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An experimental investigation on the fluid flow mixing process in agitated vessel

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Abstract. The fluid mixing process is a common supportive phenomenon that often occurs in a large number of industrial systems. This phenomenon is the subject of many numerical and experimental analysis. The mixing process effectiveness depends on: mixing tank construction, mixing phases viscosity, temperature, density of liquids and, what is crucial, the impeller shape. The optimal design of impeller geometry is still an open issue. In this research work, the main objective is experimental investigations of the influence of the newly constructed impeller type on the fluid flow motion phenomena and energy consumption. Flow field values were evaluated using PIV measurement and the power consumption using precise torquemeter. The comparison between the Rushton turbine and a novel impeller is presented and discussed. The basis for the assessment of the intensity degree and efficiency of mixing was the analysis of velocity vectors distribution and power number. Results show that the power number for both impellers are similar but the fluid motion is quite different. The pumping capacity Q_z for the novel impeller in reference to the Rushton turbine is for many cases at least one order of magnitude higher. This shows that the proposed impeller can be a very promising alternative to the classic blades and non-blades based impeller types.

1 Introduction

Agitated vessels are widely used in a large number of the process industries for example chemical, food, oil, pharmaceuticals as well as wastewater treatments. The flow and mixing phenomena of fluids in a vessel were always of particular attention among scientist and engineers. To obtain good quality products with economical way it is crucial to evaluate mixing performance, quality and fluid motion in the vessel. It is known that a large amount of electrical energy is required for a mixing process and that generates significant expenses. For this reason, many studies have been done to obtain various impellers shapes that could guarantee a high mixture quality with low axial velocity, low internal heat generation and with low power consumption.

The flow phenomena inside of agitated vessels have been analysed using various types of measurements method such as LDV, LIF, PIV. Impellers may create highly turbulent and very complex 3D flow as a result of interaction between blades and tank walls. Up to present, many analyses performed for single-phase flow allowed researchers to achieve a significant degree of awareness on the elementary mechanism of mixing. In analysis particular effort has been paid to the impeller and vessel shape. That results in several new types for the design of the impeller. Unbaffled vessel in the past was regarded as less effective to that in which baffles were installed. However recent analyses show that unbaffled vessel with properly designed impeller can be a good alternative to the baffled one in a large number of industrial processes. [1-3]. The impeller rotation for a complete mixture homogenisation can be much lower and as a consequence, electrical power required for the process is also much lower in unbaffled vessels [4,5]. Baffles are not used in the case of very viscous fluids and in applications where large shear can influence product quality (enzymes, vitamins) [6]. In the literature, there is still insufficient information on the optimal impeller design nor about fluid behaviour in unbaffled vessels. For every process industry, the target is to find an optimal way of mixing using as low power as possible and to keep high product quality.

In the past several experimental and numerical studies concentrate on laminar mixing [7] because this type of mixing can be a promising alternative to the more destructive and require higher power mixing. It has been found that the required power can be significantly decreased improving the shape of the impeller. Ferrari and Rossi [8] and Rossi et al. [9] measured the mixing efficiency in a quasi-turbulent flow via the experimental measurements of power input and output in the flow. The study of T. Su et al. [10] compared the hydrodynamics of the fluid and mixing process using the classical Rushton

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turbine and modified one. The results showed that 18% power decrease in the case of modified Rushton turbine. New design also managed to enhance the local flow motion and obtain flow structure which promotes mixing. As a result, shorter mixing time was required.

The flow pattern is typically impacted by the impeller shape and its configuration in agitated vessels. In [11] authors analyse the impact of Reynolds and Froude numbers on power consumption in the case of unbaffled stirred tanks. It has been found that the essential parameter in power consumption decrease and mixing quality is the impeller shape. T. Kumaresan and J. B. Jyeshtharaj [12] performed experimental analysis using LDA measurements and Computational Fluid Dynamics (CFD) in order to evaluate the effect of impeller shape on the mixing time and flow pattern for a preselected set of impellers. Authors obtain a good prediction for the mixing time over a wide range of impellers geometries. In other numerical studies [13] authors analyse turbulent flow characteristics in laboratory-scale stirred vessel with different shape. CFD simulations were performed for the Rushton turbine and compare with the flotation impeller. The impact of the baffles inside the stirred tank was analysed in [14] and as a results authors conclude that the power number depends on the baffles length and decrease in power consumption was observed for shorter baffles. A. Delafosse et al. [15] performed a research study on the flow rates between two adjacent compartments using numerical analysis. The analysis showed that the model accurately reproduces the spatial distribution of concentrations during the mixing process. H. Ameur et al. [16] performed a three-dimensional simulation to investigate the effects of blade diameter and curvature as well as blade number and Reynolds number on the power consumption reduction. Authors conclude that the curved blades provide the most efficient solution.

Recently Large Eddy Simulation (LES) become a very attractive way of problem-solving and promising method to get high resolution at spatial and temporal scales. In the case of flows with rotating impellers in a stirred tank, LES method is able to resolve all essential the flow phenomena related to the problems unsteadiness in referent to the others methods [17]. In [18] authors use LES method to and show a low computational cost model able to resolve all key flow features in agitated vessels, without losing accuracy. Presented results have shown very good agreement with experimental PIV measurements. It has been shown that to increase quality and reliability of the CFD results it is very important to perform the numerical grid dependence study as well as test and evaluate the proper size of the rotating zone when using multiple reference frame (MRF). H. Patil et al. [19] developed a numerical model for stirred vessels. The objective was to optimise the size of the rotating fluid zone MRF and evaluate if the optimal MRF size affects significant velocity results. Authors conclude that MRF dimension is an important issue which impact solution and finally predictions were found to be with good agreement with literature results. It this work authors also analysed the optimal MRF zone size on the mixing efficiency by comparing numerical and experimental results for the power number at several Reynolds numbers.

As the mixing process depends on the distribution of mean and turbulent kinetic energy, in many research studies authors have made assessments of various turbulent models. The *k–ε* model was compared to the Reynolds Average Stress Model and LES by the Murthy et al. [20]. Authors have done experimental measurement and numerical CFD simulation for the flow created by the different impellers. It has been found that a standard *k–ε* model under-predict the turbulent kinetic energy in the region of the impeller and failed to predict the mean flow related to the strong swirl. Similar conclusion has been found by the in the study performed by the H. Singh et al. [21]. They found that the accuracy of evaluation for the mean axial and angular velocities is good for all analysed models. However, most of the models do not predict properly the decay of mean radial velocity away from the impeller region.

Presented paper focuses on the analyses of different impeller configurations and position in order to get a high efficiency mixing process. This work provides velocity field, power number N_p and pumping capacity Q_z, two key parameters which describe the mixing process.

2 Experimental set-up and methodology

The mechanically agitated vessel configuration is presented in Figure 1, and the dimensions used are shown in Table 1. For presented analysis, 100% glycerol (ρ=1261.1 kg/m^3, μ=1410.1Pa·s at 20^{o}C) was used as a working fluid with a variable viscosity for different temperatures. The distance between the impeller and the bottom of the tank *h* was the case parameter and was equal to ¼*H*, ⅓*H*, ½*H* of the fluid initial high *H*.

Table 1. Dimensions of the stirred tank.

Impeller type	H, H_c mm	h mm	D/d mm	a/d_1 mm	b/d_2 mm	l mm
Rushton	170,	¼H,⅓H, ½H	170	12	15	2
Novel	300	42, 57, 85	85	15	18	40

The *H* denotes fluid level while H_c is the tank height and *D* is tank diameter. Impeller maximum diameter independent of the impeller type is denoted as *d*. Additional geometrical dimensions are *a, b, l* height, width and thickness for Rushton turbine blades and d_1, d_2, diameter at entrance and exit to the “blade” of the novel impeller and *l* is the length.

The stirred tank investigated has smooth walls and has no baffled pilots. Propeller is equipped with a six-bladed Rushton turbine (for case A) or three-bladed novel impeller (for case B). The Novel impeller is a rescaled copy of proposed real industrial design. The analysed impellers are created using 3D printer and have smooth plastic walls of the thickness 2 mm.

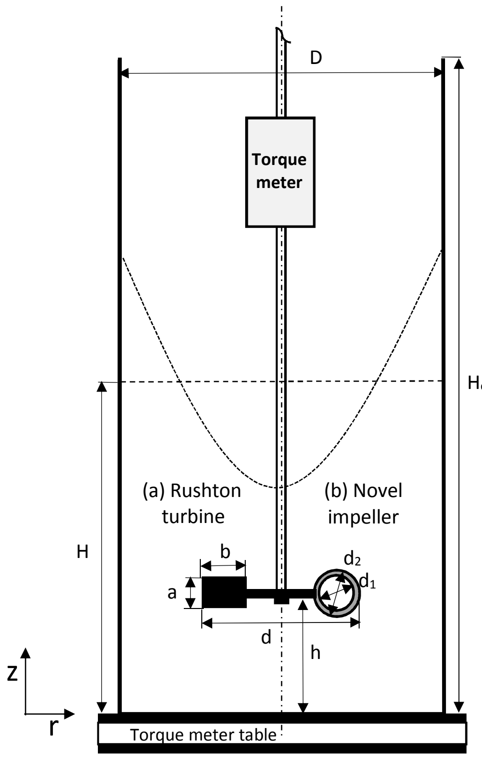

Fig. 1. Schematic diagram of the turbine and stirred tank.

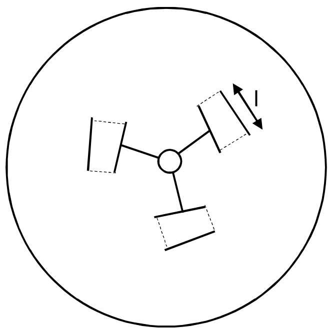

Fig. 2. Schematic diagram of the Novel impeller (top view).

The stirred tank is installed on the specially designed table equipped with torque meter FSA-2 (AXIS, max 2Nm) enabling the measurement of the analysed impeller torque with the precision of 0.001Nm and sampling frequency of 1000Hz. An additional calibrated torque transducer DATAFLEX 16 (KTR, max 10Nm, inaccuracies 0.001) was installed on the impeller shaft and connected to the data acquisition system National Instruments DAQ.

In order to evaluate mixing properties, flow field and pumping capacity, Particle Image Velocimetry (PIV) method were used. For this measurement, the cylindrical tank was placed inside of the square vessels filled with water to minimise optical distortions.

The instantaneous velocity in vertical direction were measured in the tank filed under no agitation conditions with fluid high $H=D$ (in total about 5 litres). However, it should be noticed that due to rotation fluid level close to the cylinder wall increases.

The seed particles were illuminated with a double-pulse Nd:YAG laser of energy of about 30 mJ per pulse. A vertical laser sheet of height 200 mm and the thickness about 1 mm was located through the centre of the tank directly illuminating rotor shaft and shadowing left part of the tank. At present configuration, one CCD camera (La Vision) with a resolution of 2048x2048 pixels equipped with a lens 50 mm/1.2 was used.

The flow was seeded with hollow sphere d<1μm. Reflected laser light was acquired by the CCD camera, installed perpendicular to the plane of the light-sheet. To determine the distribution of the velocity vectors, seed particles are registered by the CCD camera on two different and consecutive frames.

The measuring PIV system was subjected to testing and calibration procedures under fluid flow condition in order to evaluate the minimum number of acquired images required to ensure accurate statistics, as well as the optimal size of the interrogation window for the cross-correlation application. In each measurement, 100 frames were acquired with the CCD camera at a frequency of 5 Hz, which gives the time of single measurement equal to 20 seconds. This time and number of frames was sufficient for low Reynolds number analysis (Re=10-160) presented here. The time step Δt between 2 double-frames varied depends on Reynolds number 800-20000 μs.

During the calculations, the interrogation windows size that exhibit satisfying results varied from 32x32 pixels to 64x64 pixels. To analyse the series of double-frames and to calculate the velocity vector components the Davis software ver. 8.0 with PIV/LIF module was used.

In the mixing system analysis, there are two important criteria numbers: Power number N_p and Reynolds number Re defined and calculated according to the following equations:

$$N_P = \frac{P}{\rho N^3 d^5} \quad ; \quad Re = \frac{N d^2 \rho}{\mu} \tag{1}$$

where ρ is the density (kg/m^3), μ is the viscosity (kg/m·s), N is the number of rotation per second (rot/s) , d is the impeller rotor maximum diameter (m) and P is the power (W) required to rotate the impeller with certain rotational speed. It depends on the torque τ, and can be evaluated as follows:

$$P = 2\pi \cdot N \cdot \tau \tag{2}$$

where τ is the torque (N·m).
The third important parameter is the pumping capacity Q. It can be calculated for different Reynolds numbers through a cylindrical surface with a specified radius r or through horizontal surface at specified heights z. In the present configuration, pumping capacity was evaluated through a horizontal surface (axial pumping capacity Q_z) and for the height z=0.01 m. Axial pumping capacity Q_z can be obtained from PIV measurement by integrating the mean axial velocity over the whole horizontal positions, i.e. from $r_1 = 0$ m to $r_2 = 0.085$ m.

$$Q_z = \int_{r_1}^{r_2} |u_z| dS \qquad (3)$$

It is also common to normalise this parameter with $N{\cdot}d^3$ giving one of the global flow characteristic.

3 Results and Discussion

In order to account of mixing process economics parameters related to the energy consumption and mixing phenomena need to be evaluated. The power required by the impeller during the mixing process is an essential parameter. Figure 3 shows, one of the parameter which is directly related to the power required in the mixing process - Power number N_p - calculated from eq.(1). Results are evaluated for different Reynolds numbers and for Rushton turbine. Impeller was installed at various heights above the tank bottom - equal to ¼H (42mm), ⅓H (57mm), ½H (85mm) and ⅔H (113mm). One can infer from this figure that the Power number N_p depends on the Reynolds number and this parameter is almost independent on the distance from the tank bottom h. Only for Re=25 non-negligible differences in N_p for different h were observed. For this Reynolds number, significant Power number increase was also detected. When rotational speed exceeds certain value - in this case, Reynolds number about 20 - flow motion with large recirculation zone was observed. Flow redirection required significant power and results in large power number increase for this Re. It is worth to notice that this effect has been observed for both impellers and for all considered impellers height.

In Figure 5 power number N_p for novel impeller is presented. Results are similar and for both impellers, very similar value is observed. Although the required power is very similar flow motion generated by the impellers is quite different. Figures 5-6 present mean axial pumping capacity Q_z through a horizontal surface located 1 cm above tank bottom, and dimensionalised by the $N{\cdot}d^3$.

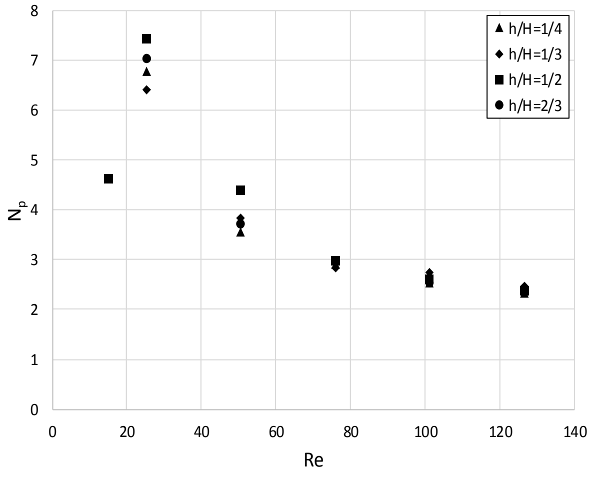

Fig. 3. Power number N_p for Rushton turbine and for different impeller distances from tank bottom.

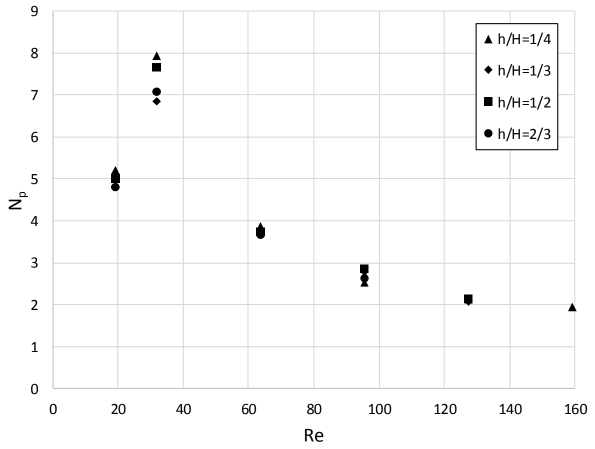

Fig. 4. Power number N_p for novel impeller and for different impeller distances from tank bottom.

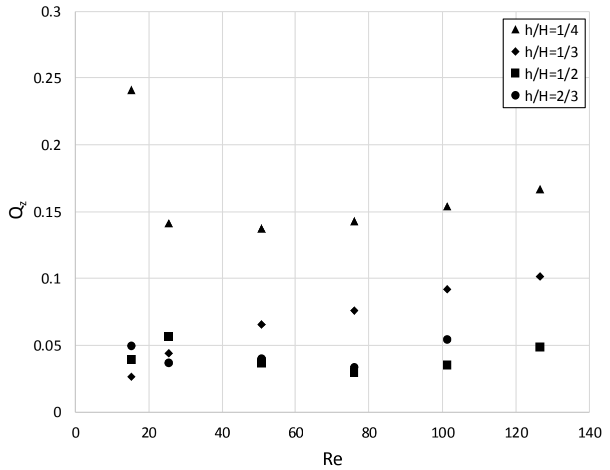

Fig. 5. Mean axial pumping capacity $Q_z\,/N{\cdot}d^3$ for Rushton turbine in function of Reynolds number and for different impeller distances from tank bottom.

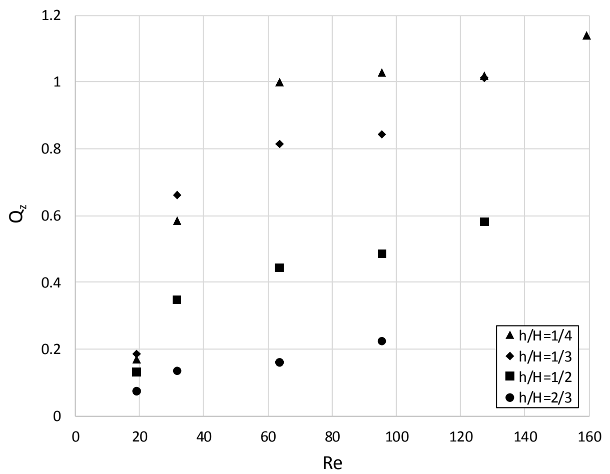

Fig. 6. Mean axial pumping capacity $Q_z\,/N{\cdot}d^3$ for novel impeller in function of Reynolds number and for different impeller distances from tank bottom.

Particularly for Reynolds numbers above 20 significant differences are observed in $Q_z/N{\cdot}d^3$ for both turbines and for all impellers heights above the tank bottom. For analysed cases, novel impeller performance is higher than the Rushton turbine and this difference can be as large as one order of magnitude. This means that proposed impeller for similar electrical power results in significantly higher flow motion which enhance the mixing process. This is particularly important for low-speed mixing which is less destructive for the mixing components and generate less heat in the fluid (a critical issue for enzymes or vitamins) and for this reason is highly promoted.

The ratio of the $Q_r/N{\cdot}D^3$ to N_p, i.e. non-dimensional pumping capacity to the non-dimensional power, can be considered as a mixing efficiency parameter. This ratio for some cases is 50 times higher for novel impeller than for Rushton turbine

In Figures 7-9 mean velocity vectors evaluated with Particle Image Velocimetry in *z-r* cross-section plane, for two rotational speeds *N*=100 and 300 rpm, for three impeller hights ¼H, ⅓H, ½H and for two different impellers analysed here are presented. It can be seen very high (radial and axial) fluid motion in the whole domain cause by the novel impeller. As can be seen, different impellers generate very different flow motion. The zone of impeller activity is much smaller for Rushton turbine while for novel impeller flow motion is significantly enhanced in whole mixing tank - from top surface until tank bottom (no dead zones).

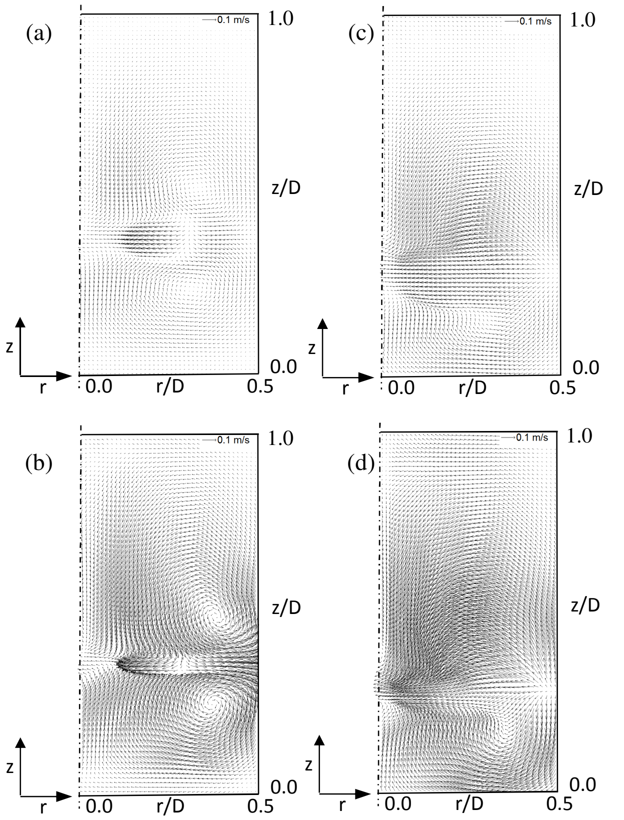

Fig. 8. Mean velocity field for *h/H*=1/3 and Rushton turbine (a,b), novel impeller (c,d) and rotational speed *N*=100 rpm (top), *N*=300 rpm (bottom).

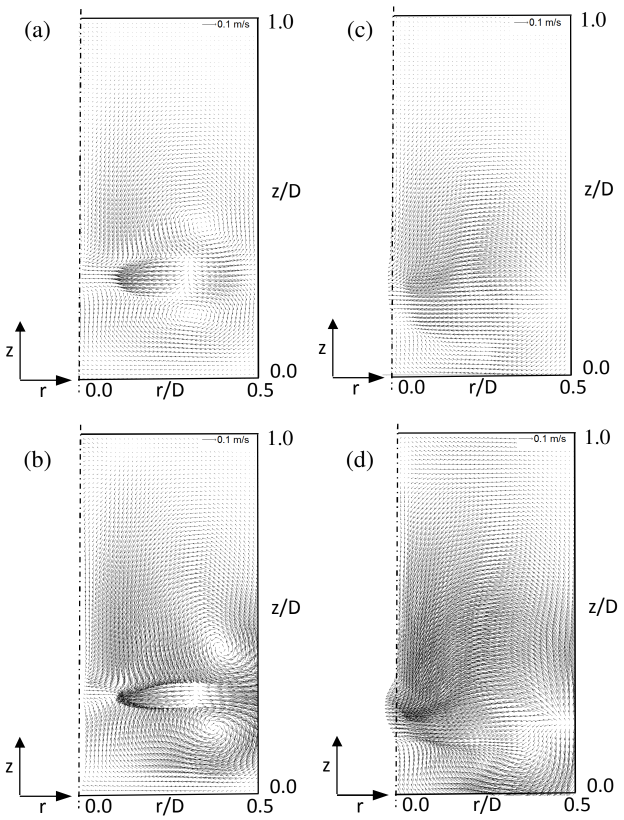

Fig. 7. Mean velocity field for *h/H*=1/4 and Rushton turbine (a,b), novel impeller (c,d) and rotational speed *N*=100 rpm (top), *N*=300 rpm (bottom).

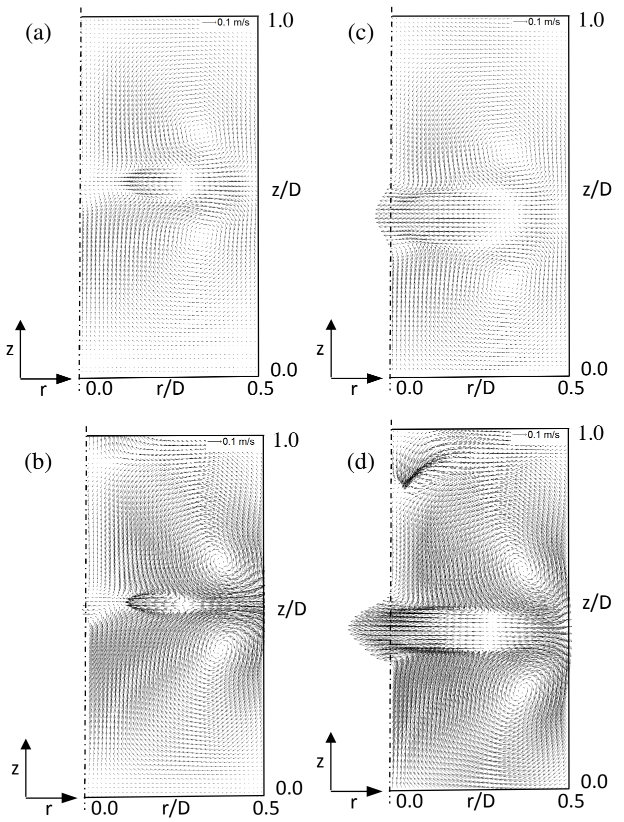

Fig. 9. Mean velocity field for *h/H*=1/2 and Rushton turbine (a,b), novel impeller (c,d) and rotational speed *N*=100 rpm (top), *N*=300 rpm (bottom).

4 Conclusions

In this work, an experimental investigation on the fluid flow mixing process in agitated vessel has been done. It has been shown that using the optimised impeller shape, it is possible to significantly increase mixing performance maintaining the same electrical power required. After exceeding the critical for the phenomena value for the Reynolds number (about Re=25), a significant initial increase in power number N_p is observed preceding a steady decline in this parameter. The power number values for the Rushton turbine and for novel impeller for highly viscous fluid (μ=1410.1Pa·s) are quite similar. Increasing Reynolds number the stabilization of N_p values is observed. It is worth to notice that even power number is similar the pumping capacity can be up to one order of magnitude larger for the novel impeller than for the Rushton turbine. This results in more intensive fluid motion at the same rotational speed. The analysed new impeller type is a promising alternative to the classic rotating disc or other blades and non-blades based impeller types.

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