diameter were not included in the results because they could not be accurately counted with the present system.

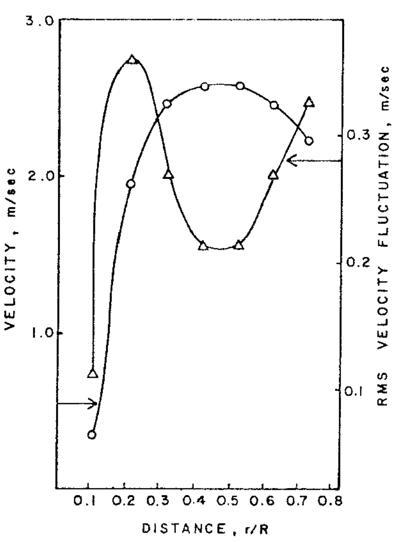
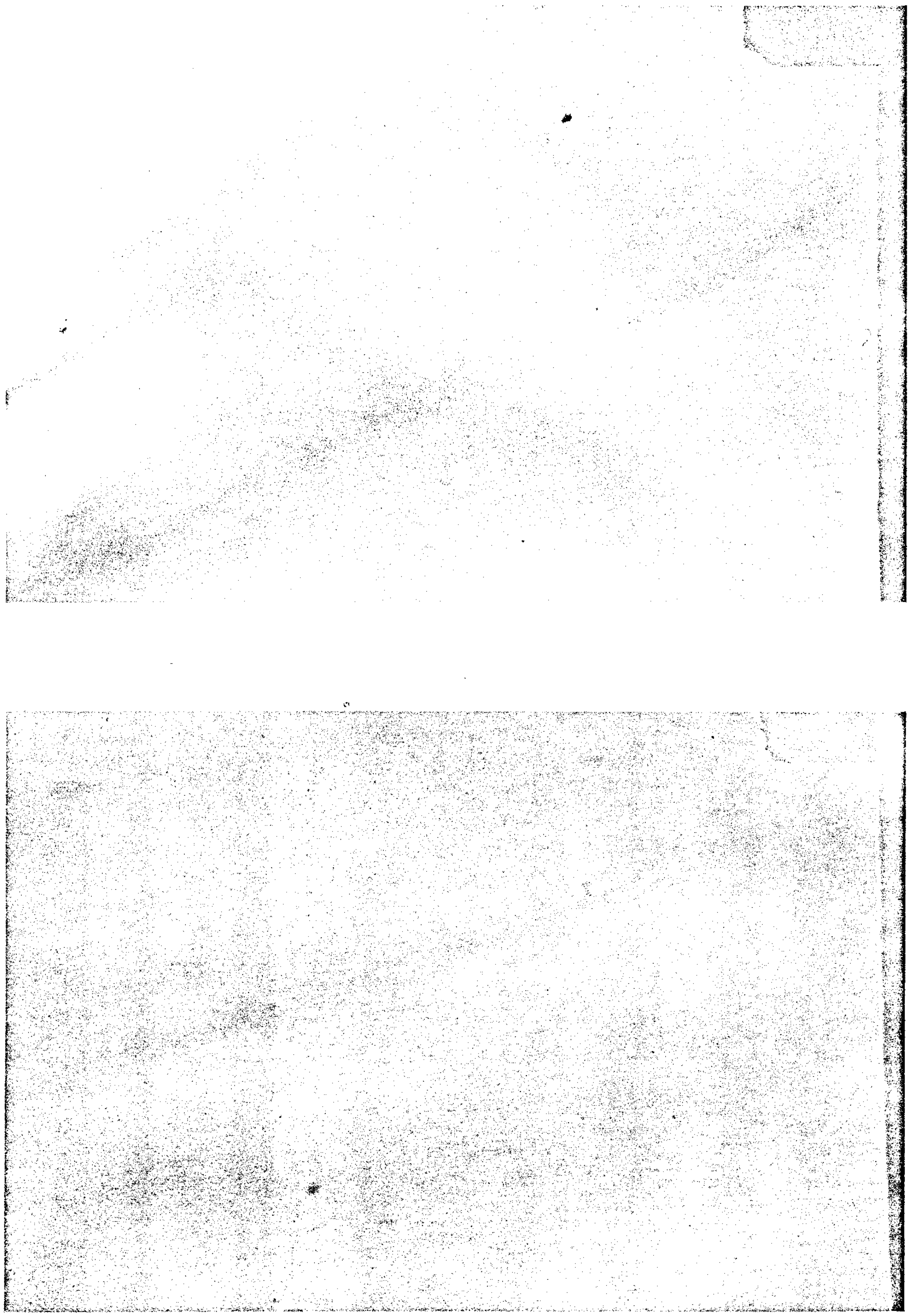


Fig. 2. Mean velocity and rms velocity distributions ahead of the flame. r/R is the nondimensional radial distance from the tube centerline. R = 1.25 cm.

Figure 3 shows schlieren images of flames obtained for three different degrees of atomization. The exposure time was 10^{-3} sec, the magnification was X3 on the film, and the depth of focus was about 6 mm. The light source was a high pressure mercury vapor lamp. Droplet streaklines can be clearly observed ahead of the flame using the photographic negatives, and can be used to track the mean position of particle paths in the flow. Occasional large scale turbulent bursts produced large scale distortions of the flame front, and only photographs where the flame front appeared smooth were used for measurements.

The burning velocity, S_u, was calculated using the equation:

$$S_u = \frac{r_1}{r_2} \frac{\Delta r}{\Delta l} \overline{V}, \qquad (1)$$



(a) (b)

Fig. 3. Schlieren images of spray flames: (a) Spray A, (b) Spray B,

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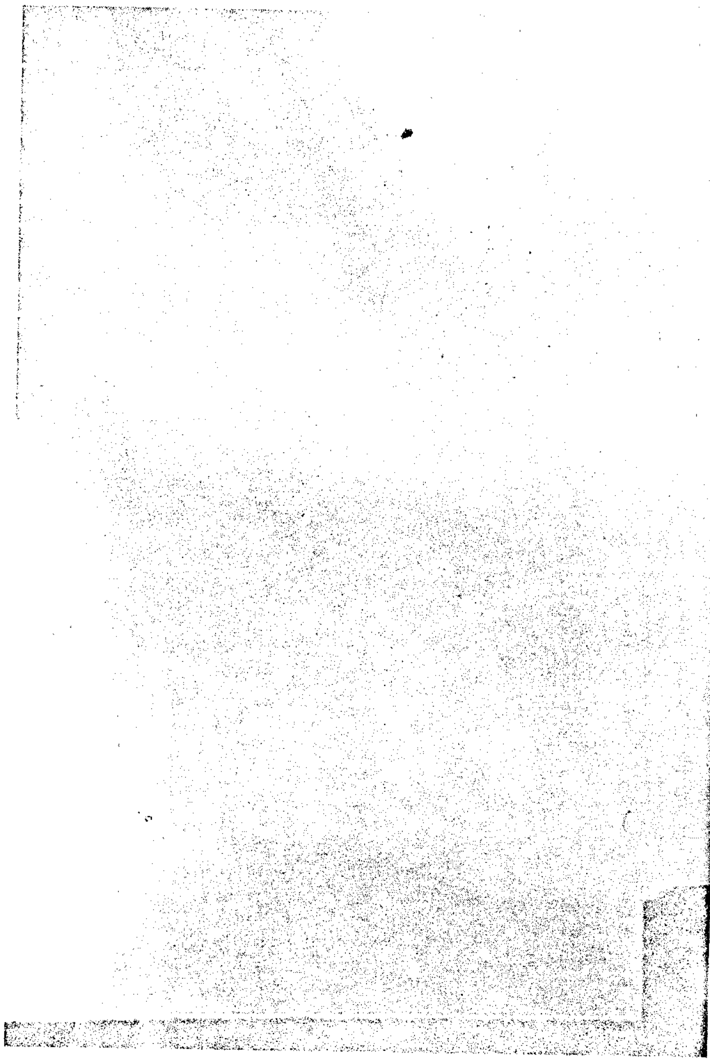

(c)

Fig. 3. Continued. (c) Spray E. Pilot flame tip shown is 3 mm high. Exposure time was 10^{-3} sec.

which is derived from the diagram on Fig. 4 using conservation of mass and constant density flow. $\bar{V}$ is the mean flow velocity over a length Δr, measured at the tube exit and at a radial distance of half the tube radius, and Δl is defined in terms of the surface enclosed by the mean particle path lines from Δr to the upstream side of the schlieren image of the flame front as shown on Fig. 4. r_2 is the mean distance of Δl from the tube centerline. It should be noted that Δl appears as a straight line in the region of measurement. Assum-

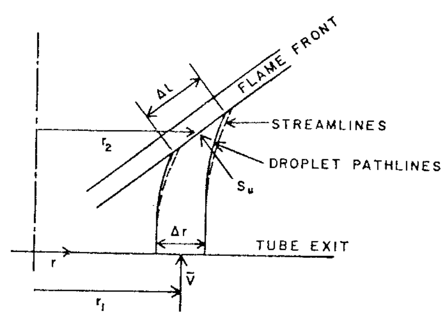

Fig. 4. Schematic diagram used for calculating S_u.

ing the maximum schlieren deflection occurs at a gas temperature of approximately 500 °K [9] it is possible to estimate the error associated with the constant density assumption in Eq. (1). This is accomplished by using the following approximate relationship for the temperature distribution in the preheat zone of the flame [9]:

$$\frac{T-T_i}{500-T_i} = \exp(-\bar{C}_p \, \rho \, S_u \, x/\bar{k}) \qquad (2)$$

where T is the temperature, $\bar{C}_p$ is the average heat capacity of the gas, ρ is the upstream gas density, $\bar{k}$ is the average thermal conductivity of the gas, and x is the distance measured from the position of the maximum schlieren deflection in the upstream direction. T_i is the upstream gas temperature. From schlieren photographs of the flame the half thickness of the schlieren deflection zone is approximately 0.03 cm. Using $\bar{C}_p = 0.25$ cal/g°K, $\rho = 10^{-3}$ g/cm^3, $\bar{k} = 10^{-4}$ cal/sec cm °K, and $S_u = 80$ cm/sec results in $(T-T_i) < 1$ °K at the upstream position of the schlieren deflection zone, thus confirming the constant density assumption.

For the sprays observed in the present work, it can be shown that the droplets were at their terminal velocity at the tube exit. More than 95% of the liquid volume was in droplet sizes below 80 μ in diameter. For such droplets the slip velocity at the tube exit was less than 6% of the mean flow velocity used in Eq. (1). Additional slip conditions at the flame front result from the divergence of the flow streamlines with respect to the tube axis as shown on Fig. 4. For this reason the particle tracks that were used were those of the smallest droplets, since tracks of large droplets, which do not adequately follow the streamlines, will result in smaller values of S_u calculated from Eq. (1), or the relationship $S_u = \bar{V} \sin\bar{\theta}$ [6].

The fuel was kerosene with a specific gravity of 0.8, and was kept at room temperature conditions before testing.

Results and Discussion

Degree of Atomization in the Sprays Tested

Figure 5 presents direct photographs of spray flames showing the effect of increasing fuel atomization on flame appearance. Fig. 5(a) is for spray A consisting of relatively large droplets that burn enveloped in yellow diffusion flames. Combustion appears to take place downstream of a well-defined region that does not necessarily coincide with the flame front recorded on schlieren photographs. Increasing atomization in sprays C and E (Figs. 5(b) and 5(c)) results in decreasing the number of individually burning large drops, and in the gradual appearance of a blue flame front that is characteristic of premixed gas flames. Spray E is for the finest atomization that was used in the present tests and shows a well-defined blue flame front with a small number of burning drops in the downstream region.

Figure 6 shows the cumulative volume distribution vs droplet diameter for sprays A to E calculated from the droplet size counts. The liquid and airflow rates were the same for all tests. As a result, the liquid volume in each size range was normalized with respect to the total volume of spray A. Spray A consisted of relatively large drops whose diameter could easily be measured. Figure 6 gives no information about the important droplet diameter range below 30 μ. However, it shows that from spray A to spray E, (a) the number of large diameter droplets decreases, and (b) the fluid volume atomized in droplet diameters below 30 μ increases. Thus, the results of Fig. 6, together with the direct photographic observations of the spray flame, confirm that from spray A to spray E the atomization becomes progressively finer.

From the data it is possible to estimate the number density of the droplets in spray A assuming a uniform particle distribution. Table 1 shows the droplets counted per cm^2 of focal plane measured from photographic negatives, together with calculated number densities (droplets/cm^3) for each size group. Lower and upper bounds of the droplet number density were obtained by assuming that either all the counted droplets were located on the focal plane of the photographs, or that the droplets were distributed in a volume defined by the estimated 1 mm depth of focus and the area of the spray image. In the first case the number density is calculated by raising to the three halfs power the number of droplets counted per unit area of focal plane, while in the second

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30 μ prevents us from mak
for the other sprays tested.

Burning Velocity Results
Table 2 shows the burning
sured for the sprays tested

Droplet diameter range (μ)
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 100

[a]Obtained using $(b) = (a)^{3/}$
[b]Obtained using $(c) = (a)/($

Spray	V cm/sec	cm
A	266	2
B	266	2
C	266	2
D	266	2
E	266	2

[a](Air-Fuel Ratio = 18)

case the number density is obtained by dividing the droplet counts per unit focal plane area by the estimated depth of focus. The combined number density for spray A is thus estimated to be between 2210 and 1750 droplets/cm^3. Using Table 1 and the liquid fuel density (0.8 gm/cm^3) it is possible to estimate the liquid concentration to be between 8.6 and 6.8 $\times 10^{-5}$ gm/cm^3. This compares favorably with the value of 7.1 $\times 10^{-5}$ gm/cm^3, which is measured directly at the tube exit, and suggests that for spray A the measured particle size distribution includes practically all the droplets in that spray. Our inability to measure diameters below 30 μ prevents us from making similar calculations for the other sprays tested.

Burning Velocity Results

Table 2 shows the burning velocities (S_u) measured for the sprays tested. Calculated values of S_u using the expression $S_u = \bar{V} \sin \bar{\theta}$ [6, 7] are also shown for comparison and are approximately 10% higher than those calculated using the expression chosen for the present work. $\bar{\theta}$ is the mean angle between the flame front and the droplet pathlines and is measured using droplet pathlines originating at a distance of half the tube radius at the tube exit. The velocities and the measured distances from the photographic negatives are averages from several different measurements. It was estimated that measurements from photographic negatives resulted in a ±6 cm/sec error in the calculated values of S_u, most of the error occurring in the measurement of r_2 and Δl (Fig. 4). Reproducibility between different measurements was within ±5 cm/sec from the average values of S_u shown on Table 2. S_u initially increased from 60 cm/sec for a relatively coarse spray to a maximum of 91 cm/sec as the degree of atomization increased. However, further

TABLE 1
Droplet Number Densities for Spray A

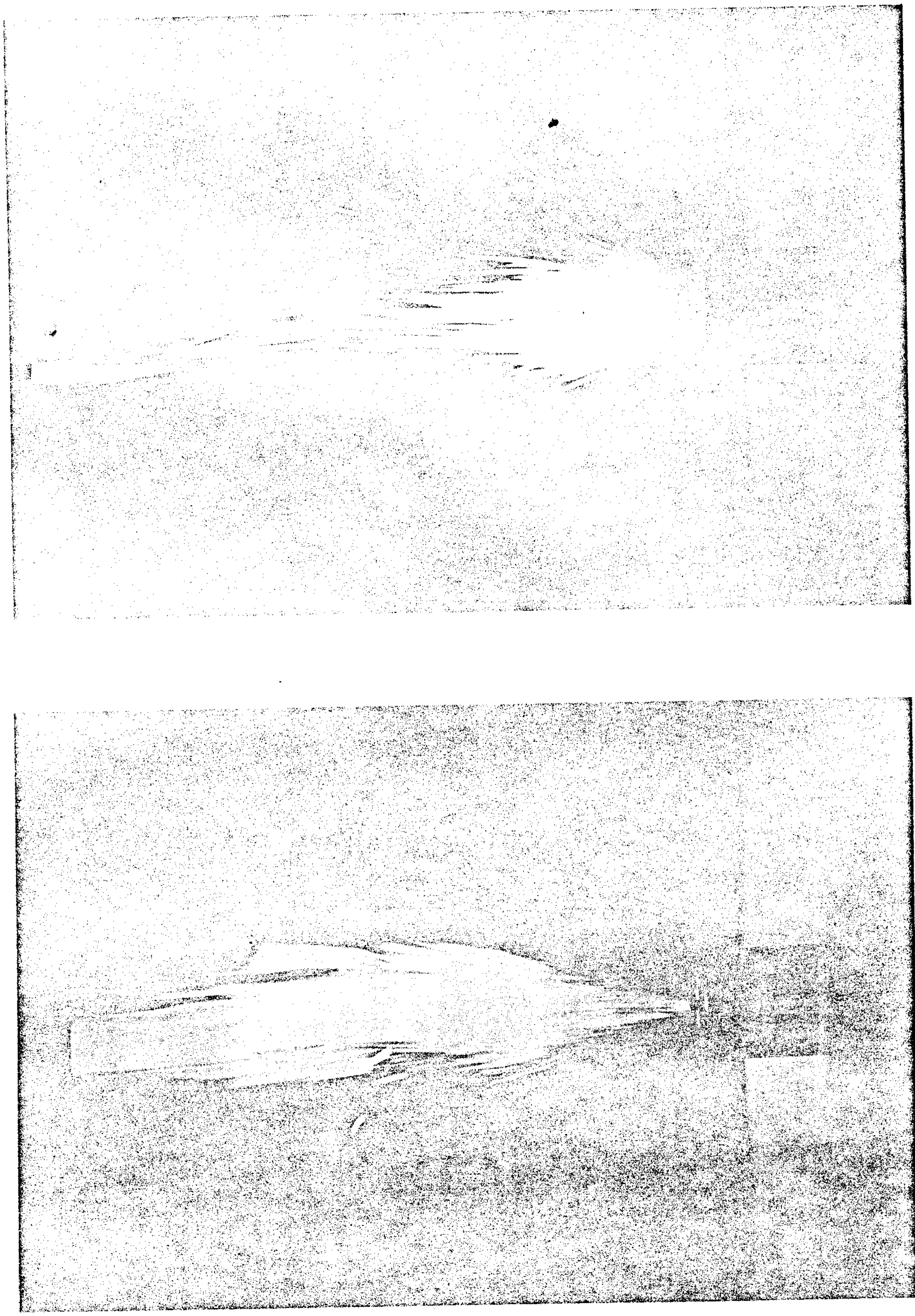
Droplet diameter range (μ)	Number of droplets cm^2 of focal plane (a)	Number of droplets/cm^3 (b)[a]	(c)[b]
31 - 40	91	868	910
41 - 50	51	364	510
51 - 60	59	453	590
61 - 70	12	41	120
71 - 80	6	15	60
81 - 90	1	1	10
91 - 100	1	1	10
		1742	2210

[a] Obtained using $(b) = (a)^{3/2}$
[b] Obtained using $(c) = (a)$/(approximate depth of focus).

TABLE 2
Experimental Data and Associated Values of S_u[a]

Spray	V cm/sec	u' cm/sec	r_1	r_2 (arbitrary scale)	Δr	Δl	θ deg.	S_u (cm/sec) Present	Ref. [6]
A	266	22	32.8	35.2	9.2	37.8	14	60	64
B	266	22	36.7	40.7	7.8	26.1	17	72	80
C	266	22	36.2	39.8	8.3	22.0	22	91	100
D	266	22	35.7	45.0	8.0	28.0	15	60	69
E	266	22	35.3	43.2	8.4	36.5	13	50	60

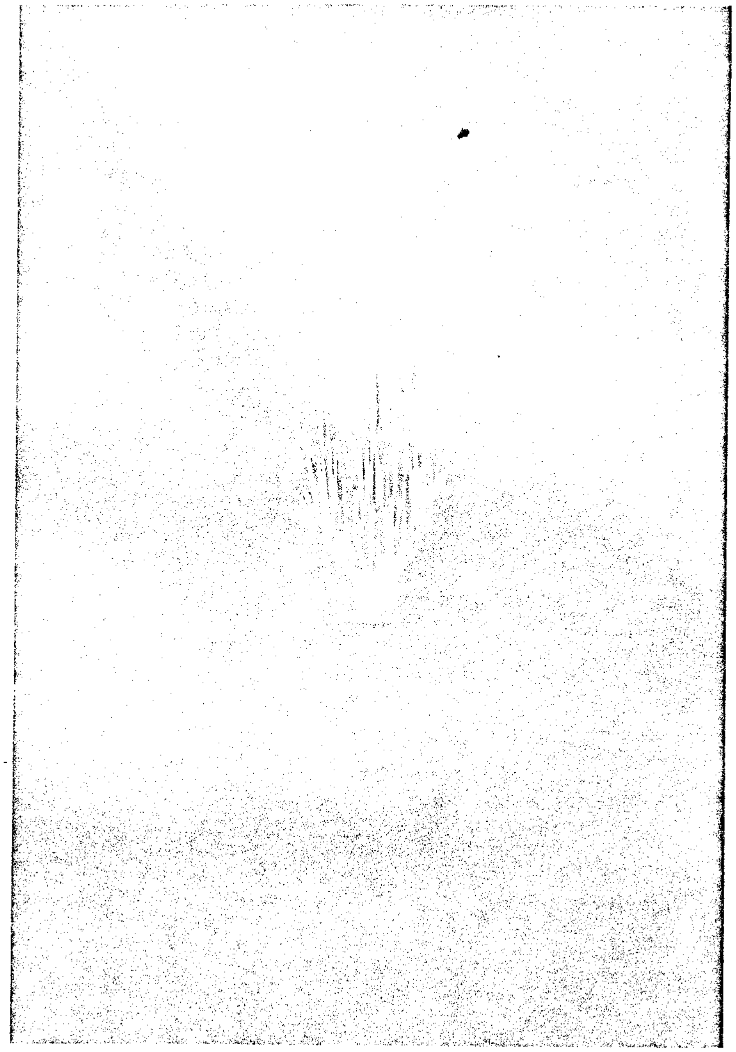
[a] (Air-Fuel Ratio = 18)



(b)

(a)

Fig. 5. Direct photographs of spray flames: (a) Spray A, (b) Spray C,



(c)

Fig. 5. Continued. (c) Spray E. Exposure time was 1/125 sec.

atomization resulted in a decrease in burning velocity to 50 cm/sec for spray E, which for the present tests appeared to burn mostly as a premixed flame. From the results of Table 2 it appears that for a given kerosene-air mixture, there is a drop size distribution that results in a maximum rate of flame propagation, which is larger than that of a premixed gas of the same air-fuel ratio.

Observation of schlieren images of the flame front such as those on Fig. 3, shows that, as expected, the flame appears to be ignited in the boundary layer ahead of the pilot tube tip, and that the point of ignition is further upstream for spray C, which had the maximum measured burning velocity. In addition, it should be noted that the angle of the flame with the vertical axis is not a true indication of burning velocity, because the effect of flow angle at the flame front must also be considered. Observation of the sample photographs of Fig. 3 shows that the particle tracks appear to diverge outwards at the flame front by an increasing amount as the degree of atomization increases. This is because the zone of fuel burning (in gaseous or droplet form) downstream from the flame front is shortened as the droplet

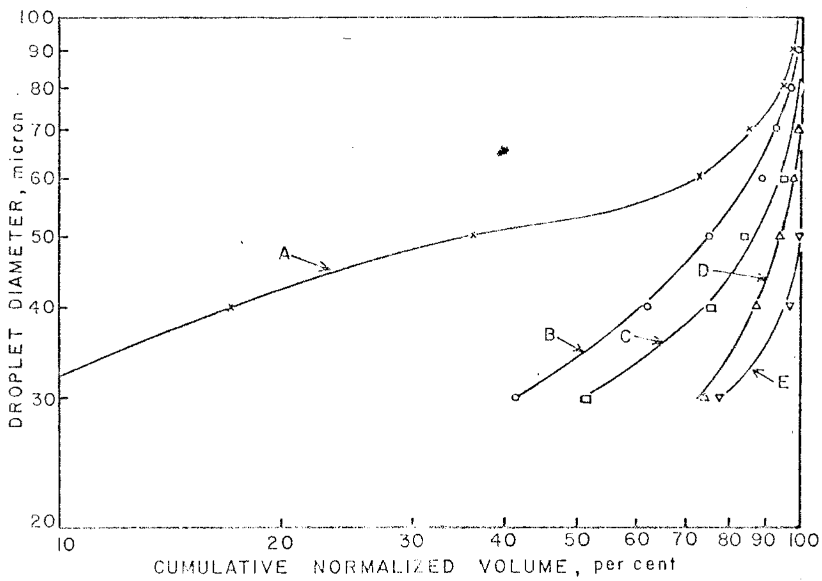


Fig. 6. Cumulative volume distribution of the sprays tested. Normalization is with respect to the liquid volume/area of focal plane for spray A.

size decreases, thus increasing the effect of flame thrust, which is the reason for the diverging droplet pathlines at the flame front.

Reference [7] gives the following empirical correlation for the burning velocity of kerosene-air sprays in apparatus similar to that used in the present study:

$$S_u = \frac{6.800}{\bar{d}} (\phi - 0.012)(u')^{1.15} \text{ [m/sec]}, \quad (3)$$

where ϕ is the fuel-air ratio, $\bar{d}$ is the Sauter mean diameter in microns, and u' is the rms velocity fluctuations in m/sec. This correlation was developed for sprays with Sauter mean diameters between 30 μ and 100 μ and predicts that S_u is inversely proportional to $\bar{d}$. This is not in conflict with the results of the present work, which show that S_u increases as the degree of atomization increases (or as $\bar{d}$ decreases) from spray A to spray C. However, since Eq. (3) was developed using experimental data for $\bar{d} > 30\ \mu$ it is not expected to predict the decrease in S_u for very small droplets as is shown by the results of the present work. It should be noted that if it is assumed that the volume of spray C for droplet diameters below 30 μ consists of droplets between 20 μ and 25 μ, then $\bar{d}$ is 33 μ for this spray. It is, therefore, safe to say that for sprays D and E $\bar{d}$ is much less than 30 μ. For spray A the value of $\bar{d}$ can be calculated and is 54 μ. For $\phi = 0.055$ and $u' = 22$ cm/sec, the value of S_u is calculated as 94 cm/sec, and should be compared with the measured value of 60 cm/sec for spray A. Possible reasons for the poor agreement are (a) the poor accuracy of the empirical correlation that was obtained in [7] using data with considerable scatter, and (b) differences in the sprays used in the present work and in [7] that may correspond to the same value of $\bar{d}$, but to different shapes of the droplet size distribution function.

Conclusions

The burning velocity of open turbulent kerosene-air sprays was measured at constant air-fuel ratio, and for various degrees of atomization of the spray. The results show that as the degree of atomization increases the burning velocity first increases to a maximum value, and then decreases to a burning velocity approaching that of a premixed gas mixture. Previous experimental and analytical work is in qualitative agreement with the present results. The question of whether the measured velocity of flame spread into the combustible mixture is indeed a true equilibrium burning velocity for the spray is left unanswered. However, the shape of the flame front in the region of measurement appeared to be flat and together with the relatively constant flow conditions indicated a constant speed of flame propagation. Further study is currently being conducted using laminar flow conditions and instrumentation for the measurement of the number density of fine droplets.

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