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Experimental investigations of superheated and supercritical injections of liquid fuels

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ABSTRACT

Single- and multi-component liquid fuels are injected in a jet-in-coflow configuration at elevated temperatures and pressures with both a custom plain orifice nozzle and a commercial pressure-swirl atomizer. The transitions in spray morphology from mechanical breakup to superheated/supercritical regimes are characterized qualitatively by laser shadowgraphy and evaluated based on quantitative measures of superheat. Although fuel preheating exhibits no discernible effect in the mechanical breakup regime, dramatic jet-to-plume transition as well as build up of fuel vapor in the spray chamber are observed with increasing level of superheat. The difference between two different atomizers in terms of spray behavior diminishes at high levels of superheat, suggesting the predominant role of thermal effect on spray morphology in superheated/supercritical regimes. For a multi-component fuel such as Jet A-1, the transition into a fully flashing spray occurs at temperatures lower than expected values, which are calculated by treating Jet A-1 as a single-component fuel. Additionally, pressure drop is shown as a sensitive indicator for the departure from mechanical breakup and the onset of thermal effect on the spray. Comparisons between measured and estimated pressure drop also reveal the differences in susceptibility to thermal effects between the plain orifice and the pressure-swirl atomizers.

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INTRODUCTION

The commercial aviation sector is expected to continue its robust growth with doubled passenger numbers in the next two decades [1]. In order to meet the ambitious goals outlined in the Flightpath 2050 by the Advisory Council for Aeronautic Research in Europe (ACARE) to curtail pollutant emission [2], disruptive combustion technologies are needed to ensure both economic and environmental sustainability.

As the operating temperature and pressure of aero engines continue to be raised for improved overall efficiency and reduced CO₂ emission, it becomes increasingly likely that liquid fuels will be injected into the combustion chamber under superheated or supercritical conditions. Superheated (or flashing) atomization occurs when a liquid is discharged into a gaseous ambient at a pressure lower than its saturation pressure. As the fuel temperature and pressure prior to injection approach its supercritical limits, the liquid fuel behaves more and more like its gaseous counterpart. Under these conditions, fuel sprays can attain finer droplets, wider opening angles [3] and smaller penetration depths [4] comparing to injections at normal conditions [5, 6, 7]. These advantages, when fully leveraged, could enable novel strategies for achieving compact flames and low pollutant emission [8,9] that are not accessible through conventional means of combustor modification. Although many applications of superheated/supercritical injections can be found in wide-ranging industries, relatively few work exists with regard to gas turbine combustion that focuses on multi-component fuels and atomizers with complex geometries.

Under the framework of the EU2020 Soot Processes and Radiation in Aeronautical Innovative Combustion (SOPRANO) project, this work aims at providing experimental data for the improvement of numerical models to account for thermal effects on fuel injection, which may not be negligible in certain combustion systems that do not incorporate active cooling on fuel delivery line and/or nozzles. A major effort of this work is to establish a database to allow quantitative evaluations of thermal effects on fuel injections with different types of atomizers. Specifically, an experimental apparatus is designed and constructed based on an existing high-pressure combustion facility to allow reproducible investigations of superheated and supercritical injection of various single- and multi-component fuels at elevated temperature and pressure conditions (for both fuel

Fig. 1. Schematic of the experimental setup: (a) a 3-D view of the modified HiPOT facility; (b) Top cross-section view of the jet-in-coflow configuration for liquid fuel injection as well as the laser shadowgraphy apparatus (not to scale). 1: Afterburner chamber; 2: Optical pressure vessel; 3: Liquid fuel preheater; 4: Main air preheater; 5: Housing for the fuel injector; 6: Spray chamber; 7: Afterburner.

and ambient). Fuel sprays from both a custom plain orifice nozzle and a commercial pressure-swirl nozzle are characterized with laser shadowgraphy. The energy barrier for bubble nucleation demonstrated in Ref. [6] is adopted here alongside classical measures of superheat to compare and analyze the results.

EXPERIMENTAL SETUP

Modified HiPOT facility

In order to examine non-reacting injection of liquid fuels under elevated temperature and pressure conditions, the High Pressure Test (HiPOT) facility at DLR was modified to incorporate several newly constructed modules, as schematically shown in Fig. 1a (with a list of major components given in the caption). With the standard configuration (grayed out parts), HiPOT is capable of

achieving up to 30 bar inside the optical pressure vessel (No.2) and up to 700 K of main air temperature at a maximum flow rate of 400 g/s. In this work, a fuel preheater with a maximum capacity of 3.6 kW (No.3) was introduced to allow raising the liquid fuel temperature (T_F) up to 650 K at a maximum design flow rate of $\dot{m}_F=2$ g/s. After injection, the liquid fuel was subsequently consumed inside an afterburner (see No.7 in Fig. 1b), which was designed following the FLOX[®] concept [10] with a ring of 12 nozzles and separate fuel (methane) and air plena. The afterburner was ignited by a gas pilot (ZMI, Kromschroeder) that was mounted on the afterburner combustion chamber (No.1) and operated with non-premixed methane and air, generating a pilot flame of the length of 2 to 10 mm. The stability of the afterburner was monitored via a small window on the combustion chamber.

Fuel injection was implemented in a jet-in-coflow configuration inside the optical pressure vessel (No.2), as illustrated in Fig. 1b. A liquid fuel injector with a replaceable nozzle was situated at the center of a square housing (No.5), which was furnished with a sintered plate that homogenizes the main air and creates a stable coflow. Fuel spray was injected into an optical spray chamber (No.6) with a clear aperture of about 80 mm by 120 mm on four sides, before being throttled by a converging nozzle into the afterburner (No.7). A custom-designed plain orifice atomizer was installed at the tip of the fuel injector for most of the experiments presented in this paper. It had a nozzle diameter of $d_0=200$ μm with a length/diameter ratio of $l_0/d_0=10$. In addition, sprays generated by a commercial pressure-swirl atomizer (Delavan, FN=1.1), often used in aerospace applications, under selected operating conditions are presented as comparisons. Fuel temperature (T_F) prior to injection was monitored via a thermocouple (T_1) 55 mm upstream of the nozzle exit (closest point possible due to limited accessibility). Air coflow temperature was monitored by another thermocouple (T_2) at the exit plane of the sinter plate. Fuel pressure (P_F) could not be measured directly in the injector due to high fuel temperature and was determined instead upstream of the fuel preheater. Tests were conducted to ensure negligible pressure loss between the measurement location and close to the nozzle exit. Additionally, readings from other sensors built into HiPOT such as chamber pressure, flow rates and material temperatures were logged every second during the measurement for cross referencing purposes. No coking issue was en-

Fuel	T_c [K]	P_c [bar]	$\dot{m}_F$ [g/s]	P_∞ [bar]
Cyclohexane	553.4	40.7		
Iso-octane	543.9	25.7		
N-nonane	594.1	23.0	0.5, 1	1.5, 3
Jet A-1	(685.0)	(23.6)		6
HEL	(732.0)	(10.4)		

Table 1. Single- and multi-component fuels examined in this work. Critical temperature (T_c) and pressure (P_c) of Jet A-1 and HEL were the upper limits provided by the manufacturer.

countered with either atomizer during the entire experimental campaign. The same nozzles were employed for repeated measurements and consistent results (e.g., spray forms and pressure drop over the nozzle) were obtained on different days throughout a span of three weeks.

Laser shadowgraphy

To characterize sprays under various fuel preheating conditions, a laser shadowgraphy was set up and shown schematically with respect to the optical chamber (No.6) in Fig. 1b. The second harmonic output of an Nd:YAG laser at 532 nm (10 Hz) was used to excite a fluorescence plate (Plexiglas), whose emission centered around 650 nm was expanded and collimated by a plano-convex lens ($f=300$ mm), and sent through the spray chamber. The resulting shadowgraph was captured by an sCMOS camera (LaVision Imager) coupled with a 100-mm f/2.8 objective (Tokina) and a bandpass filter (650 ± 20 nm). The lifetime of the fluorescence emission was on the order of 100 ns, sufficient for freezing the motion of the fuel sprays. During postprocessing, each single-shot shadowgraph was assigned a set of operating parameters by correlating the camera frame to the simultaneously generated log data from HiPOT mentioned above (based on time stamps). This was to account for possible fluctuations in measurement conditions during long periods of recordings (up to one minute at 10 Hz), especially at close to the operating limit of HiPOT.

Operating conditions

A total of five single- and multi-component fuels were examined during this work, including cyclohexane, iso-octane, n-nonane, Jet A-1 and heating oil extra light (HEL). Their critical temperatures (T_c) and pressures (P_c) were listed in Table 1. Fuel flow rates were maintained either at 0.5 g/s or 1 g/s, resulting in an exit velocity of up to approximately 100 m/s (depending on the fuel type and preheating temperature). Three different chamber pressures P_∞ were used for each fuel: 1.5, 3 and 6 bars. Due to safety concerns, fuel temperature inside the preheater was kept lower than the corresponding saturation temperature at a given fuel pressure. The hot coflow was then utilized as a second tier fuel preheater inside the main air plenum (No.4 in Fig. 1a) to further increase T_F to be closer or larger than T_c . The coflow temperature (measured at T_2 , see Fig. 1b) was consistently less than 60 K higher than T_F (measured at T_1 , see Fig. 1b). The coflow velocity was maintained at 2-4 m/s (depending on the pressure and temperature), such that it was significantly slower than the fuel sprays and was not expected to influence the spray behaviors. The afterburner was operated at $\lambda \sim 1.3$ and a thermal power of up to 180 kW (at 6 bars). The small amount of liquid fuel was not seen to influence the stability of the afterburner throughout the measurements.

RESULTS & DISCUSSIONS

In the following sections, only results from cyclohexane and Jet A-1 are shown, since the same trends were observed in other tested fuels. In order to compare the fuel sprays at various chamber pressures P_∞ , the classical definition of the level of superheat Δ_T [11]:

$$\Delta_T = T_{\text{inj}} - T_{\text{sat}}(P_\infty) \quad (1)$$

was used to classify the cases. T_F measured at T_1 (see Fig. 1b)) was taken as the injection temperature T_{inj} . The saturation temperature at the back pressure $T_{\text{sat}}(P_\infty)$ was inferred from fuel properties taken from [12, 13] at measured chamber pressure P_∞ .

Fig. 2. Single-shot shadowgraphs of cyclohexane injected at $P_\infty=1.5$ bar (blue dashed line on the P-T chart), $\dot{m}_F=1$ g/s and various initial fuel temperature T_F and pressure P_F (red dots on the P-T chart), using a plain orifice nozzle. Each shot is 10 mm by 25.5 mm in physical scale.

Superheated and supercritical injection of cyclohexane with a plain orifice nozzle

Figures 2 to 4 display collages of single-shot shadowgraphs of cyclohexane injected at $\dot{m}_F=1$ g/s and a chamber pressure of 1.5, 3 or 6 bars, using the custom plain orifice nozzle described in the previous section. Each shot was cropped with respect to the center of the nozzle to an effective physical scale of 10 mm by 25.5 mm. Signal intensity was corrected by the monitored fluctuations in laser energy. At each P_∞ , nine cases were selected based on their levels of superheat Δ_T (indicated at the bottom of each shot), such that each case has similar Δ_T across three different chamber pressures. Their specific temperatures T_F and pressures P_F measured prior to injection were plotted on a vapor pressure (P-T) chart of cyclohexane to the left of the image collages (red dots), with arrows pointing to their corresponding P_∞ (blue dashed line). Note that the chart is cropped above the P_c of cyclohexane at about 40 bars, such that the end of the right end of the solid black line represents the critical point of the liquid fuel.

Figure 2 shows the nine cases at $P_\infty=1.5$ bar. As T_F was increased, higher P_F was needed to sustain the same fixed mass flow rate. As can be seen, the chosen cases span a wide range of Δ_T : from no superheat in Cases 1 and 2 (i.e., $\Delta_T \leq 0$) up to about 170 K in Case 9, which still lies under T_c at this P_∞ . Before T_F crosses T_{sat} , the fuel spray appears as a jet with a negligibly small spreading angle, as expected with this type of atomizer at conditions controlled by mechanical breakup. Preheating within this regime has no discernible effects on the spray. As

Fig. 3. Single-shot shadowgraphs of cyclohexane injected at $P_\infty=3$ bar (blue dashed line on the P-T chart), $\dot{m}_F=1$ g/s and various initial fuel temperature T_F and pressure P_F (red dots on the P-T chart), using a plain orifice nozzle. Each shot is 10 mm by 25.5 mm in physical scale.

soon as T_F crosses T_{sat} , i.e., injection in the superheated regime, the spray appears to contain a downward skewed main jet with fine particles seeming to “peel off” from it, as shown in Case 3. This downward skew is likely the result of gravity, as the jet-in-coflow configuration is horizontally laid out and the fuel is injected from left to right in this view. As T_F inches higher, the main jet diminishes while more fine particles could be seen building up alongside and above the main jet. The effective spray angle is therefore significantly broadened from Case 3 to Case 4. Further preheating leads to the formation of a plume of dense particles from Case 5 to Case 6, resembling the fully flashing sprays reported in the literature [6]. From this point on, additional superheat results in the shrinkage of the plume, i.e., a reduction of fuel penetration into the spray chamber. Fuel vapor can also be identified as bright and small structures trailing the plume.

Figure 3 shows the nine cases with matching levels of superheat at $P_\infty=3$ bar. As can be seen, increasing Δ_T causes the fuel spray to go through a fairly similar jet-to-plume transition observed at $P_\infty=1.5$ bar in Figure 2. Although Cases 1 and 2 (mechanical breakup) do not seem to differ much from those at lower chamber pressure, the plume appears to attain a noticeably smaller spread angle. In addition, Case 9 with a Δ_T close to 170 K is already in the supercritical regime at this P_∞ . Instead of abrupt changes in spray behaviors as seen from mechanical breakup to superheated injection (Cases 1&2 to Cases 3-8), supercritical injection appears to continue the trend of a shrinking plume of particles and increased presence of fuel vapor in the field of view.

Fig. 4. Single-shot shadowgraphs of cyclohexane injected at $P_\infty=6$ bar (blue dashed line on the P-T chart), $\dot{m}_F=1$ g/s and various initial fuel temperature T_F and pressure P_F (red dots on the P-T chart), using a plain orifice nozzle. Each shot is 10 mm by 25.5 mm in physical scale.

These general trends hold for $P_\infty=6$ bar, as displayed in Fig. 4. Comparing to the lower pressure cases, the plume formed in superheated conditions (Cases 3-6) appears much narrower with respect to its spread angle. Besides, it also seems that the transition from a “diverging” jet form to the plume form (Cases 3-5) occurs much swifter than at lower pressures. The transient behavior of fine particles “peeling off” from the main jet is not present at this chamber pressure. Moreover, when compared to Figs 2 and 3, at comparable levels of superheat throughout the superheated and supercritical regimes, the penetration depth of the fuel jet (plume) reduces starkly with increased P_∞ . Particularly at Case 9 at $P_\infty=6$ bar, the plume retreats into a small spherical shape attached to the nozzle exit while the majority of the liquid fuel appears to be vaporized.

In order to provide insights into the observed evolution of spray form from Cases 1 to 9 at various chamber pressures, additional measures of superheat, R_p and χ , proposed in Ref. [6] were derived for the nine cases using their corresponding operating conditions. These two parameters are defined as:

$$R_p = \frac{P_{\text{sat}}(T_{\text{inj}})}{P_\infty}, \quad (2)$$

and

$$\chi = \frac{\Theta^3}{(\ln R_p)^2} \quad (3)$$

with $P_{\text{sat}}(T_{\text{inj}})$ representing the saturation pressure at the injection temperature, χ the energy barrier to nucleation and Θ the dimensionless surface tension following Ref. [14]. It is demonstrated that the onset of fully flashing can be correlated solely to the condition of $\chi = \mathcal{O}(1)$ and is independent of the Weber number. Moreover, the threshold R_p needed for the onset decreases with increasing back pressure P_∞ .

Figure 5a summarizes the measured liquid fuel and air coflow temperatures T_F (colored symbols) and T_A (colored dashed lines) for Cases 1-9 at the three pressures shown in Figs 2 to 4. As described in the experimental section, they were measured using thermocouples at T_1 and T_2 in the injector housing (see Fig. 1b). Since the cases were selected based on the similar levels of superheat Δ_T , the absolute T_F increases with increasing back pressure (due to the increase in $T_{\text{sat}}(P_\infty)$ in Eq.1). Since the coflow was also used to preheat the liquid fuel, T_A was higher than T_F . The difference was likely smaller at closer to the nozzle exit since T_1 was located about 55 mm upstream of T_2 . Notice also that the temperature difference becomes smaller at higher pressures due to a generally slower coflow velocity at similar air mass flow rates (a certain minimum amount was necessary for the operation of the air preheater) and hence a better heat exchange between the coflow and the fuel line.

From Fig. 5b it is clear that the nine cases at various pressures possess matching (if not identical) levels of superheat Δ_T . These cases are qualitatively classified into three categories based on spray morphology: (I) Cases 1 and 2 in the mechanical breakup regime; (II) Cases 3 and 4 in the transient regime where the jet starts to expand into a plume, which can be linked to external flashing defined in Ref. [6]; (III) Cases 5-9 in the shrinking plume regime (fully flashing or supercritical injection). Figure 5c shows that R_p starts to diverge for the cases from II to III, with the values increasing much more rapidly at $P_\infty = 1.5$ bar. From the calculated energy barrier plotted in Fig. 5d (only for superheated cases), it is clear that the fuel spray approaches the onset

Fig. 5. Comparisons of the levels of superheat under the operating conditions shown in Figs.2 to 4. The colored dashed lines in (a) represent measured coflow temperatures for the corresponding back pressures.

of fully flash ($\chi=1$ is indicated by the black dashed line) faster with increasing pressure, especially from $P_\infty=3$ bar to $P_\infty=6$ bar. This provides an explanation to the trends observed in Figs 2 to 4, where the transition from jet to plume becomes noticeably abrupt at $P_\infty=6$ bar, suggesting that bubble nucleation is likely the dominant process for controlling spray morphology responding to thermal effects as found in Ref. [6]. Note that the observed reduction in spray spreading angle with increasing pressure is also consistent with the observations in Ref. [6].

Fig. 6. Single-shot shadowgraphs of cyclohexane injected at $P_\infty=6$ bar (blue dashed line on the P-T chart), $\dot{m}_F=0.5$ g/s and various initial fuel temperature T_F and pressure P_F (red dots on the P-T chart), using a plain orifice nozzle. Each shot is 10 mm by 25.5 mm in physical scale.

Fig. 7. Single-shot shadowgraphs of Jet A-1 injected at $P_\infty=6$ bar (blue dashed line on the P-T chart), $\dot{m}_F=0.5$ g/s and various initial fuel temperature T_F and pressure P_F (red dots on the P-T chart), using a plain orifice nozzle.. Each shot is 10 mm by 25.5 mm in physical scale.

Influence of mass flow rate and type of fuel

Figure 6 examines the superheated and supercritical injection of cyclohexane at $P_\infty=6$ bar and a lower mass flow rate of 0.5 g/s, at levels of superheat comparable to the cases shown for 1 g/s in Fig. 4. In comparison, the sudden transition from mechanical breakup to superheated injection (Case 2 to 3) appears more pronounced. Additionally, the penetration depth of the plume decreases much faster, with barely discernible spray presence at supercritical conditions Cases 7-9.

As mentioned at the beginning of the section, other single/multi-component fuels exhibited similar trends found in cyclohexane. As an example, figure 7 includes Cases 1-4 of Jet A-1 injected at $P_\infty=6$ bar and $\dot{m}_F=0.5$ g/s. The vapor pressure chart was generated based on the properties

Fig. 8. Comparison of energy barrier χ of the operating conditions shown in Figs.6 and 7.

of Jet A-1 provided in Ref. [12], which was used to treat Jet A-1 as a single-component fuel in numerical simulations [15]. As can be seen, despite having matching levels of superheat, the spray appears to enter the Category II described above at Case 2, before superheated condition is achieved, such that Cases 2-4 for Jet A-1 seem to resemble Cases 3-5 for cyclohexane (see Fig. 6) at the same mass flow rate and chamber pressure. This suggests that treating Jet A-1 as a single-component fuel would not explain the early onset of spray transitions from mechanical breakup to superheated injection.

To further demonstrate the inadequacy of considering Jet A-1 as a single-component fuel, figure 8 plots the energy barrier χ calculated for Jet A-1 for the superheated cases Cases 3 and 4, compared to the cases from cyclohexane, all at $P_\infty=6$ bar. Based on the spray form seen in Fig. 7 and the observations made for cyclohexane (summarized in Fig. 5), Case 3 of Jet A-1 should reside at close vicinity of the fully flashing limit $\chi=\mathcal{O}(1)$, such as for Case 4 of cyclohexane. Therefore, by treating Jet A-1 as a single-component fuel using the properties from Ref. [12], χ is considerably overestimated and no longer valid for predicting spray transitions into flashing. This could be attributed to the fact that, small fuel components in Jet A-1 possess much steeper vapor pressure curves and could thus enter into the superheated regime prior to large fuel components. It has been shown in a mixture of single-component fuels, the flashing of small fuel components could trigger flashing of large fuel components at lower superheat than when for they are injected separately [16]. The results presented here echoes this finding, suggesting that the thermal heating effect on Jet A-1 could only be properly accounted for by considering Jet A-1 as a mixture of single-component fuels.

Fig. 9. Comparisons of measured and calculated pressure drop over a plain orifice nozzle for cyclohexane and jet A-1 at $P_\infty=6$ bar, $\dot{m}_F=0.5$ g/s and various initial fuel temperature T_F . The cases included in Figs. 6 and 7 are highlighted with larger symbols. T_{sat} is indicated by the blue vertical dash line.

Estimation of pressure drop

The influence of superheat on fuel injection was also inspected by comparing the measured pressure drop ΔP_F across the nozzle at various T_F to estimated values based on monitored operating conditions and the discharge coefficient of a plain-orifice nozzle [17]:

$$\dot{m}_F = C_D A_0 (2\rho_F \Delta P_F)^{0.5}, \quad (4)$$

where A_0 and ρ_F are the cross sectional area of the nozzle and fuel density, respectively. For the plain orifice nozzle, the discharge coefficient C_D was calculated based on the empirical formula from Ref. [18]:

$$\frac{1}{C_D} = \frac{1}{C_{D_{max}}} + \frac{20}{Re} (1 + 2.25 l_0 / d_0), \quad (5)$$

Fig. 10. Single-shot shadowgraphs of cyclohexane injected at $P_\infty=6$ bar (blue dashed line on the P-T chart), $\dot{m}_F=1$ g/s and various initial fuel temperature T_F and pressure P_F (red dots on the P-T chart), using a pressure-swirl nozzle. Each shot is 10 mm by 25.5 mm in physical scale.

where $C_{D_{max}} = 0.827 - 0.0085l_0/d_0$. In order to minimize the role of cavitation, only the cases with $\dot{m}_F=0.5$ g/s were considered. The results are plotted in Fig. 9, with the cases included in the shadowgraph collages in Figs. 6 and 7 highlighted with larger symbols (matching those used in Fig.8). The corresponding T_{sat} at $P_\infty=6$ bar is also indicated in the plot for reference (blue vertical dashed line). Note that the constant 0.827 in $C_{D_{max}}$ was slightly inflated to 0.9 for Jet A-1 to better match the measured pressure drop at low temperature conditions.

As can be seen for cyclohexane in Fig. 9a, measured pressure drop only starts to deviate from mechanical breakup across T_{sat} (i.e., in Category II defined in Fig. 5). This suggests that measured ΔP_F could also serve as a sensitive indicator for monitoring the effect of superheat and the departure from a classical regime dominated by mechanical breakup. This is particularly the case for Jet A-1 shown in Fig. 9b, where the measured ΔP_F outpaces the theoretical value about 70 K lower than the theoretical T_{sat} (considering Jet A-1 as a single-component fuel). Notably, Case 2 is seen here to no longer behave as a mechanical breakup, consistent with the observations from the shadowgraph shown in Fig. 7.

Thermal effect on a pressure-swirl nozzle

Since the ultimate goal of this work is to examine the impact of superheat on fuel injection in aero engine combustors, laser shadowgraphy was also applied to fuel injections facilitated by a

Fig. 11. Comparisons of measured and calculated pressure drop over a pressure-swirl nozzle for cyclohexane at $P_\infty=6$ bar, $\dot{m}_F=1$ g/s and various initial fuel temperature T_F . The cases included in Fig. 10 are highlighted with larger symbols. T_{sat} is indicated by the blue vertical dash line.

Delavan pressure-swirl nozzle (described in the experimental section above).

In a similar manner to those shadowgraphs carried out with the plain orifice nozzle presented above, shadowgraphs with the Delavan nozzles were selected based on the operating conditions to match the levels of superheat for injection of cyclohexane at $P_\infty=6$ bar, $\dot{m}_F=1$ g/s (see Fig. 4). The results are shown in Fig. 10. Since the transition from Case 3 to 4 appeared too abrupt, an additional case at $\Delta_T=44$ was added in the collage. Case 8 was then removed since it exhibited similar form as Cases 7 and 9. As can be seen, at no superheat (Cases 1 and 2), the fuel spray enters the chamber with a spreading angle of approximately 90° (expected of this nozzle). As in the case of the plain orifice nozzle, preheating below T_{sat} does not seem to have any impact on the spray morphology. However, as soon as the superheated regime is entered, the spray angle starts to shrink drastically (between Cases 3 and 4). At the same time, the penetration depth of the spray reduces with increasing amount of fuel vapor present in the chamber. From Case 4 onward, it is almost indistinguishable from the behavior of the sprays generated from the plain orifice nozzle shown in Fig. 4: the plume of fine particles retreats towards the nozzle with increasing superheat. The results seem to suggest that, once superheat becomes the predominant mechanism in controlling the spray morphology, the differences in mechanical breakup mechanisms (e.g., plain orifice vs. pressure-swirl) become insignificant. This observation may prove crucial when designing injection systems for future aero engines where the advantages of superheated and supercritical injections were to be leveraged.

As pointed out above, the transition from a cone spray to a plume in the case of the Delavan nozzle occurs later than the jet-to-plume transition with the plain orifice nozzle, which is made obvious by comparing Fig. 10 with Fig. 4, specifically from Case 3 to Case 4. In order to gain more insights into this difference, pressure drop ΔP_F over the Delavan nozzle was also estimated based on the manufacturer specifications ($d_0=0.35$ mm and $C_D=0.45$) and Eq. 4 and compared with the measured values, as plotted in Fig. 11. The cases used for the shadowgraph collage in Fig. 10 are highlighted with larger symbols and labeled correspondingly. It appears that up until Case 3, ΔP_F behaves as expected without any thermal effect. From then on, the measured ΔP_F starts to deviate strongly from the estimated values, which corroborates well with the observations in Fig. 10, where at $\Delta T=44$ (between Cases 3 and 4) the cone spray begins its transformation into a plume. In a stark contrast to the ΔP_F obtained with the plain orifice nozzle in Fig. 9, in the case of the pressure-swirl nozzle, the theoretical pressure drop based on discharge coefficient holds well beyond the saturation temperature T_{sat} . This result suggests that in the case of the pressure-swirl nozzle, the effect of superheat does not overtake the dominant mechanism of mechanical breakup as early as in the case of the plain orifice nozzle. This shows the necessity of investigating atomizers with complex geometries, since the knowledge regarding superheated/supercritical injection obtained with a simple plain orifice nozzle may not apply, as demonstrated in this work.

CONCLUSIONS

In this work, a jet-in-coflow configuration was implemented at the High Pressure Optical Test (HiPOT) facility at DLR to study superheated and supercritical injections of various single- and multi-component liquid fuels at elevated temperatures and pressures. The experimental apparatus facilitated reproducible investigations of up to 650 K fuel temperature (T_F) at constant fuel mass flow rates ($\dot{m}_F$, up to 1.5 g/s) and back pressures (P_∞ , up to 6 bar), with both a custom plain orifice nozzle and a commercial pressure-swirl atomizer. Laser shadowgraphy was set up to record and characterize spray morphology as the fuel temperature was increased from classical regime of mechanical breakup to superheated and supercritical regimes. Additionally, simultaneously logged operating conditions were used to quantify the injection conditions of each individual instantaneous

spray shadowgraphs, including the level of superheat Δ_T , the energy barrier for bubble nucleation χ and the pressure drop across the nozzle ΔP_F .

From the representative results obtained in cyclohexane and Jet A-1 with the plain orifice nozzle, it is shown that: (1) In the mechanical breakup regime ($\Delta_T \leq 0$), fuel preheating has no discernible impact on the spray; (2) With rising Δ_T in the superheated regime ($\Delta_T > 0$), the spreading angle of the spray increases drastically and the spray eventually transitions into a plume of fine particles, resembling a fully flashing event; (3) Further increase of Δ_T up to the supercritical regime causes the plume to shrink gradually toward the nozzle exit, trailed by a build up of fuel vapor in the spray chamber. Such jet-to-plume transition also occurs faster with increasing P_∞ , a phenomenon that can be explained by the reduction in energy barrier with increasing Δ_T , which approaches faster toward the fully flashing threshold of $\chi = \mathcal{O}(1)$ at higher P_∞ . At $\dot{m}_F = 0.5$ g/s, almost all liquid fuel is instantly vaporized exiting the nozzle under supercritical conditions. It is shown that Δ_T and χ calculated by considering Jet A-1 as a single-component fuel could not adequately explain the faster-than-expected transitions of sprays into fully flashing mode, suggesting that various components in Jet A-1 could experience transitions into superheated regime nonconcurrently and interact with each other in a complex manner. On the other hand, ΔP_F is shown to be a sensitive indicator of departure from mechanical breakup when compared to estimations based on the theoretical discharge coefficient.

Examinations conducted with the pressure-swirl atomizer demonstrates that as T_F enters the superheated regime, the spray contracts dramatically from a standard cone shape to form a plume of fine particles, which shrinks with increasing Δ_T . Up from a certain high level of superheat, the spray behavior becomes nearly indistinguishable from that observed with the plain orifice nozzle, suggesting the predominant role thermal effect plays in spray morphology in this regime. Detailed comparisons of measured and estimated ΔP_F show a different trend with respect to superheat compared to the case with the plain orifice nozzle, demonstrating the necessity of investigating atomizers with complex geometries under superheated and supercritical conditions. These results also demonstrate that fuel spray undergoes notable changes in morphology even at fairly low superheat levels, which could affect the combustion process especially in cases where the fuel

injection system is not actively cooled. The comprehensive datasets obtained in this work could be used to derive spray boundary conditions for constructing numerical models that account for thermal effects on fuel injection.

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- 1 Schematic of the experimental setup: (a) a 3-D view of the modified HiPOT facility; (b) Top cross-section view of the jet-in-coflow configuration for liquid fuel injection as well as the laser shadowgraphy apparatus (not to scale). 1: Afterburner chamber; 2: Optical pressure vessel; 3: Liquid fuel preheater; 4: Main air preheater; 5: Housing for the fuel injector; 6: Spray chamber; 7: Afterburner.
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