IDENTIFICATION OF CROSS-FLOW LIQUID-JET STRUCTURES BY MEANS OF STATISTICAL IMAGE EVALUATION

R. Ragucci* and A. Cavaliere**
email ragucci@irc.na.cnr.it
*** Istituto di Ricerche sulla Combustione – C.N.R.**
**** Dip. Di Ingegneria Chimica – Universita`Federico II**
P. Tecchio, 80 - 80125 – Napoli – Italy

Abstract

The aim of this paper is to study how the morphology of a liquid jet in cross-flow conditions can be influenced by characteristic parameters of atomization. The technological reference of this work are the LPP (Lean Premixed Prevaporized) gas turbine systems. In these systems the combustion process occurs in premixed conditions with a very high air excess in order to avoid NO_x forming. The operation of such systems with liquid fuels require a particular care in the preparation of the fuel-air mixture. Fuel injection in an air cross-flow is commonly used to favour a prompt and good mix of air and fuel. This technique presents two main disadvantages: the impact of the liquid jet against the wall; Flashback phenomenon occurring when flame propagation is faster than air velocity allowing for fuel ignition in the inlet duct. To avoid these two disadvantages, the atomization system and the complex coupling between fuel and air streams require particular care in system design. This paper contribute to the general understanding of jet dispersion and its interaction with air flow and attempt to determine a semi–empirical correlation useful to predict liquid jet trajectory in cross-flow conditions.

Introduction

The relevant problem of combustion instabilities in Lean Premixed Prevaporized (LPP) burners for gas-turbine application have been afforded mainly using passive or active control techniques acting on the oscillations in the aim of reducing their amplitudes. Another approach is the realization of more efficient premixing systems capable of dispersing more uniformly in the air-flow the fuel in a wider range of operating conditions. The design of such devices relies mainly on a trial-an-error approach due to the current difficulties to develop efficient predictive models. The problem is even more relevant when the injection of liquids by means of an atomizer is considered, as is the typical case of aeronautical engines or multi-fuel ground systems (which is a very common case). In fact, in spite of the abundance of modeling tools for the gaseous flows the modeling of liquid jets, generated using atomizers typical of gas-turbines, is still in a primordial phase. The simplifications commonly used in the liquid jet modeling in stagnant or low air velocity conditions lead to unpredictable failures when these models are applied to the gas-turbine case. In this case the high air velocity and the extreme thermodynamic conditions (approaching the critical conditions for the fuel) can amplify the errors introduced by the above mentioned simplifications in an unexpected way leading to a substantial failure of the models in predicting the atomization and mixing behavior.

As a consequence, a demand for a thorough characterization of liquid jet behavior in gas-turbine condition is currently posed both by model developers, to the aim of validation of their codes, and by manufacturers, in order to test prototypes of newly developed premixing assemblies. On the other hand, the application of diagnostic tools to the actual devices can be hardly done due to the accessing difficulties. Many experimental facilities have been realized in order to simulate portions of the practical devices as realistically as possible. In all these facilities a common problem to be faced is represented by the choice of an effective diagnostic set-up. The technical literature reports many visualization experiments aimed to determine the general behavior of the liquid jet invested by the gaseous flow. On the ground of these results several attempt have been made to derive qualitative description of the spray and semi-empirical correlation to be used in modeling activities.

This paper contribute to the development of innovative interpretative tools of the experimental evidences on the spatial and temporal evolution of a jet subject to the influence of an air stream at high velocity in a pressurized environment. The statistical evaluation of morphological characteristics of shadowgraphic images both in terms of space and time variations sheds new light in the present interpretative schemes. The approach presents interesting skills in depicting the sprays instabilities as connected to the dispersion and mixing processes and it is, thus, suitable to be applied in the characterization of combustion instabilities.

Experimental Set-up

The experimental set-up (schematically reported in Fig. 1) [1] consists of a fully optically accessible tunnel, with a square cross section of 25 X 25 mm, in which the jet is injected perpendicularly to the air cross flow. Temperature, pressure and velocity of the air-flow in the tunnel can be varied independently each other in a wide range of operating conditions. The injecting system is a plane orifice one with a nozzle hole of 0.5 mm diameter. The liquid is supplied to the nozzle by means of a nitrogen pressurized vessel allowing for a precise injection pressure setting.

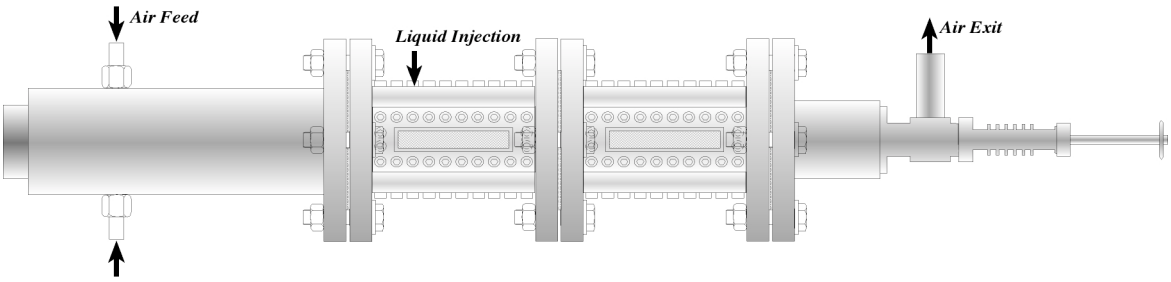

Figure 1. Experimental facility.

The optical set-up (Fig. 2) is a simple shadowgraphic scheme using a low-pressure xenon flash lamp as light source. A 1 M-pixel CCD digital camera collected shadowgraphs of the spray at each light pulse. In each test condition forty 10 bits images (1024 different tonalities of grey) of the spray were collected. A set of acquisition and elaboration procedures, written in LabVIEW programming environment and based on a standard library of image manipulation algorithms (NI-IMAQ), allowed for the characterization of statistical and morphological features of the spray. A background image, obtained by a exposing the camera in absence of the spray, was subtracted in order to reduce electronic noise. From the obtained images an average image was computed in order to study the bending and penetration of the liquid jet. Using an image binarization routine it was possible to outline the boundaries of single and averaged images in each condition in order to demarcate the spray boundary. The variation both in time and space of image boundaries were used to characterize the jet stability in statistical sense.

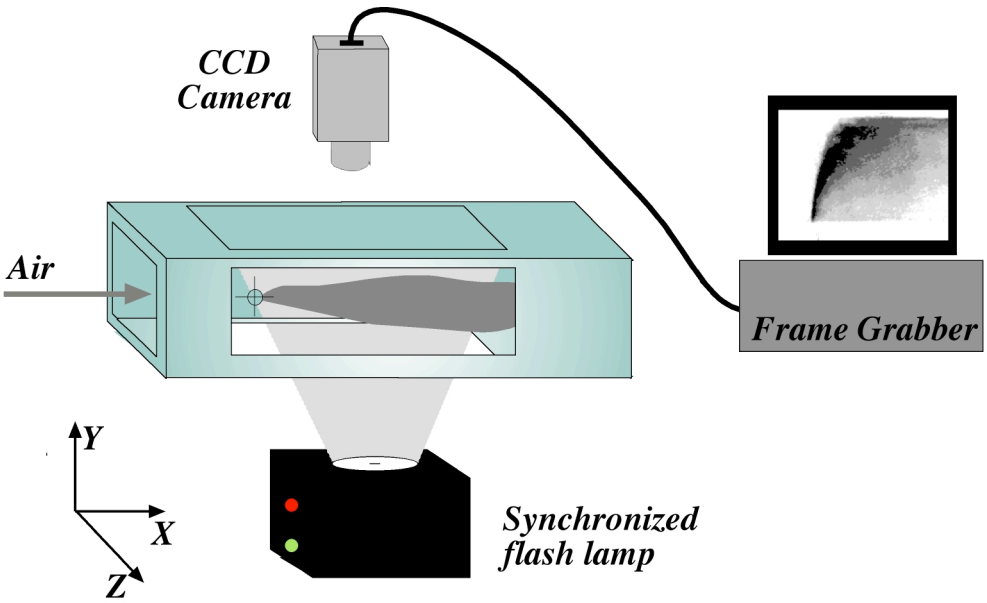

Figure 2. Diagnostics schematics.

Results and Discussion

It's generally accepted that penetration and bending of liquid jet in crossflow conditions are regulated by q-parameter which is the motion quantity stream ratio of liquid and gas:

$$q = \frac{\rho_l v_l^2}{\rho_g v_g^2} \tag{1}$$

Where ρ and v are the density and the velocity while the subscripts l and g refers to the liquid jet and the air-flow, respectively.

As matter of fact a very bended jet could be observed when q is low. On the other hand when q is very high the liquid jet penetrates more causing an impact against the wall in extreme conditions. A connection between jet stability and q could be also envisaged. Anyway a clear assessment of the dependencies of jet bending and stability on other parameters (e.g. nozzle diameter and liquid properties) needs further investigation over wide ranges of such parameters.

This paper concentrates mainly on the definition and validation of objective criteria to be used in the determination of jet properties to be used for the analysis of presented results and in future research work. The first requirements for the set-up of these procedures is the definition of spray features that can be produce quantitative description of the spray evolution. The simplest jet characteristic is represented by its contours. An external (windward) and an internal (leeward) contour can be defined and computed by applying on the numerical image an appropriate numerical filter. They give a simple indication of the jet boundary trajectories. In the present work for each image external and internal boundaries have been computed. The external boundary behaviour analysis is here reported because: 1. it appears to be more indicative of the jet trajectory, 2. it is less influenced by statistical fluctuations, 3. it gives a direct indication of the possible jet impact on the wall.

In order to clarify a possible correlation between jet stability and injection conditions a square average shifting indicator, s, has been defined as:

$$s = \frac{1}{N}\sqrt{\sum (x_n - x_m)^2} \tag{2}$$

Where x_n is the x coordinate of external boundary of nth image, and x_m is the x coordinate of average image boundary. The s indicator has been plotted as a function of the z coordinate in each experimental condition in figure 3.

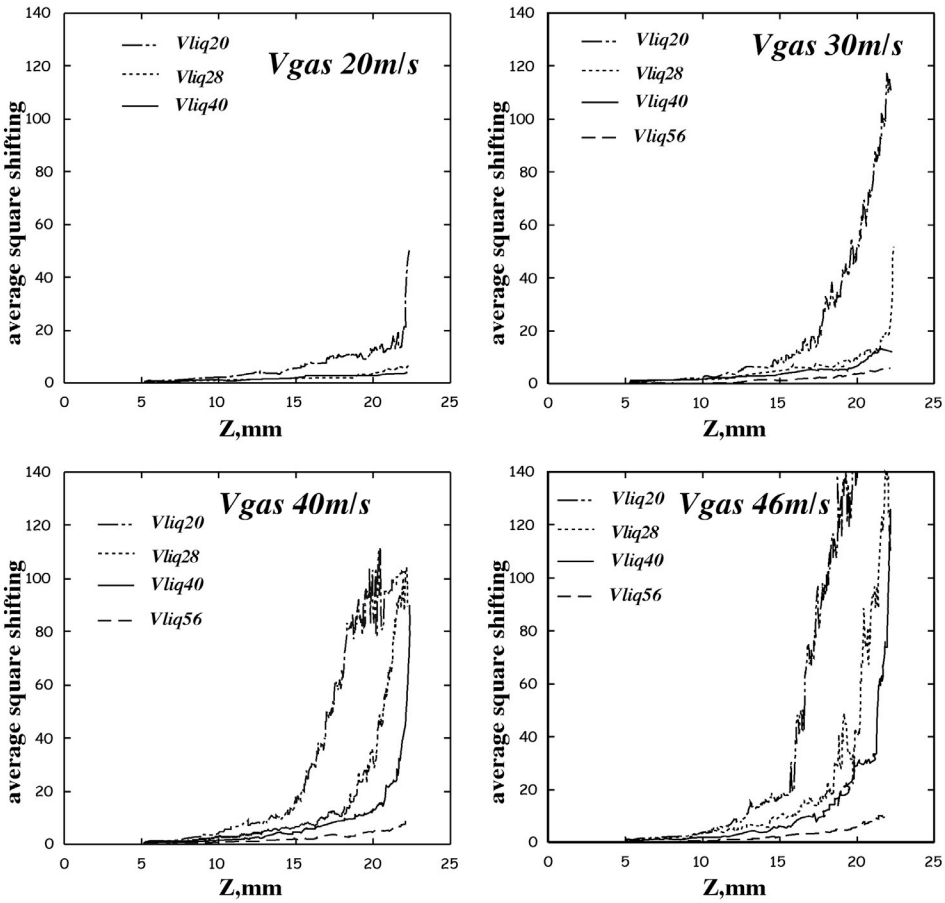

Figure 3 Square average shifting indicator versus z for some experimental conditions.

The graphs show, for low values of the ordinate, a slow and regular increase of the square average shifting error. This phenomenon is caused by the progress of the atomization process. In some conditions a square mean shifting error sudden increase can be observed at a distance from the nozzle greater than 15 mm. This increase could be tentatively attributed to the breakup of the liquid column. In this case the error increase can be explained by the different behaviour of a cloud of droplets with respect to a liquid column. Although this is not a rigorous evaluation of the jet break-up position it appears to be at least a good first approximation estimation method of this position.

A primary goal of this work was to find a semi-empirical correlation that could describe the liquid jet trajectory if the main atomization parameters were known. The correlation proposed by Wu et al [2] was used as a guideline. In addition a linear variation of transversal section diameter has been here assumed (see figure 4), in order to take in account for the transverse section area reduction due to the liquid stripping from the jet:

$$D = D_o\left(1 - z/Z_{jb}\right) \tag{3}$$

where D_o is the nozzle diameter assumed as the initial jet diameter.

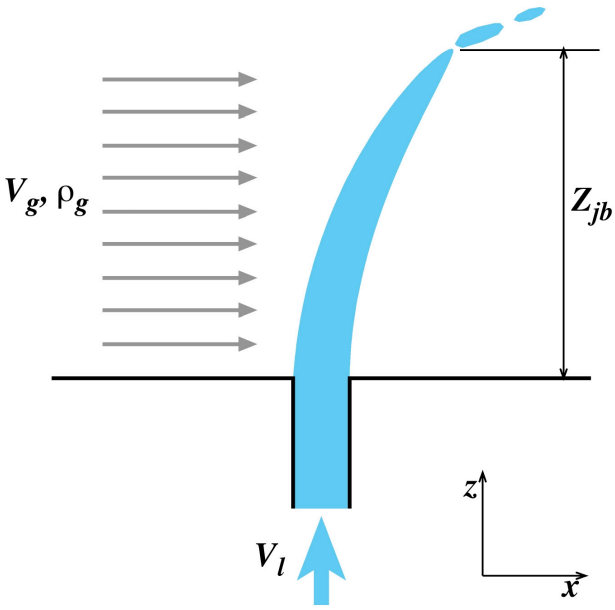

Figure 4 Schematic representation of the liquid jet - air flow interaction.

The proposed model is based on the balance of drag force (responsible of the bending) and inertial force (responsible of the penetration):

$$\frac{1}{2}C_D\rho_g v_g^2 D_0\left(1 - z/z_{jb}\right)\delta z = \rho_l \frac{\pi D_0^2\left(1 - z/z_{jb}\right)^2}{4}\delta z \frac{dV_{l,x}}{dt} \tag{4}$$

By integrating twice the forces balance a jet trajectory correlation is obtained in the form:

$$x = AZ_{jb}^2\left[\ln\left(\frac{Z_{jb} - z}{Z_{jb}}\right)\left(\frac{Z_{jb} - z}{Z_{jb}}\right) + \frac{z}{Z_{jb}}\right] \quad \text{where: } A = \frac{2C_D}{\pi D_o q} \tag{5}$$

That is obviously valid for $Z < Z_{jb}$.

In the eqn. (5) there were two parameters to be characterized: the drag coefficient C_D, and the jet break-up ordinate, Z_{jb}. The drag coefficient can be considered constant even if the cross-sectional diameter is not constant in consideration of the Reynolds number values. To simplify the balance equation's resolution the liquid velocity in the z direction was assumed as constant. Also the ordinate of the liquid jet break-up, Z_{jb}, was considered equal to the curvilinear jet break-up distance L_{jb}.

The jet break-up ordinate, Z_{jb}, could be estimated by applying the aerodynamic theory of jet break-up. In the present work an experimental procedure has been defined to evaluate Z_{jb}. On the ground of the s indicator plots in figure 3 it has been assumed as the jet break-up position the z value where the sudden increase of this

indicator could be observed. This assumption is obviously possible only when the phenomenon of the liquid column break-up occur before the jet impact on the wall of the chamber.

Knowing C_D and Z_{jb} it is possible to calculate the jet trajectory using the proposed correlation.

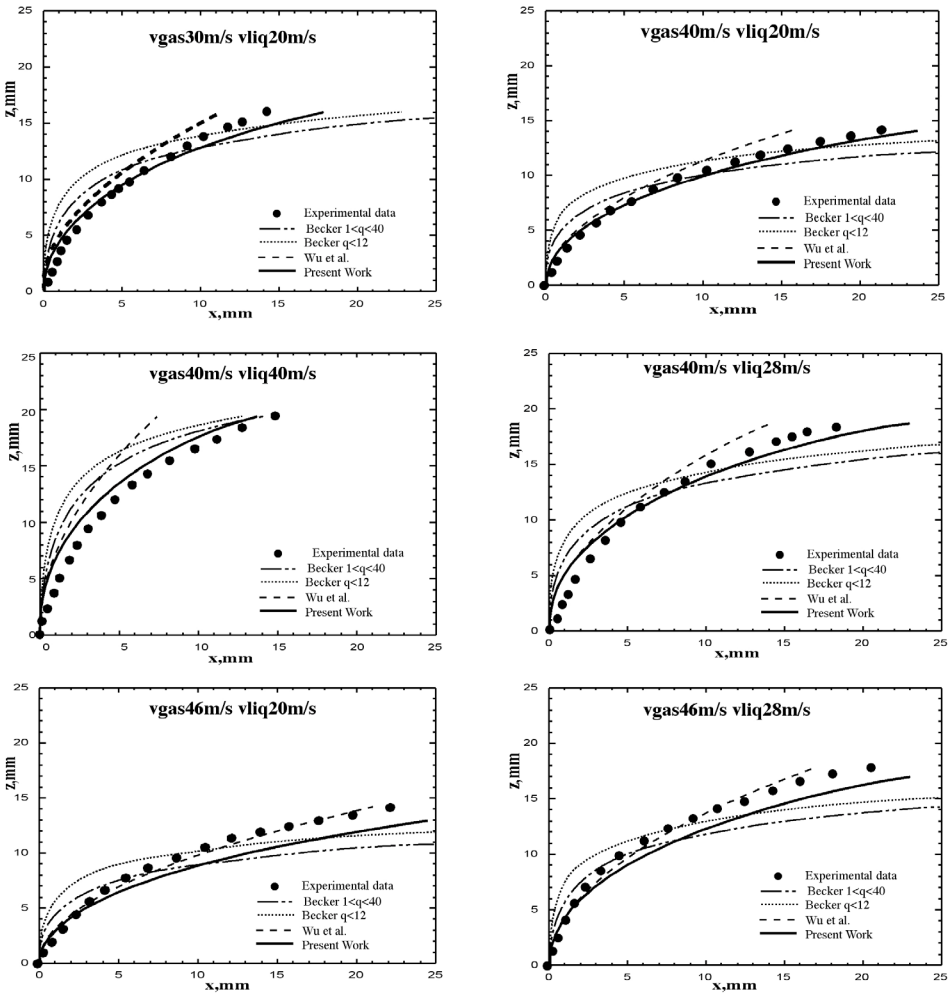

Figure 5 Comparison between the proposed correlation and the literature's ones.

In Fig. 5 the trajectories calculated using the correlation are compared with those obtained using the correlations proposed by Wu et al [2] and by Becker et al. [3].

The correlation proposed in this paper appear to well interpolate the experimental data in the region near to the nozzle as well as Wu's correlation. This is easily explained considering that the two correlations have the same initial slope. Moving away from the nozzle Wu's correlation error increases because it does not consider diameter reduction due to the progress of droplet stripping from the jet. Becker's two correlations seems to be less effective than the other ones both close to the nozzle and further downstream.

It is possible to give a numerical evaluation of the effectiveness of the above-mentioned correlations by defining a residual average error as:

$$RAE = \frac{\sum (Z_{ic} - Z_{is})^2}{\sum (Z_{ic} - Z_{is})^2 + \sum (Z_{ic} - \overline{Z_s})^2}$$

Where Z_{ic} and Z_{is} are the ordinate values of correlation points and experimental points, while $\overline{Z_s}$ is the average value of the experimental point ordinates.

In Fig 6 the RAE for the experimental conditions studied is reported. Full symbols identify the conditions where it's possible to evaluate Z_{jb} while the empty symbols are used for the conditions where the q parameter assumes high value so that Z_{jb} is determined as the mean of breakup distances for the conditions where It is possible to evaluate Z_{jb}. From the plot, Wu's residual mean error is similar to the proposed correlation only for

low values of q, while high values of q cause an increase of this error because the cross section area is decreasing in width.

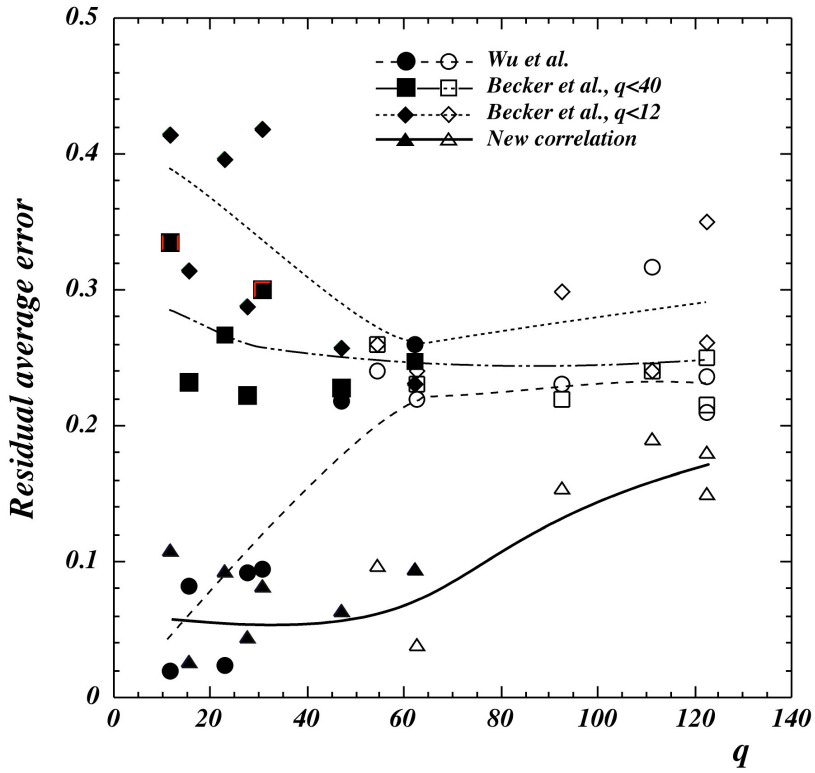

Figure 6 Residual average error of various correlations versus q parameter.

Conclusions

This paper illustrated a statistical procedure for the analysis of shadowgraphic patterns allowing for the determination of the stability behavior of the liquid jet. By the analysis of the liquid jet contour fluctuations it is possible to infer the liquid jet break-up position. The knowledge of the breakup position allowed to introduce a new semi-empirical correlation capable of describing in a very effective way the jet trajectory in a q value range larger than that of previously available correlations.

The real advantage of the proposed correlation consists in the fact that it's applicable for a wider range of q values. In fact, for q values>100 (outside the normal range of q turbine work) there is a kind of low residual error. The functional shape of the proposed correlation, as it has been illustrated, could be a sort of disadvantage. Usually the correlations are written as $z = z(x)$ in order to highlight penetration phenomenon while in this article the correlation is written as $x = x(z)$ in order to highlight the bending phenomenon. It is impossible to analytically invert the proposed correlation because there is a linear and logarithmic shape. On the other hand the proposed correlation can be easily inverted numerically.

Future development of this work will be to verify the proposed correlation in high temperature conditions and different nozzle diameters as well as to introduce a correction to take in account the effect of spray cross section deformation.

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