

Experimental Characterization of SAF using Laser Diffraction

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ABSTRACT

The development of Sustainable Aviation Fuels (SAF) is becoming increasingly important in efforts to reduce the environmental impact of aviation while preserving compatibility with existing propulsion systems. The droplet size distribution produced by the atomization process is one of the parameters that govern fuel combustion. The quality of atomization directly affects evaporation, mixing, and the following combustion behaviour. This work presents an experimental characterization of SAF sprays using laser diffraction under atmospheric conditions and non-reacting environment. The objects of investigation are SAF samples with different technological purity levels later compared with a domestic heating fuel. Detailed physical properties and chemical composition of the SAF cannot be disclosed due to confidentiality restrictions. The fuels are therefore identified solely by their technological purity level, and the study focuses mainly on the experimental methodology and on assessing whether purity variations influence the droplet sizes in the resulting spray. The liquid phase was atomized using an air-assisted nozzle mounted on a dedicated test bench equipped with independent air and liquid supply lines, both monitored by mass flow sensors. The system was remotely controlled through a custom LabVIEW interface, which allows systematic variation of the operating conditions. Droplet size measurements were performed using a Helos/Vario KR laser diffraction system with two optical configurations covering the ranges 0.1–175 μm and 1–1750 μm . Operating points were established by increasing the air to liquid ratio. In the present setup, the experimental results indicate that increasing the air to liquid ratio enhances the production of smaller droplets; however, influence of fuel purity on atomization behaviour was observed. These results suggest that conventional atomization systems may remain compatible with SAF, at least under the atmospheric conditions considered in this study.

1. Introduction

The need to reduce the environmental impact of aviation has increased interest in alternative fuels that can limit emissions while remaining compatible with existing propulsion systems. In this context, Sustainable Aviation Fuels (SAF) are being introduced as substitutes for conventional jet

fuels, but their use requires a clear characterization of their behaviour under conditions relevant to combustion.

SAF can show variations in physical and chemical properties depending on production route and level of refinement (Oldani et al., 2022). These variations may affect spray formation, evaporation, and mixing, which are directly linked to combustion performance. It is important to verify whether conventional atomization techniques can generate homogeneous sprays that enable efficient combustion without leaving excessive unburned material (S. Ferráo et al., 2021) (Zhang et al., 2025). In particular, droplet size distribution is an important parameter for describing atomization, since it influences liquid breakup, interfacial area, and the evolution of the spray (Lefebvre & McDonell, 2017). For this reason, experimental data on SAF atomization are needed to assess their use in conventional injection device.

This work reports measurements of droplet size distributions for different SAF samples obtained by laser diffraction. The sprays are generated by air-assisted injector which discharge under atmospheric, inert conditions, in order to isolate the atomization process from additional effects due to pressure, temperature, and chemical reactions. The analysis focuses on the influence of fuel purity on the resulting droplet size statistics. A subsequent discussion is carried out, derived from laser results, to assess the combustion behaviour based on a statistic analysis.

The aim is to determine whether variations in SAF technological level lead to measurable changes in the atomized spray. The results provide a first indication of the compatibility of the tested fuels with the injector considered, and the limitations of the current setup are discussed, in particular the absence of pressurized and reacting conditions. Future work will extend the measurements to more representative environments and will examine parameters that are more directly related to combustion performance.

2. Experimental setup

The experimental campaign was conducted on a spray test bench designed to provide independent control of the air and liquid supply lines and to ensure repeatable operating conditions (Di Matteo et al., 2019). The facility was originally developed to study the atomization of aircraft engine oil and has been adapted to test SAF under controlled laboratory conditions, with particular attention to the consistency of the injection parameters and to droplet size measurements by laser diffraction.

The air supply line consists on a rotary screw compressor, equipped with dryers and filters. The line includes then a pressure regulator and a mass flow sensor, which allowed continuous monitoring and setting of the air flow rate during the tests. The fuel circuit is arranged as an independent line with a pump and a mass flow sensor for the liquid phase, so that air and liquid flows could be adjusted separately. The configuration made it possible to impose well defined conditions at the

injector inlet and to analyse the spray response as a function of the selected air to fuel ratio (ALR).

Sprays are generated by a custom injector, which produces a solid cone spray pattern with fine droplets at relatively low air pressure. The detailed internal geometry is proprietary and not disclosed by the manufacturer, so the analysis is based on the operating conditions and measured spray characteristics.

The facility is operated remotely through a LabVIEW custom program developed for the setup. The control software was used to set the main operating parameters of the bench and to monitor the evolution of the test conditions during the measurements, which helped to improve repeatability and to perform systematic variations of the operating points.

Droplet size distributions are measured using a Helos/Vario KR laser diffraction system. The instrument is equipped with two optical configurations, covering the ranges $0.1/0.9\text{--}175\text{ }\mu\text{m}$ and $1/9\text{--}1750\text{ }\mu\text{m}$, so that the measurement domain could be adapted to the spray under investigation and provide adequate coverage of the observed droplet sizes.

The optical system is integrated into the spray bench to allow measurements under stable and repeatable injection conditions. Fig. 1 shows the setup during a measurement.



Figure 1. Test bench setup on the measurement frame.

The experiments are carried out at atmospheric pressure and in a non-reacting environment. This configuration was chosen to isolate the atomization process from additional effects related to elevated chamber pressure, temperature, and combustion, and to provide a controlled basis for com-

paring the spray characteristics of the tested samples.

2.1. SAF

In accordance with European regulations (European Commission, 2023), fuels meeting certain criteria based on their production and storage route are classified as SAF. Through the production path the intermediate product may have different level of technological purity. Samples of the intermediate product were included in the campaign to assess the influence of fuel purity on spray atomization. The detailed physical properties and chemical composition of the samples are not reported here because they are not authorized for publication. The fuels are therefore identified only by their purity level, and the investigation concentrates on the experimental methodology and on evaluating whether fuel purity affects the atomization process. Tab. 1 summarizes the purity levels of the fuels.

Table 1. Technological purity level of the tested fuels.

	Heating Fuel	SAF 1	SAF 2	SAF 3
Purity level	-	Low	Medium	high

The work focuses on the atomization response of the fuels rather than on a detailed chemical analysis. In this framework, the samples are treated as separate operating cases, and their behaviour is compared through the resulting particle size distributions under the same injection conditions.

2.2. Test methodology

The experimental campaign consists of testing the samples by systematically varying the air and fuel flow rates over a set of operating conditions. Tab 2 shows the test matrix. The combinations of air and liquid flow rates are chosen to observe the spray response over a representative range of injector operating points. The heating fuel (HF) of comparison and the SAF with the highest level of purity are selected for extensive characterization test, while the two intermediate SAF products are tested only for two operating conditions corresponding to the operative work environment.

For each operating point, the spray reach steady conditions before data acquisition to reduce the effect of transient fluctuations in the droplet size distribution (Ma et al., 2010). Laser diffraction measurements were recorded over a time window of 5 s. Each test is repeated 3 times and 4 acquisitions are carried out on every repetition in order to improve repeatability. Between each test the lenses of the laser were cleaned to reduce the lenses' pollution index while measuring.

The results presented are based on average values obtained from all acquisitions corresponding to a given operating point. This processing strategy was adopted to provide a representative descrip-

Table 2. Test Matrix: X: the test is done for the specified ALR; -: test is missing for the specific ALR

	HF	SAF 1	SAF 2	SAF 3
ALR = 0.064	x	-	-	x
ALR = 0.08	x	-	-	x
ALR = 0.09	x	x	x	x
ALR = 0.107	x	-	-	x
ALR = 0.134	x	-	-	x
ALR = 0.16	x	x	x	x
ALR = 0.2	-	-	-	x
ALR = 0.332	x	-	-	x
ALR = 0.401	-	-	-	x
ALR = 0.48	-	-	-	x

tion of the spray for each test case and to limit the influence of variability of single shot, so that all reported particle size metrics refer to mean values unless stated otherwise.

The same procedure is applied to all samples and operating conditions. In this way, differences in spray behaviour can be related to the operating point and to effects dependent from the fuel rather than to changes in the measurement strategy.

2.3. Report metrics and data reduction

The droplet size data obtained from the laser diffraction measurements are the parameters used to describe the spray. The particle size distribution was characterized using statistical descriptors in spray analysis. In particular, the reported quantities include x_{10} , x_{32} (Sauter Mean Diameter), x_{50} , and x_{90} , which provide information on the lower tail, characteristic size, surface area weighted mean diameter, and upper tail of the distribution, respectively. These parameters describe changes in both the tendency and the spread of the droplet population.

In addition to the characteristic diameters, the width of the distribution was evaluated through the span (n), defined as $(x_{90} - x_{10})/x_{50}$. This metric assesses the degree of homogeneity of the spray and identifies variations in atomization quality between different test conditions. A smaller span indicates a narrower distribution and therefore a more uniform spray, whereas larger values correspond to broader droplet populations.

Data Reduction

However, the most important aspect remains the impact on combustion. Therefore, selected metrics were derived to assess spray behavior in a combustion chamber. The combustion feature metrics were derived from laser diffraction particle size distribution (PSD) data using screening level analytical models. The model assumes a simplified combustion chamber operating at 900 K and 1 MPa. The primary zone reference length is 0.05 m, and the distance to the wall is 0.02 m. Nevertheless, these screening level models enable consistent comparison of spray performance and link laser diffraction data to combustion relevant metrics. They are physically interpretable, but do not replace reacting CFD or resolved droplet modeling.

Evaporation times for representative diameters $D \in \{x_{10}, x_{32}, x_{50}, x_{90}\}$ are estimated using the simplified d^2 law (Lefebvre & Ballal, 2010):

$$t_{\text{ev}}(D) = \frac{D^2}{K_{\text{eff}}} \quad (1)$$

where D is in meters and K_{eff} is an effective evaporation constant (Dalla Barba et al., 2021). From the evaporation time, the axial evaporation length can be estimated by considering the droplet path as the evaporation time multiplied by the droplet velocity u_d assuming the droplets follow the mean jet centerline trajectory:

$$L_{\text{ev}}(D) = u_d t_{\text{ev}}(D) = u_d \frac{D^2}{K_{\text{eff}}} \quad (2)$$

In the same way, the residence time in the primary zone can be estimated:

$$t_{\text{res}} = \frac{L_p}{u_d} \quad (3)$$

where L_p is the characteristic length of the primary zone.

The evaporated fraction at time t for a droplet with initial diameter D_0 is derived from the classical d^2 law for droplet evaporation (Lefebvre & Ballal, 2010). The d^2 law states that the droplet diameter squared decreases linearly with time::

$$d(t)^2 = (D_0^2 - K_{\text{eff}}t) \quad (4)$$

Assuming the droplet is spherical with constant density, its mass is proportional to droplet mass which is proportional to d^3 , the evaporated fraction is obtained as:

$$f_{\text{ev}}(D, t) = 1 - \left(\frac{(D^2 - K_{\text{eff}}t)}{D^2} \right)^{3/2} \quad (5)$$

2.4. Laser diffraction principles

Laser diffraction (LD) was selected as the diagnostic technique for droplet sizing because it provides a non intrusive and statistically robust measurement of particle size distributions. LD offers a broad particle size spectrum, allowing for the assessment of a wide range of operating conditions. The LD technique was initially developed by Swithenbank (Swithenbank et al., 1976). The LD technique is quick to perform and can be easily implemented. In terms of accuracy, the error associated with characteristic diameter measurements, e.g., Sauter Mean Diameter (SMD) and Rosin-Rammler (RR), is estimated to be around 2%. The operating principles of LD are illustrated in Fig. 2. Particles are exposed to a parallel laser beam, emitted by the laser light source.

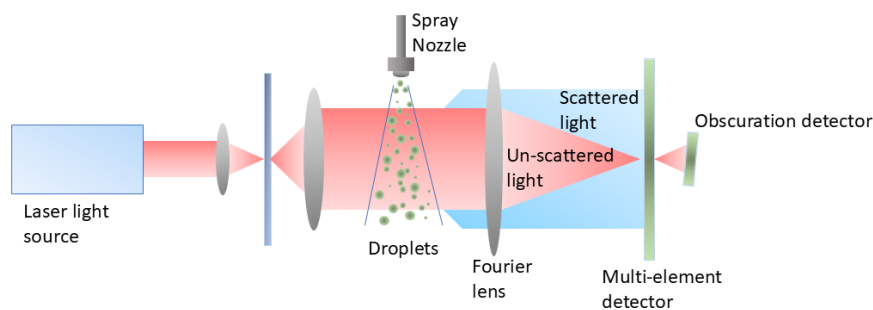


Figure 2. Laser diffraction working principles.

The method relies on the fact that light scattered by a spray depends on the size of the droplets crossing the measurement volume. Smaller droplets produce a broader angular scattering pattern, whereas larger droplets generate a more concentrated response at lower scattering angles. Light scattered by particles of the same diameter produces the same diffraction angle and remains parallel. The Fourier lens, illuminated by the scattered light, focuses all parallel beams onto a specific point on the multi element detector that measure the intensity of the scattered light. By analyzing the angular distribution of the scattered intensity, the corresponding size distribution can be reconstructed. The unscattered light is measured by an obscuration detector. The particle pattern is formed by the combination of points corresponding to light scattered at different angles (de Boer et al., 1987).

The diffraction of laser light is mathematically described by the Fraunhofer or Lorentz-Mie theory (Steimes et al., 2012). The technique is particularly suitable for spray characterization because

it allows the measurement of a large number of droplets over a short acquisition time, does not require optical access to individual particles and requires only a small sample size to describe a continuous distribution. Despite its advantages related to simplicity, LD also has drawbacks. In particular:

- Mathematical prediction assumes the sphericity of all droplets. LD tends to overestimate the diameter of non-spherical particles (Eshel et al., 2004).
- Multiple scattering effects occur when the particle concentration is too high. Laser power saturation can lead to the possibility that the light beam, scattered by a particle, undergoes secondary interactions, or even more, with additional particles present in the sample before reaching the detector (Black et al., 1996).
- The optical limit determines the lower size threshold for particles (Black et al., 1996). Particles below $0.1\ \mu\text{m}$ are not into the measurement range of the laser and require other technologies for detection.

The laser used in this study is a Sympatec Helos Vario/KR. It is equipped with two lenses to cover the expected droplet size range of the investigated sprays. The equipped optical arrangements, covering both the fine and coarse fractions of the distribution, measures droplet sizes from $0.5\text{--}0.9$ to $175\ \mu\text{m}$ (R3 lens) and from $0.5\text{--}9$ to $1750\ \mu\text{m}$ (R6 lens). The first number in the size range indicates that the system can identify droplets with a diameter of $0.5\ \mu\text{m}$, but it cannot provide a distribution in the range of $0.5\text{--}0.9\ \mu\text{m}$ for the R3 lens and in the range of $0.5\text{--}9.0\ \mu\text{m}$ for the R6 lens. All droplets inside these ranges will be counted as an average diameter. The R3 and R6 lenses have beam diameters of 13 mm and 26 mm, respectively. The working distance between the flow and the multi-element detector is a maximum of 96 mm (R3) and 566 mm (R6). The emitter and receiver can be positioned up to 2.0 m apart. The system calculates the PSD using either Fraunhofer or Lorentz-Mie methodologies, taking into account multiple scattering effects.

The measured distribution reflects the overall atomization state rather than the behaviour of a single droplet or a localized region of the spray. For comparative studies such as the present one, this is particularly useful, since the objective is to identify systematic changes in spray development across different fuels and operating points.

3. Results

The results reported are from the operating conditions considered in the experimental matrix. The analysis is focused on the spray metrics extracted from the laser diffraction measurements, with the objective of identifying possible variations associated with fuel purity and injection conditions.

The first set of results examines the effect of the imposed ALR on the measured particle size distributions. For each test condition, the averaged laser diffraction data are used to compare the evolution of the spray metrics and to identify the extent to which the atomization process is affected by the selected operating point.

3.1. Influence of purity level

The different intermediate products and the final SAF product were tested and compared with a standard heating fuel. Fig. 3 shows the evolution of the Sauter Mean Diameter, the diameter of a sphere with the same volume-to-surface-area ratio as the droplet ensemble, in function of ALR. As expected, increasing ALR leads to progressively finer droplet distributions. This is evident from the decrease in the characteristic diameter representing the distribution.

The effect of sample purity is also of interest. Statistically, the standard heating fuel generally produces a finer distribution, while the SAF samples do not exhibit significant differences among themselves under the tested operating conditions. A more pronounced difference between the heating fuel and the final SAF product is observed at very low ALR.

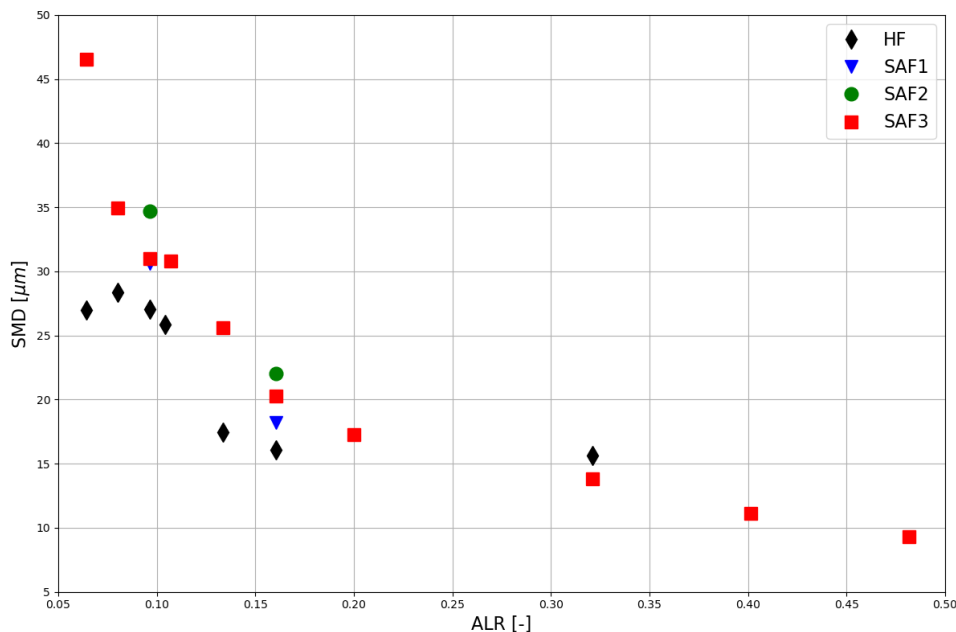


Figure 3. SMD in function of ALR.

In analyzing the other diameters used to characterize the distribution, the focus is limited to the operating conditions. Fig. 4 shows the tenth percentile, defined as the equivalent diameter at which 10% of the cumulative volume distribution consists of smaller particles. Also in this case, the samples do not show a significant difference. The standard heating fuel stands out, as its values decrease more sharply with increasing ALR compared to the SAF samples.

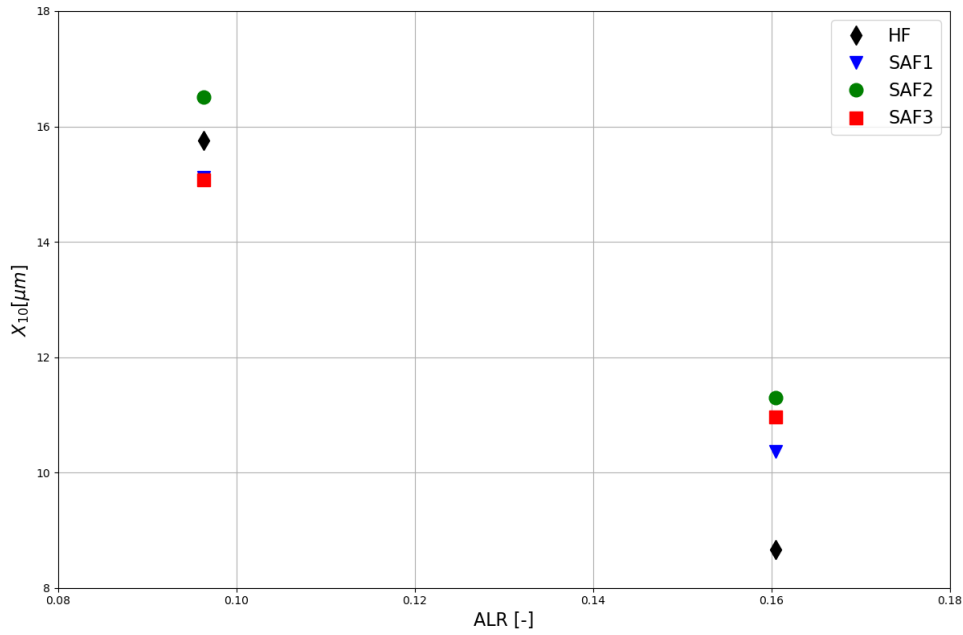


Figure 4. x_{10} in function of ALR.

Fig. 5 shows the median value of the distribution, defined as the equivalent diameter for which 50% of the cumulative volume distribution consists of smaller particles and the remaining 50% of larger particles. In this case, a larger deviation among the measured samples is observed. The sample with intermediate purity consistently exhibits a higher median value than the others. The difference decreases as ALR increases.

This behavior, which becomes less evident at higher ALR, may be attributed to variations in physical properties such as liquid surface tension during the production process. At the same time, the ambient conditions are not temperature controlled, and even small temperature changes can lead to variations in fluid properties during testing. To address this, stricter monitoring of the fluid conditions would be required.

Fig. 6 shows the equivalent diameter at which 90% of the cumulative volume distribution consists of smaller particles. In this comparison, the two higher-purity samples consistently exhibit larger values. At higher ALR, they even reach values up to an order of magnitude greater than those of the heating fuel and the least pure sample.

This difference can be explained by examining Fig. 7, which shows both the cumulative and density distributions of the two samples. Beyond a certain diameter, the cumulative distributions for both exhibit a plateau before increasing again. This is characteristic of a distribution with a bimodal structure, as also indicated by the density distribution.

Such behavior typically suggests the presence of two droplet populations generated by different mechanisms, indicating that a single atomization regime is not present. This may be related to

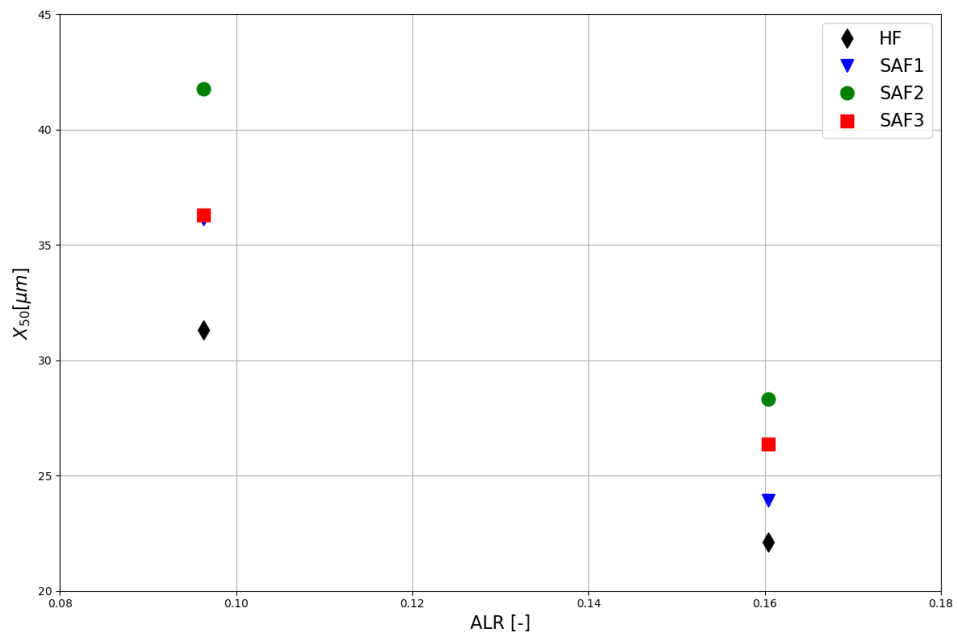


Figure 5. x_{50} in function of ALR.

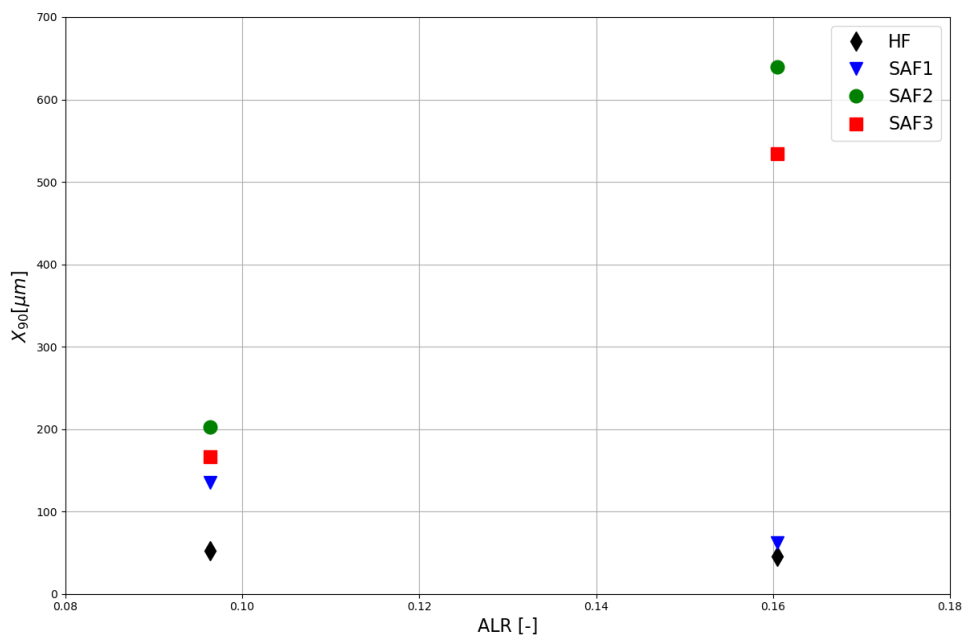


Figure 6. x_{90} in function of ALR.

cavitation effects inside the injector or to instabilities associated with the flow regime and fluid properties. A more detailed analysis of the physical and chemical properties of the higher purity sprays, as well as the internal nozzle conditions, would be required for a more thorough assessment.

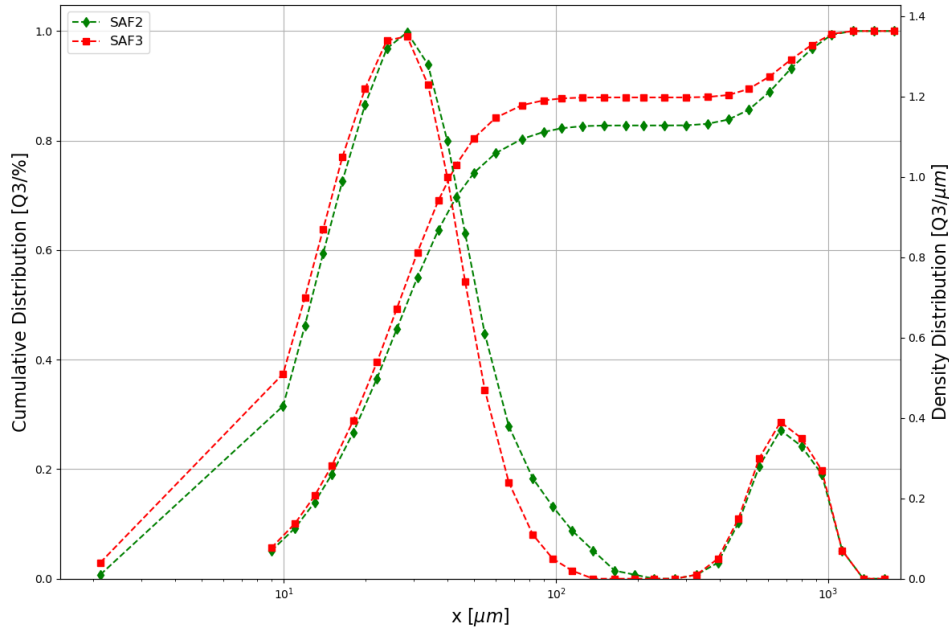


Figure 7. Cumulative and density distribution of particles in the measured distribution at ALR=0.09 for SAF2 and SAF3.

When differences are observed, they are more apparent in the spread of the distribution than in the mean characteristic diameter. This indicates that changes in fuel purity and operating conditions may influence spray uniformity more than the central size of the droplets. Such a result is relevant from a combustion standpoint, since broader distributions can lead to less homogeneous evaporation behaviour and a less uniform spray field.

3.2. Combustion statistical analysis

After analyzing the distribution metrics, the focus shifts to a statistical assessment of the combustion process. The analysis is limited to evaporation times, which are linked to the characteristic droplet size, namely the SMD, and to the fraction of droplets evaporated in the primary zone.

Fig. 8 shows the evaporation times as a function of ALR. Within this simplified framework, evaporation times scale with the characteristic droplet size in the distribution. The results indicate values ranging from approximately 0.9 ms up to about 1.5 ms for the coarsest distribution at lower ALR. This range decreases significantly as atomization becomes more effective.

Fig. 9 shows the fraction of droplets that evaporate in the primary zone of the combustion chamber.

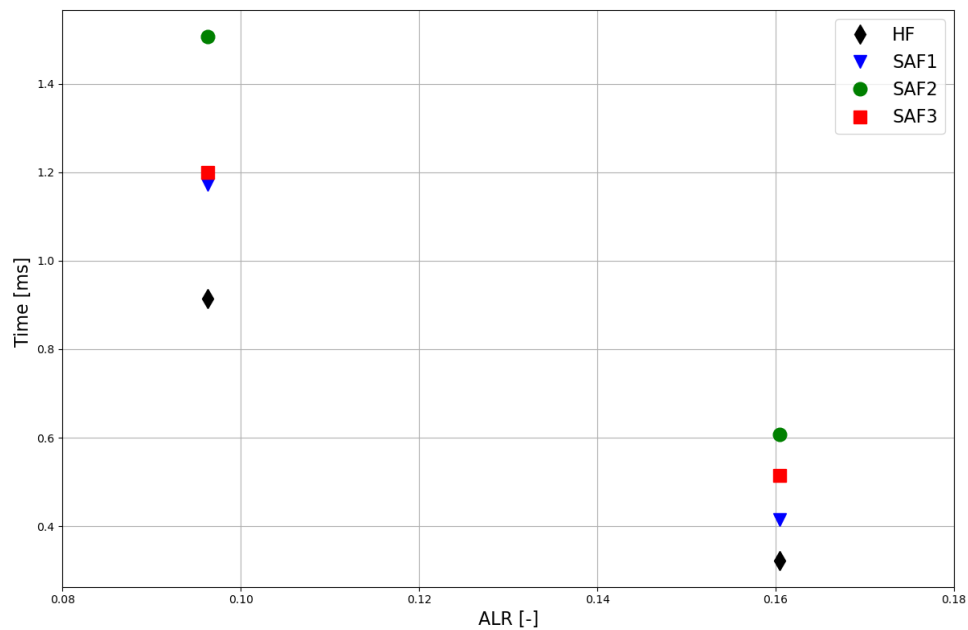


Figure 8. Evaporation time calculated for the characteristic diameters of the distribution in function of the ALR

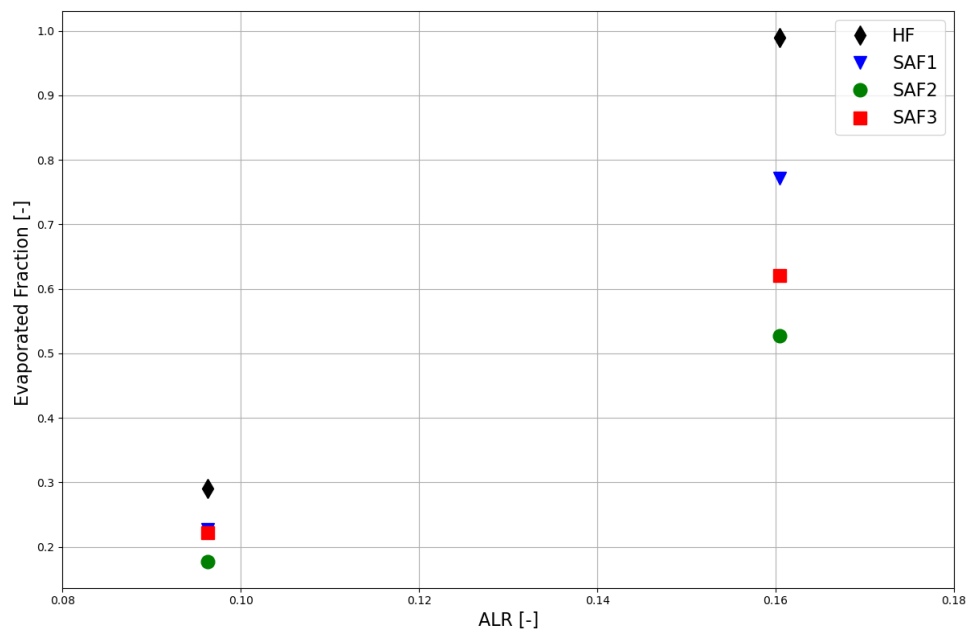


Figure 9. Evaporated fraction calculated for the characteristic diameters of the distribution in function of the ALR

Coarser distributions exhibit a relatively low evaporation fraction, indicating a higher likelihood of unburned residues at the end of the process. As ALR increases, this fraction also increases, approaching near-complete evaporation for the heating fuel. The SAF samples likewise exceed 50% evaporation under these conditions.

These analyses should be interpreted with caution, as they rely on a simplified approach and several assumptions. Nevertheless, they can provide useful insight for preliminary combustion chamber design and operating condition for these type of fuels.

4. Conclusions

An experimental investigation of the atomization behaviour of SAF samples is carried out by means of laser diffraction under non-reacting atmospheric conditions. The study focuses on the particle size metrics obtained with a custom injector for different operating points. The objective is to assess whether variations in technological purity of produced SAF leads to measurable changes in spray characteristics. The samples are confronted with a standard heating fuel with similar characteristics.

The results indicate that the tested samples produce droplet size distributions with broadly similar characteristic diameters over the range of conditions considered. A larger difference is observed for x_{90} ; however, many external factors may affect this parameter, and a more detailed investigation should be devoted to this aspect. Although some variations were observed as a function of the imposed air to liquid ratio, no systematic change in atomization behavior could be clearly attributed to fuel purity alone. This behavior suggests that, under the present test conditions, the injector response is governed primarily by the imposed flow rates. The interpretation of these findings should remain consistent with the scope of the experimental setup. The reported trends should be considered representative of the atomization stage only. Further work under pressurized and reacting conditions will be necessary to determine whether the same behavior persists in environments more representative of practical combustion systems.

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Nomenclature

ALR	Air to Liquid Ratio
HF	Heating Fuel
PSD	Particle Size Distribution
SAF	Sustainable Aviation Fuel
SMD	Sauter Mean Diameter [μm]
D	Diameter [m]
f_{ev}	Evaporation fraction [-]
K_{eff}	Evaporation constant [m^2/s]
L_{ev}	Evaporation length [mm]
t	Time [s]
t_{ev}	Evaporation time [ms]
t_{res}	Residential time [ms]
u_d	Droplet velocity [m/s]
x	Diameter [μm]
x_{10}	10th percentile of PSD [μm]
x_{50}	50th percentile of PSD or mean diameter [μm]
x_{90}	90th percentile of PSD [μm]

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