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Macro-instabilities in Eccentrically Agitated Vessels

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Laser Doppler anemometry and flow visualisation are used to shed light into the main turbulent flow features of an unbaffled vessel stirred by an eccentrically positioned Rushton turbine. Two main vortices, one above and one below the impeller, are present and the former vortex dominates the flow field, driving a strong circumferential flow around it. The vortices are not steady but oscillate slowly and periodically inducing a kind of flow instabilities, which may have a significant impact on macro-mixing. The characteristic frequencies of such flow instabilities were found to increase with reducing the impeller blade thickness, thus it is argued that their origin is related to the interaction between the impeller discharged stream and the vessel wall/bottom.

1. Introduction

Recent investigations of the flow motions inside stirred vessels have indicated that different types of flow instabilities occur inside stirred vessels and may have significant impact on macro-mixing. The graph of Fig. 1 suggests a possible classification of flow instabilities in stirred vessels.

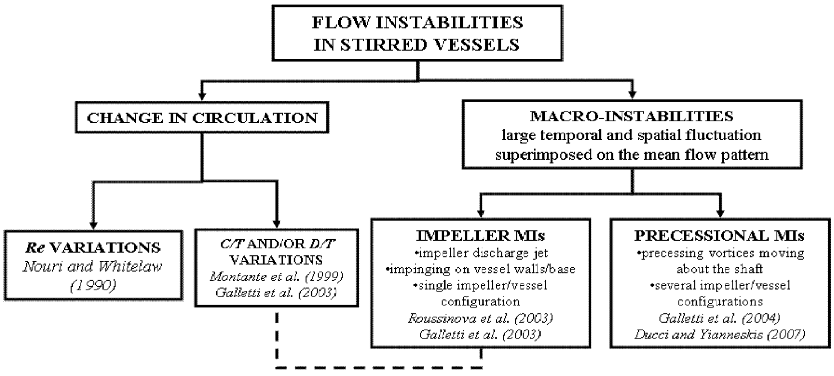

Fig. 1 – Proposed classification of macro-instabilities.

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A first kind of flow instability (LHS of the diagram of Fig. 1) manifests itself as a real change in the circulation pattern inside the tank. Two main sources of such change have been identified: a variation of the Reynolds number (e.g. Nouri and Whitelaw, 1990) or a variation of the impeller/vessel geometrical configuration (e.g. Montante et al., 1999, Galletti et al., 2003).

Another kind of instability (RHS of Fig. 1) reveals as large temporal and spatial variations of the flow superimposed to the mean flow patterns, thus such flow instabilities have been called "macro-instabilities" (MIs). Large attention has been addressed to them, because it was proven that MIs may have beneficial implications for mixing process operation and efficiency as such flow motions can enhance mixing through mean-flow variations. Even though MI features have been extensively investigated (for instance some studies indicate MI frequency variation with impeller rotational speed, flow regime, impeller to tank diameter ratio, etc.), the origin of such instabilities in not fully clarified; the graph of Fig. 1 shows an attempt of classification.

Two whirlpool-type vortices extending from the impeller to the top/bottom of the vessel, and moving precessionally about the shaft, were observed to induce macro-instabilities (precessional MIs, Galletti et al., 2004, Ducci and Yianneskis, 2007). Such instabilities are present in a vessel at all times and for most configurations. The frequency f of the macro-instabilities was found to be linearly related to the impeller rotational speed N with f/N = 0.015-0.020.

A different type of macro-instabilities is thought to originate from the interaction between the impeller discharged stream and the vessel boundaries (impeller MIs). Such instabilities occur only for some vessel/impeller combinations. They may be present constantly as the flow instabilities with f/N = 0.186 observed by Roussinova et al. (2003) for a PBT in the so called "resonant" geometry (impeller diameter D/T = 0.5, impeller clearance C/T = 0.25) or intermittently with f/N = 0.12 as pointed out by Galletti et al. (2003) for a D/T = 0.3 Rushton turbine set in a certain range of clearances for which a transition in the circulation pattern occurs.

To make things more complex, different types of MIs may coexist at the same time in a stirred vessel (Galletti et al., 2005).

Even though the importance of MIs is well recognized, little is known about their presence in vessel configurations different from the baffled with centric agitation one. For instance there is lack of data on eccentric agitation for turbulent flows, albeit this operation mode is proposed in the industrial practice in alternative to baffles to break the primary vortex (e.g. paint and food processes, Karcz et al., 2005).

In a recent work Galletti and Brunazzi (2008) pointed out with laser Doppler anemometry (LDA) and flow visualisation, the presence of flow instabilities in a vessel agitated eccentrically by a D = T/3 Rushton turbine placed at e/T = 0.21 and C/T = 0.33. Such macro-instabilities were found to be rather strong with an energetic content up to 52% of the turbulent kinetic energy: therefore their impact on the macro-mixing is relevant; moreover they have to be taken into account when evaluating real turbulence levels (Nikiforaki et al., 2003) for the determination of micro-mixing parameters.

In the present paper the analysis of Galletti and Brunazzi (2008) is extended by investigating the effect of geometrical parameters such as impeller blade thickness on macro-instabilities in order to gain insight into the mechanism triggering them, with particular reference to the classification of Fig. 1.

2. Experimental apparatus and method

Measurements were performed in a cylindrical vessel made of Perspex with inner diameter T = 290 mm. The vessel was filled with distilled water up to a height H = T and was covered with a lid (equipped with plugs of different sizes) in order to avoid air entrainment. The agitation was provided by a standard Rushton turbine with D = T/3, positioned in a off-axis location, at e/T = 0.21 from the vessel axis. The impeller off-bottom clearance was C = T/3. Impellers with two different blade thickness to diameter ratios were used, i.e. $t_b/D = 0.01$ and 0.05. The stirred vessel is depicted in Fig. 2.

The impeller was driven by a 0.3 kW power motor and a speed controller was used to vary the agitation speed. In particular the investigated impeller rotational speed ranged from N = 150 to 400 rpm, corresponding to impeller Reynolds number between Re = 23,300 and 62,300.

A single–component laser Doppler anemometer by Dantec operating in back scatter mode was used to acquire velocity data in several locations across the vessel. A detailed description of the experimental apparatus is reported in Galletti and Brunazzi (2008).

Frequency analysis based on fast Fourier transforms (FFTs), through subroutines available in the Matlab software package, was applied to the velocity recordings. The resampling of velocity-time data was performed using the "nearest neighbour" technique with a resampling frequency equal to the mean data rate.

Flow visualisation experiments were carried out by allowing some air to be entrained into the flow field through plugs in the lid, in order to trace the flow with bubbles.

A commercial digital video camera capturing at 25 frames per second was used to record flow visualisation experiments.

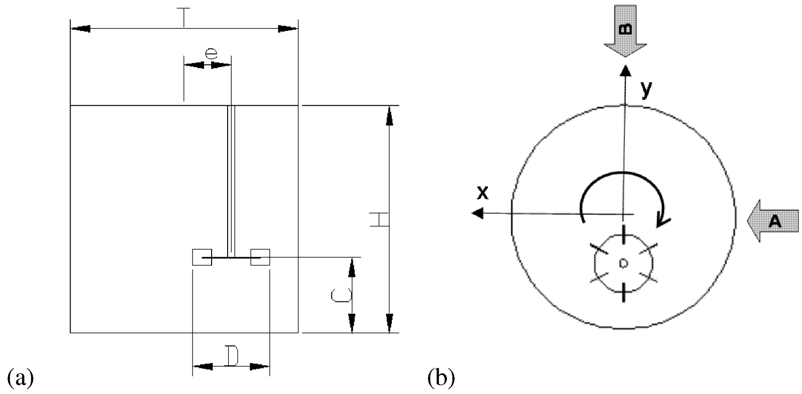

Fig. 2 – Scheme of: (a) agitation system; (b) reference coordinate system (the impeller rotates clockwise when seen from above). z is the vertical coordinate measured from the vessel bottom.

3. Results

Fig. 3 shows a frame taken from flow visualisation experiments performed with the $t_b/D = 0.01$ impeller. Two vortices are visible, one departing from above the impeller towards the top of the vessel and one originating from the impeller blades towards the vessel bottom.

The upper vortex was observed to dominate all vessel motion, leading to a strong circumferential flow around it. Such vortex moves slightly and in a periodic manner, originating a kind of flow instabilities (Galletti and Brunazzi, 2008). These are well visible from the periodic oscillations of the velocity-time series reported in Fig. 4a. The solid line was obtained by a window-moving average technique: approximately 7 and half cycles are present within 10 s of time interval, corresponding to a frequency f = 0.75 Hz (and non-dimensional frequency f/N = 0.15). The frequency analysis of Fig. 4a confirms the presence of a dominating periodic component with f/N = 0.155, thus in good accordance with the visual observation of the time series. Moreover an analysis of the energetic content due to the MIs periodic component indicates that it is 46 % of the turbulent kinetic energy. This value is very large indicating a significant potential impact on macro-mixing.

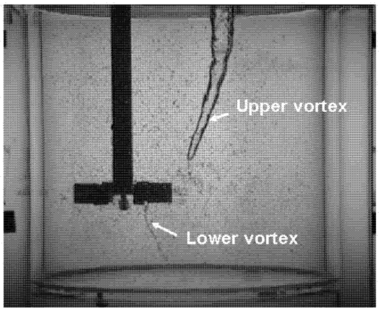

Fig. 3 – Frame taken from flow visualisation experiment at N = 400. View from A of Fig. 1b.

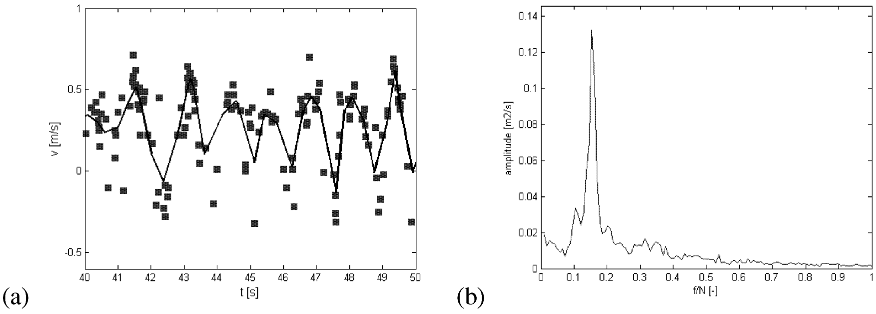

Fig. 4 – (a) time series and (b) frequency spectrum of velocity data taken at $z/T = 0.4$, $x/T = 0.02$, $y/T = 0$, $t_b/D = 0.01$, N = 300 rpm.

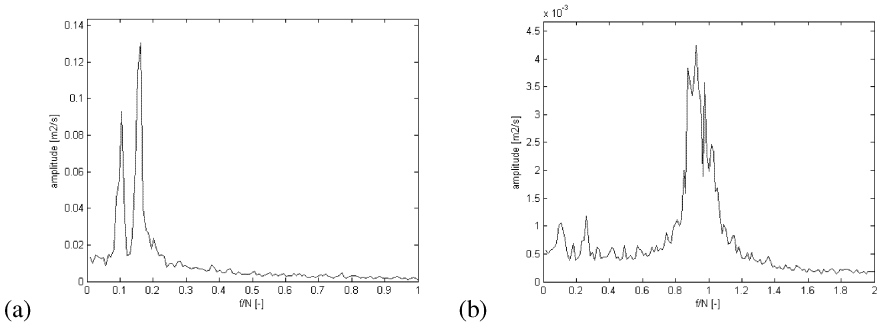

Fig. 5 – frequency spectrum of velocity data taken at (a) $z/T = 0.1$, $x/T = 0$, $y/T = -0.12$, (b) $z/T = 0.6$, $x/T = 0.31$, $y/T = 0$. $t_b/D = 0.01$, $N = 300$ rpm.

The f/N = 0.155 peak was visible in many locations. However more frequency components were identified. For instance Fig. 5a shows a frequency spectrum obtained from the analysis of velocity data taken below the impeller: two main frequency peaks are visible: f/N = 0.105 and f/N = 0.155. These are related to the movements of the lower and upper vortices, respectively.

Ultimately, a higher frequency component, with f/N = 0.94 was observed in a few locations (see Fig. 5b). Such component could be explained by vortex shedding phenomena originating from the flow–shaft interaction in eccentrically agitated systems, (see analysis of the characteristic frequencies in terms of the Strouhal number in Galletti and Brunazzi, 2008).

As far as the effect of the blade thickness is concerned, it was found a reduction of the upper vortex frequency from f/N = 0.155 to f/N = 0.144 when increasing the impeller blade thickness from $t_b/D = 0.01$ to $t_b/D = 0.05$. This may help elucidating the origin of MIs in eccentric agitated vessels. Actually, the eccentric position of the shaft and the consequently reduced distance between the impeller blade tip and the vessel boundaries, is likely to enhance the strength of the impeller discharged stream – wall interaction. In such a case, resulting flow instabilities will show a frequency which is expected to increase with increasing the velocity of the impeller discharged stream, thus with decreasing the blade thickness (Rutherford et al., 1996). This is in accordance with findings of the present work. An analysis on impeller MIs in terms of flow number (see Paglianti et al., 2006) is difficult to be performed as LDA measurements on this configuration indicated a variation of discharged velocity profiles with the angular position with respect to the impeller.

To confirm the above hypothesis on MIs in eccentrically agitated vessels, it is worth observing that values of f/N found are more similar to frequencies typical of flow instabilities originating from the interaction between the impeller stream and the vessel boundaries (f/N = 0.186 from Roussinova et al., 2003, or f/N = 0.12 from Galletti et al., 2003) rather than of precessional MIs (f/N = 0.02 from Ducci and Yianneskis, 2007).

4. Conclusions

Macro-instabilities in an eccentrically agitated vessel have been studied with laser Doppler anemometry and flow visualisation.

The characteristic frequency of such flow instabilities was found to decrease with increasing impeller blade thickness, indicating that they may origin from the interaction between the impeller discharged stream and the vessel boundaries (impeller MIs).

Importantly such macro-instabilities are rather energetic with possible effect on macro-mixing. For this reason future work will be devoted to confirm and quantify this feature, in order to exploit flow instabilities for mixing time reduction as for instance an appropriate selection of the reactants insertion point.

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