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Experimental Investigation of a Pressure Swirl Atomizer Spray

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The fuel injector has an important role in the process for an efficient combustion because it increases the specific surface area of the fuel and it allows one to reach high rates of mixing and evaporation. This paper has focused on the behavior of kerosene Jet A-1 spray produced by commercial pressure swirl atomizers in terms of mean diameter distributions, velocity component profiles, and cone angle variations over time. The analysis has been carried out experimentally with the aid of a phase-Doppler anemometer system, which provides drop sizes and velocities. The fluctuating behavior of the spray has been analyzed also with a fast imaging technique by means of a high-speed charge-coupled device camera. The instantaneous spray cone angle, estimated with a digital image analysis, has shown that the average cone angle roughly equals the one calculated with phase-Doppler anemometer data, and that it is different from its nominal value. A preliminary investigation into the frequency domain has shown two oscillation modes at low frequency around 100 Hz and at high frequency around 1800 Hz. This issue is a key result because spray oscillations affect the flame stability and the resulting combustion efficiency because a change in the local air/fuel mixture ratio is induced.

Nomenclature

D_{10}	=	mean droplet diameter
D_{32}	=	Sauter mean diameter (SMD)
N	=	number of droplets
r	=	radial coordinate
$r\,\mathrm{max}$	=	radial coordinate of the maximum axial velocity (minimum droplet diameter)
x	=	distance from the nozzle's exit
θ	=	nominal half-angle of the spray cone
θ_e	=	effective half-angle of the spray cone
λ	=	wavelength

I. Introduction

IN MODERN aircraft engine combustors the atomization characteristics of fuel nozzles as defined by the spray dispersion angle, droplet size and velocity distributions, and fuel vaporization play an important role in determining the combustor performance. The process of liquid atomization and evaporation are very important for the performance of a gas turbine combustion system [1]. Normal liquid fuels are not sufficiently volatile to produce the required vapor for ignition and combustion unless they are atomized into a large number of droplets with corresponding increased surface area. The influence of drop size on ignition is very important, because increases in ignition energy are needed to compensate a slight increase in mean drop size. Poor atomization produces degraded ignition performance, bad mixing, and increase in pollutant emissions. If the atomization quality is good, the rate of fuel evaporation will be fast and there will be a proper mixing of fuel and air, which results in better combustion and emission control [2].

Pressure swirl atomizers (simplex atomizers) are widely used in gas turbine combustors, industrial and domestic burners, rocket engines, diesel engines, spark ignition engines, and in many other engineering areas. The operating principle of these devices relies on the conversion of pressure into kinetic energy to achieve a high relative velocity of the liquid with respect to the surrounding gas, by means of a nozzle. Here, a swirling motion is imparted to the liquid so that, under the action of the centrifugal force, it spreads as a conical sheet as soon as it leaves the nozzle's orifice. Figure 1 shows a schematic view of a typical hollow cone nozzle which is, indeed, a pressure swirl atomizer.

The liquid is fed into a swirl chamber through tangential ports that impart to the liquid a high angular velocity creating an air cored vortex. The swirling motion forces the fluid against the walls, so that the fluid exits the nozzle as a thin sheet (very close to the nozzle exit) which spreads radially outward forming a hollow cone spray. Fuel is injected at high speed; a liquid sheet is prone to the Kelvin–Helmholtz instability caused by the large slip velocity between the liquid sheet itself and ambient air. The instability causes the liquid sheet to break into ligaments, and then into drops, in the form of a well-defined hollow cone spray (Fig. 2). The atomization process which occurs in swirl injectors is driven not only by the liquid sheet breakup but also by the collision between droplets and the interaction between drops and air [3–5].

The investigation of their performance has been the objective of a large number of studies. Many researchers studied the liquid atomization in these nozzles, as it is very crucial to the combustion of liquid fuel; in particular, Lefebvre [6,7] has given an important contribution. To understand the spray characteristics formed by swirl injectors, many investigations of fuel liquid sprays have been carried

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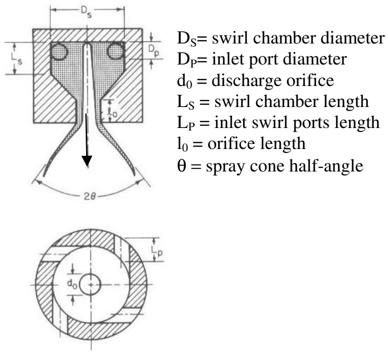

Fig. 1 Schematic of the hollow cone nozzle ([1]).

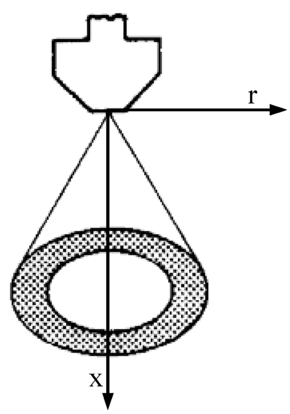

Fig. 2 Spray produced by hollow cone nozzles ([1]).

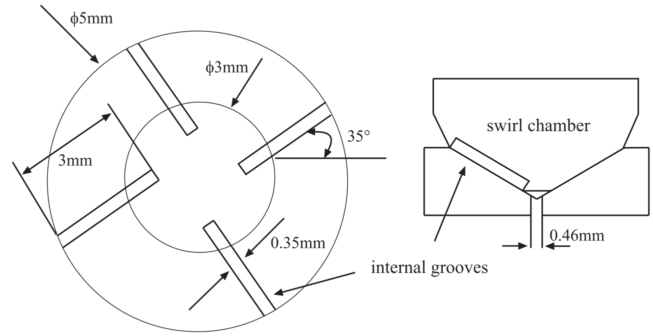

Fig. 3 Hollow cone nozzle (Delavan).

out using several measurement techniques, such as laser induced fluorescence (LIF) [8–12], phase-Doppler anemometer (PDA) [13–17], and a laser sheet method with a high-speed camera [18–21].

This work is completely experimental and has been conducted by using optical diagnostic techniques, in particular, PDA to measure the velocity and size of the droplets, and a high-speed video camera to analyze the fluctuating behavior of the spray cone angle. The spray cone angle produced by pressure swirl atomizers is of special importance in their application to combustion systems, because the spray angle exercises a strong influence on ignition performance, flame blowout limits, and the pollutant emissions of unburned hydrocarbons. Therefore, potential unsteady behaviors from such a type of nozzle are of great relevance because they may excite other types of oscillations which, in turn, can make the whole combustion process unstable. That is because the fluctuations in the fuel flow rate produce oscillations in the heat release rate and so they are a major cause of combustion oscillations in many combustion systems.

In summary, the focus of this study is to provide a well-defined and complete database regarding an isothermal hollow cone spray, useful for model validation and for its correct applications.

II. Experimental Setup

The atomizer selected for this study is a simplex pressure swirl nozzle, which produces a hollow cone spray, manufactured by the Delavan Corporation (mod. WDA 3,0-80^0); a schematic of the atomizer internal geometry is shown in Fig. 3.

In particular, the nozzle exit diameter is 0.46 mm, the nominal spray cone angle is 80 deg, and the nominal flow rate at 7 bar gauge pressure is 10.2 l/h. The liquid chosen for this study is kerosene Jet A-1.

The atomizer is set up on a vertical test stand which allows the atomizer itself to translate both in vertical and horizontal directions relative to a fixed control volume to within 0.1 mm, to make the measurement possible in several points in the vertical plane. Liquid kerosene, coming from a storage tank, is pressurized with nitrogen contained in a cylinder, and vertically injected into the environment. Kerosene is, finally, exhausted into a refuse tank.

Droplet sizes and velocities have been measured by a two component phase-Doppler anemometer. The latter is composed of an Ar-ion laser, as a light source, and a PDA Dantec system which includes a Bragg cell, transmitter and receiver probes, and flow software to process the signals and to acquire the required output quantities. The Bragg cell is used to shift the Doppler frequency of one beam for each wavelength for the purpose of direction recognition of the velocities; in particular the frequency imposed is 40 kHz. The laser beam wavelengths are 514.5 and 488 nm, for the axial and radial component of the velocity measurement, respectively. The laser power is typically 25 mW per beam. The scattered light is collected by a receiving lens with a focal length of 310 mm. The light scattering angle for kerosene at ambient temperature is 70 deg which equals Brewster's angle, and so light reflection is completely absent. Drop sizes assuming spherical particles have been measured in first order refraction. The measuring error for the velocity is estimated to be around 1%; the uncertainty of the droplet size measurements is about ±5%, which is due to possible optical misalignments and to errors in the photomultiplier voltage setting [15].

The PDA measurements of drop sizes and drop velocities have been performed in different planes downstream of the atomizer tip ($x = 0$), from $x = 8$ mm up to $x = 20$ mm. In each plane, measurements have been carried out along the radial coordinate at several points. Each measurement has been conducted either acquiring a maximum number of 100,000 samples or taking 30 s times.

The analysis of the fluctuating behavior of the spray and the measurement of the average spray cone angle has been carried out with a little bit different experimental setup that is schematically depicted in Fig. 4.

The spray was generated by pumping kerosene from a storage tank, charging the tank with pressurized air regulated to 7 bar, and opening the valve between the tank and the line running to the swirl injector. A laser sheet generated by a laser source ($\lambda = 514.5$ nm) and a cylindrical lens, passing through the nozzle axis, intercepts the hollow cone spray at a distance of 5 mm above the exit of the nozzle.

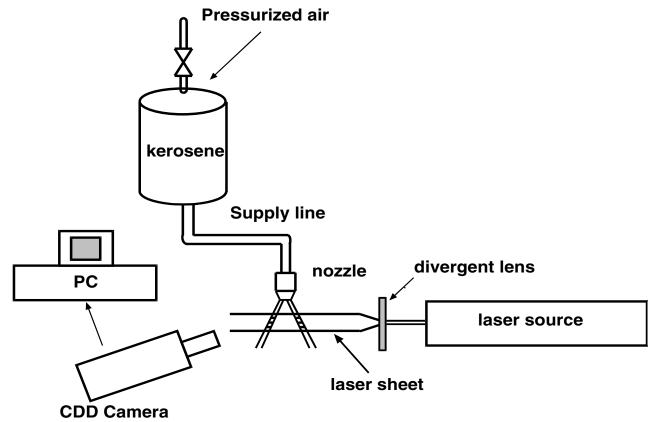

Fig. 4 Schematic of imaging analysis setup.

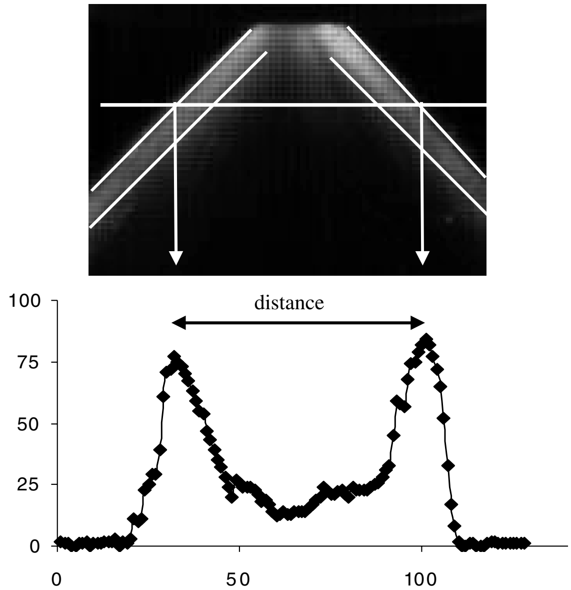

Fig. 5 Investigated Mie scattering area and scattered intensity profile.

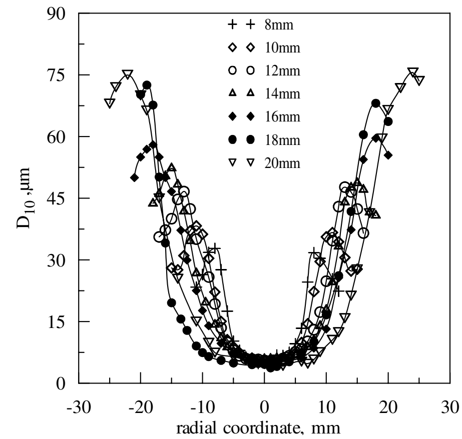

Fig. 6 Radial profiles of the mean diameter at several heights above the nozzle.

Through the axial plane of the hollow cone spray, the laser sheet induces the light scattering from the outer spray droplets so that the variation of the cone angle over the elapsed time between successive frames can be observed. The light scattered by droplets is recorded by a CCD high-speed camera (30–10,000 frames/s) which is positioned at 90 deg with respect to the laser sheet. The camera has been set to a shutter speed of 3000 Hz for the first test series and of 10,000 for the second one.

A digital analysis of the recorded images allowed us to draw some considerations about the spray behavior. By fixing an area inside the spray, it is interesting to study the fluctuation of the Mie scattering intensity of the spray and, hence, the cone angle variation.

Measured light intensity variations are caused by the changes of the spatial distribution of the droplets inside the considered area. Within each frame, an estimate of the instantaneous cone angle has been made by dividing the interested area into a number of horizontal lines and locating, over the radial coordinate of these lines, the intensity peaks which roughly correspond to the spray boundaries (Fig. 5). Taking the half-distance between the peaks of the scattered intensity profiles for all the given lines, a set of $r\,\max - x$ data have been generated; then, by linearly fitting these data, a spray cone angle has been derived. After processing all the frames acquired, the spray cone angle as a function of time has been measured.

III. Results and Discussion

A. Phase-Doppler Anemometry Measurements

Mean droplet diameters are plotted against the radial coordinate at several heights above the nozzle. Figures 6 and 7 depict the radial profiles of mean diameter D_{10},

$$D_{10} = \sum_{i=1}^{N} d_i / N \tag{1}$$

where d_i is the diameter of the ith droplet, N is the total number of samples, and the Sauter mean droplet diameter (SMD), D_{32}

$$D_{32} = \sum_{i=1}^{N} d_1^3 \Big/ \sum_{i=1}^{N} d_1^2 \tag{2}$$

The analysis of these figures shows that most of the biggest drops are concentrated at the outer edges of a conical spray pattern, and the mean diameter distributions are axially symmetric.

In particular, Fig. 6 exhibits a maximum diameter value of about 75 μm at 20 mm from the edge of the nozzle and at the peripheral boundary of the spray. From this plot, it is possible to note that at the centerline the droplets have small diameters of about 5 μm or slightly higher. Actually, the lowest drop size measurable with a PDA system is around 3 μm, so drops smaller than 5 μm cannot likely be detected. The drop sizes rapidly increase at the periphery, so the largest ones are confined on the spray boundary. The curve shows a maximum at the spray periphery which increases with the distance from the atomizer exit and moves, of course, away from the axis following the spray angle. This, in practice, means that the curves are substantially similar. More specifically, the diameter profiles relative to the different heights are practically the same in the spray central zone, whereas at the boundary the situation changes showing a little dependence of the diameter on the distance from the exit.

The SMD profiles, as a function of the radial coordinate and for different heights above the nozzle, are reported in Fig. 7. The plot exhibits a minimum value of 10 μm and a maximum value of 110 μm. This graph shows an axial symmetry of the SMD distributions and, following the variation of the maximum point along the radius, it is possible to estimate the spray cone angle.

Actually, the smaller particles are progressively brought toward the center for the aerodynamic effects generated by the entrained air caused by the larger drops. Indeed, as shown in the literature, the fuel is injected with high velocity and an airflow is induced into the spray almost at right angles to the spray sheet. The smaller drops can easily follow this inward flow, whereas the larger ones follow their ballistic trajectories along the periphery of the spray. This issue leads to a high concentration of the smaller droplets in the hollow zone, surrounded by a cloud of droplets with greater size on the periphery.

In analogy to the droplet diameter distribution, Fig. 8 shows the droplet mean axial velocity component as a function of the radial coordinate for several heights above the nozzle. All profiles have two peaks and exhibit values ranging between 5 and 15 m/s, which are relative to the velocity at 8 mm from the exit.

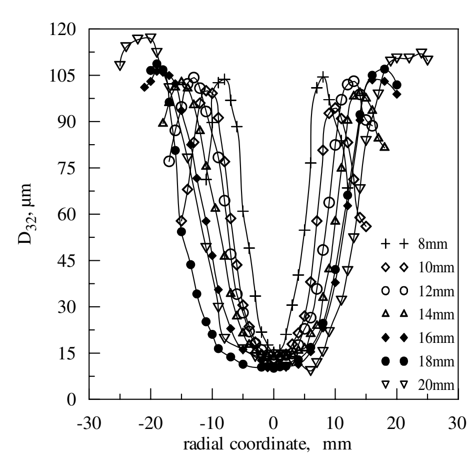

Fig. 7 Radial profiles of SMD at several heights above the nozzle.

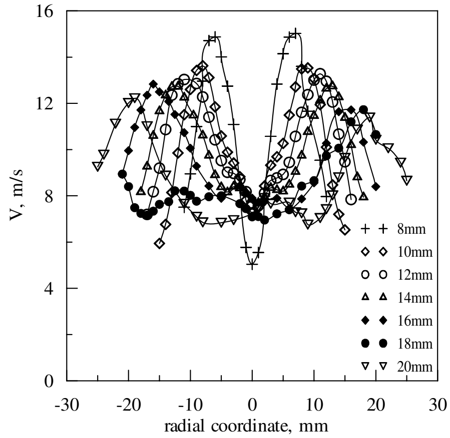

Fig. 8 Radial profiles of mean axial velocity component.

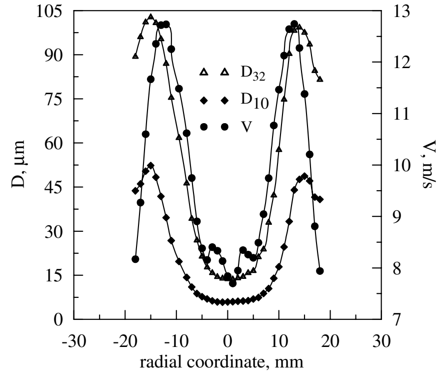

Fig. 9 Comparison between the profiles of D_{32}, D_{10}, and axial velocity ($x = 14$ mm).

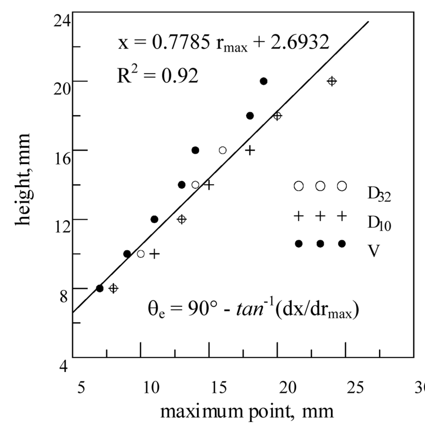

Fig. 10 Distance from the exit of the nozzle as a function of the maximum point (r max).

The flowfield is axially symmetric with a minimum at the center of the spray and a maximum at the periphery which moves to higher values of the radial coordinate as the distance from the nozzle increases. This is because in this type of nozzle the liquid emerges from it as a conical sheet and the center is characterized by the air core where the velocities are low because they are originating from entrainment flow. Furthermore, the maximum velocities decrease as the distance from the nozzle increases. This can be explained considering that, farther downstream of the nozzle exit, the droplet velocity is less influenced by the injection velocity of the liquid fuel and, on the other hand, it is more influenced by the interaction with the ambient air that causes a slower motion of the droplets.

All these results are in general good agreement with the ones from other works ([16,17]), in particular, values of SMD derived in this study are compared to those coming from the semi-empirical relationship developed by Wang and Lefebvre ([6]). The maximum difference between the measured data and their relation is about 40%. This disagreement is probably due to the different measurement techniques which have been reported to have uncertainty around 10%. In the literature several relationships for SMD exist, but only the Wang and Lefebvre relation seems to fit the experimental data of pressure swirl atomizers, because this one is based on the most comprehensive analysis.

However, this work is much more complete and then it may be considered useful for the validation of codes explicitly dedicated to the study of this special type of atomizer.

B. Estimate of the Average Effective Cone Angle

An elementary estimate of the effective average cone angle of the spray ensuing from the nozzle can be made by analyzing the radial profiles of the mean diameters and of the axial velocity. Observing that the spray configuration is characterized by a hollow zone at the center, as was clearly evidenced by the diagrams shown earlier, the boundary of the spray has been identified as the locus of the radial maximum points of both the diameters and axial velocity. This procedure is believed appropriate on the basis of the similarity between the shapes of the profiles of these three quantities although, of course, the droplet's diameter increases and the velocity decreases far from the nozzle. For the sake of comparison in Fig. 9, D_{32} and D_{10} mean diameter profiles and the axial velocity profile at 14 mm distance from the exit of the nozzle are shown, confirming that they are approximately similar.

Reporting the height above the nozzle as a function of the radial coordinate corresponding to the maximum values of the velocity, mean diameter, and Sauter mean diameter (r max) and by fitting the data with a straight line, the effective angle has been calculated based on the slope of this line. The results are shown in Fig. 10 in which the equation representing the linear spray spreading, with the relative squared correlation factor, is reported.

In Fig. 11 the profiles of D_{10} mean diameters are depicted in correspondence to the scaled heights from the nozzle exit in a

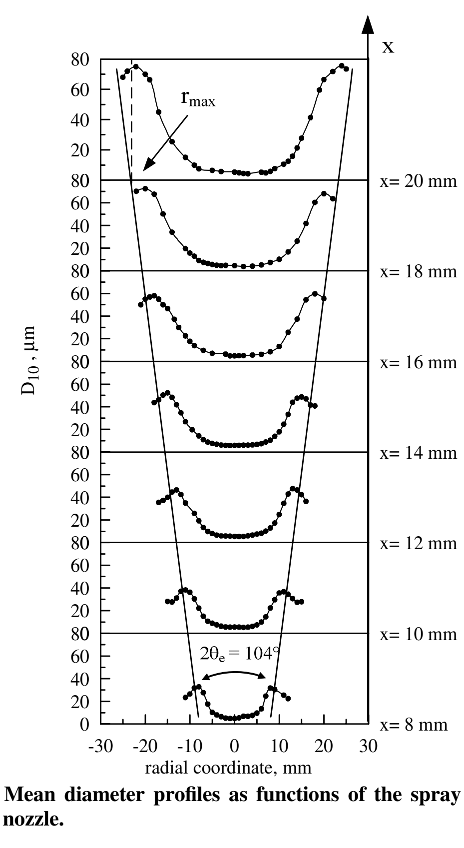

Fig. 11 Mean diameter profiles as functions of the spray spreading from the nozzle.

diagram representing the correct spreading of the spray, whose approximated boundaries are delineated with two straight lines.

In conclusion, the calculated values of the effective cone angles are 104 deg for the nominal spray cone angles of 80 deg.

C. Investigation of Hollow Cone Spray Fluctuations

The fluctuating spray behavior due to local instabilities has been analyzed by means of a high-speed CCD camera (30–10, 000 frames/s). The procedure used to find the mean cone angle is practically identical to the one described earlier except for the fact that the diameters and velocity profiles are substituted with the light scattered intensity profile as described earlier.

In Fig. 12 the average cone angle versus time is plotted for two sampling rates; it is possible to note that the average value of the cone angle for both tests is about 98 deg, but the ranges of values are different.

The histogram of the measured spray angles with the sampling rate of 3000 frames/s shown in Fig. 13a shows a peak at the mean angle value of 98 deg. According to the figure the lowest value is 90 deg, and the highest value is 108 deg.

In Fig. 13b the histogram of spray cone angles for a sampling rate of 10, 000 frames/s is plotted, and it is evident that, even in this case, the same peak value is obtained, but the range of the angles is different, in fact, the lowest value is 65 deg and the highest is 114 deg highlighting a bias at small angles.

Note that the difference between the results obtained with the two sampling rates concerning the lower and higher values of the measured angle (well clear comparing Figs. 13a and 13b) can be due to the fact that at the slower sampling frequency (3000 frames/s, Fig. 13a) the data are likely to be affected by aliasing. Indeed, as we will see later in Fig. 14, the principal component appearing in the power spectrum of the acquired data is around 1800 Hz, which is above the Nyquist frequency.

A power spectrum (PS) analysis of the spray cone angle and scattered light intensity has been carried out for both sampling rates.

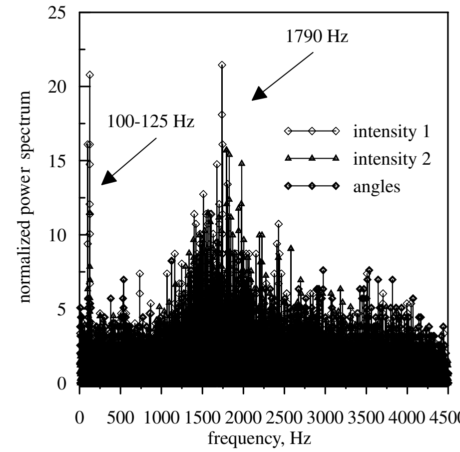

Fig. 14 Power spectrum.

Figure 14 plots the normalized PS (data have been divided by the relative average values) of the cone angle and Mie scattering intensity in two regions of each frame, obtained with 10, 000 frames/s sampling rate to which corresponds a frequency resolution of 0.46 Hz. Intensity 1 and intensity 2 in Fig. 14 refer to the light intensity averaged over the right and left subparts of the frame, respectively. The signal has been low pass filtered with an antialiasing filter.

From this figure, three characteristic frequencies of the fluctuating behavior of the spray can be noted: the first two are located around 100–125 Hz and are distinguishable as clear peaks in the power spectrum, while the other one is characterized by a broad band peak at around 1790 Hz. The same behavior is present in all three quantities taken into account.

With this preliminary work, no definite explanations can be given for the measured oscillations. However, this fluctuating behavior of

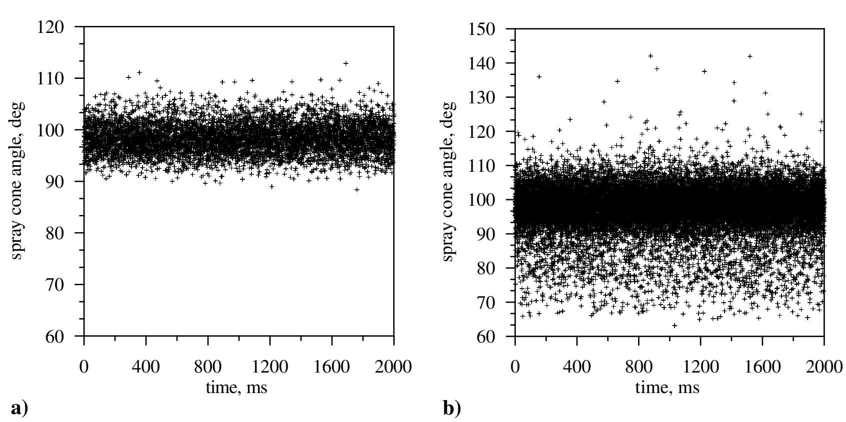

Fig. 12 Average cone angle versus time: a) 3000 frames/s; b) 10, 000 frames/s.

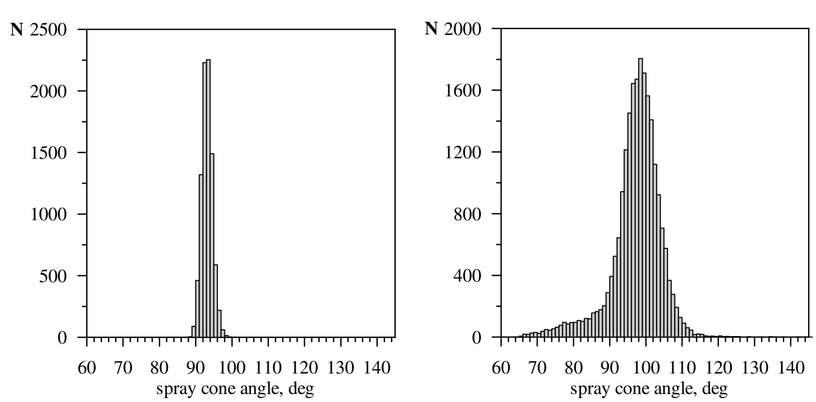

Fig. 13 Average cone angle for sampling rate of a) 3000 frames/s; b) 10, 000 frames/s.

the spray angle may be connected to the flowfield in the swirl chamber of the pressure swirl atomizer. Despite the geometrical simplicity of this kind of atomizer, the flow in the nozzle is highly complex. In particular, the flow is two-phase, turbulent and unsteady with regions of recirculation and an air core vortex with liquid/gas interfaces that exhibit unsteadiness and instabilities. Ma [22] investigated experimentally the flowfield in the swirl chamber and he concluded that the internal flowfield is generally symmetric and, principally, that the turbulence is the main reason causing the large fluctuations inside the chamber. Because the internal flow characteristics in the pressure swirl atomizer govern the properties of the sheet formed at the orifice exit, it is more likely that the dynamics of the spray cone angle will be influenced by that unsteadiness.

IV. Conclusions

Although the main aspects of pressure swirl atomizers are basically known, a full understanding of the spray behavior in terms of droplet size, velocity distributions, and spray cone angle cannot be inferred precisely without an experimental investigation into the specific configuration.

In this paper some remarks about the results from the spray in quiescent air conditions have been addressed; in particular, considerations on mean diameter distributions, velocity component profiles, and cone angle variations over time have been reported.

Analyzing the radial profiles of mean diameter and velocity, the average spray cone angle has been estimated. These results have been compared to those deriving from the imaging analysis for the nozzle, and the conclusion is that the results substantially coincide, in fact, the result relative to the analysis from the radial profiles is 104 deg against 98 deg deriving from the fast imaging analysis.

Together with the spray cone angle, the Mie scattering intensity averaged over some given regions in the spray have revealed an important result concerning the fluctuating behavior of the spray. A preliminary investigation into the frequency domain has shown two oscillation modes at low frequency around 100 Hz and at high frequency around 1800 Hz. This behavior can be attributed to the geometry of the nozzle, in particular, to the flow inside the swirl chamber and to the sheet breakup at the discharge orifice.

This issue has an important practical implication because spray oscillations affect the flame stability and the resulting combustion efficiency because a change in the local air/fuel mixture ratio is induced. In particular, if the low frequency of the spray goes in resonant condition with the frequency of the combustion, it will be dangerous for the system.

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