Chemical Engineering Science 104 (2013) 960–974

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Laminar mixing performances of baffling, shaft eccentricity and unsteady mixing in a cylindrical vessel

K.C. Ng [a],*, E.Y.K. Ng [b]

[a] Center of Advanced Computational Engineering (CACE), Department of Mechanical Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50, Nanyang Avenue, 639798, Singapore

HIGHLIGHTS

- Difference in mixing mechanism for various mixing procedures.
- Dependence on number of secondary vortices in promoting mixing.
- More uniform intensification of radial mixing for unsteady mixing procedure.

ARTICLE INFO

Article history:
Received 22 July 2013
Received in revised form
8 October 2013
Accepted 15 October 2013
Available online 23 October 2013

Keywords:
Moving Particle Semi-implicit (MPS)
Laminar mixing
Baffle
Eccentricity
Unsteady mixing

ABSTRACT

The laminar mixing performance in a cylindrical vessel agitated by a plate impeller is investigated. Several mixing enhancement strategies such as baffling, shaft eccentricity and angularly-oscillating impeller (unsteady mixing) are considered. The flow equations are solved numerically via a Lagrangian particle method based on the Moving Particle Semi-implicit (MPS) technique. It is observed that radial mixing is poor in an unbaffled vessel agitated by a concentric impeller undergoing steady rotation. In general, baffling has marginally improved the radial momentum exchange between the near-wall and inner fluid particles. This shortcoming can be alleviated by introducing the shaft eccentricity and the unsteady mixing procedure. In general, the unsteady mixing procedure with the smaller oscillating amplitude outperforms all the mixing enhancement strategies considered in the current study.

1. Introduction

In general, there are two types of mixing strategies commonly adopted in industrial practice: continuous mixing and batch mixing. A common example of the former strategy is the static mixer whereby chaotic mixing is achieved via forcing the fluid particles past the non-moving elements. In contrast, batch mixing is normally accomplished by agitating the flow with a rotating impeller (or multi-impeller system). While a lower mixing time can be expected by using continuous mixing once it is calibrated properly, it is normally designed for a specific application and the system may be recalibrated once the mixing of different ingredients is required. Batch mixing, however, offers greater flexibility in this aspect.

In order to enhance the mixing rate of batch mixing procedure, it would appear that flow turbulence can be invoked by, for instance, increasing the rotational speed of the impeller. Although mixing is usually carried out in the turbulent regime, there are instances whereby turbulent mixing is simply not practical (due to torque limitation, costly power consumption, etc.). This is particularly true when one is dealing with highly viscous fluid (e.g. such as those encountered in paint industry, polymer production, food processing, viscous fermentation, etc.) where laminar mixing is inevitable (Wang et al., 2009). Besides that, Woziwodzki and Jedrzejczak (2011) have reported that laminar mixing is frequently carried out in biotechnological industry for cell growth consideration. However, the presence of Isolated Mixing Regions (IMR) is well known in the case of laminar mixing (Yao et al., 1998) which could prohibit effective mixing. Therefore, strategies such as baffling, shaft eccentricity, angularly reciprocating impeller (unsteady mixing) etc. have been typically implemented in order to attain rapid mixing.

Clifford and Cox (2006) have argued on the importance of the placement of baffles in order to remove the large periodic island in the Poincar'e map. More recently, Hashimoto et al. (2011) have analyzed in detail the mechanism of mixing enhancement via baffling in laminar flow condition. They have observed that the

---

* Corresponding author. Tel.: +60 389212020x6478.
E-mail address: ngkhaiching2000@yahoo.com (K.C. Ng).

0009-2509/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ces.2013.10.031

mixing enhancement is achieved via the generation of streak lobe near the tip of the baffle which is beneficial to further enhance the mixing of fluids. To date, quite a number of CFD-related works have been performed on baffled vessel (Singh et al., 2007; Torre et al., 2007; Ramasubramanian et al., 2008; Zadghaffari et al., 2009; Lou et al., 2012). Torre et al. (2007) have utilized the Multiple Reference Frame (MRF) approach in order to study the vortex shape developed in a partially baffled vessel. Singh et al. (2007), on the other hand, have claimed that the sliding mesh approach is better than the MRF approach in modeling the interactions between the baffle and the impeller. They have performed a detailed CFD analysis to gain an insight of the pumping action of the impeller. Zadghaffari et al. (2009) have utilized a LES-sliding mesh model in a baffled tank stirred by two flat six-blade Rushton turbine in order to prove the usefulness of CFD in modeling such a complex turbulent flow. Very recently, Lou et al. (2012) have questioned on the effectiveness of straight baffle in eliminating the dead zones in some parts of the crystallizer and subsequently introduced certain degree of twist to avoid accumulation of solid particles near the baffle (a similar study can be found in Ramasubramanian et al., 2008).

Unbaffled vessels are normally preferred in industrial applications because the cleaning process at the interior side of the vessel is easier to be performed (Yoshida et al., 2010; Woziwodzki, 2011). Besides that, when dealing with liquids with higher viscosity, unbaffled vessels with eccentrically-located shaft can be employed to promote mixing (Karcz and Szoplik, 2004). Indeed, Alvarez et al. (2002) have reported that eccentricity can provide a remarkable improvement in axial circulation. Karcz and Szoplik (2004) have argued that shaft eccentricity provides similar effect as baffling, where tangential flow is impeded in both cases. Also, Karcz et al. (2005) have reported that the mixing time decreases as the eccentricity increases at the expense of higher agitation energy. Montante et al. (2006), for the first time, have validated the simulations of eccentric stirred vessel in turbulent flow regime by using PIV measurements. Galletti and Brunazzi (2008) have combined the LDA and flow visualization techniques to study the main flow features agitated by an eccentric impeller and performed analysis on various instabilities characterizing the flow. The application of double turbine impellers in laminar mixing has been reported later by Woziwodzki and Jedrzejczak (2011). As reported by them, eccentricity may cause stronger compartmentalization effect when one is working with multi-impeller systems. Very recently, Ascanio et al. (2012) have reported that the fluid speed around the eccentric impeller is 1.6 times more than that observed around the centered impeller, which has in turn shortened the mixing time.

In order to improve the mixing efficiency of unbaffled vessel without introducing shaft eccentricity, an innovative strategy has been proposed whereby the rotational velocity of the impeller is periodically changed (unsteady mixing). Ng et al. (2013) have recently reviewed on the works addressing on the performance of unsteady mixing procedure. Their work is principally inspired from the work by Komoda et al. (2012) whereby rapid mixing can be achieved via a simple plate impeller undergoing angular oscillatory motion. By adopting the fully Lagrangian Moving Particle Semi-implicit (MPS) particle method (originated by Koshizuka and Oka, 1996), Ng et al. (2013) have revealed the effectiveness of unsteady mixing as compared to the conventional steady mixing procedure (agitated by a concentric plate impeller undergoing steady rotation). In the current work, we intend to extend our numerical study to reveal the underlying details of the flow mechanism of other mixing enhancement strategies such as baffling and shaft eccentricity, if these procedures are applied in the laminar mixing case agitated by a plate impeller. As reported in the literatures, the intensification of axial flow due to baffling/shaft eccentricity/unsteady mixing could possibly be the main agent in promoting mixing (Myers et al., 2002; Alvarez et al., 2002; Yoshida et al., 2010). However, in the absence of axial flow (a infinitely long plate impeller is considered here), it is hypothesized that the key of promoting mixing would be the inherited mechanism to transform the dominant circumferential flow structures (found in conventional steady mixing procedure) into the radial ones. In contrast with the conventional CFD approach (Eulerian mesh-based method) commonly used in studying flow in an agitated vessel, Lagrangian analysis is preferred in the current work because it is straightforward in tracing the flow paths of fluid particles and hence the underlying mixing mechanism can be better understood. Other similar Lagrangian particle method such as Smoothed Particle Hydrodynamics (SPH) (e.g. Ma et al., 2009; Xiong et al., 2010, 2011, 2013) can be considered for this kind of study. Our particle method deviates from SPH whereby the derivatives of the kernel function are not required while evaluating the differential operators via particle interaction models.

2. Description of flow problem

The schematic diagram of the mixing case considered in the current work is illustrated in Fig. 1. Table 1 shows the geometric parameters defining the mixing case.

For all the mixing cases considered in this paper (see Tables 2–5), the impeller Reynolds number (Re_{imp}):

$$\mathrm{Re}_{imp} = \frac{\rho V_{avg} D_{imp}^2}{\mu} \tag{1}$$

of 113 is considered, following the experimental work by Komoda et al. (2012). The fluid density ρ is 1000 kg/m^3 and its dynamic viscosity μ is 0.1 Pa s. Steady mixing is employed in the baffled vessel (case B—N_b, where N_b is the number of baffles) and eccentric

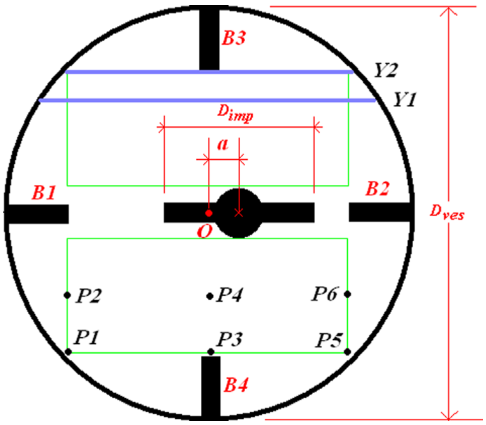

Fig. 1. Schematic diagram of the cylindrical vessel agitated by a plate impeller. $Y1 = 20.626$, $Y2 = 26.97$. P1: (−26.97, −26.97), P2: (−26.97, −15.87), P3: (0, −26.97), P4: (0, −15.87), P5: (26.97, −26.97), P6: (26.97, −15.87). Size of the rectangular compartments: 59.94 × 22.22. The lower-left hand corners of the lower and upper rectangular compartments are at (−26.97, −26.97) and (−26.97, 4.755), respectively. All dimensions are in [mm].

Table 1
Geometric parameter of the mixing vessel. $l_0 = 1.586$ mm.

Parameter	Dimension (mm)
D_{ves}	80
D_{sha}	8
D_{imp}	32 (except for case V, where $D_{imp} = 60$ mm)
Baffle size ($L_b \times W_b$)	$7l_0 \times 2l_0$
Impeller thickness (T_{imp})	$2l_0$