LDA Measurement in the Impeller Region of Stirred Vessels: An Assessment of Measurement Technique

J. Stelmach and E. Rzyski
Technical University of Łódź
Faculty of Process and Environmental Engineering
ul. Wólczańska 213, 93-005 Łódź, Poland
Correspondence to: stelmach@wipos.p.lodz.pl

Original scientific paper
Received: April 2, 2002
Accepted: September 1, 2002

Results of measurements of liquid tangential velocity in the region of a self-aspirating disk impeller taken by a laser anemometer through the side wall and bottom of the tank are compared in the paper. It appeared that the measurement method had the most significant influence on the mean velocity. The effect on other values, such as mean velocity pulsations or energy dissipation rate, is smaller or even negligible.

In the impeller region a strong dependence of instantaneous velocities on the blade position in relation to the measurement point (angular velocity distribution) was observed. A periodic velocity component can be approximated by a sinusoidal relation and eliminated. It is also possible to average velocities and velocity pulsations by intervals. This enables the extrapolation of velocity in the "dead" measurement zone.

Key words:
Agitated tank, LDA measurements, mixing, self-aspirating disk impeller, tangential velocity of liquid,

Introduction

Laser Doppler anemometry (LDA) is a modern non-invasive technique for measurement liquid velocity. It enables measurement in places inaccessible to other methods, e.g. in the impeller region. During the investigation of liquid velocity in the self-aspirating impeller region aiming at the determination of eddy size, it appeared that time-averaged liquid tangential velocities differed depending on the measurement method.[1,2] This is illustrated in Fig. 1 for the impeller of diameter d = 125 mm operating at revolutions frequency n = 400 min^{-1}. Velocities obtained in the bottom measurement (during a simultaneous measurement of both tangential and radial component as well as only tangential component) are smaller than the measurement through the side wall. This phenomenon is less pronounced with an increasing distance to the tank axis. Thus, it must be connected with the impeller design and the presence of dead measurement zones (Fig. 1).

From analysis of Fig. 1 it follows that the method of measurement has no effect on mean velocity pulsations. That is why the aim of this work is to check the impact of the tested impeller design and measurement methods on results obtained.

Experimental

Measurements of instantaneous velocities were carried out in a glass tank of diameter D = 292 mm.

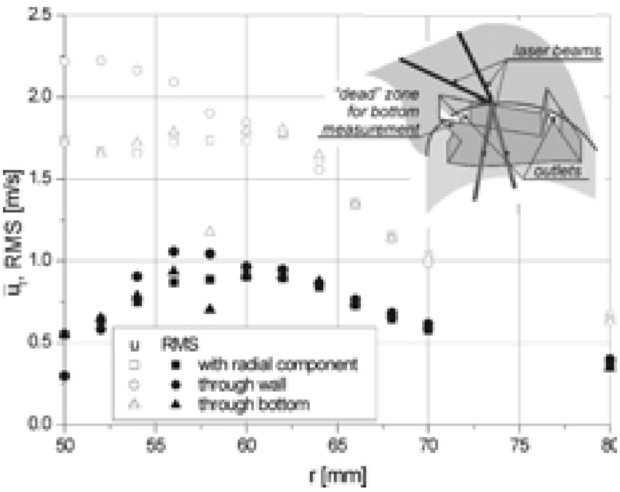


Fig. 1 – *Mean velocities and velocity pulsation*

The tank was equipped with four standard baffles and it was filled with distilled water up to the height H = D. The cylindrical tank was placed in the cuboidal glass vessel also filled with water (Fig. 2).

A Dantec laser anemometer with 58N10 processor operating at the wavelength λ = 514.7 nm (and λ = 632.8 nm during simultaneous measurement of two components) was used. The self-aspirating disk impeller with diameter d = 125 mm was employed (Fig. 2). The impeller operated in water at the revolutions frequency n = 400 min^{-1} with blanked inlet on the shaft (water was inside the impeller). Velocities were measured in the points dis-

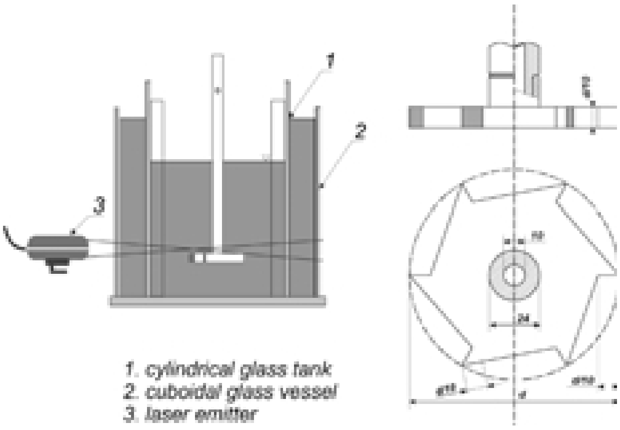


Fig. 2 – *Experimental rig*

tant from the tank axis by r = 50, 52, 54, 56, 58, 60, 62, 64, 68, 70 and 80 mm. These points were in the middle of the impeller height (distance from the bottom h = 65 mm) and on the midperpendicular of the angle between two baffles.[1]

In the measurement through the side wall of the tank a pinhole method was used to establish a measurement point. In the tank filled with water, instead of an impeller, a rod was placed on which a plate with 0.3 mm hole was mounted. When both laser beams were passing through the hole, the measurement point was considered to be just in the assumed position.

Adjustment was made for distances to the axis being r = 50, 62 and 80 mm. When in the laser emitter the lens with 400 mm focal length was applied, the angle between the laser beam and the normal to the cylindrical surface was small enough to assume with good accuracy a linear relationship between the emitter shift and the shift of the measurement point in the tank.

Measurements were made at two settings of the laser beams emitter:

1) measurement through the side wall of the tank, when the plane on which the laser beams were situated, was parallel to the horizontal surfaces of the impeller and the tank bottom,

2) measurement through the tank bottom, when the plane on which the laser beams were situated, was tangential to the vertical blade edge.

A tracer was very fine TiO_2. In each measurement point 20 000 instantaneous velocities were measured at sampling frequency of several kHz.

Results and discussion

As a result of measurements we obtained files which contained, among the other things, the time which passed since the beginning of the measurement until the moment of sampling and the instantaneous velocity in that moment. The relationship

$$\alpha = 60° \cdot [6 \cdot t \cdot n - int(6 \cdot t \cdot n)] \qquad (1)$$

where t denotes the time which passed since the beginning of the measurement to sampling, and *int* is the function calculating total part of the number, allows us to determine the angle between the blades for which sampling was made. Angular distributions of instantaneous velocities were obtained in this way for the measured data.

A big number of samplings in the region behind the blades in which instantaneous velocities exceed even the blade tip velocity, causes differences in the mean velocity pulsations (RMS). Additional information on liquid velocity in the measurement points is supplied by the analysis of distribution density (histograms) of instantaneous velocities. The densities of distribution for r = 56 mm are shown in Fig. 3.

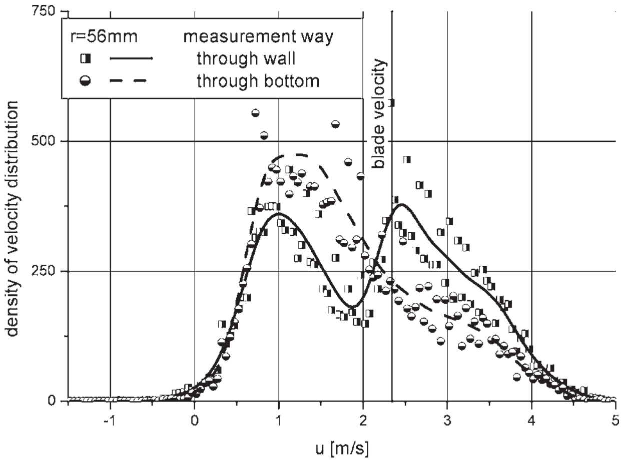


Fig. 3 – *Density of velocity distributions*

Almost in the whole impeller region in the side-wall measurement the distributions with two maxima were obtained. One of them is at the value corresponding to the blade velocity at a given distance from the axis. The lack of such a maximum in the distributions for the bottom measurement reveals that measurements (samplings), taken behind the blade which has just passed through the measurement point, are responsible for this maximum. Hence, it can be expected that in the measurements in which the measurement point is blanked off by the element of the impeller for a long time, underestimated values averaged in time will be obtained. Because the averaged velocity pulsation (RMS) provides an information on the range of deviations from the average, in the investigated case the differences in RMS depending on the measurement method will be small. This case is illustrated in Fig. 1.

For the tested impeller, a decrease of the mean velocity in the bottom measurement corresponds to the contribution of the "dead" measurement zone. Unfortunately, this observation cannot be generalised onto other impeller types and measurement conditions. In the case of mean velocity pulsations, the differences resulting from the measurement method are smaller and in many cases negligible. Changes in the liquid velocity induced by a cyclic passage of the blade through the measurement point disappear completely at the distance of 80 mm from the impeller axis. When the impeller radius is taken into account, it appears that this is only 17.5 mm from the blade tip.

Further analysis of the data leads to the conclusion that in the impeller region and in its close vicinity (r < 80 mm), there is a strong dependence of the liquid velocity on the blade position relative to the measurement point. This is fully confirmed by the frequency analysis by the linear interpolation method[3] (Fig. 4).

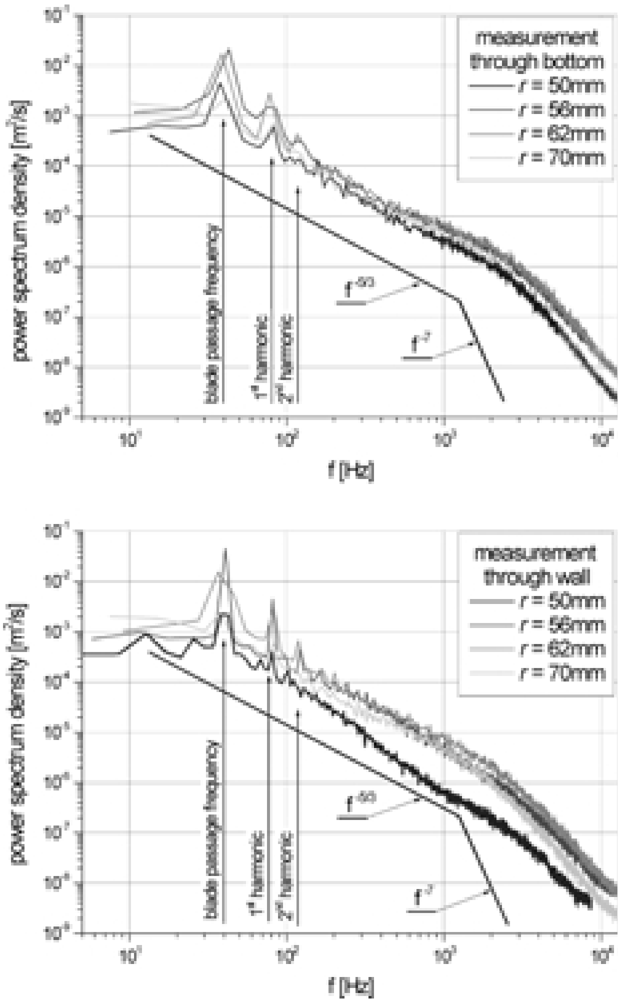


Fig. 4 – *Power spectrum density obtained for tangential component of the velocity*

Large peaks for the frequency close to 40 Hz, i.e. the frequency of blade motion (6 blades × 6.67 s^{-1}) and its multiples (the first and second harmonics) are observed for the impeller region. For r = 70 mm, these peaks disappear almost completely, although the spectral curve which informs about energy dissipation rate, is situated on the level of curves for the impeller region. No significant difference in the spectral curves obtained for both measurement methods are observed (except for r = 50 mm). So, for spectral analysis and for the determination of energy dissipation rate on this basis, one can use instantaneous tangential velocities irrespective of the measurement method.

Hence, for the tangential component of the velocity, periodical (regular) oscillations $\boldsymbol{u}_{\mathrm{per}}(t)$ can be expected[4,5], i.e.

$$\boldsymbol{u}_{\mathrm{tot}}(t)=\boldsymbol{u}_{\mathrm{rand}}(t)+\boldsymbol{u}_{\mathrm{per}}(t) \qquad (2)$$

where $\boldsymbol{u}_{\mathrm{rand}}(t)$ denotes the random component. The instantaneous velocity is divided into two components in order to isolate the study of the turbulent flow field from that of the mean flow field[5].

As suggested in[4], the periodical component can be described by the relation

$$\boldsymbol{u}_{\mathrm{per}}(t)=A_1\cdot\cos(2\cdot m\cdot\pi\cdot t)+A_2\cdot\cos(4\cdot m\cdot\pi\cdot t) \qquad (3)$$

where m denotes the frequency at which the blades pass through the measurement point. In our case, for the impeller with 6 blades $m = 6 \cdot n$.

Determination of the periodical component allows it to be subtracted from the measured values of velocity and to carry out a spectral analysis whose aim is to compare energy dissipation rate for both measurement methods. Results obtained for the side wall measurement are shown in Fig. 5. Elimination of the periodical component gives smoothing of the power spectrum curve. As shown in Fig. 5, the

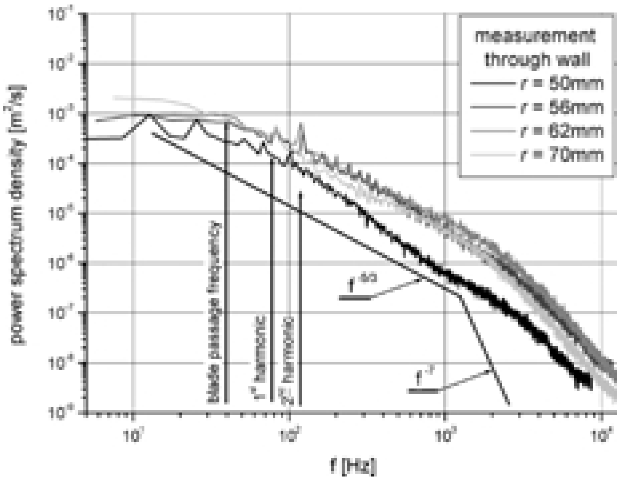
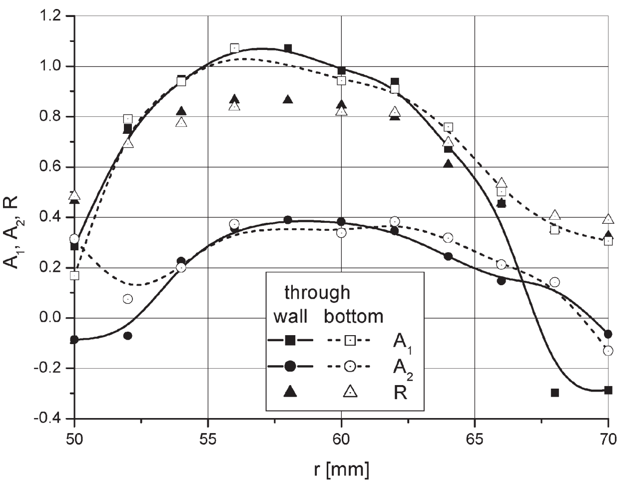


Fig. 5 – *Density of energy spectrum after removal of the periodic component*

peaks decrease – especially the one representing the blade frequency.

The highest correlation coefficients calculated iteratively at a possibly small mean relative error ensuring the coefficients A_1 and A_2 are shown in Fig. 6.



F i g . 6 – *Coefficients in equation (3)*

In the impeller region the obtained values do not depend practically on the measurement method and the correlation coefficient attains the value exceeding 0.8. Beyond the impeller region the correlation coefficient decreases which means that the contribution of periodic oscillations is reduced. This causes also the growing differences in the values of coefficients A_1 and A_2 depending on the measurement method. After deleting the periodical component, energy dissipation rates for both methods of velocity measurement were compared.

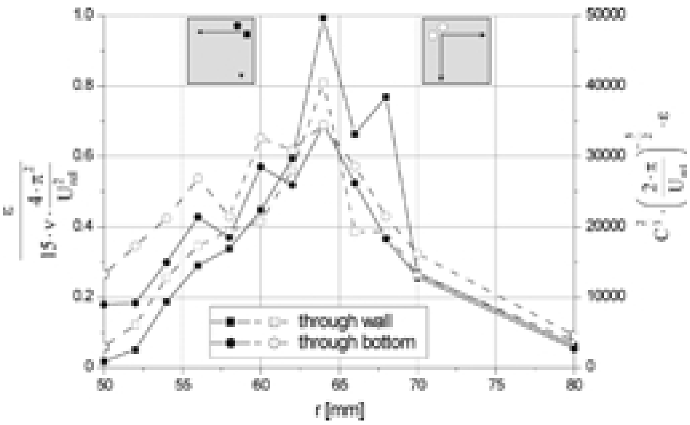
The energy dissipation rate can be calculated from the relationship on the basis of energy spectrum for one component[6].

$$\varepsilon = 15 \cdot \nu \cdot \frac{4 \cdot \pi^2}{U_{\text{ref}}^2} \cdot \int f^2 \cdot E_i(f)\,\mathrm{d}f \qquad (4)$$

Because it is important to compare two values for the same measurement point, the values of integers can be compared without knowing the reference velocity. Similarly, when the equation for a three-dimensional energy spectrum is used[6]

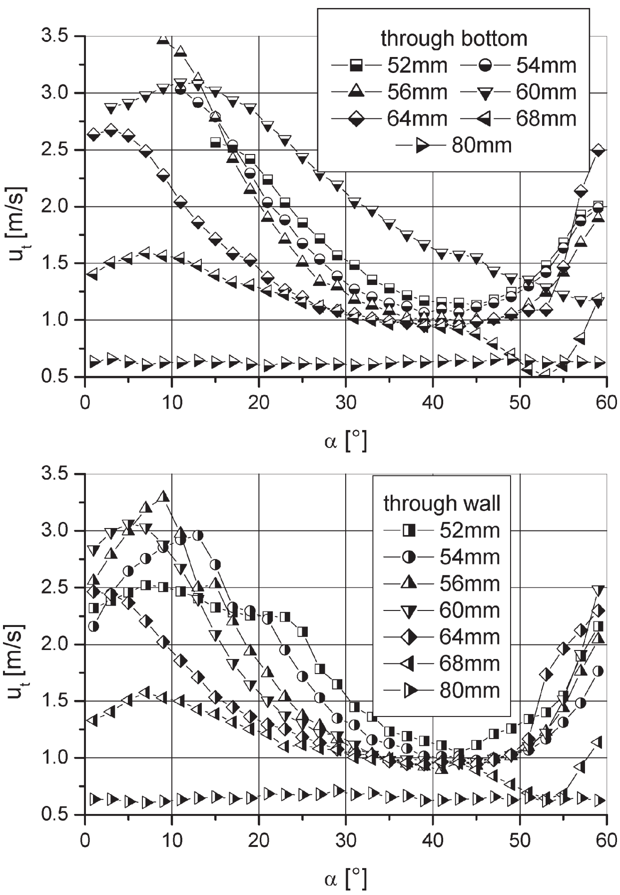
$$E(k,t) = C \cdot \varepsilon^{\frac{2}{3}} \cdot k^{-\frac{5}{3}} = C \cdot \varepsilon^{\frac{2}{3}} \cdot \left(\frac{2 \cdot \pi}{U_{\text{ref}}} \cdot f\right)^{-\frac{5}{3}} \qquad (5)$$

with constant C being unknown, the values of $C^{\frac{2}{3}} \cdot \left(\frac{2 \cdot \pi}{U_{\text{ref}}}\right)^{-\frac{5}{3}} \cdot \varepsilon$ calculated using the linear regression method, can be compared. The results are shown in Fig. 7 (to ensure better comparability of the results, the upper integration limit was reduced to 4 kHz – at this frequency the segment inclined approximately by 5/3 usually ended).



F i g . 7 – *Comparison of energy dissipation rates*

The values obtained from eqs. (4) and (5) reveal the same character of changes. However, despite of the reduction of the upper integration limit one can observe differences in the values for measurements taken through the side wall and tank bot-



F i g . 8 – *Angular distribution of mean tangential velocities averaged by intervals* tom. There are also significant differences for the values obtained on the basis of relation (5).

Because in the impeller region there is a strong angular distribution of instantaneous liquid velocities, it seems justified to investigate the mean velocities and the mean velocity pulsations in small angular intervals. In such an interval of the width up to several degrees, density of measured velocity distribution close to normal ones is observed. Angular distributions of mean liquid velocities (tangential component), averaged by intervals in the impeller region are shown in Fig. 8.

Conclusions

– The laser anemometry method enables measurements in places which are inaccessible for other methods, e.g. in the impeller region. However, in that case, the results of measurement may depend on the "dead" measurement zone resulting from the impeller design.

– The "dead" measurement zone which in some situations is connected with the impeller design has a significant effect only on mean liquid velocities in the impeller region. No differences in mean velocity pulsations were observed.

– For the impeller region it is not suitable to use the time-averaged mean velocity and tangential velocity pulsation because of high dependence of the instantaneous velocities on the location of the measurement point between the blades.

– The density curves of energy spectrum obtained for both measurement methods, i.e. through the wall and through the bottom, have a very similar shape. However, the estimation of energy dissipation rate obtained on their basis reveal significant differences. The character of changes is analogous in both cases.

– Angular distributions of velocities and velocity pulsations averaged by intervals for the tangential component do not show significant differences depending on the measurement method. A correct extrapolation of the data for the "dead" measurement zone is possible.

– For the impeller tested in this study it appeared more appropriate to measure the tangential component through the side wall of the tank.

The study was carried out within the research project no. 7T09C 036 21 financed by the Polish State Committee for Scientific Research.

Notation

d – impeller diameter, m
f – frequency, s^{-1}
k – wavenumber, m^{-1}
n – impeller rotational frequency, s^{-1}
r – distance from tank axis, m
R – correlation coefficient,
t – time, s
U_{ref} – reference velocity, $m^3\ s^{-1}\ m^{-2}$
$\boldsymbol{u}$ – velocity, $m^3\ s^{-1}\ m^{-2}$
$\boldsymbol{u}'$ – velocity pulsation, $m^3\ s^{-1}\ m^{-2}$
$\overline{\boldsymbol{u}}$ – mean velocity, $m^3\ s^{-1}\ m^{-2}$
$\overline{\boldsymbol{u}'}$ – mean velocity pulsation (RMS), $m^3\ s^{-1}\ m^{-2}$
LDA – laser Doppler anemometer
RMS – root mean square
α – paddle rotation angle, °
ε – energy dissipation rate, $m^2 \cdot s^{-3}$
λ – wavelenght, nm
ν – kinematic viscosity, $m^2 \cdot s^{-1}$

References

1. *Stelmach J.*, Inż. Chem. Proc. **22** 3E (2001) 1315.
2. *Szczygielski K.*, Measurements of liquid velocity for self-aspirating impeller (in Polish), MSc Thesis, Łódź Technical University, 2001.
3. *Nobach H., Müller E., Tropea C.*, Exp. in Fluids **24** (1988) 499.
4. *Wu H., Patterson G.T.*, Chem. Eng. Sci. **44** 10 (1989) 2207.
5. *Kresta S.M., Wood P.E.*, Chem. Eng. Sci. **48** 10 (1993) 1761.
6. *Wernersson StÍhl E.*, Some fluid dynamic characteristics in the scale-up of Rushton turbine-agitated tanks, PhD thesis, Lund University, 1997.