FUEL PROPERTY EFFECTS ON THE STRUCTURE OF SPRAY FLAMES

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The effect of fuel properties on the structure of swirling spray flames has been investigated. Droplet size, number density and velocity measurements have been carried out in pressure-atomized spray flames using phase/Doppler interferometry. Four fuels with different physical properties were studied, namely n-heptane, methanol, 50/50 methanol/1-dodecanol mixture, and kerosene. The results indicate that droplet mean size and velocity are influenced primarily by the fuel viscosity. No detectable trend could be attributed to changes in surface tension. Fuel volatility seems to have some effect on the spray flame structure, especially in the methanol flame. Flame luminosity is found to increase with increasing C/H ratio and fuel heating value. Droplet size and velocity distributions near the nozzle are found to be quite broad, and include regions of negative velocities. Some evidence has also been found to indicate the occurrence of microexplosions in the methanol/dodecanol mixture flame.

Introduction

Studies with alternative fuels (i.e., methanol and ethanol) are of particular interest because of the current initiative to gradually replace the limited supply of conventional fossil fuels (i.e., gasoline, heating oils, etc.). Alternative fuels are attractive because they provide the potential to utilize readily-available resources and reduce pollutant emissions. Conventional fuels, however, are seldom single-component; rather, they represent a complex multicomponent blend of different hydrocarbons. The simplest type of blends are binary mixtures, which can be used to study the effect of fuel properties and composition on combustion characteristics. Alcohol fuels are also of interest, since they burn much more cleanly and represent a potential to reduce the environmental impact of combustion processes.[1] Comparative investigation of the effect of fuel type on spray and flame structure (i.e., droplet size, number density and velocity) is important since chemical and physical properties of the fuel have a significant influence upon droplet atomization, vaporization, transport, combustion, pollutant and particulate formation processes.[2,3]

This paper reports the effects of physical and chemical properties of fuels on the structure of swirling spray flames, namely the spatial distribution of droplet size, number density and velocity. Experiments were carried out with four different liquid fuels, representing two single-component fuel, a conventional fuel and a miscible mixture of two single-component fuels. The equivolume mixture was selected to investigate the possibility of microexplosions.[4] Droplet size and velocity distribution were obtained using a phase/Doppler system.[5] Laser sheet beam photography was also used to observe the internal features of pressure-atomized spray flames.

Experimental

The experiments were carried out with a swirl burner designed to simulate practical combustion systems. All the experiments reported in this paper were performed at a swirl number of 0.53.[7] A pressure-atomizing fuel nozzle provided a nominal 60 hollow-cone fuel spray which was injected vertically upwards from the nozzle exit. The total air flow rate for the experiments described in this paper was 64. kg/hr and the flow rate for each fuel was 3.2 kg hr, which provided an inlet equivalence ratio of approximately $\phi = 0.75$. The Reynolds and Weber numbers for each fuel (based on the measured Sauter mean diameter and relative axial velocity) were also similar. Further details on the experimental arrangement are presented elsewhere.[8]

The fuels studied include kerosene (conventional fuel), n-heptane (single-component fuel), methanol (an alternative fuel), and a 50/50 by volume mixture of methanol and 1-dodecanol. Representative

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TABLE I

Physical properties of the investigated fuels

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Fuel	Specific gravity	Kinematic viscosity @ 298 K (10^{-6} m^2/s)	Surface tension @ 298 K (10^{-3} kg/s^2)	High heating value (kcal/kg)	C/H ratio	Boiling point range (K)	Vapor pressure @ 298 K (kPa)	Flash point (K)	Purity (%)
n-heptane	0.686	0.61	19.5	10,516.1	0.433	370	6.9	267	99.7
Methanol	0.796	0.67	20.5	4,643.1	0.222	338	16.5	285	99.8
Methanol/ 1-dodecanol (50/50 by vol)	0.804	1.58	27.0	8,666.1	0.368	338–529	—	287	—
Kerosene	0.818	2.1	23.5	10,999.4	0.51	458–555	4.1	341	—

physical properties of the fuels studied are presented in Table I; the fuels are arranged according to increasing specific gravity and viscosity.

Droplet size and velocity distributions were measured using a single-channel phase/Doppler interferometer.[5] The instrument configuration used off-axis light collection optics, positioned at a scattering angle of $\theta = 30°$. A 10 mW He-Ne laser, operating at a wavelength of 632.8 nm, provided the light source. The signal data rate was kept relatively constant (at approximately 200 Hz) by adjusting the supply voltage for the scattered light detector.

A laser sheet beam of about 1 mm thickness, was used to examine various horizontal and vertical cross sections (through the centerline) of the spray flame.

Results and Discussion

Spray Flame Visualization:

The most striking feature of the four flames investigated is the variation in luminosity. Figure 1 provides a comparison of the upstream portions of the four flames; the kerosene flame develops a highly luminous plume; the methanol flame forms a relatively nonluminous plume. The n-heptane and the methanol/dodecanol mixture provide hybrid flames; a nonluminous blue zone is observed immediately downstream of the nozzle (extending to approximately Z = 75 mm), followed by a luminous zone. The hybrid structure of the methanol/dodecanol flame may result from the possible preferential vaporization of the mixture components. For example, in diffusion-controlled liquid phase transport methanol will dominate vaporization initially (with the flame color corresponding to that of methanol). This region will be followed by dodecanol vaporization with a concomitant change in the color of the flame, hence the hybrid structure shown in Fig. 1. As expected, the change in flame luminosity (i.e., tendency to soot) appears to increase with the carbon-to-hydrogen ratio and fuel heating value (see Table I).

In luminous kerosene flames, it was difficult to use a laser sheet beam to visualize droplet trajec-

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n-heptane   **methanol**   **50/50 methanol/ 1-dodecanol**   **kerosene**
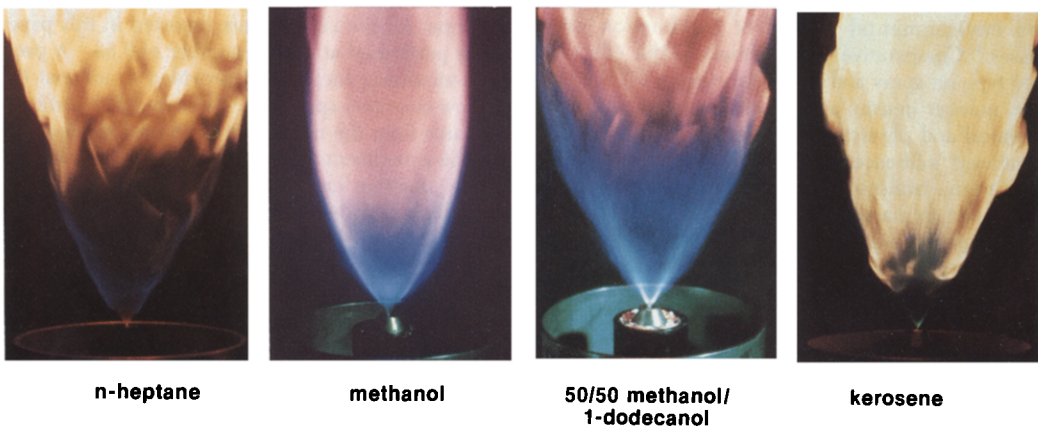
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FIG. 1. Photographs obtained with four different fuels in pressure-atomized spray flames.

tories within the plume because of the high background flame radiation; spray structure information was therefore obtained only under nonburning conditions.[9] In the *n*-heptane flame, photographs of the spray structure within the upstream blue portion of the flame were obtained with the assistance of optical filters.[10] For the methanol flame, shown in Fig. 2, a laser sheet beam (green) illuminates the larger droplets which are transported along the spray boundary. These droplets are transported downstream of the nozzle, penetrate through the flame, and escape into the surrounding environment along with the other gaseous emissions. Examination of the other spray flames also revealed similar phenomena. It is interesting to note the portion of the flame front that appears on the outer side of the spray boundary. This feature provides evidence that the central toroidal recirculation zone has little interaction with the larger droplets found along the spray boundary.

Droplet Mean Diameter and Velocity Measurements:

The effect of fuel physical properties upon droplet transport processes was investigated by determining the radial profiles of droplet mean size and velocity at different axial positions. Data obtained with the phase/Doppler interferometric system on the temporal values of the Sauter mean diameter (D_{32}), and axial velocity (U) are presented in Figs. 3 and 4 for all four fuels. The solid boxes along the abscissa indicate the position of the burner passage walls, with the fuel nozzle located at the centerline. The variation of D_{32} with radial and axial position is typical of hollow-cone pressure-atomized spray flames; the droplets on the spray boundary (i.e., the droplets at the peak of the D_{32} distribution) are much larger and travel much faster than those near the spray centerline. Comparison of the four fuels indicates that the droplet size increases with increasing fuel viscosity and density (specific gravity)
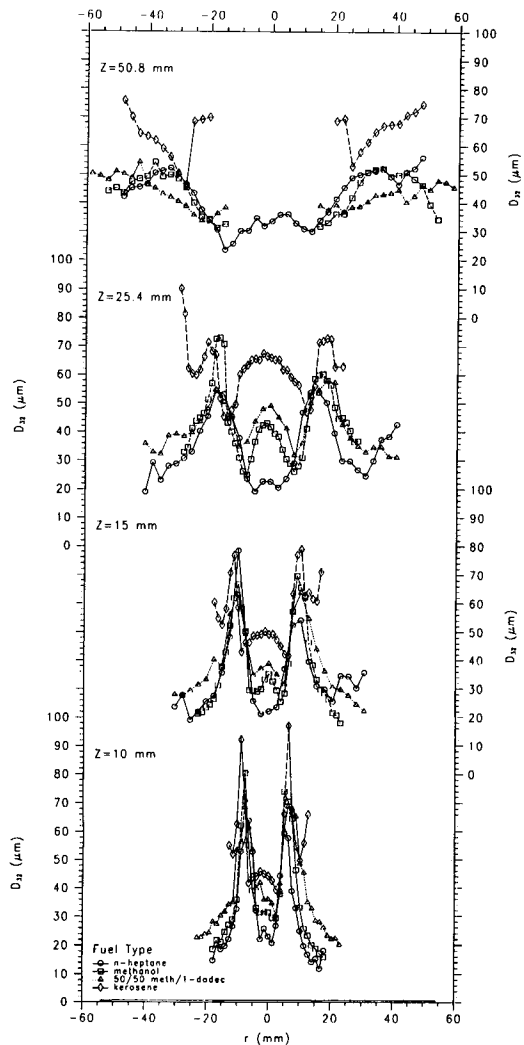

FIG. 2. Methanol flame illuminated by a vertical laser sheet beam.

FIG. 3. Variation of Sauter mean diameter (D_{32}) with radial position (*r*) and axial distance (Z) for the spray flames with four different fuels.

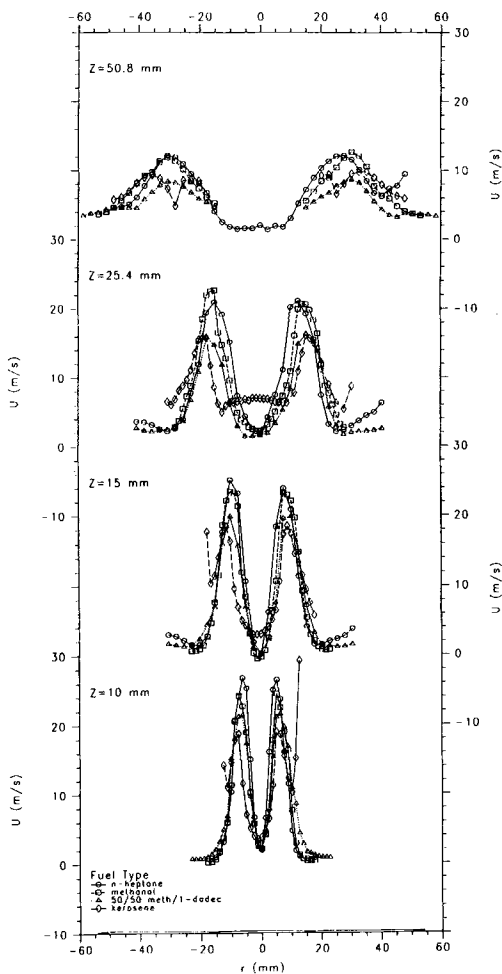FIG. 4. Variation of the axial component of droplet mean velocity (U) with radial position (r) and axial distance (Z) for the spray flames with four different fuels.

(see Table I) near the centerline and outside the nominal spray boundary. These results are in general agreement with earlier findings of Chen et al.[11]

Near the spray boundary, this order is also maintained except for methanol. Although methanol is less viscous than the methanol/dodecanol mixture, the droplet mean diameters are larger which may result from the relatively high volatility of methanol (see Table I). A similar pattern is observed for heptane, which is the next most volatile fuel, but this occurs much further downstream. Indeed, at about Z = 25.4 mm, the heptane and methanol/dodecanol droplets have quite similar mean diameters near the spray boundary.

The droplet diameters measured outside the spray boundary in the kerosene flame exhibit an unusual

behavior. In all the radial profiles for kerosene, the mean droplet diameter decreases similar to the other fuels, but it then starts to increase until no more droplets could be detected. This may be attributed to the high radiation of this particular flame (as observed by the highly luminous plume, see Fig. 1), which may result in the preferential vaporization of the smaller droplets and an increase in the mean droplet diameter D_{32}. A similar behavior is also observed along the spray centerline, where the mean diameter of kerosene droplets continues to increase with axial distance. For example, at Z = 10 mm the peak value of D_{32} at the centerline is about 45 μm, whereas at Z = 25.4 mm it is about 67 μm. This effect is less pronounced in the less luminous, cooler flames, even though heptane and methanol are more volatile. The effect of radiative heating near the centerline of the kerosene flame is also exhibited in the axial velocity profiles shown in Fig. 4. It can be seen that the kerosene droplets at the centerline do not decelerate as rapidly as the other fuels. It should also be noted that the radial distance beyond which no droplets could be detected is much smaller for the kerosene flame, compared to the other three fuels. This may be due to the higher flame temperature as well as the more radiant nature of the flame, which reduces the probability of penetration by the droplets through the flame envelope. An example of such penetration in lower temperature flames is shown in Fig. 2 for methanol.

As mentioned previously, the methanol/dodecanol mixture was selected to obtain evidence of microexplosions. Such evidence could be in the form of a sudden increase in droplet number density or decrease in droplet mean size at positions downstream of the nozzle, since microexplosions lead to shattering of single large droplets into several smaller ones. For example, Fig. 3 shows that D_{32} for the mixture fuel at Z < 50.8 mm is generally comparable or larger than those obtained with heptane and methanol. However, at Z = 50.8 mm, there is a sudden decrease in D_{32} for the mixture fuel near the spray boundary. This could be interpreted as an indication of microexplosions, since no parallel change is observed for the other fuels. Data obtained on droplet size and velocity distributions at Z = 25.4 and 50.8 mm, near the spray boundary, are shown in Fig. 5. The radial locations were selected to correspond to a trajectory along the spray boundary. The data show that at Z = 25.4 mm and r = 17.8 mm, the droplet mean diameter is fairly large (D_{32} = 55 μm) and the mean velocity is about 15.8 m/s. At Z = 50.8 mm and r = 33.0 mm, the value of D_{32} has decreased to 42.0 μm and the mean velocity is about 7.8 m/s, with a noticeable increase in the number of slower moving droplets. More dramatic evidence of this change is provided by the measurement of a lower moment of diam-
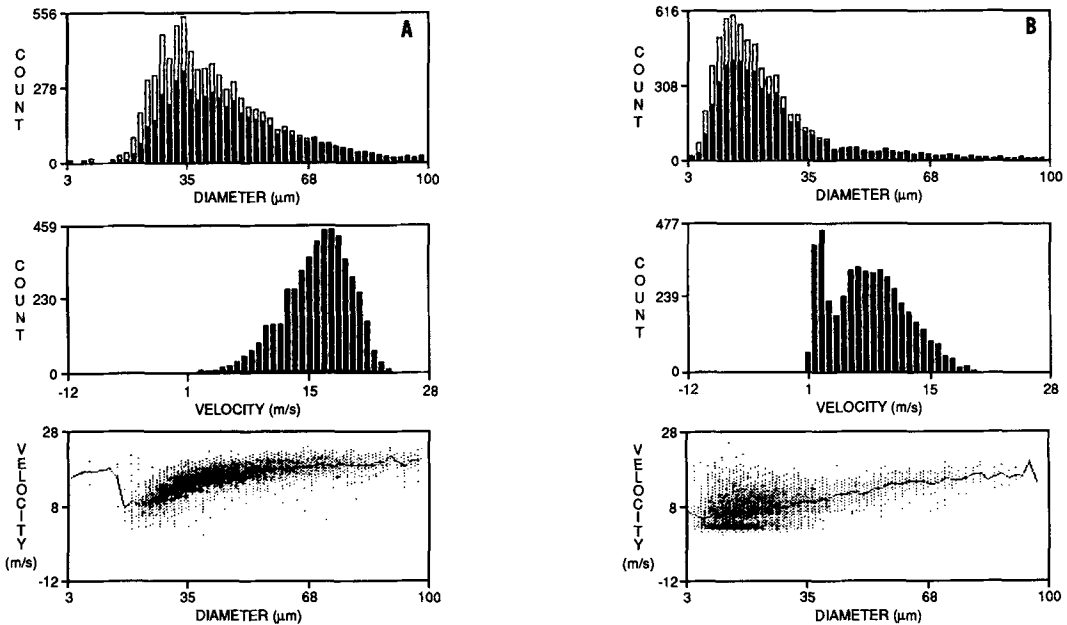
FIG. 5. Droplet size and velocity distributions and size-velocity correlations obtained at two locations in the methanol/dodecanol mixture flame. (A) $Z = 25.4$ mm and $r = 17.8$ mm, and (B) $Z = 50.8$ mm and $r = 33.0$ mm.

eter, the arithmetic mean D_{10}, which changes from 43 μm at $Z = 25.4$ mm to 23 μm at $Z = 50.8$ mm. Since this moment is more sensitive to the presence of smaller droplets, the change in D_{10} is indicative of the significant change in the population of droplets and can be construed as evidence of microexplosions.

Several other observations provide further support for the occurrence of microexplosions. For example, the droplet velocity/diameter correlations, shown in Fig. 5, graphically demonstrate the shift from larger, faster moving droplets to smaller, slower moving ones. An increase in the data rate also provides further evidence to support the same argument. The time to sample an identical number of validated data points was found to decrease from 10.6 s to 6.3 s, as the axial position changed from $Z = 25.4$ to 50.8 mm. This decrease could be interpreted as an indication of the increase in the droplet number density between these two positions. This increase is significant because in the absence of microexplosions, the number density is expected to decrease as a result of vaporization or combustion. Hence, we conclude that there is some evidence for the occurrence of microexplosions in the methanol/dodecanol spray flame. This phenomenon obviously needs further investigation.

It is interesting to relate the observations on microexplosions presented in this investigation to single droplet studies. Wang and Law have shown that,

for monodispersed droplet streams, microexplosions occur in 50/50 mixtures of methanol/dodecanol.[4] Recent evidence[12] has indicated that for stationary isolated and unsupported droplets, microexplosions have not been observed for this mixture; however, microexplosions have been observed for mixtures more diluted by methanol. Perhaps the occurrence of microexplosions in spray flames could be attributed to the influence of internal circulation within a moving droplet; the mixture components within a droplet may become distributed in a manner that creates the necessary superheat conditions for microexplosions.

The mean velocity profiles shown in Fig. 4 are again indicative of the overall characteristics of hollow-cone spray flames. The variation between flames is most prominent near the spray boundary; the droplet axial velocity is found to increase with decreasing viscosity. This trend is to be expected, since the droplet size and velocity would be inversely proportional, for a given initial droplet momentum. These findings are in agreement with the results found in the literature.[3] The rate of expansion of the spray boundary increases with increasing fuel viscosity, as indicated by the radial position of the velocity peak in each case. This is again to be expected, since the larger droplets generated by the more viscous fuels can maintain their momentum and original trajectory over a longer distance.

The profile for kerosene indicates an unusual in-

crease in velocity outside the nominal spray bound-
ary. This increase may be explained by the high
temperature luminous zone (surrounding the spray
boundary) which leads to higher droplet velocities
and more rapid evaporation of smaller droplets. As
mentioned previously, the velocity profiles for ker-
osene exhibit a reduced rate of deceleration near
the spray centerline. This is also attributed to the
much higher flame temperature and the more lu-
minous nature of the flame, which enhances the ra-
diative energy transfer rate. The droplet mean ve-
locities near the centerline for the other three fuels
remain relatively constant and near zero. However,
examination of only the mean velocities could be
misleading. Indeed, even in this region where the
mean velocities are very small, the measured ve-
locity distributions indicate the presence of nega-
tive droplet velocities and therefore a recirculation
zone. More detailed results on this topic are dis-
cussed in the next section.

Droplet Size and Velocity Distributions:

Droplet size and velocity distributions are pre-
sented in Fig. 6 for the heptane flame along the
spray centerline at Z = 10 and 50.8 mm. The val-
ues of D_{32} are presented on a temporal basis and
are corrected for changes in the measurement vol-
ume dimensions with droplet size.[5] The droplet size
distributions indicate a gradual decrease with axial
distance, in the droplet mean size as well as in the
width of the distribution. The arithmetic mean di-
ameter D_{10} changes from 15.0 μm at Z = 10 mm
to 5.0 μm at Z = 50.8 mm. The measurement of
D_{32} becomes much less reliable at downstream lo-
cations, where the number density has been re-
duced drastically, and the D_{32} values are affected
by noise found in the measurement bins corre-
sponding to larger droplet sizes. Therefore, D_{10}
provides a more representative value for the mean
droplet size. At Z = 50.8 mm, there are extremely
few droplets left at the centerline. Indeed, heptane
was the only flame where any measurements could
be made at this location.

The velocity distribution obtained at Z = 10 mm
exhibits a broad bimodal form; distributions at all
positions along the centerline indicate the presence
of both positive and negative valued velocities. The
positive values correspond to droplets transported
downstream directly from the fuel nozzle, while the
negative values represent recirculated droplets. The
droplet mean velocity at Z = 10 mm is about 1.9
m/s. At Z = 15 mm, the distribution becomes nar-
rower and the mean velocity is nearly zero, indi-
cating a local "stagnation" point. However, both
upward and downward moving droplets are de-
tected at this point; therefore, the concept of a
stagnation point is somewhat ill defined. Further
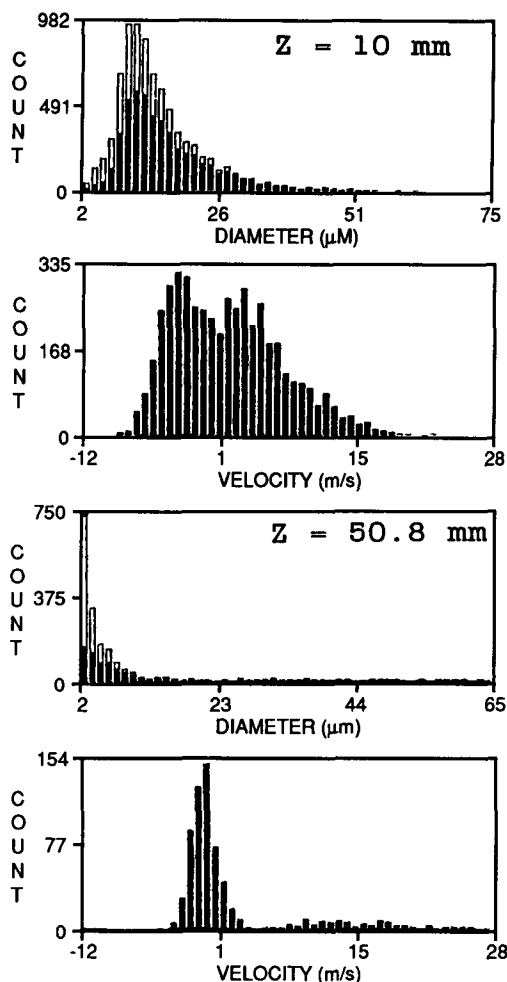downstream, the relatively small droplet mean ve-

FIG. 6. Droplet size and velocity distributions ob-
tained at two locations along the centerline of the
heptane flame.

locity is maintained, but the distributions become
much narrower. These results highlight the diffi-
culty of interpreting the experimental observations
based on only mean properties. They also point out
the importance of modelling the time dependent
nature of spray flames.

Summary

Spatially resolved information on droplet size and
velocity distributions have been obtained in pres-
sure-atomized spray flames of four different fuels.
The results have shown that the fuel viscosity ap-
pears to have the largest infuence upon the droplet
mean size and velocity. Higher viscosity fuels gen-
erate larger droplets; larger droplets tend to have

lower velocities. Fuel volatility, indicated by the corresponding boiling point range and the vapor pressure, seems to have some effect on the spray flame structure, especially in the methanol flame. Otherwise, the burning spray characteristics are found to be affected by the fuel physical properties that control droplet atomization, rather than those properties that influence vaporization processes.

Photographic studies of the flames indicate that the flame luminosity increases with increasing carbon-to-hydrogen ratio and heating value. Data indicate the existence of much higher droplet vaporization rates in the higher temperature, luminous kerosene flame.

Some evidence has been found in the methanol/dodecanol mixture flame to indicate the occurrence of microexplosions. This evidence is in the form of a sudden decrease in droplet size and velocity, and an increase in number density.

The droplet size and velocity distribution measurements indicate the presence of both positive and negative droplet velocities, especially in regions of relatively low mean velocities, such as near the center of the spray. The droplet size distributions found near the nozzle exit are quite broad, but they are observed to become much narrower at downstream positions, as droplets rapidly vaporize. These results emphasize the importance of acquiring detailed data on droplet size and velocity distributions, as well as their mean properties, in order to develop a fundamental understanding of the structure of spray flames and the effect of fuel properties.

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