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Evolution of Field Velocity Throughout an SMX Static Mixer: Experimental Investigation by Pulsed Ultrasonic Velocimetry

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Abstract: Data are collected for the Sulzer SMX mixers in the transitional and turbulent flow regimes (for Re = 1963; 4879; 9984; 13270), using a pulsed ultrasonic velocimetry technique. Velocity profiles before, after and within the static mixer is reported. Turbulence intensity is computed for various recorded data and the rate of mixing according to Reynolds number is deduced.

Key words: Static mixer, sulzer SMX, turbulent flow; pulsed ultrasonic velocimetry, mixing

INTRODUCTION

In-line static mixers do not need an introduction anymore since they now cover a wide range of industrial applications: Continuous mixing, heat and mass transfer processes and chemical reactions. The complex geometry of Sulzer SMX mixer ensures the material properties homogenisation such as concentration, temperature... Determination of the velocity field is of interest for its inter-dependence with convective phenomena induced.

In spite of many applications of static mixers, the comprehension of fundamental process remains, up to now, insufficiently described[1]. However, the literature reports investigations on pressure drop[2-4], residence time distributions[3,5], experimental velocity profile from Laser Doppler Anemometry (LDA)[6], friction factor by polarographic techniques[7,8]. In addition, the impact of the SMX on phase inversion has been studied[9]. Furthermore, computational simulations with Fluent™ and more recently Femlab™, supplemented experimental approaches[10].

It should be pointed out that few independent data regarding the SMX performance in the turbulent regime are available in the literature. In the present study, a vertical duct of diameter D, with Sulzer SMX static mixer, fed with perpendicular submerged injection, is described and analyzed for four Reynolds number (Re= 1963; 4879; 9984; 13270), the latter being based on bulk velocity and pipe diameter. The experiments are based on Pulsed Ultrasonic Velocimetry (PUV) method allowing, then, to extract velocity profile along a slotted line. This study is dictated by the precision of the method and its exclusive use for this type of static mixer. The main objective, of this investigation, is the velocity profile measurements before, within and after the static mixer. The turbulence intensity, obtained from experimental data, gives appreciations on the rate of mixing with respect to axial positions and Reynolds number.

Experimental set-up: The Pulsed Ultrasonic Velocimetry (PUV) technique has been used to get velocity profiles outside and inside the SMX Fig. 1. The choice such experimental method (PUV) has been dictated by its high degree of accuracy, the number of points constituting the profile, its possible extension to study emulsions and evidently it is a non intrusive technique.

The measurement device (DOP 1000, Signal Processing S.A) gives the mean velocity, standard deviation, minimum and maximum velocity for each position using generally 512 emission/profile. The velocity and turbulence intensity profiles are extracted from such data. The velocity modulus is calculated from the following expression:

$$V = \frac{C_{eff}\, f_D}{2\, f \cos(\theta)} \qquad (1)$$

The experimental set up is a pipe, with an inside diameter of 50 mm and an overall length of 14 D. In fact this pipe is made of two identical parts interconnected by a static mixer SMX 50 Fig. 1. The ultrasonic probe can

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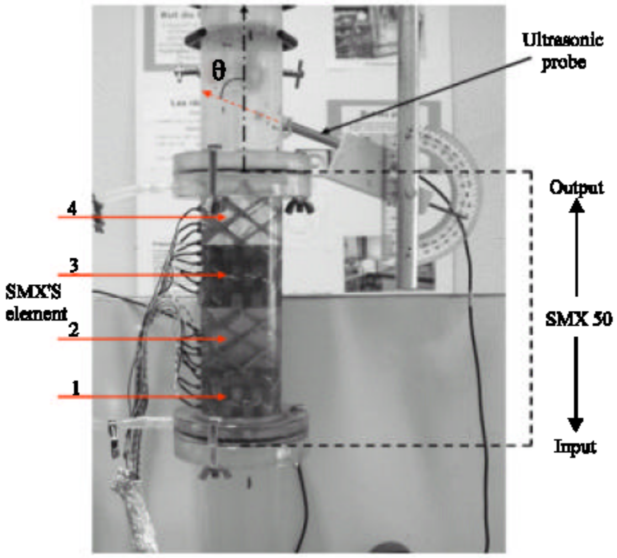

Fig. 1: Position of the ultrasonic probe

be displaced along the pipe and is localized as Z1 = 50 mm before the SMX, Z2 = 35 mm after the latter and by Z0 within the forth elements of the mixer. It should be noted, within the SMX, the value used for the angle Θ is 81°, whereas on both sides mixer the angle of attack used is of 65°. The first choice is governed by the skeleton of the matrix constituting the SMX while the second choice, for θ corresponds to the optimal value adopted in the literature. The fluid is water and the proprieties are taken at T= 30°C, with density $\rho = 992$ (Kg/m^3), dynamic viscosity $\mu = 0{,}77910^{-3}$ (Pa.s) and sound celerity Ceff = 1509 m s^{-1}.

RESULTS AND DISCUSSION

This experimental investigation covers data recordings for Re= 1963; 4879; 9984; 13270. The Reynolds number (Re) is based on bulk velocity and pipe diameter:

$$\mathrm{Re} = \frac{\rho D U_b}{\mu}$$

The velocity profiles upstream the SMX are first presented. For the same Reynolds numbers the profiles recorded inside the SMX (within the forth element constituting the static mixer) are then reported. Finally the evolutions of the velocity profiles at the exit and various axial positions from the SMX are compared.

Each curve shows the velocity profile as function of x/D (the relative distance from the wall). Each plot includes the data relative errors.

On the velocity profile: It should be noted that the velocity profile is not zero at the distal wall. This is in fact due to an effect referred as “Ghost Flow”[11-13]. The latter is induced by the ultrasonic wave reflection on the distal wall perturbing then the recordings in the wall vicinity.

All the data recorded upstream the SMX, Fig. 2a-5a, reveal a flat velocity profile exhibiting then the turbulent nature of the flow. However, some fluctuations are recorded as Re increases. This can be explained by the fact that the probe is positioned at 1D from the Static Mixer (SMX) and therefore as the value of Re increases the influence of the obstacle is felt.

The flow behaviour within the forth element of SMX is reproduced through Fig. 2b-5b. The plots are on the overall identical with increasing maxima as function of flow regime. In this axis of measurement negative values for velocity in the vicinity of the wall proximal are recorded. The peak values are proportional to the flow regime whereas their position is inversely proportional to the latter (from 0,3 D to 0,25 D for Re>10000). This observation highlights the presence of a recirculation zone which increases axially and get narrower in the radial direction as Re increases. In the distal wall vicinity, it is observed the presence of a velocity peak which decreases to the profit of a homogenisation as Re increases. Therefore in the proximal part of the measurement zone the presence of a recirculation zone of extent lower than 0,4 D and a zone of fluid acceleration in the remainder of control are revealed. This fact highlights the highly mixing character of the SMX.

At the mixer exit Fig. 2c-5c, from probe position Z2 recordings, all the curves behave identically, exhibiting velocity peaks by the parietal zones. The velocity maxima are proportional to the flow rate. The proximal zone reveals the presence of a privileged flow channel, whose extent does not exceed 0.18 D. The latter equals the spacing between the 4 blades constituting the SMX. In addition an accelerating zone is localised in the vicinity of the distal wall. The extent of this zone is more significant and remains constant for any flow regime. The peak velocity is proportional to Reynolds number Re.

Turbulence intensity: With the pulsed ultrasonic velocimetry, the instantaneous velocity is measured during a relatively short sampling time (462---149 ms). Furthermore, 512 data points are recorded for each local position along the beam. It is, thus, possible to calculate the turbulent intensity along the probe axis based on the fluctuations of the instantaneous velocity measurements and the bulk velocity U_b[14].

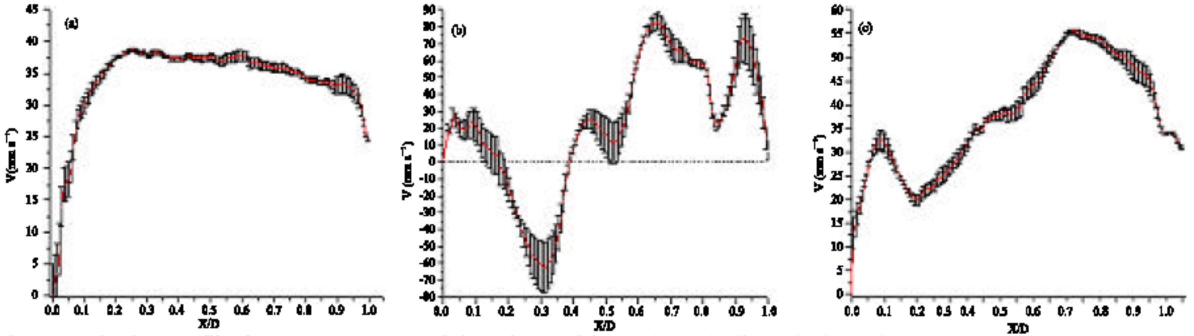

Fig. 2: Velocity profile for Re = 1963 at axial probe positions: (a: Z1), (b: Z0), (c: Z2)

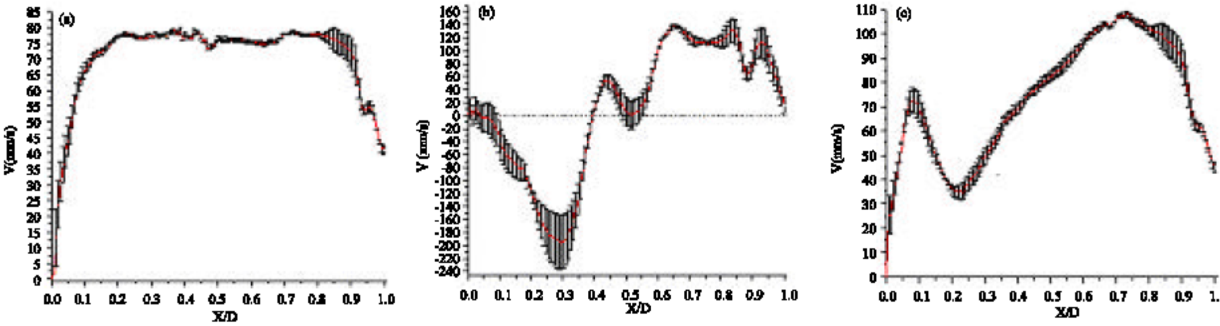

Fig. 3: Velocity profile for Re = 4879 at axial probe positions: (a: Z1), (b: Z0), (c: Z2)

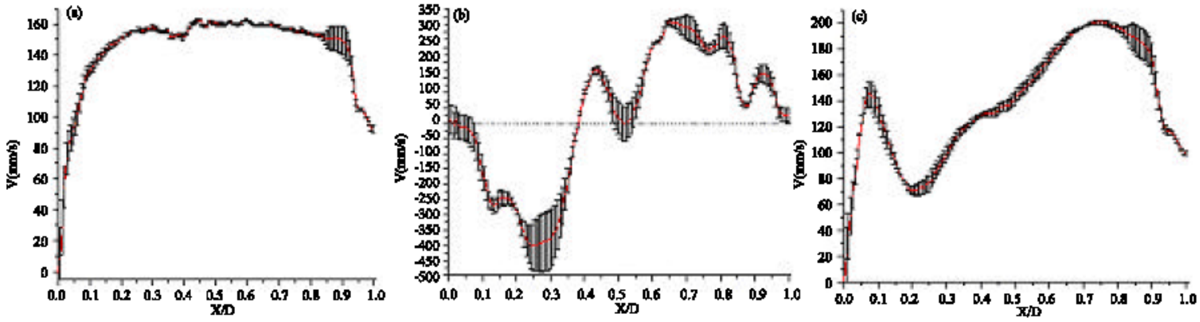

Fig. 4: Velocity profile for Re = 9984 at axial probe positions: (a: Z1),(b: Z0), (c:Z2)

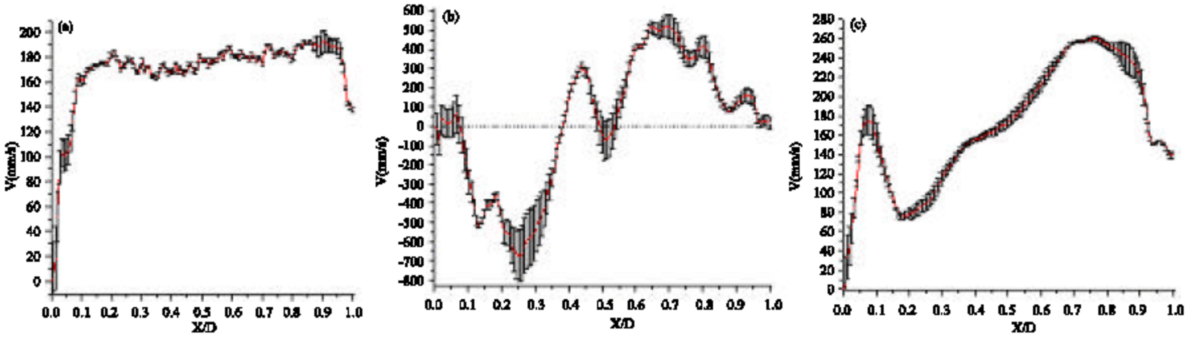

Fig. 5: Velocity profile for Re = 13270 at axial probe positions: (a: Z1), (b: Z0), (c: Z2)

$$I(\%) = 100\frac{\sqrt{(u-\bar{u})^2+(v-\bar{v})^2}}{U_b} \qquad (2)$$

The compared evolution of the turbulence intensity downstream, upstream and within the static mixer is examined. This information will allow to estimate

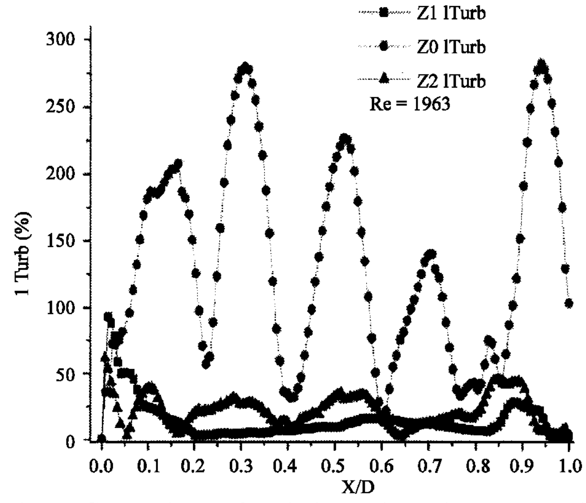

Fig. 6: Comparison of turbulence intensity at 3 axial probe positions for Re = 1963

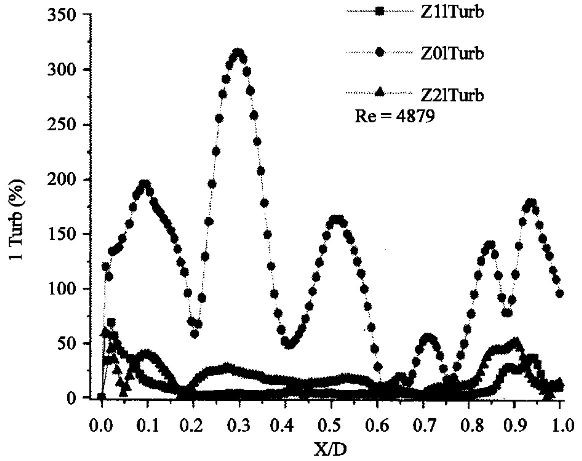

Fig. 7: Comparison of turbulence intensity at 3 axial probe positions for Re = 4879

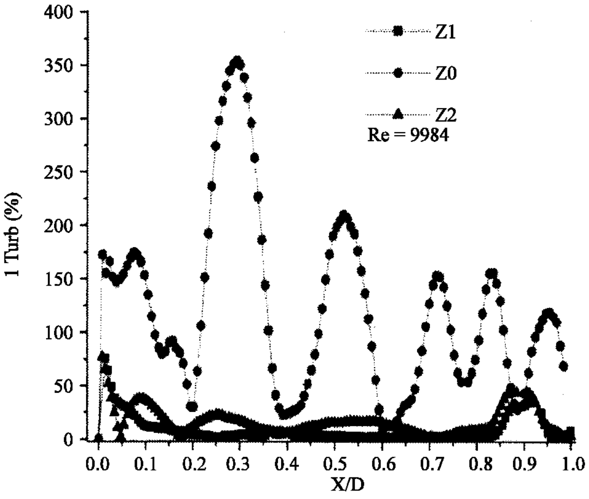

Fig. 8: Comparison of turbulence intensity at 3 axial probe positions for Re = 9984

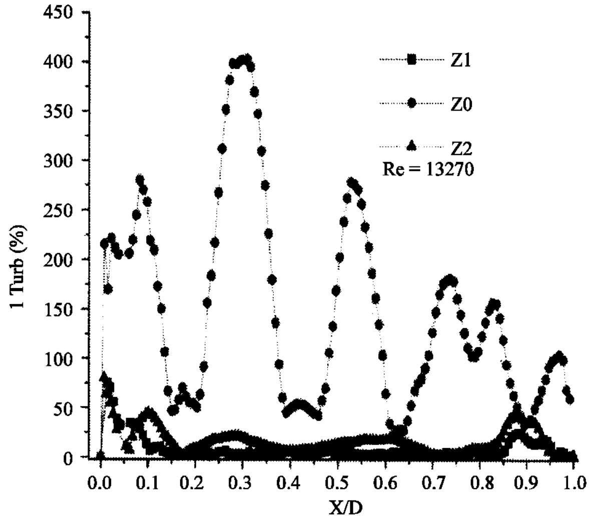

Fig. 9: Comparison of turbulence intensity at 3 axial probe positions for Re = 13270

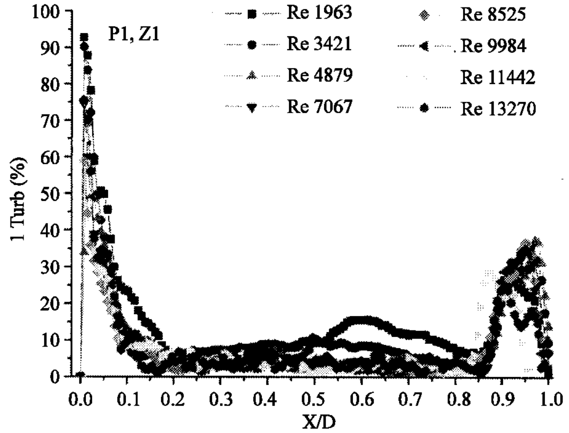

Fig. 10: Turbulence intensity for different Re at position Z1 upstream the SMX

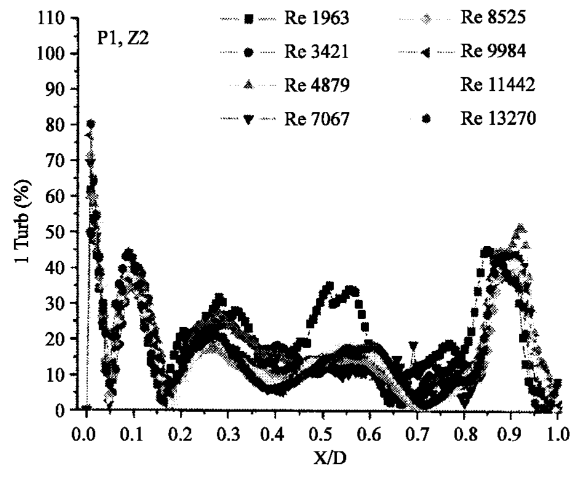

Fig. 11: Turbulence intensity for different Re at position Z2 downstream the SMX

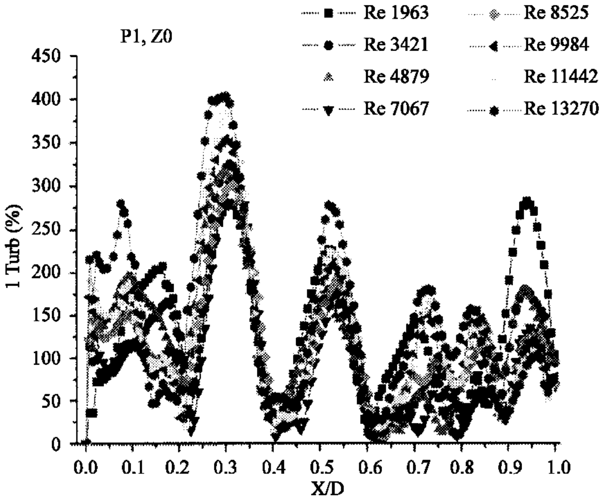

Fig. 12: Turbulence intensity for different Re at position Z0 within the SMX

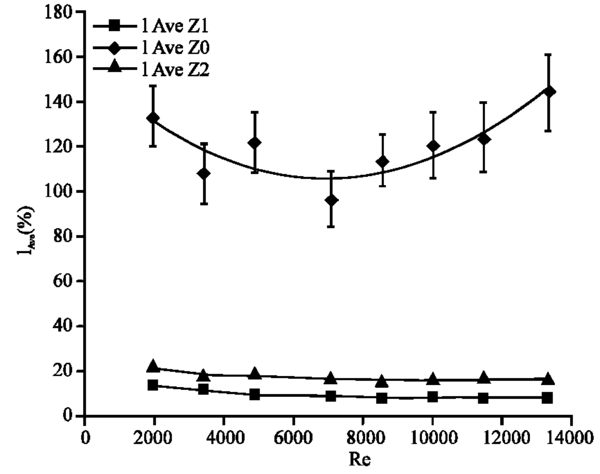

Fig. 13: Compared average turbulent intensity values for different probe position

the rate of mixing[15,16]. Fig 6-9 highlight the differences on turbulence intensity evolution for various probe positions (downstream, upstream and within the SMX). While the Fig. 10-12 exhibit the impact of regimes flow.

The increase of the flow regime does not modify the behaviour of the recorded curves. Upstream the mixer, the curves present a maximum close to the wall while the centre (main flow direction) remains relatively flat with weak fluctuations.

Figure 6-12, shows an increase in Re is accompanied by a progressive reduction of the turbulence intensity profile. The intensity of turbulence within the SMX, reveals a sinusoidal type of evolution, whose intensity is on average 13,5 times more significant than the one upstream. The increase in the flow regime creates new oscillations without changing the existing peaks' sites. The turbulence intensity presents a set of peaks whose amplitude decreases with respect to the parietal position, but increases proportionally to flow regime Fig. 12. Downstream from the SMX, one observes a sinusoidal evolution of the profile of turbulence intensity. These evolutions follow those observed within the mixer, but in smaller proportions. Concerning the average value it is 6 to 8.8 times less significant than that collected within the SMX and the same applies to the maximum values which do not exceed the 1/5 of the value collected in (Z0). With the increase of the flow rate, the intensity of the peaks decreases locally to the profit of the average evolution Fig. 11. Elsewhere, one note the presence of quite specific positions where the rate of turbulence is low and remains constant within and outlet the mixer. These positions correspond to privileged channel flow, characteristic of a porous medium (approach largely adopted in the literature concerning the SMX and reported by[16,17]). It should be noted that the nature of the matrix of SMX is comparable to a porous media, whose vacuums of the 4 connected stacks produce tortuous ways within this mixer.

This last observation shows the highly mixing character of the SMX, but reveals its local nature. The fluid is stirred in a very effective way within the SMX, but the intensity of this mixture is confined in the immediate vicinity of the mixer. In Z2 probe position at 35 mm after the SMX, the rate of turbulence decreases rapidly, in comparison between the values collected within the forth element of the static mixer.

As a whole the curves show the intensity of turbulence downstream from the SMX is on average 1.5 to 2 times more significant than upstream. Moreover the increase of the average rate of turbulence within the mixer is 9,7 to 17,5 times more significant than observed upstream the mixer Fig. 10-12. The increasing of the flow rate produces a reduction on the average value of the turbulence intensity on both sides of the SMX. This evolution is similar for both positions of the probe, previously mentioned and takes a decreasing exponential form, whereas within the mixer the evolution of IAve presents a minimum for Re = 7067 and is described by a parabolic law Fig. 13.

CONCLUSION

The experimental study by pulsed ultrasonic velocimetry of the eight flow patterns, at the three probe positions upstream, within and downstream the SMX made it possible to first extract the velocity profiles and then to estimate local and total turbulence intensity. The latter is regarded as indicator of the rate of mixing. Upstream SMX, a flatness of the profile speeds are noted, this last is in conformity with the literature of the bearing field on the flows of the turbulent type. Within the mixer a substantial modification of the velocity profiles is observed. Profiles are divided into two quite distinct areas:

- **A proximal area:** A zone of recirculation where velocities are negative and presenting maxima whose intensity are proportional to the flow regimes. In this area the position of the peaks does not cease approaching the wall and passes from 0, 3D to 0,25D for Re > 9984.

- **A distal area:** A zone of a multiple acceleration of the fluid, comprising multiple peaks whose intensity is proportional to the flow rate, but of less importance in comparison with those present in the first area.

Generally the velocity profiles collected in this position take a no monotonous form leading to a sinusoid. The form of the velocity profiles thus collected let's suppose the presence of swirling cells. Downstream the velocity profiles present a double peak in the vicinity of the two walls, these evolutions are similar to those met at the exit of a porous media, thus exhibiting two privileged channel flow. The increase of flow rate does not modify the shape of the curves, but just the amplitude of the peaks in the vicinity of the two walls.

The study of the turbulence intensity highlighted the local character of the mixture and it's quartering in the vicinity of the SMX. Upstream of the mixer the average intensity of turbulence lies between (13 and 8%), whereas downstream from the SMX it is included between (21,6 and 15,8%). The most significant variations of the intensity of turbulence are observed within the SMX where they remain localised. The performances of the mixture depend on the distance to the wall (x/D) and vary for a mode given of 25 to 280% for Re = 1963 and of 25 to 402%, for Re = 13270. The maximum intensity of turbulence is located, independently of the flow at 0,3D of the proximal wall and its value increases by 280 to 402%, proportionally with Re.

It was noted the emergence of flow regime supporting the mixing and giving average intensities of turbulence of about 150%, whereas others decreasing these average performances to 96% for (Re = 7067). The profiles of the turbulence intensity reveal the presence of localised minima of intensities and are not modified by the flow regime. Their positions correspond to the site of the velocity peaks collected within the SMX. The average and maximum performances of mixing obtained by pulsed ultrasonic velocimetry are in agreement with literature and show the local character and highly mixing of the SMX.

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NOTATION:

C_{eff}: Speed of sound in the medium (m/s)
D: Diameter of control (m)
f: Frequency of emission (Hz)
f_D: Doppler Frequency (Hz)
f_{PRF}= 1/T PRF: Pulsed Recurrence frequency (Hz)
PI Circumferential position of the probe of measurement (-)
Re = $\rho D U_b/\mu$: Reynolds number. (-)
U_b = $4Q_v/\pi\ D^2$: Bulk velocity (m/s)
V: component velocity according to the axis of control (m/s)
X/D: outdistances relating to the wall (-)
Z: Position of the probe according to the axial direction (m)
Θ: the angle of attack interns ultrasounds (°)
μ: dynamic viscosity of the fluid (Pa.s)
ρ: fluid density

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