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PIV measurements and POD analysis as a tool to study mixing of non-Newtonian fluids in stirred vessels

J.-C. Gabelle[1,2,3,5], A. Liné[1,2,3], J. Morchain[1,2,3], D. Anne-Archard[3,4], F. Augier[5]
[1]Université de Toulouse, INSA, UPS, INP; LISBP; 135 Avenue de Rangueil, F-31077 Toulouse, France.
tel. +33 (0)5 6155 9786, e-mail: alain.line@insa-toulouse.fr; fax: +33 (0)5 6155 9776.
[2]INRA UMR792 Ingénierie des Systèmes Biologiques et des Procédés, F-31400 Toulouse, France.
[3]CNRS ; Fédération de Recherche FERMAT ; F-31400 Toulouse, France.
[4]Université de Toulouse ; INPT, UPS ; IMFT (Institut de Mécanique des Fluides de Toulouse), Allée Camille Soula, F-31400 Toulouse, France.
[5]IFP Energies nouvelles, Rond-point de l'échangeur de Solaize, BP3, 69360 Solaize, France.

In bioprocess, the stirred tank reactor is often chosen to perform reaction operations or blending because it offers high mixing and mass transfer capacities. Most of the previous works on this topic are concerned with Newtonian fluids. But industrial fluids such as fermentation broths are hardly ever Newtonian. Although there has been recent progress, there are still a lot to understand about physical mechanism, especially with non-Newtonian fluids. This lack of knowledge can lead, sometimes, to erroneous design and scale-up.

2D-PIV measurements were performed in a 70 L stirred tank equipped with four equally spaced baffles. A Rushton turbine (D/T = 0.33) was used and driven at three volumetric power draws (82, 212 and 384 $W \cdot m^{-3}$, corresponding to Reynolds numbers 85, 145 and 200). Measurements were successively performed on four rectangular areas (9x7 cm^2): one in the impeller stream, one under the stirrer and two above. The yield stress shear thinning fluid Carbopol 980 (0.08 %) (Noveon Canada Inc., Waterloo, ON) was used. It offers good transparency even at high polymer concentration.

Rheological parameters of the Herschel-Bulkley model were identified using a Haake Mars III rheometer (Thermo Scientific, Germany). A serrated plates geometry (P60/Ti L) was used to avoid wall slip effect at low shear rate.

The PIV system used in this study consisted of a laser and an image acquisition system provided by LaVision (LaVision GmbH, Goettingen, Germany). The system includes a Nd-Yag laser (Quantel, 10 Hz, 2 × 200 mJ), a synchronization system and a CCD camera (Imager Intense, 12 bits, 1376×1040 $pixels^2$). Fast Fourier transform (FFT) cross correlation was used to examine the two images, which are divided into interrogation area (16×16 $pixels^2$). For all experiments, 400 − 1000 image pairs are recorded and statistical convergence of the velocity is checked. In order to study the influence of spatial resolution in the vicinity of the impeller, two spatial resolutions Δx were tested (0.7-1 mm). The delay between each frame in an image pair Δt was chosen in relation to the agitation speed and the medium (range: 200 to 3000 μs).

A Proper Orthogonal Decomposition (POD) was used. It is a linear procedure which decomposes a set of signals into a modal base (Lumley 1967). POD is proven to be a complementary analysis tool to identify organized motion in a stirred tank (Doulgerakis et al. 2011; Moreau & Liné 2006; Tabib & Joshi 2008). This tool allows separating the different motions without the necessity to collect angular phased data (Moreau & Liné 2006). POD is carried out using snapshot method with 700 "non-conditioned" instantaneous velocity fields

directly calculated from the measurements. The result is then an orthonormal basis of eigenfunctions and the associated eigenvalues. Moreover the energy brought by the three first modes is about 92% to 97% of the total energy. Mode 1 is structurally closed to the average velocity field (Figure 1.a, classical result with the instantaneous velocity fields containing mean contribution). The second and third eigenvalues are almost equal thus involving that the energy brought by these modes is the same. These two modes reveal large scale rotating structures (Figure 1.b).

The instantaneous velocity field is projected on each POD modes. The value of this projection gives a good evaluation of the square root of the energy of the instantaneous flow contained in the corresponding mode. From these projections it is possible to reconstruct the velocity field. As shown in the presentation, three modes seem to be sufficient to reproduce the hydrodynamics of Carbopol 980 flow.

Finally, the velocity field is then post processed to determine the size of the cavity, characteristic of such flow pattern (Elson et al. 1986).

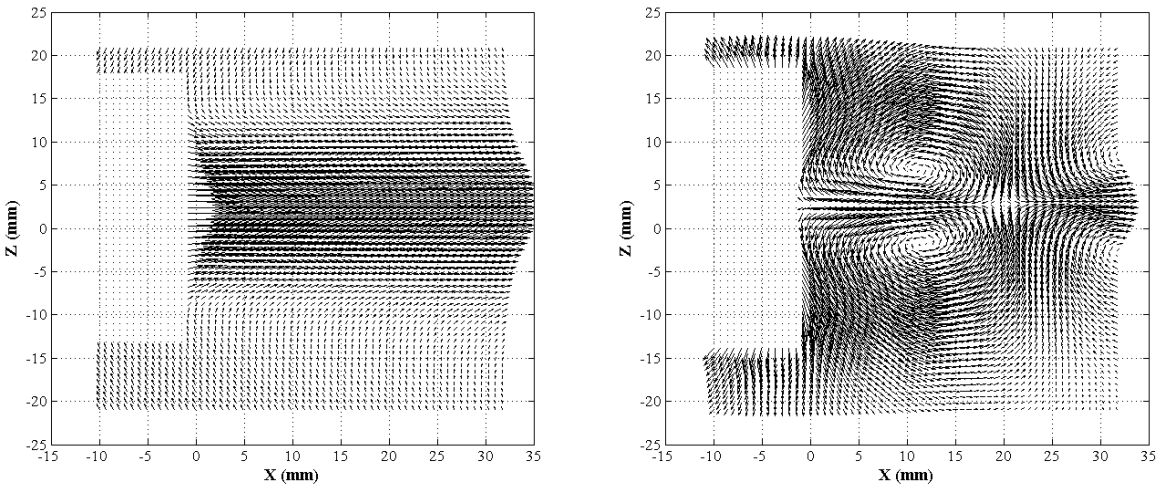

Figure 1: Vector plot of the velocity field associated with: a) 1st mode, b) reconstructed field based on 2nd and 3th modes (Re = 85, in the impeller steam).

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