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STABILIZATION AND STRUCTURE OF N-HEPTANE FLAME ON CWJ-SPRAY BURNER WITH kHz SPIV AND OH-PLIF

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Abstract

A curved wall-jet (CWJ) burner was employed to stabilize turbulent spray flames that utilized a Coanda effect by supplying air as annular-inward jet over a curved surface, surrounding an axisymmetric solid cone fuel spray. The stabilization characteristics and structure of n-heptane/air turbulent flames were investigated with varying fuel and air flow rates and the position of pressure atomizer (L). High-speed planar laser-induced fluorescence (PLIF) of OH radicals delineated reaction zone contours and simultaneously stereoscopic particle image velocimetry (SPIV) quantified the flow field features, involving turbulent mixing within spray, ambient air entrainment and flame-turbulence interaction. High turbulent rms velocities were generated within the recirculation zone, which improved the flame stabilization. OH fluorescence signals revealed a double flame structure near the stabilization edge of lifted flame that consisted of inner partially premixed flame and outer diffusion flame front. The inner reaction zone is highly wrinkled and folded due to significant turbulent mixing between the annular-air jet and the fuel vapor generated from droplets along the contact interface of this air jet with the fuel spray. Larger droplets, having higher momentum are able to penetrate the inner reaction zone and then vaporized in the low-speed hot region bounded by these reaction zones; this supports the outer diffusion flame. Frequent local extinctions in the inner reaction zone were observed at low air flow rate. As flow rate increases, the inner zone is more resistant to local extinction despite of its high wrinkling and corrugation degree. However, the outer reaction zone exhibits stable and mildly wrinkled features irrespective of air flow rate. The liftoff height increases with the air mass flow rate but decreases with L .

Keywords: Turbulent spray flame, CWJ burner, Flame structure, SPIV, OH-PLIF

Nomenclature

A_o	Exit area	[mm ²]
d_{eff}	Effective diameter ($d_{eff} = \sqrt{4A_o/\pi}$)	[mm]
H_l	Liftoff height	[mm]
L	Position of pressure atomizer	[mm]
$\dot{m}$	Mass flow rate	[kg/hr]
r	Radial coordinate	[mm]
R	Radius	[mm]
Re	Reynolds number ($Re = d_{eff} V_o / \nu_a$)	[-]
V	Velocity component	[m/s]
V_o	Velocity at slit exit	[m/s]
V'	Root mean square velocity component	[m/s]
U	Velocity	[m/s]
u'	Root mean square velocity	[m/s]
y	Normal coordinate	[mm]
z	Axial coordinate	[mm]
ϕ	Orifice size	[mm]
ϕ_l	Equivalence ratio of liquid fuel	[-]
ϕ_g	Equivalence ratio of gaseous fuel	[-]
ν_a	Kinematic viscosity	[m ² /s]
Subscripts		
	Air	
a	Fuel	
f	Gaseous	
g	Liquid	
l	Radial component	
r	Axial component	
x	Normal component	
y		
Abbreviations		
AJ	Annular jet	
CWJ	Curver-wall jet	
IJ	Interaction jet	
ISL	Inner shear layer	
MJ	Merged jet	
OSL	Outer shear layer	
RZ	Recirculation zone	

1. Introduction

Liquid fuel sprays are adopted in a variety of practical combustion devices such as gas turbines, compression-ignition engines, industrial furnaces and boilers [1]. Understanding the

physical phenomena that control spray combustion processes is desirable, as most of these devices principally consume the fuel in a two-phase flow. Phenomena such as flame stabilization, structure, and extinction are important aspects of spray combustion that are still not well characterized. The mutual interaction of spray and oxidizer flow field can play an important role in determining the dominant mechanisms that control spray flame behaviour, i.e., flame stabilization and structures [2]. These structures are responsible for determining combustion efficiency and pollutant emissions [3].

Extensive experimental and numerical studies have been conducted on turbulent spray combustion in various configurations [4]. The present spray burner adopted the Coanda effect [5] not only to improve flame stabilization but also to enhance droplet evaporation in the near-injector region. Such Coanda effect has been studied for turbulent premixed flames [6] by injecting premixture over a curved wall as a form of annular-inward jet in the curved wall-jet (CWJ) burner. Due to curvatures of streamlines, a low-pressure region was generated, resulting in flow adherence to the curved surface. As the static pressure recovered, the wall-jet separated to form a recirculation zone (RZ). The annular-inward jet collided over the RZ in an interaction jet region, generating a high level of turbulence by the collision as well as the effect of ambient air entrainment; this was subsequently developed as a merged jet in the downstream region. Such a burner resulted in improved flame stabilization and a short flame length. Kim et al. [7] further improved premixed flame stabilization by modifying the burner tip, introducing a concave cavity on the tip. Mansour and Chung [8] proposed a configuration for stabilizing non-premixed turbulent flame. Similar curved wall-jet (CWJ) burner was designed for flame synthesis [9].

We propose here a new burner concept that utilized the aforementioned Coanda effect to stabilize turbulent spray flames. This was achieved by using a liquid fuel (n-heptane) that was injected through a spray nozzle at the centre of the burner as schematically shown in Fig. 1a without and with a pilot-like flame. The latter was functioned by supplying small amount of reactants (e.g., ethylene) through the curved wall along with air. The evaporation of the liquid fuel can be augmented due to the following: (1) the recirculated hot gases upstream could enhance the droplet evaporation; (2) the collision of the air with spray at the interaction jet region could disperse the droplets; (3) the air entrainment along with injected air could enhance mixing the spray with oxidizer; (4) the steep velocity gradient, formed along the curved wall could enhance the interaction between the air and droplets.

Simultaneous application of particle image velocimetry (PIV) and laser induced fluorescence (LIF) techniques [10,11] contributed to better understanding of turbulence-flame interaction [12]. This included flame extinction phenomena in turbulent non-premixed jet flames [13,14], low-swirl turbulent premixed flames [15, 16], strain rate in non-premixed jet flames [17,18], and swirl-stabilized premixed flames [19]. Flame surface density, flame front curvature and turbulence statistics in lean premixed flames [20,21] were also studied using such techniques. The flow field and structure of spray flames were also characterized using PIV [22] and OH [23,24] measurements, respectively.

We investigate the stabilization characteristics of flames in the CWJ-spray burner under various operating conditions (Table 1). Also, the flow-spray-flame interactions are addressed particularly close to the injector point for such burner with detailed spatial and temporal measurements using high-speed laser diagnostic techniques. Multi-kHz stereoscopic particle image velocimetry (SPIV) and planar laser-induced fluorescence of OH radical (OH-PLIF) techniques were used to provide insights about turbulent non-reactive flow field and reactive structures of spray flames. This database of high-resolution measurements is required for turbulent spray combustion modeling in the future.

Figure 1. CWJ burner with dimensions (a) and optical setup for OH-PLIF and SPIV diagnostics (b).

2. Experiment

The apparatus consists of a CWJ-spray burner and flow control system, a SPIV system, and a PLIF system for OH detection as schematically shown in Fig. 1b.

2.1 Experimental facility

The CWJ burner (Fig. 1a) is composed of an inner hollow cylinder with 70 mm in diameter and 150 mm in length, having a hemi-spherical end. On the top, a cavity of spherical shape has a radius that depends on the nozzle position, L . This cavity has a width of 31 mm, within which the fuel injector was equipped coaxially along the burner centreline. The distance from the injector tip to the burner exit, L , can be controlled, affecting droplet dynamics. Two values of L are investigated: 5 and 20 mm. The solid cone nozzle injector (Danfoss) is characterized having a 45° cone angle with ϕ 0.23 mm orifice. An outer flow guide has a concentric cylinder with 72 mm i.d.; this forms a converging section at the end having an exit diameter of 56 mm with $R = 36$ mm. The slit height between the hemisphere and the tip of the outer cylinder can be controlled. The dimensions of this concave cavity are modified as compared with [6-8] to accommodate larger RZ.

An adjustment of the slit height could not only control flame height and stability, but also can prevent flashback by keeping the height smaller than a quenching distance in case of gaseous fuel/air premixtures when it is used. Additionally, this converging section enables velocity field directing tangentially into the curved wall surface then toward the burner axis. This annular-inward jet, when collides in the interaction jet region, could generate high level of turbulence.

Air was metered using a mass flow controller and supplied through the curved-wall slit. Liquid fuel (>99% n-heptane) is supplied from a pressurized tank, with the injection pressure in the range of 0.4 – 1.1 MPa, corresponding to the fuel flow rates of 0.81 - 1.39 kg/hr. Details of test conditions are listed in Table 1, where $\dot{m}$ is the mass flow rate and the subscripts a and f indicate air and fuel, respectively, ϕ_l is the liquid fuel equivalence ratio while ϕ_g denote the premixture one (cases F5, F10), when air and ethylene (99.995%) were supplied through the curved-wall slit. The characteristic Reynolds number, $Re = d_{eff} V_0 / \nu_a$, is based on the mean jet velocity, V_0 , the kinematic viscosity of the air, ν_a , calculated from Gaseq code [25] and the effective diameter, d_{eff} , defined as $d_{eff} = \sqrt{4A_0/\pi}$, where A_0 is the exit area at the slit, which is calculated from the normal projection from the tip of the outer cylinder to the inner one. The exit area was kept constant at 200 mm² in the present study and V_0 ranges from 4.95 to 16.50 m/s corresponding to Re of 5256 to 17519, respectively. Several parameters in Table 1 will be further discussed later.

Table 1. Experimental conditions and parameters of flames F1-F10

Flame	L [mm]	$\dot{m}_a$ [kg/hr]	$\dot{m}_f$ [kg/hr]	ϕ_g	ϕ_l	V_0 [m/s]	Re	H_L [mm]
F1	5	4.248	1.247	0	4.318	4.95	5256	18
F2		6.372		0	2.878	7.43	7884	24
F3		8.496		0	2.159	9.90	10511	26
F4		14.16		0	1.295	16.50	17519	30
F5		4.248		0.55	4.318	4.95	5256	0
F6	20	4.248	1.247	0	4.318	4.95	5256	0
F7		6.372		0	2.878	7.43	7884	12
F8		8.496		0	2.159	9.90	10511	14
F9		14.16		0	1.295	16.50	17519	27
F10		4.248		0.55	4.318	4.950	5256	0

2.2 Instrumentation

The SPIV system (La Vision, LDY 300) consisted of a high-repetition rate (up to 10 kHz) twin-cavity diode-pumped Nd:YLF laser (Litron, LDY304-PIV at 527 nm, 28 mJ/pulse, 5 ns pulse duration) and two CMOS cameras (La Vision, Imager Pro HS 4M with 2016×2016 pixels) coupled with a high speed controller. The laser output formed into a sheet of about 1 mm thickness and the height of about 90 mm using two-lens cylindrical telescope and time separation of 30 to 50 μ s are repeated at 2.5 kHz, producing 3D vector field every 0.4 ms.

Seed particles were TiO₂ having 0.18 μ m nominal diameter. Seed levels were adjusted for accurate vector computation and maintained the number of spurious vectors during image processing less than 5%. The Mie scattered light from each laser pulse was recorded on a separate frame. The two cameras were placed equidistant from, and on the same side of, the laser sheet to collect forward and backward scattered light at an angle of 40° with the laser sheet plane as shown in Fig. 1b. Scheimpflug, joining the lens to the camera, had an angle of 5-7° to project focus plane to the target frame. Two different apertures were used to match recorded light intensity for the two cameras in order to compensate the intensities of forward and backward scattered light. A perspective distortion from the camera system was calibrated by imaging a 3D dot target (La Vision type 11), which was also used to align the field of view from SPIV cameras with those from the OH-PLIF camera.

The velocity vector fields were determined through multi-pass vector computation technique (La Vision Davis 8.1 software) with interrogation region size of 32×32 pixels having 50% overlap, equivalent to a spatial resolution of 1.1×1.1 mm². The system was operated at 2.5 kHz for recording 0.2 s duration such that 500 double-frame images were analyzed.

The fluorescence from OH radicals, as a marker of reaction zone, was measured with the high-speed (up to 10 kHz) PLIF system. The system consisted of a frequency-doubled, diode-pumped solid state Nd:YAG laser (Edgewave, IS16II-E) that pumped a dye laser (Sirah, Credo-Dye). The dye is Rhodamine 6G in ethanol (0.09 g/L concentration). The output of the dye laser was frequency-doubled to UV using BBO crystals and then tuned to excite Q₁(8) line of the A-X (1,0) OH transition at 283.57 nm with output energy of about 300 μ J/pulse at 10 kHz repetition rate. The UV laser beam was expanded through a two-lens cylindrical telescope configuration forming a collimated sheet of 70 mm in height at the target.

The fluorescence signals of OH at 295-345 nm were captured at a right angle to the laser sheet with an intensified CMOS camera (La Vision, HSS8 and IRO) with 1024×1024 pixels. Elastic scattering noise from the laser sheet and background luminosity were reduced

by using a high-transmission band-pass interference filter ($>80\%$ at 320 nm) and also by minimizing intensifier gate time (200 ns). Spatial resolution was about 0.11 mm/pixel. The system was operated at 10 kHz for recording 0.15 sec duration such that 1500 images were analyzed after applying background, energy, and sheet corrections.

3. Results and discussion

3.1 Flame shape and stability

Experiments were performed for the test conditions F1-F10 listed in Table 1 with special focus on rich flames, since previous studies exhibited excellent flame stabilization characteristics for rich mixtures [6-9]. Direct photographs near the nozzle region of these flames are shown in Fig. 2. For F1-F5 (upper row), the nozzle is at $L=5$ mm below the exit of the flowing air (Fig. 1a), while the lower row represents the cases for $L=20$ mm. Flames F5 and F10 represent the cases in which very lean premixtures of ethylene/air are supplied through the curved nozzle. These flames have blue color at upstream close to the burner tip followed by yellow-sooting flames in the downstream region.

The flame length, based on the visible luminosity, ranges from 700 to 150 mm that decreases with air mass flow rate but they are insensitive to L . Also, the flames with large L extend further radially compared to the corresponding small L cases. This intensifies the volumetric combustion intensity as flames become more compact. These images show that the liftoff height (H_L) of the flame base (leading edge) increases with air mass flow rate while it decreases with L .

For the flame with partial premixing (F5, F10), a premixed flame stabilized near the tip of the cavity supports a flame front that surrounds the spray cone, and could shorten the residence time for droplet vaporization in the recirculation zone. Similar stability results are obtained in [8] for propane nonpremixure flames.

The stability diagram of the CWJ-spray burner is shown in Fig. 3 in terms of the fuel and air flow rates for the two nozzle positions. Three regimes can be identified, namely attached flame to the cavity tip, lifted flame and flame quenching regimes. For example, for $\dot{m}_f = 1.0$ kg/hr (blue dashed arrow) with small $\dot{m}_a$, the flame base is attached to the tip of the cavity and stable. As $\dot{m}_a$ increases above the lower limit, 2.2 (2.8 kg/hr) for $L = 5$ (20) mm, the flame base becomes lifted. As $\dot{m}_a$ increases further over the upper limit, the flame is completely quenched. Between these two limits, the liftoff height increases with $\dot{m}_a$ as exhibited in Table 1 for $\dot{m}_f=1.247$ kg/hr. The attached flame regime broadened for flames of $L = 20$ mm while the lifted flame regime shrinks as compared with the case of $L = 5$ mm. When $\dot{m}_f$ is small (< 0.95 kg/hr), the nozzle position has minor influence on the extent of the lifted flame regime. As $\dot{m}_f$ increases over say, 1.0 kg/hr, $\dot{m}_a$ increases rapidly with $\dot{m}_f$ at the quenching condition. Due to the limitation in the air flow rate in the laboratory $\dot{m}_a$ was limited to 14 kg/hr in the present experiment. The result indicates that the burner can be operated stably as either nozzle-attached or lifted flame for relatively large fuel loading, typically with global rich conditions.

Figure 2. Photographs of flames F1-F10 (upper row $L5$, lower row $L20$).

Figure 3. Flame stability diagram (asterisks denote flames in Table 1, $L5$ (black) solid and $L20$ (black) dotted lines).

3.2 Non-reacting flow-field characterization

The SPIV system was used to characterize the turbulent flow field of both non-reacting and reacting flows. A coordinate system is adopted in representing data with (r, z, y) in the radial, axial and normal to the plane coordinates, respectively, with $z = 0$ at the tip of the cavity (Fig. 1a). Data collected from 500 images at 2.5 kHz were analyzed and the mean velocities (V_r, V_z, V_y) and rms velocities (V'_r, V'_z, V'_y) in the radial, axial and normal coordinates, respectively, were determined. The spatial distributions of (V_r, V_z) , together with color-coded magnitude of $U = \sqrt{(V_r^2 + V_z^2 + V_y^2)}$ and the corresponding rms turbulent velocity, $u' = \sqrt{(V_r'^2 + V_z'^2 + V_y'^2)}/3$, are shown in Fig. 4 for the cold flow conditions corresponding to the cases (F1(F6), F3(F8), F4(F9)) without supplying fuel spray.

The general features of the flow field exhibit typical flow characteristics of the CWJ burner [8]; a recirculation zone (RZ) near the cavity exit, an interaction jet (IJ) region with the collision of the annular-inward jets near $z = 10$ mm, and a downstream merged jet (MJ) region as marked in Fig. 4a. Inner and outer shear layers (ISL and OSL) surrounding the annular-inward jets (AJ) can also be identified. As can be seen in Fig. 4b for the velocity fluctuations, the velocity gradients in these shear layers generate turbulence augmented by the collision of annular-inward jets, and have large u' .

Figure 4. Spatial distribution of mean velocity vector fields with the background color indicating U (a) and velocity fluctuation (b) for the cold flow conditions corresponding to F1(F6), F3(F8) and F4(F9) flames.

The axial ($r = 0$) and radial (at $z = 4$ mm) profiles of the mean and rms velocities are plotted in Figs. 5 and 6, respectively. The recirculation zone is clearly exhibited by V_z having negative values for $0 < z < 10$ mm (Fig. 5a), which could reach up to -4 m/s (case F4 and F9). In the interaction jet region, V_z increases rapidly and then in the merged jet region slightly decreases (F4, F9) or maintains near uniform values (F1, F3, F6, F8) up to $z = 90$ mm. The radial profiles of V_z (Fig. 5b) at $z = 4$ mm again exhibit RZ (negative values), inner and outer shear layers (large velocity gradient), and annular-inward jets. Values of V_z and V_r peak near $r = 15$ mm in the annular jet region. The values of V_r diminish at both of the centreline and the outer shear layer while values of V_y are negligible.

The axial profiles of rms velocities (Figs. 6a-d) show that V_r' , V_y' and u' have large values in RZ and decreases in the interaction jet region, and maintains reasonably uniform values in the downstream merged jet region for the investigated flows. V_z' maintains a reasonably low uniform values. These results indicate that the collision of annular-inward jet near the boundaries of RZ influences turbulence generation.

The presence of the outer shear layer dominates over the inner shear layer in generating large values of all the rms velocity components, particularly in high Re flames as shown in Fig. 6e-h. However, V_r' and V_y' and consequently u' exhibits relatively high values at $r = 0$ due to the collision of annular-inward jets. These rms velocities are expected to be influenced by the heat release in reacting flames [26].

Figure 5. Axial V_z (a) and radial V_z (b), V_r (c), V_y (d) profiles of mean velocities for cases in Fig.4.

Figure 6. Axial V'_z (a), V'_r (b), V'_y (c) u' (d) and radial V'_z (e), V'_r (f), V'_y (g), u' (h) profiles of rms turbulent velocities for cases in Fig.4.

3.3 Spray flame structure

Measurements of OH-PLIF for the current spray flames reveal insights on various dynamics of turbulent spray flames and clarify their structure. The general features of the reaction zone can be obtained from the time-averaged OH-PLIF images shown in Fig. 7 for spray flames (F1-F10). The corresponding experimental conditions are summarized in Table 1; flames (F1^{*}) and (F6^{*}) designate flames (F1) and (F6) without air respectively.

The investigated spray flames were generally characterized with double reaction zone that consisted of two conical-shape flame fronts located on each side of the spray centreline that emanated from the flame base (leading edge). The inner flame front corresponds to a reaction zone located along the spray cone and follows its shear layers with the annular-inward air jet while the outer reaction zones presumably follow the influence of the ambient air. The large-scale mixing seems to influence remarkably the location of these reaction zones that are significantly affected by air flow rates as shown in Fig. 7.

It is apparent that the mixing between the droplets and its vapour with the annular air jet alters the structure of these reaction zones and its spatial extend. The existence of annular-inward air enhances the mixing between air and the small liquid droplets and consequently droplet evaporation. Flames associated with high air flow rate have an obvious inner flame front. The location of these reaction zones (liftoff height) increases with air mass flow rate (F1 to F4, Table 1). The relative position of the fuel nozzle with respect to the annular-air jet influences significantly the mutual interaction between the oxidizer and fuel droplets. Flames F6-F10 ($L=20$ mm) exhibit wider area of OH signal compared to flames F1-F5 ($L=5$ mm) that is confirmed by direct photos in Section 3.1, indicating high transport and mixing in these flames. This is probably due to the coexistence of fine droplets along the shear layer, enabling in the formation of a flammable mixture that support the inner reaction zone. Premixed flame of ethylene/air mixtures (F5, F10) influences substantially the droplet evaporation, resulting in a high probability of propagating partial premixed flames. The air entrainment is likely to stabilize the outer reaction zone only in flames F1^{*} and F6^{*}.

The instantaneous snapshots of the time-resolved OH-PLIF shown in Fig. 8 illustrate more details about the structure of reaction zones. Again such OH images revealed the double reaction zone structure. Local extinction occurred frequently at different locations of the inner reaction zone (e.g. F2, F6 and F7) [27]. However, the outer reaction zone is likely to be stable and has mildly wrinkled OH contour. Mie scattering images of spray droplets shown in Fig. 9 illustrate that there is no evidence for the effects of large-scale turbulence, disturbing this zone as its survival depends mainly upon the ambient entrained air. In this regard, the small droplets that are easily vaporized are probably consumed in the inner reaction zone under partial premixed conditions. But large droplets, penetrating the inner zone, can be settled and vaporized between the reaction zone structures, resulting in fuel vapour for the outer diffusion flame.

Figure 7. Time-averaged images over 1500 frames of OH-PLIF for spray flames (F1-F10). F1* and F6* represent flames F1 and F6 without air.

The leading edge or the flame base was stabilized at different locations, depending on the mass flow rate of the air, the position of the fuel nozzle (L) and finally on whether this is a single- or dual-fuel flame. As $\dot{m}_a$ increases, the liftoff height increases as shown in Fig. 8 and Table 1. The position of the injector, L , influenced significantly the OH distribution of the inner reaction zone. As L increased from 5 to 20 mm, the liftoff height decreased remarkably as shown in Fig. 8. Eventually, adopting premixed flame by supplying ethylene/air mixtures through the curved wall affected considerably the structure of the double reaction zone as shown in Fig. 8 for flames F5 and F10; they are merged together. The local extinction of the inner reaction zone was unlikely at high $\dot{m}_a$. This is in good agreement with [27] where high liftoff height was associated with increased air entrainment that strengthened the scalar dissipation within the inner zone and consequently reduced the localized extinctions.

Figure 8. Typical instantaneous images of OH-PLIF for spray flames (F1-F10). F1* and F6* represent flames F1 and F6 without air.

Figure 9. Typical Mie scattering images for spray flames (F4 and F1*).

As we change the location of the fuel nozzle, the near-field structure is significantly affected as the interaction jet region impacts different zone of the spray cone. As a result, the leading edge is located in a different region of the spray. This is attributed to that the annular jet interacts with more of the spray cone and with specific range of droplet sizes as L

increases. The inner reaction zone is wrinkled and shows characteristics of partially premixed combustion due to turbulent mixing at downstream locations that is increased with $L=20$ mm cases (F6, F7). Another characteristic of $L=20$ mm flame is that wider and distributed areas of OH are observed. This can be attributed to the significant effect of annular-inward air jet in dispersing the fuel droplets than that in $L=5$ mm cases (F1-F4), therefore creating a wider region, being favourable for combustion.

The flowing air retains significantly radial momentum (Section 3.2), interacting with the spray base before being redirected axially in the merged jet region. Such momentum interaction between the air jet and the dense spray cone controls significantly both the droplet distribution and their evaporation rate and consequently the OH distributions when we compare F1 with F6. This is confirmed by the Mie scattering images shown in Fig. 9. This favours partially premixed combustion at the downstream locations of the inner reaction zone for flames of $L=20$ mm cases as shown in Fig. 8 (F6 and F7). This can be clearly observed as the addition of annular air alters significantly both the gas phase flow field and the double flame structure practically for $L=20$ mm cases as shown in Fig. 8 for flames F6 and F6*. When we impose gaseous fuel (ethylene) with the air jet, this enhances the spray evaporation [28] and diffusion flame can be stabilized as shown in Fig. 8 (F5 and F10). The outer reaction zone disappeared as no droplets are able to penetrate into such regions.

Figure 10 shows the distributions of simultaneous OH fluorescence and velocity vectors for flames F6, F8 and F9. The OH distribution shows different features depending on $\dot{m}_a$ and in turn, ϕ_l and Re . For low $\dot{m}_a$ (flame F6), the inner flame front behave in partial premixed flames as there is plenty of fine droplets. This affects the velocity vectors particularly along the centre zone. However, this is not the case for high Re (flames F8 and F9) as annular air jet dominates the flow field and convects the central flame front downstream. The value of velocity vectors increases as they pass the leading edge as shown in Fig. 9 for flames F8 and F9. Also shown is that the velocity vectors tend to align with the two reaction zones due to probably the thermal expansion [27]. The upstream combustion structure of the inner zone burns in a partially premixed mode and is somewhat thinner than the outer diffusion flame. This is attributed to that this inner zone experiences relatively high strain rates compared to the outer zone which burns in the low-velocity gas flow that is well isolated from turbulence as shown in Fig. 9 (F6). Also, it is clear that the outer reaction zone is dominated by the diffusive fuel vapour existed between the double reaction zone and the ambient entrained air particularly for low Re flames (F6).

Figure 10. Simultaneous OH-PLIF and velocity distributions on axial plane for flames (F6, F8, and F9).

4. Conclusions

A curved wall-jet spray burner was proposed and employed to investigate the fuel/air interactions in n-heptane sprays. Time resolved SPIV and OH-PLIF measurements were conducted simultaneously to obtain spatially resolved information on the flow field

characteristics and on the structure of spray flames as they are significantly influenced by the annular combustion air which surrounds the fuel nozzle. We investigated the relative location between the pressure nozzle and the annular air jet as well as the air mass flow rate.

SPIV measurements revealed that the flow field consists of the wall jet region, recirculation zone, interaction jet region and a merged-jet region. Turbulence is generated through a shear effect along the boundaries of the annular jet as well as by collisions in the interaction jet region. High values of rms turbulent velocity within the recirculation zone are responsible for stabilizing such flames in this CWJ burner.

The time resolved OH fluorescence revealed that spray flames stabilized on CWJ burner are characterized with double reaction structure, propagating as two conical-shape flame fronts having the same flame base. The fine spray droplets that are well-mixed with the annular-inward air jet and easily vaporized are probably consumed within the inner reaction zone under partial premixed condition. However, the outer reaction zone seems to be smooth and stable as its OH contours reveal the diffusion flame structure. Droplets of large momentum can penetrate the inner reaction zone and inhabit the region between these reaction zone structures, resulting in fuel vapor for the outer diffusion flame that is survived by air entrainment. The OH-PLIF revealed also the occurrence of local extinction within the inner reaction zone that decreases with air flow rate. The leading edge location, indicating the lift-off height is function of air mass flow rate as well as the pressure atomizer position.

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Highlights

Curved wall-jet (CWJ) spray burner is proposed to stabilize turbulent spray flames.

Very compact spray flames can be realized with the curved wall-jet of air.

The liftoff height increases with the air flow rate but decreases with nozzle position.

OH fluorescence revealed a double flame structure at the stabilization edge of flames.

The inner reaction zone is highly wrinkled while the outer one exhibits stable features.