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PASSIVE SCALAR MIXING IN A TURBULENT JET

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ABSTRACT

The present work investigates passive scalar turbulent mixing by means of experimental optical techniques capable to simultaneously measure the instantaneous velocity and scalar fields in a non-intrusive way. In particular, passive scalar mixing of a water jet ejected from a pipe duct onto the surrounding quiescent pure fluid is studied by simultaneously using Particle Image Velocimetry for the velocity field and Planar-Laser Induced Fluorescence for the scalar field. The Reynolds numbers (Re) of the jet flow, based on the jet diameter and exit maximum velocity, is 23700 so a fully turbulent jet emerges from the pipe allowing investigating the mixing mechanisms driven by velocity fluctuations. In order to avoid diffusion to be important compared to advection, a scalar substance, Fluorescein sodium salt, with a Schmidt number equal to 2050 has been employed. This ensures turbulent transport to be investigated focussing on Reynolds fluxes, $\langle u_i'c'\rangle$, whose measure is the main aim of this work.

A detailed and accurate description of these quantities is given, unveiling some new interesting features in the pipe jet near field, $0<x/D<17$, where few experimental data are available for the scalar concentration field. At the end of the investigated region, the present data approach the Literature data for the self-similar region.

INTRODUCTION

Mixing is one of the most studied topics in Fluid Mechanics both for its importance in basic research and for the engineering applications in which is involved. When two pure miscible substances are put in a defined space region, they tend to mix; they are fully mixed when their concentration is constant over the volume, down to molecular scales, reaching intermediate values in comparison to the starting ones. From the research viewpoint, apart for the standing-alone importance of understanding how a passive substance spreads out, mixing provides an insight of turbulence phenomena complexity being characterized by many different features not reproduced in the advecting velocity field. Thus, the investigation of mixing is a tool to better understand turbulence growth, evolution and dissipation in many different flows – shear flows, bounded flows, turbulent flows. Concerning engineering applications in which mixing of two, or more, substances is important, spacing from the aeronautical to the environmental field, the enhancement or the reduction of dispersion, and thus the comprehension of these phenomena, is the main parameter to control in order to well design a jet burner or a factory chimney. For a steady, incompressible fluid, the scalar mass concentration equation is:

$$\tilde{U}_i \frac{\partial}{\partial \tilde{x}_i} \tilde{C} = -\frac{\partial}{\partial \tilde{x}_i} \langle \tilde{u}'_i \tilde{c}' \rangle \qquad (1)$$

where ˜ indicates non-dimensional quantities and a high Peclet number is assumed.

Under the current assumptions, in order to theoretically or numerically predict the mean scalar concentration field, the knowledge of the Reynolds fluxes, which appear in equation (1) through gradients on the right hand-side, is mandatory. Apart from DNS, capable of solving the fluid-dynamic field down to the smallest scales both for the velocity and the scalar field for Reynolds number up to some thousands, the other numerical approaches, RANS and LES, need a closure model for this quantity or the introduction of equations that again need closure relations for higher order moments in the classical framework of turbulence cascade (Tennekes and Lumley 1972, Pope 2000). For this reason, direct measurements of these quantities are important to furnish data to be modeled accordingly and used in numerical codes.

The investigation of mixing in a jet flow has the advantadge of a well known underlying velocity field. In fact, many researchers have devoted a huge amount of work to jet flows being both of fundamental importance in turbulent fluid flow research and in industrial applications. Some of the basic studies were conducted by Wygnanski and Fiedler (1969) and Capp (1983). A milestone in jet research is the work of Hussein et al. (1994) on high Reynolds number jet using flying hot wire anemometry providing a deep insight into turbulent kinetic energy dissipation and budget. Panchapakesan and Lumley (1993a) conducted a similar investigation extending their interest also to scalar mixing (1993b).

In addition to that, in the last two decades, following the work of George (1989), attention has been payed to differences of the initial conditions on the achievable self-similar state in the jet far region as in the work of Ferdman et al. (2000) and Xu and Antonia (2002).

Regarding the scalar field in a momentum or buoyancy driven jet, few works are available, especially in the past years. Among these, some have to be mentioned.

As reported before, one of the most comprehensive work is that by Panchapakesan and Lumley (1993b) who present joint velocity-scalar concentration second and higher-order moments in the self-similar region of a high Reynolds number buoyant jet.

In the paper of Papanicolau and List (1989), accurate measurements of scalar concentration and scalar fluxes are reported at the centerline of a buoyant round jet. Also important is the work of Dahm and Dimotakis (1990) investigating the effect of Reynolds number with a high Schmidt number scalar on the mixing of a round jet in the far field. In the investigation of Wang and Law (2002), a second-order integral model has been developed for the scalar concentration in the far field validated by measurements. In Aanen (2002), scalar concentration measurements for the evaluation of Reynolds fluxes are presented downstream a point-like source and at the exit of a pipe jet. The same investigation, even if performed using a different acquisition system, has been conducted by Zarruck and Cowen (2007) for a low Reynolds number neutrally buoyant round jet.

In the present work passive scalar turbulent mixing at the exit of a pipe has been investigated by means of experimental optical techniques capable to simultaneously measure the instantaneous velocity and scalar fields in a non-intrusive way. To this aim, combined Time-Resolved PIV and P-LIF measurements, have been performed; the PIV technique allows the planar instantaneous velocity fields to be obtained, while P-LIF provides the instantaneous scalar concentration fields. Measurements at a Reynolds numbers equal to 23700 have been performed in order to understand the influence of convective forcing on mixing mechanisms. Working with water, a suitable scalar substance, Fluorescein Sodium Salt, has been selected with a Schmidt number of 2050, with Sc=ν/D where ν is the kinematic viscosity and D is the molecular diffusivity. This ensures turbulent transport is investigated focusing on Reynolds fluxes $\langle u_i'c' \rangle$. The attention has been focused on the near and developing regions of the pipe jet where no literature data are available for comparisons differently from the self-similar one, Aanen (2002), Hussein et al. (1994), Panchapakesan and Lumley (1993a and b). In this work, particular attention is paid to the first and second order statistics both for velocity and scalar fields separately and for the joint ones.

A good collapse of the present data with those reported in literature has been achieved. In fact, approaching the far field, i.e. x/D > 16, the well-known values, see as an example Panchapakesan and Lumley (1993b) and Wang and Law (2002), are generally recovered. On this basis, as an important consequence, a detailed description of Reynolds fluxes have been given, unveiling some new interesting features in the pipe jet near field; the evolution of the axisymmetrical shear layer generated at the jet exit is described in fine detail.

EXPERIMENTAL SET-UP

This experimental apparatus is an open loop hydraulic circuit; to ensure reliable P-LIF measurements, the main tank feeds the circuit and water is not recirculated avoiding a change to the scalar concentration. A free surface test section was used to avoid optical disturbances in the imaged scalar concentration fields (cioe' ?); a volumetric pump was used to transfer water from the main tank to the constant level tank in order to suppress artificial velocity fluctuations at the pipe exit due to the pump. Two different screens have been used to avoid swirling in the jet and large structures to come out from the pipe. The water jet facility consists of an axisymmetrical water jet flowing downstream a 2.5 m long pipe.

The investigated Reynolds number was, using the average jet outlet velocity U_0 and the jet diameter D = 2.2 cm, (L/D = 113, being L the pipe lenght) Re = 23700; the Reynolds numbers based on the Taylor microscale, Re_λ, was about 570. The characteristics lenght scales for the jet flow, evaluated accordingly to Tennekes and Lumley (1972) are reported in Table 1 both for the velocity and the scalar fields.

The acquiring system is composed by two high speed camera. Two different Photron APX CMOS camera with 1024×1024 pixels resolution were used to simultaneously acquire the velocity and the concentration fields. The camera acquires 2000 images per second at full resolution and the repetition rate of the system is 2 kHz (the time resolution of the system, for the present measurements, has been under-sampled at 1 kHz).

The illumination was provided by a continuous Ar-ion Laser, driven at 488 nm in wavelength only, with a maximum power equal to 2.4 W. Considering the shutter time (1/1000 s), the effective energy available for the camera sensor was about 4 mJ.

Two different interference bandpass filters, centred respectively at 488 nm and 540 nm wavelengths, placed in front of each camera, were used to separate the reflection of the seeding particles and the fluorescence of the passive scalar – Fluorescein sodium salt. This optical set-up allows to simultaneously acquire images to be processed with the PIV algorithm and P-LIF one.

To improve the illumination uniformity in the images, a scanning laser light beam was used through the aid of rotating mirrors; using a photodiode to detect the passage of the laser beam, the cameras were triggered to perform simultaneous acquisitions. The total amount of acquired images was 20000; such a large number of images was necessary to derive averaged velocity and scalar fields and other turbulent statistical quantities, *i.e.* turbulence *rms* values, Reynolds stresses and fluxes.

Measurements have been performed in the developing region of the pipe jet (0 < x/D < 17) with the jet axis imaged at the center of the region of interest; three different areas along the jet axis have been investigated, each of them was 6D long. Overlapping of the acquired areas allows to overcome border problems in PIV results for a total of 17D of length investigated from the jet exit. Images from camera 1 (with filter at 488 nm) were analysed by PIV to derive the velocity fields. The analysis was conducted using a standard iterative multi-pass multi-grid window deformation algorithm; the used final interrogation window was 32x32 pixels with 75% overlapping giving a spatial resolution of 1 mm. Images from camera 2 (with filter at 514 nm) were analysed to derive the scalar field. The spatial resolution for the scalar concentration field was 0.1 mm. In Figure 1, an example of the acquired images is reported.

Table 1: Characteristics length scales.

Re	λ (mm)	λ_b (mm)	η (mm)	η_b (mm)
23700	4.8	0.1	0.1	0.002

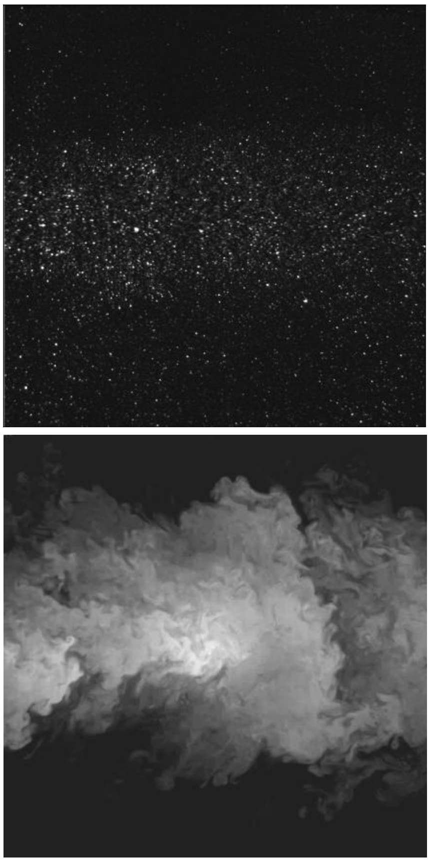

Figure 1: Example of acquired images; above PIV image, below PLIF image.

RESULTS

In this paragraph an overview of the results is presented. The results are presented in terms of velocity and scalar concentration; axial and radial profiles at the exit of the jet, are useful to qualify the pipe flow, *i.e.* fully developed flow. In addition to that, the two Reynolds fluxes are represented as a color map in the investigated region; some radial profiles are also given as long as Literature data for comparisons. As a first step of the work, the pipe jet had to be qualified from a fluid dynamic point of view; for the pipe jet there are requirements that have to be fulfilled to get a fully developed turbulent flow. Firstly, the ratio of length to diameter, *L/D*, is known to be larger than 70 to make the laminar-turbulent transition occur. Secondly, it is fundamental not to have large structures, *i.e.* vortices or coherent structures, to exit from the pipe; to avoid this, as previously mentioned, two different screens were used to generate small scale turbulence. In Figure 2, radial and axial profiles for the velocity and the scalar concentration mean non-dimensional values and non-dimensional root mean square are presented at the exit of the pipe, $x/D = 0.05$.

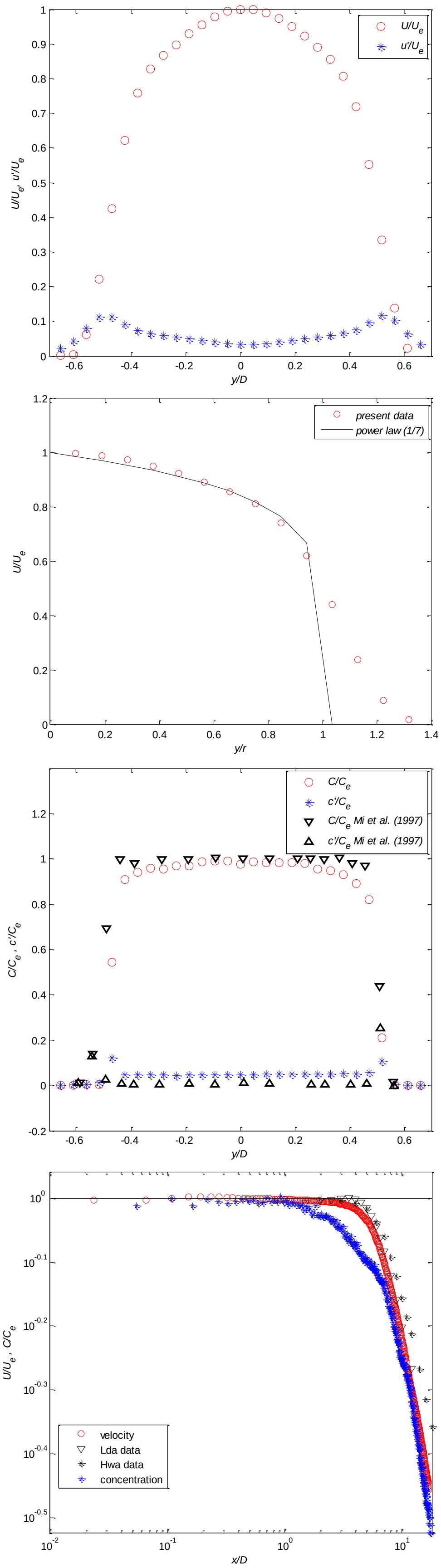

Figure 2: Radial and axial velocity and scalar concentration profiles.

In the first plot of Figure 2, the radial mean and rms profiles of the axial velocity are presented; in the second plot, a comparison between the radial profile of the axial velocity and 1/7 power law is shown. It is possible to observe a good agreement indicating that the issuing jet is fully turbulent, as reported in Pope (2007).

In the third plot of Figure 2, mean and rms of scalar concentration are presented against the data of Mi et al. (1997); the comparison shows a good accordance in the non-dimensional values.

In the last plot, axial profiles of the mean axial velocity and scalar concentration are compared with the data of Burattini Antonia and Burattini (2004) and with the ones of Djeridane et al. (1993); the collapse of the velocity profile is good while the scalar concentration shows a larger decrease in the first 6-7 diameters.

In Figure 3 and 4, the <*u'c'*> and <*v'c'*> fields are represented respectively as color map; the presented maps are made non-dimensional by the local mean axial velocity and scalar concentration. The general features of the presented fields are well-known from published data, see Aanen (2002) and Webster et al. (2001); in the two shear layers, two wakes are generated and develop up to the end of the studied region where the values they assume approach the self-similar ones. At x/D=4÷5, the two layers merge at the jet centreline; the non-dimensional values for both the quantities increase along the jet axis approaching the self-similar ones.

In Figure 5, the radial profiles for <*u'c'*>, where the values are non-dimensional by using the local mean velocity and scalar concentration, are presented. It is possible to note how starting from very low values, the self-similar value is approached more or less at 16*D*; the radial position of the peak value is shifted in the present data towards the jet centreline in respect to the data reported in Panchapakesan and Lumley (1993b). This could be due to the different nature of the investigated jet; in that case, in fact, a buoyant jet has been investigated.

Figure 6 present the <*v'c'*> radial profiles. For this case too, the values at the end of the investigated region approach the self-similar ones. As a matter of fact, in the present work, the statistics involving the *v*-component present a higher quality level; this can be observed both in the fields and in the radial profiles.

The radial position of the peak values is shifted towards the jet axis for this quantity too. As noticed before, moving along the jet axis away from the jet exit, a constant increase in the value is present; just in the first region the maximum radial value at 3*D* appears to be underestimated. This can be due to the fact that the shear layer for the *v*-component develops at a higher x/*D* in comparison to the *u*-component one; moreover the scalar fluctuations start to develop just at the sides of the jet exit too. So an initial decrease can be due to the different axial distances at which the two fields start to interact.

In conclusion, with the proposed simultaneous techniques, the Reynolds fluxes have been evaluated with a good level of confidence especially for the higher Reynolds number case; convergence problems are evident for the lower Reynolds number due to the reduced number of data samples. Anyhow, good results have been obtained also in this case; with a larger data samples, much better results are expected. To conclude, these measuring systems seem to well estimate the simultaneous velocity and scalar concentration fields.

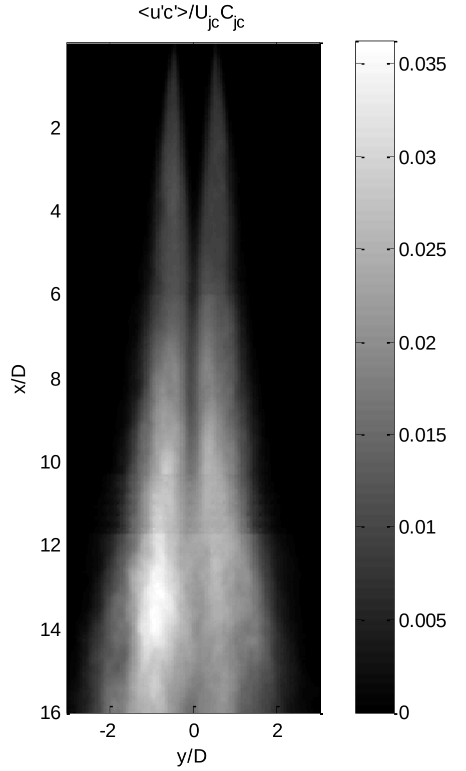

Figure 3: <*u'c'*> map.

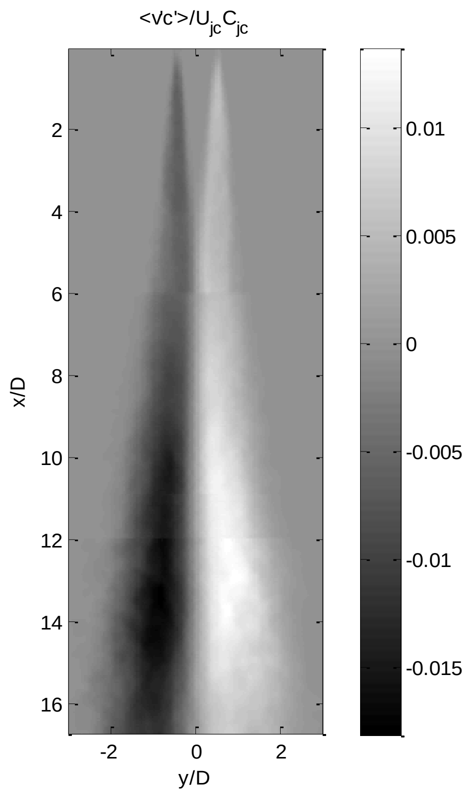

Figure 4: <*v'c'*> map.

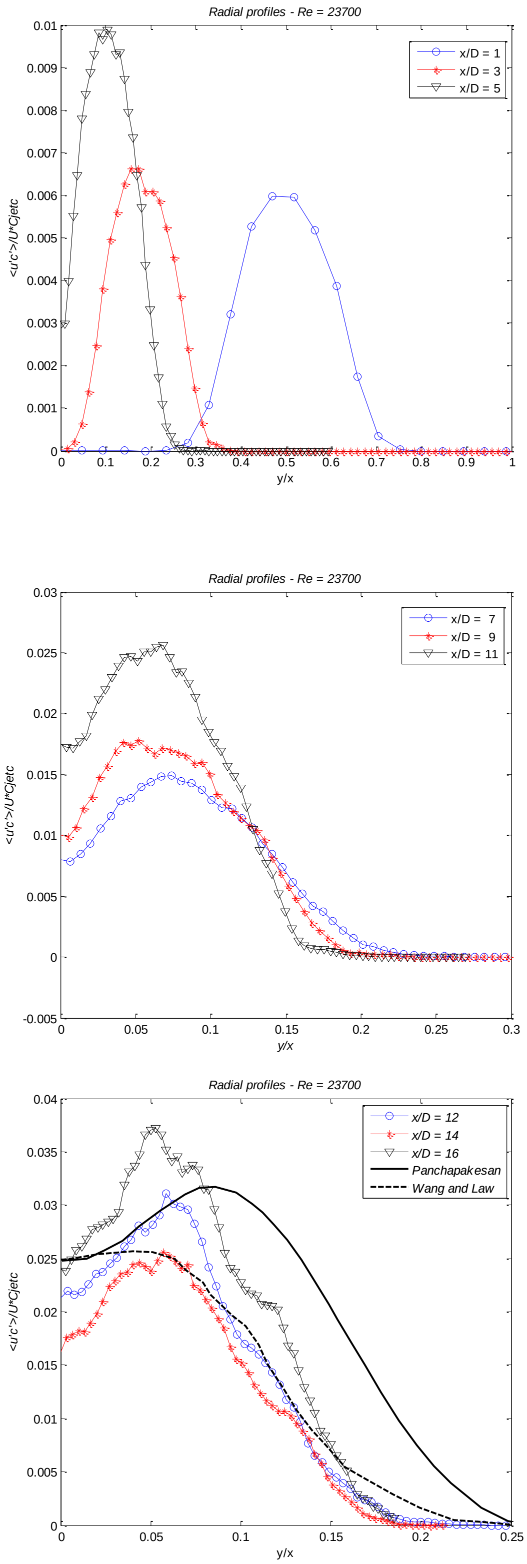

Figure 5: $\langle u'c' \rangle$ radial profiles.

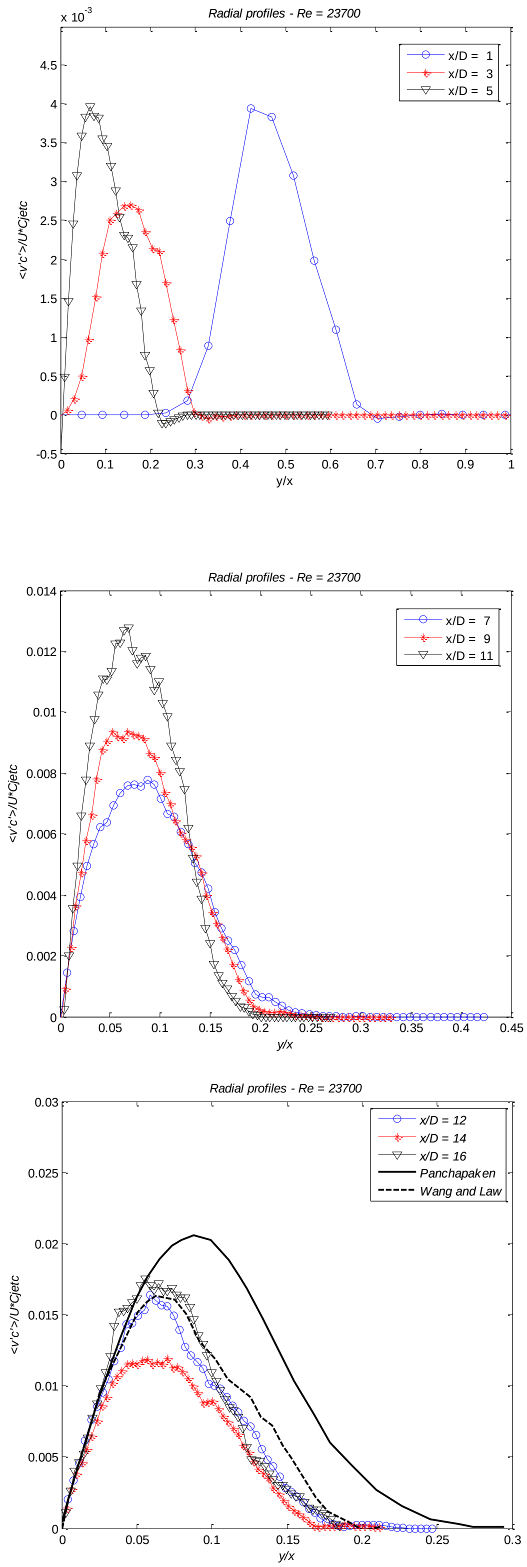

Figure 6: $\langle v'c' \rangle$ radial profiles.

CONCLUSIONS

Passive scalar turbulent mixing in a pipe jet has been investigated by means of experimental optical techniques capable to simultaneously measure the instantaneous velocity and scalar fields in a non-intrusive way. To this aim, combined Time-Resolved PIV and P-LIF measurements, have been performed; the PIV technique allowed the planar instantaneous velocity fields to be obtained, while P-LIF provides the instantaneous scalar concentration fields. Fluorescein Sodium Salt, with a high Schmidt number (2050) has been selected. This ensured turbulent transport was investigated focusing on Reynolds fluxes –$<u_i'c'>$– whose measure was the main aim of this work.

A new experimental apparatus has been set-up; a jet issuing from a pipe with known and controlled flow quality is now available.

Regarding the results, the advantages of the simultaneous use of Time-Resolved PIV and P-LIF techniques has been confirmed by correctly evaluating the Reynolds fluxes at the end of the developing region; a good collapse of the present data with those reported in Antonia and Burattini (2004), Djeridane et al. (1993) and Wang and Law (2002) has been achieved. Slight discrepancies with the data of Panchapakesan and Lumley (1993), are present.

On this basis, as an important consequence, a detailed description of these quantities have been given, unveiling some new interesting features in the pipe jet near field; the evolution of the axisymmetrical shear layer generated at the jet exit is described for the Reynolds fluxes.

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