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Effect of low fuel temperature on combustion deterioration of kerosene swirling spray flames using OH-PLIF



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ABSTRACT

Keywords: Low fuel temperature Swirling spray combustion Combustion deterioration Flame structure OH-PLIF The low fuel inlet temperature poses challenges to the flame stability of aircraft engine combustors. In order to investigate the combustion deterioration of swirl-stabilized kerosene spray flames under conditions of low fuel inlet temperature (T < -16 °C), a comprehensive system was established, comprising a burner commonly used in aircraft engines and a cooling setup. Upon analyzing OH-PLIF images, it becomes evident that sub-zero Celsius temperatures significantly lead to a decrease in OH radical concentration, resulting in a diminished heat release rate. The strongest signals decrease by a minimum of 5 times. Additionally, through the analysis of LIF spectra and detuned images, the differences between OH-LIF and kerosene-LIF are beneficial for recognizing the kerosene particles from the OH-LIF signals at the same time. For atomization assessment, employing the LOG operator blob detection method, it is found that at sub-zero Celsius temperatures, the overall count of fuel LIF particles experiences a slight reduction, while the count of larger particles increases across various air flow rates. This observation highlights an inferior droplet distribution at lower fuel temperatures. The image processing of kerosene LIF particles opens up the possibility for a rapid evaluation of atomization, especially when assessing combustion deterioration in kerosene spray flames through the use of a simple OH-PLIF technique.

1. Introduction

The fuel injection system of the combustor in the aircraft engine sometimes needs to operate at unfavorable conditions, such as low temperatures. Low fuel temperature can lead to poor atomization and slower fuel evaporation rate in engine chambers, which results in difficulty for a start-up with cold fuel or relight after flameout. An advanced understanding of combustion deterioration is a prerequisite for achieving clean combustion, hence the practical study for combustion deterioration at low fuel inlet temperature is very critical. As for practical tests in engine combustors, the study of unignited spray at ultra-cold temperature is relatively easy to achieve [1,2], but when performing combustion studies, the artificially created system is always affected by the surrounding environment and the fuel temperature is not easily below -10 °C. The combustion studies of Mosbach et al. [3] were performed at a combustor temperature and pressure of 278 K and 0.5 bar, respectively. These studies confirmed that the laser technique could be applied well in extreme conditions. Read et al. [4] also conducted a combustion experiment with cold fuel at 288 K. But the fuel temperature in the previous combustion tests is seldom close to $-20\ensuremath{\,^\circ C}$ and this needs further research.

Incomplete combustion is very common when combustion deterioration happens. The low fuel temperature will prevent the liquid film from breaking down into small droplets, and many large droplets can be present at the near-nozzle area. These large droplets can't burn out immediately and reflect to some extent the deterioration of the fuel atomization in the kerosene spray flame. It has become possible to record the distribution of the liquid droplets using non-contact laser technology, such as 3D off-axis holography [5]. However, the optical system is complicated and not suitable for widespread use. Quickly assessing the atomization by recording only the distribution of large droplets exceeding 500 μ m seems to be a more convenient approach, especially for the combustion deterioration of kerosene flame when lots of liquid fuel exits.

For analysis of the heat release and distribution of intermediate radicals, the planar laser induced fluorescence of hydroxyl radical (OH-PLIF) is commonly utilized as a kind of efficient optical diagnostics [6–8]. In addition, the differences in fluorescence spectra between kerosene and hydroxyl confirm the applicability of PLIF imaging to separate the signals of kerosene fuel and OH radicals [9–12]. In recent

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years, kerosene LIF has been used as a tracer substance for fuel distribution in kerosene spray flames. And due to the spectral properties of kerosene LIF, it is possible to excite both kerosene and OH to generate fluorescence using only one UV laser beam. Chterev et al. [9] performed the simultaneous PLIF for kerosene and OH, successfully capturing the transient distribution of liquid fuel film. Legros et al. [13] recorded the kerosene signals in high-pressure kerosene flames to visualize the fuel distribution and calculate the kerosene temperature. Spray flames usually have a large number of fuel particles and droplet scattering [14,15], and if the kerosene fluorescence is only on the fuel particles, then the kerosene fluorescence particles can be used not only to characterize the distribution of the liquid fuel, but also for the atomization evaluation in a way. This is possible in kerosene spray flames with particularly poor atomization. So this provides an opportunity to identify kerosene and obtain OH-LIF simultaneously in a kerosene flame by simple PLIF imaging.

In this work, an optical measurement system as well as a combustion system including a burner, fuel supply, air supply, and fuel cooling, was established for swirl-stabilized kerosene spray combustion investigation. OH-PLIF measurements were performed at different conditions including low/normal fuel inlet temperature, and different air flowrate. LIF spectrum in the flame and spray, as well as detuned analysis, were then carried out to identify the main LIF species in the flames. With the utilization of the blob detection algorithm, the number of the fuel LIF particles was counted, and the atomization effect was then evaluated with a simple PLIF judgment.

2. Experimental details

2.1. Experimental setup and ignition details

The experimental apparatus to investigate kerosene swirling spray combustion is illustrated in Fig. 1 The air supplied from an air compressor was adjusted to a specific pressure by valve. The pressure differential was monitored by a single crystal silicon pressure transmitter, and the relationship between pressure and flowrate was calibrated in advance by a rotameter. The fuel supply system consisted of a fuel tank, a servo motor system for pumping the liquid kerosene, and a cooling system for cooling fuel to sub-zero Celsius. The refrigerating unit used ethanol to cool the flowing fuel to a certain temperature through a heat exchanger. In order to monitor the fuel flowrate and fuel temperature, a flowmeter (accuracy of 1 mL/min and full scale of 0–400 mL/ min) and a thermocouple (accuracy of 0.1 $^{\circ}$ C) were installed in the fuel supply pipeline. All the measurement data was collected at a frequency of 20 Hz. In the present work, the fuel injection system composes of a special Laval fuel nozzle and radial counter swirlers. The structure is illustrated in Ref. [5], and the specific explanation of the injection system is similar to the description in Ref. [8]. The RP-3 kerosene used in this paper is normally for civil aviation in China [5]. Detailed experimental conditions are listed in Table 1.

2.2. Optical diagnostics

The arrangement of OH-PLIF measurement system is shown in Fig. 2. The 532 nm laser from a 10 Hz Nd:YAG laser (Powerlite DLS 8010, Continuum) was used to pump the Rhodamine 590 dye to generate ~566 nm laser, and then the needed ~283 nm UV laser was generated after second harmonic. The laser power at 283 nm was around ~ 10 mJ/ pulse. The UV (ultraviolet) laser was passed through a concave lens (f =-75 mm) and a convex lens (f = +500 mm) to form a planar laser sheet with height of 30 mm and thickness of 200 µm. The OH fluorescence was captured by an ICCD camera (PI-max 4 emICCD, Princeton Instrument), which was equipped with a 105 mm, f/4.5 UV-NIKKOR lens, a 310 nm narrow-band filter (FWHM of 10 nm, peak transmittance of ~60%, Alluxa), a 305 nm long-pass filter (305FG01-50, Andover), and a UG11 filter (FGUV11, Thorlabs). These combined filters had an optical density over 6 at range of 200-305 nm and 317-400 nm for effectively eliminating the interference of the UV laser elastic scattering and flame luminosity. The in-plane spatial resolution was 0.15×0.15 mm², and the ICCD gate width was set as 50 ns. 283.567 nm was selected corresponding to the spectral location of the Q1(5) rotational transition of the $A^{2}\Sigma^{+} \leftarrow X^{2}\Pi$ (1,0) electronic band by comparing with LIFBASE [16]. Raw OH-PLIF images were firstly corrected from the distortion and spatial energy distribution of the laser sheet, and then were filtered with a two-dimensional 3×3 median filter after size calibration.

For the non-excited UV laser wavelength detuned experiment, the dye laser wavelength was shifted by 0.05 nm and other conditions were kept constant. The LIF signal was sensitive to the excited laser wavelength. When the laser was shifted to a non-excited wavelength, the PLIF signal would disappear. By comparing tuned and detuned images, the signals from OH radicals can be judged. Fig. 2 also shows the arrangement of the spectral analysis setup. The LIF spectral signal was focused by two convex lenses (f = +100 mm) into the slit of about 200 µm at the entrance of the spectrometer (SP2300, Princeton Instrument), and the 3 cm target field of view is narrowed to a height comparable to that of the slit.

3. Results and discussion

3.1. Flame structure analysis of PILF images

The actual flame images of case 1-6 are shown in Fig. 3, which are



Fig. 1. Experimental apparatus for kerosene swirling spray combustion.

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Table 1

All recorded experiment conditions.

Case		$m_{fuel}(g/s)$	$T_{fuel}(^{\circ}C)$	ΔP_{air} (kPa)	Air volume flux (m ³ /h)	Re _{air}	Φ	ALR
1	NT ^a	0.285	25.4	0.986	7.1	4587	3.06	8.9
2		0.291	24.6	2.023	8.8	6810	2.10	10.8
3		0.292	24.5	3.018	10.3	8485	1.69	12.6
4	LT ^b	0.288	-18.4	1.037	7.1	4716	3.01	8.8
5		0.285	-17.7	2.063	8.8	6883	2.04	11.1
6		0.300	-16.6	3.035	10.3	8511	1.74	12.3

 m_{fuel} : the mass flow rate of kerosene.

 T_{fuel} : the kerosene temperature measured near the fuel injection port.

 ΔP_{air} : the air pressure differential at the air inlet of burner cavity.

*Re*_{air}: the air Reynold number at the burner exit.

 Φ : the total stoikiometric ratio.

ALR: the mass ratio of the air and liquid fuel.

^a NT denotes cases of combustion at normal kerosene inlet temperature condition.

^b LT denotes cases of combustion at low kerosene inlet temperature condition.



Fig. 2. OH-PLIF measurement system and spectral analysis setup.



Fig. 3. Instantaneous pictures of all cases taken with the same gate width.

taken by a high speed camera. In all cases involving kerosene combustion deterioration, a prominent feature is the presence of bright yellow zones within the flames, indicative of a high concentration of soot and incomplete combustion. This phenomenon is often observed during the start-up stages of kerosene combustion when conducting ignition with reduced airflow. The global fuel-air equivalence ratios for these flames are from 1.6 to 3.1. But in cases with increased air flow, like case 3, blue zones emerge within the flames. It seems that local premixed combustion happens at a higher air flow rate. Besides, when the fuel inlet temperature falls below -16 °C, compared with the flames at normal

temperature, there is a noticeable reduction in flame brightness, probably resulting from the increasingly worse incomplete combustion of spray droplets. These phenomena need more instantaneous data for validation. So the OH-PLIF analysis are performed subsequently.

Instantaneous turbulent OH-PLIF images are shown in Fig. 4. Images on the left are for cases at normal kerosene inlet temperature at different air mass flow rates, while the right images are for cases at low inlet temperature below -16 °C. It can be seen that intensities of the transient OH signal for room temperature cases are much higher than that of low temperature cases, regardless of air flowrate. The PLIF was conducted at



Fig. 4. Instantaneous OH-PLIF images at different temperature and air pressure differences. (a) to (c) are images in case 1 to 3 (inlet temperature at around 25 °C), (d) to (f) are images in case 4 to 6 (inlet temperature below -16 °C).

the same laser pulse power, so it can be approximated that the intensity is closely related to the OH radical concentration and flame temperature. It can be inferred that the OH radicals in these flames of sub-zero Celsius cases are scarce and flame temperature is not high enough. The combustion deterioration can't ease even with the increased air flowrate. At sub-zero Celsius, the flame structure is fragmented and the particles near the nozzle are denser, which suggests worse incomplete combustion and atomization, which may lead to the combustion instability and flameout.

More quantitative information can be seen in Fig. 5 (a) for signal distribution at strong OH-LIF zone (x/D > 0.6, z/D = 0.75, D is the diameter of the burner outlet), extracted from averaging all the OH

images. When the fuel inlet temperature is reduced from above 20 °C to below -16 °C, the strongest mean OH-LIF signal decreases by at least 5 times, indicating a significant negative effect of the sub-zero Celsius on combustion intensity. Besides, the OH-LIF intensity gradient can represent the combustion heat release rate [17] and the x-direction gradient $|\nabla I|$ can be calculated from the derivative for the OH-LIF intensity curve. As seen in Fig. 5 (b), sub-zero Celsius reduces the heat release rate severely on the flame front at 0.7 < x/D < 1.1. The normalized $|\nabla I|$ is below 0.2 average for sub-zero Celsius cases, while over 0.4 average for normal temperature cases. An explanation is that, at cold fuel temperature, the worse atomization always affects the heat release of the flame front [18]. As seen in the PLIF images, many large particles are present



Fig. 5. (a) distribution of average LIF signals at strong OH-LIF zone (x/D > 0.6, z/D = 0.75) for case 1 to 6. (b) normalized absolute value of OH-LIF intensity derivative ($|\nabla I|$), which can represent the intensity of combustion heat release.

at the near-nozzle area of the spray flames at sub-zero Celsius, suggesting more kerosene droplets that can't burn out. To evaluate the worse atomization, these large particles need to be discussed further.

3.2. Detuned PLIF images

For analyzing the near-nozzle particles, the origin of these granular signals needs further confirmation. As shown in Fig. 6, when using the same filters to measure the instantaneous kerosene spray LIF without ignition, liquid kerosene signals remain widespread even in the OH-LIF detection wavelength range. Note that the LIF signals (around 310 ± 5 nm) in Fig. 6 are all from kerosene LIF, not the laser scattering or OH-LIF. A similar phenomenon is found in n-heptane spray. In Ref. [17], using a 310 nm bandpass filter, fuel LIFs from n-heptane are found in both spray and flame, and the n-heptane LIFs are all round speckles. Different from kerosene, n-heptane is a pure substance without an aromatic compound, but the round fuel LIFs are still detected. An approximate reason is the liquid fuel density is much larger than the gaseous density, resulting in strong liquid LIF signals limited in round fuel droplets.

All detuned images acquire 200 shots, showing the same phenomena as the image in Fig. 7 (b), not by accident. When the laser wavelength is shifted, the signals of OH-LIF disappear, but spotted kerosene LIFs remain widespread. Although faint signals also exist at the OH-LIF locations, the signal intensity is over 20 times weaker than the OH-LIF. These faint signals are probably soot LII signals, PAH-LIFs, and gaseous kerosene-LIFs. However, these interferences always exit despite well optical filtering of the combined filters. But considering the obvious difference, it is undoubted that the relatively continuous signals are almost all from OH radicals and dispersive round speckles are from kerosene-LIF. This indicates that the current combined filters are just enough to detect the fuel LIF particles and OH-LIF, as well as suppress other signals at the same time. And the difference between these two signals facilitates the identification of kerosene particles from the OH-LIF.

The curves of normalized spectral statistics are shown in Fig. 8, which is based on over 50 regions of fuel LIF particles found in 200 image shots of case 2. In Fig. 8 (a), the 283 nm laser is located in the leftmost peak of the spectrum, and the kerosene LIF appears in the range of 308 to 410 nm, agreeing well with kerosene spectrum of Ref.[19]. The OH-LIF is located in the middle peak of 308 to 317 nm and the detailed spectrum can be seen in Fig. 8 (b). Besides, before ignition, comparing the curves in Fig. 8 (a), the UV laser scattering is stronger due to more fuel droplets. These statistics of spectral information further explains the fluorescence composition in the flame with UV laser excitation.

3.3. Analysis of fuel LIF particles

The signal differences between OH-LIF and kerosene-LIF are beneficial for recognizing the kerosene particles in the PLIF images. To



Fig. 6. Kerosene spray droplets fluorescence at approximately 310 nm \pm 5 nm, before ignition. The LIF is all from liquid kerosene, not laser scattering or flame luminosity. The filters used are the same as OH-PLIF.



Fig. 7. Instantaneous tuned image (a) and detuned image (b) of case2. Detuned process: the laser wavelength is redshifted by 0.05 nm to prevent the production of OH-PLIF so that kerosene-LIF can be imaged without OH-LIF. Tuned process: the laser wavelength is on the OH excitation line to excite OH-PLIF. The emission of round speckles combines both Mie scattering and LIF from the droplets.

analyze the effect of fuel fluorescence, LOG (Laplacian of Gaussian) operator blob detection [20] was adopted for counting the number of fuel LIF particles. The LOG kernel function can be described as follows.

$$LOG(x,y) = \Delta G_{\sigma}(x,y) = \frac{x^2 + y^2 - 2\sigma^2}{\sigma^4} \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right)$$
(1)

where $G_{\sigma}(x,y)$ is Gaussian function, LOG(x,y) is the second derivative of $G_{\sigma}(x,y), \sigma$ is a standard deviation parameter in $G_{\sigma}(x,y)$. The shape of LOG kernel function is similar to a spot, with strength strong in the middle and weak around. In a blob detection zone of a two-dimensional ICCD image $I_0(x,y)$, LOG response value of binarized circular speckle in the image can be written as $LOG^*I_0(x,y) = \Delta G_{\sigma}(x,y)^*I_0(x,y)$, the convolution of $\Delta G_{\sigma}(x,y)$ and $I_0(x,y)$. When executing the iterative algorithm, the LOG operator will change its scale to calculate and compare the response value. At a certain characteristic scale, the LOG response value will reach maximum, indicating the speckle size in the image converges to the shape of the Gaussian Laplace function, at which time the size and location of the speckle are recorded. A typical example can be seen in Fig. 9.

Results of the counted fuel LIF particles are shown in Fig. 10. However, distribution of all droplets can't be counted because the actual droplet cannot be distinguished under the limited resolution of our ICCD camera. Only when a droplet is large enough, the fuel LIF intensity can reach saturation value of the ICCD camera, and LOG algorithm can only work for particles with saturation value. To distinguish these round speckles from actual droplets, these particles are named after "fuel LIF particles". In Fig. 10 (a), it seems that the number of total fuel LIF particles for LT cases is slightly lower than that for NT cases. But a careful comparison in Fig. 10 (b) shows that the number of fuel LIF particles with diameter over 1 mm for LT cases is larger than that for NT cases at any air mass flow. During particle counting, fuel LIF particles over 1 mm are regarded as large particles. In fact, LOG algorithm can only count particles of certain diameters, and only LIF of diameter over 0.7 mm can be counted. In spite of this disadvantage, the distributed fuel LIF particles can reflect the characteristic of big droplets and the counted number of fuel LIF particles can be regarded as a supplementary evaluation for fuel atomization. Take case 1&4 as an example. When at subzero Celsius, number of large particles NKL is 2.55 and total number NKT is 15.48, while NKL is 1.31 and NKT is 16.86 for normal temperature cases. It can be inferred that part of the kerosene is not atomized at



Fig. 8. Normalized LIF average spectrum of (a) 270–410 nm (solid blue line represents LIF of flame and dashed red line represents kerosene spray LIF before ignition). (b) 305–335 nm.



Fig. 9. Location recognition of fuel LIF particles in OH-PLIF grayscale image using LOG operator blob detection. (a) Raw OH-PLIF image. (b) The same image with locations of fuel LIF particles marked by white dots.



Fig. 10. Results of LOG operator blob detection for the mean number of fuel LIF particles counted in the OH images at different conditions. (a) total fuel LIF particles average. (b) large fuel LIF particles average. (c) the mean number of large near-nozzle spray droplets without ignition. The burner nozzle of Ref. [22] is the same as this paper. Red bar charts are for normal temperature cases, and blue bar charts are for sub-zero Celsius cases. (N_{KT} : the mean number of total fuel LIF particles. N_{KL} : number of large fuel LIF particles. NT: cases under normal inlet temperature. LT: cases under low inlet temperature).

sub-zero Celsius and small droplets formation becomes difficult, thus the total number slightly decreases and the number of large fuel LIF particles increases instead. This indicates that it gets more difficult for air to interact with liquid kerosene. Because density and the dynamic viscosity of kerosene increase fast at sub-zero Celsius and the atomization gets worse, like droplet mean diameter gets larger and spray cone angle gets smaller [21]. Droplet size distribution measurement is difficult in soot flame but it can be achieved easy in spray without ignition. In Ref. [22], picosecond pulsed digital off-axis holography is used to measure the near-nozzle droplet size distribution of the same burner nozzle of our

work. The data is in Fig. 10 (c). In near-nozzle spray, droplets in the range of $30-90 \ \mu m$ accounts for a large percentage, while droplets of $210-690 \ \mu m$ are considered to be large droplets and account for a relatively small proportion. Distribution of these large droplet presents the same phenomenon as fuel LIF particles in this paper. So from another perspective, the counted fuel LIF particles data in this paper can be considered as a supplementary evaluation for large droplets in the soot flame. This can be considered as a quick judgment for the atomization evaluation in a soot kerosene flame with a simple OH-PLIF technique.

4. Conclusions

In this study, the combustion deterioration is evaluated for the kerosene swirling spray combustion under varying conditions including both low and normal fuel inlet temperatures. Upon analyzing OH-PLIF images, it becomes evident that sub-zero Celsius temperatures (below -16 °C) lead to a significant decrease in OH radical concentration, resulting in a diminished heat release rate. The most intense signals decrease by a minimum of fivefold. This deterioration in combustion performance is closely linked to poorer nozzle atomization. The disparities in signals between OH-LIF and kerosene-LIF offer an opportunity to simultaneously identify kerosene particles within the OH-LIF signals, as nearly all the scattered, round speckles originate from kerosene-LIF. For atomization assessment, we employ the LOG operator blob detection method for particle counting. It is observed that at subzero Celsius temperatures, the overall count of fuel LIF particles experiences a slight reduction, while the count of larger particles increases across various air flow rates. This observation indicates a deterioration in atomization quality. Although the diameter of the fuel-LIF particles may not precisely represent the actual particle size due to limited ICCD resolution, the counted number of fuel LIF particles can serve as an additional measure for evaluating fuel atomization. Fuel-LIF counting presents a convenient method for assessing atomization in spray combustion, particularly under conditions of combustion deterioration.

CRediT authorship contribution statement

Shirong Xin: Experimental & Writing. Wenyu Wang: Writing – review & editing. Yong He: Methodology, Conceptualization, Validation, Writing – review & editing. Yanqun Zhu: Writing – review & editing. Zhihua Wang: Funding acquisition, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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