A Comparative Study of Methanol and Acetone Spray Combustion in a Simple Turbulent Jet Flow

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Introduction

A laboratory burner has been developed to study the combustion characteristics of dilute sprays dispersed in a turbulent round jet of air flows. The burner design is intended to extend previous work with piloted jet diffusion flames [1] into turbulent combustion of spray jets. A nebulizer is placed upstream to generate droplets of different sizes, the distribution of which becomes fairly uniform at the burner exit. The slender shear flow field developed downstream is fluid mechanically well understood. Such flow fields are easily predicted with existing commercial CFD codes, so that the focus can be placed on evaporation and other aspects of droplet dynamics in turbulent spray flames. Similar burner design has also been used to investigate effects of the droplet-size distribution [2], burning modes of droplet clusters [3], and droplet/turbulence interactions [4, 5].

Salient features of droplet dispersion and evaporation in non-reacting [6] and reacting [7] acetone spray jets generated by this burner have been reported recently. The aim of this work is to extend the data base to a different fuel and to investigate its effects on turbulent spray combustion. Methanol is chosen here because of the small difference in liquid density by less than 1%. It has also the same index of refraction at 1.36 as acetone, but a lower vapor pressure and a larger binary diffusion coefficient in air. This results in a longer evaporation time for methanol than acetone droplets of the same diameter. The Phase Doppler anemometry (PDA) technique is applied to measure droplet size, two-component velocity, number density and the axial volume flux in three acetone spray flames. The mean and rms velocities conditional on different size classes are compared between methanol and acetone spray flames. The differences in droplet dispersion between non-reacting and reacting sprays are also explored.

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Experimental Conditions

The reacting acetone spray jet AHF investigated in Ref. [7] is chosen as the reference flame since its characteristics have been reported earlier. The global conditions for the methanol spray flame MHF are listed in Table 1 and compared with the spray jet AHF and the corresponding non-reacting spray jet LFS reported in Ref. [6]. The spray burner used here is identical to that in the earlier work [7], and is shrouded by air co-flow of a bulk velocity at 3 m/s. On the thin burner lip, an annular premixed pilot flame anchors the spray flames. The inner diameter of the main fuel tube, D, is 9.8 mm. The carrier air flow rate is also maintained the same between MHF and AHF.

	MHF	AHF	LFS
liquid fuel injected	methanol	acetone	acetone
liquid fuel injection rate (g/min)	26.3	21.1	7.0
carrier air flow rate (g/min)	170.4	170.4	135
overall fuel/air equivalence ratio of the jet	0.99	1.17	0.49
vapor flux at nozzle exit (g/min)	-	11.4	5.9
gas-phase equivalence ratio at nozzle exit	-	0.63	0.41
D_{32} at nozzle exit (μm)	19.2	18.0	13.7
flame height (x/D)	$15 \sim 20$	$15 \sim 20$	

Table 1: Global operation conditions.

Measurements have been carried out that scan along the radial direction at several axial stations downstream until less than 5% of the injected fuel remains as liquid. Droplet diameters as well as the axial, x-, and radial, r-, components of droplet velocities are recorded with a PDA instrument (Aerometrics, RSA 3100) arranged in the forward scattering mode. More details about the settings for the PDA system can be found in Ref. [7].

Results and Discussion

The centreline axial mean, $\overline{U}_{CL}$, and rms, u'_{CL}, veocities conditional on a particular size class are compared in Fig. 1 between the spray flame MHF and AHF investigated previously [7]. At axial locations of $x/D < 15$, both spray flames have almost the same velocity distributions. This indicates the same response of droplet dispersion to turbulence convection. Because the liquid density is the same for methanol and acetone, the droplet relaxation time is expected to be the same for droplets of the same diameter. However, the methanol spray flame is slightly shorter as seen in the faster decline of $\overline{U}_{CL}$ as well as the corresponding rise of u'_{CL} for $x/D > 15$. The shorter flame length is also supported by thermocouple measurements that the temperature rise along the centreline is faster in flame MHF. Despite a smaller droplet evaporation time, the longer acetone flame length is attributed to its slightly rich overall fuel/carrier air equivalence ratio of the jet, as seen in Table 1. The corresponding laminar burning velocity can be higher in the MHF than the AHF flame. This is related to the premixed-dominated nature for both spray jet flames investigated here.

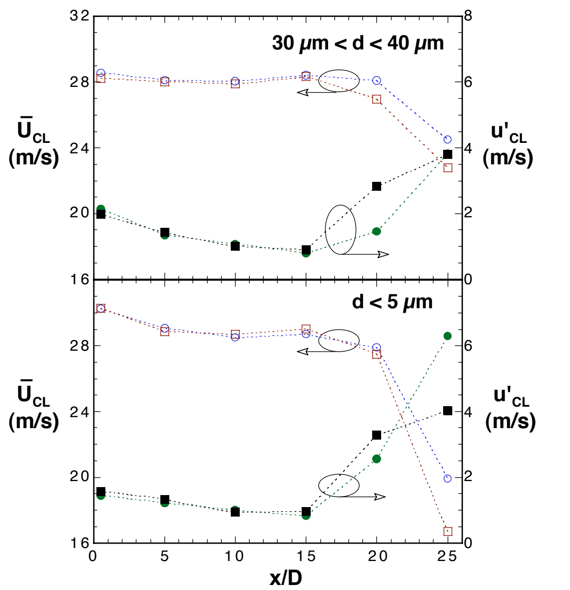

Figure 1: Comparison of the axial mean, $\overline{U}_{CL}$, and rms, u'_{CL}, velocities of droplets conditional on different size classes along the centreline for flame AHF: ○ and ●; and MHF: □ and ■.

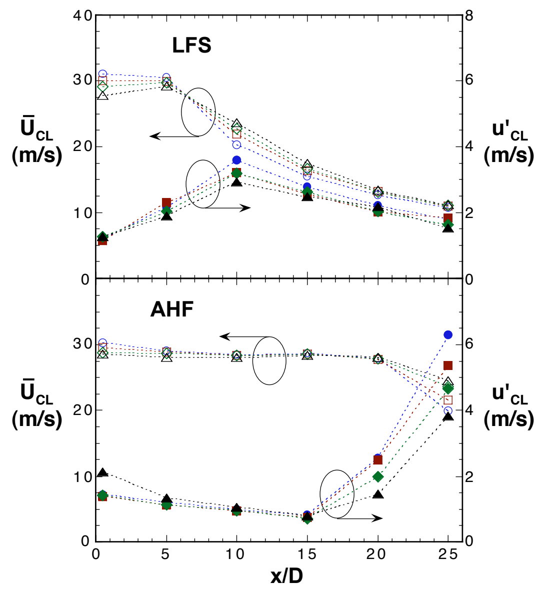

Figure 2: Comparison of the axial mean, $\overline{U}_{CL}$, and rms, u'_{CL}, velocities of droplets conditional on different size classes ($d < 5$ μm: ○ and ●; 10 μm $< d <$ 20 μm: □ and ■; 20 μm $< d <$ 30 μm: ◇ and ◆; 30 μm $< d <$ 40 μm: △ and ▲) along the centreline for the non-reacting LFS and reacting AHF spray jets.

Quite different droplet velocity distributions have been measured in non-reacting spray jets [6]. Figure 2 compares the centreline axial mean and rms velocities of the spray jet LFS with the corresponding spray flame AHF. The axial mean velocity remains almost unchanged along the centreline up to the flame tip for both methanol and acetone spray flames, as shown in Fig. 1. This feature is related to the premixed flame nature as air is used here as the carrier flow [7]. The obvious decay of $\overline{U}_{CL}$ begins almost at the flame tip near $x/D = 20$ for the spray flames. In contrast, the decline of $\overline{U}_{CL}$ occurs already at axial locations of $x/D > 5$ for LFS in Fig. 2, in line with the developmeant of substantial droplet dispersion effects. The different trends for both $\overline{U}_{CL}$ and u'_{CL} are clearly associated with the much longer potential core in the spray flame than in the non-reacting counterpart. A similar extension of the potential core length has been observed before in turbulent premixed jet flames [8] where the turbulent flame brush is located at a smaller radius than the mixing layer, and thus retards the inward transport of turbulence generated at the mixing layer. The resemblance to a premixed jet flame of the spray flames investigated here has been confirmed by OH-LIF imaging [9]. Almost all of the droplets are observed to evaporate within 1 mm or 2 of the local, instantaneous OH-fronts, irrespective of the fuel type. As the gas flow does not decay within the lengthened potential core, no apparent mean slip velocity is developed in the axial direction. Thus, the values of $\overline{U}_{CL}$ for droplets of all the size classes remain the same as $\overline{U}_o$ for $x/D < 20$ in spray flames.

Acknowledgements

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