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Local characteristics of fragments in atomizing sprays

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ABSTRACT

Dual-angle particle tracking velocimetry (PTV) developed previously by the authors Pham et al. (2017) has been extended in this study to simultaneously measure volume and velocity of both irregular and sub-ranged spherical fragments generated in the near-field of atomizing sprays, enabling measurements of local Weber number. Dual-angle PTV is an imaging based technique where fragment morphologies are captured using two cameras oriented at 90 degrees to each other. Both cameras operate under PIV (particle imaging velocimetry) mode to enable tracking of fragment locations. In this contribution, fragments are sub-ranged, depending on their size, into 3 different groups: larger fragments (d10 > 150 μm), medium fragments (150 μm > d10 > 15 μm) and small droplets (d10 < 15 μm). The dual-angle PTV technique is used to track the larger fragments only given the difficulty in tracking the medium and small counterparts between two viewing angles due to spray dispersion. The medium and small drops, being ellipsoidal-like shapes, are imaged with a single-view under PIV mode. Combining the dual-angle PTV (3D) and single-view processing (2D) approach has enabled one of the first direct measurements of the local Weber number of arbitrarily shaped fragments. The results and the associated analysis suggest that larger fragments in the near-field zone generally do not deviate significantly from a nominal square root of local Weber number of 0.8. This is in direct agreement with the Direct Numerical Simulations (DNS) of Shinjo and Umemura (2010) and the experiments by Sallam et al. (2002) which employ pressure atomization. Using local Weber numbers has generally been absent and the results here shed more light into air-blast atomization as well as standard pressure atomization, where shear is relevant.

1. Introduction

Primary atomization of a liquid jet to form fragments and subsequently breakup into smaller filaments (secondary breakup) is a critical part of the initial mixing and vapour preparation that strongly dictates the spray structure and hence the performance of practical combustors. In internal combustion (IC) engines, for example, the size and distribution of the droplets generated downstream of the fuel injector heavily affect engine combustion and emission characteristics [4,5]. The initial mode of atomization of the liquid jet, which generates fragments near to the nozzle, is critical. Therefore, controlling the length of the primary atomization zone accurately, and predicting downstream features of the spray such as droplet size and evaporation rate is an overarching goal of fuel injector design. To date, knowledge of the specific mechanisms of primary and secondary atomization are still limited albeit with a consensus that both Rayleigh-Taylor and Kelvin-Helmholtz instabilities are important drivers. However, even accurate estimations of the relevant wavelengths cannot universally recover the observed droplet size [6,7]. The influence of local aerodynamic conditions in the atomization zone (e.g. local slip velocity, volume flux, and characteristic size) on fragment breakup evolution is not well understood due to difficulties in measuring both the gas phase and dispersed phase simultaneously in this region. In the primary atomization zones, global parameters such as nozzle diameters and bulk velocities are employed in dimensionless numbers such as the Weber number [8] even though it is local parameters of a given fragment that will drive the breakup mechanism. Secondary breakup studies are commonly based on spherical breakup models [6,7] despite it being well known that during atomization, fragments with irregular shapes are very common [9–12].

This paper is part of a larger effort aimed at providing a more in-depth understanding of atomization through more detailed measurements of the local aerodynamic conditions of liquid fragments in the near-field. A newly developed optical diagnostic technique is used to directly measure the local (rather than a global) Weber number as this may shed more light into the breakup mechanisms of irregular liquid shapes. The Weber number (We), defined as the ratio of the inertial force to the surface tension force acting on a particular fluid shape, is a well-known dimensionless parameter to describe atomization and is typically calculated as follows:

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$$We = \frac{\rho \cdot U_s^2 \cdot D_c}{\sigma} \tag{1}$$

The most common definition of the Weber number to date is the global Weber number (We_{global}) calculated using the jet diameter (sometime radius) [8,13] while the local Weber number (We_{local}) is only mentioned in a few studies [2,3,12–14] with inconsistencies in its definition. With flows involving the interphase mixing between liquid and air like in air assisted atomization, ρ is air density; σ is the liquid surface tension, U_s is slip velocity, and D_c is the characteristic dimension of the liquid shape. The quantity D_c is defined differently depending on the form of the Weber number used. In a simulation of a liquid jet in air cross-flow stream [12], We_{local} is estimated using the drop diameter. However, this approach is invalid for irregular fragment shapes. Shinjo et al., in their DNS work [2], used the semi-minor axis (or baseline radius) of fragments for We_{local} estimation. To the authors' knowledge, the work done by Shinjo et al. [2] is among the very few reports describing We_{local} for ligaments. The boundary conditions used in their DNS studies is based on their previous experimental work [13,14].

Umemura [13,14] investigated the breakup length and breakup time of a laminar liquid jet by observing the jet's recession velocity in which the jetting-to-dripping transitions upon a stepwise decrease in jet issue speed was noted as the first Plateau-Rayleigh instability [13]. The liquid Weber number in this study was defined as $We_{local} = \rho \cdot U_o^2 \cdot \frac{a}{\sigma}$, where U_0 is the jet exit velocity and "a" the jet radius. The jet tip recession velocity was defined as $U_t = \left[\frac{\sigma}{\rho \cdot a}\right]^{0.5}$ so that $We^{0.5} = \frac{U_t}{U_0}$. It is very interesting that the occurrence of jetting-to-dripping transition was noted by Umemura when $We^{0.5} = 0.8$ [13,14].

Using pulsed shadowgraphy, Sallam et al. [3] examined the turbulent primary breakup properties of a round liquid jet in standard temperature and pressure air environment and measured drop velocity after turbulent primary breakup. The drop velocity clarified in that work is the local streamwise drop surface velocity. The ratio of the surface velocity to the bulk liquid jet velocity was found to be 0.88, which is comparable to the $We^{0.5}$ value at the transition regime of a laminar liquid jet observed by Umemura [13,14]. In the DNS work done by Shinjo et al. [2], the velocity ratio or square root of We_{local} of fragments matched the experiment data described in Umemura [13,14] and Sallam et al. [3]. While it is clear that both DNS and simple experiments have addressed the need to identify local conditions in the spray, measurements of local conditions in more complex atomizing sprays, dominated by high speed non-spherical fragments are rare. This is largely due to limitations in the techniques used for characterization of atomization.

While planar imaging has been widely used in atomization studies [9–11,15,16], information from single-view images are insufficient to characterize 3D-structures of irregular shapes like ligaments. For example, a ligament can appear as a droplet from one viewing plane and as a cylindrical shape from the other plane. Three dimensional information can only be extracted through the use of multi-angle imaging. Using holography with an assumption of ellipsoidal geometries for irregular liquid fragments derived from a turbulent primary breakup jet, Wu and Faeth [17,18] estimated the volume of irregular shapes from the measured major and minor axis of the ellipsoids. Since the issue of fragment orientations was not addressed, it is not surprising that high uncertainty in the liquid flux measurements were obtained in that study [17,18]. Analysis of non-spherical fragments has also been undertaken by a number of other authors [9,15,16]. However, these studies are limited to a single viewing angle and hence cannot be used for accurate fragment volume measurement, or for a fully resolved analysis of atomization.

To address these problems, multi-dimensional imaging techniques have been developed. Sipperley and Bachalo [19] introduced multi-angle volumetric imaging able to reconstruct a 3D object with a spatial resolution down to 39 µm, using an array of CMOS sensors. Liu et al. [23] used 4D X-ray imaging of a dense fuel spray and reconstructed the overall spray structure, however this did not entail simultaneous imaging from multiple angles. Kourmatzis et al. [9] have extended their standard single-angle backlight imaging with an image processing methodology presented in [10,11] to observe atomizing fragments at both front and side views. A particle tracking technique (PTV) capable of simultaneously measuring volume and velocity of irregular shapes has also recently been developed [1]. Despite this being a significant step forward in the measurement of atomizing sprays, the PTV tool to date, is still limited to low We_{global} sprays ($We_{global} < 20$). At high We_{global} cases, matching identified fragments or droplets from images taken from just two cameras is very challenging, and for certain cases, not possible. The processing script must reject a large proportion of small filaments resulting in under-estimation of the overall volume flow rate [1], even though measurements for $We_{global} < 20$ are excellent. This issue will be further addressed in this study.

The aims of this work are: (i) to extend the dual-angle particle tracking velocimetry technique [1] in measuring volume flow-rate of realistic air assisted sprays (ii) to combine the dual-angle processing method (3D processor), with a standard single angle processing method (2D processor) in order to provide accurate statistics on both droplets and irregular shapes, and (iii) to measure and analyse the local Weber number, $We_{local,}$ of fragments derived in the near-field nozzle for a typical air assisted spray.

2. Experimental layout

The experimental setup is schematically shown in Fig. 1. This layout is an extension of a one-dimensional backlight illumination system

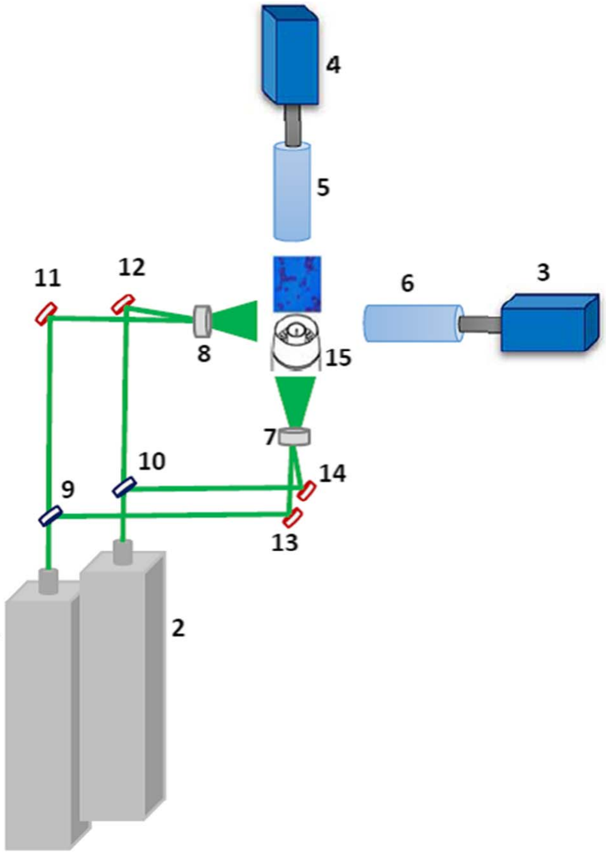

Fig. 1. Schematic of experimental setup for joint volume and velocity measurement of liquid fragments. (1 & 2: 532 nm-15 W-5 kHz Edgewave lasers; 3 & 4: High speed cameras (HSS6); 5 & 6: QM100 long-distance microscopes; 7 & 8: Opal glass-diffusing optics; 9 & 10: 523 nm 50:50 beam-splitters; 11–14: 532 nm Mirrors; and 15: Atomizer and probe volume).