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Design of “model-friendly” turbulent non-premixed jet burners for C_{2+} hydrocarbon fuels

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TABLE III. Flow parameters of the flames used in our experiments.

Fuel	Re	Q^{a} (kW)	Fr_f^{b}	$L_{f,e}^{c}$ (mm)	$L_{f,m}^{d}$ (mm)	FR_f^{e} (slpm)	FR_p^{f} (slpm)	U^{g} (m/s)	T_f^{h} (°C)	T_p^{i} (°C)
C2H4	10 000	12.0	1.0	652	730	13.2	4.45	0.60	21	21
	15 000	18.0	1.4	755	775	19.8	6.68			
	20 000	24.0	1.9	832	830	26.4	8.91			
	25 000	30.0	2.4	890	861	33.0	11.14			
JP-8	20 000	16.5	1.0	860	872	0.0295	6.09	0.67	300	205

[a] Heating value of the main fuel jet.

[b] Froude number of flame; for JP-8, assumes 40% radiation loss.

[c] Estimated visible flame length; for JP-8, assumes 40% radiation loss.

[d] Measured visible flame length.

[e] Volumetric flow rate of main fuel jet (liquid flow for JP-8).

[f] Volumetric flow rate of pilot flame premixture.

[g] Velocity of coflow air.

[h] Temperature of unburnt fuel.

[i] Temperature of pilot flame premixture.

2% of the heat release rate of the main fuel jet. Detailed flow parameters are listed in Table III. Note that these flames with Fr_f ranging between 1.0 and 2.4 fall in the transitional regime, where both buoyancy and jet momentum are important.[54] Visible flame heights estimated from Eq. (1) generally match measured values well, confirming the validity of using this relation.

III. PRELIMINARY CHARACTERIZATION

The open flame configuration permits convenient access for both optical and probe-based measurements. The five canonical flames were characterized with qualitative methods, including direct photography, OH LIF planar imaging and soot LII planar imaging. In addition, measurements of the burner lip temperature boundary with line Rayleigh imaging are presented for ethylene flames. Much can be learned from these preliminary measurements, such as the flame size, the frequency of occurrence of local extinction, and soot behavior.

A. Visual observation

In general, a sooty jet flame has a blue soot-free region near the nozzle (Fig. 1(c)) followed by a soot-laden region downstream. Soot produced in the flame is either consumed or escapes from the flame as smoke. The length of the soot-free region depends on the fuel, the fuel jet diameter, and the fuel jet velocity. Figure 7 presents fast-shutter photos of the four ethylene jet flames. With the 1/1600 s exposure time, the soot-free region is nearly invisible and the sooty regions appear orange, from the broad-band soot radiation. An increase in jet velocity pushes the sooty edge (the bottom edge of the soot-containing region) downstream. The photographs of the flames also show a progression in flame wrinkling with increasing jet Re. The flame with a Reynolds number of 10 000 shows smooth, large-scale vortex rollup, particularly as the distance from the nozzle increases (and buoyancy effects become relatively stronger). For flames with higher Re, the luminous flame front shows more intense wrinkling and smaller characteristic flame structures, reflecting a more turbulent flow field. The flame also broadens radially with the increase in Re, reflecting the increased rate of mixing between the fuel jet and the air coflow.

Since the JP-8 flame uses a burner with a smaller fuel tube diameter than the ethylene flames, there is limited value in comparing these flames. Instead, we can compare the JP-8 flame to an ethylene flame established on the same (liquid-fuel) burner with the same fuel jet Re (20 000). As shown in Fig. 8, these two flames look somewhat different. While the ethylene jet flame has a fairly long blue, soot-free region near the nozzle, the JP-8 flame is almost completely devoid of

FIG. 10. (Color online) Instantaneous false-color OH PLIF images of three turbulent ethylene jet flames (a, Re = 15 000; b, Re = 20 000; c, Re = 25 000) and one JP-8 flame (d, Re = 20 000). The same intensity map was used to process all of the OH PLIF images.

local Rayleigh scattering cross section of the chemical species mix in this region.

A similar measurement of the temperature boundary was not performed for the JP-8 flame, but the nearly identical design of the pilot plate for this burner as for the gas burner is expected to give equivalent temperature profiles at the burner exit plane.

C. OH LIF imaging

As OH is an important flame marker, planar imaging of OH is an effective method of capturing extinction events, which appear as breaks within otherwise continuous OH layers. To perform these measurements, a UV laser beam at 283.55 nm was generated from the frequency doubled output of a YAG-pumped dye laser. The beam was shaped into a laser sheet with sheet-forming optics and subsequently intersected the flame on an axial plane, exciting OH radicals. The OH fluorescence was detected by an intensified CCD camera (ICCD-MAX, Princeton Instruments) operating with a 100 ns exposure time using a 105-mm focal length, f/4.5 UV Nikkor lens and a band-pass filter set that transmits 304–320 nm. This OH detection scheme provides good discrimination against flame emission, laser scattering and fluorescence from polycyclic aromatics, but accepts fluorescence from single and double-ring aromatics.[59]

Figure 10 shows false-color OH LIF images centered about 24 jet diameters downstream, where strong strain coupled with diminishing influence of the pilot flame results in the highest probability of local flame extinction. For ethylene flames with a Reynolds number of 15 000 or less, breakup of OH layers rarely occurs (Fig. 10(a)). Breaks in the OH layers are occasionally apparent in the ethylene flame with a Re of 20 000 (Fig. 10(b)), and become a frequent feature when the flame Re reaches 25 000 and above (Fig. 10(c)), suggesting frequent local extinction followed by reignition downstream. Flames remain attached to the burner lip until the fuel jet Re is increased beyond 35 000, when extinction becomes so severe that the flame is partially attached or lifted off from the burner. Clearly, this relationship between the flame Reynolds number and extinction frequency is consistent with our prediction based on U_J/D as shown in Fig. 2. It is also noted that, with the increase in Re, the OH layers at this height change from smooth sheets (Fig. 8(a)) to rugged and kinked structures (Figs. 10(b) and 10(c)), indicating the enhanced interactions between turbulence and the flame zone.

Figure 10(d) shows an OH fluorescence image of the JP-8 flame over a similar range of near-burner heights as for the ethylene flame images. Note that the strong fluorescence around the jet axis ($r/D = 0$) is due to small-ring aromatics,