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# High-Speed Optical Imaging of Cavitation and Spray Dynamics for Sustainable Aviation Fuels

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**Abstract.** This study investigates the in-nozzle flow dynamics and near-nozzle spray characteristics of multiple fuels relevant to sustainable aviation, including conventional diesel, Jet-A, two sustainable aviation fuel (SAF) samples, bicyclohexyl (BCH) and C-4; and a surrogate, dodecane. Experiments were conducted with two orifices that have distinct internal geometries, one straight and one converging, under varying injection-pulse durations. Overall, cavitation and spray behaviours did not differ substantially among the fuels, apart from BCH in the converging orifice, where its higher viscosity led to pronounced string cavitation. This converging geometry suppresses geometric cavitation yet enables string cavitation, resulting in a noticeably larger spray cone angle for BCH. Conversely, the straight orifice design does not suppress geometric cavitation, BCH exhibiting similar cavitation levels to the other fuels under these conditions. These cavitation patterns were reflected in the spray cone-angle measurements, where BCH showed the highest angles in the converging orifice and only average angles in the straight configuration.

## 1. Introduction

In recent years, the necessity for a transition of the transportation sector to sustainable operation has been highlighted by stringent environmental regulations aimed at mitigating harmful emissions and facilitating the adoption of cleaner energy alternatives. This transition is of paramount importance in the aviation sector, which stands as a significant contributor to the global climate crisis. The aviation sector is responsible for approximately 2% of worldwide greenhouse gas emissions, predominantly through carbon dioxide outputs [1]. Projections indicate that by 2050, aviation could represent as much as 5% of the planet's total greenhouse gas burden [2]. However, aviation is the most challenging mode of transportation for achieving decarbonisation, primarily due to its adherence to strict safety protocols and weight restrictions [3].

Although the potential integration of innovative technologies such as electric or hydrogen-powered aircraft holds promise, these alternatives are not yet viable, especially for long-distance flights, in the immediate or medium-term future [4],[5]. Given these constraints and the current limitations of alternative energy sources for aviation, the industry faces a significant challenge in achieving near-term decarbonisation goals. This reality necessitates a continued reliance on liquid fuels for the foreseeable future. Notwithstanding these challenges, the aviation industry is increasingly turning to carbon-neutral fuels, known as Sustainable Aviation Fuels (SAF), to mitigate environmental impact [6]. Consequently, significant research efforts are being channelled towards the exploration and development of various approaches to produce these carbon-neutral aviation fuels using renewable resources [7],[8],[9].

Fuel injection plays a critical role in the successful deployment of SAFs because of the direct relationship between fuel delivery and both engine performance and emissions levels [10]. Recent advancements in diesel injector technology have significantly improved operational efficiency and contributed to emissions reduction, by enabling high injection pressures and micrometre-sized orifice diameters and leading to enhanced atomisation quality and combustion efficiency. Modern fuel systems operate at very high pressures and employ orifices with micrometre-scale diameters to enhance atomisation [11], thereby improving combustion efficiency and reducing emissions. However, these conditions promote cavitation within fuel delivery components, creating a two-phase flow that influences spray formation and its dynamic characteristics [12].

Consequently, it is essential to thoroughly examine the transient characteristics of the in-nozzle cavitating flow, especially considering its significant influence on spray morphology. However, visualising in-nozzle flow is a challenging task due to the small size of the nozzles, rapid time scales of injection, and the highly turbulent flow within the nozzle. Therefore, early studies often relied on scaled-up nozzles to facilitate the visualisation of in-nozzle flow [13],[14]. The studies have revealed that the macroscopic topology of cavitation exhibits comparable characteristics in both scaled-up replicas and real-size nozzles [15],[16]. However, discrepancies in bubble residence and collapse durations have been noted [17]. The last decade has witnessed significant advancements in microfabrication and imaging technologies. The assembly of real-size injectors with transparent tips [18],[19] typically made of acrylic material, offers a close match to realistic operating conditions, as acrylic tips can withstand extreme pressures, reaching up to 1000 bar [20].

Established research on fuel cavitation and spray dynamics has predominantly focused on diesel fuel and its alternatives, primarily driven by the high potential for cavitation in diesel injector nozzles operating at elevated pressures. N-dodecane, widely used as a primary surrogate for diesel fuel, provides a sufficiently accurate approximation and is also utilised as a surrogate for jet fuel [21],[22], especially Jet-A, due to its substantial presence by weight [23]. However, a significant research gap exists in the established literature with respect to cavitation and spray formation of aviation fuels, and even more so for SAFs and surrogates.

Alternative fuels evaluated in this study, namely Jet-A and C-4, are notable for their inclusion in the National Jet Fuels Combustion Program (NJFCP), an endeavour augmented by international collaboration with the primary objective of developing universal methodologies for the testing and modelling of fuel combustion processes, thereby facilitating the expedited adoption of novel alternative jet fuels [24]. Bicyclohexyl (BCH) is a dicyclic hydrocarbon compound found in Jet-A [25], particularly promising as an alternative to conventional jet fuels owing to its high energy density and superior heat capacity [26]. It can be sustainably produced from renewable biomass through advanced biorefinery methods, such as catalytic pyrolysis and hydrodeoxygenation, which enable the conversion of lignocellulosic biomass into BCH [27],[28]. C-4 is a test fuel created as part of the NJFCP with boiling characteristics similar to those of Jet-A and low cetane number (28). A recent study by Di Sabatino and coworkers [29] indicates that C-4 and BCH fuels produce significantly less soot than Jet-A due to enhanced diffusive mixing under high-pressure conditions. Experiments were conducted in a constant-volume combustion vessel simulating combustor conditions relevant to cruise and take-off scenarios. Further work by the same group [30] examined the evaporation behaviour of spray droplets under aero-engine conditions using high-speed microscopy and a machine-learning. The results revealed a transition from classical to diffusive evaporation at take-off conditions, which contributed to the observed reduction in soot formation compared to Jet-A.

Conventional jet fuels constitute Jet-A, a widely used type consisting of a complex blend of hydrocarbons [24],[31], as well as its variation JP-8, which, enhanced with additives for anti-icing and lubrication [25], is used in both diesel and aero-prop engines, both single and blended with diesel fuel [32],[33]. Moreover, standardisation efforts driven by the military emphasise a single-fuel approach, for example a policy promoting the use of JP-8 for both aviation and ground vehicles [34], thereby streamlining logistical processes and improving overall interoperability. Consequently, there has been significant research in the past focused on the use of aviation fuels in diesel injector systems [35],[36],[37]. Notable work by Pickett and Hoogterp [38] investigated the combustion characteristics of JP-8 and diesel fuel under diesel engine conditions. Using high-speed shadowgraph and Mie-scatter imaging simultaneously in a constant-volume combustion vessel, the research compared JP-8 with diesel, examining aspects like liquid and vapour penetration, spreading angle, and ignition timing and location. The results revealed that the vapour-phase penetration and spreading angle of both fuels are similar under identical injector and ambient conditions despite the faster evaporation rate of JP-8. This suggests comparable air entrainment levels in the fuel jets of both JP-8 and diesel.

Injection strategies have also been identified as pivotal in augmenting combustion efficiency and mitigating emissions [39]. The quantity of fuel, which is directly influenced by the duration of pulse width and the pressure at which fuel is injected, plays a crucial role in this process [40]. Pratama et al. [41] explored the impact of injector needle dynamics on spray formation using high-speed X-ray visualisation. They analysed the interaction between spray dynamics and needle lift within the injector. The results show that the needle lift has a strong influence on the spray angle in the sense that the angle is suppressed when the needle lift reaches a certain point regardless of the injection pressure and injection duration. The study highlighted that the internal flow area is crucial in determining the flow state and spray characteristics. Wei et al. [42] showed that shorter pre-injection pulse widths cause lower needle lifts and higher turbulence, leading to significant cavitation, while opposite trends were verified for longer pulse widths. Bai et al. [43] delved into the effects of diverse injection rate profiles on diesel combustion and its resultant emissions through the application of CFD simulations. Following validation with experimental data, the study examined five injection-rate profiles. The main findings highlighted the significant impact of the injection rate on combustion processes and resultant NO<sub>x</sub> and soot emissions.

Heavy-fuel aero-diesel engines operate successfully on Jet-A under injection conditions comparable to those explored in this study [44],[45], and current research programmes are now extending the same hardware to sustainable-aviation-fuel blends [46], [47]. Recent experiments carried out by Kleissner and Hoffman [47] showed that modern compression ignition aircraft engines can run SAFs, such as hydrotreated vegetable oils (HVO) and kerosene-based synthetic fuels, without hardware changes, while remaining within mechanical and thermal limits of operation. However, to achieve peak performance and emissions minimisation, optimisation of the fuel injection strategy is required. Thereby, studying the influence of varying injection pulse duration, as performed in the present work, offers valuable insight on the injection behaviour under conditions relevant to aero-diesel systems operating with both conventional and sustainable aviation fuels.

Addressing the verified gap in the open literature, the present investigation explores a diverse range of fuels comprising diesel, n-dodecane, Jet-A, C-4 fuel -a blend of iso-paraffins, dodecane, and hexadecane, as well as a bio-derived cyclo-alkane fuel, bicyclohexyl. By exploring this diverse range of fuels, the research aims to shed light on cavitation and near-nozzle spray dynamics specific to aviation fuels, thus, facilitating the adoption of more efficient fuel alternatives for the aviation industry. Different injection durations were investigated to further explore their influence on cavitation and spray dynamics of SAFs. This work aims to reveal the intricate dynamics within the nozzle and near the nozzle exit, crucial for optimising fuel delivery and combustion processes. To the author's knowledge, it is the first one in the open literature emphasising upon alternative aviation fuels.

## 2. Methodology

This study employed diffuse back-illumination (DBI) extinction imaging to investigate the cavitation patterns and near-nozzle spray dynamics in real-size, single-hole transparent injectors, standardised as Spray C and Spray D by the ECN. The experiments utilised a specially designed, optically accessible chamber enabling detailed internal flow visualisation. Fuel was pressurised by a syringe pump, with the injection pressure set to 500 bar for Spray C and 700 bar for Spray D. The injection pressure for the tapered-hole Spray D was limited to 700 bar after initial tests to avoid damaging the acrylic test piece. The set pressure allowed the evaluation of at least four distinct injection events per fuel type across three different pulse durations. In contrast, the injection pressure for the straight-hole Spray C injector was limited by visualisation constraints since for the injection pressures above 500 bar; the injector hole was rendered completely opaque throughout the injection process for some of the investigated fuels.

The injector needle-lift profile was controlled using electronic signals of 0.65, 0.95, and 1.25 milliseconds, respectively, provided by a high-current injector, with the same needle-lift profile imposed for each signal duration. As reported by Manin et al. [20], the injection duration depends on hydraulic phenomena governing needle motion and, therefore, varies with injection pressure. Consequently, Spray D at 700 bar exhibited hydraulic injection durations of 1.175, 1.8, and 2.5 milliseconds, respectively, as shown in Table 1. In contrast, Spray C at 500 bar showed durations of 1.125 and 2 milliseconds for imposed signals of 0.95 and 1.25 milliseconds, respectively, whilst a 0.65 millisecond signal at 500 bar did not initiate injection. Figure 1e, which shows the needle-lift position with respect to injection duration for Spray C and D for 1.25 ms electronic signals, confirms that the total event for Spray D at 700 bar reached 2.5 milliseconds, which is 0.5 ms longer than for the same nominal signal at 500 bar with Spray C. It is interesting to note that the needle lift and decay rates are higher for Spray C, despite the lower injection pressure. Past experiments, including X-ray studies by Swantek et al. [48], have shown that needle lift and decay rates depend on injection pressure, with higher pressures generally increasing both. Manin et al. [20] further confirmed this trend using high-

speed microscopy in transparent nozzles. Ambient pressures 1 and 10 bar were examined, whilst maintaining a constant temperature of 20 °C. Each experiment was repeated four times to minimise uncertainty and avoid compromising the acrylic component, thereby maintaining consistent conditions for the entire experimental matrix. A summary of the experiments and operating conditions is provided in Table 1.

**Table 1:** Summary of injection operating parameters and ambient conditions.

| Injector layout                      | Spray C                      | Spray D       |
|--------------------------------------|------------------------------|---------------|
| Injection Pressure [Bar]             | 500                          | 700           |
| Hydraulic Injection Duration [ms]    | 1.125-2                      | 1.175-1.8-2.5 |
| Ambient gas                          | N <sub>2</sub>               |               |
| Ambient temperature [K]              | 293                          |               |
| Ambient pressure [Bar]               | 1-10                         |               |
| Ambient density [kg/m <sup>3</sup> ] | 1.15-11.5                    |               |
| Fuel                                 | Diesel-Dodecane-Jet A-C4-BCH |               |

As fuel properties have a critical influence on in-nozzle flow dynamics and the resulting spray formation, Table 2 provides a detailed overview of the properties of the fuels investigated in this study.

**Table 2:** Properties of the investigated fuels at ambient temperature of 20°C [49],[50],[51].

| Fuel Properties                | Diesel | n-Dodecane | Jet-A | C-4   | BCH   |
|--------------------------------|--------|------------|-------|-------|-------|
| Density [kg/m <sup>3</sup> ]   | 835.2  | 751.2      | 800.6 | 756.9 | 864   |
| Viscosity [mm <sup>2</sup> /s] | 2.80   | 1.44       | 1.41  | 1.53  | 4.34  |
| Initial Boiling Point [°C]     | 155.1  | 214.0      | 130   | 161   | 227.0 |
| Final Boiling Point [°C]       | 363.1  | 218.0      | 300   | 239.6 | 228.0 |
| Surface Tension [mN/m]         | 28.73  | 25.35      | 24.69 | 22.34 | 32.68 |
| P <sub>sat</sub> [Pa]          | 237    | 184        | 900   | 758   | 14.4  |

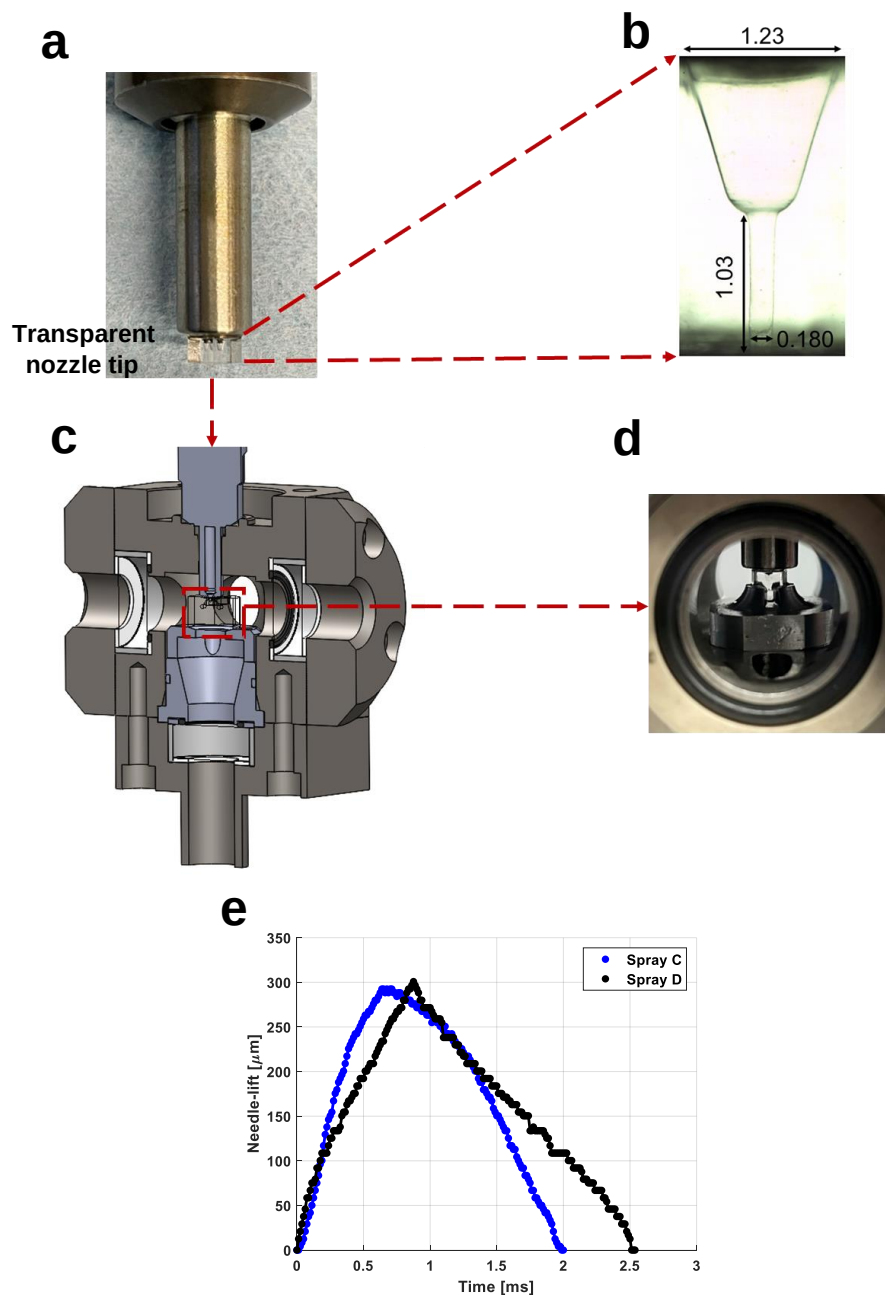
Notably, n-dodecane and BCH are single-component fuels, so they are characterised by fixed boiling points. In contrast, diesel fuel, Jet-A, and C-4 are multi-component fuels, resulting in broader boiling characteristics. Among these, diesel fuel exhibits the broadest distillation curve, indicative of its complex hydrocarbon mixture [52],[53]. Jet-A and C-4 also display significant boiling ranges. Additionally, BCH stands out with its relatively high boiling point and higher density and viscosity compared to the other fuels. Variability in cavitating flow dynamics is anticipated between mono-component fuels, such as dodecane or bicyclohexyl, and complex, multi-component fuels, like diesel, Jet-A and C-4. This variability is attributed to each constituent's unique surface tension and vapour pressure characteristics, significantly impacting their cavitation behaviour [54].

## 2.1. Experimental Setup

The experimental campaign utilised two injector designs, i.e., transparent variants of the ECN Spray C and Spray D single-hole injectors, specifically modified for in-nozzle visualisation. The transparent injector tips were mated to the modified original nozzle, interfacing right below the nozzle valve portion, i.e., the needle seat. This optical injector setup was assembled by securing the metallic body, optical tip, and a supporting pedestal, as illustrated in Figure 1. The pedestal design, which is hollow and corrugated, enables the observation of the spray area up to 1.5 mm downstream of the injector outlet and the flow of the mixture into the exhaust tube. Both Spray C and Spray D transparent nozzle tips, made from micromachined cast acrylic, share similar overall dimensions; however, they exhibit key differences in their design features.

The Spray D orifice features a tapered-hole design with a  $k$ -factor defined as  $(D_{\text{inlet}} [\mu\text{m}] - D_{\text{outlet}} [\mu\text{m}])/10$  of 1.5, indicating the difference in dimensions between the injector-hole inlet and outlet. Additionally, the hole entrance has been smoothed using hydro-erosion. Hence, a more moderate level of cavitation emerges in Spray D compared to the straight-orifice Spray C injector. Full details of Spray C and Spray D geometries are available in Refs. [55] and [56] respectively.

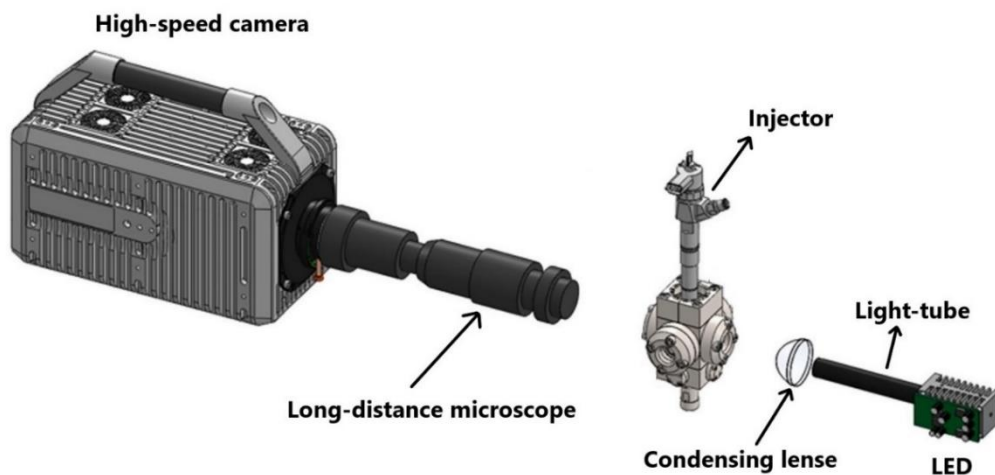
Experiments were conducted in an optically accessible pressure chamber. Nitrogen gas was injected through four ports at the top of the chamber to maintain and control the internal pressure, ensuring a constant flow that prevents window contamination during repeated spray activities. The fuel-gas mixture was exhausted after injection through an exit port at the bottom of the chamber. Pressure levels for both the injection and ambient conditions were monitored by pressure transducers located along the fuel and exhaust lines. The pressure chamber is illustrated in Figure 2, and detailed dimensions of the chamber are provided in prior research [57],[58].



**Figure 1:** Layout of the injector and spray chamber assembly: (a) Transparent tip integrated into the tip of the metal injector. (b) Acrylic transparent Spray D nozzle with basic dimensions. (c) Sectional view of the spray chamber. (d) Field of view from the chamber window. All dimensions are in mm. (e) Needle-lift profiles of Spray C and Spray D under injection and ambient conditions of 500/1 bar and 700/1 bar, respectively.

## 2.2. Optical Setup and Image Processing

High-speed images were captured at 80,000 frames per second using a Photron SA-X2 CMOS camera equipped with a long-distance microscope objective (Infinity K2-DistaMax); the reader is referred to the schematic of the optical layout of Figure 2. The dimensions of the active window were  $640 \times 128$  pixels, with a corresponding spatial resolution of  $3.78 \mu\text{m}/\text{pixel}$ . The experiment is initiated by the injector driver, which also triggers the high-speed camera. A blue LED illumination system with a wavelength of 455 nm was used for backlighting. The LED was operated with a pulse width of  $4 \mu\text{s}$  and was synchronised with the camera frame acquisition, operating at the same rate as the high-speed imaging system. The LED pulse was aligned with the midpoint of the camera exposure duration, which was set to  $10 \mu\text{s}$ .



**Figure 2:** Schematic of the optical layout for the DBI.

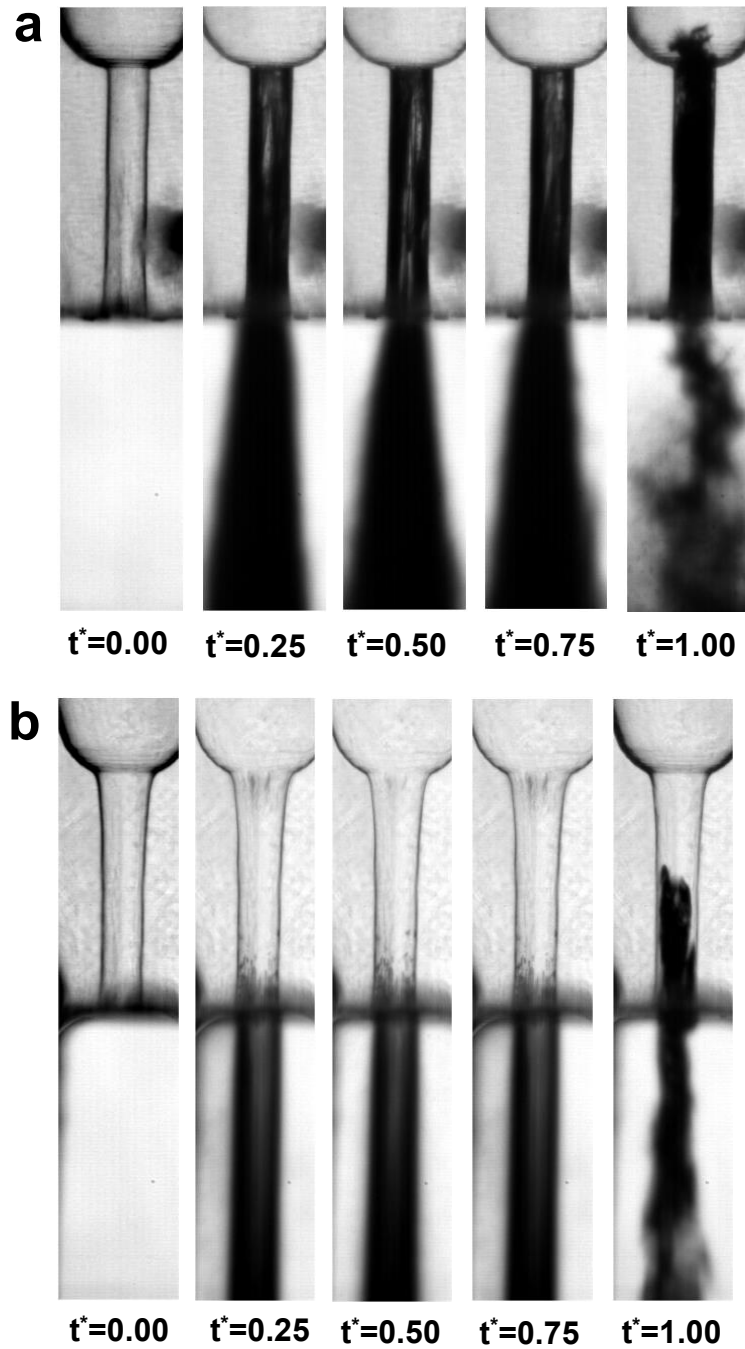
A series of image-processing techniques were employed to extract data pertinent to the extent of cavitation inside the nozzle and its temporal variation, as well as to the topology and dynamic behaviour of the fuel spray. The details of image processing for both cavitation and spray dynamics were thoroughly outlined in our previous publications [58],[59]; thus, they are not repeated here in full. In brief, for the detection of cavitation projected area, the initial pre-processing step involved cropping the region of interest from raw images and subtracting a background image of stagnant liquid. A denoising algorithm was initially applied to retain only significant vapour structures. Otsu's algorithm [60] was first employed to obtain a histogram-based threshold. Building on this baseline, a sensitivity analysis was conducted by systematically varying the threshold level and assessing its impact on segmentation accuracy. From these trials, a fixed threshold was ultimately selected, ensuring robust vapour structure detection while minimising noise. From the binarised images, the vapour-projected area was measured for each frame. Similarly, for spray-cone measurement, the near-nozzle region of interest was cropped and binarised using a threshold determined through sensitivity analysis. Edge detection on the binarised image was performed using the Canny edge detection algorithm as implemented in MATLAB. To mitigate the impact of rogue droplets on the measurement, denoising was applied to the detected edges. The centroids of the two edges of

the spray periphery were identified, and the spray half-cone angles were determined based on the perpendicular distance of these centroids from the central axis of the injector.

### 3. Results and Discussion

Since the hydraulic injection duration depends, apart from the electrical pulse duration, on the injection pressure, a non-dimensional time parameter  $t^*$ , i.e., time over total injection time ( $t^*=t/t_{total}$ ), is introduced to make the comparison more straightforward for different conditions. Even for identical electric pulses, the hydraulic injection duration varies between the two injector layouts due to differences in injection pressures. A series of raw images captured using the single-orifice, Spray C and D, injectors, and dodecane fuel are illustrated in Figure 3. A key distinction between Spray C and Spray D lies in their cavitation behaviour and its impact on spray morphology. Spray C, with its straight orifice, experiences significantly higher cavitation levels, filling most of the nozzle with vapour. In contrast, Spray D's tapered orifice design suppresses cavitation, allowing more liquid presence within the nozzle. This contrast directly affects the cone angle measurements, which also vary substantially between the two injectors. Previous work by our group [59] has provided deeper insights into nozzle geometry's role in cavitation and spray behaviour, highlighting the correlation between cavitation intensity and cone angle fluctuations.

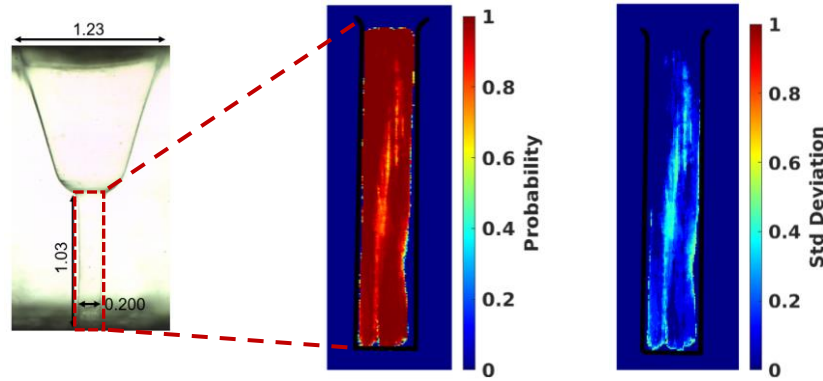
The image sequence for Spray C (Figure 3a) demonstrates that the injector orifice is entirely filled with vapour, rendering it opaque. The camera was focused on the nozzle edges to maintain sharpness; however, owing to the three-dimensional nature, the spray inevitably appears slightly blurred. An animation of the full injection event employing DBI imaging (offered as a Supplementary Movie 1) indicates that cavitation actually forms a vapour sheet along the hole periphery, i.e., along the walls, with transient features emerging in the orifice core. In contrast, the conical configuration of Spray D leads to moderate cavitation, with the nozzle primarily containing pure liquid, as shown in Figure 3b. Notably, machining imperfections introduce micro-cracks, visible near the nozzle throat, that could potentially also give rise to incipient cavitation, as mild refractive index gradients can also be discerned. However, these regions were excluded from further analysis focusing on the in-nozzle cavitation extent. In addition, pockets of vapour can be discerned near the injector outlet, also due to machining imperfections. The wall roughness in this area provides the necessary nucleation sites for cavitation to set in, subsequently sustained by the low pressure prevailing in the region (refer also to Supplementary Movie 2). It is important to note that the precise termination of injection can vary, as shown in [20], due to complex gas exchange occurs in the nozzle, including cavitation collapse and potential ambient gas ingestion. This phenomenon, often referred to as hydraulic flip, which varies slightly from injection-to-injection, is not always synchronised with the actual frame acquisition, leading to slight differences in the precise timing of flow termination at  $t^*=1.00$ , based on the acquired image closest to the end of injection. Consequently, Figure 3 reflects these minor variations in spray behaviour at closing. It should also be noted that the initial fluctuations observed during the ramping phase are a result of the transient hydraulic response of the injector during needle opening. Fluid throttling and the rapid evolution of the in-nozzle flow field during this phase leads to temporal variations in cavitation and spray characteristics [61]. This phenomenon is a fundamental characteristic of injector dynamics and was consistently observed across all investigated fuels.



**Figure 3:** Sequential raw images depicting the entire injection event for the following injector cases: (a) Spray C at injection and ambient pressures of 500 bar and 10 bar, respectively, and (b) Spray D at 700 bar and 10 bar, respectively. Both cases feature a pulse duration of 1250  $\mu$ s, using dodecane. Animations of the full injection event are provided as supplementary movies SM1 and SM2.

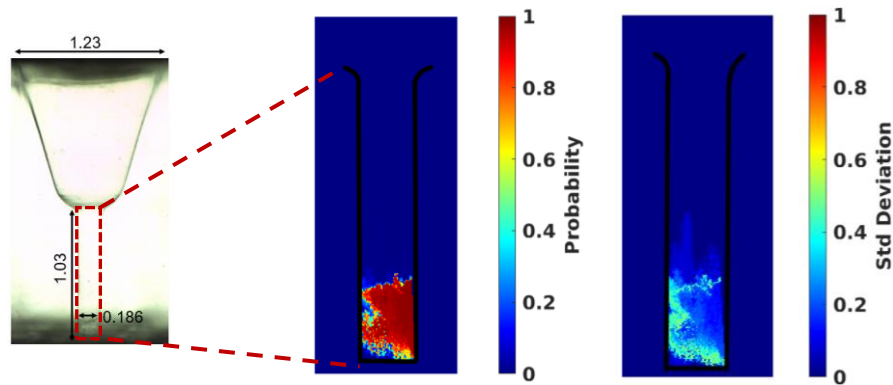
Post-processing of high-speed images throughout the injection event facilitated the calculation of vapour presence probability and its associated standard deviation, as illustrated in Figure 4 for the Spray C injector. The straight-hole Spray C layout results in extensive cavitation, with the nozzle being occupied by vapour throughout most of the injection process,

as indicated by the mean probability values. It is important to underpin that a peripheral vapour layer enveloping the wall is sufficient to induce significant scattering to prevent light from penetrating further into the channel core. However, the high standard deviation values locally in parts of the channel core are indicative of the presence of transient cavities within, which can be identified with clarity by the animation of the supplementary movie SM2.



**Figure 4:** Vapour presence probability and respective standard deviation within the straight Spray C injector. Contour plots correspond to diesel fuel and ambient pressure of 500/10 bar. The black line indicates the outline of the injector-hole straight part. All dimensions in the schematic are in mm.

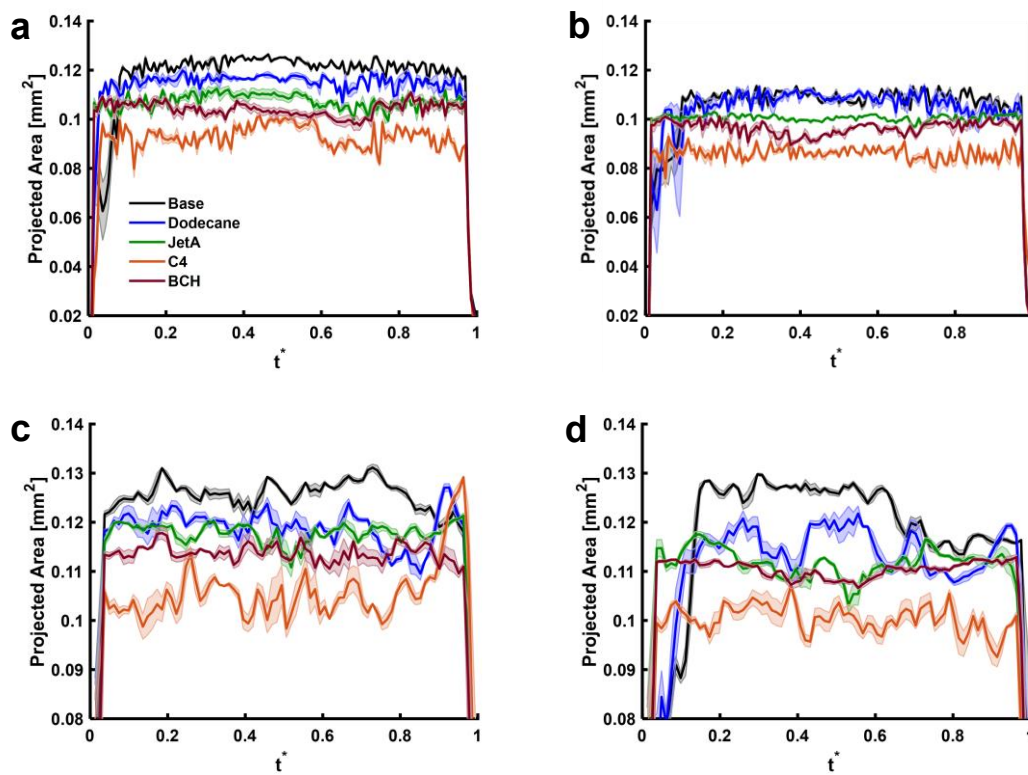
In a similar manner to Figure 4, Figure 5 presents vapour presence probability and standard deviation plots for the Spray D injector. It is evident that vapour formation is suppressed in this nozzle geometry due to its tapered layout and hydro-grinded entrance. Transient cavities emerge towards the orifice outlet, as confirmed by the relatively high standard deviation values, which are primarily attributed to machining imperfections [58]. Most of the injector orifice is filled by pure liquid, with cavitation being completely absent from the sac region.



**Figure 5:** Vapour presence probability and respective standard deviation within the straight Spray D injector. Contour plots correspond to diesel fuel and injection/ambient pressures of 700/10 bar. The black line indicates the outline of the injector-hole straight part. All dimensions in the schematic are in mm.

Five injection events recorded for each one of the examined experiment cases. The shaded error bands in the figures represent the standard error of the mean based on these repeated injection events. Each measurement was acquired across five runs, with the standard deviation ( $\sigma$ ) then divided by the square root of the total number of repeats ( $n$ ) to obtain the standard error ( $\frac{\sigma}{\sqrt{n}}$ ). Plotting the mean measurement alongside this standard error interval produces the shaded region around the mean, thereby indicating the variability across the repeated injections.

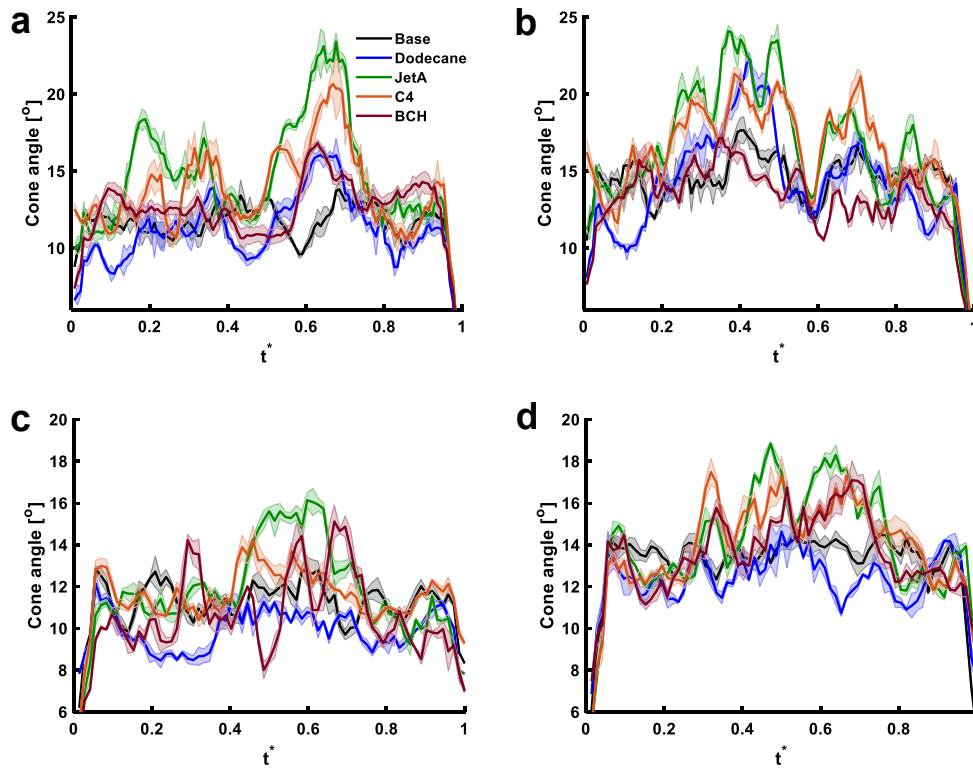
The vapour projected area was quantified for each frame using the binarised images, and its distribution over time for the entire injection event is depicted in Figure 6 for all test samples explored and an injection pulse duration of 1250  $\mu\text{s}$ . The results depict well-expected trends, i.e., an increase in ambient pressure leads to reduced in-nozzle cavitation regardless of the fuel properties, thus justifying the validity of the experiments. The trend between fuels does not change with different pulse durations, as discerned by juxtaposing Figure 6a and 6b and Figure 6c and 6d, and the effect of ambient pressure remains consistent across different pulse durations. It can be discerned that the projected vapour area remains relatively constant during the quasi-steady phase of the injection process ( $0.2 < t^* < 0.8$ ), irrespective of the prevailing ambient conditions for the longer pulse duration of 1250  $\mu\text{s}$ . The needle lift varies with injection duration. Under analogue pressure conditions, longer durations generally increase the maximum needle lift, reducing throttling effects and stabilising the flow, allowing it to reach a steady state. In contrast, shorter injection durations result in lower needle lifts, potentially keeping the flow in a more transient state.



**Figure 6:** Distribution of vapour projected area with time for Spray C for different injection-pulse durations and ambient pressures of: (a) 1250  $\mu\text{s}$ , 1 bar (b) 1250  $\mu\text{s}$ , 10 bar, (c) 950  $\mu\text{s}$ , 1 bar, (d) 950  $\mu\text{s}$ , 10 bar. At each time point, the projected area corresponds to the total area of the structures identified in the binarised images. The shade of the same colour encompassing each graph line corresponds to standard statistical error. For graphs (c) and (d), a 3-point moving average was applied to smooth the data and improve clarity

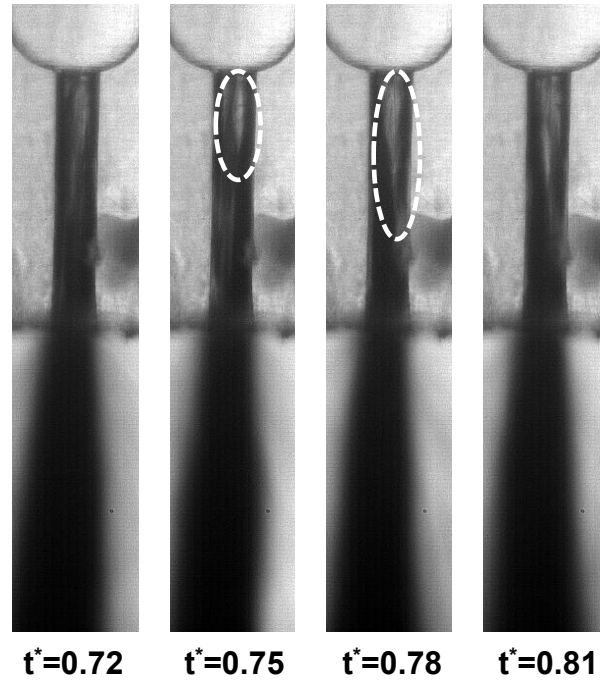
There is a direct link between the in-nozzle extent of cavitation and the near-field spray morphology and cone angle of the expelled spray. At 1 bar, as shown in Figure 7a, the spray cone angles for various fuels remain generally close to each other. Dodecane and diesel, in particular, demonstrate very similar behaviour, with both maintaining cone angles between 10 and 15 degrees, showing relatively minimal fluctuations throughout the injection period. Jet-A and C-4, however, show wider cone angles, peaking up to 25 degrees due to their higher evaporation rates and lower viscosities. BCH exhibits the highest variability, with cone angles

ranging between 7 and 16 degrees. Similarly, at 10 bar, as depicted in Figure 7b, dodecane and diesel remain closely aligned, with cone angles still grouped around 10 to 15 degrees. However, the mean cone angles at 10 bar are slightly higher than those at 1 bar, due to the increase in backpressure and, therefore aerodynamic drag. Jet-A, C-4, and BCH exhibit more significant fluctuations, with cone angles regularly exceeding 20 degrees. It is important to emphasise that these observations are specific to the near-nozzle region, where spray morphology is more directly influenced by in-nozzle flow dynamics. These effects may not be as evident farther downstream, where additional aerodynamic and mixing processes shape the spray behaviour.



**Figure 7:** Distribution of the spray cone angle over time in Spray C for different injection-pulse durations and ambient pressures of: (a) 1250  $\mu$ s, 1 bar 1250  $\mu$ s, (b) 1250  $\mu$ s, 10 bar, (c) 950  $\mu$ s, 1 bar, (d) 950  $\mu$ s, 10 bar. The shade of the same colour encompassing each graph line corresponds to standard statistical error. A 5-point moving average was applied to smooth the data and improve clarity.

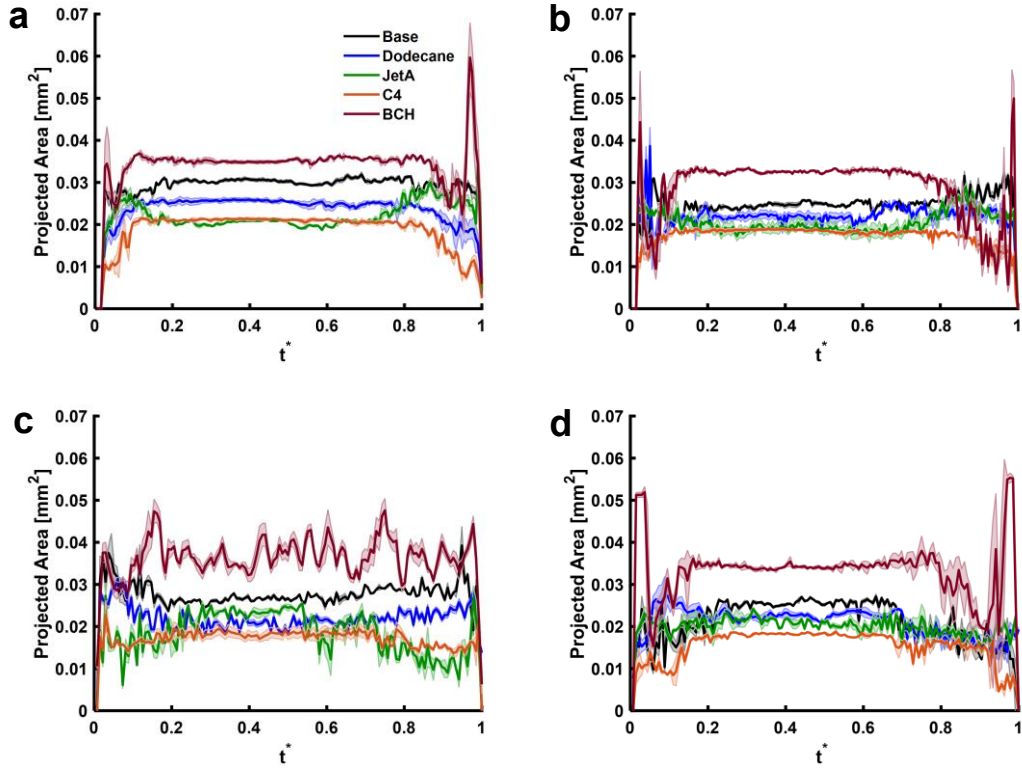
Sequential images for Spray C with fuel C-4 are presented in Figure 8, under injection and ambient pressures of 500 bar and 1 bar, respectively, with a pulse duration of 950  $\mu$ s, highlighting the distinct patterns observed in Figure 6 and Figure 7. As observed from the high-speed images, cavitation within the Spray C nozzle exhibits a multitude of transient features, apart from the wall-attached vapour layer already reported, which are reflected as fluctuations in the cavitating area (Figure 6c) and variations in spray angle values (Figure 7c) at the corresponding injection times. The shorter pulse duration of 950  $\mu$ s enhances the fluctuating trend for C-4 fuel, leading to more pronounced variations in the cavitating area and greater variability in the spray angle.



**Figure 8:** Sequential images depicting cavitation structures (highlighted by the white dash-line ovals) and spray behaviour for Spray C, with injection and ambient pressures of 500 bar and 1 bar, with a pulse duration of 950  $\mu$ s, using C-4.

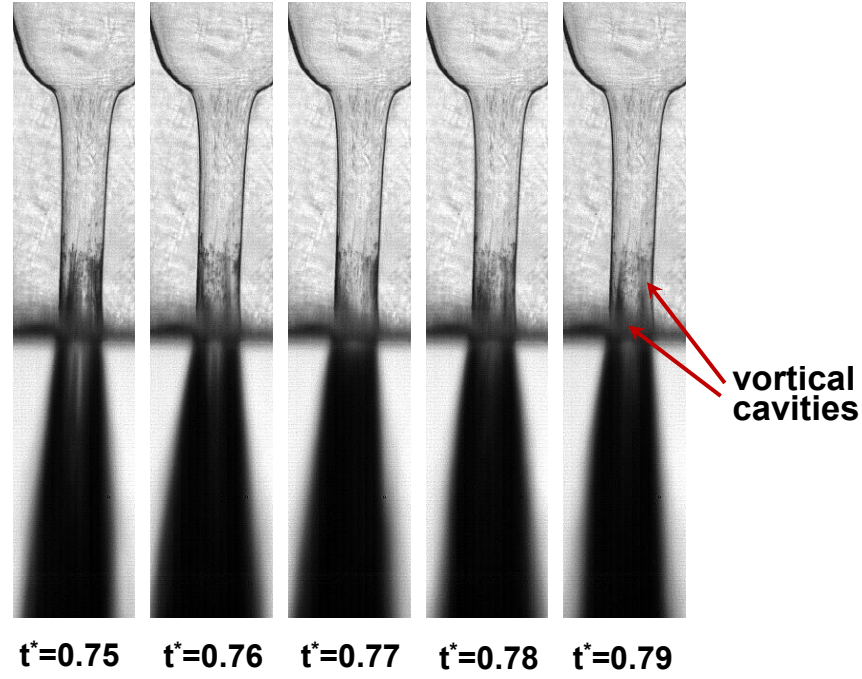
The vapour projected area was also quantified within the Spray D injector using binarised images, as shown in Figure 9. The data shows that increasing ambient pressure reduces cavitation across all fuels, as also observed in Spray C. The trends remain unchanged for different pulse durations, as in Figure 9c and 9d), and the projected vapour area is stable during the quasi-steady phase ( $0.2 < t^* < 0.8$ ), regardless of ambient conditions. The fuel behaviour mirrors Spray C, except for BCH. For Spray D, BCH exhibits the highest cavitation area, showing more fluctuations than other fuels. The cavitation area increases significantly during the needle opening and closing phases for all fuels, but this effect is more intense for BCH, which is attributed to its higher viscosity [41], as further demonstrated by the spray cone angle graphs presented shortly thereafter (refer to Figure 12).

Since vapour pressure is often regarded as the critical thermodynamic parameter designating the extent of wall-attached cavitation, it would be expected that BCH, having a lower vapour pressure, would exhibit reduced cavitation relative to the other fuels. However, experiments indicate that viscosity has a more prevalent influence under the examined conditions. A higher viscosity reduces the in-nozzle Reynolds number for a fixed injection pressure, and hence the level of turbulence. Consequently, given the fact that cavitation emerges in the form of elongated vortical cavities in the Spray D nozzle, cavitation is actually promoted by the reduced turbulence intensity in the sense that large-scale vortices do not decay due to momentum exchange to smaller scales. Cavitating vortices in the case of BCH therefore exhibit higher lifetimes compared to other fuels, a trend also leading to increased cone angles.



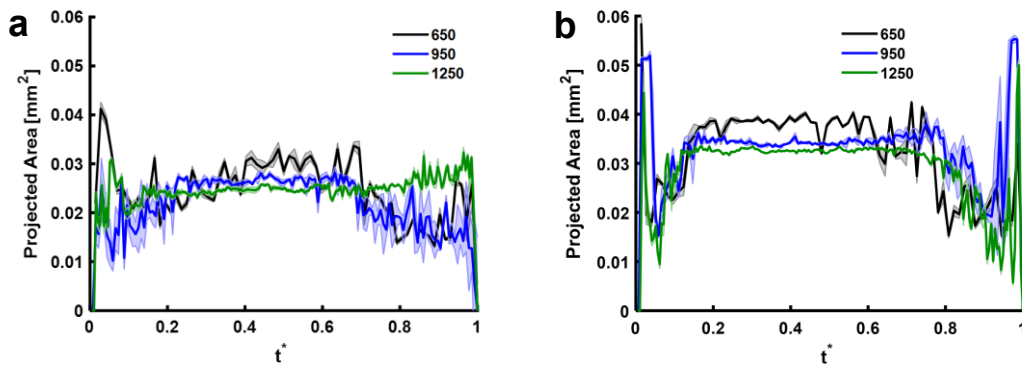
**Figure 9:** Distribution of vapour projected area with time for Spray D for different injection-pulse durations and ambient pressures of: (a) 1250  $\mu\text{s}$ , 1 bar 1250  $\mu\text{s}$ , (b) 1250  $\mu\text{s}$ , 10 bar, (c) 950  $\mu\text{s}$ , 1 bar, (d) 950  $\mu\text{s}$ , 10 bar.

Sequential images for Spray D with C-4 fuel are presented in Figure 10, highlighting the distinct patterns identified in Figure 8 and Figure 9, and offering enhanced insight into the dynamic flow processes occurring within the nozzle. Spray D operates at injection and ambient pressures of 700 bar and 1 bar, respectively, with a pulse duration of 950  $\mu\text{s}$ . Unlike Spray C, the cavitation features within the Spray D nozzle are comparatively stable, with fewer fluctuations observed in the cavitating area and spray angle values. These differences highlight the influence of operating pressures on cavitation dynamics and spray characteristics. Due to the suppression of geometric cavitation, string-type cavitation becomes observable in certain frames, as illustrated in Figure 10. Following the methodology established in the authors' previous works [58],[59] these elongated structures are classified as vortical cavities based on their distinct morphology and position within the nozzle core, away from the wall boundaries. These string structures appear intermittently, causing some variations in the cavitating region within the Spray D nozzle, considerably milder compared to Spray C as presented in the cavitating area (refer to Figure 9c) and spray angle (refer to Figure 12c) distributions for Spray D.



**Figure 10:** Sequential images depicting cavitation structure and spray behaviour for Spray D, with injection and ambient pressures of 700 bar and 1 bar, respectively, with a pulse duration of 950  $\mu$ s, using C-4.

Figure 11 illustrates the distribution of the projected area over time for varying injection durations in Spray D at an ambient pressure of 10 bar for diesel and BCH fuels. As the pulse duration decreases, both the cavitating area and fluctuations increase. Diesel and BCH fuels were chosen from the five fuels examined because diesel is the most commonly used and representative fuel, while BCH demonstrates the most distinct behaviour, making it particularly informative for understanding the effects of injection duration. Both fuels show notable variation over the injection period. BCH exhibits a greater sensitivity to changes in pulse duration, as evidenced by a larger variation in the projected cavitation area, especially in the highly transient early and late injection stages, relative to diesel. This greater variation indicates that BCH experiences more pronounced vortical cavitation effects when the injection duration is altered. However, this variation cannot be discerned for Spray C, as demonstrated in Figure 6. This is expected because vortical cavitation is less pronounced in Spray C as geometric cavitation occupies most of the nozzle.

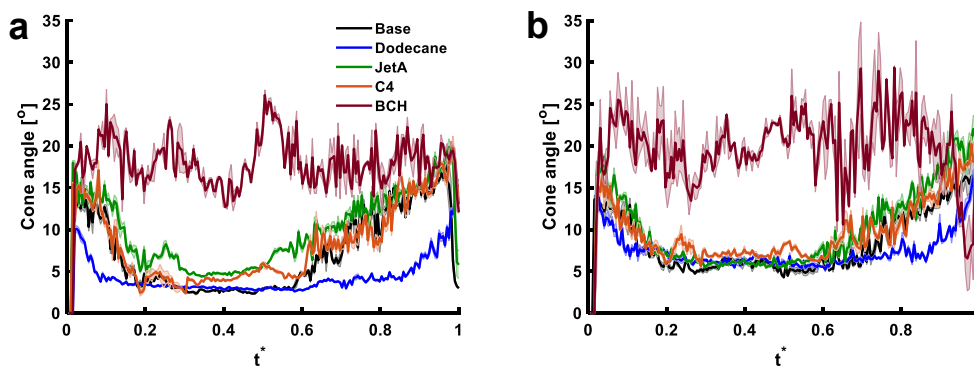


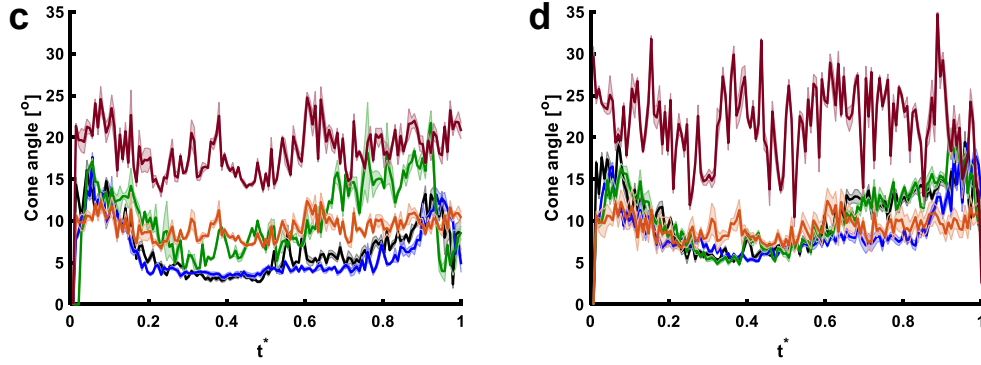
**Figure 11:** The distribution of the projected area with time for varying injection durations in Spray D at 10 Bar ambient pressure for fuels: (a) Diesel, (b) BCH.

Figure 12a and 12b present the relationship between spray cone angle and normalised injection time ( $t^*$ ) for various fuels. Four of the fuels, dodecane, diesel, Jet-A, and C-4, show similar mean values that are relatively close to one another, although BCH stands out with significantly higher mean cone angles. Diesel and dodecane display similar behaviour, with dodecane consistently maintaining a relatively stable and low cone angle throughout the injection process. Diesel, however, shows slightly higher cone angles at both the start and end of the injection process, which can be attributed to its higher cavitation potential, consistent with the behaviour observed in Spray C, as shown in Figure 9. Jet-A and C-4 display wider and more variable spray cone angles throughout the injection period compared to diesel and dodecane. Jet-A, in particular, demonstrates a broader spray cone angle than diesel, which is consistent with findings in the literature [62], largely due to Jet-A's higher evaporation rate and lower viscosity. The similarity observed between C-4, and Jet-A can be primarily attributed to their similar vapour pressures, with their overall fuel properties being closely related, as evidenced by the occurrence of peaks at similar points during the injection.

In contrast, BCH exhibits the greatest variability among the fuels tested, with cone angles consistently exceeding 15 degrees and often reaching up to 30 degrees. This pronounced variability is attributed to BCH's higher viscosity, leading to a greater cavitation tendency reflected in its larger projected cavitation area throughout the injection process. This correlation between high viscosity and increased cavitation in BCH aligns with findings from previous studies. Nouri et al. [63] investigated the effect of viscosity on string (vortex) cavitation in a single-piston ring assembly. They observed that higher viscosity strongly promotes the formation and elongation of string cavities, as it helps preserve the coherent vortex structures. In contrast, lower viscosity accelerates string breakup, causing cavitation length to decrease by up to 35%. Similarly, Li et al. [64] stated that the cavitation area increases for high-viscosity lubricants, while lower viscosity leads to smaller cavitation areas and improved lubrication quality as the internal friction decreases and the lubricant flows more rapidly.

Figure 12c and 12d extend the analysis to a shorter injection pulse duration of 950  $\mu$ s. The trends among the fuels remain largely consistent with those previously discussed; however, the shorter injection duration introduces more pronounced transient effects, resulting in increased average cone angles as the injection becomes more transient, as expected. This increase is anticipated due to the enhanced influence of unsteady flow dynamics associated with rapid needle movements during shorter injections. While the overall spray patterns are similar to those at 1250  $\mu$ s, the reduced duration leads to slightly higher cone angles and increased variability, particularly during the start and end of the injection process.



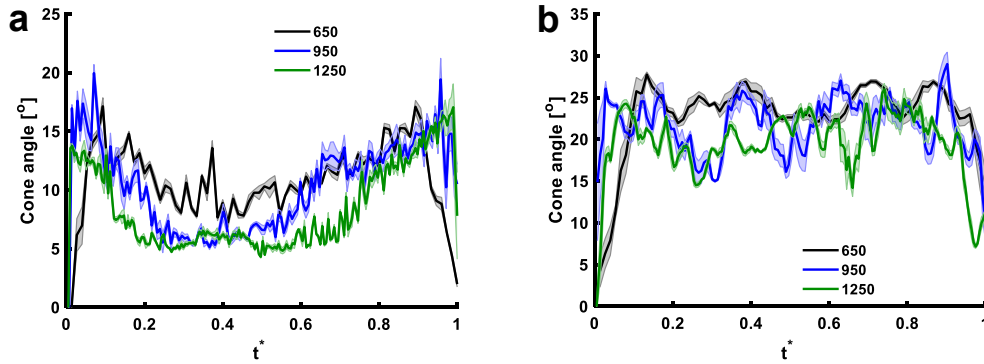


**Figure 12:** Distribution of the spray cone angle over time in Spray D angle for an injection pulse duration of 1250  $\mu\text{s}$  at ambient pressures of (a) 1 bar, (b) 10 bar, (c) 950  $\mu\text{s}$ , 1 bar, (d) 950  $\mu\text{s}$ , 10 bar.

The cone angle displays consistent behaviour across both low and high ambient pressures, with an increase in backpressure correlating to a rise in the average cone angle, as observed in Spray C. Overall, results show a marked increase in cone angle at the start and end of injection for most fuels. Notably, Jet-A and C-4 remain close to each other and exhibit higher cone angles than dodecane and diesel. While diesel angle values occasionally approach those of C-4 near the start and end of the injection, C-4 generally surpasses diesel for most of the injection period. BCH stands out with the largest cone angles reflecting its highest cavitation projected area (refer to Figure 9), owing, to its high viscosity and the prevailing cavitation regime in the Spray D orifice, as explained above.

Although the Spray C and Spray D injectors share similar nominal dimensions, Spray D is a tapered orifice that is meant to suppress cavitation. Considering that vortical cavitation, especially if set in the vicinity of the injector outlet, has a critical influence on the spray cone angle [65],[66] compared to geometric cavitation [18],[67], the cone angle variations in the Spray D injector should be primarily attributed to this regime. In contrast, Spray C experiences both geometric and vortical cavitation, resulting in a greater overall extent. The difference in cavitation regime is postulated as the underlying cause leading to the counter-intuitive variations in spray-cone angle observed for BCH in the two injector outlets. Spray D suppresses geometrical cavitation due to its smooth, tapered orifice geometry, while vortical cavitation is still present near the exit. This contrasts with Spray C, in which both wall-attached and vortical cavitation co-exist and exhibit cavitation with all fuels, leading to consistently larger spray cone angles.

In a similar manner to Figure 11, as a way to illustrate the effect of pulse durations on specific fuels, Figure 13 presents comparative analyses of cone angles for diesel and BCH fuels at each pulse duration spanning from 650-1250  $\mu\text{s}$ . As can be seen, a longer pulsation duration leads to stabler sprays in the quasi-steady injection period,  $0.2 < t^* < 0.8$  for both fuels, with relatively small cone angles of around  $7^\circ$  for diesel and about  $22^\circ$  for BCH. By contrast, for a pulse duration of 650  $\mu\text{s}$ , the spray topology becomes more fluctuating, and the cone angle reaches higher values during the steady-injection phase, up to  $13.5^\circ$  for diesel and  $27^\circ$  for BCH.



**Figure 13:** Spray D cone-angle distribution of (a) Diesel and (b) BCH for different pulse durations at ambient of 10 bar. For graph (b), a 3-point moving average was applied to smooth the data and improve clarity.

#### 4. Conclusion

In-nozzle flow dynamics and near-nozzle spray characteristics were analysed using high-speed DBI extinction imaging and two injector geometries, a straight-orifice (Spray C) and a converging-orifice (Spray D), under varying injection durations for multiple fuels relevant to sustainable aviation, including conventional diesel, Jet-A, two SAF samples, BCH and C-4, and a surrogate, dodecane. The comparative analysis revealed distinct cavitation and spray behaviours among the fuels, with BCH demonstrating particularly notable characteristics under Spray D conditions. Jet-A and C-4 exhibited similar cavitation and spray angle characteristics, reflecting their close fuel properties. Diesel and dodecane demonstrated the most stable cavitation and spray behaviour, showing relatively fewer fluctuations in projected vapour area and spray angles. In Spray D, BCH shows the highest level of cavitation, primarily attributed to the significant formation of cavitation linked to its higher viscosity. Conversely, Spray C, due to its straight design, does not suppress cavitation, resulting in high levels of geometrical cavitation across all fuels. Consequently, BCH exhibits only moderate cavitation in this configuration, as reflected in the spray cone angle measurements, where BCH displays only average angles in Spray C compared to the other fuels studied.

The injection pulse duration also had a strong impact on cavitation and spray dynamics. Shorter injection pulses led to more unsteady flows and intensified cavitation, resulting in greater fluctuations in the spray cone angle. Longer injection pulses allowed for higher needle lifts, stabilising the flow, reducing cavitation, and creating more consistent spray patterns. To the authors' best knowledge, this is the first experimental evaluation of the cavitation and spray behaviour of highly promising sustainable aviation fuels and offers a new database that will allow model validation and further research, enabling wider adoption for the decarbonisation of the aviation sector.

#### Supporting Information

**Supplementary Movie 1:** High-speed DBI video of the full injection event for Spray C injector at 500 bar injection and 10 bar ambient pressure using dodecane, with a pulse duration of 1250  $\mu\text{s}$ .

**Supplementary Movie 2:** High-speed DBI video of the full injection event for Spray D injector at 700 bar injection and 10 bar ambient pressure using dodecane, with a pulse duration of 1250  $\mu\text{s}$ .

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