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VISUALIZATION OF PSEUDOCAVERNS IN STIRRED VESSELS

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Abstract

A new technique for reconstructing the geometry of well-mixed regions (pseudocaverns for Newtonian fluids) in unbaffled vessels agitated with radial discharge impellers eccentrically placed has been developed for obtaining their three dimensional geometry. The mixer frame rotates at low speed allowing the video system to capture a sequence of pictures of the flow patterns by using the laser induced fluorescence technique. The recorded video sequence was used to isolate the contours of the pseudocaverns for reconstructing the three dimensional structure of the well-mixed regions within the tank.

Keywords: Mixing, 3-D visualization, homogenization, imaging, Laminar flow.

1. INTRODUCTION

Mixing has been recognized as a key unit operation involved in many industrial processes with numerous applications in fermentation, pigment or powder dispersion, emulsions, personal care products, etc. Some of the mixing applications are carried out with a rotating impeller. Due to the lack of optimization, mixing is commonly low cost-effective. Although a number of studies have been reported in the literature, most of them have focused on mixing times, flow patterns and power draw in turbulent regime. The presence of important segregated and dead zones at low Reynolds number has been observed when using open impellers such as Rushton turbines [1] or propellers. Well-mixed regions have been observed around the impellers surrounded by stagnant fluid, which are known as caverns in the case of yield stress fluids [2-5]. Empirical correlations were proposed for determining the geometric characteristics of these regions as well as their size.

Guided by qualitative observations, some authors have considered caverns as elliptical torii [6] or circular torii [7], while others considered them as spheres with center on a Rushton turbine (see for instance Solomon et al. [2]). Assuming that the flow within the cavern is purely azimuthal up to the time when the baffles are reached, a quantitative expression for the radius as a function of time has been proposed by Solomon et al. [2]. Cavern shapes were also investigated experimentally by means of laser Doppler anemometry (LDA) by Hirata and Aoshima [4]. They assumed that the shear stress in a dissipation zone is proportional to the average shear stress, which is responsible for the dissipation rate in the caverns. Considering a cylindrical cavern around the impeller, the cavern sizes were determined by an empirical correlation. The formation of caverns in the case of yield stress fluids or pseudocaverns for shear-thinning fluids as well as isolated regions is considered as mixing pathologies, which yields to long or infinite mixing times and as a consequence the process becomes inefficient [1]. The use of sophisticated techniques allowed the detailed study of the flows in the various parts of the vessel, pointing out that it may be necessary to re-define the flow patterns induced by the various impellers. For example, a detailed flow mapping, using laser Doppler velocimetry showed that axial impellers leave a substantial part of the fluid in the upper part of the vessel poorly agitated, often with velocities lower than 10% of the agitator tip speed [8], and that with a Rushton turbine the upper circulation loop is narrower than expected, with the fluid in the region near the upper vessel wall agitated in a secondary flow loop.

The precedent works reported in the literature allow determining or predicting analytically the geometric features of caverns, however, the most precise technique reported for analyzing caverns in stirred vessel was developed by Pakzad et al. [9], who modelled such flow structures by using electrical tomography. Although the data obtained with this technique is complete and informative, the equipment and infrastructure required is sophisticated and expensive. The aim of the present work is to describe an alternative three dimensional image analysis technique for reconstructing the flow structures, focusing on the pseudocaverns generated by a radial flow discharge impeller eccentrically placed. The use of such a technique allows measuring the irregular shape of pseudocaverns in off-centered configurations.

2. Materials and Methods

2.1. Experimental setup

Figure 1 shows the experimental setup used for the present work. It consists of a transparent polycarbonate unbaffled vessel of 165 mm in diameter and 210 mm height. A Rushton turbine was used as radial discharge impeller for the experiments. The impeller was mounted on a rigid shaft driven by DC motor, which speed is set and controlled with a DC control. A non-contact tachometer was used for registering the agitation speed. The mixer frame was placed on a turning base, driven by a DC motor coupled to a gearbox. With this system, the video camera captured images at different angular positions from 1 to 360º. Due to the low rotational speed of the tank (0.0166 rpm), no effects were observed in the flow patterns in comparison to the ones obtained under static conditions. Also, technically it was easier to turn the tank instead of the camera.

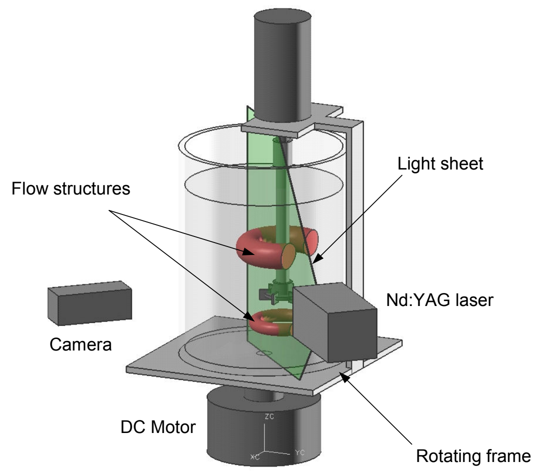

Fig. 1. Experimental Setup.

2.2. Flow visualization and fluids

Laser induced fluorescence (LIF) was used in this work for visualization of different planes of the flow structures in the stirred vessel as the frame rotates. The working fluid was an aqueous solution of pure glycerine (99.5% USP) with a density of 1250 kg/m^3 and a viscosity of 1.41 Pa·s. The tracer solution was prepared with 15 mg of rhodamine 590 dissolved with 50 ml of pure glycerine and the solution was added to the tank. A thin light sheet, generated by a Nd-YAG laser was passed through the vessel. A Canon EOS Rebel digital camera was placed perpendicularly to the laser sheet. Once the hydrodynamic steady conditions were reached into the tanks and the flow structures generated by the impeller, a sequence of images were acquired while the frame was turning, permitting to reveal the detailed distribution of the tracer in the flow. For all experiments, the tank was allowed to sit overnight to eliminate air bubbles that might have been entrained during filling. Mixing experiments were performed at room temperature (24°C).

2.3. Image processing

While the tank was turning (1 to 360º), the flow structures into the stirred vessel were recorded (DVD format) for several seconds (around 20 seconds for a whole turn) with the digital video camera at a rate of 30 frames per second. The recorded video sequence was converted to a digital movie file (.avi format) using a public domain DVD to VCD AVI DivX Converter v3.2 program. In order to create a three dimensional image of the pseudocaverns, the following steps were performed. We sampled the original video to obtain a reduced number of images for a selected angular resolution. For our experiments, one image each 6º showed acceptable results (60 images for the whole turn).

Once the sub-sampled movie was created, a geometric correction was applied to each image of the sequence in order to compensate the distortion introduced by the optical effect of the cylindrical acrylic tank surface. This optical deformation is produced along the horizontal axis, null at the centre of the tank (where the horizontal acrylic tangent is parallel to the focal plane defined by the camera) and more prominent as this tangent tends to be orthogonal to this focal plane. To correct this optical deformation, a regularly spaced metal grid was introduced in the tank, perpendicular to the optical axis of the TV camera, Figs. 2(a) and (b). The horizontal width of each cell was measured to generate the corresponding real pixel size as a function of its horizontal position within the tank. This grid was used to correct the images, by applying to the original images the inverse deformation function extracted from the optically deformed grid as seen in Figs. 2(c) and (d).

Once the images were corrected, the contours of the pseudocaverns were isolated semi-automatically from each slice. As a result of this procedure, we created a set of binary images containing white masks corresponding to the segmented pseudocaverns on a dark background as shown in Figs. 2(c) and (d). Then, we transferred this sequence of slices to the 3D constructor program v.5.1 (Media Cybernetics, USA) to view the three dimensional shape of the pseudocaverns. Quantitative data including the volume of pseudocaverns are available from this reconstruction. The procedures were achieved in a Pentium IV, PC computer, under Windows XP.

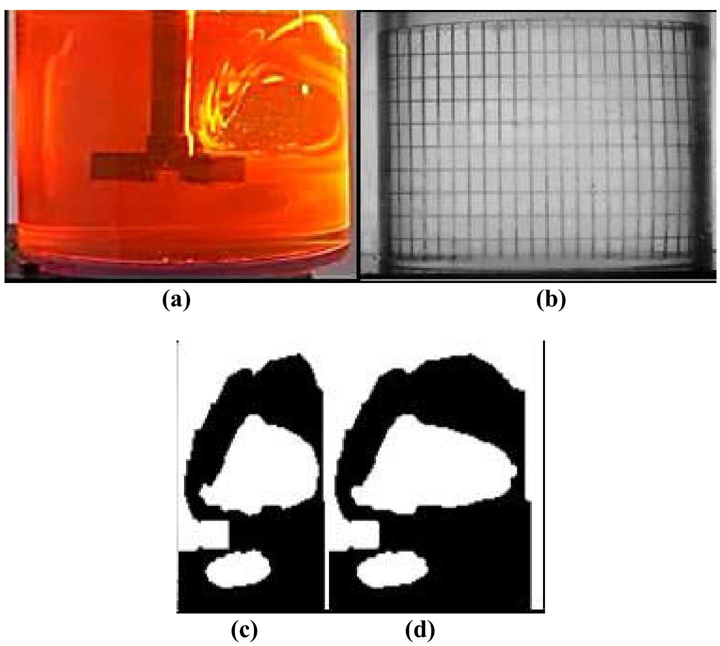

Fig. 2. Cross-Section of Flow Structures Revealed with LIF.
(a) Tank, (b) Grid for Image Correction,
(c) Uncorrected Image, (d) Corrected Image.

3. Three Dimensional Reconstruction of Pseudocaverns

For visualization purposes, the impeller was eccentrically positioned at 5 mm from the vessel centreline and it rotated at 40 rpm (Re = 1.8). The rhodamine was initially supplied at the free surface, near the shaft. The mixer frame rotated at 1.5 rpm allowing the video system to capture a sequence of pictures at different positions in the azimuthal direction. An example of the flow patterns observed with LIF is shown in Fig. 2. The images were obtained 2 min after the onset of the stirring process or approximately 70 turns of the impeller. The obvious structure displayed by this visualization technique is the cross-section of two sets of nested torii, one above and one below the impeller, forming the familiar pseudocaverns. The flow moves radially outward from the paddle and turns near the wall, branching in an upper and lower directions. The flow moving upwards generates a counterclockwise rotating toroidal vortex as is clearly seen in Fig. 2. The flow moving downwards forms a smaller toroidal clockwise vortex.

Figures 3 and 4 show the three dimensional reconstructed geometry of the well-mixed region and its corresponding pseudocaverns with the technique described before. The path of the rhodamine in the fluid forms the external and internal boundaries of the pseudocaverns, and the integration of the two dimensional slices to reconstruct the three dimensional structure yield the volume of the pseudocavern. The rhodamine distributes itself along well defined lines which stretch and fold generating efficient stirring in some regions, specifically near the zone where the shaft and the disk that holds the paddles meet. In contrast, the rhodamine does not flow into the core of the pseudocavern, suggesting that this region is poorly mixed, probably indicating the presence of an island. For illustration purposes, the torii formed above and below the Rushton turbine were cut and extended, which allows observing that the upper pseudocavern exhibits an azimuthally dependent internal radius as a consequence of the eccentric placement of the impeller.

The structures displayed in Fig. 3 show irregular boundaries suggesting the presence of local secondary structures. Descriptive geometrical properties can be extracted from these figures. The position of the centroid with respect to the center of the agitation shaft of the upper and lower pseudocaverns, averaged over the azimuthal angle are 60 mm and 43 mm, respectively, while the diameter of the upper and lower pseudocaverns, also averaged over the azimuthal angle are 57 mm and 26 mm, respectively.

From the information contained in the reconstruction, it is possible to extract the quantitative data displayed in Table 1. For instance, it can be asserted that the ratio of the volume of the upper to lower pseudocaverns is roughly 3:1 while the volume to area ratio is less than two. Also, it was found that for the present observation, the well mixed volume as defined by the pseudocavern structure is about 2/3 of the total volume. The sphericity of the cylinder that results from unfolding the torus is approximately 0.7, which is about 25% smaller than that of an ideal cylinder.

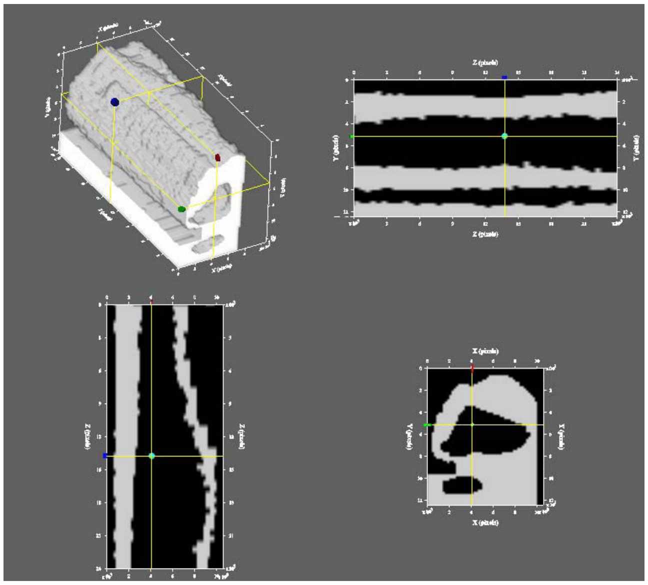

Fig. 3. Flow Structures Formed above and below the Impeller after Image Processing. They are Extended for Showing the Irregular Shape along their Volumes.

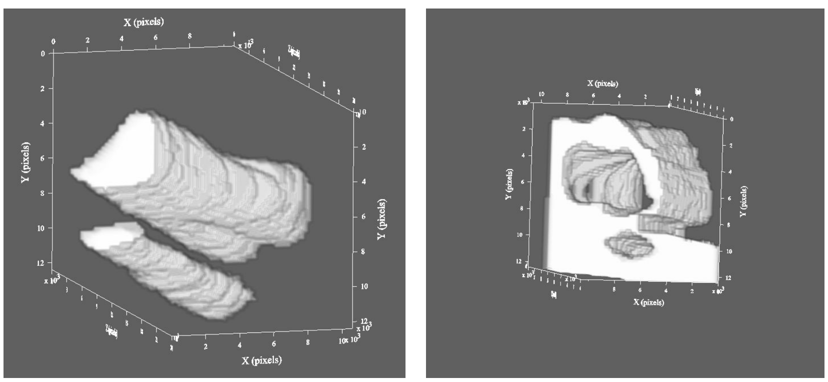

Fig. 4. 3D Shape of a Well Mixed Region and the Shape of its Corresponding Caverns.

Table 1. Geometric Features of the Flow Structures from Fig. 3. Percentages are Referred to the Total Volume or Surface Occupied by the Working Fluid in the Vessel.

Object	Volume %	Surface Area %	Volume/ Area	Sphericity
Upper cavern	23	35	2.1	0.74
Lower cavern	7	17	1.3	0.71
Total well-mixed	64	55	1.9	0.5
Total not well-mixed	36	45	2.6	-
Ratio well/not well mixed	1.8	1.2	1.5	-

4. Conclusions

A three-dimensional image processing technique was developed for reconstructing the well-mixed regions (pseudocaverns) generated under laminar regime by a Rushton turbine eccentrically placed in a stirred vessel containing a Newtonian fluid. Such a technique allowed creating the volume of torii formed above and below the impeller. This technique is a powerful tool for the precise determination of geometric features of flow structures with the aim of analysing the performance of the mixer system. This technique can also be used for determining the volume of the well-mixed regions generated with non-Newtonian fluids.

Acknowledgments

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