Phase Doppler anemometer for instantaneous measurements of droplet concentration

by

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ABSTRACT

In two-phase flows, droplet concentration fluctuations can occur due to the atomisation process of a liquid or the interaction of droplets or particles with turbulent structures. The importance of the amplitude of droplet concentration fluctuations caused by nearly deterministic processes in sprays has not been quantified partly due to difficulties associated with measurement techniques. The current work describes an approach to obtain measurements of droplet concentration fluctuations and applies it in a swirl-stabilised burner to quantify droplet concentration fluctuations.

A method was developed to quantify deterministic droplet concentration fluctuations based on Phase Doppler Anemometry (PDA). The method sampled time-dependent droplet velocity and size measurements within equal sampling times to determine instantaneous droplet concentration. Two methods were used to define instantaneous droplet concentration : *the first* was associated with the data rate of droplets within the sampling time and *the second* was defined by the sum of residence times of all droplets crossing the probe volume of the anemometer divided by the sampling time and the volume of the probe volume of the anemometer for different droplet sizes. Analysis of the instantaneous data was developed to calculate the mean and rms values of instantaneous droplet concentration. The resulting droplet concentration fluctuations were due to random appearance of single droplets and deterministic appearance of droplet clouds in the probe volume and their values could be quantified from the energy of the deterministic fluctuations in the frequency spectra within the frequency bandwidth of the associated process.

The data processing method of PDA measurements was assessed in a pulsated injector operating at frequency of 20 Hz, injecting a liquid spray in the swirling flow of a laboratory burner. Comparisons between droplet concentration fluctuations, measured by a light scattering technique and phase Doppler measurements indicated agreement within 15%. The technique was applied in the swirl burner to measure the amplitude of deterministic droplet concentration fluctuations of an otherwise steady spray, which were caused by the unsteadiness of the atomisation process, which occurred at frequencies between 400 and 800 Hz. The intensity of droplet concentration fluctuations due to the break-up process was quantified to 15% of the mean droplet concentration in the flow.

The frequency spectra of droplet velocities and concentrations within two droplet size ranges, 1-20 and 20-60 µm, were measured. Velocity fluctuations of droplets smaller than 20 µm indicated the gas flow velocity fluctuations and showed the presence of a deterministic unsteadiness in the flow field at the same frequency as the break-up unsteadiness. This was well correlated with regions of the flow where droplet concentration fluctuations were maximum and, therefore, the deterministic droplet concentration fluctuations with amplitude 15% of the mean value could modify the gas flow velocity. Droplets larger than 20 µm were mostly influenced by the unsteadiness of the atomisation process and had droplet concentration and velocity fluctuations in the frequency bandwidth of 400 to 800 Hz, associated with the break-up process.

1. INTRODUCTION

The existence of temporal and spatial fluctuations of concentration of the dispersed phase in two-phase flows may reduce combustion performance by causing unexpected fluctuations of local air-to-fuel ratio or reduce the efficiency of chemical processes, such as spray drying, by modifying local droplet concentration and, therefore, probability of droplet collision. Concentration fluctuations of the disperse phase may also modify the carrier fluid turbulence and, therefore, the resulting mixing process in the flow. However, the experimental quantification of the amplitude of temporal and spatial particle concentration fluctuations has not been achieved.

It has been shown that the break-up process of liquid jets and sheets in liquid fuel atomisers may produce a deterministic and nearly periodic unsteadiness, leading to spatial and temporal droplet concentration fluctuations, as reported by Engelbert et al. (1995), Hassa & Arold (1995) and Hardalupas et al. (1996). Also, large scale structures of the continuous phase flow can influence droplet dispersion and lead to preferentially increased concentration of the disperse phase between fluid eddies due to droplet centrifuging associated to droplet inertia, as reported by Crowe et al. (1997) or Eaton & Fessler (1994). The droplet response to fluid turbulence was quantified in terms of Stokes number, defined as the ratio of droplet response timescale to the relevant fluid flow timescale, and the centrifuging effect is maximised when the Stokes number associated with the timescale of coherent flow eddies is around unity. Bachalo et al. (1993) studied experimentally using a phase Doppler anemometer droplet-flow interaction in two phase flows in the wake of cylinder and observed fluctuations of droplet concentration at the frequency of the coherent flow structures in the wake of the cylinder. However, the frequency of these flow structures was below 50 Hz and perfectly periodic, which is not true for unsteadiness of the break-up process in sprays, where frequencies are much higher and spread over a bandwidth.

Although experimental observations have confirmed the presence of droplet concentration fluctuations, limited attempts have been made to quantify the amplitude of such fluctuations, because of limitations of current experimental techniques. Numerical models of liquid atomisation process or droplet dispersion cannot predict deterministic fluctuations due to their assumptions of random flow process. Also, in Eulerian numerical models droplet concentration fluctuations form an integral part of the modelled equations (Delhaye & Achard, 1976; Aliod & Dopazo, 1989 and 1990) and, therefore, experimental information is required for their assessment. It is, therefore, important to be able to quantify the amplitude of droplet concentration fluctuations experimentally, so that their importance can be evaluated and, therefore, assess the accuracy of current numerical approaches to predict particle dispersion when deterministic droplet concentration fluctuations are not considered.

Droplet concentration fluctuations are associated with fluctuations of droplet diameter and number density. Although planar imaging techniques can provide temporal and spatial droplet distributions, they are limited to dilute two phase flows and they cannot provide simultaneous information of droplet diameter and number density and, therefore, their fluctuations. Although imaging techniques are becoming available, which may have the potential to address this issue (Sankar et al., 1999, LeGal et al., 1999, Domann & Hardalupas, 2000), there is a need to assess the ability of point measuring techniques, such as Phase Doppler anemometry (PDA), to measure instantaneous droplet concentration in sprays and derive statistics, in terms of droplet concentration fluctuations.

The purpose of the current work is to develop a method for data processing of time-dependent Phase-Doppler Anemometer measurements to quantify droplet concentration fluctuations and apply it in a liquid-fuelled combustor to quantify the amplitude of droplet concentration fluctuations caused by the deterministic unsteadiness of the breakup process. The phase Doppler results are compared with a Mie scattering technique, measuring the fluctuations of the intensity of light scattered from droplets. Section 2 describes the experimental arrangement and instrumentation, section 3 presents the data processing of phase Doppler measurements for instantaneous droplet concentration. Section 4 assesses the technique and presents measurements of frequency spectra of droplet concentration fluctuations and droplet velocity obtained in the burner geometry. Section 5 summarises the main findings.

2. FLOW ARRANGEMENT and OPTICAL INSTRUMENTATION

The burner, shown in figure 1, was the same as that used by Tsai (1997). It was operated with swirl number of the annular air flow at the burner exit 0.6, the exit gas velocity was 8.5 m/s, leading to a Reynolds number of 28,900, based on mean air velocity and the outer diameter of the annulus of 50.8 mm. The liquid fuel was injected from the centre of a centrally placed pipe of 18 mm diameter with an air-assist atomiser (Delavan 30609-7). The overall mass loading of the steady spray was 0.03, based on the overall air flow and liquid flow rate of 35 cc/min.

Two spray operating conditions were considered. The first operating condition was unsteady injection of liquid fuel at a controlled frequency. This was achieved by placing an automotive fuel injector at the entrance of the fuel supply line to the liquid fuel atomiser of the burner, which pulsated the fuel supply at a frequency of 20 Hz. The pulsed injection provided a spray with droplet concentration fluctuations at a specific frequency and, therefore, a base case to assess the phase Doppler measurements of droplet concentration fluctuations associated with the pulsating frequency. It should be noted that, since the fuel was introduced in a pipe and had to flow in it to get to the injector, the pulsed spray injected in the burner was due to pressure fluctuation of the fuel supply and the liquid flowrate was not fluctuated between zero and a maximum, but there was always a minimum amount of liquid injected in the burner due to the suction generated by the atomising air. Therefore, the imposed droplet concentration fluctuations had to be quantified independently, in order to evaluate the phase Doppler technique technique.

The second operation was with a steady supply of liquid fuel to the air-assist atomiser. However, the break-up process of the liquid jet imposed a deterministic and nearly periodic unsteadiness on the liquid spray downstream of the atomiser and the influence of the operating conditions of the atomiser on the frequency of the unsteadiness was quantified in the study of Hardalupas et al. (1996). The atomiser, which was operated with a steady fuel supply of 35 cc/min and atomising air flowrate of 15 l/min, produced a spray, which had a nearly

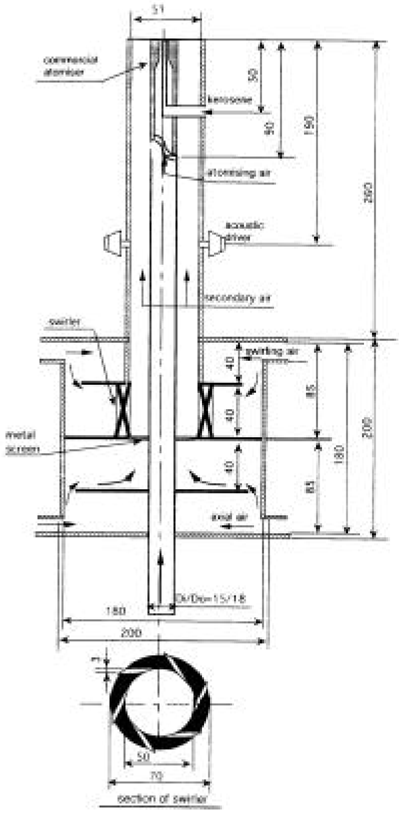

Figure 1. Set-up of the swirl burner geometry.

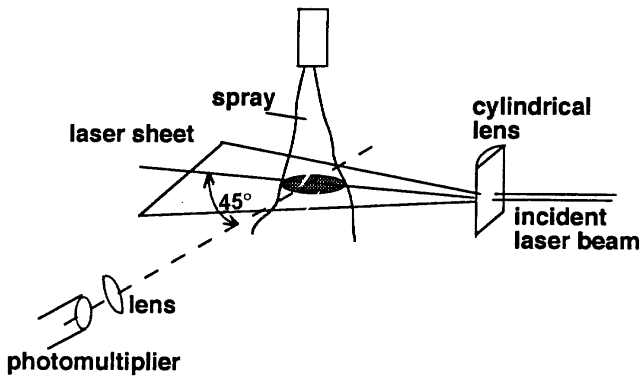

Figure 2. Set-up of the Mie-Scattering System

deterministic unsteadiness of droplet concentration in the spray with frequency around 500 Hz. However, the amplitude of the droplet concentration fluctuations associated with the unsteadiness frequency was unknown and the current work quantifies the amplitude to these deterministic fluctuations.

A single component phase Doppler anemometer (PDA) based on an Argon laser operating at 514.5 nm wavelength and power 500 mW, and collection optics located at 30° off-axis in the forward direction was used to measure time-dependent droplet diameter and velocity, as described by Hardalupas et al. (1989 and 1990). The transmitting optics were based on a rotating grating as beam splitter and frequency shifter, which provided two collimated laser beams, focused to intersect at an angle of 3.24 degrees, resulting in a probe volume of 322 μm length, a diameter of 235 μm and fringe spacing of 17.1 μm. The scattered light from the droplets crossing the probe volume was collected by a 500 mm focal length lens and, after collimation, was focused to the centre of a 3 mm x 100 μm rectangular aperture, resulting in an effective length of the probe volume of 312.5 μm. Then, the scattered light was passed through a mask with three evenly spaced rectangular apertures, before reaching three photodetectors (Hamamatsu Model R-1477). The optical arrangement of the anemometer allowed measurement of droplet diameters up to 230 μm and the resulting Doppler signals were processed with the counter described by Hardalupas & Laker (1993) to provide a Doppler frequency and phase shift proportional to velocity and diameter of the measured droplet.

Figure 2 shows the optical arrangement of a Mie-scattering technique, which was used to quantify the instantaneous droplet surface area of droplets in the spray and which was described by Hardalupas et al. (1996) and used by Tsai (1997). An Ar^+ laser, operating at 514.5 nm wavelength and power 100mW, was used to form a laser sheet by expanding the incident laser beam of diameter 1.25 mm, which was arranged to cross the spray normal to its geometrical axis, as shown in figure 2. The scattered light was collected by a lens with focal length 90 mm at an off axis angle of 45° relative to the forward direction and focused on a 1 mm pinhole placed in front of a photodetector. The receiving optics defined a rectangular probe volume of 30x40 mm with a thickness 1.25 mm in the laser sheet from where the scattered light from droplets in the spray was collected. In this way, the scattered light from all droplets in the spray crossing the laser sheet was observed up to a distance of 30 mm from the atomiser exit, since the spray width was less than 30 mm. The crossing of droplet clouds in the spray associated with the deterministic unsteadiness of the break-up process, was detected by the temporal fluctuation of the amplitude of the signal from the photodetector, which was operated within the linear dynamic range. The signals were amplified by a factor of 10 and then digitised with a sampling frequency of 2000 Hz. Since the scattered light intensity is proportional to the droplet diameter squared, the sum of the scattered light intensity from droplets crossing the probe volume in the laser sheet corresponded to the instantaneous droplet surface area. The power spectrum of the fluctuations of the intensity of the scattered light was quantified using Fast Fourier Transform (FFT) based on 16384 samples, processed in batches of 512. It should be noted that the Mie scattering technique quantified the imposed droplet concentration fluctuations in the pulsed spray to allow the evaluation of measurements with the phase Doppler technique.

Hardalupas et al. (1996) presented an analysis that links the intensity of the scattered light with the sum of droplet surface area in the probe volume for forward scattering angles between 30° and 60° and relative changes of the intensity in the spray quantified the amplitude of the temporal fluctuations of the droplet surface area in the spray with uncertainties less than 15%. Hence, the measurement of the scattered light intensity can quantify changes of droplet surface area in the spray, although it cannot distinguish between changes due to mean droplet diameter or droplet number density. However, phase-averaged droplet diameter measurements by the phase Doppler anemometer at different times of the imposed pulsation of the spray showed that the droplet diameter did not vary with time and, therefore, the temporal fluctuations of the scattered light intensity were associated with the fluctuations of droplet number density. Therefore, measurements of droplet number density fluctuations by the phase Doppler technique could be compared with the Mie scattering technique after integrating the PDA point measurements across the spray to obtain a single value of fluctuations across the spray.

3. DATA PROCESSING of PHASE DOPPLER ANEMOMETER MEASUREMENTS

The instantaneous droplet concentration was defined using the time-dependent measurements of droplet diameter, velocity and arrival time of the PDA according to two methods. The first sampling method was associated with the droplet data rate (van de Wall & Soo, 1994). Figure 3 shows an illustration of the considered quantities for this sampling method, which defines the droplet concentration c_i over a constant sampling interval Δt, as being proportional to the number of droplets K_i present within this interval and $1/\Delta t$.

$$c_i \propto \sum_{k=1}^{K_i} \frac{1}{\Delta t} = \frac{K_i}{\Delta t} \qquad (1)$$

This corresponds to sampling of the instantaneous data rate and represents the number flux of droplets through the probe volume (i.e. the units are no. of droplets/s). The second sampling method is associated with the definition of droplet number density for phase Doppler anemometer of Hardalupas & Taylor (1989), according to :

$$c^n{}_i \propto \sum_{k=1}^{K_i} \frac{t_{res,k}}{\Delta t \cdot V(d_{p,k})} \qquad (2)$$

with $V(d_p)$ being the volume of the probe volume for droplet diameter d_p, and t_{res} is the residence time of the droplet in the probe volume. The definition of equ. (2) is in agreement with the discussions of the mathematical modelling of void fraction fluctuations of Kozma (1995). The latter method is associated with the number density of the droplets (i.e. the units are no. of droplets/m^3), rather than the flux, although for flows with a dominant direction of motion, like sprays, the two approaches may lead to similar results (Hardalupas & Taylor, 1989).

The choice of the sampling time Δt in both definitions (equ. (1) & (2)) is crucial for the measurements and, is influenced by two opposing effects, namely the deterministic frequency of the fluctuations, which must be resolved, and the average data rate in the droplet flow. The frequency sets a maximum sampling time above which the desired frequency cannot be resolved and the higher the frequency, the shorter the sampling time. The average data rate determines the number of samples per unit of time and, therefore, sets a minimum sampling time below which no droplets would be present within the sampling time. Hence, if the droplet flow is dilute and the frequency of the deterministic unsteadiness to be resolved is high, it may be impossible to choose an appropriate sampling time to resolve the frequency. Fig. 3 shows an illustration of this effect.

Further description of the data processing for droplet concentration measurements is presented for data rate (equ.(1)) and the same formulation is valid for the number density (equ.(2)). For estimating the mean droplet concentration and the rms of droplet concentration fluctuations from the time-dependent data an apropriate analysis was developed as follows.

Assuming that the concentration is a continuous function, the mean and rms values are (Bendat & Piersol, 1976)

$$C = \frac{1}{T}\int_0^T c(t)dt \qquad \text{and} \qquad \overline{c'^2}^{1/2} = \sqrt{\frac{1}{T}\int_0^T c'^2(t)dt} = \sqrt{\left(\frac{1}{T}\int_0^T c^2(t)dt\right) - C^2}$$

For an equal sampling interval method with sampling time Δt, c(t) is a step function, hence the integral becomes a sum, leading to mean value :

$$C = \frac{1}{T}\sum_{i=1}^{T/\Delta t} c_i \Delta t = \frac{1}{T}\sum_{i=1}^{T/\Delta t} K_i = \frac{K}{T} \qquad (3)$$

which is the well known definition of the data rate, and rms of fluctuations :

$$\overline{c'^2}^{1/2} = \sqrt{\left(\frac{1}{T}\sum_{i=1}^{T/\Delta t} c_i^2 \Delta t\right) - C^2}\ . \qquad (4)$$

Fast Fourier Transform analysis was developed to quantify the amplitude of the fluctuations at specific range of frequencies of the spectrum. Since the instantaneous droplet concentration is strongly influenced by the random distribution of single droplets within the droplet clouds, the resulting sampled signals will have noise due to this randomness. Hence, the spectrum of fluctuating droplet concentration was estimated by first computing the

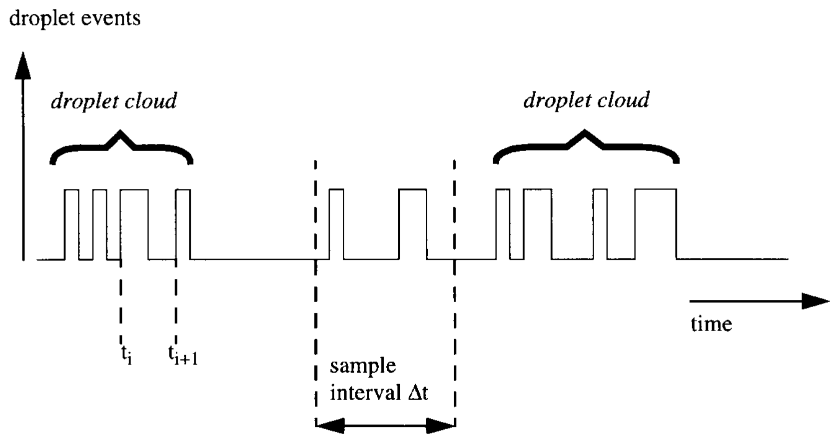

Figure 3. Illustration of droplet clouds passing through the PDA probe volume.

autocorrelation function and, subsequently, the frequency spectrum from the autocorrelation function.

4. RESULTS

The results will be presented first for the operation of the burner with a pulsating liquid fuel flowrate followed by an operating condition of the atomiser, for which, although the fuel flowrate was maintained constant in time, the breakup process generated an unsteadiness. The axial and radial distances are normalised by the outer diameter of the burner annulus, D_G.

4.1 Measurements in the spray with pulsed fuel flowrate

The measurement of concentration fluctuations using the PDA technique and data processing described above was tested in the pulsating, with frequency of 20 Hz, spray, which was injected in the swirling air flow of the burner. Figure 4 shows an example of the calculated frequency spectrum of droplet concentration fluctuations measured at a point on the burner centreline and axial distance from the burner exit of $z/D_G = 0.8$, using sampling time of 5 ms and the data rate definition of equ. (1). Figure 4 also shows the frequency spectrum of the droplet surface area fluctuations measured by the Mie-Scattering system of figure 2, which was spatially averaged over the whole spray crossing the laser sheet at axial distance $z/D_G = 0.8$. A sharp peak at a frequency of 20 Hz was detected in the spectrum by both techniques. However, the values cannot be compared, since one corresponds to a measurement at a point, while the other is spatially averaged over the whole cross section of the spray. The second maximum in the spectrum at around 92 Hz was due to light intensity fluctuations in the probe volume of the PDA system caused by the rotating grating frequency shifter, used in the transmitting optics, and corresponds to its speed of rotation. This was verified by measurements of the fluctuating light intensity in the PDA probe volume by introducing a stationary scattering target in the probe volume of the anemometer. The maximum at 92 Hz was not observed by the Mie scattering technique and this is an additional verification that was not related with the flow. The peak at frequency 20 Hz was identified by both techniques in agreement with the driving frequency of the pulsating spray, however it remains to compare the measured magnitudes of droplet concentration fluctuations.

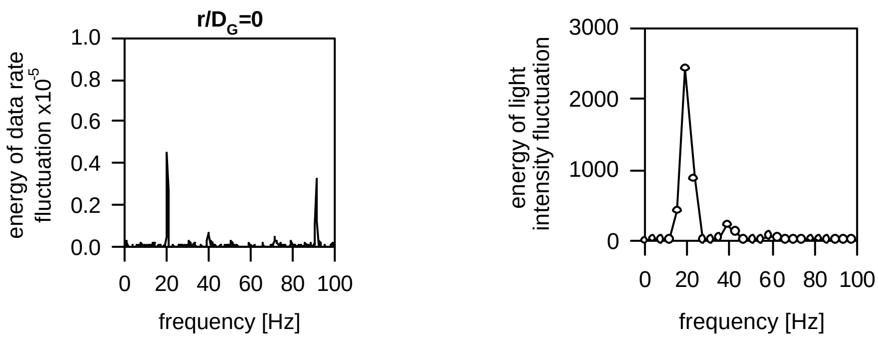

Figure 4. Left graph: Spectrum of fluctuating data rate as a measure for particle concentration based on sampling time 5 ms, measured at axial position $z/D_G = 0.8$ at the centre line. Right Graph: Spectrum of light intensity fluctuations measured using the Mie-Scattering at same axial location.

Figure 5 presents the rms of droplet concentration fluctuations in the pulsed spray, defined according to equ. (4), normalised by the mean droplet concentration (equ. (3)), measured from the time-dependent PDA data with the data rate (equ. (1)) and the number density approach (equ. (2)) as a function of sampling time Δt. Both approaches gave qualitatively the same results. The observed decrease of concentration fluctuations up to sampling times of 50 ms, corresponding to the frequency of 20 Hz, occurs due to averaging out random concentration fluctuations associated with the variation of the distribution of droplets in different droplet clouds of the pulsed spray. It is not clear, which sampling time between 1 and 25 ms, would be the appropriate value to resolve the concentration fluctuations associated with the 20 Hz pulsation. However, this choice could lead to concentration fluctuations differing by a factor of 3, as can be seen from figure 5. The problem in the choice of appropriate sampling time has also been recognised in discussions of two-phase flow modelling by Delhaye & Achard (1976). Therefore, the frequency spectrum of droplet concentration fluctuations was computed and the rms of the fluctuations of droplet concentration was evaluated from the energy within the peak at 20 Hz, since all the other energy in the spectrum can be regarded as random noise associated to random fluctuations of droplet arrival time in the probe volume. This value is then independent of the random distribution of droplets and hence independent of sampling time. It should be noted that the measurements using data rate and number density show the same qualitative behaviour.

Since the PDA technique provides point measurements, radial profiles of mean and rms of fluctuations of droplet concentration at four axial distances from the exit of the injector (z/D_G = 0.4, 0.8, 1.2 and 1.5) were measured in the pulsed spray. Figure 6 shows that the mean data rate was maximum close to the burner exit and at radial positions away from the centreline, as expected, since the injector generated a hollow cone spray which was dense close to the injector. The data rate reduced with distance as the droplets dispersed and the profiles became more uniform as the droplets became equally distributed in the spray. The rms of the fluctuations were measured from the energy present in the frequency spectrum at frequencies around 20 Hz and, in this way, avoided the contribution of random droplet fluctuations within different droplet clouds. The fluctuations were large in regions, where the mean data rate was large and followed similar behaviour as the mean data rate with axial distance from the burner exit.

The measured radial profiles of droplet concentration fluctuations in the spray have to be integrated over the whole cross section of the spray to compare the overall intensity of droplet concentration fluctuations by the phase Doppler with the Mie scattering technique. Therefore, the integrated spatially averaged mean and rms of fluctuations of the data rate across the four spray cross sections were estimated and are presented in figure 7(a).

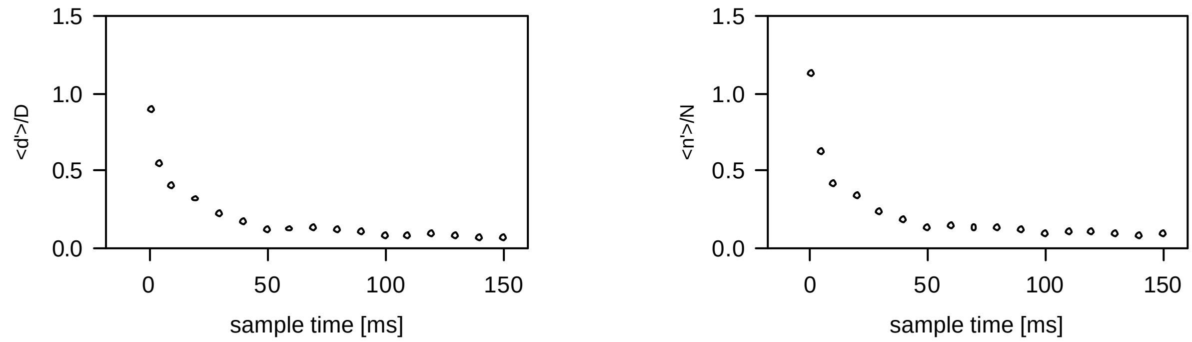

Figure 5. Ratio of rms of fluctuating droplet concentration and mean droplet concentration in the pulsed spray, using the data rate as a measure of droplet concentration (left graph) and the number density (right graph).

The PDA spatially averaged mean data rate increased with axial distance from the burner exit, since the spray became more dilute downstream, reducing the probability of multiple droplets being present in the probe volume of the anemometer and, hence, improving the validation rate of droplet measurements. This was confirmed by the increase of the validation rate of the phase Doppler by 50% with the axial distance. The rms of the fluctuations increased by a small amount with the axial distance, for similar reasons as the mean. However, the small change of the rms of fluctuations suggests that the air flow turbulence did not influence the deterministic structure of droplet clouds injected with frequency 20 Hz within the examined axial distance from the burner exit. The droplet number density was also measured according to equ. (2) and, after integration, the results were qualitative the same as for the data rate and are not presented here. It should be noted that the axial distance of z/D_G=1.5 corresponds to the length of the recirculation zone for the current burner operating conditions. This region is responsible for flame stabilisation, and therefore, the spray unsteadiness was able to survive, despite the air flow turbulence, and this may have consequences on flame stability and possibly could induce combustion oscillations.

Figure 7(b) shows the mean and rms of light scattered intensity measured by the Mie-Scattering technique, which represents the droplet surface area. The mean and rms of fluctuations of the light intensity decreased with axial distance, mainly because the edges of the spray did not cross through the probe volume, observed by the optics, as the droplets dispersed radially. The comparison of droplet concentration fluctuations and droplet surface area fluctuations is possible here, because the phase-averaged droplet diameter remained constant with time within the pulsed spray. Therefore, figure 7(c) presents the fluctuations normalised by the corresponding mean value measured by the three methods, namely the integrated data rate and number density measurements of the PDA and the light intensity of the Mie scattering technique. The agreement between the three techniques was within the experimental uncertainties of 15% and all indicate that the amplitude of the droplet concentration fluctuations associated with the pulse frequency of 20 Hz was around 25% of the mean value.

Hence, this comparison provides confidence in the PDA data processing approach and the following measurements in the spray with the steady fuel flowrate will be done with the PDA using the data rate as measure of droplet concentration. The intensity of droplet concentration fluctuation is around 0.25 to 0.30 which seems relatively low in a pulsed injection spray. However the droplet concentration was not going down to zero between the droplet clouds, which could be seen on the data from the Mie-Scattering which showed a non-zero droplet concentration between the clouds.

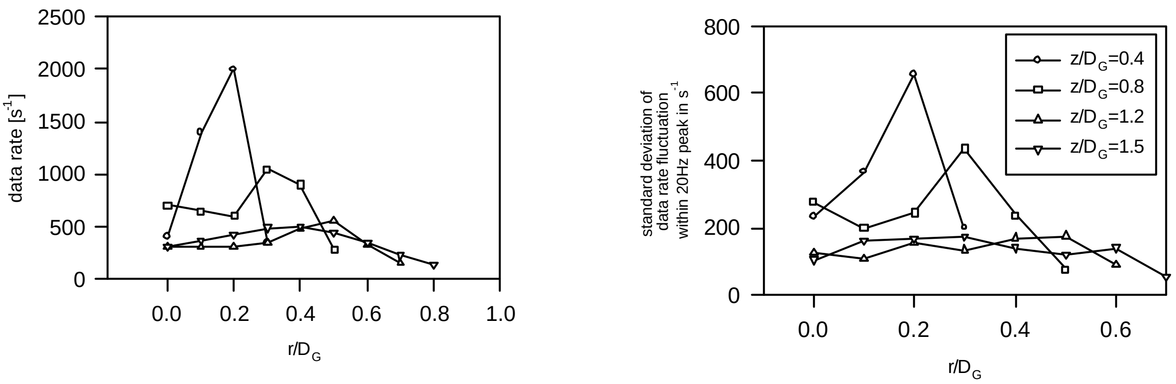

Figure 6. PDA point measurements of mean data rate (left graph) and corrected rms of data rate (right graph) by considering only the energy within the 20 Hz peak for four axial positions.

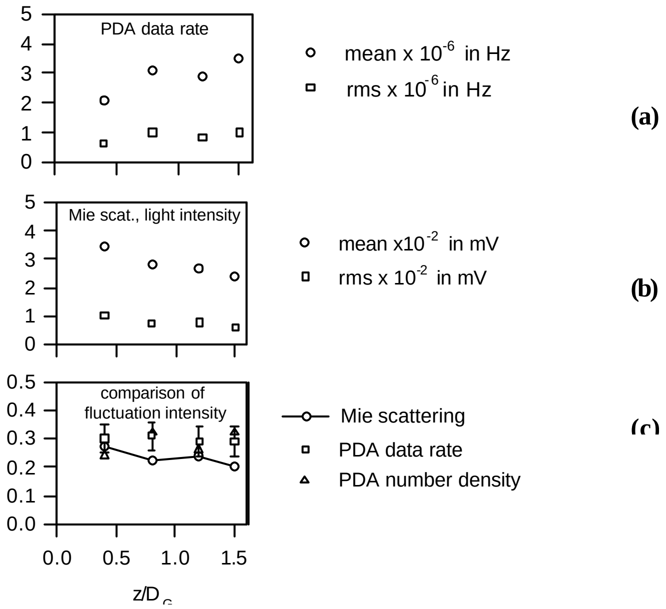

Figure 7. (a) Integrated mean and rms of data rate for four axial distances. (b) Mean and rms of light intensity fluctuations measured using the Mie-Scattering technique. (c) Comparison of measured fluctuation intensities for

4.2 Measurements in the spray with steady fuel flowrate

Measurements of instantaneous droplet concentrations and velocities were performed in the isothermal flow of the swirl-stabilised burner in the spray from the air-assist atomiser with steady fuel flowrate, and the droplet characteristics are presented in figure 8. It includes radial profiles of the axial mean and rms velocities for two droplet size classes, 1-12 μm and 30-40 μm, and mean data rate, flux and arithmetic mean diameter for three axial distances (z/D_G=0.24, 0.40 and 0.76). The reduced axial velocity of the droplets in the centre of the spray was due to the recirculating air flow. However, the droplets never reversed their motion due to the weak recirculation zone formed for swirl number of 0.6, for which the spray penetrated through the central part of the flow. The structure of the spray was hollow cone in the near nozzle region, as for the pulsed spray, and this is reflected in the droplet flux and data rate measurements, which had a minimum in the central region. The arithmetic mean diameter indicated also smaller droplet in the centre in agreement with the characteristics of hollow cone sprays.

Figure 9 presents the frequency spectrum of concentration fluctuations of two droplet size ranges, namely 1 to 20 μm and 20 to 60 μm, for two sampling times of 0.17 and 0.30 ms, measured at z/D_G=0.24 and at radial distance r/D_G=0.1. Hardalupas et al. (1996) and Tsai (1997) showed that spray unsteadiness, associated with the break-up frequency, occurred, for the current operating conditions of the atomiser, at a frequency around 600 Hz. However, the unsteadiness was not perfectly periodic and energy of fluctuations was present within a frequency bandwidth of 400 and 800 Hz. Similar observations were present in the point measurements of the PDA of figure 9 for the small and large droplet size ranges. By quantifying the energy of the fluctuations at frequencies, which were associated with the break-up unsteadiness, the intensities of droplet concentration fluctuations were estimated by calculating the energy of the power spectrum, outside the frequency range between 400 and 800 Hz, where a clear maximum was present. The square root of the area contained in the peak, minus the constant background level present in the spectra of figure 9, which was due to random fluctuations of droplet events within the droplet clouds, corresponds to the rms of the droplet concentration fluctuations due to the deterministic spray unsteadiness. Dividing this value by the mean droplet concentration quantifies the relative amplitude of the droplet concentration fluctuations due to spray unsteadiness, which was found for the spectra of figure 9 to be 0.14 and 0.15 for sampling times 0.17 and 0.30 ms respectively. Hence, the choice of sampling time was

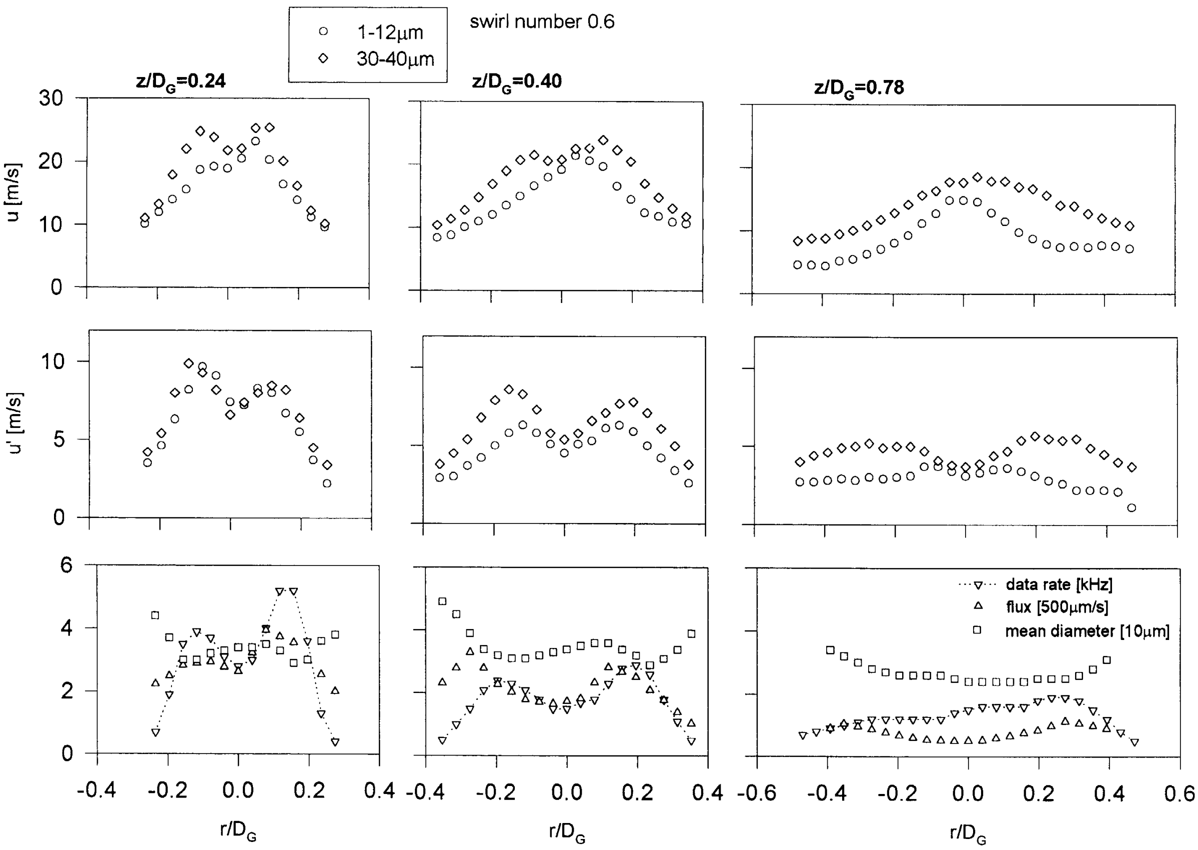

Figure 8. Radial profiles of axial velocity (mean u and rms u') for three axial distances measured in the steady spray for droplet size range 1-12 μm and 30-40 μm. The bottom row of graphs shows the measured data rate, flux and the arithmetic mean diameter (AMD).

appropriate, since the results are independent of the sampling time. It should be noted that the peak at around 100 Hz occurs, as for the pulsed spray, due to the light intensity fluctuations in the probe volume of the PDA, caused by the rotating grating. In summary, the results suggest that the amplitude of the droplet concentration

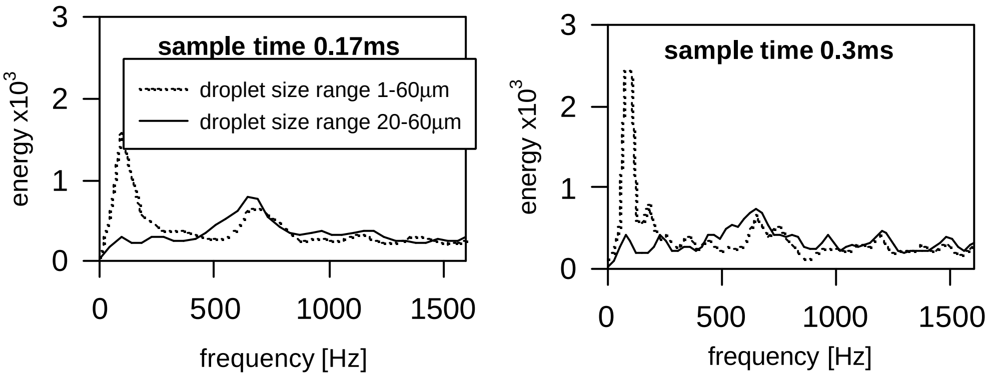

Figure 9. Spectra of fluctuating data rate measured at position z/D_G=0.24 and r/D_G=0.1 for two droplet size ranges.

fluctuations due to deterministic unsteadiness was around 15% of the mean value and the following results will indicate that this was enough to modify the air flow field.

Figure 10 shows the spectra of droplet concentration fluctuations within two droplet size ranges of 1-20 µm and 20-60 µm, based on the data rate for two axial and two radial positions. The spectra of figure 10 are presented after removing the constant background associated with random droplet events, as explained in the previous paragraph. The maximum at 92 Hz again occurs due to light intensity fluctuations in the PDA probe volume caused by the rotating grating. Figure 10 shows that this has no influence on the measurements of concentration fluctuations of droplets larger 20 µm, because large droplets are detected also when the light intensity is lower, whereas the smaller droplets are mostly measured during the high intensity part in the period of light intensity fluctuations. The results show that the amplitude of the deterministic unsteadiness at the frequency range between 400 and 800 Hz decreased with the axial and radial distance. This is expected, since increased axial distance attenuates deterministic fluctuations due to droplet interaction with the flow, and increased radial distances are in dilute regions at the edge of the sprays and the unsteadiness becomes negligibly small.

The presence of the deterministic unsteadiness of droplet concentration fluctuations could interact with the air flow field and measurements of the droplet velocity spectra within two size ranges of 1-20 µm and 20-60 µm were obtained to evaluate this possibility. Figure 11 shows the frequency spectrum of velocity fluctuations of two different droplet size ranges at axial and radial positions corresponding to those of the droplet concentration spectra of figure 10. The velocity fluctuations of the smaller droplets were associated with the velocity fluctuations of the air flow turbulence and a precessing vortex, present in the central region due to the swirling component of the flow, since these droplets can respond faithfully to the air flow. Therefore, the velocity fluctuations of the small droplets had energy spread over a wide range of frequencies from below 100 Hz up to 800 Hz, as expected for a turbulent flow, and the increased energy at low frequencies was associated with air flow precession. However, in regions where droplet concentration fluctuations were higher (see figure 10 at z/D_G =0.24 and r/D_G=0.1), the velocity fluctuations of the small droplets had increased energy at around 600 Hz. In regions where the deterministic concentration fluctuations were low (see figure 10 at z/D_G=0.39 and r/D_G=0.2), the velocity fluctuations of the small droplets was negligible in the range of frequencies of the deterministic unsteadiness. The velocity of the larger droplets was not influenced by the air flow fluctuations and maintained the fluctuations associated with the break-up unsteadiness produced by the atomiser at a frequency of around 600 Hz, even when the droplet concentration fluctuations were reduced. These measurements show that droplet concentration fluctuations of around 15% can lead to modification of the air flow field, so that increased velocity fluctuations appear at the frequency of the spray unsteadiness. This may suggest that increased deterministic droplet unsteadiness may lead to amplified deterministic fluctuations of air flow field and lead to increased instabilities in combustion.

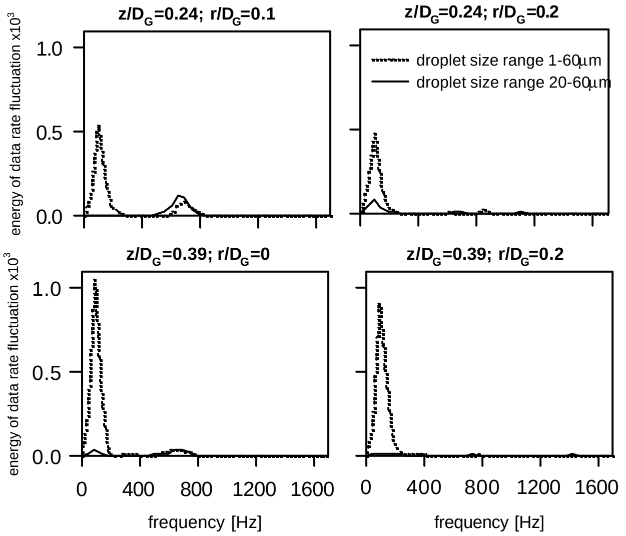

Figure 10. Variation of concentration fluctuations at two axial and two radial positions for two droplet size ranges.

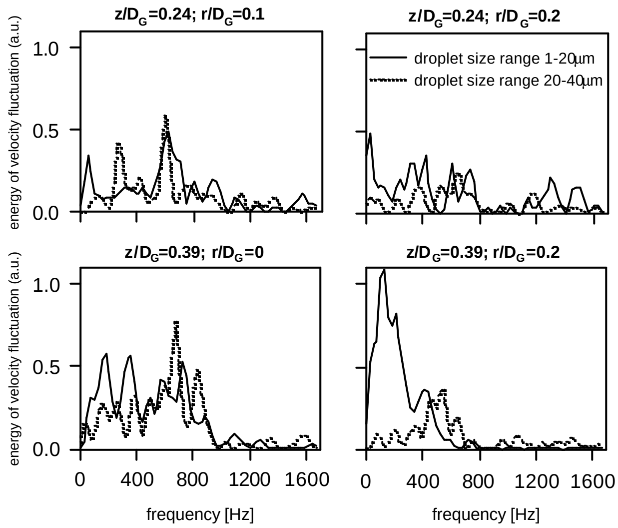

Figure 11. Velocity fluctuations at same positions as fig. 10, for two droplet size ranges.

5. SUMMARY

A data processing technique to measure temporal fluctuations of instantaneous droplet concentration using phase Doppler anemometry was developed and evaluated by comparing it with a Mie scattering technique for measurements in a pulsed spray with a frequency of 20 Hz injected in a swirling stabilised burner. Deterministic droplet concentration fluctuations were quantified by computing the frequency spectrum of droplet concentration fluctuations and removing the average value of the power spectrum, corresponding to fluctuations due to random appearance of single droplet events within coherent droplet clouds. The square root of the area, which is contained within the frequency bandwidth associated with the deterministic unsteadiness of droplet clouds above the random fluctuations, corresponds to the rms value of the deterministic droplet concentration fluctuations. The phase Doppler measurements of instantaneous droplet concentration, based on droplet data rate or number density, were within 15% of the Mie scattering light intensity measurements, which was the experimental uncertainty.

The developed technique was applied in a fuel spray operating with steady fuel flowrate in the swirl stabilised burner and quantified the amplitude of deterministic droplet concentration fluctuations, caused by the break-up process of the liquid fuel at the atomiser, to be 15% of the mean value. Frequency spectra of velocity and concentration fluctuations of droplet sizes 1-20 and 20-60 μm were measured. The small droplets had velocity fluctuations at wide range of frequencies associated with response to flow turbulence and increased energy of fluctuations at a frequency bandwidth associated with the deterministic spray unsteadiness. This shows that deterministic fluctuations of the droplet concencentration of 15% is capable to modify the air flow field and generate deterministic fluctuations correlated with the concentration fluctuations. The large droplets did not respond to flow turbulence and maintained the deterministic unsteadiness of the break-up process over axial distances of around one burner diameter in the flow, even when the droplet concentration fluctuations were reduced.

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