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Curvature-surface analysis to characterize the early stage of the atomization process of the pressure swirl injector

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Abstract

This work aims to characterize the spray in near-field regions up to droplet formation. For this purpose several approaches both numeric and experimental are analysed. The analysis of curvature distribution allowing to characterize the spray before the final formation of droplet was first applied by Palanti (Palanti et al. 2022) within the context of Computational Fluid Dynamics (CFD) using the Volume of Fluid (VOF) method to model the multiphase flow. In the present study, this analysis is applied to the n-heptane hollow cone spray from numerical simulations and experimental images based on two-photon laser-induced fluorescence (2p-LIF) technique. It uses the curvature and surface interface between liquid and gas to achieve droplet size distribution (DSD) despite not having a fully formed spray. In other words, it allows characterizing the spray from nonspherical liquid structures. In addition to the droplet size, the size-velocity distribution is also estimated from an adapted technique (Ferrando et al. 2021). The results obtained from the curvature-surface analysis are compared with those obtained from the Phase Doppler Anemometry (PDA) measurements. The numerically obtained DSD is in good agreement with PDA measurements. The numerical results showed a slightly higher droplet velocity than the measured values. Further, the DSD obtained from 2p-LIF curvature-surface analysis is also compared with numerical and PDA results.

Introduction

Droplet size has a significant impact on reacting and non-reacting processes. A sequence of complex physical phenomena that breaks the continuous liquid structure results in a wide range of droplets. They evolve in space and time in the near field regions, where such primary breakup occurs. This early stage of the atomization process significantly impacts the final spray. Thus, characterizing the spray in the near-field zones could be used to improve the accuracy of reacting simulations and our understanding of the spray evolution. In the present work, the n-heptane hollow cone spray at its early stage of atomization process is characterized using curvature-surface analysis.

There are many techniques to image optically dense regions of spray (Linne 2013). However, it is difficult to describe the entire spray using a single method. The choice of diagnostic technique is based on the region under investigation. Here, 2p-LIF technique is used to capture dense regions to reduce multi scattering effect. An analysis technique of the curvature-surface interface (Palanti et al. 2022) is able to characterize the spray in near-field regions. This work aims to adapt this analysis from numerics to experiments and compare their results.

Experimental Methods

Since the primary breakup of n-heptane hollow cone spray took place in the first 1.5 mm, the experiments were begun with microscopic shadowgraphy. The near injector spray was captured using a microscope (LDM, QM-100, Questar) with a CMOS camera (1280 × 800 pixel² resolution, Phantom V2512) was used (Durst 2018).

The microscopic shadowgraphy provided the overall spray topology. However, it could not deliver clear insights into near-field regions because of line-of-sight imaging. Hence, the current analysis employed two-photon laser-induced fluorescent (2p-LIF) technique to characterize the primary atomization (Berrocal 2018) of n-heptane spray. A schematic of the 2p-LIF arrangement is shown in Fig. 1. A more detailed description of the experiments can be consulted in (Vegad et al. 2022).

For the same experimental arrangement and flow conditions, a two-color phase Doppler anemometry (PDA) system (Dantec make) was used to measure droplet size and velocity at near field locations.

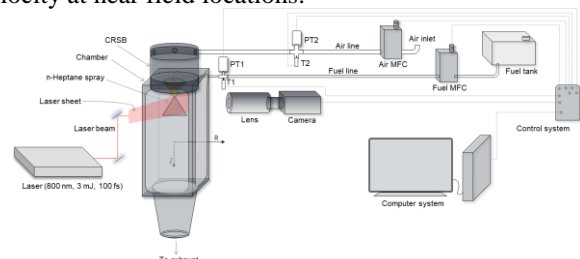


Figure 1: Schematic of 2p-LIF experimental setup.

Numerical Methods

The modelling of the simplex swirl atomizer studied is reported in (Ferrando et al. 2021, Ferrando et al. 2022). The OpenFOAM v6 toolbox was used and in particular the incompressible multiphase solver, *interFoam*. Three transport equations are solved: the continuity equation, the momentum transport equation and the liquid volume fraction (α) transport equation. Knowing the α field, the curvature (κ) and the surface interface density (Σ) fields are derived as:

$$\kappa = \nabla \cdot \left(\frac{\nabla \alpha}{|\nabla \alpha|} \right) \quad (1)$$

$$\Sigma = \nabla \alpha \quad (2)$$

where, Σ represents the surface interface by total volume.

Thus, the total surface in function of the curvature ($S(\kappa)$) is calculated. From this parameter, the DSD is extracted and also the velocity of the droplets (Palanti et al. 2022, Ferrando et al. 2021). For this particular injector, the DSD and the Sauter Mean Diameter (SMD) obtained from CFD analysis matched with PDA data from experiments (Ferrando 2022 et al.) as is shown in Fig 3.

Results and Discussion

Figure 2 shows a threshold image obtained from 2p-LIF technique. The white and black colors represent liquid and gas, respectively. The interface is represented with a grey scale. A correlation can be done with the α field from the VOF method. Considering 1 for white (liquid) and 0 for black (gas). Then, Eq. (1) and Eq. (2) can be applied to obtain the curvature and the surface interface density. The curvature derived from the 2p-LIF analysis is represented on the right in Fig. 2.

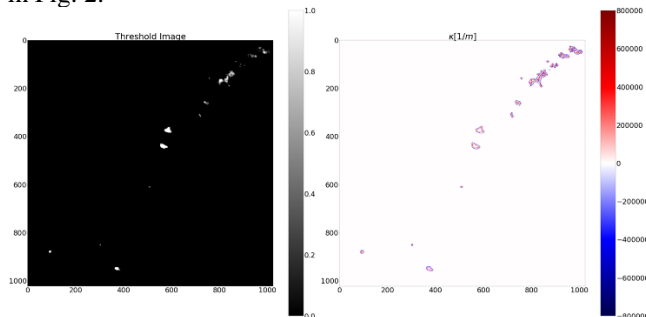


Figure 2: Left: 2p-LIF image. Right: Curvature κ [1/m].

The DSD obtained from experimental measurements (PDA) and CFD simulation are represented Fig. 3. The red line DSD obtained from experiments using PDA at 3mm from the nozzle. This point was the nearest point to the orifice with over 90% of validation. Both distributions have a good agreement between them.

Conclusion

The DSD and mean droplet diameter (D_{10}) obtained from the curvature-surface analysis of numerical simulations are in close agreement with the PDA measurements at $Z = 3$ mm axial distance. Further, these numerically obtained droplet statistics are also in the same order of magnitude as those

determined from the 2p-LIF analysis. It is to be concluded that the curvature-surface methodology proposed in this work is able to provide the droplet information from the initial spray.

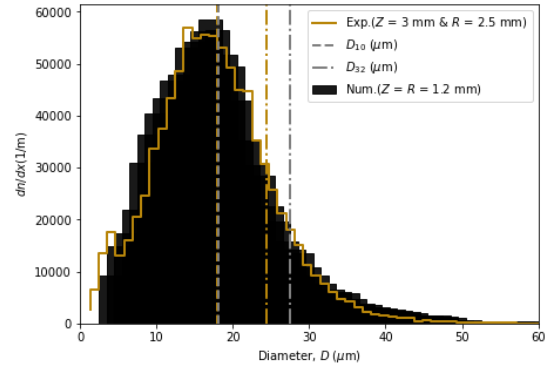


Figure 3: On black: DSD from CFD. On golden line: DSD from PDA.

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