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INVESTIGATIONS OF LIQUID FLOW VELOCITY IN A VIBROMIXER USING STEREO PIV ANEMOMETRY

BADANIA PRĘDKOŚCI PRZEPŁYWU CIECZY W MIESZALNIKU WIBRACYJNYM METODĄ ANEMOMETRII OBRAZOWEJ STEREO PIV

Abstract

This paper presents the results of investigations of liquid flow in a vibromixer with a single, reciprocating disc. Measurements were conducted using Particle Image Velocimetry (Stereo PIV). Liquid circulation was analysed for two cases: in a whole mixing vessel; in selected zones of intensive flow, e.g. in a gap between the disc and the tank wall. Results of measurements are presented as vector and contour maps of flow velocity distribution. Also, curves illustrating changes of flow for various instantaneous disc positions are shown. Results presented in this work can be used in practice during designing and design optimization of vibromixers applied in the production of multiphase systems and also for the creation of theoretical foundations for the dispersing of phases using mixing equipment of this kind.

Keywords: *mixing*, *liquid flow*, *vibromixer*, *reciprocating agitator*, *Stereo PIV anemometry*

Streszczenie

W artykule przedstawiono wyniki badań przepływu cieczy w mieszalniku wibracyjnym z pojedynczym, tarczowym mieszadłem, wykonującym ruch posuwisto-zwrotny. Pomiary prowadzono z wykorzystaniem metody anemometrii obrazowej Stereo PIV. Analizowano ruch cieczy w dwóch przypadkach: w skali całego aparatu i w wybranych obszarach intensywnego przepływu, np. w szczelinie pomiędzy ścianką zbiornika a mieszadłem. Wyniki pomiarów przedstawiono w postaci wektorowych i konturowych map rozkładu prędkości cieczy oraz krzywych obrazujących zmiany parametrów przepływu przy różnych chwilowych położeniach mieszadła. Efekty pracy mogą być praktycznie wykorzystane podczas projektowania i optymalizacji konstrukcji mieszalników wibracyjnych stosowanych do wytwarzania układów wielofazowych oraz do tworzenia podstaw teoretycznych procesów dyspergowania faz w tego typu aparatach.

Słowa kluczowe: *mieszanie*, *przepływ cieczy*, *mieszalnik wibracyjny*, *mieszadło wykonujące ruch posuwisto-zwrotny*, *anemometria obrazowa Stereo PIV*

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1. Introduction

Vibromixers equipped with solid or perforated reciprocating agitators have been gaining popularity in recent years. Their advantages, such as their simple design, their ability to be used for various applications and their ability to generate a specific circulation in a vessel (without rotational liquid motion, central vortex or unfavourable liquid aeration) make vibromixers an interesting alternative to classical stirred tanks [1, 2]. So far, research on vibromixers has focused upon determining their suitability for multiphase systems production. Interesting results were obtained for the application of reciprocating discs during emulsion formation [3,4], drawdown of solids [5] or in mass transfer processes [6]. In some cases, for the proper selection of geometric and operating parameters, a vibromixer is characterized by a greater efficiency than stirred tanks equipped with turbine impellers. Also, great shear stresses that conventionally appear at the tip of blades of fast moving rotational impellers can be avoided. The mixing of liquids by reciprocating discs should therefore be preferred in a popular biotechnology, where great shear stresses lead to bio-cell damage [7].

In spite of all these advantages, mixing vessels with reciprocating agitators have thus far been seldom tested and investigated. The literature lacks comprehensive review papers, which would characterise the hydrodynamics of liquid flow in a vibromixer, e.g. values and distribution of velocity and turbulence parameters in a flow stream generated by a reciprocating disc. It significantly complicates the comparison of a vibromixer performance to classical stirred tanks with rotational impellers which is presented in the literature.

The first publications on this problem [8, 9] were based on CFD simulations, and they required experimental validation and verification. The current state-of-the-art shows a need for further research work, especially using modern anemometry methods, e.g. Particle Image Velocimetry (PIV) [10] or Laser Doppler Anemometry (LDA) [11]. Our results will enable the creation of comprehensive hydrodynamic models of flow for mixing vessels with reciprocating agitator(s). They will also make it possible to precisely analyse multiphase system formation and calculate the power consumption in vibromixers.

2. Experimental Methodology

The vibromixer used in the tests and details of the experimental set-up are shown in Fig. 1. The experimental system consisted of a cylindrical vessel (1) (internal diameter $D = 2R = 0.286$ m) and a single, reciprocating agitator (2). The circular flat disc ($d = 0.220$ m) without perforations was used as an agitator. It was selected that $D/d = 1.3$. The thickness of the disc $g_d = 0.003$ m. The agitator clearance (measured from the bottom of the vessel) was set at $h = 0.5H$. The liquid height $H = D$. The reciprocating movement of the disc was provided from the top of the vessel by a driving system (4) (variable speed motor, flywheel, connecting-rod and vibrating-rod). The vibration amplitude was set at $A = 0.04$ m and the frequency was set at $f = 1$ Hz. Distilled water ($\rho = 998$ kg/m^3, $\eta = 0.001$ Pa·s (at 20°C)) was used in the experiments as the model liquid, and polyamide solids (PSP-50) of 50 μm in diameter were applied as tracer particles.

The Stereo PIV measuring system consisted of a dual-impulse laser Dantec DualPower 50-200 (5) (impulse energy > 50 mJ, repetition rate 200 Hz, light wave length 532 nm), two optical systems – laser beam (6) and 'light sheet' (7) and two Dantec Speed Sense 9040 high-speed cameras (9) (recording frequency 1016 FPS). The use of two cameras at the same time (Stereo 3D) enabled the determination of all three components of flow velocity, according to the X, Y and Z axes (see Fig. 1).

The cameras and 'light sheet' optical system were located on movable sections of the traversing system. They could be moved synchronically during the measurements and the calibration process.
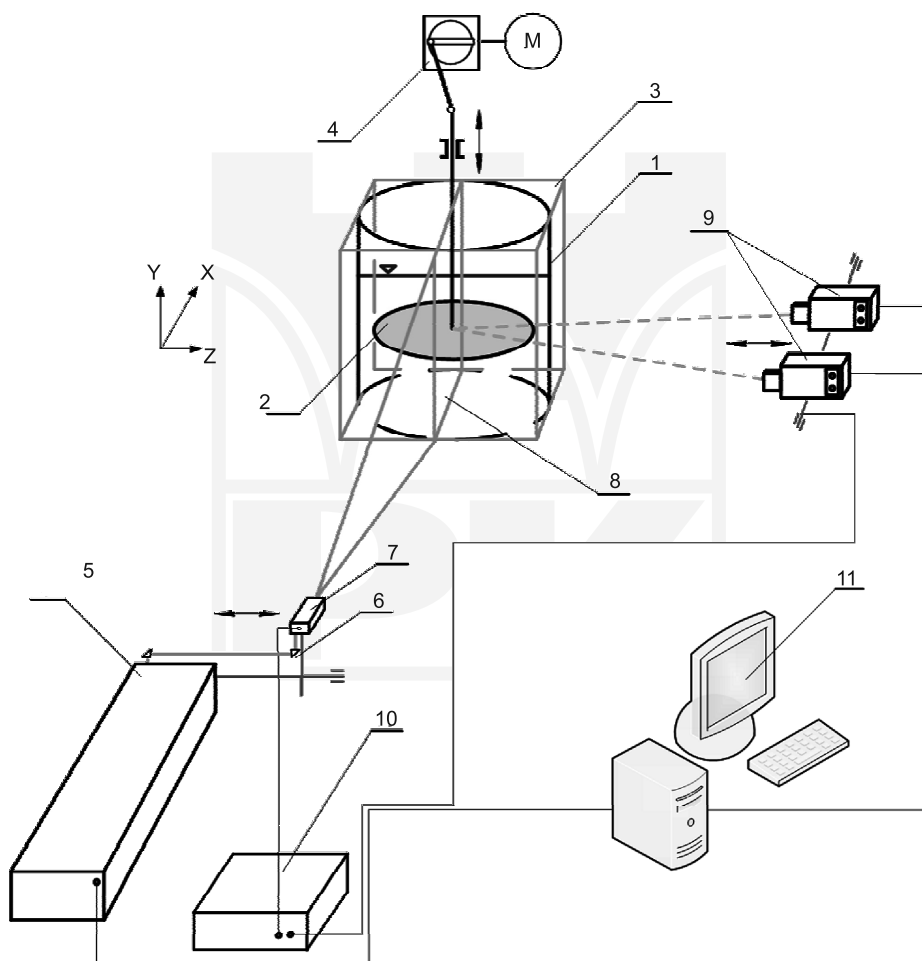

Fig. 1. Details of experimental set-up: 1 – tank; 2 – reciprocating agitator; 3 – cuboid jacked; 4 – driving system; 5 – dual-impulse laser; 6 – laser beam optical system, 7 – 'light sheet' optical system; 8 – 'light sheet', 9 – high-speed cameras; 10 – traversing system; 11 – computer with software

Images recorded by cameras were analysed using the advanced computer software, Dynamic Studio 3.20 [12]. Consequently, liquid flow velocity values for three perpendicular directions were determined. Stereo PIV Processing was applied, whereas Adaptive Correlation and Average Filter modes were used to obtain vector maps.

3. Results and discussion

Figure 2 presents example 3-D maps of liquid flow obtained during a complete, upward disc motion. Vectors exemplify components of a radial (u_x) and axial (u_y) velocity, whereas the contours illustrate values of a tangential one (u_z). For a more precise analysis of flow in the vibromixer, 3-D maps were created for three basic disc positions (the lowest, the middle and the highest) and for two intermediate positions located in between the basic ones. All measurements were carried out in a vertical-section plane, located along a central, vertical tank axis.

It can be seen that the most intensive flow occurs in the region of vortex generation (below and above the disc) and in the gap between the disc and the tank wall. For the lowest disc position ring (Fig. 2a), axial-symmetric, large-scale vortices are observed below as well as above the disc. However, the upper vortex is larger in diameter and takes up more space (the whole region between the wall and the disc shaft).

The successive upward disc movement induces an intensive liquid flow through the gap between the disc and the wall. A vortex in the bottom part of the vessel yields to gradual deformation, becoming increasingly larger (Fig. 2b). At the middle disc position (Fig. 2c), we can see fully-developed, large-scale vortices in the bottom and upper part of the vessel with comparable diameters. Furthermore, a successive upward motion of the disc (Fig. 2d) causes gradual disappearance of the upper vortex and inhibits the flow through the gap. When the agitator takes the highest position (Fig. 2e), liquid motion in the top part of the vibromixer is very weak and flow through the gap does not occur. When we analyse the liquid flow in the scale of the whole mixing vessel, velocity values are diverse. Vortex cores can be located in various vessel zones, their scale and shape change essentially not only owing to disc action and also as a result of both bottom and wall.

For these operating conditions, values of radial (u_x) and axial (u_y) velocity components (vectors) are not greater than 0.75 m/s. In comparison to classical stirred vessels with turbine impellers, the tangential (rotational) liquid flow in the vibromixer is significantly weaker. Values of a tangential velocity (u_z) for the majority of a measuring plane do not exceed 0.2 m/s. It is noteworthy that in the same regions we can see a few, irregular located zones of high tangential velocities ($u_z > 1.2$ m/s). These results can show a strong, unstable flow for this direction. As previously stressed, these zones are relatively uncommon and have a small surface compared to the whole measuring area (Fig. 2).

An intensive liquid flow during disc movement was observed in a ring-shaped gap between the disc tip and the tank wall. Precise 3D-maps of this region are shown in Figure 3, and a quantitative analysis is presented in Figure 4.

The upward disc movement does not only initiate vortex generation, but also an intensive axial flow in the opposite direction to the disc movement. Vectors also illustrate a strong radial
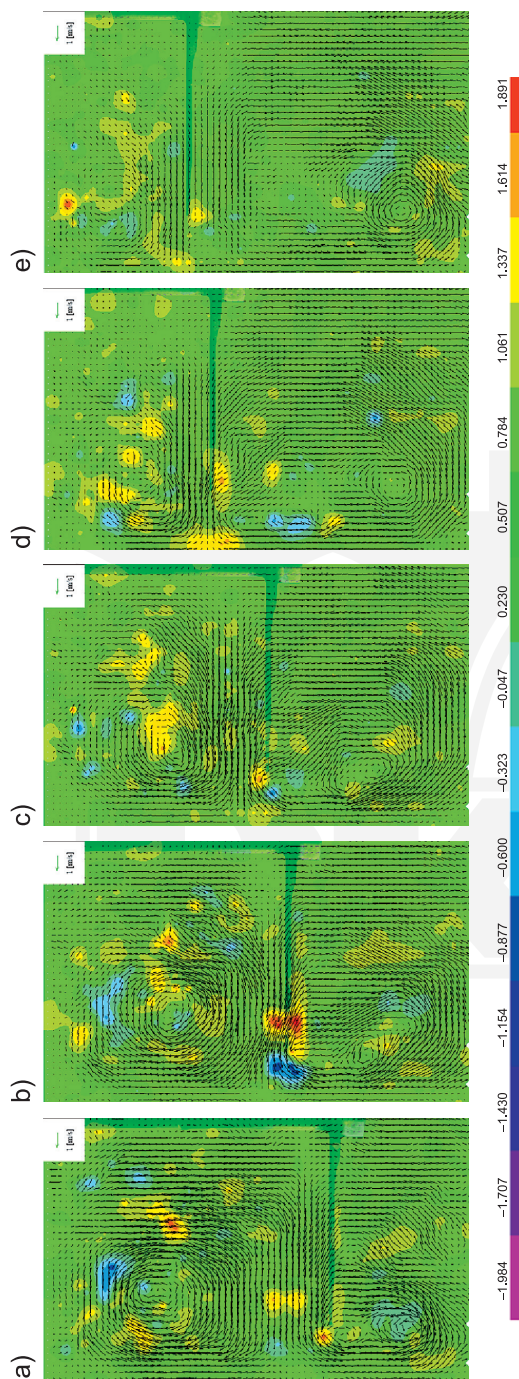
Fig. 2. 3-D maps (vector-contour) of a liquid flow velocity in a vibromixer at various disc positions (upward movement): a) the lowest; b) the intermediate (between lowest and middle); c) the middle; d) the intermediate (between middle and highest); e) the highest
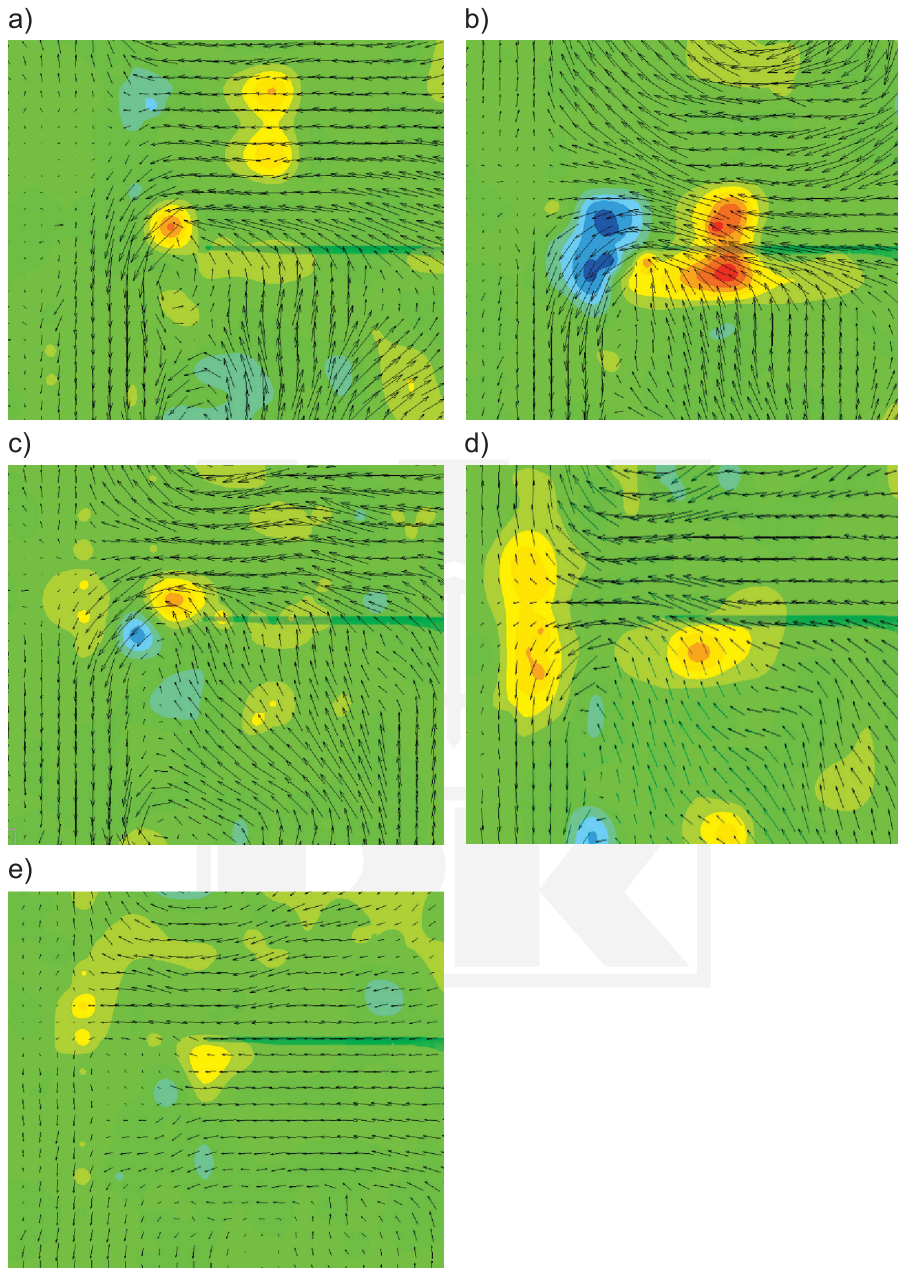
a)

b)

c)

d)

e)

Fig. 3. 3-D maps (vector-contour) of liquid flow in the ring-shaped gap between the disc and tank wall at various disc positions (upward movement): a) the lowest; b) the intermediate (between lowest and middle); c) the middle; d) the intermediate (between middle and highest); e) the highest

flow along the disc surface, which in the region of the disc tip changes direction and axial velocity components start to dominate. 3-D maps present distinct regions of liquid stream separation into lower (under the disc) and upper (above the disc) zones of vortex interaction. Instability of tangential flow can also be seen, determined practically for both (along z-axis and opposite) directions, coloured red and blue, respectively. A significant obstruction of radial-axial flow through the gap is visible for the highest disc position (Fig. 3e).

Additionally, to facilitate quantitative flow analysis, graphs illustrating values of velocity components were drawn. Curves represent values of individual velocity components (radial, axial and tangential) at the examined disc positions as a function of the relative vessel radius ($r* = 2r/D$) including the gap.

Changes of radial velocity (Fig. 4a) have a similar course regardless of disc position. The radial liquid flow is generated from the disc to the tank wall. Along the gap width, the
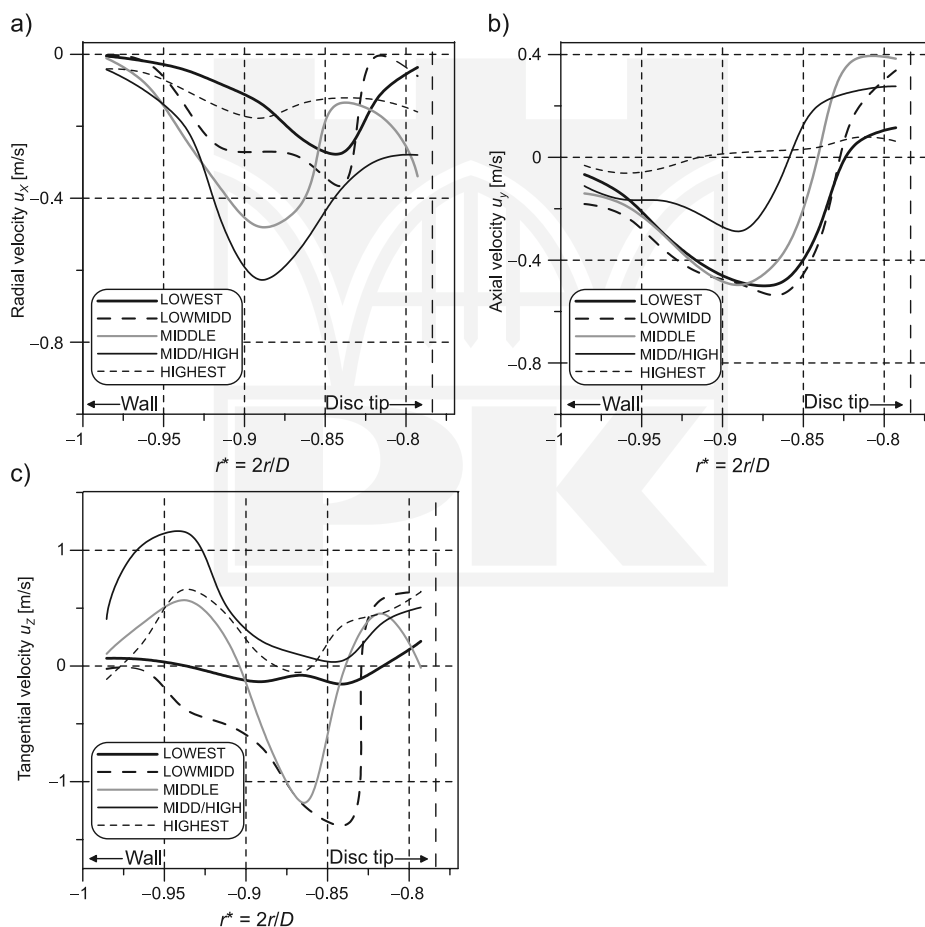

Fig. 4. Changes of flow velocity components as a function of a relative vessel radius ($r* = 2r/D$): a) radial velocity (u_x); b) axial velocity (u_y); c) tangential velocity (u_z)

values of this velocity component increase, reach a distinct extremum near half of the gap width. Next, they decrease as the distance to the wall decreases. With a successive upward disc movement, extreme values of a radial velocity component increase with the maximum ($u_x = 0.6$ m/s) for the intermediate (middle/highest) disc position. A very low radial flow for the highest disc position following change of disc movement (upward to downward) and a relatively weak flow circulation in the whole volume of the mixing vessel at this stage is but an isolated case. A similar tendency with extreme values in the region of half of the gap width is also observed for axial velocity (Fig. 4b). However, in this case the values are lower ($u_y = 0.4 - 0.5$ m/s) in comparison with the radial velocities. The curves representing the axial velocities for the lowest, intermediate (lowest/middle) and middle disc positions have very close maximum values, and, in the near wall zone, they overlap. The flow at the tip and under the disc also has an interesting structure. For most investigated disc positions (Fig. 3), we can see vortices with reversed flow (axially consistent with disc movement) which is also confirmed by data in Fig. 4 (positive values of velocity).

As is mentioned above, the third (tangential) component of velocity is characterised by a large irregularity and high velocities of flow. This interesting problem will be analysed in our further investigations. Also, results obtained in the present study will be used for the validation and verification of numerical CFD simulations.

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