Experimental identification of the flow vortex structures generated in the agitated vessels

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Abstract: - Mixing is a very important operation in chemical industry and process engineering because more than sixty percent of all processes are represented by mixing. The knowledge of the flow inside the agitated vessel is also the background for better understanding of the mixing processes, scale-up modelling, and geometry improvement. Here we present results obtained by TR PIV measurements focused on detailed flow analysis in two different regions in the context of impeller movement and processed with POD and OPD algorithms as well as flow development analysis.The agitated vessel fitted with standard Rushton turbine impeller was running in fully turbulent regime in water. Investigated areas were chosen according to the knowledge of the mean flow that should be examined under high frequency analysis to uncover fast moving flow structures.

Key-Words: -Agitated Vessels, Oscillating Pattern Decomposition, Proper Orthogonal Decomposition, Time-resolved PIV

1 Introduction

Mixing is a very important operation in chemical industry and process engineering because it represents more than sixty percent of all processes. Huge amount of mass is mixed in vessels stirred by an impeller. Large agitated tanks with impellers are also used in mining industry, waste water treatment, etc.In all of the above mentioned industries, the development of new technologies requires higher quality of products with lower energy demands during the product treatment. Hence, the trend is to develop more efficient mixing equipment where better knowledge of hydrodynamics is essential. Therefore, the original empirical data from basic experiments are replaced by more sophisticated numerical simulations and complex models that are continuously improved and validated by experiments [1, 2].

The knowledge of the flow inside the agitated vessel is also the background for better understanding of mixing processes, scale-up modelling, geometry improvement, etc. The results of the CFD (Computational Fluid Dynamics) based on the RANS (Reynolds Averaged Navier Stokes) approach were formerly validated by the mean values obtained by LDA (Laser Doppler Anemometry) [3] or PIV (Particle Image Velocimetry) measurements. The fast improvement in the CFD requires higher quality of the measured data. For the successful validation we should reach the highest resolution in time and space to cover the needs of the LES (Large Eddy Simulation) [4,5, 6, 7,8,9, 10] and the DNS (Direct Numerical Simulation) approach [4].

The main part of published results in CFD development requirements is summarized in [11, 12]. For this reason TR PIV (Time Resolved Particle Image Velocimetry) method seems to be fine instrument that allows detailed flow analysis [13]. The PIV measurements have been used by many investigators e.g. [14, 15, 16, and 17]. In most of these experiments, the cylindrical vessel with standard Rushton impeller was used e.g. [13, 14], and [17]. The same trend follows also CFD [12], therefore the similar equipment with standard Rushton impeller for basic experimental data comparison has been chosen.

The TR PIV technique brings a novel view on the data processing but also comes with complex statistical interpretation. The frequency information on the flow process and its changes can be statistically analyzed by Proper Orthogonal Decomposition – POD. The existence of traveling coherent structures and its stability can be studied with Oscillating Pattern Decomposition – OPD. The most important information while dealing with

ISBN: 978-960-474-402-2

coherent structures is the kinetic energy that is captured in energetic modes. These energetic modes can be calculated by the Proper Orthogonal Decomposition and Bi-Orthogonal Decomposition known as POD and BOD algorithm.

The BOD method gives us information about time and frequency relation in time (Chronos) and space (Topos) domains. The OPD gives us complex knowledge about the flow dynamic behavior and its interactions. Frequency of typically ascending run is a sorting parameter that is good to know before detailed study. E-fold time of descending run gives the mode importance in the meaning of its higher probability of the given mode occurring in the flow.

In this article we use the mentioned methods on the data evaluation and comparison taken in investigated areas close to the blades where the development of vortex structures source is supposed.

2 Experimental setup

2.1 Mixing vessel setup

Measurement of the velocity field was realized in a pilot plant flat bottomed mixing vessel with four baffles at its wall (see Fig. 1), with water as the working liquid (density ρ = 1000 kg•m3, dynamic viscosity μ = 1 mPa•s) under constant impeller speed of 300rpm, 450rpm, and 600rpm. The standard Rushton turbine impeller was used for the investigation (see Fig. 2).

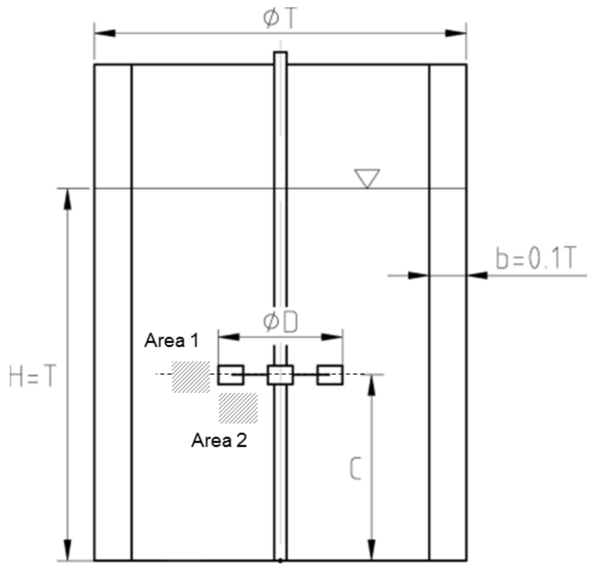


Fig. 1 Mixing vessel setup (H/T = 1; D/T = 1/3; C/T = 1/2; b/T = 1/10; four baffles) impeller speed from 300 rpm to 600rpm and the position of the investigated areas.

The central axis of the first investigated area was aligned 4mm to the horizontal blade axe and with the right edge 3mm far from the blade edge. The second investigated area was placed into the region, where the main flow of the liquid towards the impellers bladesis assumed (Fig. 1).

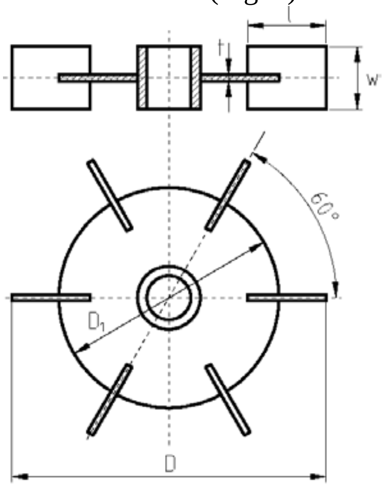


Fig. 2 Standard Rushton turbine impeller (w/D = 1/5; D1/D = 3/4; l/D = 1/4; t/D = 1/50; six blades)

Investigations were performed in fully turbulent regime where the mixing Reynolds number is high enough (ReM> 10^4), and the power number of impeller become independent on Reynolds number.Moreover, the mean flow field is only dependent on the impeller tip speed for similar geometry.

$$Re_M = \frac{n\,D^2\rho}{\mu},$$

where$n$ is impeller speed, D impeller diameter, ρ operating liquid density and μ dynamic viscosity.

Table 1. Experimental impeller speeds.

Impeller speed [rpm]	Reynolds number
300	$5.0\cdot10^4$
450	$7.5\cdot10^4$
600	$1.0\cdot10^5$

2.2 Measurement technique

The investigated area in the mixing vessel was examined by the time-resolved PIV technique. This measurement technique enables to measure highly turbulent flow and the development of turbulent structures over the whole investigated area. The resolution of the method depends on the setup of dynamic range. The supposed velocity range was up to 5m/s so the time between pulses was adjusted to this flow velocity. We expected the fluid flow

ISBN: 978-960-474-402-2

deceleration in the steady part of the flow. So the setup of dynamic range was taken into account so the final measurement accuracy entered the 5%.

Here we used DantecDynamic TR-PIV setup that consists of the Litron Ld:Y300 laser operation on the frequency 1kHz. This kind of double cavity laser emits pulses of energy reaching 15mJ in each pulse on wavelength 527nm. The laser beam was extended into the vertical plane with cylindrical optics to reach the parameter of the planar laser sheet of thickness 1mm and spread into the 100mm width.

The working liquid was seeded with 20um fluorescent particles labeled with Rhodamine B emitting on the wavelength 570nm.

The high speed camera SpeedSense working on frequency 1kHz with resolution of (1280x800)px in double frame mode was equipped with low-passing filter to eliminated the backward flashes from the laser sheet that arises on the blades surfaces. The wavelength of the optical filter corresponds with the emitted light of the fluorescent particles.

The camera was mounted with optical lens system Nikkon Macro 200 to get detailed image of magnification 1:1 in the distance 700mm far from the blade central axis.

The laser and camera system was synchronized via timer box and controlled from the DantecStudio software. The dataset of 5000 images was captured in one run. The raw images were also processed in this software.

As the glass cylindrical body of the mixing vessel was closed in the glass square box and the space between both walls was filled with water, the captured pictures were distort by the different index of refraction of each phase (liquid and solid).

Due this complication the pictures had to be pre-processed by the dewarping algorithm and masking function. The PIV analysis run under standard cross-correlation method with interrogation area size (32x32) pix and overlap 50%.

The raw vector maps were validated with peak and range validation methods to obtain correct dataset. For the purpose of overview of the complex flow behavior, the statistical evaluation and the turbulence index were calculated.

The dynamically changing velocity field was analyzed by the Proper Orthogonal Decomposition (POD) for identifying the energy fractions. The probability of the structures were calculated with the help of Bi-Orthogonal Decomposition (BOD) and taken into relation with stirrer's rounds setup.

3 Results and Discussion

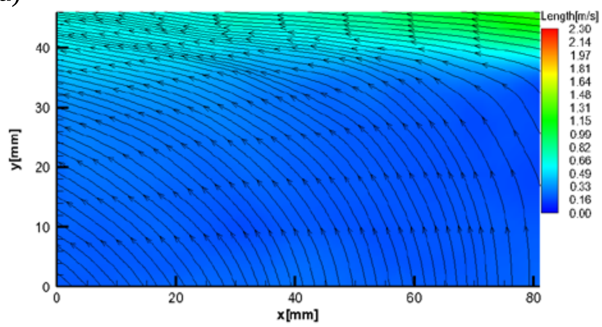
There were set two investigated areas: the first one was placed 3mm above the blades axis and 5mm far from the blade edge, the second area was set below the impellers blade and align to the blade's edge. In these areas, it was assumed the massive outgoing flow of the main accelerated liquid. In the second area,there was presumption of the ascending flow towards the impeller blades.

The captured images were firstly analyzed on the mean velocity distribution and the intensity of turbulence {UV} statistics.

3.1 The first investigated area

Figure 3 shows the mean flow field and the pictures show the scalar field filled with the streamlines of the main averaged water flow. This statistics were obtained from the datasets of 5000 pictures and here the impact of each one vortex structure presence is suppressed. The meaning of the flow field statistics is in the description of the velocity distribution, the stream acceleration and its main tendency.

a)



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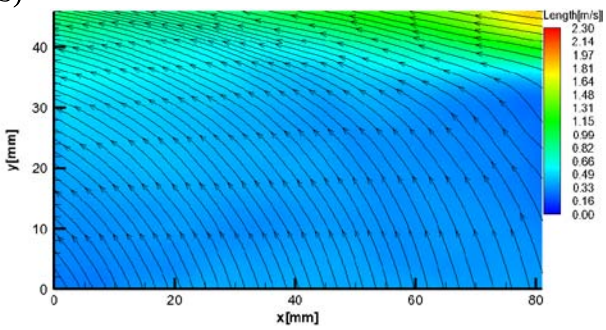

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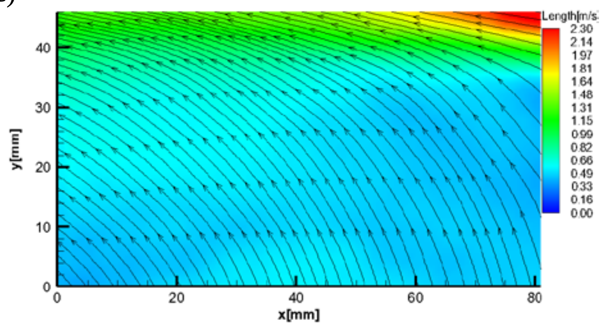

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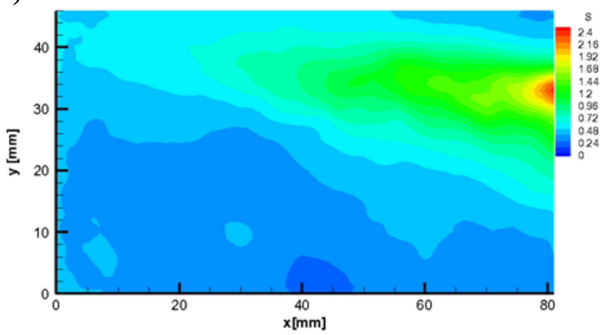
Fig. 3 The statistics of the velocity flow field in the first investigated area for a) 300rpm, b) 450 rpm and c) 600rpm of the impeller.

The presence of vortex structures takes shape in the statistics of the intensity of turbulence {UV}. From the figure 4 it is obvious that behind the edge of the propellers blade the massive vortex structures is developed and this non-stationary structure moves in horizontal plane in the main flow stream. These turbulent structures are one of the important part for the calculation of the complex kinetic energy of the whole field as well as the mean velocity part.

a)



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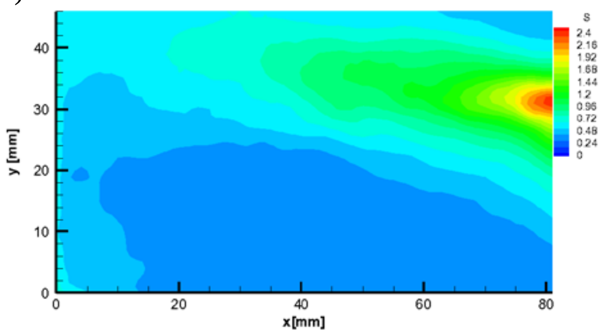

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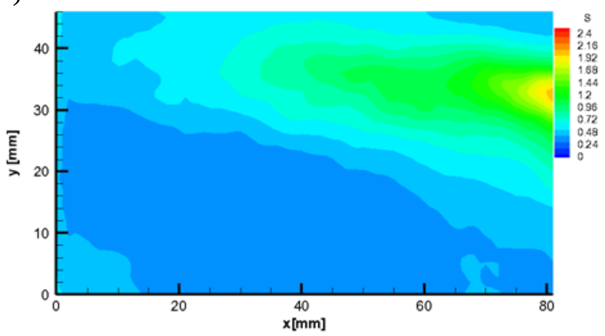

Fig. 4 The statistical results of turbulence intensity {UV} for a) 300rpm, b) 450rpm and c) 600rpm.

The figure 4 shows the most dominant vortex structure arisen in regime 450rpm and the maximum of turbulence intensity are concentrated into the area that corresponds with the main stream acceleration. The vortex structures here are significantly higher in correlation to 300rpm and 600rpm. In these regimes the intensity of turbulence is spread into the whole area and the vortex structures are larger (600rpm) and on the other hand the maximum speed is lower and the vortex is strictly located and collapse after 8ms and coalesces with the main stream. In the regime 450rpm the vortex structure can be identified in the main stream over the whole width of investigated area (more than 20ms).

The Fig. 5 shows the relative contribution of individual POD modes for each rotation setup. There can be seen different distribution of energy for 300rpm and 600rpm of the first 4 modes.The dependence of the kinetic energy on the rounds and the rest of the curve indicates the same characteristics. The first POD mode of the flow contains 16.5% of energy for 600rpm but 18.5% for 300rpm this shows that in the rotation 600rpm more kinetic energy is carried by the vortex structures in the second and higher modes; compared to 450rpm the difference is for the second POD mode 14% (600rpm) to 13% (450rpm) and for the third POD mode 11% (600rpm) to 9.5% (450rpm).

The most significant difference in the POD modes and the vortex structures can be seen between 300rpm and 600rpm as it is seen on the figure 6.

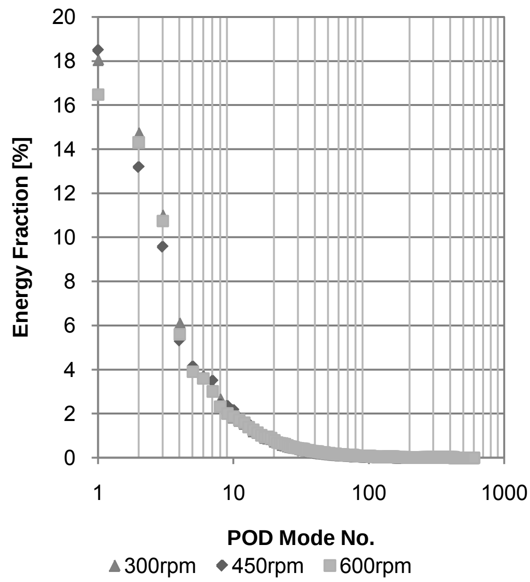

Fig. 5 The Energy fractions on the POD mode numbers for the first investigated area.

The amount of energy obtained in the first four modes indicates the level of coherency that is present in the flow. This means that the more kinetic energy is presented in certain modes, the more coherency structures exist in the flow and less energy participates on the noise (Fig. 7). From the POD analysis it is obvious which vortex structures are dominant in the flow and that the energy

ISBN: 978-960-474-402-2

spectrum is directly related to the turbulent kinetic energy. The most energetic structure is found in the dataset in the mode no. 1.

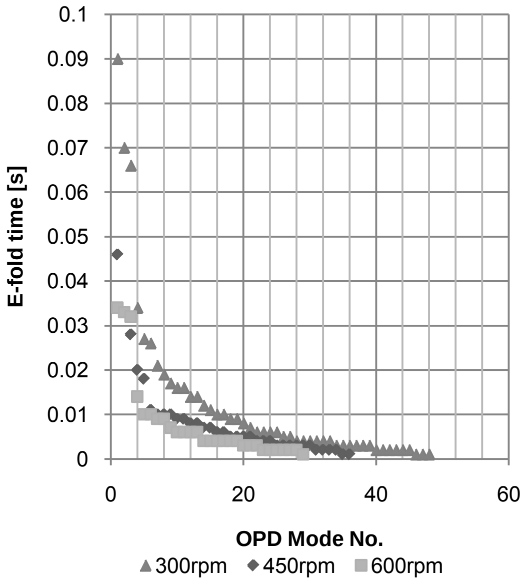

Fig. 6 The probability of the flow structure occurring in the flow represent by the OPD chart for the first investigated area.

Figure 7 shows how the OPD corresponds with the temporary statistics of turbulence intensity – for the 300rpm the most vortex structure is presented and the extremes in the velocity changes are increased; for 450rpm the statistical analysis leads to the maximal intensity of turbulence {UV} (Fig. 4) that corresponds with the OPD higher probability of the main vortex structures presence; for 600rpm the frequency of the vortex structure occurrence is high enough to join the structures together – this behavior is reflected in the suppression of the kinetic energy of each vortex structure. The OPD analysis also reflects the lifespan of the single vortex structure and its spatial position.

The vortex structure that is moving in the horizontal axis from the impeller blade is occurring in the regime of 450rpm and 600rpm. In this structure the flow stream is also the most accelerated and these results correspond with the temporary statistics of flow velocities.

Anyway, bellow this most dominant structure that is in the focus of most researchers, there arethe secondary swirling structureshidden in the further modes. These structures are moving across the area and are influenced by the main stream. As these structures take place in the sixth and higher modes, their energy contribution is about 3%. Even though the importance of these energy modes is lower, they cannot be neglected in the frequency studies and complex evaluation of TKE in the system.

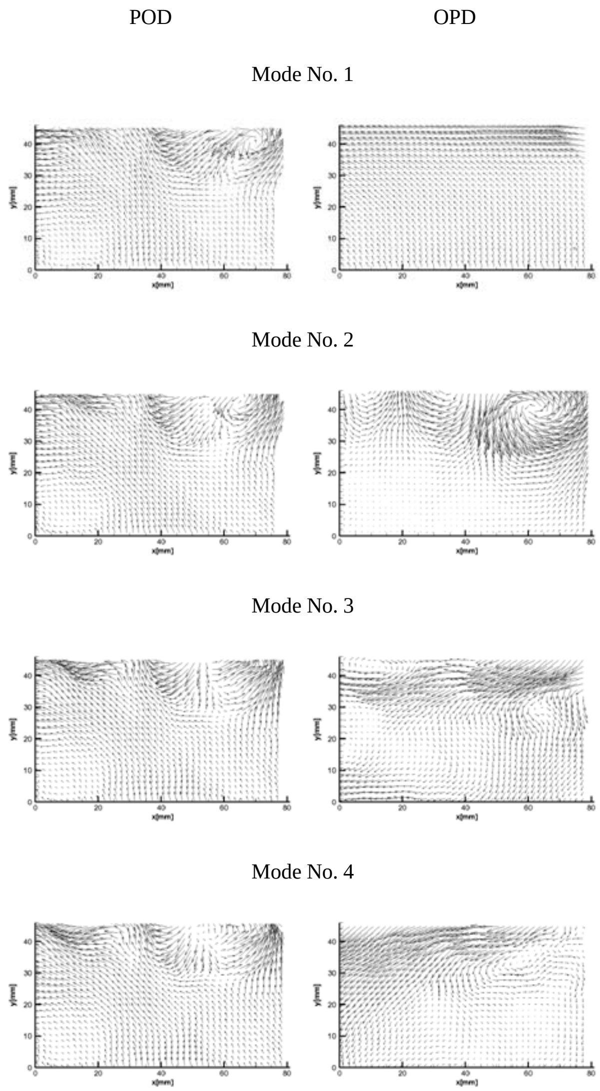

Fig. 7 The selected POD modes with the maximum of energy and OPD modes of the most probably structures in the flow for the 450rpm in the first investigated area.

3.2 The second investigated area

The second observed area was studied on the upward fluid flow that was assumed to be directed toward impeller blades. This area was monitored synchronously with the first region, so the results are temporary comparable and under same conditions.

Although relatively streamlined flow without obvious vortex structures was assumed; this flow is unsteady and on sampling frequency 1 kHz highly variable. In previous statistical measurements that were done with conventional PIV on 16Hz frequency, these rapid changes were elusive.

The relationship between the impeller rounds and flow rate in the second region corresponds to anascending velocities of both the input and output flow. The input statistical velocity field of the flow in the second region is varying in the velocity maximum, thus the scaling is modified for each statistics, unlike as it is interpreted in Fig. 3. During the evaluation of statistical data we have used the different scales due to the visibility and highlight of any changes (Fig. 8).

a)

b)

c)

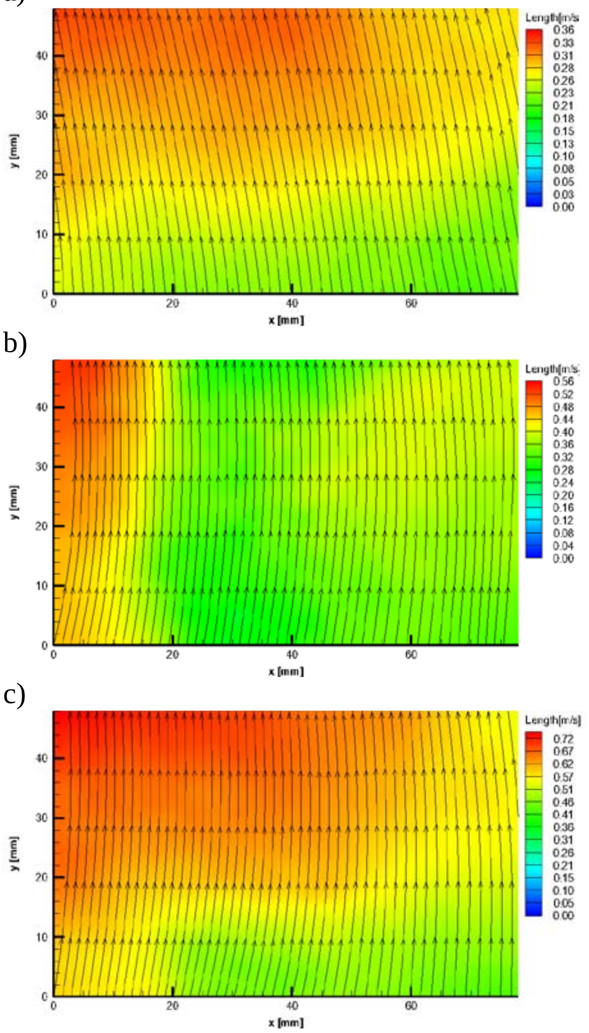

Fig. 8 The statistics of the velocity flow field in the second investigated area for a) 300rpm, b) 450 rpm and c) 600rpm of the impeller.

On figure 9 it is seen the intensity of turbulence {UV}. Comparing the results of scalar maps it is obvious that this energy is not varying significantly according to the rounds rate.

From the statistical point of view the input seems to be stabilized with continuous streamlines and acceleration but the detailed study with TR PIV reveals the presence of complex structures.

a)

b)

c)

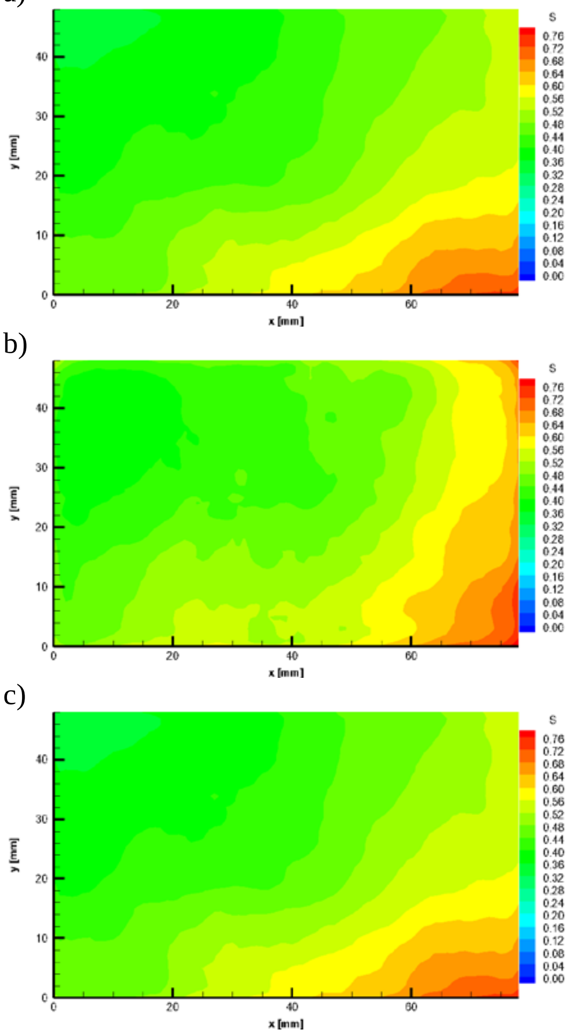

Fig. 9 The statistical results of turbulence intensity {UV} in the second investigated area for a) 300rpm, b) 450rpm and c) 600rpm.

Although the statistics of flow velocities below the impeller blade shows the uniform behavior, the intensity of turbulence {UV} uncovers the probability of vortex structures occurrence close to the central axis of the impeller. For this reason the second area was also evaluated on the POD and OPD modes to discover the relevance of single energy fraction and probability of vortex structure.

In the second investigated area it was supposed to observe the effect of secondary flow loop without any complex structures. It was studied to prove the stable character of the flow. The analysis of PIV results in this section confirmed the dependence of the flow speed on the rounds of the impeller that

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takes here more effect than in other areas of the primary flow loop. The higher speed of the impeller is also increasing the turbulence intensity in this area, particularly in the area round the central axis of the impeller.

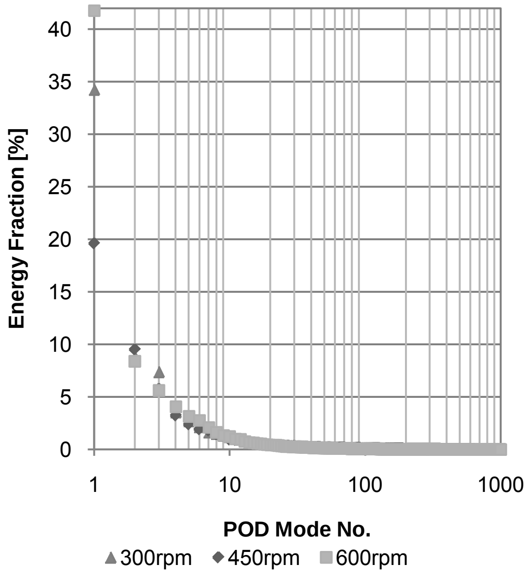

Fig. 10 The Energy fractions on the POD mode numbers for the second investigated area.

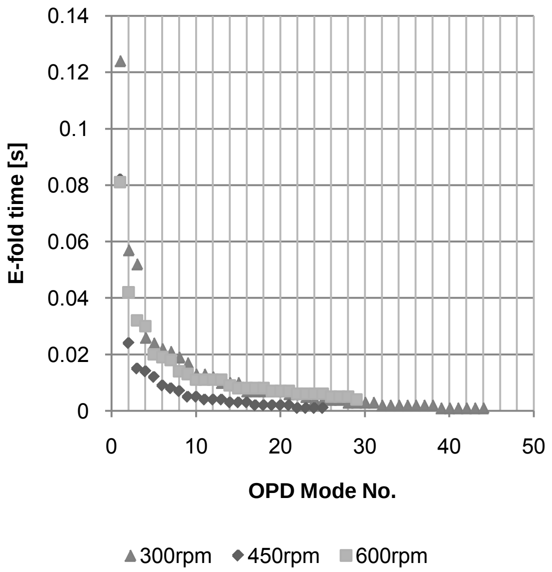

Fig. 11 The probability of the flow structure occurring in the flow represent by the OPD chart for the second investigated area.

The figure 10 shows the POD mode, the most energy contribute is in the first mode, i.e. 42% for 600rpm, 34% for 300rpm. The first mode contains the uniform flow distribution over the whole investigated area. The second mode with energy round 8% for all three regime of round brings the increase of the flow from the central axis in the opposite sense of the dominant flow. This effect is stronger in the third mode with energy contribute round 5%.

The OPD Mode analysis with the most probable structures is seen in the figure 11 and the comparison of the most dominant modes is seen in the figure 12.

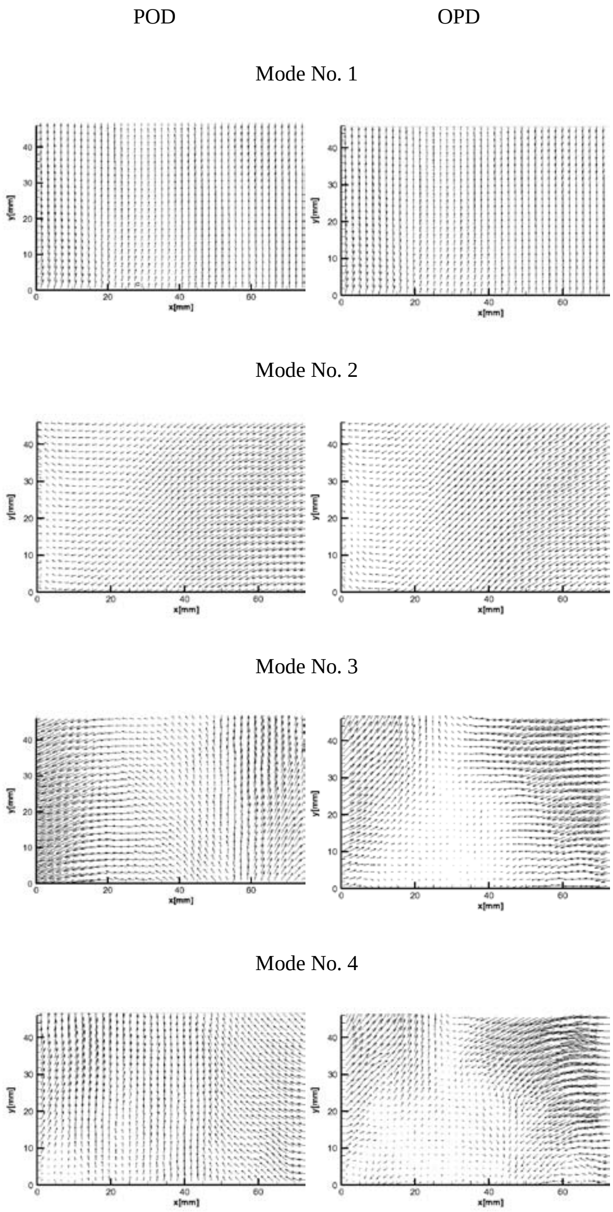

Fig. 12 The selected POD modes with the maximum of energy and OPD modes of the most probably structures in the flow for the 450rpm in the second investigated area.

4 Conclusions

Here we used the time resolved technique for the experimental study of the flow field in the agitated vessel. The results of the application POD and ODP algorithm on the captured datasets uncovered the existence of unsteady structures in the area that was

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assumed to be stable. The existence of these structures is bringing a novel view on the mixing process.

Within this measurement techniquethe dominance of inner flow structures and its energy contribution on the turbulent kinetic energywas proved. As these flow structures are not limited to the 2D plane, which most of the studies were focused on,the next step in this research is to follow the newest trends in fluid dynamics using 3D TR-PIV with two synchronized high speed cameras.

Acknowledgement

The results of this project LO1201 were obtained through the financial support of the Ministry of Education, Youth and Sports in the framework of the targeted support of the “National Programme for Sustainability I”

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