DYNAMIC CHARACTERIZATION OF A PRESSURE SWIRL HOLLOW CONE SPRAY.

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Abstract

This research work analyzes the structure of a pressure swirl hollow cone spray. The spray characterization has been made by using a two components PDPA system to obtain the size of droplets and two components of their velocity.

Size and velocity components have been obtained for the overall of droplets and by size classes. The gas phase velocity has been identified with the velocity field of the smallest droplets (St \leq 0.1).

Radial velocity profiles show that the gas flow toward the central zone happens in the test sections near to the liquid film breakup. The axial velocity profiles of both phases equalize quickly for the central zone of the spray. In this region, there was a predominance of small droplets and the continuous phase develops in a similar way to a single-phase jet. The external region, with a progressive presence of large droplets, presents quite high values of momentum at any test station for both phases.

The inertial effects, the aerodynamic drag by the mean gas flow and the droplet diffusive transport by the gas turbulence are relevant phenomena in the spatial distribution of the droplet volumetric flux intensity. The influence of these phenomena depends on the droplet size class.

The quantitative study of the above-mentioned effects and others as function of spray injection parameters is in progress.

Introduction

The sprays are an important part of many industrial applications and particularly in combustion process, where the detailed knowledge of the physical process involved in the interaction, transport and mixing of phases, secondary breakup phenomena, evaporation and coalescence of droplets is essential to achieve more efficient and clean processes.

The pressure swirl nozzles have frequently been used for liquid combustion. In this kind of atomizers (fig.1-a), the liquid is injected into the swirl chamber through several tangential ports that give it a high angular velocity and thereby creating an air-cored vortex. Fluid goes out through the discharge orifice as a thin film with high axial and tangential components of velocity. This film opens forming a hollow cone film that disintegrates at some distance of the exit as result of different breakup mechanisms.

The fluid properties, the injection conditions and the design and dimensions of the atomizers fix the generation of the discharged flow and the development and disintegration of the liquid film, as has been exposed by Ballester [3] and Lefebvre [4].



Figure 1-a) Inner pressure swirl injector design



Figure 1-b) Atomization flow. $p_{inj}=16$ bar and $T_{inj}=95^{\circ}$ C.

For the atomization flow considered in this experimental work (fig.1-b) it is possible to distinguish three regions. The first one is a cone shape film perturbed by strong oscillations. The second is constituted by the droplets formed by the primary breakup of the film, with possible secondary breakup of droplets. The third one is a zone with a regular evolution of the spray.

The studied regions include the near to the film disintegration zone and the regular evolution zone of the spray. Recent studies in this type of sprays have been made by Sommerfeld [2] and Wigley [5].

Experimental Setup

Figure 2 shows the scheme of the experimental setup for this study. The purpose is to generate a spray with controlled conditions providing optical access in order to carry out the study of the spray by PDPA technique. The injector is a pressure swirl type with an angle cone of 80° and low flow rate.

The liquid is oil whose properties have been measured in a laboratory, as shown at table 1. The oil was filtered to eliminate the undesirable solid particles and was heated by an electrical resistance to decrease their high viscosity.

The facility sets a pressure, p_{inj} , and temperature, T_{inj} , ranges from 0 to 24 bar and from 20°C to 95°C respectively. For nominal operation conditions, $p_{inj}=16$ bar and $T_{inj}=95$ °C, the flow rate is $q_{inj}=0.77$ ml/s. Temperature and pressure sensors, near the injection point, gives the information about those parameters. The flow rate is measured with an auxiliary element placed on the liquid supply pumping system.

The oil was injected into a square section chamber where a low velocity air flow was induced by an extraction fan. The liquid was recovered by means of filters and sedimentation elements.

$T_{inj} = 95^{\circ} C$	ρ (Kg/m ³)	ν (m ² /s)	σ (N/m)				
$p_{inj} = 16 \text{ bar}$	850	16·10 ⁻⁶	0.032				
Refraction index, $m = 1.483 + 0.00072i$							



Visualization of the instantaneous disintegration of the liquid film has been obtained by using an image system constituted by a low noise CCD and a stroboscopic light source.

The measurements have been made by a Phase Doppler Analyzer system from TSI-Aerometrics with simultaneous acquisition of size and two components of velocity. The receiving optics was placed at 70° from the beams' plane and into the bisector plane; both emitter and receiver were mounted into a rigid computer controlled three-dimensional traversing system.

The data have been obtained for a set of points placed at four sections, s_0 , s_1 , s_2 , s_3 , at their respective axial distances: x = 9, 18, 36 y 72 mm.



Figure 2. Experimental Setup.

Measurements and results

After a verification of symmetry, the two-phase flow variables distribution are plotted as radial profiles.

The Phase Doppler study has been made over the spray without additional seeding either for the primary flow or for the coflow. Therefore, the statistical parameters have been calculated over the population of detected signals corresponding to the spray droplets.

The number of measured signals for each point varies between n_{max} = 50000 for points at the central region of the jet and n_{min} corresponding to the maximum acquisition time of 1000 s.

The data processing includes the following hypothesis:

- The statistics have been made for both velocity components and size of the signals corresponding to the total distribution of droplets.
- The same calculations have been made for each droplet size class. Particular attention have been done to these three size classes: 5-10 μm (small size), 20-30 μm(medium size) and 50-60 μm (large size).
- The velocity field of continuous phase has been identified with the one of the smallest droplets. This hypothesis has been supported by the small values of the involved Stokes number, which shows the ratio between droplets and the turbulence characteristic times. However, for the external zone of the spray there was a bias associated to the intermittent presence of small droplets, because of the lack of oil at the external surrounding air.
- The droplets local flux intensity and the number density have been obtained by means of a custom made correction post processing method, based on integral calculation methods, after a probe volume self-calibration for each particle diameter class [1].

Velocity fields and droplet size characterization.

The following results and analysis are referred to the whole population of droplets and to the three characteristics classes with central diameters: $d_1=7,5 \ \mu m$, $d_2=25 \ \mu m$, $d_3=55 \ \mu m$.

The dimensionless representation of mean axial velocity profiles for the overall of droplets is showed on figure 3. The dimensionless velocity, V_x^+ , have been referred to the maximum value, which corresponds to the axis position. The dimensionless distance, r^+ , have been referred to the r_{50} radius where the velocity gets a value of $V_x=0,5$ · V_x max. This is a usual representation for single-phase jets. For comparison, a gaussian profile for a single-phase self-similar jet is plotted.

As can be seen, the central zone, $r^{+} \leq 1$, shows a quasi-gaussian evolution, while for the external part the axial velocity values are clearly higher than the gaussian reference. The velocity approach to the gaussian value for test sections downstream to the nozzle.



Figure 3. Dimensionless mean axial velocity profiles. Comparison with Gaussian function.

The axial velocity profiles, V_x (r), corresponding to the three considered size classes are shown in fig.4-a, 4-b and 4-c. Figure 4-d exhibits the smaller size class dimensionless velocity profiles, which are approximated to gas velocity, for x=18, 36 and 72 mm measurements sections.





On the other hand, the velocities RMS values have been calculated for the smallest size class, d_1 , representative of the gas turbulence agitation v'_x . Taking the b_{50} radius (b_{50} is r_{50} for the smallest size class) as the turbulence macro-scales length, and the maximum value of the gas turbulence agitation, v'_x máx, the characteristic times of turbulent fluctuation, τ_{tur} , and the Stokes number have been calculated. All of them are shown at table 2.

	b ₅₀ (mm)	v' _{x máx} (m/s)	$\tau_{tur}(s)$	$St(d_1=7,5)$	St(d ₃ =55)
$(s_1) x = 18 mm$	4,6	2,5	$1,84 \cdot 10^{-3}$	0,0842	4,53
(s ₂) x =36 mm	5,3	1,5	3,53·10 ⁻³	0,0439	2,36
$(s_3) x = 72 mm$	8	1,5	5,33·10 ⁻³	0,029	1,56

Table 2. Stokes number values.

From the calculated Stokes values, the droplets with a characteristic diameter of $d_1=7,5 \ \mu m$ follow the continuous phase with enough accuracy. The droplets of the class $d_3 = 55 \ \mu m$ show moderate or low levels of interaction with the surrounding air which gives rise to an incomplete adaptation to the gas phase for advanced test sections.

The droplet radial velocity, $V_r(r)$, has been plotted versus the radius for the four test sections in figure 5-a. Figure 5-b draws the radial velocity profiles, classified by droplet size classes, for the x=9 mm section. Negative velocity values with a maximum over 2 m/s at the central region and positive radial velocity values to the periphery starting at the radial position r=6 mm are measured.

The analysis by classes for section s_0 (fig. 5-b) reveals that the radial movement toward the inner part was related to small droplets. Because the coupling of smaller particles velocity with the gas movement, revealed by the Stokes number, this radial development corresponded to a flow of gas with this direction.



The larger droplets were almost not present at the central zone for section s_0 , while at the external part of the spray they presented a high radial velocity to the outward zone.

The medium size droplet class has a radial velocity profile similar to the small size class with lower values for the inner zone but higher values for the external area. The $V_r(r)$ shape for the overall population of droplets develops with a manifest reduction of the radial component for both the inner and the outer part of the spray.

Fig 8 presents the mean velocity vector field at the test sections build from the measured values V_x and V_r .



Figure 8. Velocity map.

The figure 6 draws the profiles of Mean Sauter Diameter, D_{32} , versus the dimensionless radial position, r⁺. It could be seen that there was a regular evolution of the medium size droplet profile for all radial positions. The size smallest values are found at the central region of the spray and the largest sizes appears at the edge of the spray and grow from 50 to 70 μ m.



Figure 6. Sauter Mean Diameter profiles.

Droplet flux intensity

The analysis of local droplet volumetric flux was carried out by a post-processing for correction of the measurement volume corresponding to each size class of droplet and an integral method based on transit time of the signals.

The axial local flux intensities are referred to the global droplet distribution and separated by size classes. These local flux intensity radial profiles for the overall of droplets, F_v (r), are shown in fig. 8-a for the s_1 , s_2 , s_3 test sections. At s_1 a strong memory of the film cone shape could be seen. This contour evolves to a more complex shape for s_2 and s_3 . A progressive reduction of maximum value of flux intensity and the broadening of the spray section has been observed.

Figures 8-b, 8-c and 8-d, represent the profiles of flux intensity by size classes. The volumetric flux of the small droplets is the main part of the total flux at the central zone, more clearly analyzing the droplet number

density. The medium size droplet flux has a strong peak at s1, which develops broadening and approaching the axis. The large size droplet flux has a similar profile that matures reducing its value, broadening and approaching to the border of the spray.



Volumetric flux intensities in section x=72

Conclusions

The structure of the flow for a pressure swirl hollow cone spray has been studied.

The presented results, obtained over a pressure swirl injector for the base injection mode, show up the aerodynamic drag of small droplet toward the axis zone for the region near to the liquid film breakup area.

A size distribution resulting of the inertial movement, aerodynamic drag by the mean gas flow and continuous phase turbulence interaction acting as function of sizes has been obtained. Particularly, it has being shown the dominance of small sizes at the axis zone and the large size at the edge of the spray.

Present-day and future work includes quantitative study of the observed effects and their influence parameters.

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