PASSIVE CONTROL OF MIXING BY FLOW PULSATION IN A CURVED PIPE

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ABSTRACT

Mixing enhancement usually referred to the reduction of non-homogeneities. Mixing operations are encountered widely throughout industrial processes in different energy systems and chemical reactors involving physical and chemical change. The requirement of this process has always been to obtain an energy efficient and environmental friendly mixing in multifunctional heat exchangers/chemical reactors. Poor mixing can affect the product quantity and quality as well as other losses.

The passive control of mixing enhancement is meant to the special surface geometries or fluid additives. This work emphasizes on the tracer deformation and analysis of cross-sectional concentration distribution due to imposition of pulsation. An experimental system comprising of a pulsation generator (scotch-yoke mechanism), a 90° curved pipe and a tracer injection system is used. Measurements are carried out by a Planar Laser-Induced Fluorescence (PLIF) technique. To avoid laser light diffraction effects during experiments, a T-shaped flow divider are installed at the exit of the 90°curved pipe. The measurements are carried out for a range of steady Reynolds number Re_{st} [420-1000] and different values of Womersley frequency parameter α for a velocity amplitude ratio β = 1. Tracer distribution due to pulsation in a curved pipe flow is observed. Effects of pulsation on the mixing in laminar flow regime are analyzed. The results showed an important and encouraging role of pulsatile flow on mixing enhancement.

Keywords: *Chaotic advection - Pulsatile Flow - Mixing enhancement - PLIF measurements.*

1. INTRODUCTION

Mixing operations are encountered widely throughout industrious processes involving physical and chemical change. Therefore mixing is an essential feature of many processes in food, pharmaceutical, paper, plastics, ceramics and rubber industries. Mixing in the laminar flow regime occurs in many industrial processes especially in chemical and pharmaceutical ones.

In order to enhance mixing, different geometries more or less complex have been studied, i.e. closed configurations where fluid flow is confined in a volume [1] and open ones [2] and [3]. Previous studies of [1], [4] and [5] show that geometrical modifications to a steady curved pipe flow have an important influence on mixing and heat transfer.

Furthermore, by imposing pulsation to convert the steady flow into a pulsatile flow; some important alterations in the secondary flow in terms of stretching and folding of Dean Roll cells have been observed. Therefore, controlling pulsation parameters, one can make this flow much more complex and favorable for efficient mixing. Pulsatile flow is a periodical oscillating flow superimposed on a steady flow in the laminar, transitional and turbulent flow regimes. Pulsatile flow has many applications in industrial and medical applications, including heat transfer intensification, fluid mixing enhancement, augmentation of cleaning, mass transport in porous media, thermo acoustic devices, reciprocating and micro pumps, and bio fluids engineering, etc. The Pulsatile flow in a curved pipe has been the focus of research since many years. The main focus of most of the previous studies in this domain was on physiological flow applications [6], [7], [8], [9]. Pulsatile flow in a curved pipe as an application of heat transfer enhancement in industrial energy systems has also been studied by [10], [11], [12], [13], [14], [15] and [16].

This work contributes to the estimation of mixing enhancement by flow manipulation in a curved pipe. Planar laser induced fluorescence technique (PLIF) is used to highlight the information of a tracer distribution by using the pulsation conditions for a range of steady Reynolds number [420-1000] and different Womersley frequency parameter α and velocity amplitude ratio β=1. Tracer deformation due to pulsation in a curved pipe flow is observed. Effects of different pulsation parameters on the mixing in laminar flow regime are analyzed.

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This paper is organized as follows: in the Section 2 materials and methods are described, Section 3 is devoted to the explanation of the experimental setup, Section 4 is expresses the measurements and the PLIF calibration, Section 5 is discussing the results and in Section 6 the works are concluded.

2. MATERIALS AND METHODS

2.1 Pulsatile Flow

The pulsatile flow used in this study is a result of a pure sinusoidal flow imposed on a steady flow. Therefore analyzing pulsatile flow, it is obvious to consider the fluid motion as composed of a steady flow and a pure sinusoidal term. The equation (1) for the pulsatile velocity U_P can be written as:

$$U_P(t) = U_{st} + U_{sin}(t) \quad (1)$$

where U_{st} is the mean steady velocity and $U_{sin}(t)$ is the pure sinusoidal flow, which is the time-dependent component of the pulsatile velocity. If the amplitude of the sinusoidal flow is $U_{sin\,max}$, and the angular frequency of the oscillation is ω, then Eq. 1 can be written as:

$$U_P(t) = U_{st} + U_{sin\,max}\ \sin(\omega t) \quad (2)$$

The angular frequency, ω , can also be described by a dimensionless parameter, α , called the Womersley parameter, defined as:

$$\alpha = r_o\left(\frac{\omega}{\vartheta}\right)^{\frac{1}{2}} \quad (3)$$

where r_o is the radius of the pipe and ϑis the kinematic viscosity of the fluid. The Womersley number is a dimensionless expression of the inertial effects due to pulsatile flow frequency in relation to viscous effects and is used in what follows to express the angular frequency of the oscillation.

A velocity amplitude ratio β is defined as the ratio between the maximum sinusoidal amplitude of the sinusoidal velocity term and the average value of the steady velocity term. Mathematically:

$$\beta = \frac{U_{sin\,max}}{U_{st}} \quad (4)$$

2.2 Mixing Quantitative description of mixing

Quality or goodness of mixing of a given mixture can be developed by the comparison of the state of the mixture to the most complete mixing state achievable. The complete mixing corresponds to the statistical randomness of the ultimate properties of the ingredients being mixed which would follow the binomial distribution. Different parameters of mixing quantification are discussed as follows.

Mean concentration

If one makes N measurements of concentration, of C_i of one of the components, then the mean concentration $\bar{C}$ is calculated according to

$$\bar{C} = \frac{1}{N}\sum_{i=1}^{N} C_i \quad (5)$$

where $\bar{C}$ should not differ significantly from the overall concentration of the component, the difference between $\bar{C}$ and overall concentration of the component decreases as the number of characterized samples N is increased. The measured concentration values of the minor component also depend on the sample size. These values approach the overall concentration of the minor component as the sample size is increased.

Variance

A basic measure of homogeneity of a mixture is the extent to which the concentration values at various regions of the volume of the mixture differ from the mean concentration. The variance σ^2 arising from the individual concentration C_i measurements provides such an index to quantitatively assess the degree of mixing. The variance σ^2 is expressed as

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(C_i - \bar{C})^2 \quad (6)$$

A small variance implies that most of the samples yield concentration C_i values are close to the mean $\bar{C}$ of all samples, thus suggesting a homogeneous system.

Standard deviation

The deviation of the sample measurements from the mean $\bar{C}$ is given by the standard deviation:

$$\sigma = \sqrt{\sigma^2} \quad (7)$$

This is the square root of the variance, and is in the same unit as the concentration data.

Coefficient of variation C_oV

When the means of two concentration data sets differ greatly, a measure of relative variability is defined with coefficient of variationC_oV.

$$C_oV = \frac{\sigma}{\bar{C}} \quad (8)$$

Maximum variance

$$\sigma^2_{max} = \bar{C}(1 - \bar{C}) \quad (9)$$

The maximum variance occurs if the components are completely segregated.

Intensity of mixing

One can define intensity of mixing I_{mix} as:

$$I_{mix} = 1 - \frac{\sigma^2}{\sigma^2_{max}} \quad (10)$$

Intensity of mixing values range from zero, for completely segregated to one for ideally homogeneous system.

3. EXPERIMENTAL SETUP

Fig. 1 illustrates the experimental setup used in this work. The circular water duct made up of Plexiglas was used to provide controlled flow through the test section. Steady flow is pumped in the setup through a volumetric pump from a tank of 300 L capacity. The steady flow rate is measured by an electromagnetic flow meter. Pulsations are superimposed on the steady flow by a scotch yoke pulsation generator. To be sure about clean and stable inlet conditions and to develop a Poiseuille flow in the setup a straight 2.50 m pipe is used. The scotch yoke pulsation generator allows adjusting different pulsation conditions by regulating the dimensionless frequency parameter α and amplitude ratio β. This scotch yoke mechanism consist a crank of 40 mm diameter connected by a metallic stem. The piston stroke is controlled on the crank in steps of 20 mm to a maximum of 200 mm. A motor speed reducer is used to control the pulsation frequencyω.

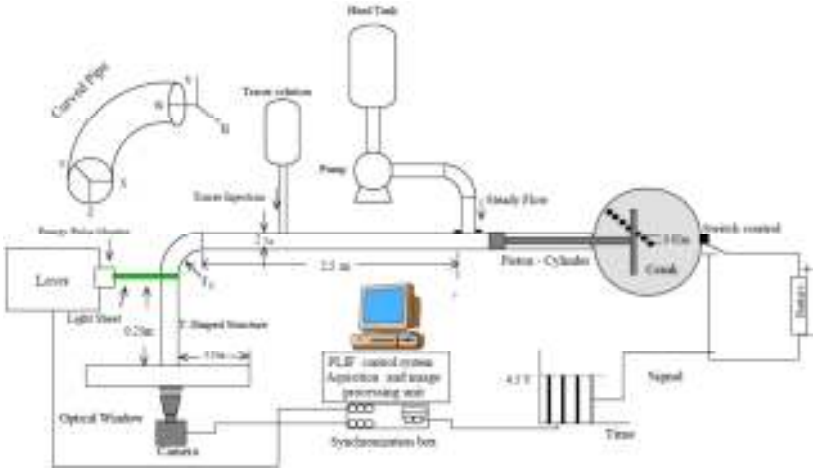


Fig. 1. Experimental setup.

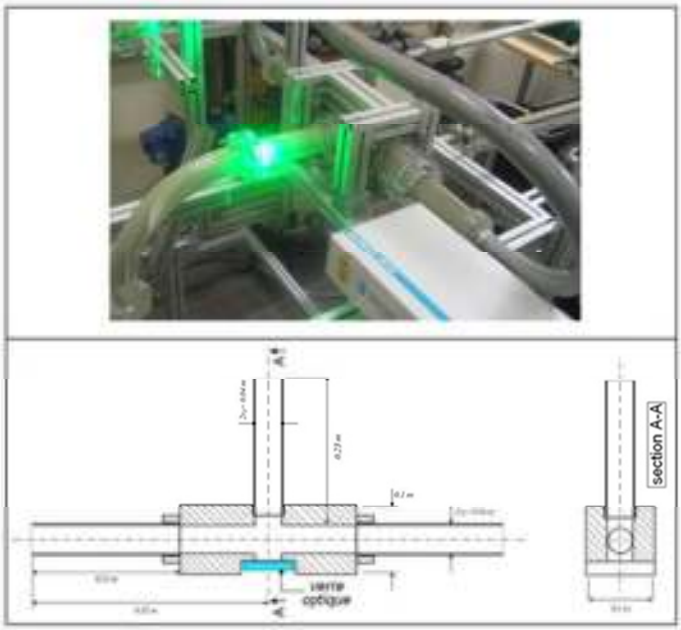


Fig. 2. T-shaped flow divider.

Therefore both parts of the flow i.e. steady and sinusoidal join upstream of the curved pipe in such a way that a fully developed flow enters in the 90° curved pipe of 40 mm diameter, radius of curvature 220 mm. A tracer injection setup was designed and fabricated to inject the tracer dye through an injecting needle of 1 mm diameter. Injecting needle was positioned at the center of the cross-sectional area of the duct.

A T-shaped Plexiglas flow separator shown in Figure 2, comprising a central tube with two symmetric pipe sections of the equal diameter as the 90° curved pipe (40 mm) is installed at the exit of the curved pipe to avoid the light refraction effects during PLIF measurements. The middle straight pipe section connected to the 90° curved pipe outlet is passed through a water box to get better flattened image quality.

3.1 PLIF Measurements

The Planar Laser Induced Fluorescence (PLIF) technique is an optical method to obtain instantaneous concentration (or temperature) measurements: it is used to determine the concentration spreading in the secondary flow at the exit of the curved pipe. A Nd YAG laser (50 mJ, 532 nm) with sheet thickness 2 mm and a recording camera (7 Hz) are used. The camera is equipped with a lens (focal distance of 60 mm) and is placed with a filter in front of the optical window; the laser sheet illuminates the outlet of the curved pipe (Fig. 1). The injected tracer dye is Rhodamine B. The resolution of each picture is 2048×2048 pixels. A Dantec Dynamics processing system is used to obtain the concentration distribution information. Except in the steady-state flow cases, the measurements for pulsatile flows are time-dependent and need a synchronization system. Thus the acquisition system is connected to an electric power source controlled by a switching contact device. Each contact of the switch and the small knob fixed on the periphery of the crank sends a 4.5 V signal to the acquisition system. The acquisition occurs after a delay that can be calculated based on the desired phase position and the angular velocity of the crank. The measurements are obtained in the four principal phase positions: ωt = 0°, 90°, 180° and 360°.

4. MEASUREMENTS AND CALIBRATION

The different conditions of pulsation cases are obtained with the adjusting the different parameters shown in the Table 1.

Table 1. The different conditions of pulsation.

Re_{st}	U_{st} (m/s)	β	α
420	0.0105	1	10
600	0.015	1	10
800	0.020	1	10
1000	0.025	1	10

4.1 PLIF Calibration

Planar Laser-Induced Fluorescence is an optical-based technique used to perform nonintrusive whole field concentration measurements in liquids. There exists a well-defined relationship between the intensity of fluorescence and concentration when all other experimental parameters are fixed, which allows deriving a calibration curve for the intended measurement.

The fluorescent dye used in the present study is Rhodamine 6G with calibration range between zeros to a maximum concentration of 100 micrograms per liter. The camera filter is replaced by a 570 nm cut-off filter to ensure the fluorescent light to be captured while adequately suppressing the 532 nm laser light. To get reference PLIF images, a series of images of a calibration test section corresponding to different concentrations is recorded. A series of 50 images for each concentration ranging between 0 to 100 µg/L of a calibration test section corresponding to different concentrations is recorded. The gray value response of the camera is then monitored to ensure a linear response to the dye concentration. This procedure is used to find the appropriate maximum concentration solution. Calibration curve is obtained in such a way that the experimental setup, laser and the optical arrangements are on the same positions. An analog beam monitor is also used to monitor the laser energy. To calibrate a LIF setup, images must first be acquired at known experimental conditions i.e. concentration or intensity of laser and stored as calibration images. For this calibration the intensity of laser light for all concentrations are constant.

In the Fig. 3, the linearity between the fluorescence signal (grey-level) and concentration defined locally is observed. Camera is sensible to detect even small concentration of 1.50 µg/L. Fig. **3**. Calibration curve. The calibration curve includes for each and every pixel in the entire image, some of these will have stronger response to varying concentrations, and some will have weaker response.

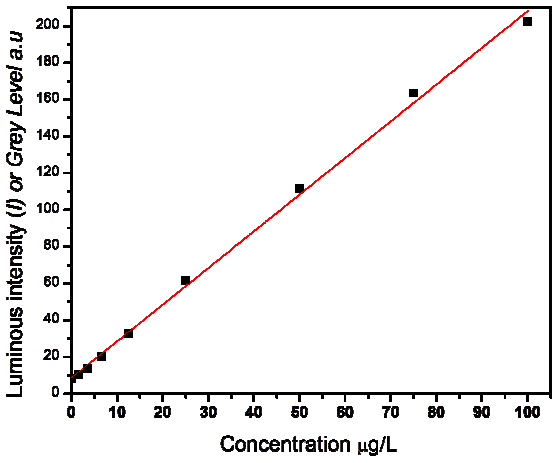


Fig. 3. Calibration curve.

The vertical bars illustrate the level of variation in Luminous intensity/gray scale values when nominal concentration and laser energy is otherwise constant. The units of the luminous intensity are a.u. (arbitrary units). The measurements are carried out with an intensive surety of keeping the experimental conditions right from the calibration to the final experimental measurements constant. This means the laser intensity, camera aperture and position remain unchanged. The concentration C is then assigned to the detected fluorescence intensity I for each pixel P(i,j) of the CCD camera (i = 1...2048, j = 1...2048). A linear correlation between I and C is verified. The calibration curve starts from a level different to zero, due to the luminosity in the laboratory. It can be observed that the camera used is sensible to detect even small concentration of 1.50 µg/L. The error in amount of colorant injected and amount of colorant measured/captured by the camera was found from 9% to maximum 15 %.

5. RESULTS AND DISCUSSIONS

5.1. Qualitative Measurements

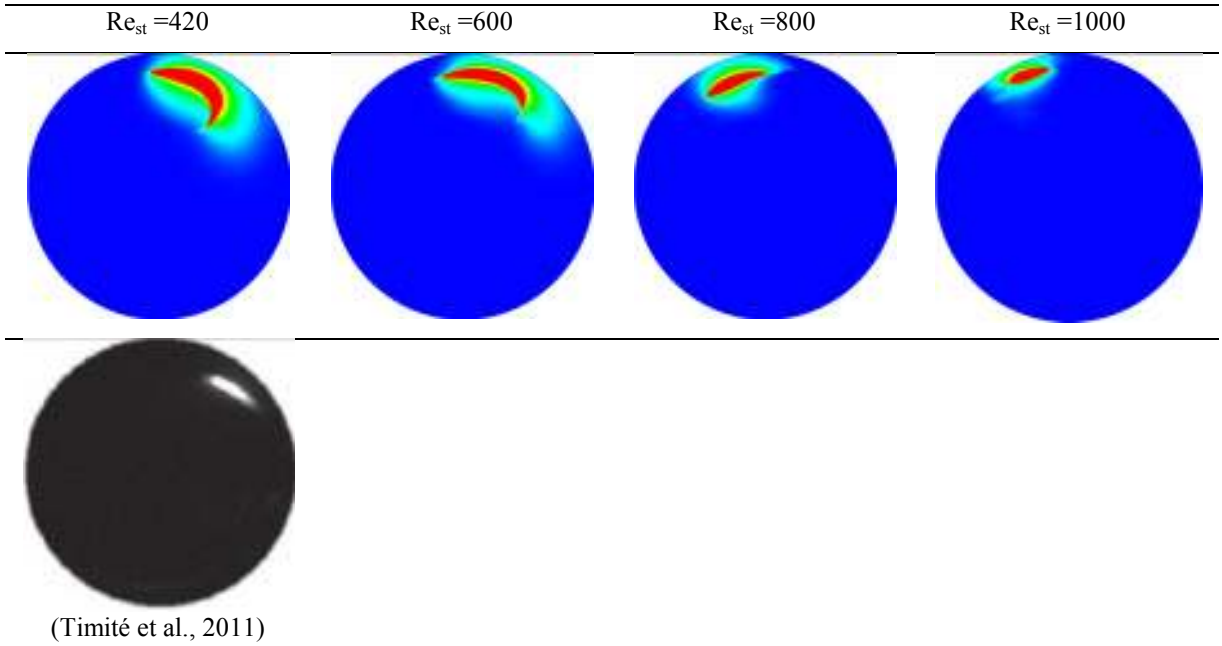
A comparison of the results of a tracer deformation in steady and pulsatile flow cases shows the influence of the pulsation on the mixing in a 90° curved pipe. Rhodamine 6G as a tracer was injected through an injection system by a needle of 1 mm in diameter. The tracer injection position was at the center of the pipe section.

For the steady Reynolds number $420 \leq Re_{st} \leq 1000$, tracer mark was always with a constant mark in the upper part of the pipe section. This was moving slightly back to the left side of the upper side pipe section with the increase in steady Reynolds number.

When the velocity amplitude ratio is unity ($\beta = 1$) the tracer is deformed in the boundary layer near the wall in the upper part of the section.

5.1.1. Flow visualization for Steady Cases

In the steady flow, the tracer injected in at the center of the pipe follow the streamlines of the main flow and remains near the upper wall by occupying a constant and very small space. But on the other hand when looking at qualitative images, the tracer dye deforms well and occupies the more space in pipe with the pulsation impositions on the steady flow. This is may be due to the disturbing Dean Roll cells structures by pulsations. Qualitative images show that tracer distribution for steady Reynolds numbers Re_{st} lies in the upper part at the exit of a 90° curved pipe. When the velocity amplitude ratio β is unity with a constant frequency parameter α, tracer distribution is increasing in the cross-sectional area. More homogeneity is visualized by increasing steady Reynolds number Re_{st}. For a constant steady Reynolds number and a constant velocity amplitude β with the variation of frequency parameter α, the secondary flow remains more or less the same in structure.



(Timité et al., 2011)

Fig. 4 Qualitative images at the exit of a 90° curved pipe for different Reynolds numbers.

Fig.4 show the chaotic behavior of the fluid particles at the exit of a 90° curved pipe when there is no pulsation imposed. In the steady state flow fluid particles do not diverge and remain always in the upper part of the cross-section with occupying more or less same amount of area. The tracer line decreases with increasing Reynolds number. This is because the rate for colorant injection is constant for all cases. Therefore with the high Reynolds numbers the colorant mixes well and we observe the less tracer line in the cross sectional area.

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5.1.2. Flow visualization for pulsated case, α=10, β = 1

Fig5 presents the qualitative images of $Re_{st} \leq 1000$, $\alpha = 10$ and $\beta = 1$, the fluid particles deviation is clear in the images and tracer occupy much more surface than the steady state cases. The first qualitative observation for an injection at center of the pipe section proposes that particle trajectories can be spatially chaotic in pulsatile alternating Dean Flow and certain zones in the flow are more likely than others to intensifying this deviation

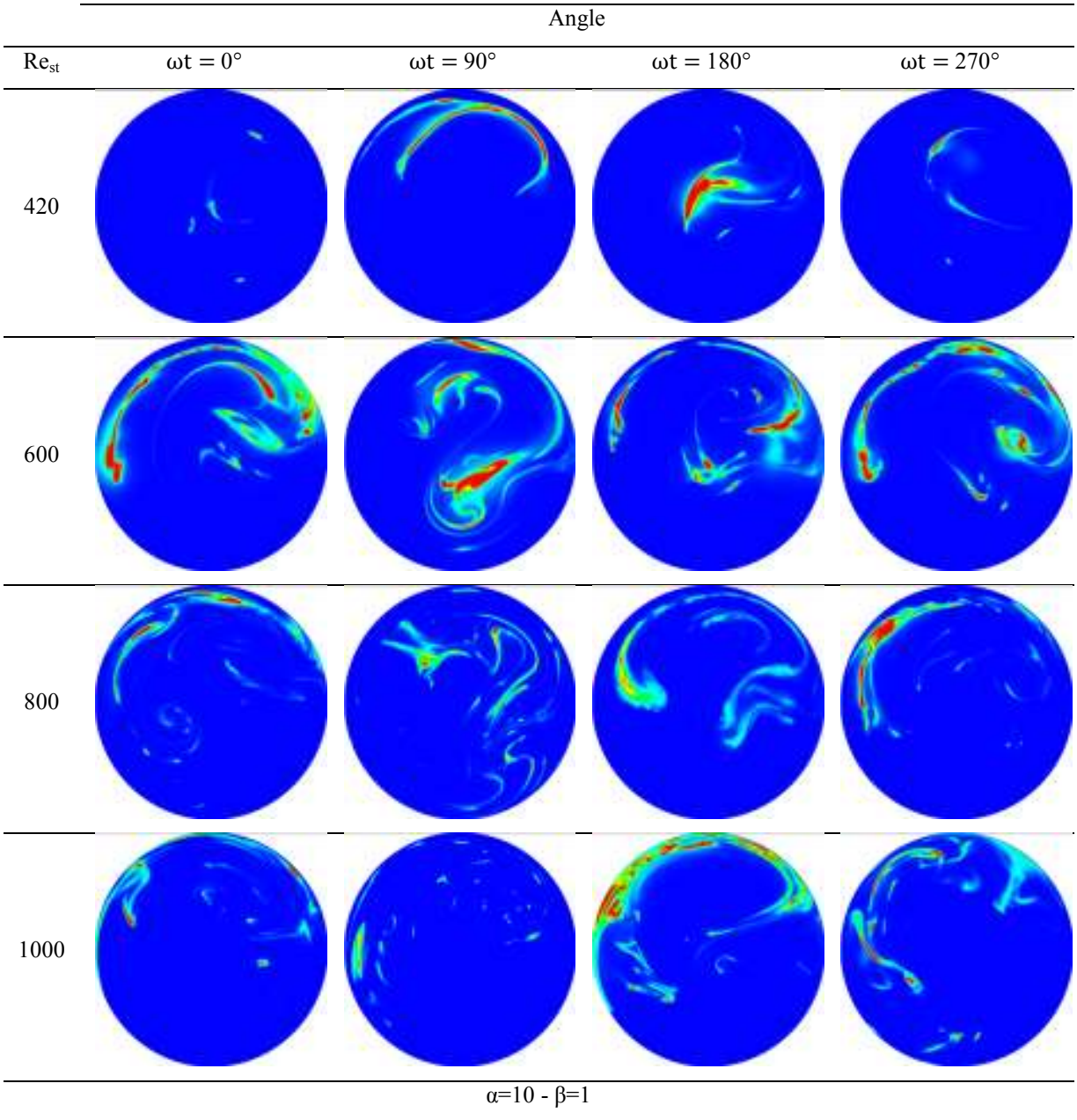

Fig. 5. Qualitative images at the exit of a 90° curved pipe for different Reynolds numbers of same pulsation condition α=10 - β=1.

5.2. Quantitative Measurements

5.2.1 Mixing enhancement during different phase angles.

Figure 6 represents mixing degree versus the phase angle ωt over an oscillation period for Re_{st}=420, 600, 800 and 1000 and α=10 and β=1. Here mixing degree increases between phase angles of 0° and 90° for all cases except in pulsation case of Re_{st} =420 where we observe the maximum Degree of mixing about 0.65 at phase angle ωt=270°.

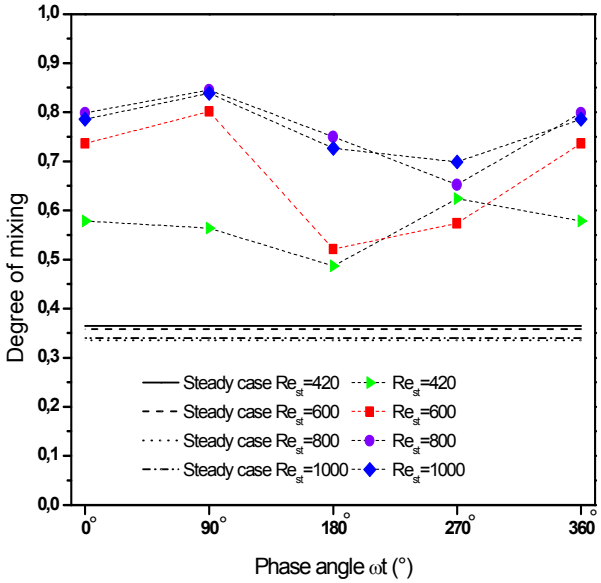

Fig. 6 Influence of phase angle ωt on mixing intensity for α=10 and β=1

The mixing degree increases between phase angles of 0° and 90° for α≤10. Then it gradually decreases in the phase 180° of the oscillation period. Beyond this phase angle, it increases again until the phase 270°. The increasing mixing degree in a phase between 0° and 90° in the oscillation period can be attributed to the acceleration of the flow in this part of the oscillation period (see [14] and [15], the vorticity and the strain rate play a significant role in transverse mixing increase between 0° and 90°).

5.2.2 Mixing Enhancement After a Complete Pulsation Cycle.

Figure 7 shows the influence of Re_{st} on the enhancement of mixing as the function of steady Reynolds number Re_{st} for constant velocity amplitude ratio β=1. The degree of mixing represented in the Figure 7 is calculated at phase angle ωt=360°, it means after a complete pulsation cycle. Degree of mixing increases as Re_{st} increases for pulsated cases. The maximum value of Degree of mixing 0.75 is obtained for Re_{st}= 1000 and α=10.

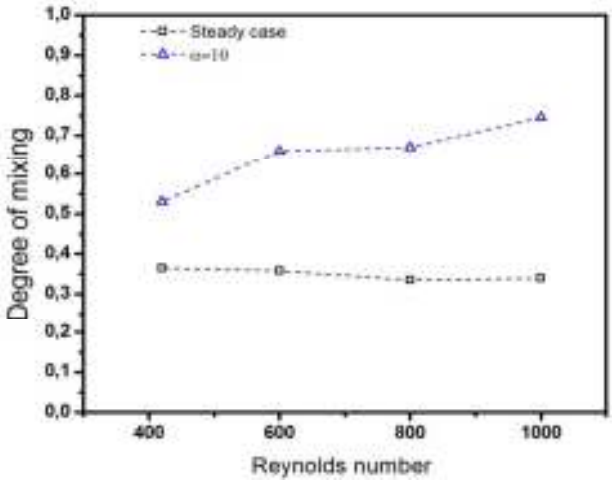

Figure 7 Mixing enhancement after a complete pulsation cycle for α=10 and β=1 at ωt=360°.

6. CONCLUSIONS

Planer Laser Induced Florescence (PLIF) technique is used to study the concentration field in a developing laminar pulsatile flow in a 90° curved pipe. Planar laser induced fluorescence technique is for the first time used in the laboratory. Calibration of the experimental setup with PLIF technique is a delicate process and it takes a lot of time to perform the experiments for the different pulsation conditions. The PLIF measurements are carried out for Reynolds numbers Re_{st}=420, 600, 800 and 1000 both for steady cases and pulsatile flows with Womersley number α=10 and velocity component ratio β=1. The effects of these parameters on the mixing intensification are studied. The PLIF results of secondary flow for four different phase positions ωt=0°, 90°, 180° and 270° are analyzed. The detailed PLIF measurements of the secondary flow showed that pulsatile flow in a curved pipe has a great influence on mixing enhancement. The arrangement of the three control parameters: Reynolds number Re_{st}, frequency parameter α and velocity amplitude ratio β extracts the consequential flow extremely complex.

The influence of Re_{st}, α and β on mixing degree is analyzed. For pulsation cases, degree of mixing increases with the Reynolds number.

In summary, the experimental results showed some information on tracer transportation and diffusion. The first type of information is related to the stretching and folding mechanisms of tracer due to pulsation. Secondly flow visualizations showed that the pulsation works well to amplify the mixing by diffusing the tracer lines in a larger space of the 90° curved circular pipe section.

Analysis of the dye deformation suggested that the pulsation imposition on a flow in 90° bend can generate better mixing.

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