Application of combined ILIDS and PLIF techniques to study droplet and vapour phase interaction in an evaporative and non-reacting spray

Srikrishna Sahu¹, Yannis Hardalupas² and AMKP Taylor²

1: Indian Institute of Technology Madras, Mechanical Engineering Dept., Chennai, 600036 India
2: Imperial College London, Mechanical Engineering Dept., London SW7 2BX, UK
* correspondent author: ssahu@iitm.ac.in

Abstract This paper reports the application of simultaneous Interferometric Laser Imaging Droplet Sizing (ILIDS) and Planar Laser Induced Fluorescence (PLIF) measurements, developed by Sahu et al. (2014), to an acetone spray evaporating under ambient conditions. The purpose here is to study the mutual interaction between droplet dispersion and evaporation in a spray with an aim to understand the consequences of group evaporation of droplets. This necessitates simultaneous planar measurements of droplet properties (position, size, velocity and number density) and vapour concentration around the droplets, and only the combined application of the two techniques has the ability to provide this information. The two-phase measurements are reported 350 mm downstream of the injector exit and for four different radial locations beginning from the spray axis up to the edge of the spray. For comparative study of droplet dispersion without and with droplet evaporation, droplet measurements are also reported for a non-evaporating water spray at the same measurement locations relative to the injector, and under the same flow conditions. The paper presents the average and fluctuations of local droplet characteristics and vapour concentration, the correlation between droplet number density fluctuations of different size classes ($R_{nn}$), and between droplet number density and vapour mass fraction fluctuations ($R_{nnyn}$). The Group evaporation number ($G$) is measured without and with the assumption of uniform droplet spacing. This assumption is shown to lead to overestimation of the measured values of $G$. The agreement between the trends of $R_{nnyn}$ and $G$ for different measurement locations explained the low correlation between droplet number density and vapour mass fraction near the spray center indicating reduced droplet evaporation rate as a consequence of group evaporation of droplets.

1. Introduction

Droplet vaporization is crucial in combustion of liquid fuel sprays since it can be the slowest process determining the overall burning rate, Sirignano (1999). The carrier flow turbulence significantly influences the evaporation process in sprays, either directly by modifying mass and heat transfers or indirectly through droplet dispersion. Due to the wide range of droplet size distribution in sprays, different dynamic behaviour of droplet dispersion and interaction with the surrounding gas leads to local formation of instantaneous clusters of droplets in the flow (Eaton and Fessler 1994; Zimmer et al 2003). Droplet clustering leads to significant increase of the instantaneous local droplet concentration above the mean value, which causes the inter-droplet spacing to become sufficiently small so that interaction between neighbouring droplets prevents the penetration of oxidizer. Consequently, a fuel rich mixture is formed in which droplets do not burn individually, but rather in a group. Chiu and Kim (1983) characterized this phenomenon by the Group combustion number, $G$. For a mono-disperse cloud of droplets, the magnitude of $G$ specifically depends on droplet diameter ($D$), number of droplets ($N_0$) and inter-droplet distance ($l$), and can be expressed as

$$G = 3(1 + 0.276 Re^{0.5} Sc^{0.33} LeN_0^{2/3} D \frac{D}{l})$$  \hspace{1cm} (1)$$

where $Re$ is the droplet Reynolds number, and $Sc$ and $Le$ are the gas Schmidt number and Lewis number. Depending on whether $G > 1$ or $G < 1$, either external or internal group evaporation can prevail (Sirignano1999). The magnitude of $G$ has been shown to have profound effect on flame location and distributions of temperature, fuel vapour and oxygen. However, experimental verification of cloud-burning regimes has been limited to either qualitative observations in turbulent sprays or more quantitative studies on mono-sized droplet streams or array of droplets (Castanet et al 2003; Orain et al 2006; Watanabe et al 2007).
Though there are additional parameters influencing droplet evaporation in reacting flows, understanding non-reacting and evaporating flows is a first step. Although the dispersion of droplets or particles embedded in turbulent flows is one of the major research fields of two-phase flows, any direct link has been rarely made between droplet turbulent dispersion, vapour source distribution and vapour mixture fraction evolution in a generic configuration. Since measurements of these quantities are difficult, most of the previous researches are based on modeling turbulent two-phase flows. One of the main input parameters of any non-premixed turbulent combustion model is the mixture fraction variable (\(Z\)), which characterizes locally the mixing between the evaporated fuel and the gaseous oxidizer. In either Reynolds averaged (RANS) modeling or large eddy simulations (LES), the properties of mixing are characterized with the mean mixture fraction, its variance and its dissipation rate. When vaporization occurs, due to the local sources of fuel, \(Z\) is not a conserved scalar, resulting in additional unclosed terms in the transport equations for mean and variance of \(Z\), Reveillon and Vervisch (2000). Those terms contain correlations between fluctuations of mixture fraction and, carrier phase velocity and droplet number density. Thus, measurements of those terms are essential not only to assist developing models but also to explore the underlying physics.

Considering the complexities involved in spray combustion, idealized sprays are studied to minimize the coupling between the different effects and to provide parametric results. In this paper, we consider an acetone spray evaporating under ambient, non-reacting conditions. Even this apparently simplified configuration poses tough challenges in the measurements of droplet and vapour phases. For measuring the dispersed phase, the Phase Doppler Anemometer (PDA) has been used. However, being a single point technique, PDA cannot provide instantaneous inter-droplet distance and droplet number count essential for evaluation of the group combustion/evaporation number, \(G\). In the present paper we use a novel approach of combining ILIDS (Interferometric Laser Imaging for Droplet Sizing) and PLIF (Planar Laser Induced Fluorescence) techniques, as developed by Sahu et al.\(^a\) (2014), for simultaneous droplet and vapour phase measurements in evaporative sprays. ILIDS (Glover et al 1995; Maeda et al 2000) is an optical technique for instantaneous planar measurements of the spatial distribution of individual droplet size, velocity and number density in poly-disperse sprays. The instantaneous vapour concentration distribution is measured by PLIF. Application of ILIDS in conjunction with Particle Image Velocimetry (PIV) for two phase flow measurements in an isothermal spray has been reported in Hardalupas et al. (2010). Sahu et al.\(^b\) (2014) employed the combined ILIDS and PIV technique to study the effect of droplet size and flow length scales on spatial droplet-gas velocity correlations in the spray.

The purpose of the present paper is to apply the combined ILIDS and PLIF techniques to the evaporative spray to investigate the interaction between droplets and vapour phases aiming to study the collective behaviour of droplet evaporation and identify differences relative to single droplet evaporation. Apart from presenting the results including basic statistical quantities (e.g. mean and standard deviation of droplet size, velocity and vapour mass fraction), the correlations between droplet number density and vapour mass fraction are presented. The group evaporation number (\(G\)) is quantitatively evaluated, and its link with the above correlations is established to understand the prevailing modes of group evaporation in the spray.

2. Experimental set-up

The fundamental principle and instrumentation of the combined ILIDS and PLIF technique is described in detail by Sahu et al.\(^a\) (2014), who also demonstrate the ability of the technique to measure droplet and vapour phases in evaporative sprays. Figure 1a shows the optical arrangement for the combined ILIDS and PLIF techniques. For droplet measurements by ILIDS, the flow field was illuminated by a double pulse Nd:YAG laser (\(\lambda = 532\) nm), denoted as Laser 1. The scattered light was collected through Lens 1, and the ILIDS images were captured through Camera 1 set at an angle \(\theta = 70\)°. The Scheimpflug condition was maintained to ensure uniform defocusing at Camera 1. For PLIF measurement, acetone droplets and vapour were excited by a fourth harmonic generator, single pulse Nd:YAG Laser (\(\lambda = 266\) nm), denoted as Laser 2. The two beams are then combined by using a beam combiner. The fluorescent intensities were collected through Lens 2 with a suitable band pass filter (260–490 nm) to restrict the scattered light from droplets at 532 nm. The fluorescent light was imaged by Camera 2 coupled to a gated intensifier. For both cameras the field of view was approximately \(9 \times 12\) mm\(^2\), and the spatial resolution was about 9 µm/pixel. The lasers, cameras and
intensifier were synchronously operated so that the PLIF image was captured at the same time as the first of the two ILIDS images. To suppress the high-frequency signal (noise) in the PLIF image, the intensity values are binned with a bin size of $4 \times 4$ pixel$^2$, thus resulting in a spatial resolution of $36 \mu m/pixel$ for the PLIF image.

As shown in figure 1b, an air-assist nozzle producing a solid cone spray was considered for the present experiment. Liquid acetone, pressurized at 1.2 bar in a pressure vessel, was fed to the nozzle through stainless steel hoses. The flow rates of liquid acetone and air were controlled by the respective rotameters and were set to 0.03 and 15 lt/min, respectively. The two-phase measurements were performed 350 mm downstream of the nozzle exit where significant evaporation has occurred and vapour-air mixing is expected to be higher than at the near nozzle region. The corresponding width of the spray was about 100 mm. Four radial measurement locations were considered beginning from the nozzle axis towards the outer spray at $R =$
0, 15, 30 and 45 mm, where R refers to the beginning of the measurement area measured from the nozzle axis. The image processing procedure for droplet size and velocity measurements by ILIDS is elaborated in Sahu et al. (2011). The minimum measurable droplet size was 15 µm, which is obtained as a trade-off between object distance of the collecting lens and size of the measurement area. Similar to Hardalupas et al. (2010), we account for the droplet centre discrepancy while determining droplet position by ILIDS.

We should mention here that, the droplet concentration or number density measurements in the spray are obtained using the ILIDS images. It is not possible to validate all the droplets, which appear on the ILIDS image (due to criteria imposed by image processing). However, in any instantaneous image the validation procedure of the image processing does not reject preferentially some droplet sizes. Therefore, the relative droplet number counts of different size classes remain the same compared to the case when all droplets in an image are considered. The droplet concentration was measured by counting the number of detected droplets in the ILIDS image, which corresponds to a volume of 9×12×1 mm$^3$ in the present case (thickness of the laser sheet ≈ 1 mm).

Experiments in evaporative sprays impose many challenges, the most important being the discrimination between droplet and vapour phases on the PLIF images. Since the PLIF image contains fluorescence from the liquid droplets as well as the vapour phase, the contributions from the liquid phase must be eliminated to obtain the vapour-phase concentration. For this purpose, instead of relying on the conventional approach of setting an intensity threshold (Bazile and Stepowski, 1995), application of continuous wavelet transformation (CWT) to the fluorescent intensity values leads to minimum cross-talk between the two phases, Sahu et al. (2014). For quantitative evaluation of vapour concentration in the droplet-filtered PLIF image, the raw fluorescence images need to be corrected for background luminosity, non-uniformities in collection optics, variations in the laser sheet profile and absorption due to vapour. Finally, the corrected fluorescence image is converted into vapour concentration based on calibration with a well-known acetone vapour concentration (saturated vapour of liquid acetone in a closed cuvette). The acetone vapour mass fraction is computed from the vapour concentration values by assuming ideal gas behaviour of the vapour-air mixture. Since the absorption of laser energy due to droplets and vapour was low (3-15%) at the considered measurement locations, the corresponding corrections were not taken into account in the vapour concentration estimation. Figure 1c shows an example of instantaneous contour plots of acetone vapour mass fraction (normalized with respect to the saturated value at the ambient temperature) superimposed with size and velocity vectors of the droplets obtained by the combined techniques.

In order to examine the effect of evaporation on droplet properties, comparison with a non-evaporative spray was essential. Hence, experiments were performed with a water spray under same operating conditions of liquid and air flow rates, and measurement locations as for the acetone spray. Although at the ambient temperature of 15°C, the surface tension of water is about three times greater than that of acetone, for the considered experimental regime in the spray, the droplet size can be considered to be independent of the surface tension due to high value of Weber number at the nozzle exit.

At any given measurement location, the instantaneous quantities are denoted by upper case letters (droplet axial velocity ‘$U$’, radial velocity ‘$V$’, number density ‘$N$’, vapour mass fraction ‘$Y$’), and corresponding fluctuations by lower case letters (u, v, n, y). The $U$ and $V$ velocity components are according to the Cartesian coordinate system x-y (Figure 1b). Throughout the text, ‘overbar’ over any quantity indicates time-averaging and the subscript ‘r’ denotes the root mean square (r.m.s.) of that quantity.

3. Results

Figure 2a shows the probability of droplet size distribution at R = 0 mm for the evaporative spray. Similar size distributions of droplets (15 µm – 100 µm) were observed at other measurement locations, and also for the water spray. The statistical analysis is presented for three different droplet size classes, namely, 15-30 µm, 30-45 µm and 45-60 µm. A width of each size class of 15 µm was selected as a compromise between higher statistical uncertainty (with smaller $\Delta D$) and obtaining size averaged information (with larger $\Delta D$). Figure 2b compares the probability of the three droplet size classes at different measurement locations for
acetone and water spray. It can be observed that the small droplets of size 15-30 µm dominate the droplet size distribution for all locations in the spray. For the water spray, the probability of droplets of any size class remains almost invariant at different spray locations, thus the Sauter mean diameter (SMD) is nearly constant, as shown in figure 2c. However, for the acetone spray, away from the spray axis, the probability of 15-30 µm droplets increases, while that of larger droplet size classes decreases, though slightly, thus the SMD is smaller towards the edge of the spray (figure 2c). This is attributed to evaporation of acetone droplets since radial transport of droplets away from the spray axis is not expected to increase due to droplet evaporation.

It should be noted that the magnitude of evaporation at any measurement location depends on two factors, namely droplet evaporation rate and number density of droplets. The evaporation rate of a droplet in turn depends on the droplet size and the vapour concentration around the droplet. So, comparison of SMD is not sufficient to conclude on the extent of evaporation at any measurement location, since SMD is determined by the droplet probability distribution, which may not be altered due to evaporation. Thus, the knowledge of droplet number density is equally essential, which is presented below.

3.1 Mean and fluctuations of characteristics of droplet and vapour phases

Droplet number density

Figure 2a shows the average droplet number density (normalized by the corresponding value for evaporative spray at R = 0 mm) of the considered drop size classes at different measurement locations for both acetone
and water sprays. The average number density decreases towards the spray edge though the gradient is always higher for the non-evaporative spray. Also significant reduction of 15-30 µm droplets in the central spray region can be observed for the acetone spray in comparison to the water spray. So, the vapour mass fraction is expected to be higher in this region. Though, the number density of droplets of other size classes reduces proportionately, so that their probability remains the same at R = 0 mm as shown in Fig. 1a. The intensity of fluctuations of droplet number density (ratio of rms of N fluctuations to the mean of \( N \), \( \frac{N_{fluctuation}}{N} \)) is shown in Fig. 2b implying increased fluctuations (relative to mean) towards the edge of the spray in contrast to trends in variations of the mean values (Fig. 2a). Also, considerable increase in the number density fluctuations due to evaporation can be observed for droplets of all size classes.

![Figure 3](image_url)

Figure 3: (a) Normalized mean droplet number density (b) intensity of fluctuations of droplet number density for the three droplet size classes at different measurement locations for the acetone and water spray.

**Droplet velocity**

Figure 3 shows the vector plots for average droplet velocity of 15-30 µm droplets for the acetone spray, which indicate that the droplet velocity is mostly axial and with a downward direction (away from the nozzle), and its magnitude decreases away from the spray centre. The droplets at higher size classes show similar trends though the corresponding average velocity was found to be slightly higher according to their
droplet size. Similar trends were observed for water droplets, so are not presented here. Though, comparison of the water and the acetone sprays indicated that evaporation caused the mean velocity of acetone droplets to marginally reduce near the spray axis and increase towards the spray edge. For both sprays, the intensity of axial velocity fluctuations ($u_r/\bar{U}$) was higher for smaller droplets, and it increased away from the spray axis for all droplets. Also, $u_r/\bar{U}$ was higher for evaporating droplets near the spray axis. The anisotropy ($v_r/u_r$) was about 0.5-0.7 in all cases, though it was found to slightly increase away from the spray axis.

![Vector plots of mean droplet velocity for acetone droplets of size class of 15-30 µm at different measurement locations.](image)

**Vapour mass fraction**

The contour plots of average vapour mass fraction normalized by the saturation value (corresponding to the ambient temperature of 15°C) are presented in Fig. 4. The area averaged mass fractions (normalized) at different locations are presented in Fig. 5. As compared to the saturated condition, the mean vapour concentration was low (5-10%) throughout the measurement region. Since the measurement region is far downstream the nozzle exit, this suggests considerable mixing of the acetone vapour with the surrounding air. The contour plots show that the spatial gradient in vapour concentration exists mostly in the axial direction. This is supported by the average velocity vector plots in Fig. 3, which show that the magnitude of droplet radial velocity and its spatial variation are negligible at the presented measurement locations. Fig. 5 also shows the intensity of fluctuations of vapour mass fraction ($y_r/\bar{Y}$), which increases away from spray axis as a consequence of fluctuations of droplet number density and velocity for which similar trends were observed. In fact near the spray boundary the fluctuations of vapour mass fraction are of the same order as the mean value. Figure 6 presents the probability of instantaneous fluctuations of vapour mass fraction (normalized as before) in the acetone spray at the measurement locations R = 0 mm and 45 mm respectively. While at the spray centre, the probability function of the vapour mass fraction is approximately Gaussian,
near the spray edge the probability function is positively skewed. Also, a peak appears on the left side of Fig. 6b. This is attributed to the presence of low vapour mass fraction when few or no droplets are present in the domain of the measurement.

![Figure 4](image1.png)

**Figure 4:** Contour plots of normalized mean mass fraction of acetone vapour at different measurement locations of the acetone spray.

![Figure 5](image2.png)

**Figure 5:** Area averaged and normalized vapour mass fraction, and intensity of fluctuations of vapour mass fraction at different measurement locations of the acetone spray.
### 3.2 Number density correlation coefficients between droplet size classes

The correlation coefficient between fluctuations of number density between different droplet size classes, denoted as $R_{n_i n_j}$, can be useful for understanding evaporation of different droplet sizes. The expression for $R_{n_i n_j}$ can be written as

$$R_{n_i n_j} = \frac{n_i(D_i) \times n_j(D_j)}{(n_i \times n_j)}$$

where $i, j$ denote the droplet size classes. Large values of $R_{n_i n_j}$ signify that any increase or decrease in droplet concentration of one size class is accompanied with a similar variation in the other, which means that droplets belonging to both size classes respond similarly to the gas motion and, therefore, may both contribute to droplet clustering affecting droplet evaporation. $R_{n_i n_j}$ is obtained for both acetone and water sprays, and the results are plotted in Fig. 6 for different measurement locations, $R$. The uncertainty in $R_{n_i n_j}$ was about ±0.05-0.07.

![Figure 6: Number density correlation coefficients ($R_{n_i n_j}$) between the droplet classes at different measurement locations for acetone spray (open symbols) and water spray (closed symbols). The uncertainty in $R_{n_i n_j}$ was about ±0.05-0.07.](image)

It can be observed that $R_{n_i n_j}$ is always positive in the present case. The correlation between fluctuations of the considered smallest and largest size classes is always lower than the other combinations. The correlations increase towards the spray edge when there is no evaporation (water droplets), but are more or else uniform throughout the spray. In the central spray region, $R_{n_i n_j}$ increases significantly due to evaporation.
3.3 Correlation coefficients between droplet number density and vapour mass fraction

As mentioned before, the correlation between fluctuations of droplet number density and vapour mixture fraction appears in the transport equation for $Z$, which requires a closure model. Since the definition of mixture fraction in sprays (containing vapour sources) is not straightforward (Reveillon and Vervisch, 2000), we present, as a first step, the correlation between fluctuations of droplet number density and vapour mass fraction. The corresponding correlation coefficient, denoted as $R_{n*y}$, can be expressed as $R_{n*y} (D) = n(D) \times (n_x \times y_y)$, and is evaluated for each droplet size class and for different measurement locations in the acetone spray. The uncertainty in $R_{n*y}$ was about $\pm 0.05$ with 95% confidence interval.

![Figure 6: Correlation coefficient ($R_{n*y}$) between fluctuations of number density (for different droplet size classes) and vapour mass fraction at different measurement locations in the acetone spray. The uncertainty in $R_{n*y}$ was about $\pm 0.05$ with 95% confidence interval.](image)

It can be observed in Fig. 6 that the correlation is always positive, which means that positive/negative fluctuations of droplet number density results in higher/lower vapour mass fraction at any instant in time. Also, as shown in the figure, this trend is inversely proportional to the ability of droplets to follow the carrier phase gas flow or the droplet Stokes number ($St$). Since the Stokes number of 15-30 µm droplets is very low ($St \sim 0.01$), the local vapour mass fraction is proportional to the corresponding droplet number count. Larger droplets ($St \sim 0.1$) are associated with larger slip velocity, thus the local vapour field around such droplets is weakly correlated to the droplet number density. Fig. 6 also shows that $R_{n*y}$ increases away from the spray axis towards the spray boundary. However, this increase is smaller for larger droplets. The knowledge of $R_{n*y}$ is important as its higher magnitude suggests appropriateness of modeling droplet evaporation according to $d^2$-law (Spalding, 1951), which is commonly employed in numerical simulations of evaporative sprays.

3.4 Group evaporation number

The planar measurement of droplet position and size through ILIDS facilitates the measurement of the instantaneous group combustion/evaporation number ($G$) in a spray. Considering equation 1, for low Reynolds number of droplets, and near unity value of Lewis number (such as in the present flow conditions),

$$ G = 3N_o^{2/3} \frac{D}{l} $$

(2)

In the literature, mostly single particle counter techniques (mainly PDA) have been used for dispersed phase characterization. So, $G$ is evaluated under the assumption of uniform inter droplet distance within the droplet cloud. Equation 2, thus, further simplifies (Chen and Gomez, 1997) to
where $N$ is the droplet number density and $L_c$ is the droplet cloud radius. However, for a practical spray, the inter droplet spacing and the droplet size can have significant variation from one time instant to another. Hence, it is important to evaluate the instantaneous group evaporation number, which can elucidate on the dominant mode of evaporation for a given location in the spray. Thus, the group evaporation number $G$ was evaluated for each time instant following both of the above equations.

The droplet cluster dimension ($L_c$) required for Eq. 3 was obtained by evaluating the radial distribution function (RDF) for different measurement locations in the spray. RDF essentially measures the probability of finding a second droplet at a given separation distance from a reference droplet compared to a case where the droplets are homogeneously distributed, Sundaram and Collins (1999). It is computed from a field of $M$ droplets by binning the droplet pairs according to their separation distance, and calculating the function

$$RDF_i = \frac{N_i / \delta V_i}{N / V}$$

Equation (4)

where $N_i$ is the number of droplet pairs separated by a distance $r_i \pm \delta r/2$, $\delta V_i$ is the volume of the discrete shell located at $r_i$, $N = M (M - 1)/2$ is the total number of pairs and $V$ is the total volume of the system. In the present case RDF was obtained conditional on drop size classes as shown in Fig. 7a for acetone spray at the measurement location $R = 0$ mm. Effectively, the value of RDF = 1 means that the droplet distribution is random. For values of RDF > 1, this means that clustering occurs. The value of $r$ for which RDF(r) becomes larger than 1, provides an estimate of the scale of the clusters. RDF was evaluated for different distance of separation from a droplet and different size classes. The length scale of the droplet clusters were found to be of about half of the measurement window dimension ($L_c \approx 4-5$ mm), and also, increases for higher droplet size classes though not considerably, as shown in Fig. 7a. The comparison of RDF for 15-30 µm droplets for acetone and water spray in Fig. 7b for locations $R = 0$ mm and 45 mm. It can be observed that the tendency of droplets to form clusters and the cluster dimension increases due to evaporation in agreement with the increase in number density fluctuations in Fig. 3b.

Figure 7: (a) Radial distribution function (RDF) for the considered droplet size classes corresponding to the acetone spray and measurement location, $R = 0$ mm. (b) Comparison of RDF for 15-30 µm droplets of acetone and water sprays at measurement locations $R = 0$ mm and 45 mm.

Figure 8a presents the evolution of mean group evaporation number $G$ at different radial measurement locations in the evaporative spray following Eq. (2) and Eq. (3) as mentioned before. The uncertainty in calculation of $\overline{G}$ was ± 0.015-0.02 with 95% confidence interval. The standard deviation of the fluctuations of $G$ is also shown (as errorbars). This indicates variations in the mode of group evaporation
at different time instants. Comparison of the magnitude of $G$ in both approaches signifies the overestimation of the mean group evaporation number following equation 3, which resulted from the assumption of uniform droplet spacing in the cloud. Also, the standard deviation of $G$ is overestimated. For the considered experimental region of 350 mm downstream of nozzle exit in the spray, the group evaporation number, as per equation 2, was found to increase towards the spray axis implying that the tendency of droplets to evaporate as a group becomes higher closer to the spray axis. At $R = 0$ mm, the magnitude of $G$ ($\leq 1$) suggests that the mode of evaporation falls in the regime of ‘internal group evaporation’ (Sirignano, 1999). Thus, a first ring of individual evaporating droplets is expected to be centred on a core of droplets. The small value of $G$ near the spray edge suggests that droplets evaporate individually without interacting with each other. If the approach of equation 3 was used, $\overline{G} \approx 1$ and even higher especially close to the spray axis, so the evaporation regime would be in between internal and external group evaporation. This implies an increased size of the core with its boundary enveloping all the droplets and the single droplet evaporation ceases to exist. However, as suggested by the contour plots of instantaneous and average vapour concentration (figures 1c and 4 respectively), this mode of evaporation is less probable to occur at the measurement locations considered in this study. The trend in $G$ is opposite to that of $R_n*y$, thus the greater the tendency of droplets to evaporate as a group, the lower is the correlation between droplet number density and local vapour mass fraction. Thus, the same number of droplets generates small amount of vapour when the droplet spacing is smaller in comparison to the case when the same number of droplets are widely apart. Figure 8b shows the intensity of fluctuations of $G$, i.e. ratio of standard deviation to mean value of $G$ (i.e. $G_r/\overline{G}$). It can be observed that following Eq (2), the intensity of $G$ fluctuations increases towards the spray edge in accordance to the similar trends of droplet number density and velocity, and vapour mass fraction. In contrast to this, according to Eq. (3), the intensity is not only higher but also decreases away from the spray axis.

Figure 8: (a) Evolution of mean $G$ and its standard deviation (as errorbars) at different measurement locations following Eq. (2) and Eq. (3), which is based on the assumption of uniform droplet spacing. (b) Intensity of fluctuations of $G$ (i.e. $G_r/\overline{G}$) at different measurement locations corresponding to the above approaches.

4. Conclusions

Understanding the physics of mutual effects of droplet dispersion and vaporization in evaporative sprays is important in liquid fuel atomization because phenomena such as group evaporation of droplets can significantly affect the spatial and temporal distribution of fuel-air mixture. For such studies, detailed knowledge of droplet properties (position, size, number density, velocity) is equally important as the vapour mass fraction. Aiming at such investigations, we presented a novel application of the combined ILIDS and PLIF technique, developed by Sahu et al. (2014), to an acetone spray evaporating under ambient conditions. Simultaneous measurements of droplet characteristics and vapour mass fraction are reported 350 mm
downstream from the exit of an air assist atomiser for four different radial locations. Droplet measurements are also reported for a non-evaporating water spray in order to examine the effect of evaporation on droplet dispersion. The probability of 15-30 µm acetone droplets was found to increase towards the edge of the spray, while that of higher size classes decreases slightly, thus resulting in reduction of SMD away from the spray axis. However, the SMD remains almost spatially invariant for the water spray. At any measurement location, the average droplet velocity was mostly axial and downward. Also, the contour plots of average vapour mass fraction show that the vapour concentration decreases in axial direction away from the injector exit, while no spatial gradient is present in the radial direction. Away from the spray axis, i.e. from R = 0 mm to 45 mm, the average values of droplet number density, axial droplet velocity and vapour mass fraction decreases. However, the intensity of fluctuations of those quantities increases towards the edge of the spray, and also with droplet size, as a consequence of evaporation at any measurement location in the spray. The number density correlation coefficients between droplet size classes were obtained and found to increase due to evaporation in comparison to water droplets. The measurement of correlation between fluctuations of droplet number density and vapour mass fraction, $R_{n*y}$, are reported for the first time. The correlation $R_{n*y}$ was obtained conditional on droplet size classes and found to increase towards the spray boundary. The group evaporation number was estimated both with and without the assumption of uniform droplet spacing. It is shown that this assumption leads to overestimation of mean and fluctuations of $G$ at all measurement location. The measured values of $G$ suggest presence of internal group evaporation regime close to spray axis, while individual droplet evaporation prevails near the spray boundary. The trends in the measured values of $R_{n*y}$ and $G$ were found to be in agreement with each other indicating low correlation between number of droplets and local vapour mass fraction due to collective vaporization of droplets, which reduces the droplet evaporation rate.

Acknowledgements

The authors would like to acknowledge support from the Engineering and Physical Sciences Research council (EPSRC) in UK under grants GR/R34714/01 and EP/G01597X/01, European Union Framework 7 contract agreement 265848 entitled 'Fuel Injector Research for Sustainable Transport (FIRST)' and Asian Office of Aerospace Research and Development (AOARD) under contract FA2386-13-1-4065. S.S. received the Outstanding International Student fellowship from the Department of Mechanical Engineering, Imperial College London, a scheme promoting studies of Indian Institute of Technology (IIT) graduates in UK.

References


velocity and size with gas phase velocities in a spray by combined ILIDS and PIV techniques. Exp Fluids 49:417–434


