# *LIQUID ATOMIZATION BY ANNULAR SWIRLING GAS*

**Arnaud Dunand, Rémy Sorin, Jean-Louis Carreau and Francis Roger**

**e-mail : dunand@lcd.ensma.fr**

**Laboratoire de Combustion et Détonique CNRS UPR 9028**

**University of POITIERS**

**ENSMA, 1 Avenue Clément Ader, BP 40109**

**86961 Futuroscope Chasseneuil Cedex**

**Phone : 05 49 49 83 05, Fax : 05 49 49 82 91**

## ABSTRACT

Swirling flows have been widely used, for many years, in technical applications, such as aeronautics, spray drying, combustion, etc. Introducing swirl in turbulent jets causes an increase in jet growth, rate of entrainment and rate of decay of the jet. In spray systems, the swirl motion is generally imparted to the liquid jet in order to favour its fragmentation, but in coaxial atomization application, due to his higher momentum, the dynamic of the flow is controlled by the gas jet. As a consequent, we examine the effect of a swirling coaxial gas on the atomization of a liquid jet as a function of the rotation intensity, given by the swirl number S, and the momentum flux ratio J. The main results were: no major changes in the jet development for low swirl but, when a critical amount of rotational flow is imparted to the stream, the topology of the flow is significantly modified. This transition leads to an improvement of the atomization characterized by a decrease in the jet break-up length and in the distribution of mean droplet diameters. The second kind of flow is linked with the apparition of a stagnation point on the jet centreline and thus a recirculation region, which occurrence depends on the value of the momentum flux ratio. The apparition of this particular flow topology must improve the stabilization of the cryogenic flame.

## INTRODUCTION

A great challenge in liquid propellant rocket engine is to ensure a good stabilization of the cryogenic flame; atomization of the inner low momentum liquid jet by high-speed coaxial gas must be therefore improved. In order to achieve this aim, and by analogy with studies dealing with swirl burner combustion characteristics [1, 2], we examine the atomization of a liquid jet achieved by an annular gas jet with a swirl motion. Actually, it is well known that swirling flows have been commonly used for the stabilization of high-intensity combustion processes. The main advantage resulting from a swirling flow is the apparition (for a certain amount of swirl) of a central recirculation zone, which enables faster mixing and provides a hot flow of recirculated combustion products and a reduced velocity region where flame speed and flow velocity can be matched. As a result flames lengths and distance from the burner at which the flame is stabilized are shortened significantly. In this paper, we study the influence of the strength of the annular swirling flow coupled with the variation of the most important coaxial non-dimensional parameter: the momentum flux ratio on the liquid jet atomization.

## EXPERIMENTAL SET-UP AND OPERATING CONDITIONS

The experimental set-up, called JETCOAP [3], allows measurements in the pressure range of 0.1 MPa to 0.9 MPa with a motorized two dimension displacement system of the injector (precision 10 µm) but for this study the ambient pressure is kept constant to 0.1 MPa (atmospheric pressure). The coaxial injector has the following dimensions: 2.1, 2.5 and 3.6 mm respectively for the inner liquid diameter ($D_i$) and the gas tube ($D_{gi}$ and $D_{g0}$). The axial gas mass flow rate is supplied through two symmetric inlets and the swirl motion is imparted to the annular flow by means of two tangential inlets located just 10 mm before the exit (in order to minimize the swirl decay). Although it cannot describe entirely the flow [4], the degree of swirl is characterized by the swirl number S, which is a non-dimensional number representing axial flux of swirl momentum divided by axial flux of axial momentum, times the nozzle radius.

S can be related, if perfect mixing and conservation of momentum is assumed, to the measured axial gas mass flow rate ($m_a$) and the tangential gas mass flow rate ($m_{tang}$) by [5]:

$$S = \frac{\pi\, r_0\, R}{A_t}\left(\frac{m_{\text{tang}}}{m_{\text{tang}} + m_a}\right)^2 \tag{1}$$

With $r_0$ the axial air tube radius where the tangential air is introduced, R the gas tube exit radius ($D_{g0}/2$) and $A_t$ the total area of the two tangential inlets. By controlling $m_a$ and $m_{tang}$ and from our injector geometry, S range from 0 to 0.685 conserving the total mass flux constant. For this study, the liquid injection velocity stays constant to 2.5 m/s. Working fluids are water and air at ambient temperature.

In order to characterise the different spray regions, we used two kinds of measurement techniques. The measurement of the liquid presence probability (LPP) in the liquid core region is achieved by means of an optical fiber probe [6]; the velocity and diameter of the spherical liquid droplet distributions in the spray were obtained by a Phase Doppler technique.

*Optical fiber probe:*

The light emitted by a photodiode was focused at the entrance of the optical fiber probe. At the end (a 90 µm diameter sapphire head), the light was totally reflected or not, depending on the medium refractive index. This technique makes it possible to determine the local liquid presence probability (LPP = 1 void fraction). This probe enabled us to explore thoroughly the liquid core and the very dense spray with liquid ligament structures above 150 µm [7, 8].

*Phase Doppler Analyser:*

Quantitative informations on the spray were obtained with a two dimensional Phase Doppler Analyser device, which enabled simultaneous measurements of the temporally averaged droplet size and (axial and tangential) velocity distributions at a point within the spray. The optical configuration for these tests included an Argon laser coupled with a transmitter fitted with a 600 mm focal length lens and a receiver oriented at 60° from the forward direction of the transmitter optical axis. This optical configuration enables velocity measurements from –25 to 125 m/s and particles sizing up to 145 µm. The number of samples validated at each acquisition is 5000, within a time limit set at 60 s.

Operating conditions are summarized in the following table where J, S, $m_{tot}$, $m_a$ and $m_{tang}$ are respectively the momentum flux ratio ($\rho_{gi}U_{gi}^2/\rho_l U_l^2$), the Swirl number (see equation (1)), and the total, axial and tangential mass flow rate.

| | **J = 3 ($m_{tot}$ = 0.86 g/s)** | | | | **J = 13.3 ($m_{tot}$ = 2.01 g/s)** | | | |
|---|---|---|---|---|---|---|---|---|
| **S** | **0** | **0.2** | **0.4** | **0.6** | **0** | **0.2** | **0.4** | **0.6** |
| **$m_a$ (g/s)** | 0.860 | 0.396 | 0.203 | 0.056 | 2.010 | 0.924 | 0.474 | 0.129 |
| **$m_{tang}$ (g/s)** | 0 | 0.464 | 0.657 | 0.804 | 0 | 1.086 | 1.536 | 1.881 |

**Table 1.** Operating conditions.

## RESULTS AND DISCUSSION

*Near-field region:*

As can be seen in figure 1 and for J = 3, increasing swirl intensity from 0 to 0.4 affects the liquid jet atomization very slightly with nevertheless an amelioration of the atomization. For S = 0.6, $L_c$, the potential liquid core (LPP = 1), is reduced and the LPP decrease a lot more with the axial distance. The swirling flow tends to destabilise the liquid jet a little bit more and $L_b$, the break-up length (LPP = 0.5), is reduced. In the case of J = 13.3, one can observe different behaviours. For the non-swirling flow, the increase in injection velocity leads to a confinement of the liquid structures on the spray axis [6]. Because of the decrease in the axial mass flux, this phenomenon seems to diminish as the swirl number rises. The most remarkable effect of a high swirl number (S = 0.6) is well illustrated in the figure. Actually, for S = 0.6, the potential liquid core was not visible at the exit of the injector and the LPP decrease very quickly becoming zero at X/Di = 2 and $L_b$ is very low. This observation seems to be linked with the apparition of a stagnation point on the axis of the spray as observed on other swirling flows. The liquid jet impacts this kind of obstacle and its atomization is greatly enhanced. It is interesting to note that this value of the swirl number is the same as in combustion studies [1] or in monophasic coaxial gas jets [9] and depends on the value of the momentum flux ratio because the critical value of S is reached for J = 13.3 but not for J = 3.

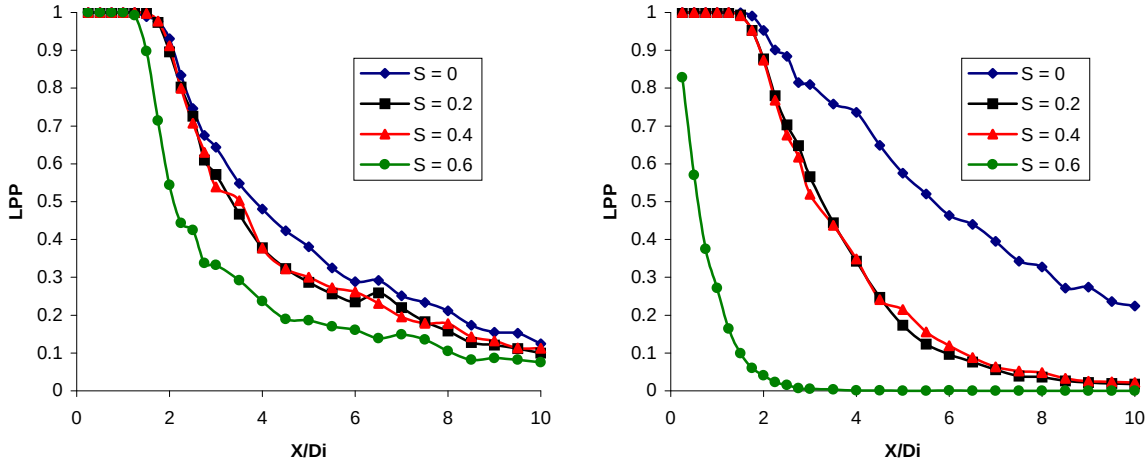


**Figure 1: Axial evolutions of LPP for J = 3 (left) and J = 13.3 (right).**

*Spray field region:*

Radial evolutions of the mean axial droplet velocities for two values of the momentum flux ratio are displayed in figure 2. For a low value of the momentum flux ratio, the jet development is the same for all the values of S. As we decrease the axial mass flux in order to increase S, it seems normal that, on the jet centreline, the mean axial velocities of the droplets fall with the swirl number. For a swirl number of 0.4, we obtain the maximum droplet velocities in the annular gas. This observation is in good agreement with other author's visualisations [9], which display a contraction of the inner jet for moderate swirl number and thus an acceleration of the spray. This trend must lead to an improvement of the liquid jet atomization. For a greater value of S, the axial mass flux is too low and therefore the axial droplet velocities decrease on the whole spray, which will cause a reduction of the atomization intensity.

These characteristics are conserved, with an overall increase of the droplets velocity, in the case of J = 13.3. There is a little discrepancy for the mixing in the injector due to the high injection velocity therefore differences on the jet centreline are amplified. As for the study of the axial evolutions of the LPP, we note the apparition of a second kind of flow for, S = 0.6, with a maximum velocity of the spray axis and a radial evolution typical of a fully developed jet. So the transition between the two stages of flows leads to a more precocious establishment of the spray.

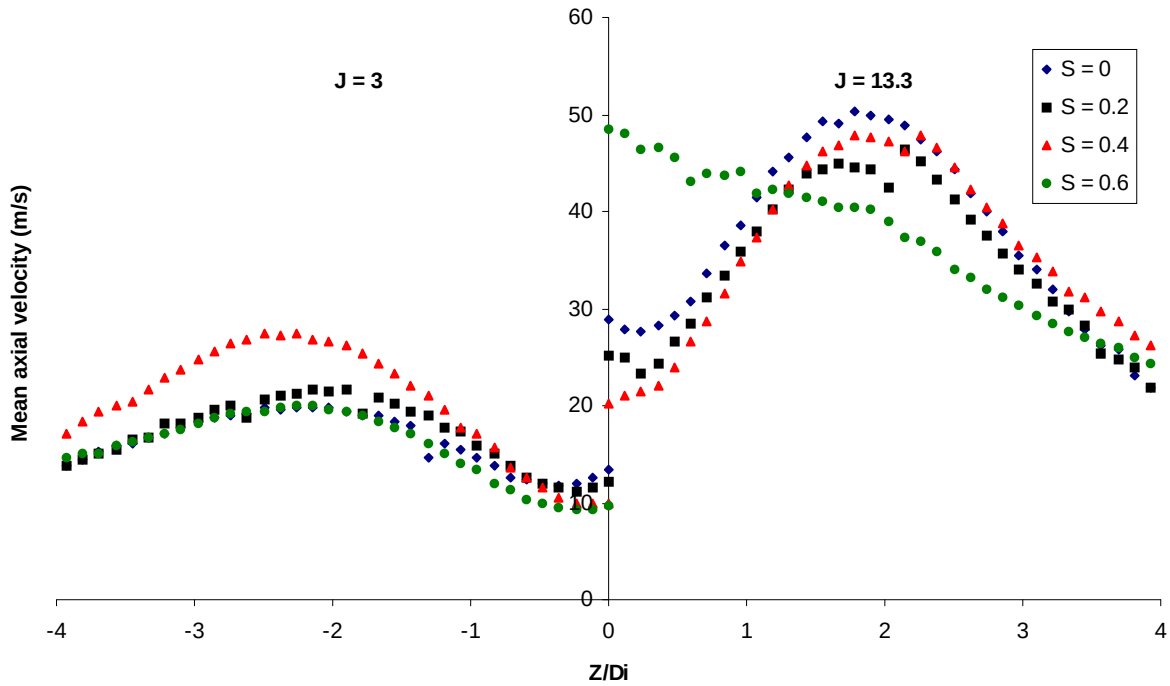


**Figure 2: Radial distributions of the mean axial velocity (X/Di = 10).**

Radial evolutions of the tangential velocity (figure 3) exhibit a well-known forced type vortex (i.e a soly body rotation flow) [4]. We encounter the same behaviour that for the axial profiles, that is to say a maximum for

S = 0.4. The centrifugal forces are more intense radially on the near field of the spray but in the same time more concentrated for a higher value of the momentum ratio. The second type of flow has a non zero value on the axis because of the precession of the stagnation point [10] and the profile increase slightly up to a constant level.

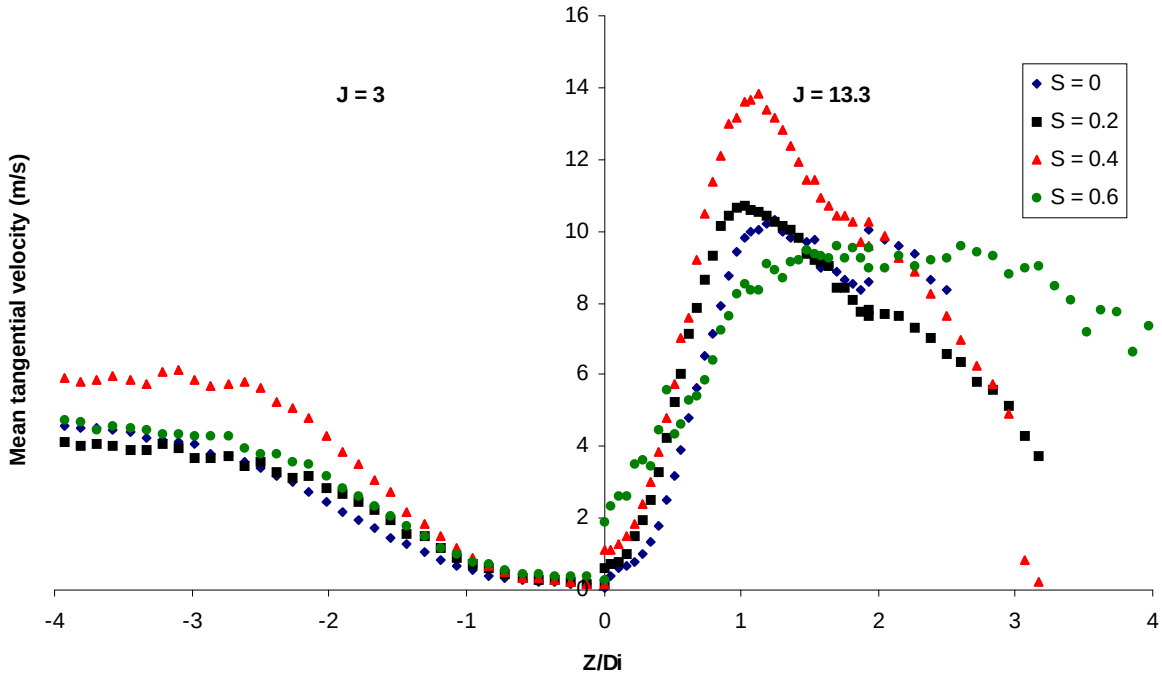


**Figure 3: Radial distributions of the mean tangential velocity (X/Di = 10).**

Observations for the radial distribution of the mean diameter (figure 4) derive from the study on the axial velocity profile. At J = 3, the maximum velocity is obtain with S = 0.4 and we see, on figure 4, that atomization is better for this swirl number. For all the other value of S, the $D_{10}$ are nearly the same. When J = 13.3, atomization processes are increased with a diminution of the mean diameters. When the critical swirl number is exceeded, the $D_{10}$ are minimal on the spray axis so we can say that atomization is finished at this axial location but on the periphery of the jet, the $D_{10}$ do not stay constant but increase significantly. Thanks to these observations, we can conclude that the second type of flow displaces the population of droplets. The small ones are located on the spray axis and the large liquid structures are situated on the edge of the jet.

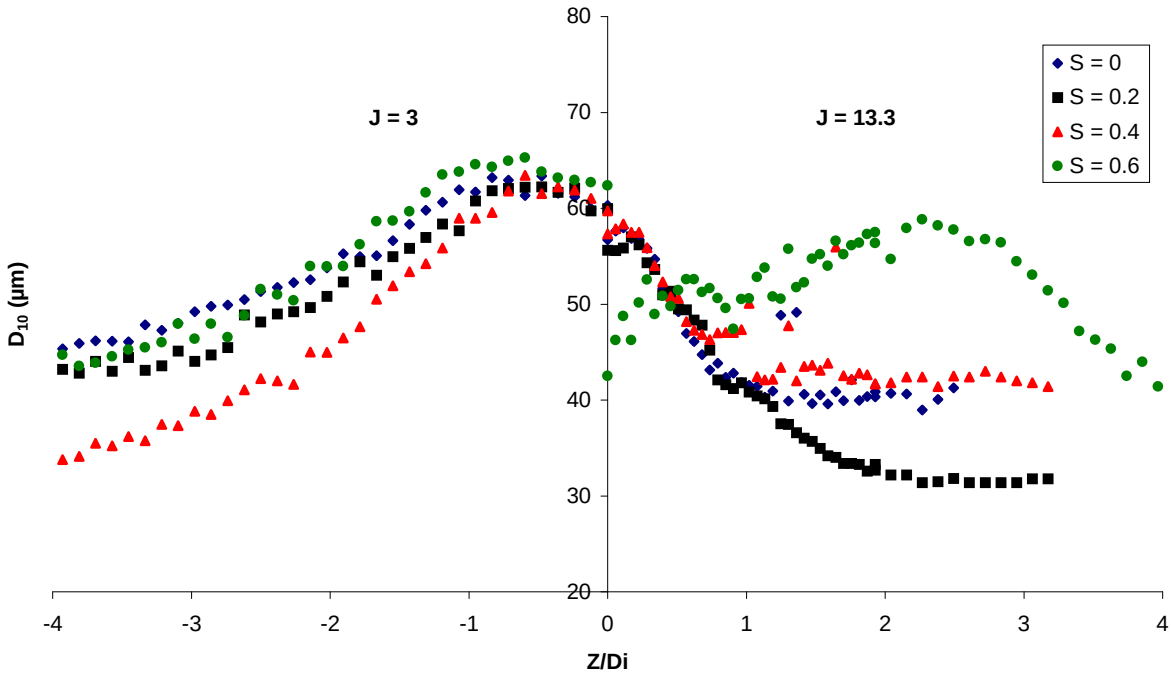


**Figure 4: Radial distributions of the mean diameter (X/Di = 10).**

*Interpretation of the phenomenon:*

Explanations of these trends are illustrated on the figure 5. Actually, the visualisations give us quantitative information on the morphology of the flows. Below the critical swirl number ($S_{cr}$), the high momentum annular gas jet destabilises the liquid jet and creates liquid ligaments, which becomes droplets in the secondary atomization process. In the centre of the spray, we can see the liquid core (dense liquid region). This visualisation corresponds well to the radial distribution of mean diameter, displayed in figure 4, with small droplets on the edge of the spray and large ligaments on the axis. For S = 0.6, the spray angle becomes higher, due to the great centrifugal momentum, the large liquid structures are ejected immediately after the injector exit at the jet periphery and the central zone is composed by very small droplet population.

By analogy with combustion studies [11], as the swirl number increase, an adverse pressure gradient appears on the jet centreline. When the positive axial velocity becomes too low to compensate the slowing down, a stagnation point takes place on the spray axis and a recirculation zone behind it. The liquid jet impacts on this point of elevated static pressure and therefore spray expansion is enhanced. Liquid structures, which have ballistic trajectories, based on studies of the Stockes number [6], are ejected of the flow, but small droplets, which follow preferentially the gas phase, go round the stagnation point and finally stay inside the recirculation region. The occurrence of the recirculation region, characterized by a population of very small droplets on the spray axis, increase the exchange surface between the gas and the liquid, which favour the vaporization of the mixture and will therefore enable a better stabilization of the cryogenic flame [12].

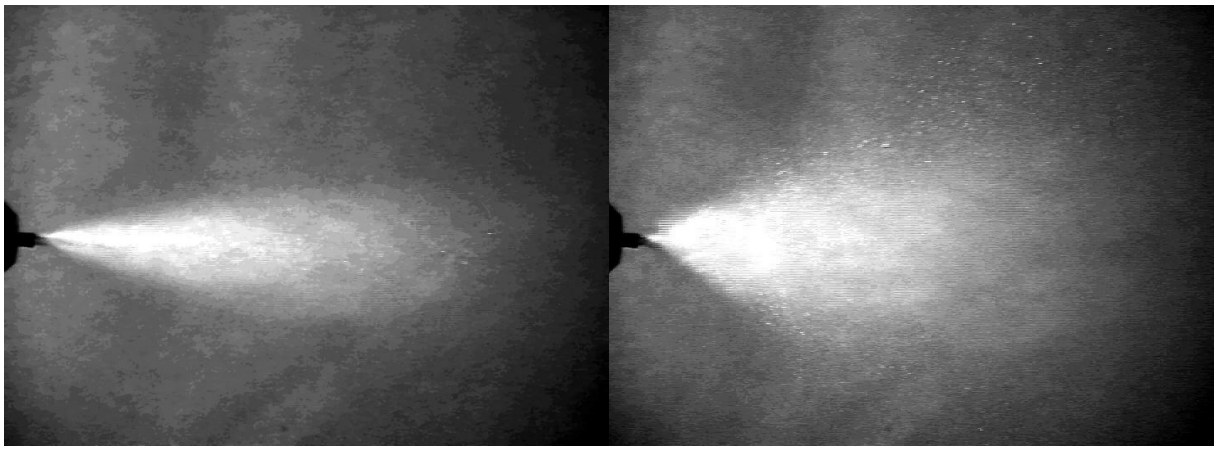

**Figure 5: Visualisations of the two topologies of the spray at J = 13.3, S = 0.4 (left) and S = 0.6 (right).**

*Critical swirl number:*

The value of $S_{cr}$ seems to depend on the momentum flux ratio, and therefore with the mass flux ratio [9] as we see that for J = 3 the critical flow is not reached. The variation of $S_{cr}$ with J, illustrated on figure 6, is achieved by means of visualisations. As J increase, the $S_{cr}$ diminishes as far as an asymptotic value of 0.4. The regression indicates a dependence with J by an exponent equals to (-0.14), a little bit higher than other studies [13].

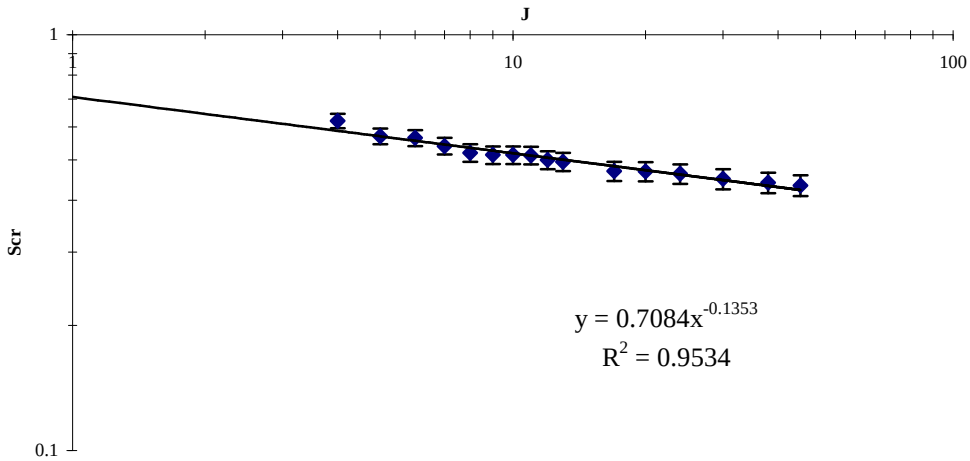


**Figure 6: Variation of the critical swirl number with J.**

## CONCLUSION

As expected from the previous studies on swirling jets, two stable flow topologies take place according to the value of the swirl number. Below a critical value, the spray is little affected by the swirl motion but if the swirl number exceeds this critical value (depending on the momentum flux ratio and the mass flux ratio), the atomization of the liquid jet is strongly improved; velocity and diameter radial distributions exhibit a totally different kind of evolution. These differences are linked with the occurrence of a recirculation region initiated by a stagnation point on the spray axis. For rocket engine application, according to this study, we can conclude that introducing a swirl motion to the coaxial gas stream favours the cryogenic flame stabilization but nevertheless it is necessary to control the influence of swirl in order to prevent interpenetration of sprays issued from different injectors and avoid the surface of the combustion chamber to be polluted by a high combustible mixture and therefore be damaged after ignition.

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## NOMENCLATURE

| | |
|---|---|
| $D_i$ | Nozzle diameter for the liquid |
| $D_{10}$ | Mean Diameter |
| J | Momentum flux ratio |
| $L_b$ | Break-up length |
| $L_c$ | Liquid core break-up length |
| LPP | Liquid Presence Probability |
| m | Mass flow rate |
| P | Pressure |
| S | Swirl number |
| U | Axial Velocity |
| W | Tangential Velocity |
| X | Axial distance from the liquid tube exit |
| Z | Radial distance |
| ρ | Density |

Subscript

| | |
|---|---|
| a | axial |
| c | chamber |
| cr | critical |
| *g* | gas |
| i | injection |
| l | liquid |
| tang | tangential |
| tot | total |

## REFERENCES

[1] Gupta A.K., Lilley D.G., Syred N., “Swirl Flows”, Energy and Engineering Science Series. London: Abacus Press, 1984.

[2] Syred N., Beér JM., “Combustion in Swirling Flows: a Review”. *Combustion and Flame*, 23, pp. 143-201, 1974.

[3] Prévost L., Carreau J-L., Porcheron E., Roger F., “Coaxial Atomization under Different Ambient Pressure”, *ILASS-Europe 1999, Toulouse*, 1999.

[4] Farokhi S., Taghavi R., Rice E.J., “Effect of Initial Swirl Distribution on the Evolution of a Turbulent Jet”, *AIAA Journal*, Vol. 27, n°6, pp. 700-706, 1988.

[5] Claypole T.C., and Syred, N., “Effect of swirl burner aerodynamics on $N_{ox}$ formation”, *Eighteen International Symposium on Combustion*, pp. 81, 1981.

[6] Carreau J-L., Dunand A., Prévost L., Porcheron E. Le Visage D., Monoté G. et Roger F., “Paramètres et Caractéristiques de l’Atomisation d’un Jet Liquide Rond par un Jet de Gaz Annulaire et Coaxial”, Combustion dans les moteurs fusées, Proc. Colloque de Synthèse du Groupe de Recherche, CNES/CNRS/ONERA/SNECMA, CEPADUES-EDITIONS, pp. 136-149, 2001.

[7] Monoté G., Carreau J-L., Le Visage D., Porcheron E., Prévost L. and Roger F., “Atomisation Coaxiale Assistée : Analyse du Mélange dans la Zone Dense”, *Combustion*, 2 (1), pp. 55-93, 2002.

[8] Porcheron E., Carreau J-L., Prévost L., Le Visage D. and Roger F., “Effect on Injection Gas Density on Coaxial Liquid Jet Atomization”, *Atomization and Sprays*, Vol. 12, n°1, 2002.

[9] Champagne F.H., Kromat S., “Experiments on the Formation of a Recirculation Zone in Swirling Coaxial Jets”, *Experiments in Fluids*, 29, pp. 494-504, 2000.

[10] Syred N., Gupta A.K., Beér J.M., “Temperature and Density Gradient Changes Arising with the Precessing Vortex Core and Vortex Breakdown in Swirl Burners”, *Fifteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp. 587-597, 1975.

[11] Tangirala V., Chen R.H., Driscoll J.F., “Effect of Heat Release and Swirl on the Recirculation within Swirl-Stabilized Flames”, *Combustion Science and Technology*, Vol. 51, pp. 75-95, 1987.

[12] Dunand A., “Atomisation Coaxiale sous Pression : Etude de l’Effet du Retrait et du Swirl du Gaz”, Thèse de l’Université de Poitiers, to be published.

[13] Hopfinger E.J., Lasheras J.C., “Explosive Break-up of a Liquid Jet by a Swirling Coaxial Gas”, *Physics of Fluids* 8 (7), pp. 1696-1698, 1998.