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# Effect of eccentricity on laminar mixing in vessel stirred by double turbine impellers

Szymon Woziwodzki*, Łukasz Jędrzejczak

*Department of Chemical Engineering and Equipment, Poznan University of Technology, pl. M. Sklodowskiej-Curie 2, 60965 Poznan, Poland*

## ABSTRACT

Laminar mixing is often conducted in industrial processes, for example in polymerization reactors or in biotechnological processes. The laminar flow conditions caused problems of inefficient mixing due to some mixing anomalies like occurrence of the isolated mixing regions (IMR), segregation or compartmentalization phenomena. In this paper, flow visualization experiments are used to examine the size, positions and structure of the IMR regions as a function of Reynolds number and eccentricity ratio in the vessel equipped with double turbine impellers. It was found that the eccentricity brings deformation and reduction of the IMR volume. Moreover another benefit of using eccentrically located impeller systems is an improvement of axial flow. Two types of IMR regions are found: undulated IMR (UIMR) and ribbon-like IMR (RIMR). The structure of IMR depends on the eccentricity ratio defined as $E/R$. At the low eccentricity values the structure of single filament wrapped around core of the IMR is found. Additionally, the IMR region is inclined to the impeller plane.

*Keywords:* Laminar mixing; Stirred vessel; Eccentricity; Segregation; Compartmentalization

## 1. Introduction

Mixing is a unit operations commonly found in chemical and biochemical (biotechnological) industries. Especially multi-impeller systems are in the point of interest, because of the advantages of the longer residence time, lower decrease of heat exchange area in scale-up treatment, lower power consumption per impeller as compared to single-impeller systems, higher mass transfer coefficient in comparison to single impeller vessels. Usually mixing is carried out in the turbulent flow regime but sometimes this flow regime is not recommended. Laminar mixing is often conducted in the polymerization reactions and biotechnological applications. In case of biotechnological processes, the laminar flow regime is recommended for cells growth to guarantee adequate mixing. However, the laminar mixing faces many problems. One of them is the presence of segregated regions.

The mixing system can be divided up into two regions: active mixing regions (AMR) and isolated mixing regions (IMR) (Bresler et al., 1997). In the AMR regions mixing is fast and this regions must dominate in the whole volume of vessel. The IMR regions do not easily exchange material with outside active mixing regions AMR, and they are obstacles to global mixing. The IMR regions, usually have a toroid shape, but there are also other shapes of isolated regions e.g. elliptic islands (Bresler et al., 1997). Nevertheless, these regions are isolated from the rest of the system, they have good internal mixing. Mixing within these regions is significantly weaker than in the AMR regions. Various aspects of laminar mixing in stirred tank have been previously studied (Lamberto et al., 1996, 1999, 2001; Harvey et al., 2000; Zalc et al., 2001; Makino et al., 2001; Alvarez et al., 2002a,b, 2005; Arratia et al., 2004; Cabaret et al., 2008a,b). Lamberto et al. (1996, 1999) found the toroid-shaped segregated regions, above and below the impeller, which exchanged material with the AMR regions through diffusion. The IMR regions were formed in the single impeller system as well as at the multiple impellers, and the presence of these regions is independent of impeller type. Lamberto et al. (1999) also found that the positions of toroid-kind IMR regions depend on Reynolds number. Harvey et al. (2000) found

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* Corresponding author at: Department of Chemical Engineering and Equipment, Faculty of Chemical Technology, Poznan University of Technology, Poznan PL 60-965, Poland. Tel.: +48 616652147; fax: +48 616652789.
E-mail address: szymon.woziwodzki@put.poznan.pl (S. Woziwodzki).

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**Nomenclature**

| | |
|---|---|
| $D$ | impeller diameter (m) |
| $D_{\mathrm{shaft}}$ | shaft diameter (m) |
| $E$ | eccentricity, i.e. distance of the shaft from the vessel axis (m) |
| $H$ | liquid level (m) |
| $N$ | impeller rotational speed ($s^{-1}$) |
| $P$ | impeller power input (W) |
| $Po_{\mathrm{m}}$ | mixing power number, $Po_{\mathrm{m}} = PN^{-3}D^{-5}\rho^{-1}$ |
| $Pt_{\mathrm{m}}$ | mixing energy (Ws) |
| $R$ | tank radius (m) |
| $r^*$ | radial position of segregated regions (cm) |
| $Re_{\mathrm{m}}$ | impeller Reynolds number, $Re_{\mathrm{m}} = ND^2\rho\mu^{-1}$ |
| $T$ | tank diameter (m) |
| $t$ | time (s) |
| $t_{\mathrm{m}}$ | mixing time (s) |
| $V$ | volume fraction of segregated regions ($m^3\,m^{-3}$) |
| $y^*$ | axial position of segregated regions (cm) |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | angle of inclination (°) |
| $\mu$ | dynamic viscosity (Pa s) |
| $\rho$ | density ($kg\,m^{-3}$) |

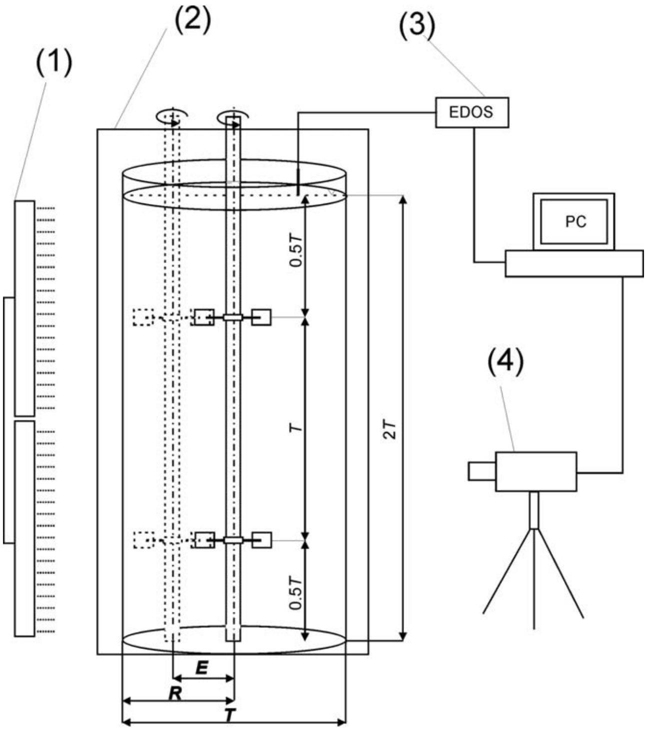

**Fig. 1 – Experimental set-up. (1) lights, (2) vessel, (3) injection device (Eppendorf EDOS 5222), (4) camera.**

that the internal structure of the IMR (KAM toroid) is similar to the Poincare sections. Harvey et al. (2000) have shown that the relative impeller size and spacing can be altered so as to increase the size of the AMR. Lamberto et al. (2001) also found that Poincare sections of the flow reveal a complex internal structure of such regions. Laminar flow in a stirred vessel equipped with three Rushton turbines on common shaft were investigated by Zalc et al. (2001). They found six recirculation loops. The size and locations of segregated poor-mixing regions are very similar to the Poincare sections and depend on the Reynolds number. An increase in Reynolds number caused decrease in the number of IMR regions. Lamberto et al. (1996) and Makino et al. (2001) found that the structure of IMR is more complex. Lamberto et al. (1996) found the system of stable filaments wrapped around a well defined torroidal core. Lamberto et al. (1996) found the system of five filaments whereas Makino et al. (2001) found three filaments. The identification of swirling filaments around torroidal core is very difficult, therefore Makino et al. (2001) have not observed that filaments wrapped around core. Moreover, Makino et al. (2001) have shown that mixing in the AMR regions depends on secondary circulation flow and periodical perturbations caused by rotating turbine blade. Alvarez et al. (2002a) investigated the creation of structure and the emergence of mixing patterns in stirred tanks by tracer experiments. According to these investigations the main fluid stream is convected toward the impeller, after which is expelled by the blades toward the tank walls in the pattern of nested spirals, and near the walls it formed envelopes, that surrounded and enclosed the regular region. In the multiple impeller system tracer is transported down around the shaft and then is spreading according to the above mechanism. Alvarez et al. (2005) investigated the existence of flow compartmentalization especially in the multiple impeller systems. Compartmentalization in these systems imposes severe mass transfer limitations, particularly when controlling the pH or oxygen concentration. Moreover they found another mixing anomaly like cell focusing or fluid shortcuts. Arratia et al. (2004) investigated laminar mixing in continuous stirred tank reactors. They have shown that, similarly to batch mixing, the segregated and chaotic regions occur.

There are few methods to eliminate the IMR regions. One of them is to introduce chaos in mixing system (e.g. eccentrically located impellers, unsteady mixing) or to design new asymmetric turbine impellers (Cabaret et al., 2008a). Many authors have shown that eccentricity is equivalent to baffling, in turbulent flow regime (Nishikawa et al., 1979; Medek and Fořt, 1985; Hall et al., 2004; Karcz and Cudak, 2006; Karcz et al., 2005; Szoplik and Karcz, 2004, 2008, 2009; Cudak and Karcz, 2008; Montante et al., 2006; Galleti and Brunazzi, 2008; Galleti et al., 2009; Woziwodzki et al., 2010). It is important to point out that only limited data is available to describe the effect of shaft eccentricity on the laminar mixing (Alvarez et al., 2002b; Ascanio and Tanguy, 2005; Cabaret et al., 2007, 2008a,b). In this paper, flow visualization experiments are used to examine the size, positions and structure of the IMR regions as a function of Reynolds number and eccentricity ratio in vessel equipped with double turbine impellers.

## 2. Methods and materials

Experimental set-up (Fig. 1) consisted of motor, inverter, speed sensor, PC computers, torquemeter, injection device (Eppendorf EDOS 5222) and camera. The vessel with diameter $T = 0.19$ m was equipped with flat bottom. The height of liquid level was taken $2T$. The two types of impellers were used (Fig. 2): Rushton turbine (RT) and six pitched-up blade turbine (PBT). The PBT impeller was pumping upwards liquid. Impellers were mounted on common shaft ($D_{\mathrm{shaft}} = 0.012$ m) in following configuration: RT–RT, PBT–PBT and PBT–RT. The following method for determining the configuration of impellers was adopted: down-up. This means that first impeller was