Effect of the Inner Gas Jet on Annular Liquid Sheet Atomization

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Abstract
An annular liquid sheet assisted by two co-flowing gas streams with inner gas swirl and exiting in a pressurized chamber is analyzed in order to optimize new injectors used in cryogenic propulsion (O_{2liq}/H_{2gas}). The liquid used is water and the gas is air. Particle Image Velocimetry (PIV) and Phase Doppler Analyzer (PDA) are performed to measure the size and velocity of droplets and liquid structures. It is found that the atomization of an annular liquid sheet is more effective than a round liquid jet. High values of swirl and momentum flux ratio of the inner gas promote primary atomization. The swirl also homogenizes the droplet velocities and enlarges the spray angle. Finally, the SMD of the spray increases slightly with the chamber pressure.

Introduction

The atomization process is one of the most important parameter in liquid-propellant rocket engines (O_{2liq}, H_{2gas}), to ensure a good stabilization of cryogenic flames. Therefore, numerous studies are done in this field, the greater part of them by using water and air in order to simulate liquid oxygen and gaseous hydrogen mixing. Prevost et al. [1] and Dunand et al. [2] studied respectively the pressure chamber influence and the swirl effect of an annular gas jet on the atomization processes of a round liquid jet. The first authors found a faster break-up of the jet and an increase of the droplet diameter in the periphery of the spray with the pressure. Three distinct behaviors of the primary atomization have been observed by the second authors: with a momentum flux ratio of 3 and under a critical swirl number (i), it is very slightly improved, but over this number (ii), it is greatly enhanced. At higher momentum flux ratio (13.3) and under the critical swirl number (iii), the primary atomization is also greatly improved but over the critical swirl number (iv), large droplets are produced in periphery of the jet. The second and third cases are the most interesting ones for engines. Other authors studied the atomization of an annular liquid sheet with two co-flowing gas streams: Lavergne et al. [3] investigated the instability amplitude and the disintegration length of a 400 µm thickness annular liquid sheet with outer gas swirl effect. They observed a break-up length growth when the air velocity decreases. Cao [4] found similar influences of the air velocity on a 200 µm annular liquid sheet but noted also a periodically variation of the break-up length. Fu et al. [5] examined the development of interfacial waves and the ligament formation of a 255 µm thickness annular liquid sheet using a high speed camera. They also observed the base of the “Christmas tree” like that shown in Fig. 1. Jeandel et al. [6] found a stabilizing effect of viscosity, which reduces the characteristics of the dominant wave of an annular liquid sheet. Li and Shen [7] analyzed the spray produced by an 82.5 thickness annular liquid sheet in the intermediate and far fields; their major conclusions are the following: (i) the inner gas promotes a better atomization than the outer gas, (ii) the mean axial velocity profile is Gaussian and, (iii) the SMD of the produced droplets increases from the spray centerline to the periphery.

Specific Objectives

The previous studies show that the atomization from an annular liquid sheet is more effective than that produced from a round liquid jet. Generally, the results have been obtained under atmospheric pressure and only the outer gas swirl is analyzed. In this work, the chamber pressure and the inner gas swirl effects are experimentally investigated by analyzing images of the spray obtained and measuring velocity of the droplets and their SMD.

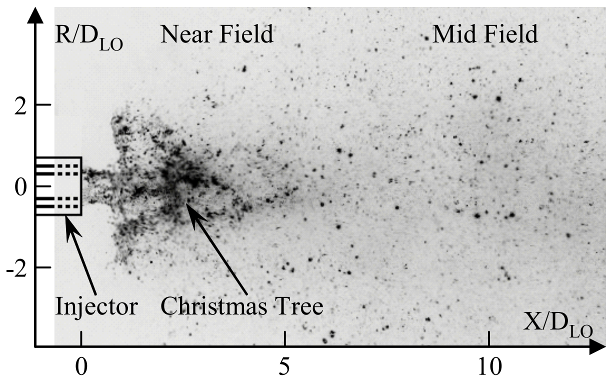

Fig. 1: Snapshot of the liquid sheet atomization for $J_C = 5.5$, chamber pressure P = 0.1 MPa, without swirl.

Experimental Setup

The experimental set-up, called JETCOAP, is carefully described in [1]. A compressor and a surge tank supply the injector in air and allow a chamber pressure from 0.1 to 0.9 MPa. Three flowmeters, two thermocouples and two pressure transducers allow the determination of density and velocity of the gas at the injector exit by considering an adiabatic expansion in

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the pipes. A water-meter and a by-pass system are used to adjust the liquid velocity at the exit. The injector is basically composed by three co-axial tubes (Fig. 2) and mounted displacement tables motorized in two directions. The diameter corresponding to inner gas is 2.5 mm. The 500 µm thickness liquid sheet has an outer diameter of 4 mm and the annular outlet gas exit is set by 4.5 and 5.6 mm. So, the outer annular gas section is about the double of the inner gas section.

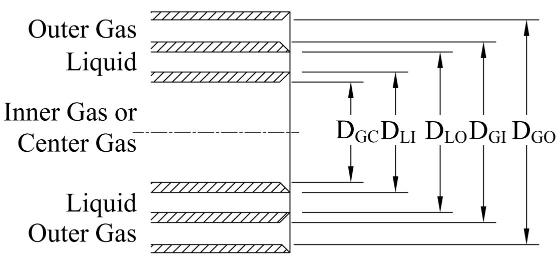

Fig. 2: Injector characteristics.

An exit liquid velocity $U_L = 2$ m/s is fixed and the corresponding Reynolds number, based on hydraulic diameter is $Re_L = 1990$. The momentum flux ratio $J_G = (\rho_G U_G^2)/(\rho_L U_L^2)$ is $J_{GC} = 3$, 5.5 or 8 for the inner gas jet and $J_{GO} = 2.5$ for the outer gas jet; the corresponding Reynolds numbers are included between 10000 and 50000. This injector has also two tangential inlets for the inner gas which allow swirl movement until a swirl number of 0.95 when all the gas is injected by those inlets [8]. This swirl number is defined as:

$$S = 2\int_0^R U\,W\,r\,dr \Big/ R^2\,U_B^2$$

R is the tube radius and U_B the bulk axial velocity.

Measurement Methods

In this study, two measurement methods are used: the Particle Image Velocimetry (PIV) and the Phase Doppler Analyzer (PDA). The first one is composed of a Laser Nd-Yag Quantel Twins CFR 200/400-PIV and a CCD camera FlowMaster 3S La Vision. The maximal power of this laser, of wavelength 532 nm, is 120 mJ. The 12 bit 1280x1024 pixel camera is connected to a treatment software Davis 6.2 to allow intercorrelation method for droplet bigger than 60 µm. PIV means velocity fields are done with 200 images.

The PDA used is a Dantec system composed of an Argon laser, with wavelength beams respectively of 514.5 and 488 nm, coupled with a transmitter fitted with 600 mm focal length lens and a receiver (600 mm focal length also), oriented at 60° from the forward direction of the transmitter axis. This technique allows the measurement of axial and radial velocities, and diameter for droplets measuring from 5 to 150 µm. The number of samples is 5000 within a time limit set at 60 s and the spherical validation criterion is 10%. The precision of this method is better than 10%.

Results and Discussion

PIV measurements cover a field of 56*70 mm². An axial PDA profile is done on the spray axis and the radial profiles correspond to abscissas X = 2.5, 5, 7.5, 11.25, 15, 18.75 D_{LO}. All measurements are performed with a chamber pressure equal to 0.1, 0.3, 0.5 and 0.7 MPa.

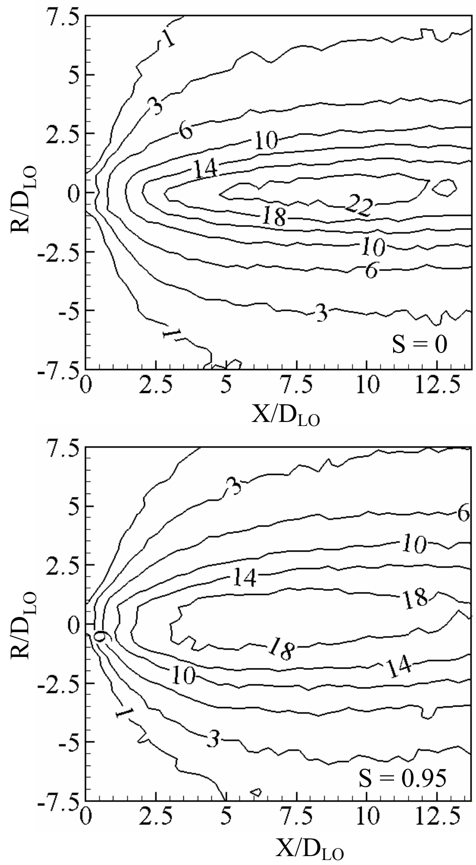

Fig. 3: PIV mean velocity field (m/s) for J_C = 8, chamber pressure = 0.3 MPa, without (S = 0) and with swirl (S = 0.95).

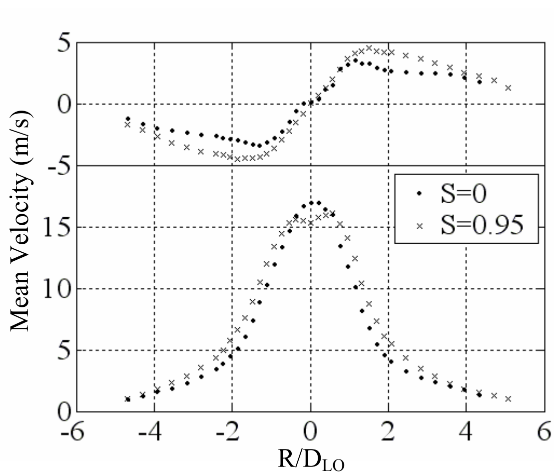

Fig. 4: Mean axial velocities (bottom) and mean radial velocities (top) at X = 2.5 D_{LO} for J_C = 8, chamber pressure P = 0.3, without (S = 0) and with swirl (S = 0.95).

The behavior of the resulting flow and the steps of the atomization due to interactions between liquid and gas flows is shown in the snapshot (Fig. 1). Near the injector, a short intact length of the liquid sheet is observed. Then, and according to Fu et al [5], the sheet breaks-up into a "Christmas tree" with a very large base: the jet spread out suddenly at 90° of the sheet until a radial distance of 2 D_{LO} and produces small droplets. In this zone, the primary atomization is very fast and large droplets do not exist in the periphery of the jet, even if a strong inner gas swirl is used. This result, confirmed by PDA measurements, corresponds to the most interesting case observed by Dunand et al [2] atomizing a round liquid jet.

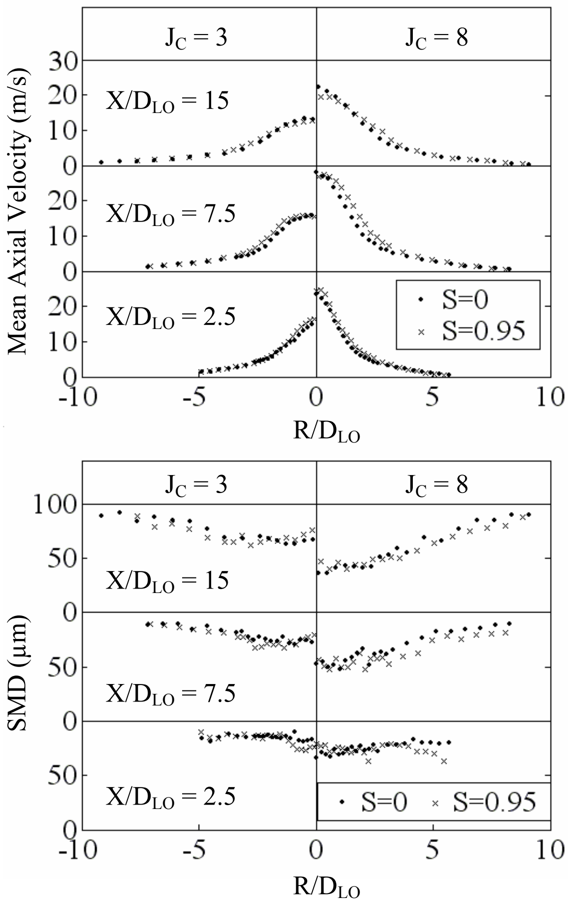

Fig. 5: Mean axial velocities and SMD at three different locations, chamber pressure P = 0.1 MPa, without (S = 0) and with swirl (S = 0.95).

The PIV means velocity field (Fig. 3) and the PDA velocity profiles (Fig. 4) are symmetric with regard to the spray axis so only half-profiles are presented in the other figures. In all conditions reported in Fig. 5, 6 and 7, the SMD is always smaller than 100 µm and the mean axial velocity profiles have a Gaussian shape, very similar to those existing in a well mixed jet. These elements show that the atomization is very effective and the obtained mean droplet diameters are about 20 µm under atmospheric pressure. This behavior is different from that observed by Prevost et al. [1] and Dunand et al. [2] where the atomization was less effective and the PDA velocity profiles had more complex evolution. Moreover, the mean droplet axial velocity on the spray centerline increases first with the axial distance, due to the atomization of the liquid sheet and acceleration of the corresponding droplets, and next decreases like a single jet.

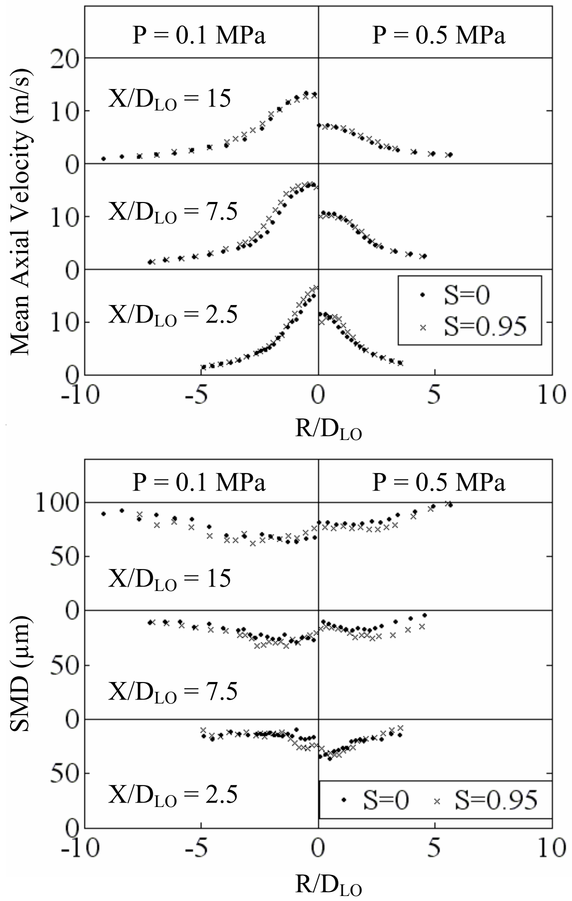

Fig. 6: Mean axial velocities and SMD at three different locations, for J_C = 3, chamber pressure P = 0.1 or 0.5 MPa, without (S = 0) and with swirl (S = 0.95).

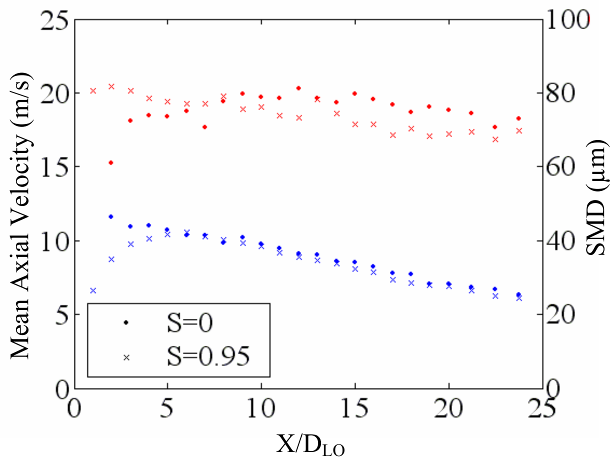

Fig. 7: Mean axial velocities (blue) and SMD (red) on the spray axis, for J_C = 3, chamber pressure P = 0.5 MPa, without (S = 0) and with swirl (S = 0.95).

The results presented in Figs. 5 and 6 show that the SMD of the liquid droplets increases slightly with the radial distance, but remains nearly uniform in the central region. Moreover, the distributions of droplet radial velocity show that small droplets are more entrained toward the central region than large droplets. Indeed, large droplets have a higher momentum and are less affected by the air entrainment motion. It is also noticeable in Figs. 5, 6 and 7 that the axial evolution of SMD is very slow, showing that primary and secondary atomizations are very fast.

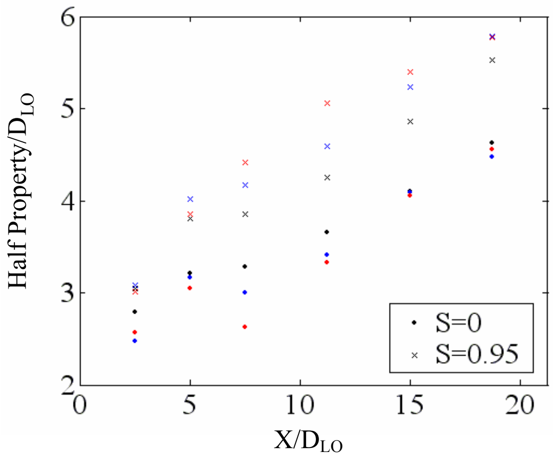

Fig. 8: Half property evolution of mean droplet axial velocity profile, for J_C = 3 (black), 5.5 (blue) and 8 (red), chamber pressure P = 0.3 MPa, without (S = 0) and with swirl (S = 0.95).

In the central region of the spray, the mean droplet axial velocity increases, the SMD decreases (Fig. 5), and the primary atomization is improved with inner gas momentum flux ratio. Nevertheless, some properties are weakly influenced by this parameter: the SMD near the spray periphery (Fig. 5), the half property evolution of the mean droplet axial velocity (Fig. 8) like the spray angle and mean radial velocity profiles.

If the momentum flux ratio J_C is constant, the SMD increases moderately with the pressure chamber whereas the correspondent velocity drops (Fig. 6). Moreover, the SMD increases more quickly toward the spray periphery with a higher pressure chamber; Prevost et al. [1] obtained similar results, atomizing round liquid jets. It can be explained by a fast decrease of the mean axial velocity toward the periphery under high chamber pressure. This behavior is due to a better droplet entrainment in central region because of the gas density. At last, the radial profile of mean axial velocity becomes larger with a decrease of chamber pressure.

When the inner gas swirl number increases, the primary atomization is faster and the spray angle becomes larger (Fig. 9). A high inner gas swirl number changes the velocity profiles: in Fig. 4, the radial profile of mean droplet axial velocity presents a relative minimum near the spray centerline in the near field, the mean droplet radial velocity and the half property of mean axial velocity profile (Fig. 8) become larger. In the near field, the mean droplet axial velocity profile is not Gaussian with swirl effect, so the point X = 2.5 D_{LO} is displaced from the other points in this diagram. One reason of this phenomenon is a modification of the gas velocity profile with swirl effect at the tube exit.

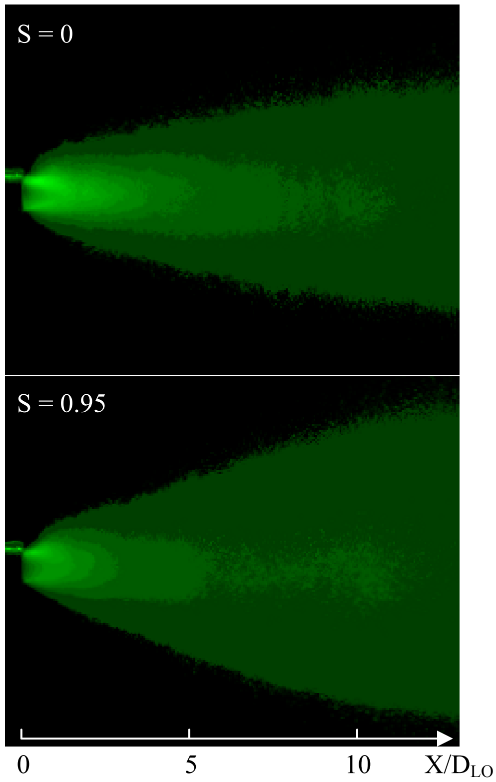

Fig 9: Average images of the spray for J_C = 8, chamber pressure P = 0.3 MPa, without (S = 0) and with swirl (S = 0.95).

In Fig. 4, the mean droplet radial velocity increases quickly toward the spray periphery with inner gas swirl and reaches a maximum value higher than that obtained without swirl. After this maximum, the velocity decreases more quickly in periphery of the spray. In Fig. 3, the mean axial velocity reaches a maximum value with swirl effect lower than that without swirl effect. We should specify that in the case with swirl, the gas velocity at the injector exit is weakly reduced because of a higher loss of pressure decreasing gas temperature and increasing gas density. In this diagram, the maximum velocity is reached quickest with swirl effect. These results are in agreement with a better atomization of the sheet with inner gas swirl. In Fig. 11, the size-velocity diagram shows a homogenization of the droplet velocities. The SMD increases more slightly toward the periphery region in radial profile with swirl effect, due to the enlargement of the mean axial velocity profile. In Fig. 7, the SMD is weakly reduced with swirl effect. At last, in this diagram and near the injector, the SMD and the mean droplet velocity can be affected by the validation rates.

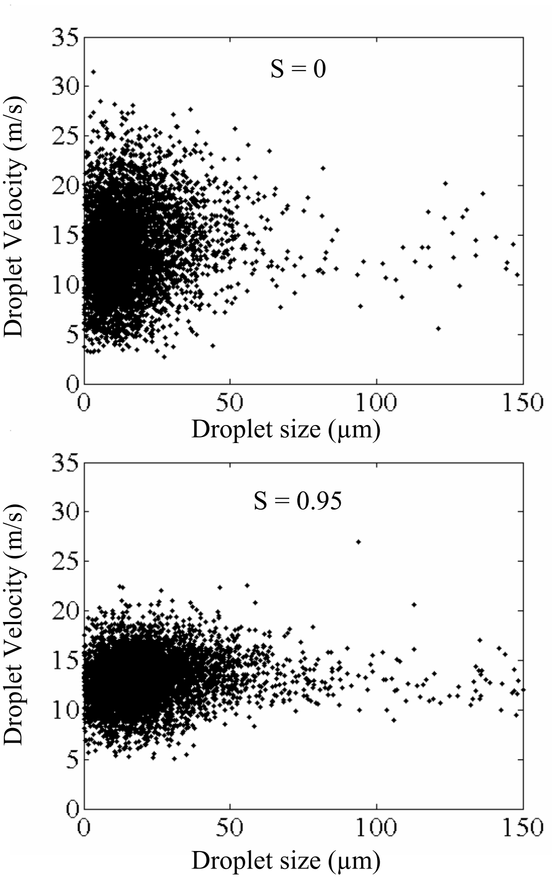

Fig. 10: Size-velocity droplet repartition on the spray centerline and $X/D_{LO} = 15$, for $J_C = 8$, chamber pressure P = 0.3 MPa, without (S = 0) and with swirl (S = 0.95).

Conclusions

In this article, we point out that the atomization of an annular liquid sheet by two co-flowing gas streams is very effective. When the inner gas momentum flux ratio rises, (i) the mean droplet axial velocities increases, (ii) the mean droplet radial velocity becomes larger, (iii) the SMD decreases and, (iv) the primary atomization goes faster. Pressure chamber growth produces a slight increase of SMD with a drop of mean droplet axial velocity. Radial profiles of mean droplet axial velocity have a relative minimum on the spray centerline in the near field with strong inner gas jet swirl. This swirl enlarges the mean radial velocity and, consequently, the radius of the half-property of the resulting flow. Moreover, it allows a faster primary atomization and a homogenization of droplet velocities.

We analyzed the effects of the swirl inner gas jet and the pressure chamber on the SMD and mean velocity droplet profiles. Other important parameters can be studied: (i) the breaking length of the liquid sheet, (ii) the aerodynamic effects by means of velocity distributions of small droplets representative of the gaseous phase, (iii) the swirl of the outer gas, and (iv) the respective effects of the inner and outer gas. This last one is already being studied.

Acknowledgements

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