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Spray and soot characteristics of liquid spray flames in a high-pressure sector combustor

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Abstract: Conventional aviation combustors use liquid fuels where spray atomization is important for efficient combustion process and resultant emissions. In this study, a three sector combustor with commercial pre-filming airblast injectors are utilized to analyze the effect of operating conditions on spray and soot formation. Measurements are performed with both Jet-A and sustainable aviation fuel (SAF) at different operating pressures, preheat temperatures and global equivalence ratios. Phase Doppler particle anemometry is utilized to measure instantaneous drop-sizes in both non-reacting and reacting conditions. Instantaneous soot particle temperature and soot volume fraction distributions were measured in the primary zone of the combustor using two-color planar auto-compensating laser induced incandescence for both Jet-A and SAF flames. The drop-sizes shifted towards larger diameters for reacting conditions compared to non-reacting flow, possibly indicating the complete evaporation of smaller droplets at a given operating condition. In comparison to Jet-A, SAF fuel spray produced slightly smaller droplets owing to its reduced surface tension and higher vapor pressure values. The maximum averaged SVF were observed to be along the main reaction zone with values around 5 ppm for Jet-A flames at the operated conditions. For the SAF flames at the same conditions, the averaged SVF reduced by almost 2-3 times compared to Jet-A flames.

Keywords: *swirl-stabilized Jet-A/SAF flames, soot in high pressure Jet-A flames, spray atomization, phase Doppler anemometry, laser induced incandescence*

1. Introduction

Utilization of carbon-based fuels such as Jet-A in aviation combustors have a huge impact on climate through emissions from soot, CO₂, NO_x, etc [1]. One of the main factors affecting these emissions in such combustors is the atomization characteristics of the fuel injector, which in turn can affect fuel-air mixing and combustion efficiency. Spray atomization is mainly affected by fuel properties such as surface tension, viscosity and density [2] and injection conditions. With the use of new sustainable fuels and their blends, changes in the physical properties of fuels is important to understand the spray and combustion characteristics of the injectors [3]. Similarly, soot formation is also highly dependent on small changes in fuel structure, amount of aromatics [4] and operating conditions. Hence, it is important to characterize both spray and soot formation in realistic flow environments where combustors are usually operated.

Phase Doppler particle anemometry (PDPA) has been used extensively for measuring drop-sizes, which can provide high spatial and temporal accuracy for instantaneous measurements [5].

Optical access in most high-pressure combustors can fog the windows due to particulate matter or unburnt spray causing light distortion, leading to poor signal quality. In spite of these shortcomings, several studies have utilized PDPA in challenging environments including high-pressure conditions where drop-sizes can be only a few microns [6], or in dense-spray conditions where multiple droplets can occupy the probe volume [7]. With respect to combustion environments, studies [8] utilizing PDPA for characterizing spray suffered from several issues such as low signal to noise ratios and beam steering due to varying ambient density conditions. But there are very few studies where such characterization has been done in high-pressure sooting flame environments close to realistic gas turbine conditions. Soot measurements using laser induced incandescence (LII) have been performed previously in several lab-scale burners including laminar [9], turbulent and even liquid-spray flame environments [10]. But such measurements cannot be scaled to high-pressure, high-temperature flames as soot formation rates are highly non-linear with operating conditions. Although, few studies have obtained soot measurements in more realistic combustor configurations [11, 12], there is still lack of data at these conditions primarily due to difficulties in obtaining reliable LII measurements, soot intermittency, lack of optically accessible facilities, etc.

In the present study, PDPA and two-color planar auto-compensating LII have been utilized in a three-sector high-pressure turbulent spray flame to characterize in-situ droplet size distributions and soot volume fractions within the primary zone of the combustor. Several operating conditions are chosen to understand the effect of changing ambient environment on atomization and soot formation characteristics of the spray injectors with Jet-A and SAF as primary fuels.

2. Experimental conditions and diagnostics

2.1 Combustor and operating conditions

Measurements were conducted in an optically accessible combustor housed inside a large pressure vessel rated for pressures upto 30 bar at preheat temperatures of 727 K. The combustor design represents a rich-burn, quick-quench, lean-burn (RQL) concept representative of a typical aero-engine but with fused quartz windows for optical access, same as the one used in our previous study [12]. It consists of three inline swirl nozzles with commercial pre-filming airblast fuel injectors. The combustor and the windows were cooled with effusion and film air on all the walls. Air was supplied through storage tanks pressurized using a high-pressure compressor and metered using a sub-critical orifice. Liquid fuel for the combustor was supplied through a 38 L cylindrical tank with a piston accumulator pressurized using nitrogen gas. The fuel flow was metered using a mass flow controller (Alicat CODA KC-series, range 0-27.7 g/s, accuracy of $\pm 0.6\%$ of the flow rate) and equally divided using a manifold into the three fuel injectors.

PDPA measurements were performed at both non-reacting flow and reacting flow conditions to study the possible effects of combustion environment on droplet vaporization and subsequent drop-size. In all cases, only the central injector was operated so that the spray from the neighboring injectors do not cover the combustor windows which may affect PDPA measurements, especially in non-reacting conditions. A total of four operating conditions were chosen with varying pressure (0 psig, 35.3 psig, 85.3 psig), preheat temperature (450 K, 600 K), and global equivalence ratio (0.264, 0.315). The global equivalence ratio (ϕ_g) for 600 K preheat conditions was 0.264, whereas for 450 K preheat, it was 0.315. LII measurements were performed at slightly different operating conditions due to some experimental constraints and soot covering the windows at $\phi_g > 0.2$. Two

ϕ_g values (0.12 and 0.2) were chosen for LII measurements corresponding to an operating pressure of 35.3 psig and 450 K preheat temperature.

2.2 PDPA system

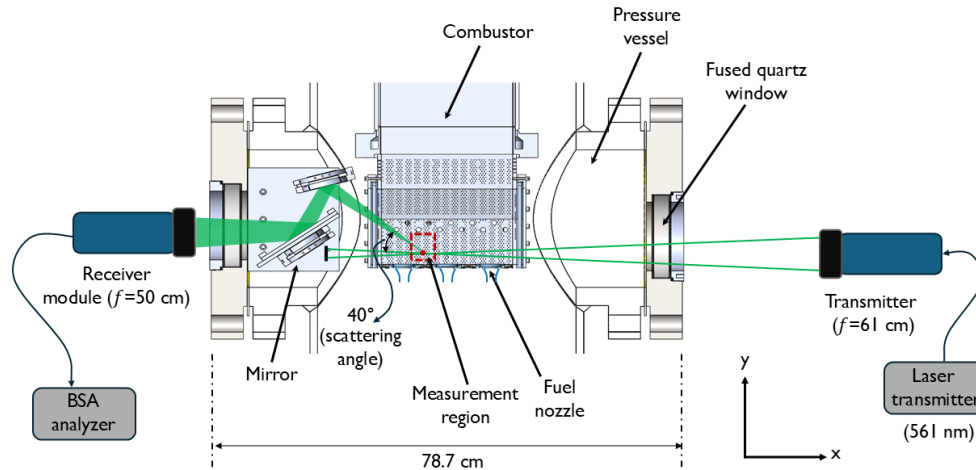


Figure 1: Schematic of the PDPA setup and mirror system for drop-size measurements within the confined high-pressure combustor.

The PDPA system (Dantec dynamics Inc.) consists of a diode-pumped solid state (DPSS) laser transmitter capable of emitting a pair of 1000 mW, 561 nm, frequency shifted (by 40 MHz) laser beams. The laser light is then sent into a transmitter probe (TSI Inc.), where a lens ($f=61$ cm) is used to focus the two beams into the measurement volume. The phase-shifted light scattered from the droplet in the small measurement volume is then collected by a receiver module ($f=50$ cm) through two mirrors placed inside the vessel and aligned such that the collection angle of the scattered light is $\sim 40^\circ$. The collected signal passes through a three slit mask mounted onto the receiver and then analyzed using a Dantec BSA spectrum analyzer.

The large distance between the pressure vessel windows restricted the amount of off-axis scattering angle available for PDPA to less than 20° , which is not ideal. To overcome this issue, a mirror mount system has been proposed wherein, the refracted light can be detected at off-axis scattering angles close to 40° . This mirror system is mounted onto the inner face of the quartz window flange as shown in Fig. 1. It consists of two mirrors, with the first mirror having a 7.5 cm diameter clear aperture and the second mirror having a 15 cm \times 10 cm rectangular area. They are aligned together to collect the refracted light from the droplets and directed onto the PDPA receiver module for further analysis. The measurement region was restricted to a 5 cm \times 5 cm area on left-hand side of the central nozzle as shown in Fig. 1, due to the constraints on the current PDPA setup, mirror system and the combustor window size.

The transmitter and receiver had to be mounted on separate translation stages and operated separately for performing measurements at different locations, as the mirrors are fixed inside the vessel. A monitoring camera (Teledyne Blackfly GigE) was mounted onto the eye slit of the receiver to align the receiver position to the required focus as the measurement locations are varied. Although, the entire vessel was operated at high preheat conditions up to 600 K, the mirror system

did not show any significant deformation or misalignment during operation. This mirror arrangement for the PDPA system is first such measurement technique utilized to obtain reliable droplet size data in a three sector combustor housed inside a pressure vessel.

2.3 Auto-compensating laser induced incandescence (AC-LII)

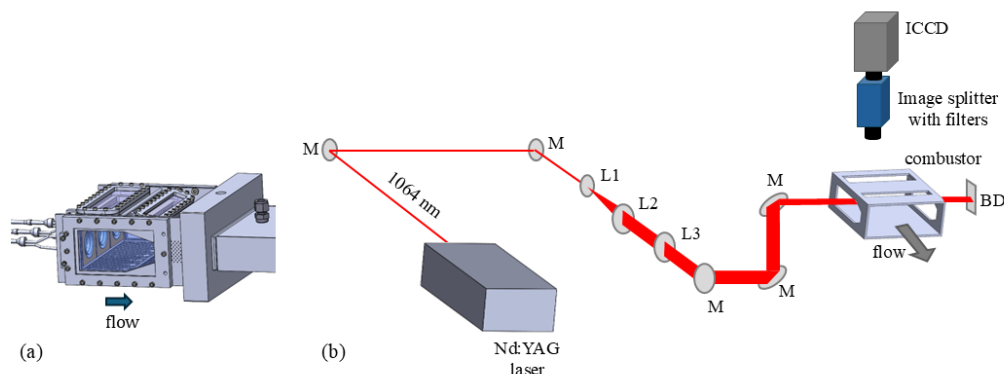


Figure 2: (a) RQL type combustor with fuel injectors and optical access. (b) Schematic of the LII setup used in the current study. M: Mirror; L: cylindrical lens; BD: beam dump.

Soot measurements within the flame region were performed using two-color auto-compensating laser induced incandescence technique based on the methodology by Snelling et al. [13]. The soot particles are heated using an Nd:YAG laser (Quanta-ray Pro-250) emitting 1064 nm beam having a pulse width of 8-12 ns with a frequency of 10 Hz. The laser beam is then passed through a combination of cylindrical lenses ($f=-25.4$ mm, $f=400$ mm and $f=1000$ mm) and iris to obtain a laser sheet of height 27 mm and waist < 1 mm. The laser sheet was created using the central part of the initial beam to obtain a near top-hat fluence profile across the entire height. For operating LII in the low-fluence plateau regime avoiding soot sublimation, the laser fluence across the sheet was kept to $\sim 0.25-0.3$ J/cm². The schematic of the optical setup for LII is shown in Fig. 2.

The resulting broadband LII signal is captured using an intensified CCD camera (PI-MAX4, Gen-III) and a macro lens (Tokina, $f=100$ mm, $f/\# = 2.8$). Since the technique requires detecting LII signals at two different wavelengths simultaneously, an image doubler (LaVision Inc.) was coupled to the ICCD. The image doubler houses a splitting prism to split the LII signal and pass through two band-pass filters, eventually focusing on the the ICCD sensor. The bandpass filters are centered at 447 ± 60 nm and 680 ± 42 nm, eliminating most of the scattering and fluorescence from soot and PAH particles present in the flow. The intensifier gate was set to 80 ns with a gain of 75% for all conditions to obtain a good signal to noise ratio.

To calibrate the detected LII signal to convert into soot volume fraction, a calibration lamp of known radiance-wavelength relationship is used. The calibration lamp (Stellarnet, 75W) mounted inside an integrating sphere is placed coincident with the LII measurement location, and the spectral radiance from the lamp is obtained with the same optical and camera setup as the actual measurements. The values are then used to convert the LII signal intensity to soot volume fractions. This calibration technique ensures that the quantification is independent of flame conditions, operating pressure and temperature. The LII signals detected at two different wavelengths is used to obtain soot particle temperatures using the two-color pyrometry technique, which is eventually used to calculate soot volume fractions [13].

3. Results and Discussion

3.1 Non-reacting spray measurements (Jet-A)

At every spatial location, a total of 10,000 instantaneous measurements were made for all cases. The droplet diameters were typically in a broad range of 1-100 μm at most locations, although the maximum frequencies were within the small range of 10-40 μm suggesting good atomization at these operating conditions. The Sauter mean diameters (SMD) for non-reacting Jet-A spray at different conditions are shown in Fig. 3. Due to the right skewed nature of the number frequency distributions, the SMD values tend to shift towards larger diameters but the peak diameters are always lower. It can be seen that the SMD values of the droplets reduced with increasing axial distance downstream of the injector along the spray cone as the swirling air assists in secondary atomization of the spray. Another reason for the decrease of SMD along the flow direction is vaporization of the droplets while moving downstream. Additionally, the region of measurement within the spray can have an effect on the drop-size being measured, leading to bias in the comparison of the range of drop-size. It is to be noted that the present PDPA system can detect droplets only in the range of 0.1-170 μm based on the slit size and mask used on the receiver module. But this range was sufficient to cover the entire spray as the probability of detecting droplets larger than 150 μm was almost negligible in the present study.

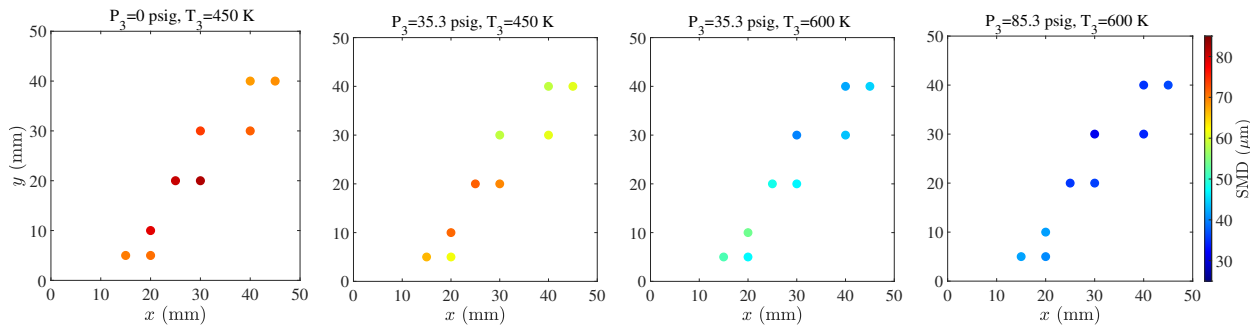


Figure 3: Spatial variation of Sauter mean diameter (SMD) values for non-reacting Jet-A fuel spray at different operating conditions. P_3 and T_3 represent the operating pressure and preheat temperature respectively.

Figure 3 shows the SMD values measured at different operating conditions for Jet-A in non-reacting conditions. Apart from the general trend of decreasing diameters with increasing downstream distance, there are trends observed with different pressures and preheat temperatures. With increasing operating pressure, the SMD decreases for a given location and preheat temperature. This could be due to the increase in Reynolds number of the surrounding air causing larger relative velocities between the liquid and gas phase, thereby inducing faster primary breakup of liquid jet and subsequent smaller droplets. The amount of reduction is highly dependent on the Reynolds number range or the operating pressure. The reduction in SMD due to increasing preheat for surrounding air is due to droplets being able to evaporate faster as they travel downstream of the fuel nozzle. Compared to the atmospheric conditions, the mean SMD values have decreased by more than two times when the combustor is operated at 85.3 psig pressure at a preheat of 600 K. Our results suggest that measurements and characterization need to be conducted at practical engine operating conditions.

3.2 Reacting spray measurements (Jet-A)

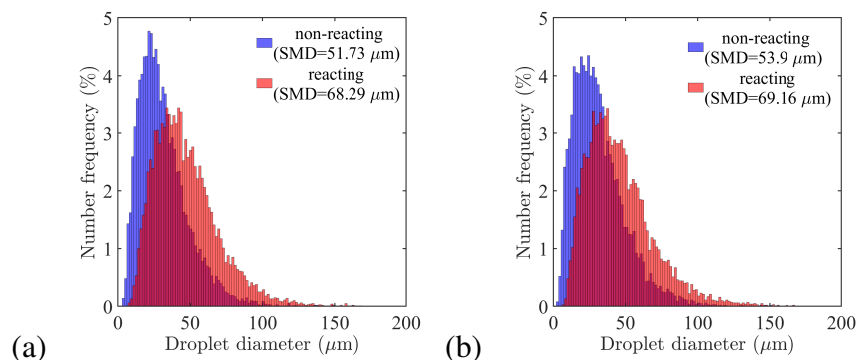


Figure 4: Comparison of number frequency distributions for Jet-A fuel at reacting and non-reacting conditions with 35.3 psig pressure and 600 K preheat temperature for locations (a) $x=15$ mm, $y=5$ mm (b) $x=20$ mm, $y=10$ mm. The frequency curves are obtained based on total counts for individual cases.

To study the effect of reacting conditions on the spray, measurements were performed with the same PDPA configuration at the same operating conditions. To avoid the highly soot regions in the flame where signal quality was low, the measurement region is confined to a small region 10-20 mm downstream of the dump plane within the spray cone. The number frequency distributions for non-reacting and reacting conditions are compared in Fig. 4 for Jet-A at 35.3 psig pressure and 600 K preheat at two different locations. For the reacting case, the distributions seem to shift towards larger diameters for all locations. This is counter-intuitive in the sense that reaction or the presence of flame should help the droplets evaporate faster adding to the preheat leading to smaller droplets. The plots in Fig. 4 suggests that the smaller droplets not only evaporate faster but are almost non-existent, leaving only the larger droplets being detected. Hence, the SMD values tend to be considerably higher in the reacting cases as compared to the non-reacting ones owing to the disappearance of small droplets which are vaporized promptly. An increase in almost 15-20 μm is observed for SMD consistently in reacting cases compared to their non-reacting counterparts. Additionally, these distribution changes also provide information on the number of smaller diameter droplets available in reacting cases at any downstream location. It is worth mentioning that the signal to noise ratio was much lower in reacting cases at the same measurement location due to laser extinction as the laser beam passes through the flame/spray regions downstream of the neighboring nozzles before reaching the measurement zone. Additionally, the large density differences within the flow leads to beam steering causing the PDPA focal region to keep shifting, in turn reducing the signal rate. For reacting conditions, the signal rate sometimes reduced to almost 500 Hz depending on the location, whereas for non-reacting conditions, the signal rate was consistently higher than 5 kHz.

3.3 Effect of SAF on drop-size measurements

The second part of the measurements involved utilizing sustainable aviation fuel (SAF) for the measurements at the same conditions as Jet-A. The SAF used here is a HEFA (hydroprocessed

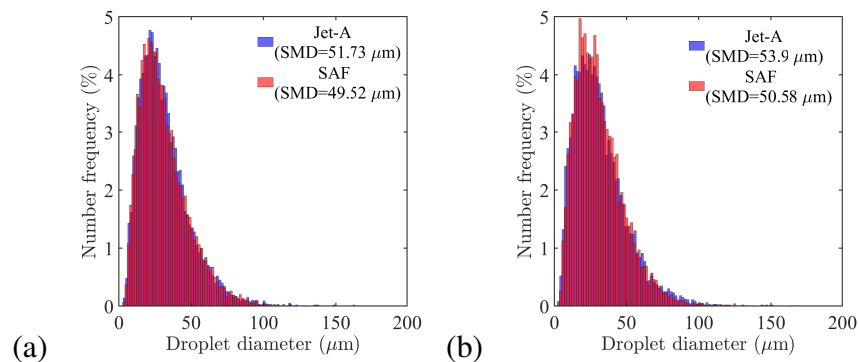


Figure 5: Comparison of number frequency distributions for Jet-A and SAF at non-reacting conditions with 35.3 psig pressure and 600 K preheat temperature for locations (a) $x=15$ mm, $y=5$ mm (b) $x=20$ mm, $y=10$ mm.

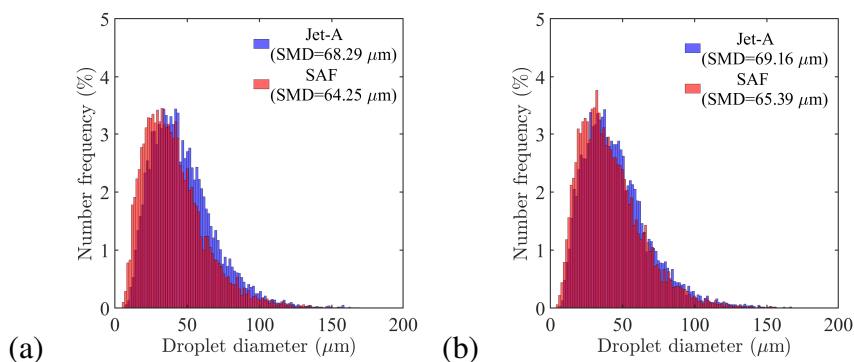


Figure 6: Comparison of number frequency distributions for Jet-A and SAF at reacting conditions with 35.3 psig pressure and 600 K preheat temperature for locations (a) $x=15$ mm, $y=5$ mm (b) $x=20$ mm, $y=10$ mm.

esters and fatty acids) based fuel with almost negligible amount of aromatic content in it. Figure 5 shows the comparison in number frequency distributions between Jet-A and SAF in non-reacting case for the same operating conditions. It is seen that the SAF spray produces slightly smaller droplets compared to Jet-A, giving a smaller SMD value. This is mostly due to the changes in physical properties of the two different fuels. The SAF utilized in this study has $\sim 10\%$ lower surface tension as compared to Jet-A. Reduction in surface tension helps in formation of new surface areas promoting droplet/jet breakup, thereby creating smaller droplets. This can also be looked at in terms of Weber number which is inversely proportional to the surface tension force. Higher the Weber number, better is the atomization quality of the liquid spray. Also, at temperatures above 100°C , the vapor pressure of SAF is $\sim 5\%$ higher than Jet-A which can contribute to better vaporization and smaller droplets. The variation in SMD values at different operating conditions followed similar trends as Jet-A at all the measurement locations. Similar trends were observed for reacting cases between Jet-A and SAF as shown in Fig. 6. The frequency distributions for SAF case shifted towards smaller diameters, suggesting an overall reduction in SMD for a given condition and location.

3.4 Two-color AC-LII measurements

The image pairs acquired for a given test condition is first split to obtain intensities from the two different wavelengths separately to match the exact regions of interest on both the images. Since the pixelated intensities tend to give erroneous values when dividing the pixel values from the two image pairs, the images are smoothed using a 3 x 3 convolution filter. After applying the flat-field correction and removing any background noise, the soot temperature values are obtained using the Planck's law for blackbody radiation. The averaged soot temperature distribution for the case of Jet-A at the global equivalence ratio (ϕ_g) of 0.2 with 35.3 psig pressure and 450 K preheat is shown in Fig. 7. The temperature values lie below 4000 K in the entire region, satisfying the low-fluence LII criterion. Although a laser sheet with uniform fluence should heat up the soot particles uniformly to the same temperature instantaneously, the differences in soot temperatures spatially can be due to several factors. The soot maturity will not be uniform throughout the flame and hence nascent soot and mature soot will heat up differently. Additionally, the laser fluence along the sheet is not completely top-hat; the fluence drops slightly towards the upstream direction.

The mean soot volume fractions (f_v) for the Jet-A case at $\phi_g=0.2$ is shown in Fig. 8(a). The masked regions in images are due to the quench holes of the combustor inadvertently appearing in one of the image pairs which could not be avoided in the present measurements. The mean f_v values are below 5 ppm at most of the locations throughout the flame regions. The maximum values occur near the shear region of the conical spray where the main reactions occur as expected. The high values near the borders of the flame is due to insufficient signals over time leading to a higher mean. So, the actual time-averaged values should be lower than the values depicted in Fig. 8(a). Due to the highly turbulent nature of the flame along with the swirling nature of the flow, the soot detection probabilities are much lower than a laminar flame case at a given location. Another important feature to notice in the contours is that the laser extinction along the beam path from right to left in Fig. 8(a) can also make the f_v values to appear to be decreasing for the same regions downstream of the different fuel injectors. This absorption will be hard to correct as the soot concentration and their extinction coefficients must be known instantaneously throughout the flame region. Improvements on most of these measurement features will be made in future campaigns to obtain more accurate soot distributions.

To study the effect of the type of fuel, the same LII measurements were made with SAF as the fuel at similar conditions as Jet-A. Since SAF has different fuel physical and chemical properties, the soot formation tendencies are expected to differ. The f_v contours for both Jet-A and SAF are shown in Fig. Fig. 8 for the same operating conditions and global equivalence ratio. There is a

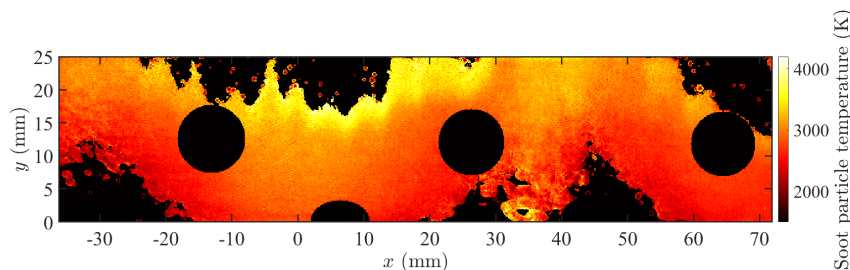


Figure 7: Averaged soot particle temperature distribution for Jet-A combustion at $\phi_g = 0.2$, $P_3=35.3$ psig and $T_3= 450$ K.

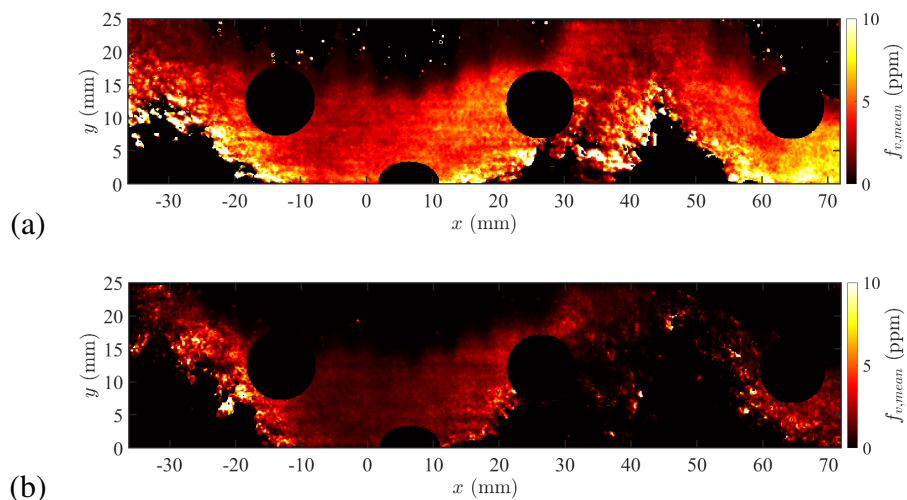


Figure 8: Averaged soot volume fraction contours for (a) Jet-A and (b) SAF combustion at $\phi_g = 0.2$, $P_3=35.3$ psig and $T_3= 450$ K.

considerable difference seen in the soot volume fraction values for the case of SAF as compared to Jet-A. The f_v values are almost 2-3 times lower for SAF at the same spatial locations as the Jet-A case. This is mainly due to the chemical composition of SAF utilized in the current study. As there is negligible amount of aromatics present in SAF, the tendencies for soot precursor formation is reduced leading to reduced overall soot production. Comparing the spray properties in the previous section, SAF also produced slightly smaller droplets as compared to Jet-A which will contribute to better fuel-air mixing and more complete combustion. Although the contribution from differences in spray is much lower as compared to the contribution from the chemical effects, the combined effects help in reducing soot formation considerably in the case of SAF combustion.

4. Conclusions

In this work, instantaneous drop-sizes and soot volume fractions have been measured in a three sector high-pressure combustor having fuel injectors at several operating conditions. Reliable droplet size data was obtained with a mirror system housed inside the vessel using PDPA. The SMD values dropped with increasing preheat and operating pressure at a given location in the spray. In reacting conditions, the number frequency curves shifted towards larger diameters, indicating near complete evaporation of smaller droplets at a given operating condition. SAF produced slightly smaller droplets owing to its changes in physical properties compared to Jet-A. Soot volume fractions obtained using two-color LII measurements showed that the values were mostly below 5 ppm for Jet-A at the operated conditions. The values dropped by 2-3 times with the introduction of SAF due to the absence of aromatics, compared to Jet-A.

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