Laser Scattering Patternator: a novel technique for the measurement of industrial, optically dense sprays

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A novel non-intrusive, laser based instrument for the characterization of optically dense, industrial sprays is presented. It is based on the combined application of phase-Doppler and 90º Mie-scattering measurements. The phase-Doppler data is used to obtain spatially resolved statistical information of the spray velocity-size correlation. This is complemented with Mie-scattering measurements to resolve the spray volume-flux distribution within a plane located at a certain distance from the injector location. The information extracted from the phase-Doppler technique is highly insensitive to the optical noise that characterize optically dense, industrial spray situations. A dedicated, novel algorithm is used to correct the data obtained from the Mie-scattering sensor for the effects of optical noise introduced by dense sprays. The technique has been exposed to a metrological study using gas turbine spray nozzles with volume flows as high as 150 liter/hour and optical attenuation levels higher than 90%. Strategies to reduce the number of needed phase-Doppler measurements are presented that allow to greatly reduce the total characterization time per nozzle, making the technique valuable for industrial spray quality control efforts.

1. Introduction

There are a number of spray technology applications where is it of mayor concern determining how the spray nozzle distributes the input volume flowrate at a certain distance from the injection point. Such measurements often consist on the characterization of the spray volume flux (volume per unit time per unit surface) crossing a measurement plane perpendicular to the spray nozzle axis. For example, this type of measurements are essential in sprays used in power generation applications, where the combustion efficiency and the pollutant formation levels are directly linked to how the atomizing nozzle distributes the fuel in the combustion chamber.

For gas turbine applications in the aerospace industry, a malfunction of a single atomizing nozzle leading to abnormal volume flux distributions can be sufficient to penalize the engine efficiency or its allowable pollutants formation levels, including CO, NOx, or smoke. The problem is so sensitive that every atomizing nozzle undergoes periodic quality checks prior to be mounted in the engine.

At present, there are two different techniques that can be used to carry out quantitative volume flux characterizations of spray nozzles. The first is the isokinetic patternation (IP), an intrusive measurement method where a number of aspirating, isokinetic probes are located in an array configuration at some distance from the atomizing point. The array is moved sequentially in different meridian planes to complete the spatial characterization. Although IP is a technique widely used in spray quality control checks it has some important limitations, including its intrusiveness, inaccuracy, and long characterization times.

The second method is the non-intrusive phase-Doppler technique (PD) [1], now widely used in laboratory spray characterization efforts. While the technique has proven robust for the determination of the spray velocity and size statistics, it faces mayor problems when trying to extract the volume flux information, particularly if a 1-D system is used [2-7]. The problem stems from the way in which the volume flux information is obtained, after adding the volume of all the single particles that cross a (in principle) known probe volume during a known measurement time. The mayor drawbacks are detecting all the particles passing the probe volume and the determination of the effective probe volume size, which depends on the particle size. A number of problems can complicate both aspects, including burst splitting events, non-perpendicular particle trajectories, coexistence of several particles in the probe volume, or signal drop due to light obscuration effects. Some of these problems become more significant as the spray optical density (defined for example as the level of light attenuation across the spray) is increased. Thus, for industrial sprays characterized by light attenuation levels of order unity, order one errors can be created when characterizing the volume flux. In addition, being a local counting technique, the phase-Doppler method requires long measurement times.

Other methods based on particle scattering have being developed for the measurement of dense sprays [8-9], although they do not provide spatially resolved information or they exhibit considerable complexity.

Laser scattering patternation (LSP) is a novel technique conceived to partially alleviate these limitations. It makes use of PD measurements, but only to extract size-velocity spray statistics that are highly insensitive to the optical noise problems characterizing dense sprays. The phase-Doppler characterizations are complemented with fast, 90º Mie-scattering measurements, which are corrected to take into account light attenuation effects occurring in dense sprays. The overall characterization times are reduced with respect to pure PD measurements since the phase-Doppler information needed is a smooth spatial function, thus allowing to limit the number of grid points where the PD characterizations must be performed.

2. LSP technique description

The technique is non-intrusive and aiming at the measurement of the spatially resolved liquid volume flux generated by industrial spray atomizing nozzles. The spatial resolution refers to the determination of the volume flux passing through points lying in a plane normal to the injector axis and located some distance from it (shaded plane in Figure 1). The industrial spray refers to liquid flows delivered to the nozzle as to produce order one attenuation of a laser beam passing through the spray.

The LSP technique is based on the following principles:

a) The critical element in industrial spray volume flux measurements by PD or other similar particle counting techniques is the determination of the probe volume size and effective measurement time. On the other hand, the individual size and velocity information are much more robust with respect to noise problems encountered in the industrial environments.
b) The attenuation and scattering activity in each point of the spray has a linear dependence with respect to the local spray number density.
c) Experimentally, it is found that the spatial modulation of the number density information is much more severe than that characterizing the mean spray diameters and velocity. This is related to the fluid dynamics of the atomization and spray evolution processes.

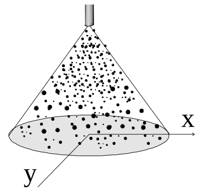

Fig. 1 Characterization geometry for the Laser Scattering Patternation technique.

A schematic view of the elements composing the LSP experimental apparatus is shown in figure 2.

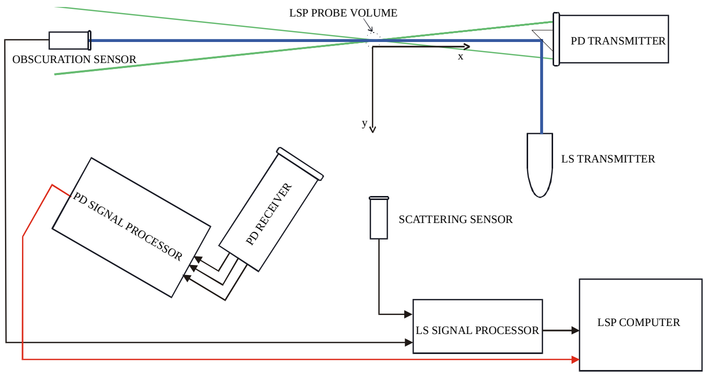

Fig. 2 Schematic lay-out of the LSP instrument.

The 90º Mie-scattering measurements are used to obtain information related to the spray number-density N_D (number of particles/unit volume):

$$N_D D_{20}^2 = N_D \int n_s(D) D^2 dD \qquad (1)$$

The information extracted from the PD measurements is connected to the spray axial velocity-size correlation:

$$\overline{DU} = \frac{\int n_s(D) D^3 U dD}{\int n_s(D) D^2 dD} \qquad (2)$$

The spray volume flux information is then obtained by combining these two quantities:

$$q = \frac{\pi}{6} \left(N_D D_{20}^2 \right) \cdot \overline{DU} \qquad (3)$$

The obscuration sensor (figure 2) is used by the Mie-scattering measurements to determine a scattering constant that allows to convert the measurements into the relevant information given by expression (1). The obscuration sensor strives to measure the attenuation of the Mie-scattering ray after passing through the spray, by using an angular filter optical arrangement able to sense light included in a 1.5 mrad cone from its optical axis. The scattering sensor is based on a small depth of field imaging system, a slit aperture that images the probe volume, and a photomultiplier. The aim is to achieve, for a point isotropic light emitter, a collected light intensity transfer function which is 1 within the probe volume and decays sharply to zero elsewhere. A view of the probe volume region showing the laser beams used by the PD measurements (green) and by the Mie-scattering measurements (blue) is shown in figure 3.

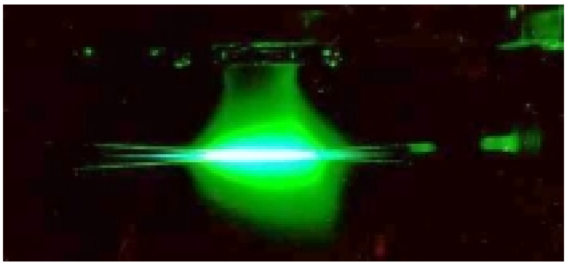

Fig. 3 Probe volume region during one spray characterization.

2.1. Mie-scattering measurements

Although, due to interference effects of superficial waves, the 90º Mie-scattering of individual, transparent droplets exposed to coherent, linearly polarized light shows sharp variations as a function of the droplet size, the oscillations are highly damped when considering particle families characterized by a finite diameter span. In this case, the smoothed scattering relationship approaches the geometrical optics limit [10]:

$$w_{sc}(D) = kND^2\,, \tag{4}$$

where $w_{sc}(D)$ is the light power produced by the N droplets of the family with size D located in the illuminated probe volume and k is a scattering constant which depends on the set-up of the scattering collecting optics. When a spray with a continuous size distribution is considered, the scattering power contains contributions from the different size classes. Expression (4) is then modified to give:

$$w_{sc} = k_1 N_D \int n_s D^2 dD = k_1 N_D D_{20}^2\,. \tag{5}$$

If the scattering is achieved by using a laser beam passing through the spray, the scattering signal is modulated by the passage of individual particles. A measurement proportional to the spatial spray number-density is obtained if the scattering power is measured as the temporal average of the instantaneous signal:

$$\overline{w}_{sc} = \frac{1}{T_{sc}} \int w_{sc}(t)dt = k_1 N_D D_{20}^2\,. \tag{6}$$

Expression (6) holds if the particles are exposed to a coherent radiation whose intensity varies over distances much bigger than the particle size ($D/d_b << 1$, with d_b denoting the gaussian diameter of the laser beam), if independent scattering conditions apply ($N_D D_{10}^3 << 1$), and if long enough scattering temporal averaging intervals are used ($T_{sc}/t_I >> 1$, with t_I denoting the a characteristic time for the spray variations, typically given by the integral time of the underlying turbulence in which the spray develops). These conditions are met except for extremely high particle concentrations.

However, in the measurement of optically dense sprays, there are two difficulties when converting the scattering signal into a magnitude proportional to N_D. First, the scattering constant k_1 must be determined. This difficulty can be properly addressed through the information provided by the light attenuation probe. In addition, the scattering measurement must be corrected to take into account that the illumination condition at the probe volume changes as a result of the light scattered by the spray material located between the laser head and the probe volume. Finally, the scattering measurement must also be corrected to take into account that the scattering signal produced at the probe volume is further attenuated by the spray material located between this region and the scattering collecting optics. For sprays with laser attenuation levels of order one, neglecting these last two aspects will cause order one errors in the estimate of the spray number density. Both problems can be circumvented by developing a specialized correction algorithm to be applied to the scattering measurements.

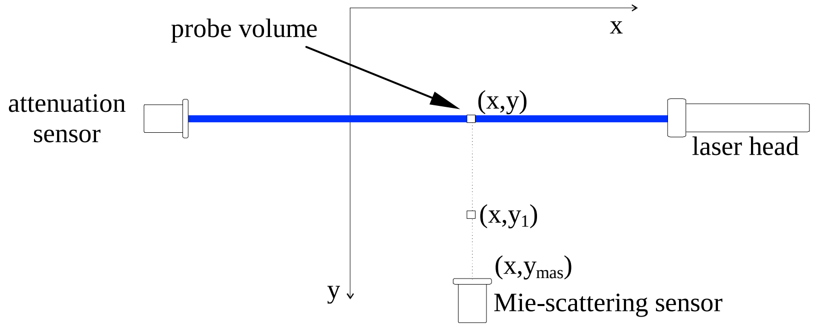

Fig. 4 Mie-scattering measurements notation.

The following notation will be used to describe the algorithm (figure 4):

a) $w_1(x,y)$: laser power available at probe volume (x,y) that is sensed by the attenuation sensor.
b) $w_2(x,y)$: laser power available at (x,y) that is sensed by the scattering sensor.
c) $w_{sc}(x,y,y_1)$: laser power scattered at (x,y) that will be ultimately measured by the scattering sensor, with y_1 being an intermediate position between the probe volume and the Mie-scattering sensor.

Equations can be written for the evolution of these quantities. Thus, w_1 follows the evolution of a beam attenuated by two different particle scattering mechanisms: the concentrated lobe diffraction, and the wide angle scattering. In the Mie-scattering regime, both contribute equally to the attenuation of w_1. Due to the small angular spread in the particle forward lobe diffraction and to the geometry details of the experimental set-up, w_2 is only reduced by the wide angle scattering. Finally, a given fraction of the mechanism creating the w_2 reduction, i.e., the wide angle scattering, is the power measured by the scattering optics, w_{sc}. These assumptions can be supported by Mie-scattering theory and by proper design of the experimental set-up. Details will be provided elsewhere, but the error in the above assumptions made for a spray with a typical 50 μm Sauter Mean Diameter can be of the order of 10^{-2}. Based on the above reasoning, difference equations can be written to describe the evolution of the light powers obtained in a measurement grid composed by a finite number of locations separated a distance Δx in the laser beam propagation direction. Specifically:

$$\Delta w_1 = \frac{\pi}{2} N_D D_{20}^2 w_1 \Delta x \Big|_{(x,y)}, \quad w_1(x_{max}, y) = w_{10} \tag{7a}$$

$$\Delta w_2 = \frac{\pi}{4} N_D D_{20}^2 w_2 \Delta x \Big|_{(x,y)} = \frac{\Delta x}{K} w_{sc}\Big|_{(x,y,y)}, \quad w_2(x_{max}, y) = w_{10}, \tag{7b}$$

with the scattering constant K being determined as part of the resolution of the scattering problem. This is achieved through the attenuation measurements.

A similar analysis can be performed to take into account the effect of the attenuation of laser light scattered at the probe volume as it travels towards the scattering receiving optics. A correction algorithm can be constructed if the number density of the spray located between the probe volume and the scattering receiving optics is known. The difference equation for the evolution of the light intensity scattered at the probe volume as it travels towards the Mie-scattering receiving optics is then:

$$\Delta w_{sc}(x,y,y_1)=\begin{cases}0 & ,\left|y-y_1\right|\le L_{sc}\\ -\frac{\pi}{4}N_D D_{20}^2\Big|_{(x,y_1)} & ,\left|y-y_1\right|>L_{sc},\end{cases} \qquad (8)$$

where L_{sc} represents the distance around the probe volume where the wide angle scattering of the light emitted from the probe volume reaches the scattering receiving optics. Equation (8) states that, after some distance from the probe volume, the scattered light is only attenuated by the large angle scattering of the spray located between the probe volume and the receiving optics location. This equation can be supported by proper configuration of the optical set-up. As before, it is possible to evaluate the errors introduced by this expression, which, for the used optical configuration, amount to a few percent in the scattered light evolution.
Proper manipulation of the above written expressions allow to completely extract the required Mie-scattering information. The algorithm, based on an advancing front strategy that resolves first the spray y locations closer to the Mie-scattering sensor, is structured so that the determination of the spray number density can be performed only with the signals given by the scattering ($w_{sc}(x,y,y_{max})$), and attenuation ($w_1(x_{min},y)$) sensors, both of them scaled with the unperturbed laser power level w_{10}. Once that the number density information has been obtained, the dense spray correction procedure allows to recalculate the light power measured by the attenuation sensor, thus providing an internal error check over the entire procedure.

2.2. Phase-Doppler measurements

The phase-Doppler measurements are needed to obtain an estimate of the velocity-size correlation given in expression (2):

$$\overline{DU}\cong\frac{\sum_i n_s(i)U(i)D^3(i)}{\sum_i n_s(i)D^2(i)}, \qquad (9)$$

where $n_S(i)$ is the spatial number-size distribution corresponding to class-diameter D(i), an information that is available from commercial PD instruments. The determination of the spatial number-size distribution requires knowledge of the probe volume size. However, only a relative figure of the probe volume size with respect to a reference value (for example, that associated to the biggest particles) is required. Furthermore, the number size information appears both in the numerator and denominator of expression (9). Both aspects make the $\overline{DU}$ statistic rather insensitive to the optical noise that exists in dense spray characterizations.
Experimentally it is found that, for axi-symmetric spray nozzle configurations, the $\overline{DU}$ statistic exhibits a high azimuthal symmetry. As a result, it is possible to perform the PD characterizations only in a reduced number of points. One possible strategy is to perform PD measurements just along the x and y axis shown in figure 2 and to interpolate the $\overline{DU}$ data in the rest of grid points where the Mie-scattering measurements are performed. Thus, for a volume flux characterization surface composed of 16x16 points only 32 PD measurements are needed. It is found that, with respect to a full PD characterization, small errors are born from this procedure.

3. Results

When measuring low number density sprays with small cone angles and small light attenuation levels, the results obtained from the LSP technique can be compared to volume flux measurements obtained with the PD method, since, in these conditions, the latter should give accurate results. Figure 5 shows the outcome of such a comparison. A nominal 5 liter/hour nozzle was operated in a small pressure drop mode with low swirl number. The peak diametrical attenuation was 13%. A 31x31 measuring grid was used to characterize the spray. The measurement plane was located 40 mm downstream of the injection point.

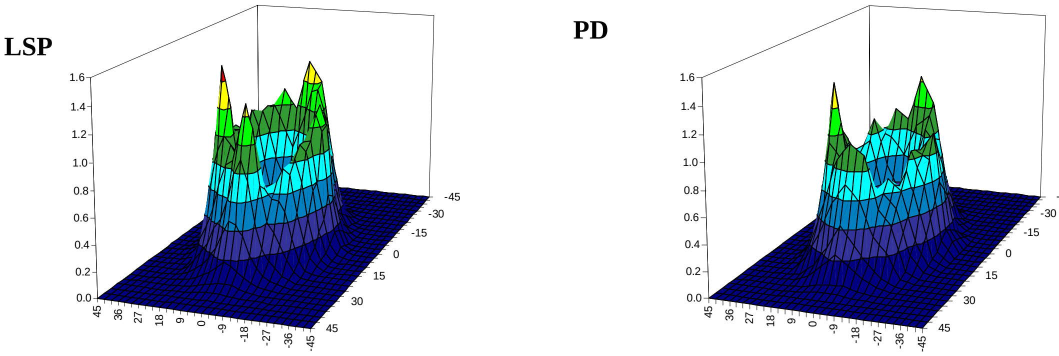

Fig. 5 LSP and phase-doppler results for a low attenuation spray. Horizontal scale: characterization location (mm). Vertical scale: volume flux ($mm^3/s/mm^2$).

It can be seen that the volume flux surfaces given by both methods are very similar, and that both reproduce also similar azimuthal non-homogeneities. The integral volume flux recovered after integration of the surfaces was 4.9 (LSP) and 5.1 (PD) liter/hour, comparing well with the metered flow input to the nozzle. The LSP results presented in figure 5 were obtained using the reduced grid for the $\overline{DU}$ statistic determination. In this way, the LSP characterization time was 1/8 of the time required by the PD characterization.

Results obtained with a large attenuation spray are given in figure 6, corresponding to a high swirl, large cone angle, 150 liter/hour nozzle. In this case the cross-spray attenuation levels were as high as 90%. The PD characterizations overpredicted the input volume flux almost by 100%. However, the integration of the surface given in figure 6 exhibited a 6% error with respect to the nominal input flowrate.

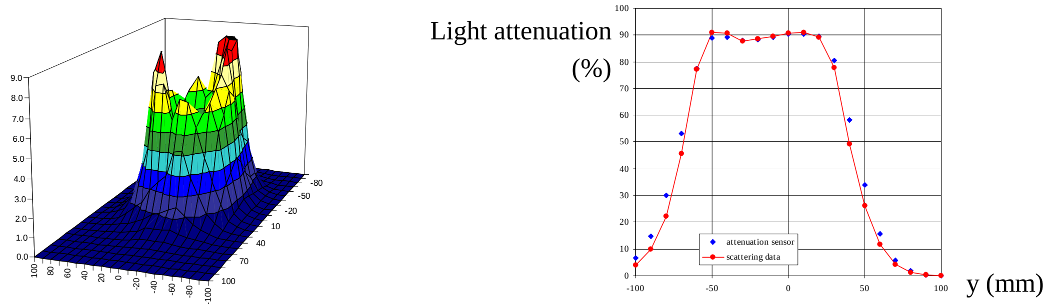

Fig. 6 LSP results for a high throughput (150 liter/hour) spray. Left: volume flux surface (axis similar to those of figure 5). Right: spray attenuation as measured with the attenuation sensor and reconstructed from the computed scattering data.

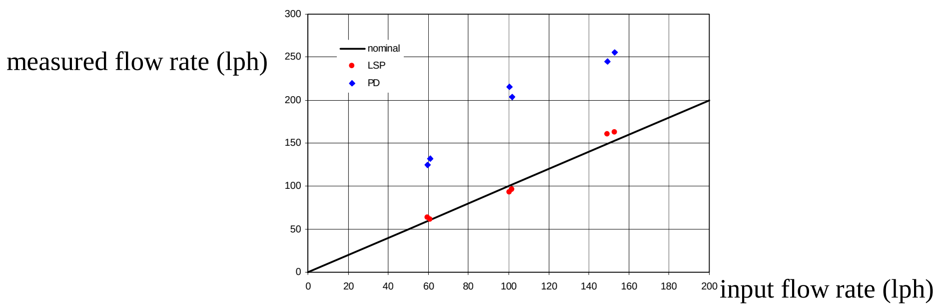

Fig. 7 Volume flowrate obtained from the volume flux measurements with the PD and LSP method as a function of the input flowrate. Same spray nozzle as in figure 6.

Figure 6 also highlights the ability of the Mie-scattering algorithm to reconstruct the attenuation levels measured by the obscuration sensor. Finally figure 7 displays a comparison between the flowrates obtained through integration of the volume flux data for the PD and LSP methods, as a function of the nozzle input flowrate. The large error produced by PD and the ability of the LSP technique to reproduce the correct volume flowrate can be observed.

4. Conclusions

A novel technique for the characterization of the volume flux distribution in optically thick, dense sprays has been developed. It is based on the combined use of the phase-Doppler technique, 90º Mie-scattering, and laser attenuation measurements. The phase-Doppler characterizations are used to obtain spray statistics highly insentive to optical noise and which exhibit a high degree of axi-symmetry. This allows to introduce reduced grid characterization strategies with the phase-Doppler measurements, greatly reducing the characterization time. The Mie-scattering and attenuation measurements are used to extract the spray number density. The technique has been demonstrated in gas turbine sprays with light attenuation levels ranging from 5 to 90%. An algorithm has been developed to correct the number-density information when characterizing optically dense sprays. The procedure makes use only of the 90º Mie-scattering and attenuation measurements. In addition, it has an internal error-check capability built from the comparison between the measured attenuation profiles and the ones reconstructed from the scattering results.

The technique results have been compared against pure PD data obtained in a low attenuation, small cone angle spray. Under these circumstances, the phase-doppler technique should provide reliable volume-flux data. Indeed, both techniques show very similar results, with integrated spray flowrates within 2% of the one fed to the atomizing nozzle. The technique has also been used to characterize a high throughput (150 liter/hour), large cone angle spray, with diametrical attenuation levels close to 90%. The PD techique showed in this case large errors in the volume flux determination, with integrated flow rates close to 100% higher than the nominal input to the spray nozzle. For the LSP technique, a 6% error was found. This error level also characterized the measured and reconstructed light attenuation profile. The characterization time was one order of magnitude smaller with respect to the pure PD measurements, showing the technique potential to be used not only for accurate dense spray characterizations, but also for industrial spray quality control purposes.

5. References

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