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Identification of the liquid turbulent flow based on experimental methods

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Abstract This paper presents the results of experimental testing of parameters of the flow of an agitated liquid in a stirred tank with an eccentrically positioned shaft and with a Rushton turbine. The investigations were focused on the impact of the stirrer shaft shift in relation to the stirred tank vertical axis on the agitated liquid mean velocities and the liquid turbulent velocity fluctuations, as well as on the turbulence intensity in the tank. All the experiments were carried out in a stirred tank with the inner diameter of 286 mm and a flat bottom. The adopted values of the shaft eccentricity were zero (central position) and half the tank radius. The liquid flow instantaneous velocities were measured using laser Doppler anemometry.

Keywords: LDA; Turbulence; Fluid-flow machines

Nomenclature

d – stirrer diameter, m
D – tank diameter, m
e – stirrer eccentricity
I – turbulence intensity
k – kinetic energy of turbulence, m^2/s^2
n – stirrer rotational speed, 1/s
N – number of measurements
P – stirring power, W
R – tank radius, m
u – flow instantaneous velocity, m/s

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u' – fluctuation velocity component (RMS), m/s
$\overline{u}$ – mean velocity component, m/s
σ^2 – variance
ρ – liquid density, kg/m^3
Ne – stirring power number (Newton number) ($= P/(n^3 d^5 \rho)$)

1 Introduction

Mixers consisting of a Rushton turbine blade rotating in a cylindrical chamber are common in industry. The mechanisms of mixing in such systems are not well understood, nor are the relationships between mixing mechanisms and dissipation mechanisms [1]. Turbulent dissipation in a stirred tank was measured by Wu and Patterson, who, using laser Doppler velocimetry data, calculated it locally based on the turbulent macroscale and turbulent velocity [2]. Rao and Brodkey determined the velocity microscale (the dissipation length) and the root mean square velocity from the hot-film anemometer data [3]. These parameters were then used to estimate turbulent dissipation. Cutter used the energy balance coupled with photographic velocity data to estimate dissipation [4]. Okamoto *et al.* [5] used energy spectra results to estimate the turbulence microscale. A modified method of determination of the liquid turbulence macro- and microscale in a stirred tank, which is based on the experimentally determined velocity autocorrelation function is presented in [6, 7].

It should be noted that despite the fast development of numerical methods and faster and more efficient computers used for the computations [8,9], experimental testing based on state-of-the-art measuring techniques is an essential tool for identification of parameters of the liquid turbulent flow in a stirred tank. Among these techniques, laser Doppler anemometry (LDA) occupies a special place.

The measurements presented in this paper are carried out in a stirred tank with no baffles and with a Rushton turbine. Instantaneous velocities are identified using the LDA method. Based on the results of the LDA measurements, mean velocity, fluctuation velocity, turbulence kinetic energy and turbulence intensity values are calculated. The obtained results indicate that by introducing eccentricity of the stirrer position, the agitated liquid flow becomes more turbulent compared to centric positioning. In addition, it is pointed out that using stirred tanks with no baffles and with the stirrer positioned eccentrically can be an attractive alternative compared to standard solutions with baffles.

Practical application of agitated tanks with no baffles and with an eccentric position of the stirrer can be an attractive alternative to standard solutions with baffles which require much higher energy outlays, what was analyzed and presented in the works [16, 18].

2 Experimental set-up

The stirrer and the tank configuration, together with the coordinate system, is shown in Fig. 1. The measurements were performed in a cylindrical no-baffle tank with diameter $D = 286$ mm, height $H = 540$ mm. The tank was filled with a liquid up to height 286 mm. So that the LDA measurements should be correct, the stirred tank had to be characterized by full transparency and an identical refractive index along the whole path of the laser light beams. Therefore, the stirred tank was made of borosilicate glass (Duran) and filled with dimethyl sulfoxide (DMSO) with viscosity $\eta = 0.0023$ Pa·s and density $\rho = 1100$ kg/m^3. The liquid was stirred using a standard Rushton turbine with dimensions $d = D/3$, blade height $d/5$ and blade width $d/4$. The stirrer was placed at height $h = d$ measured from the tank bottom.

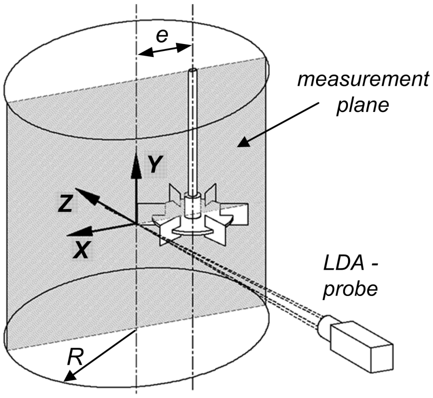


Figure 1: Stirred tank with an eccentrically located Rushton turbine – measurement plane location in the tank.

The liquid instantaneous velocities in the stirred tank were measured using two-component Laser Doppler Anemometry (LDA) operating in the backscatter mode [10]. The source of the laser beam was an argon-ion laser with maximum power of 300 mW, which produced a pair of blue beams of light of wavelength 488 nm and a pair of green beams of wavelength 514.5 nm. The measurement data were processed using a Dantec Burst Spectrum Analyser. The working liquid was seeded with silver-coated hollow glass spheres with the mean diameter of 10 μm and the density of 1150 kg/m^3. The visualization results of the liquid flow in the stirred tank were documented using a digital camera.

Testing was performed for 2 different positions of the stirrer shaft from the tank axis: central position $e = 0$ and $e = R/2$. The agitated liquid flow velocity was measured in the plane passing through the tank axis and the stirrer shaft axis (Fig. 1). The stirring intensity was altered by changing the frequency of the stirrer shaft revolutions within the limits of 200 to 600 rpm, which corresponded to a fully developed turbulent flow in the stirred tank and to Reynolds numbers included in the range of $1.44 \times 10^4 \leq \mathrm{Re} \leq 4.32 \times 10^4$.

3 Elaboration on measurement results

Based on anemometric measurements of the liquid instantaneous velocities in the stirred tank $u(t)$ obtained in the tank individual points, mean values of the liquid flow velocities are determined. The measured instantaneous velocity is a random variable in its common sense, i.e. a discrete one. In such a situation, mean velocity (for each velocity component $i = x, y, z$) is expressed by the following formula:

$$\overline{u}_i = \frac{1}{N} \sum_{j=1}^{N} u_{i,j} \,, \tag{1}$$

where N is the number of independent measurements of instantaneous velocities in a single measuring point. During the testing, $N = 10000$ (subscript i denotes the direction of the velocity component (x, y, z) and j is the summation index.

Unfortunately, mean velocity determination from Eq. (1) is burdened with what is referred to as the sampling bias resulting from the anemometer measuring signal discontinuity, which is an effect of the unavoidable non-homogeneity of the tracker particles concentration [11]. In order to minimize the sampling bias, mean velocity was ultimately calculated as a weighted mean with weights corresponding to the tracker particle residence time,

$\Delta t_{i,j}$, in the measuring space

$$\overline{u}_i = \frac{\sum\limits_{j=1}^{N} u_{i,j}\Delta t_{i,j}}{\sum\limits_{j=1}^{N} \Delta t_{i,j}}. \tag{2}$$

The correction to the mean velocity determination introduced by formula (2) is referred to as transit-time weighting or residence-time weighting [12, 13].

The measure of the intensity of fluctuations in measured momentary velocities, $u_i(t)$, is expressed as the following variance:

$$\sigma_i^2 = \overline{u'^2_i} = \frac{\sum\limits_{j=1}^{N} \left(u_{i,j} - \overline{u}_i\right)^2}{N}. \tag{3}$$

After "three-dimensional correction" was introduced – like in formula (2) – variance of the velocity fluctuations were found using the following relation:

$$\sigma_i^2 = \overline{u'^2_i} = \frac{\sum\limits_{j=1}^{N} \left(u_{i,j} - \overline{u}_i\right)^2 \Delta t_{i,j}}{\sum\limits_{j=1}^{N} \Delta t_{i,j}}. \tag{4}$$

The values of individual components of the liquid flow fluctuation velocities in the stirred tank were finally calculated as a standard deviation, i.e., the variance square root or root mean square value of velocity fluctuations (RMS values):

$$u'_i = \sqrt{\sigma_i^2} = \sqrt{\overline{u'^2_i}}. \tag{5}$$

As for the turbulence intensity, one of the measures is the mean kinetic energy of fluctuation motions, i.e. turbulence kinetic energy which is usually defined by the following general relation:

$$k = \frac{1}{2}\left(\overline{u'^2_x} + \overline{u'^2_y} + \overline{u'^2_z}\right). \tag{6}$$

In the case of measuring two components of the fluctuation velocity (u'_x and u'_y), kinetic energy of turbulence was found using the following relation [14, 15]:

$$k = \frac{3}{4}\left(\overline{u'^2_x} + \overline{u'^2_y}\right). \tag{7}$$

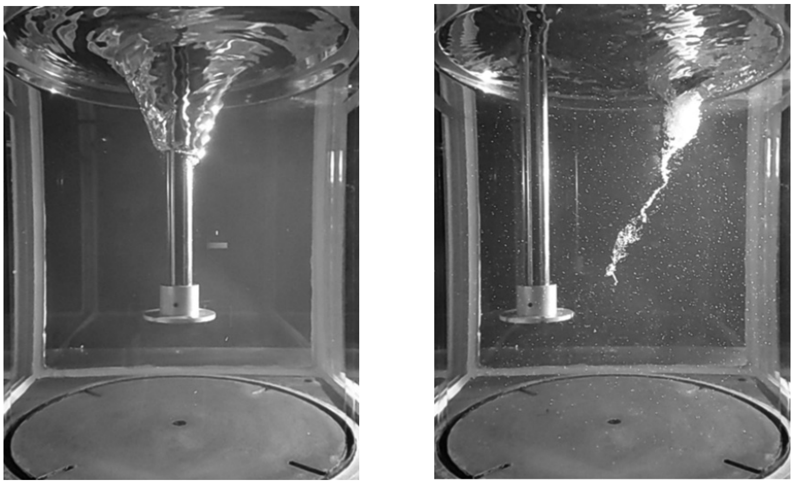
The determined kinetic energy of turbulence is used to find turbulence intensity I according to the following equation [16]:

$$I = \frac{\sqrt{\frac{2}{3}k}}{\pi d n} 100\,\%. \tag{8}$$

Product πdn in the denominator is peripheral speed on the blade tips of the stirrer with diameter d and revolutions frequency n.

4 Results

Figure 2 presents photographs illustrating quality testing in a stirred tank with no typical vertical baffles located on the tank walls. The lack of baffles results in lower demand for power and causes a substantial change in the device hydrodynamic conditions [16]. Due to the centric location of the stirrer shaft in a stirred tank with no baffles, i.e., in the tank vertical axis,



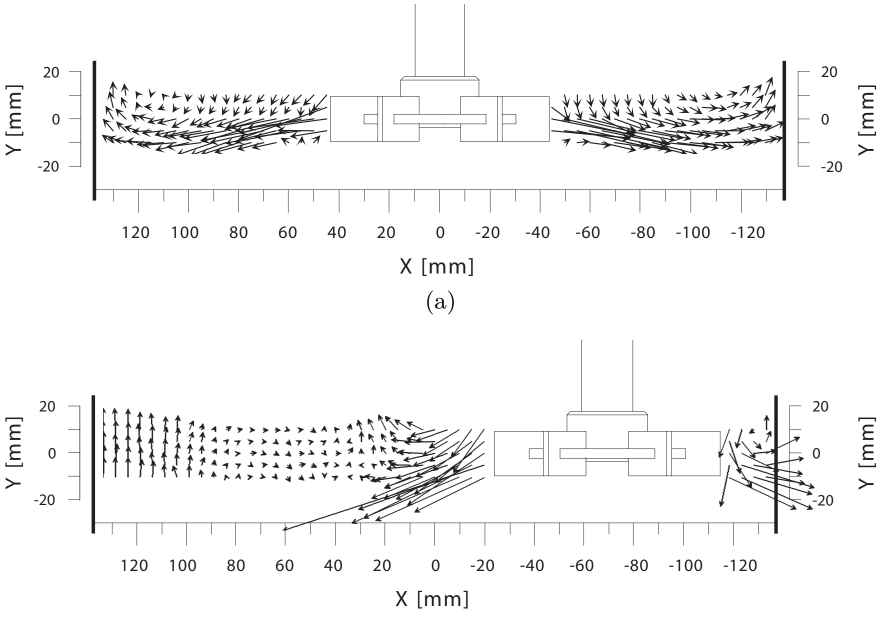
(a) (b)

Figure 2: Local swirling of the liquid for stirrer rotational speed $n = 255$ rpm and for the shaft different eccentricity: a) $e = 0$, b) $e = 0.5R$.

a central vortex is created around the shaft. The vortex depth increases with the rise in frequency of revolutions. If the shaft rpm number is high enough, the vortex may even reach the stirrer blades. This is an unfavourable effect causing hydraulic impacts due to the stirrer periodic rotation in air [17].

A shift in the shaft position in relation to the tank axis, i.e., the shaft eccentric location, prevents the creation of the unwanted vortex around the stirrer shaft. Slight local swirling of the liquid can only be observed in the area between the shaft and the tank wall. The aim of the measurements using laser anemometry was a quantitative determination of parameters that are involved with the presented changes in flow conditions in the stirred tank.

Figure 3 presents example results of the measurements and calculations of mean velocities of the liquid flow in the radial and axial direction (u_x and u_z, respectively) in the area of the liquid outflow from the stirrer, i.e., in the area of the liquid flow generation in the stirred tank. If the shaft is in the centric position, the velocity distribution is symmetric on both sides

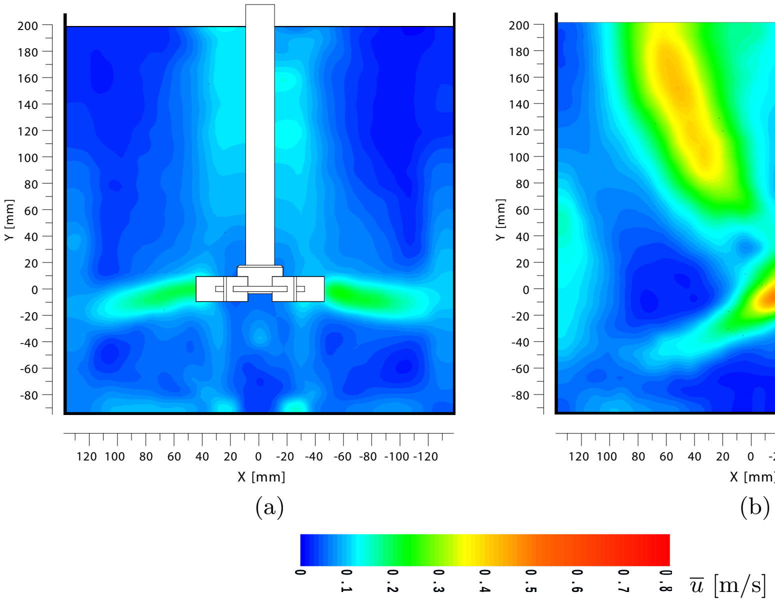


(a)

(b)

Figure 3: Distribution of liquid mean velocities (resultant from radial and axial velocity $\overline{u}_x$ and $\overline{u}_z$, respectively) in the zone where the liquid is pumped by the stirrer for different eccentricity values: a) $e = 0$, b) $e = 0.5R$. Stirrer rotational *speed* $n =$ 225 rpm.

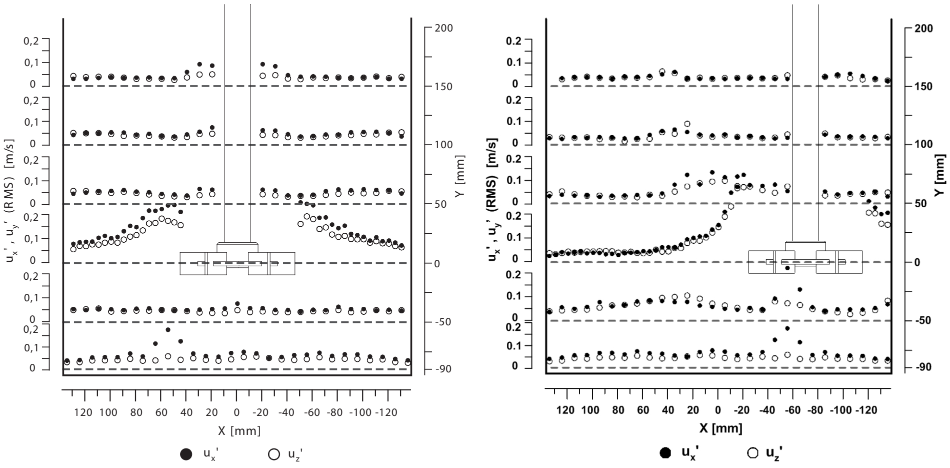
of the stirrer. If the shaft is shifted, qualitative and quantitative changes arise in the distribution of mean velocities of the liquid outflow from the stirrer. Figure 4 illustrates a comparison between the liquid mean velocities (resultant from the radial and axial velocity) in the entire volume of the stirred liquid by means of three-dimensional contour maps. The highest values of velocity are observed in the area of the liquid local outflow from the stirrer and in the area where local swirling of the liquid occurs. The velocity values rise as the shaft eccentricity increases.



(a) (b)

Figure 4: Contour maps of the liquid mean velocities (resultant from radial and axial velocity $\overline{u}_x$ and $\overline{u}_z$, respectively) in the entire volume of the stirred liquid for different eccentricity values: a) $e = 0$, b) $e = 0.5R$. Stirrer rotational speed $n = 225$ rpm.

The increase in average liquid velocities, along with the stirrer eccentricity, is also associated with an increase of flow turbulence parameters. Figure 5 shows fluctuation velocities in the radial and axial direction for different values of eccentricity. The largest values of fluctuating components of both radial and axial velocities were found in the outflow area of the stirrer. In the case of the eccentric position, a non-symmetrical distribution of velocity pulsations on both sides of the stirrer is observed. Larger pulsation velocities are also observed in the area of local liquid turbulence at the eccentric position of the shaft.



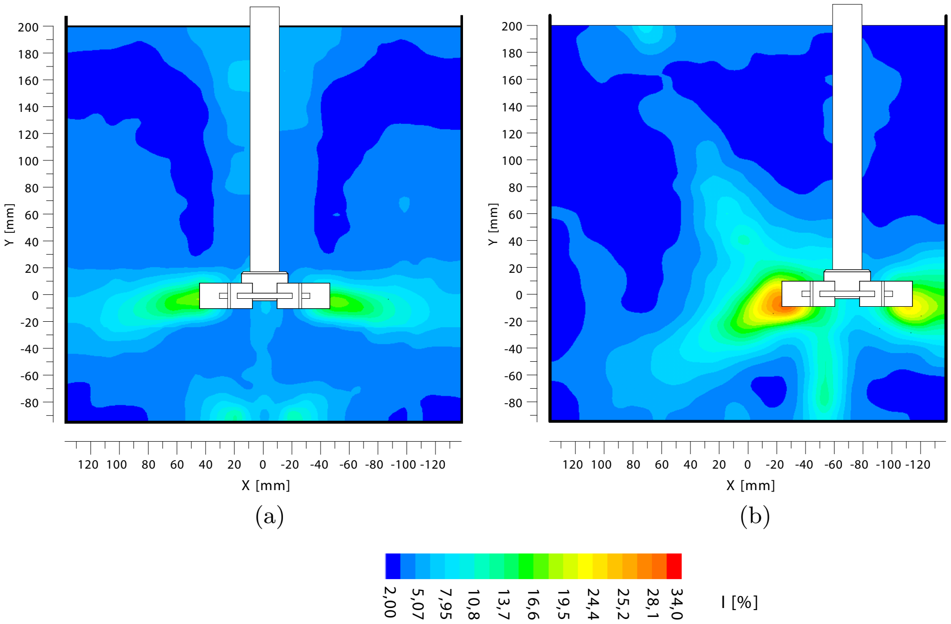
(a) (b)

Figure 5: Fluctuation velocities in the radial and axial direction u'_x and u'_z, respectively, at the liquid different levels in the stirred tank (rotational speed $n = 225$ rpm) and for different values of eccentricity: a) $e = 0$; b) $e = 0.5R$.

Figure 6 presents contour maps illustrating the distribution of the turbulence intensity (Eq. (7)) in a stirred tank with no baffles for two eccentricity values: $e = 0$, (Fig. 6a) and $e = 0.5R$ (Fig. 6b). Spatial distribution of measurement points was equal 5 mm.

Analysing the obtained results of turbulence intensity distribution and size, it can be stated that the turbulence intensity is the highest in the area of the liquid outflow from the stirrer. At the same time, an increase in the shaft eccentricity to the value of $e = 0.5R$ causes a rise in the turbulence intensity in the stirrer outflow area. In both cases, the areas with locally higher turbulence intensity levels are the liquid swirling regions in the agitated tank with no baffles. The areas coincide with the places where a rise in velocity fluctuations was found earlier. An effect of the increase in eccentricity to $e = 0.5R$ is that higher turbulence intensity values occur locally in the stirring region directly beneath the stirrer (Fig. 6b).

The measurement results of the turbulence intensity in a stirred tank with an eccentrically located shaft were compared to the case where the shaft was positioned centrically. It follows from the comparison that with the increase in eccentricity, the maximum values of the liquid flow turbulence intensity in the agitated tank also rise from the value of $I = 24.8\%$ for $e = 0$ to $I = 34.6\%$ for eccentricity $e = 0.5R$.



(a) (b)

Figure 6: Contour maps of the intensity of the liquid turbulence in the stirred tank for the stirrer different eccentricity values.

5 Conclusions

The presented turbulence intensity contour maps indicate that by introducing the stirrer eccentricity ($e = 0.5R$), the stirred liquid turbulence is increased compared to the case with the stirrer centric position ($e = 0$). The highest values of the liquid flow turbulence intensity occur in the stirrer outflow area, on the side where the stirrer is more distant from the tank wall. The effect is particularly visible for eccentricity $e = 0.5R$. At the same time, the shaft shift in relation to the tank vertical axis prevents the creation of an unfavourable vortex around the stirrer shaft, which at a sufficient frequency of the stirrer revolutions may cause hydraulic impacts due to the stirrer periodic rotation in air.

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