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Mixing of viscous Newtonian fluids in a vessel equipped with steady and unsteady rotating dual-turbine impellers

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ABSTRACT

This paper presents investigation on the possibility to improve the efficiency of mixing of the highly viscous Newtonian fluids in a vessel with utilization of unsteady rotating dual turbine impellers. Flow visualization experiments were used to examine the size, positions and structure of the IMR (Isolated Mixing Regions) regions as a function of Reynolds number as well as mixing time. Additionally, the effect of frequency of impellers' oscillation on mixing efficiency was examined. It was found that the use of unsteady forward–reverse mixing mode enhance the mixing efficiency in comparison to standard mixing (up to about eight times). The structure of IMR in the forward–reverse mixing is much more complicated than in standard mixing, because of liquid division into spiral-shape filaments. This had caused that dimensionless mixing time was up to about eight times shorter in comparison to standard mode.

Keywords: Mixing; Segregation; Chaos; Hydrodynamics; Imaging

1. Introduction

Mixing process is usually conducted in turbulent flow regime. However when high viscous fluids are mixed it is often carried out in the laminar regime. Laminar mixing faces many problems like segregation, compartmentalization, flow bypasses and cell focusing (Alvarez et al., 2005). These problems are mainly related to the homogeneity in the whole volume of the stirred vessel which can be divided into two regions. First region is called as the active mixing region (AMR) while the second one the isolated mixing region (IMR) (Bresler et al., 1997). In the AMR regions mixing is a fast process in contradiction to the IMR regions. The IMR regions are obstacles to global mixing, because these regions are isolated from the rest of the vessel, and material is exchanged with AMR regions through diffusion. The IMR regions usually have a toroidal shape (Lamberto et al., 1996, 1999, 2001), but there are also other shapes of isolated regions, e.g. elliptic islands (Bresler et al., 1997). The IMR regions are formed in the single impeller system as well as in the multiple impellers; however the presence of these regions is independent of impeller type.

There are a few methods to eliminate the IMR regions. First one is to introduce chaos in mixing system (e.g. eccentrically located impellers, unsteady forward–reverse mixing, and use of reciprocating impellers (Komoda et al., 2000, 2001, 2012; Hirata et al., 2007)) or to design new asymmetric turbine impellers (Cabaret et al., 2008a). The effect of eccentricity on laminar mixing was investigated in a few papers (Cabaret et al., 2007, 2008a,b; Alvarez et al., 2002; Woziwodzki and Jędrzejczak, 2011). It was found that eccentricity improves the axial mixing, directly shortening the mixing time. In this case, impellers generating axial flow were preferred (Woziwodzki and Jędrzejczak, 2011).

Various aspects of laminar unsteady mixing in stirred tank had been previously studied (Lamberto et al., 1996; Nomura et al., 1997; Yao et al., 1998; Dieulot et al., 2002, 2005; Kato et al., 2005; Yoshida et al., 2009). Efficient mixing can be achieved under low Reynolds numbers using time dependent

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Nomenclature

A	cross-sectional area of the IMR region (m^2)
b	height of impeller blade (m)
C_1, C_2	coefficients in Eq. (11) (dimensionless)
C_3, C_4	coefficients in Eq. (12) (dimensionless)
C_5, C_6, C_7	coefficients in Eq. (16) (dimensionless)
C_d	drag coefficient (dimensionless)
C_m	added mass coefficient (dimensionless)
CV	coefficient of variation (dimensionless)
D	impeller diameter (m)
f	frequency of oscillations (Hz)
H_L	liquid height (m)
N	impeller rotational speed (s^{-1})
N_{FR}	average impeller rotational speed (s^{-1})
N_{max}	maximal impeller rotational speed (s^{-1})
N_{min}	minimal impeller rotational speed (s^{-1})
P	mixing power (W)
P_{FR}	mixing power for forward–reverse mode (W)
R^2	coefficient of determination (dimensionless)
R_e	distance between centre of the ellipse and shaft axis
r_1	minor axis of ellipse (m)
r_2	major axis of ellipse (m)
S	segregation intensity (dimensionless)
T	vessel diameter (m)
T_s	torque (N m)
T_{FR}	torque for forward–reverse mode (N m)
t	time (s)
t_m	mixing time (s)
V	volume of torroidal IMR (m^3)
w	width of impeller blade (m)
x	radial coordinates (m)
z	axial coordinates (m)

Greek symbols

α	angle of inclination of the impeller blades (°)
μ	viscosity (Pa s)
ρ	density ($kg\,m^{-3}$)

Subscripts

FR	forward–reverse mixing mode

Abbreviations

PBT	pitched blade turbine
RT	Rushton turbine

fluctuations because fluctuation of impeller speed enhances mixing in stirred vessel (Lamberto et al., 1996). Using of unsteady mixing causes that location of IMR regions is changed due to oscillation of impeller speed. This process is similar to kneading bread dough, where the dough is stretched and folded repeatedly to create good mixing (Lamberto et al., 1996). Enhancement of mixing is explained by change in direction of impeller rotation is due to generation of chaotic flow, therefore leading to complete mixing (Nomura et al., 1997). Enhancement of global mixing is valid for radial, axial impeller and low-speed impellers (Dieulot et al., 2002, 2005). Also, the frequency of oscillation and amplitude may have a beneficial effect on increasing the mixing efficiency (Yoshida et al., 2009), but an effect of oscillation frequency on mixing efficiency is still ambiguous. Yao et al. (1998) found that increasing of oscillation frequency caused shortening in dimensionless mixing time, while Yoshida et al. (2007) investigation revealed that smaller oscillations frequency is more efficient. Numerical studies by Sun et al. (2009) confirm that the mixing rate is worse when the cyclic period is shorter. Takahashi et al. (2011) investigated forward–reverse and time periodic fluctuations of rectangular wave of impeller speed and pointed that forward–reverse motion of impeller could enhance the global mixing.

The knowledge about unsteady mixing with forward–reverse rotating impellers is still incomplete. The previous studies have shown that in turbulent flow regime forward–reverse mixing proceeds more uniformly within the vessel but the high shear level of forward–reverse mixing mode increases the mixing time and mixing power (Woziwodzki, 2011, 2013). Greater power consumption, in comparison to standard mixing, could cause limited use in industrial applications. However studies by Tezura et al. (2007, 2008) indicate that turbulent forward–reverse mixing can be use in particle solid–liquid systems to enhance mass transfer. Also Yoshida et al. (2008) showed that use of forward–reverse mixing results in increase of gas–liquid mass transfer.

Most of the previous studies focused on sinusoidal time-course of impeller speed (Yao et al., 1998; Kato et al., 2005; Yoshida et al., 2009, 2010). Use of such characteristics could be difficult in industrial applications; therefore it should be proposed special mechanism for angular rotations (Yoshida et al., 2001).

In this work author proposes use of triangular time-course of impeller speed. The use of such characteristics allows easy programming of inverters with curve generator in industrial applications. The curve generator provides a cyclically processed reference curve that is to be configured by setting reference values and time. In this work, mixing of the liquid phase in the unbaffled vessel agitated by forward–reverse and unidirectional rotating impeller was investigated experimentally for Newtonian liquids with high viscosities. At first, the impeller power characteristic was evaluated and then the homogeneity degree in the mixing process was expressed.

2. Materials and methods

Experimental set-up (Fig. 1) consisted of motor, inverter (pDrive MX Eco by Schneider Electric Company), PC computer, thermostat (Polyscience 5012) and camera (Canon EOS 1D Mark III and Casio Exilim FX-F1). The vessel, made from Plexiglas, with diameter $T = 0.19$ m was equipped with flat bottom. The height of liquid level H_L was taken $2T$. The two types of impellers were used: Rushton turbine (RT) and six pitched-up blade turbine (PBT). The height of the impeller blade b for PBT was $b/D = 0.125$ and for the RT impeller $b/D = 0.2$. The blade width w for the RT impeller was $w/D = 0.25$ and for PBT $w/D = 0.385$. The pitch angle α of PBT impeller blades was 45°. Impellers were mounted on a common shaft ($D_{shaft} = 0.012$ m) in following configurations: 2RT, 2PBT and RT-PBT (RT as upper impeller and PBT as lower one). The ratio of impeller diameter ($D = 0.065$ m) to vessel diameter was equal to $D/T = 0.342$. The bottom clearance of the lowest turbine was $T/2$ and the spacing between turbines was chosen T, which is the safe distance to prevent hydrodynamic perturbation. The working viscous Newtonian fluid was the 98% solution of glycerol ($\mu = 1.12$ Pa s, $\rho = 1220\,kg/m^3$). The cylindrical vessel was installed in second rectangular water-filled vessel in order to minimize optical