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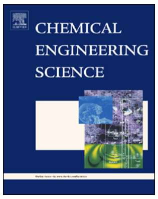

Experimental study of mixing enhancement of viscous liquids in confined impinging jets reactor at low jet Reynolds numbers

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HIGHLIGHTS

- The mixing performance in a CIJR is studied with PLIF.
- Influences of viscosity and excitation on mixing enhancement are investigated.
- The mixing at low *Re* can be effectively enhanced by excitation.
- Compared with *Re*, the fluid viscosity has an insignificant impact on the mixing.

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ABSTRACT

Mixing performance of water and glycerol–water solution in a confined impinging jets reactor (CIJR) with and without excitation was experimentally studied using planar laser induced fluorescence (PLIF) at $100 \le Re \le 500$. The effects of the jet Reynolds number (Re), fluid viscosity and excitation on the oscillation behaviors and mixing performance in CIJR have been qualitatively and quantitatively investigated. Results show that for $Re \le 100$ the flow is segregated with poor mixing; for $Re \ge 150$ the flow evolves to an oscillation regime with strong mixing. Compared with the Reynolds number, the fluid viscosity has an insignificant effect on the mixing in CIJR. The mixing in CIJR at low jet Reynolds number can be effectively enhanced by excitation with low frequency, as a periodic oscillation is induced by the pulsed inflow, which further causes the continuous folding and stretching of the impingement plane. The enhancement of mixing is strengthened with the increase of excitation amplitude and is weakened with the increase of excitation frequency.

1. Introduction

Mixing is one of the most common unit operations in chemical industrial processes, which leads to the homogenization of different concentration of miscibility materials and promotes the heat transfer, mass transfer and chemical reaction of different materials or phases. Several conventional mixing methods in engineering include mechanical stirring, jet mixing, static mixing, etc. As impinging jets can effectively intensify mixing process, they have been widely used in industrial processes such as rapid reaction, the polymer or nanoparticles synthesis, combustion and gasification (Tamir, 1994; Kolodziej et al., 1982; Johnson and Prud'homme, 2003; Santos and Sultan, 2013). Especially, the confined impinging jets reactors (CIJR) and T-jets reactors, as typical impinging jets reactors, attract increasing attention of many researchers (Wood et al., 1991; Teixeira et al., 2005; Santos et al., 2002; Thomas and Ameel, 2010; Icardi et al., 2011; Sultan et al., 2012, 2013; Tu et al., 2014, 2015).

In recent three decades, the effects of operational conditions, flow boundaries and geometrical parameters on the flow and mixing in CIJR have been investigated by flow visualization techniques with passive tracers and numerical simulations. The results in the literature have indicated that for $Re \le 100$ a segregated steady flow regime occurs and at higher Reynolds numbers the flow is observed to transform to a dynamic chaotic flow regime in CIJR (Tucker and Suh, 1980; Mahajan and Kirwan, 1996; Johnson and Wood, 2000; Santos et al., 2005, 2008, 2009; Li et al., 2014). Up to now the flow regime in CIJR has been intensively investigated, but the internal relationship between the oscillation behaviors and mixing performance has not been clearly revealed yet.

The mixing performance in CIJR is the main concern of numerous researches. Tucker and Suh (1980) investigated the

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mixing quality in reaction injection molding (RIM) by flow visualization at $40 < Re < 2000$. They have found that the mixing quality is very poor at $Re < 150$, and increases with Re until a value around 1000, above which no further improvement is detected. Unger and Muzzio (1999) successfully used a laser-induced fluorescence technique to quantify concentration profiles and mixing performance in impinging jets reactors. The experimental results show that the mixing degree increases sharply from $Re = 150$ to 200 and levels off for $Re > 500$. Santos et al. (2008) used the particle image velocimetry (PIV) technique to characterize the flow field in RIM, and results indicate that the mixing in RIM occurs for $Re > 120$. Fonte et al. (2015) studied the flow regimes and mixing performance in a confined impinging jets (CIJ) mixer with PLIF at $50 < Re < 600$, and have found that the mixing scales in the flow become smaller and the mixing quality increases with the increase of Reynolds number. As the viscosity of fluid in micro/mini-CIJR applied in the practical industry is large commonly (20–1000 mPa s) (Macosko, 1989), the jet Reynolds number is low. The previous studies show that for low jet Reynolds number, the flow in CIJR displays a stable separated regime with poor mixing quality (Tucker and Suh, 1980; Unger and Muzzio, 1999; Santos et al., 2008; Fonte et al., 2015). As a result, how to improve the mixing in CIJR under low jet Reynolds numbers is the key issue.

Pulsation techniques have been used to cause the onset of convective mixing in some mixers. Ito and Komori (2006) experimentally investigated the promotion of the mixing efficiency in a micro-channel by a vibration technique. Their results show that the mixing quality is improved with increasing frequency of the mechanical vibration, and almost complete mixing can be accomplished as the frequency exceeds 90 Hz. Ian and Aubru (2003) numerically demonstrated that periodic pulsating fluid could effectively intensify the physical mixing of two aqueous reagents in a T-shape channel. They have found that the best mixing quality occurs when two inlets are pulsed with 180° phase difference. Niu et al. (2006) used pulsation flow to enhance the mixing in a microfluidic channel, and have reported that good mixing can be achieved at an optimal pulsation frequency range, beyond which the pulsation becomes ineffective. Erkoç et al. (2007) performed numerical simulations to study the effect of pulsation on the flow dynamics of a 2D laminar RIM mixer, and have found that the effect of pulsation is enhanced with increasing pulsation amplitudes. Above studies show that pulsed inflow can improve the mixing in mixers, but the effects of oscillation behaviors modulated by the pulsed inflow on the mixing performance have been unclearly revealed yet. Moreover, most studies about pulsation techniques are on the T-mixers or microfluidic channels, while the experimental study on the mixing enhancement in CIJR by active pulsation at low Reynolds number is very rare.

In our recent study (Li et al., 2014), a segregated flow regime, a self-sustained deflective oscillation and a combination regime of vortex shedding and axial instability in CIJR have been clearly characterized at $100 \leq Re \leq 2000$. Moreover, our team (Li et al., 2015) has successfully used the excitation of pulsation inflows of the opposed jets to modulate the flow dynamics in CIJR. It is observed that for low Reynolds number the flow in CIJR under excitation is characterized by the formation of oscillation and vortices in the impingement plane. The work has pointed out that the mixing in CIJR may be enhanced by excitation, but the fluid in that work is air and the mixing quality has not been quantitatively assessed.

In order to further investigate the effects of the excitation on the mixing performance in CIJR, we successfully used the PLIF to obtain 2D concentration field of water and glycerol–water solution in CIJR at $100 \leq Re \leq 500$. We aim to reveal the mixing mechanism and rules of the mixing enhancement in CIJR under excitation, and exploit a method to intensify the mixing of impinging jets at low jet Reynolds numbers in CIJR for engineering applications.

2. Experimental setup and methods

2.1. Experimental setup

The schematic setup is shown in Fig. 1. Two streams of liquids (indicated by Stream A and Stream B) were pumped into the reactor and then impinged on each other. The pumps were placed 6 m above the CIJR, and the inflow pipes were long enough to eliminate the pulsation caused by pumping. Pure water and glycerol–water solution with concentration of 52.8% (w/w) and viscosity of 11.4 mPa s were experimentally studied, respectively. The working fluids' temperature was at 10 ± 1 °C. The pumps shown in Fig. 1 were mute micro-pumps with maximum flux of 166 ml/s, and their working frequencies were in the range of 50–60 Hz. The respective measurement ranges of the rotameters in Fig. 1 were 0.0067–0.067 ml/s and 0.042–0.42 ml/s, and the accuracies were $\pm 2.5\%$ of full scale deflection. The schematic diagram of the CIJR is shown in Fig. 2, and its dimension with precision of ± 0.02 mm is shown in Table 1. The original point o is the intersection of the axes of nozzles and chamber. The reactor had a flat top and a conical constriction at the outlet and was made

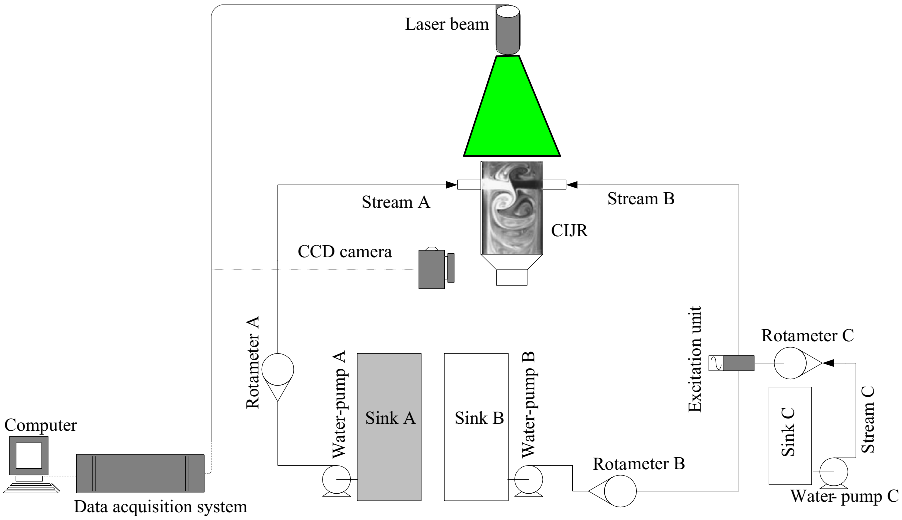

Fig. 1. Schematic diagram of experimental apparatus.