PLANAR DROPLET SIZING FOR QUANTIFICATION OF SPRAY UNSTEADINESS

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Abstract

A planar droplet sizing technique, based on combined measurements of Laser Induced Fluorescence intensity emitted by Rhodamine dye added in liquid droplets and scattered light intensity, was developed in order to quantify spray unsteadiness. The spray unsteadiness is defined as the time-dependent variation of local droplet surface area, liquid volume and droplet diameter. The results quantified the mean and rms of fluctuations of liquid volume, surface area and Sauter Mean Diameter in a spray, generated by a pressure swirl atomiser, injected within the air flow of an industrial burner. The formation of droplet clusters, associated with droplet surface area and liquid volume higher than the local mean value and droplet Sauter Mean Diameter lower than the local mean value was observed, and the lengthscale of these clusters was quantified. The origin of spray unsteadiness was linked to droplet-air flow turbulence interaction.

Introduction

Considering the strict limitations on pollutant emissions and increased requirements in fuel efficiency that are placed on future combustion systems, the demands on spray performance are currently growing and the need for an improved physical understanding of atomisation and spray-flow interaction becomes more important. A variety of phenomena, such as temporal and spatial variations of droplet size and concentration, droplet dispersion due to flow interaction and collision effects in dense sprays are associated with unsteady processes within the spray and have, to a varying extent, important consequences for numerous engineering applications. Previous experimental studies clearly indicate that regimes of steady and unsteady spray behaviour are possible in connection with sheet atomization, coaxial flow atomization, effervescent sprays and jet flows and photographs of sprays (e.g. Lefebvre 1989) identify the presence of spray unsteadiness by the lack of uniformity in the scattered light intensity from drplets present in the sprays. However, there are few experimental studies quantifying the amplitudes of temporal and spatial droplet concentration fluctuations, apart from considerations of single droplets in air jets and empirical descriptions of discrete frequencies appearing in primary jet breakup.

Most of these studies are based on Phase Doppler Anemometer (PDA) point measurements for quantification of the temporal variation of droplet concentration and size in sprays (e.g. Bachalo et al. 1993, Van de Wall and Soo 1994, Hardalupas and Horender 2000 and 2001). However, Edwards and Marx (1992) showed theoretically and Hardalupas and Horender (2001) experimentally that the requirement of a single particle in the probe volume of the PDA technique may limit its ability to detect deterministic temporal fluctuations of droplet concentration at frequencies above a few hundred Hz. Therefore, planar imaging techniques have a better chance in quantifying spray unsteadiness.

A recent method for characterisation of dense sprays is the Planar Droplet Sizing (PDS) technique [Yeh et al 1993; Sankar et al 1999; Le Gal et al 1999; Domann and Hardalupas 2000 and 2001 a and b], that determines the liquid volume, droplet surface area and Sauter Mean Diameter on an illuminated plane of a spray. The technique relies in fluorescing light being emitted by droplets, as well as scattered light. Fluorescence can occur due to inclusions, naturally present in liquids, or due to the addition of a fluorescing dye in the liquid. Assuming that the intensity of scattered light, $I_s(x,y)$, is proportional to the droplet surface-area and the fluorescence intensity, $I_f(x,y)$ to its volume, the technique employs both intensities to directly determine the Sauter Mean Diameter, SMD, on a single plane of the spray according to the relation described in Eq 1.

$$\frac{I_f(x,y)}{I_s(x,y)} = k \cdot D_{32}(x,y) \tag{1}$$

Additionally, the spatial liquid volume distribution is provided by fluorescence intensity images and the liquid surface area distribution is available from the scattered light images. An advantage of the sizing principle of the technique is that it considers the ratio between two intensities, which eliminates the influence of attenuation of the laser light present on techniques using absolute intensity measurements for sizing. Although the technique is limited to spherical droplets, it may be possible to identify the presence of non-spherical ligaments or continuous liquid sheet from the fluorescence intensity distribution, which is related to the liquid volume distribution. The assumptions involved in Eq. 1 and their dependence on droplet diameter, light collection angle, light absorption by the dye and spatial resolution of the CCD array have been recently evaluated [Domann and Hardalupas 2000 and 2001 a and b] and this allowed the application of the technique to quantify the Sauter Mean Diameter of droplets on instantaneous images.

Therefore, the PDS technique could be used to quantify the time-averaged mean and RMS of fluctuations of droplet surface area, liquid volume and Sauter Mean diameter and, as a consequence, describe the unsteady behaviour of a spray, injected into the air-flow of a domestic burner. This paper presents the results, discusses the main findings and suggests a mechanism, which could originate spray unsteadiness.

Flow and Method

In the present study, water is injected through an air-assisted pressure swirl atomiser that produces a hollow cone spray of 60 degrees cone angle. This atomiser is part of a gun-type burner, of 98 mm outer diameter, with a mounted baffle plate that introduces a swirling component to the co-flowing air stream. The fluorescence and scattered light measurements were taken under the following experimental conditions. Water was injected at a pressure of 0.7 MPa, corresponding to a flow rate of 9.46 l/h. The air flow rate was set to 110 $Nm^3\ h^{-1}$, which considering the geometry of the burner results in an air exit velocity of v_{air}=14.7 m/s, in the annulus between the baffle plate and outer tube, and a Reynolds number Re_{air}=1.67 10^{-5} based on the effective diameter of the air flow. The combination of nozzle and baffle plate generates a central recirculation zone, which in the combusting case is used to stabilize the flame.

For laser induced fluorescence measurements, a Rhodamine fluorescent dye was added to the atomising water at an adjusted concentration of 0.0089 g/l that was appropriate to ensured volume proportionality of the fluorescence intensity signal. In order to obtain planar scattered light and fluorescent light signals, a cross-section of the spray is illuminated by a laser sheet of less than 1 mm thickness formed with the beam of a dual cavity Nd:Yag laser (SP PIV-400) at 532 nm wavelength, providing an energy of 400 mJ per pulse.

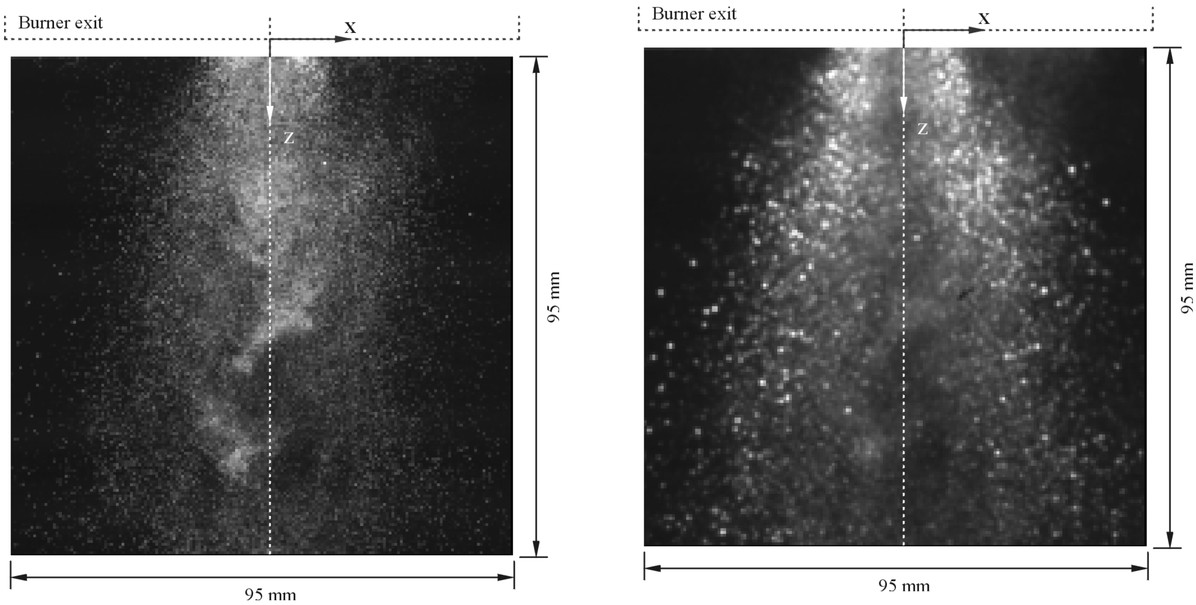

Figure 2: Typical images obtained after distortion correction, background correction and binning of the initial images for (a) scattered light and (b) fluorescence.

Typical instantaneous images recorded with the present experimental setup are shown in Fig. 2(a) and Fig. 2(b) for fluorescence and scattered light respectively. For both cameras a field of view of 100 x 100 mm is obtained, corresponding to 1 burner exit diameter and a mapping ratio of 0.105 mm per image pixel. In contrast to the fluorescence image of Fig. 2(a), the scattered light image, Fig. 2(b), shows mainly the central ``hollow" region of the spray, where unsteady clusters of high droplet surface area are visible. The edge of the spray cone can be clearly identified on the fluorescence image, due to the volume proportionality of fluorescence emission. Large droplets in the high liquid volume region of the spray cone are responsible for a higher fluoresence intensity signal, allowing us to precisely determine the spray cone angle. For the present injection system, this angle is of the order of 60^o. Comparison of these two raw images illustrates the significant differences in the information about spray structure and dynamics that can be obtained from fluorescence and scattered light imaging. It should be noted that most of the spray visualisation studies use scattered light intensity to observe the sprays. It is obvious from Fig 2 that such studies could suggest qualitatively wrong spray characteristics, since the scattered light image, Fig. 2(b), does not identify a hollow cone spray. The fluorescence intensity of Fig 2(a) successfully identifies these characteristics and is more appropriate for spray visualisation. In order to obtain quantitative information of liquid volume, surface area and SMD, however, additional steps were taken regarding image processing and calibration, such as matching of the physical space captured by both cameras to pixel accuracy, elimination of background noise and binning of pixel intensities into interrogation areas.

In this work, instantaneous space-resolved distributions of droplet size, liquid volume and surface area are used to provide statistical information about the magnitudes and corresponding lengthscales of the fluctuations leading to spray unsteadiness. Droplet clustering effects, defined as the appearance of spatial structures, which show a deviation from the mean fields in all three measured quantities are investigated and quantified. The details of the data processing required for the calculation of these quantities are presented in Domann (2002).

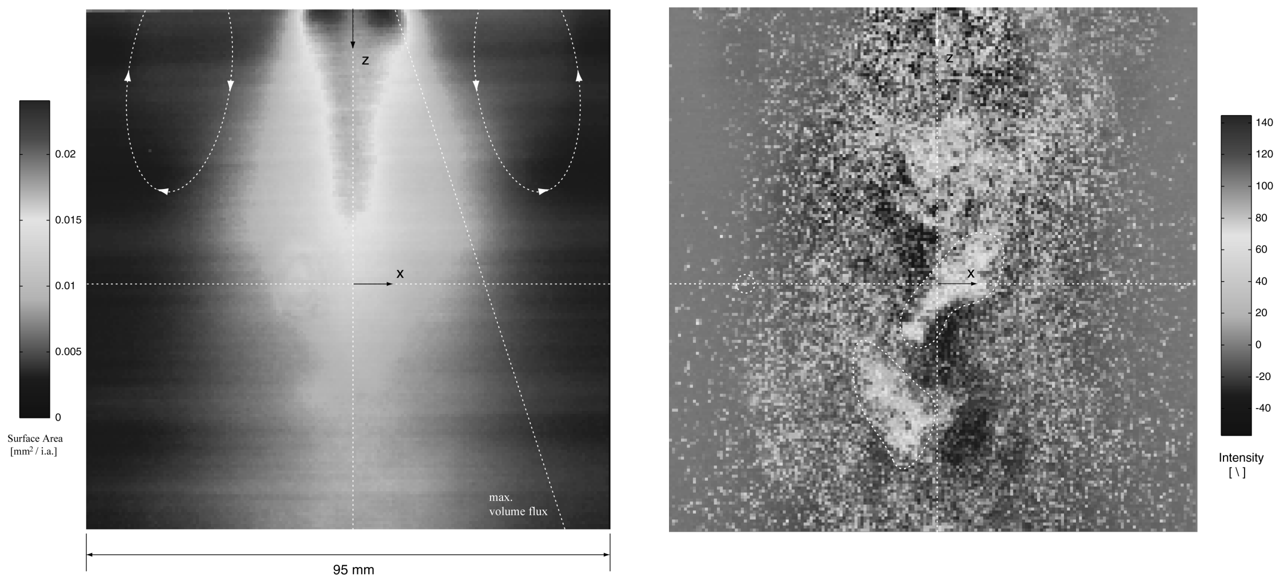

Figure 3: (a) Spatial distribution of the time-averaged mean surface area, (b) Instantaneous scattered light fluctuation field showing unsteady effects as deviations from the mean.

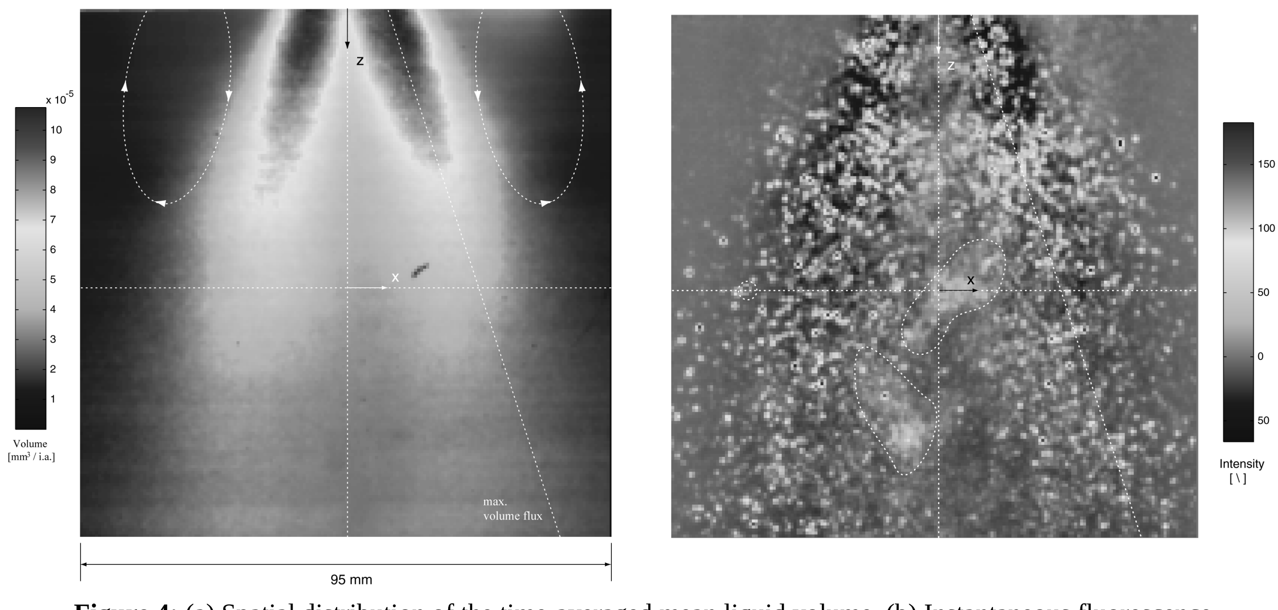

Figure 4: (a) Spatial distribution of the time-averaged mean liquid volume, (b) Instantaneous fluorescence intensity fluctuation field showing unsteady effects as deviations from the mean

Results and Discussion

The time-averaged mean scattered light intensity, Fig. 3(a), multiplied with a calibration constant, corresponds to the surface area distribution. In contrast to the fluorescence intensity distribution, indicating liquid volume distribution, of Fig. 4(a), scattered light intensity is weighted towards smaller droplet sizes and is expected to represent better the droplet number density distribution of the spray. The surface area distribution shows a maximum in the spray center and a rapid decline in the radial direction can be identified. A possible explanation of these characteristics is that the air flow recirculation zone surrounding the spray cannot disturb the motion of large droplets in the spray cone, while, at the same time smaller droplets with insufficient momentum do not penetrate the spray cone, identified by the line of highest liquid volume. The small droplets are entrained on the centerline of the spray, where they follow the mean flow leading to the highly populated central region. In the liquid volume field of Fig. 4(a), the values obtained for the spray central region are low and the hollow cone structure of the spray is visualized by the large volume measured at the edges of the spray cone. Larger droplets containing the main liquid volume are not entrained into the spray center, since they do not follow the entrained air flow.

Information about spray unsteadiness cannot be extracted directly from the instantaneous measurements, since these images contain a superimposed mean field contribution, which make the fluctuations difficult to detect in regions of high mean values. Therefore, as a first step to identify the larger fluctuations that represent droplet clusters and to quantify their instantaneous magnitude and lengthscale, the mean quantities are subtracted from the instantaneous distributions, producing the fluctuation fields shown in Fig. 3(b) for surface area and in Fig. 4(b) for liquid volume.

In qualitative terms, Fig. 3(b) indicates that droplet clustering is associated with regions of higher liquid surface area. Compared to the surface area fluctuation field, the clusters detected in Fig. 4(b), are not so clearly defined, since they represent only a small volume deviation from the mean in the liquid volume region within the spray cone. However, positive deviation of the liquid volume from the mean value is observed at the regions identified by the dashed line in figure 4(b), which coincide with the high positive deviation of the droplet surface area from the mean in figure 3(b). The corresponding fluctuation field in Fig. 7(a) on the basis of the fluorescence to scattered light intensity ratio, confirms these observations.

Following the qualitative analysis, spray unsteadiness is quantified from the instantaneous surface area, liquid volume fluctuation and Sauter Mean Diameter fields. The latter field is obtained by the ratio of the fluorescence to scattered light intensities, after taking into account the calibration constant. The local RMS of the fluctuations is computed, providing a quantitative measure of the magnitude of unsteady effects, while spatial correlations within the fluctuation fields are computed, in order to estimate the lengthscale of droplet clusters.

The spatial distribution of the RMS of the fluctuations of the droplet surface area is normalised by the corresponding local mean value and presented in Fig. 5(a). It shows a region of low RMS in the center close to the nozzle exit limited radially by the line of highest volume flux, as determined from the mean volume distribution. In the corresponding region of the mean fields, high surface area and small droplets are found, therefore, fluctuations relative to the mean surface area values appear low, but are still significant and of an order of 20 %. Outside the spray cone over the diameter of the coaxial air-stream, the RMS value remains constant and fairly high at about 25 % due to the low mean values used for normalization. For the planar liquid volume measurements, the characteristics of the normalized RMS of the fluctuations are presented in Fig. 5(b), where a low RMS region within the spray cone is identified, which is radially limited by the line of maximum volume flux, as previously observed in the distribution of the RMS of the droplet surface area fluctuations.

Since the corresponding central region of the mean liquid volume field in Fig. 4(a) contains a low proportion of the liquid volume, a high value for the normalized RMS is expected. However, the RMS is about 10 % and lower than the corresponding value for surface area fluctuations in Fig. 5(a). It is observed that the RMS and mean fields of the liquid volume are weighted towards larger droplet sizes, which cannot follow the fluctuations of the air flow. Therefore, the absolute RMS values in the liquid volume fields are lower than in the surface area case and unsteady spray effects caused by interaction of small droplets with the air flow are not easily detected.

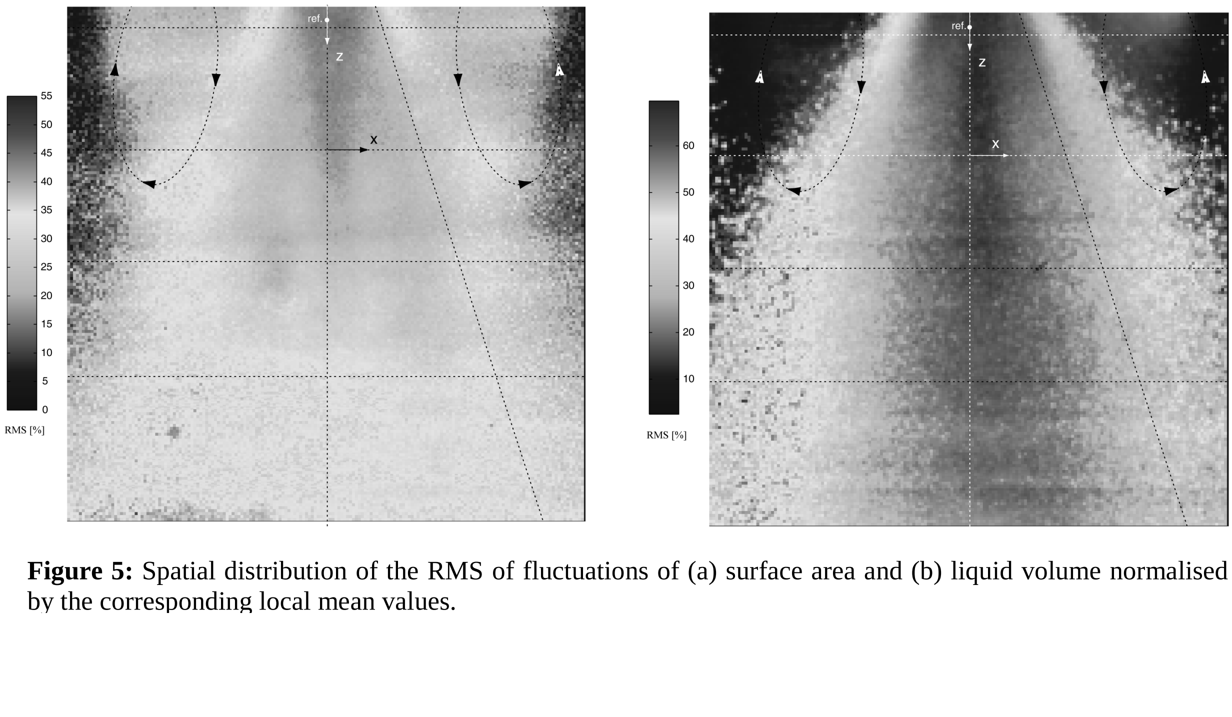

Figure 5: Spatial distribution of the RMS of fluctuations of (a) surface area and (b) liquid volume normalised by the corresponding local mean values.

The RMS of Sauter Mean Diameter fluctuations normalized by the corresponding local mean value is presented in Fig. 7(b) and shows a combination of the characteristics found in the surface area and liquid volume RMS distributions. As expected, in the central spray zone close to the nozzle a region of low RMS is visible, which is radially limited by the maximum liquid volume line. The corresponding RMS value is of the order of 20%, which is slightly lower than the locally normalized RMS found in the surface area case, but much higher than the 12% in the liquid volume case, suggesting that SMD fluctuations in this region are dominated by fluctuations of small droplet sizes. The maximum RMS outside the highest volume region, which determines the radial dimension of the spray cone, is also visible on the SMD fluctuations and describes the droplet size fluctuations caused by large droplets occasionally ejected from the spray cone at the edge. The low RMS region of SMD fluctuations, found at radial positions outside the spray cone corresponds to the region of the air flow recirculation zone, where the size distribution remains fairly constant at small droplet sizes, since large droplets are not entrained by the air flow avoiding large size fluctuations.

The lengthscales of droplet clusters within the spray, were obtained form the spatial correlation coefficients, which were quantified relative to the values at different reference positions, such as the spray centerline and radial cross sections at different axial distances from the nozzle. The actual axial and radial lengthscales L_{axial}, L_{radial} that determine the shape and size of the droplet clusters are obtained by integration of the correlation coefficient vs. *x* and *y*-axis profiles, such as those presented in Fig. 8(a). These lengthscales provide the radial and axial dimension of droplet clusters located at the spray center for a range of axial distances from the nozzle exit. In this way, the size and shape evolution of these structures over the axial length of the spray can be quantified, which can assist in the identification of the origin of droplet cluster formation in the spray. It can also evaluate its practical importance on the basis of the three measured quantities, surface area, liquid volume and SMD.

The spatial correlation coefficients functions, presented in Fig. 8(a), are obtained from the surface area measurements and show that the axial dimension of droplet clusters increases with downstream position. These effects are quantified in the corresponding axial and radial lengthscale profiles of Fig. 8(b), showing a small value of L_{radial} close to the nozzle, followed by a quick increase by a factor of 2 up to *z*=35 mm and further increase with reduced slope at downstream positions. These effects can be explained by the air flow within the spray cone, which interacts with the droplets and determines the average radial lengthscale of droplet clusters. The corresponding axial lengthscale profile shows an increase of L_{axial} from 2 to 3.2 mm. The profiles also indicate an effect of the recirculation zone on the air entrainment and, consequently, on the axial dimensions of the droplet clusters, showing a size increase at z=35 mm and nearly no additional axial spreading at further downstream positions, since spreading of the spray cone does not strongly affect the axial dimensions of the cluster type structures. This observation shows that the air flow determines the droplet cluster dimension rather than the droplet initial conditions.

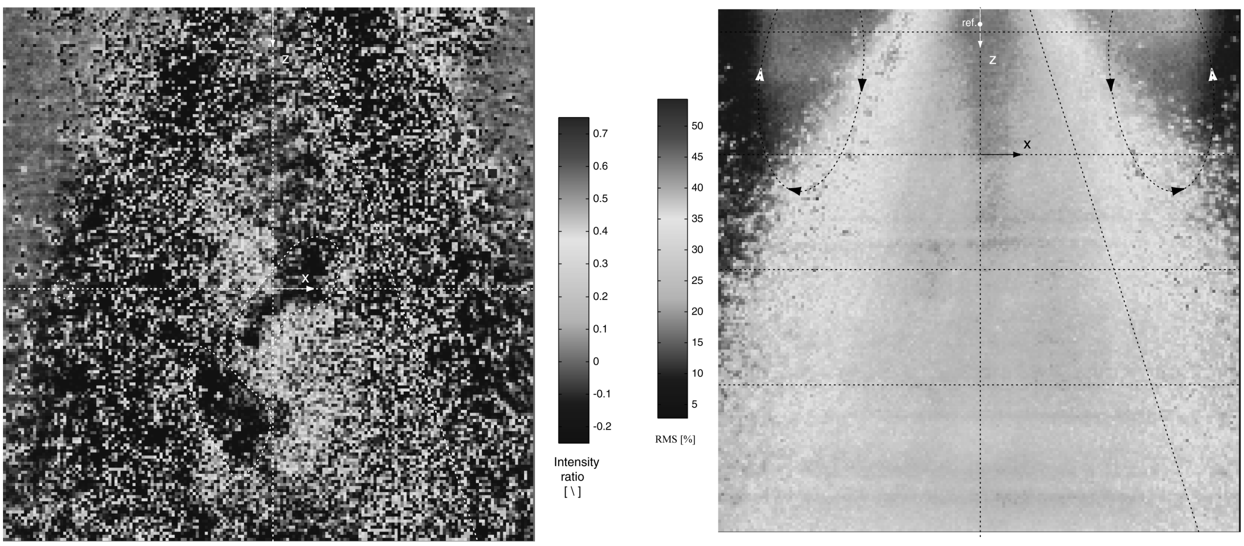

Figure 7: (a). Fluctuation field of intensity ratio showing droplet clusters as deviations from the mean. (b) Spatial distribution of the RMS of SMD fluctuations normalised by the local mean value.

Conclusions

1. Qualitative analysis of the instantaneous fields suggests the existence of spray unsteadiness in the form of droplet clusters, and confirms that the present imaging methods are suitable to detect and quantify such fluctuations of local droplet size and concentration. The investigation of fluctuating quantities indicates that clusters appear as coherent regions of high droplet number density and small diameter with the corresponding high surface area and low liquid volume quantities.

2. Quantitative characterisation of liquid volume, surface area and SMD fluctuation magnitudes found that spray unsteadiness could be identified to a different extent in the three investigated RMS fields. For surface area, the shape of RMS profiles changes considerably downstream of the region of high air entrainment present in the burner, indicating that clusters of small droplets with high surface area appear at random intervals. The liquid volume had a high RMS of fluctuations region at the spray cone limit, confirming that droplet clusters within the spray cone are not associated with large liquid volume. An increase in RMS downstream of the region of high air entrainment into the spray center is also visible in the SMD fluctuation field, indicating that the cluster type unsteadiness observed from the surface area view is associated with a distinct range of small droplet sizes.

3. Quantitative values of lengthscales and shapes of droplet clusters showed that different characteristics of the dimensions and axial evolutions of droplet clusters could be identified from the three investigated quantities. For droplet surface area, the calculated lengthscales are strongly influenced by the air flow, which limits the size of droplet clusters. The lengthscale increased with axial distance downstream of the burner, which confirmed the link between formation of droplet clusters and air flow turbulence.

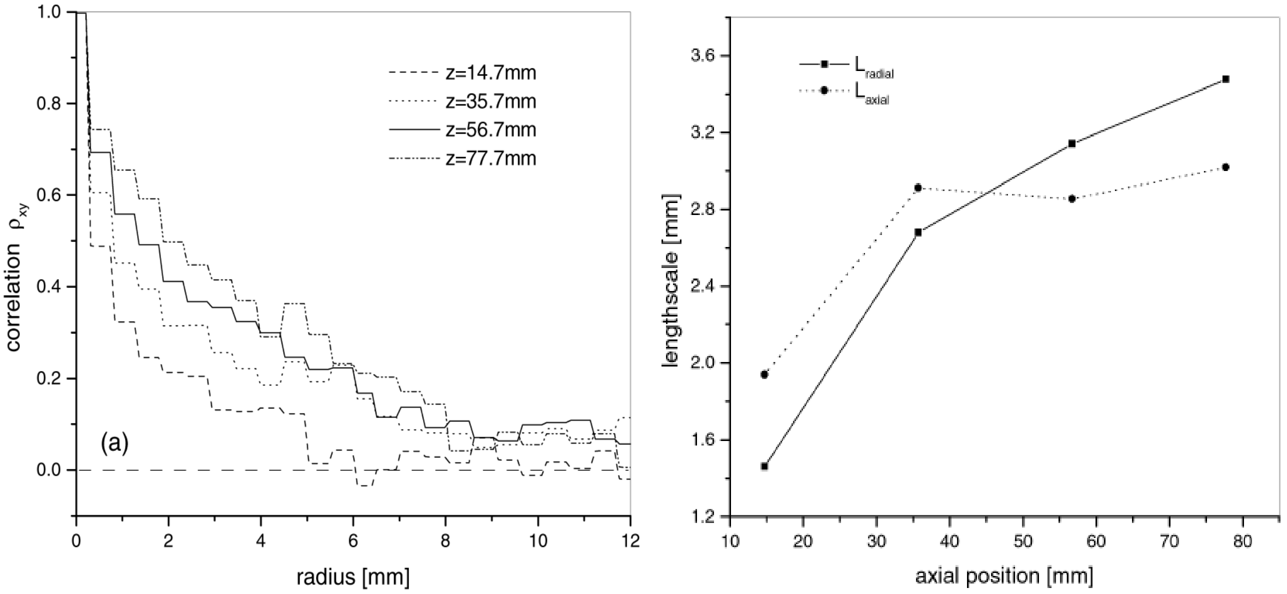

Figure 8 :(a) Correlation coefficient functions relative to the spray centerline, determining the radial extent of droplet clusters at the spray center for various axial distances. (b) axial evolution of radial and axial dimensions of droplet clusters located on the spray canterline. (from droplet surface area measurements)

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