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Mixing times in single and multi-orifice-impinging transverse (MOIT) jet mixers with crossflow☆

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ABSTRACT

We study the macromixing behavior of single and multi-orifice-impinging transverse (MOIT) jet mixers with crossflow, in particular, the overall mixing time and the back-splash mixing time of the injected flow with the crossflow, using the PLIF technique. It is found that for a given mixer configuration, there is a critical jet-to-crossflow velocity ratio r_c at which the back-splash begins to occur. Further increase in the velocity ratio r leads to sharp increase in the back-splash mixing time, which can offset the intensification of the downstream mixing. The dimensionless overall mixing time decreases as r increases to reach either a plateau or a local minimum, and the corresponding r value represents the optimal velocity ratio r_{opt} for the macromixing. The momentum ratio of the two liquid streams is a key factor determining r_c and r_{opt}. For a larger scale mixer, a higher momentum ratio is required to achieve the optimal macromixing with the minimum dimensionless overall mixing time.

1. Introduction

The jet mixer with crossflow is widely used in the fields of gas mixing, *e.g.* mixing fuel and air in gas turbine combustor, as well as in the field of liquid mixing, especially in the chemical industrial processes with parallel or consecutive competitive reactions. In the latter cases, the efficiency of reactants mixing can greatly affect the yield and selectivity of the target products when the time scales of the reactions are smaller than those of the mixing [1,2].

The mixing process in jet mixers with crossflow (or transverse jet mixing process) has been investigated widely in the past few decades. The topics range from the fundamental understanding of the generation and evolution of vortex structures [3–6], to the macro-scale features of the mixing process, *e.g.* the fluid field distributions [7,8], jet trajectories and their correlations [8–11], the degree of unmixedness, and the mixing time [12–19]. It is noted that the reported studies (in particular on the multi-orifice-impinging transverse (MOIT) jet mixers) in the literature focus mainly on gas mixing [20–22], while few can be found for liquid mixing, which is more important in practical applications in chemical industry. When the transverse jet mixer is applied to achieve effective mixing of reactants for mixing-sensitive reactions, the macromixing step (or bulk mixing) is likely to determine the product distribution of the multiple reactions [1].

For the jet mixer, the macromixing time is always calculated from the mixing uniformity along the flow direction, which mainly depends on the interaction between the jets and the crossflow, as well as the interaction among the jets in the case of multiple jets [21]. The jet-to-crossflow velocity ratio (or momentum ratio) and the jet mixer configuration are two main factors that affect the flow structure of the transverse jet mixing process. At low jet-to-crossflow velocity ratio, the jets always attach to the pipe wall, referred to as underpenetration of the jets. As the velocity ratio increases, the jets are detached from the pipe wall and start to penetrate deep into the crossflow. When the velocity ratio reaches a certain value for the single jet mixer, the jet begins to hit the opposite pipe wall, whereas for the MOIT jet mixer, the jets collide with each other in the center of the mixing pipe. When the impingement is intensive enough, part of jet (or jets) will go upstream above the jet injection plane, referred to as back-splash in our previous study [23]. Recently, Kartaev *et al.* also observed the back-splash in the region upstream the side jets in the gas mixing process [24]. Such back-splash will prolong the mixing process, thus not beneficial for the mixing-sensitive reactions. However, in the literature the emphasis is always on the downstream mixing process, and little information can be found on how the back-splash in the upstream affects the mixing performance.

The main objective in this work is to carry out detailed investigations on the macro-mixing behavior of the liquid fluids in the single and MOIT jet mixers. In particular, we focus on the study of the dimensionless overall mixing time and how the back-splash affects it. The mixing time is calculated based on the spatial variance and the temporal variance of concentration distribution obtained by using the non-invasive

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planar laser-induced fluorescence (PLIF) technique. We determine the conditions in which the back-splash occurs in the mixer with different configurations (*e.g.* the mixing pipe diameter, the diameter and number of the side jets), and the effect of the back-splash on the overall mixing time.

2. Experimental

2.1. Configuration parameters of the jet mixer

Fig. 1 shows schematically the configuration of the jet mixer. It consists of a mixing pipe, on which one (single jet mixer) or several identical orifices (MOIT jet mixer) embedded on the pipe wall symmetrically and perpendicularly, and a rectangular buffer chamber around the mixing pipe. Stream A flows along the mixing pipe. Stream B enters the buffer chamber first, then being divided into equal sub-streams and injected into the mixing pipe from the orifices. The origin of the reference frame is the cross sectional plane perpendicular to the y axis (flow direction) through the center of the orifices. In this work, we varied the diameters of both the mixing pipe (D, from 16 to 40 mm) and injecting orifices (d, from 4 to 10 mm), and the number of the orifices (n, from 1 to 4), to investigate their effect on the mixing performance of the process. The mixer is named as MD-$n\Phi d$, *e.g.* a mixer with name, M16-2Φ4, has 2 orifices (4 mm in diameter) on the mixing pipe (16 mm in diameter). We have investigated 6 jet mixers with different configuration parameters, as listed in Table 1.

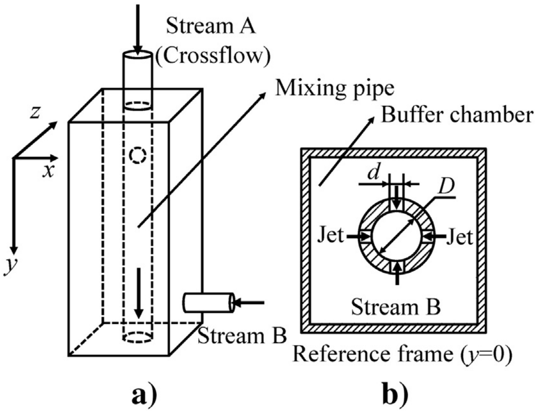

Fig. 1. Setup of the jet mixer. (a) Overview of the mixer configuration and (b) cross sectional plane perpendicular to the y axis (flow direction) through the center of the orifices.

Table 1
Configuration parameters of the jet mixers

Mixer name	D/mm	d/mm	n
M16-1Φ4	16	4	1
M16-1Φ8	16	8	1
M16-2Φ4	16	4	2
M16-2Φ5.6	16	5.6	2
M16-4Φ4	16	4	4
M40-4Φ10	40	10	4

2.2. Flow conditions of the mixing process

The flow conditions of different runs for each mixer are listed in Table 2. The Reynolds number of both the jet flow in the orifices (Re_j, from 3500 to 34900) and that in the pipe (Re_c, from 4200 to 17500) has been designed to ensure they are all in the turbulent regime, which is also a general interest in the literature [21]. Since the two fluids have the same density, the jet-to-crossflow velocity ratio, r, is particularly suitable to characterize the flow field of the transverse jet [22].

$$r \equiv u_j / u_c \tag{1}$$

where u_j and u_c are the velocities of Stream B in the jet and Stream A in the pipe, respectively. In addition, the flow rate ratio, R_F, may be defined as

$$R_F \equiv Q_B / Q_A \tag{2}$$

where Q_B and Q_A are the flow rates of Stream B and Stream A, respectively. The R_F value shows directly the amount of the two liquids to be mixed.

2.3. Measurement of the mixing process by PLIF technique

The mixing process in the jet mixer was studied using the 2-D non-invasive planar laser induced fluorescence (PLIF) technique. In all the experiments tap water was used for both Streams A and B, and Stream A contained Rhodamine 6G as the tracer for the PLIF experiment. Both liquids were pumped into the mixer at desired flow rates using two gear pumps. The entire fluid in the pipe was excited by a continuous laser with the wavelength of 532 nm (Kinder™ Optronics, KDPSL-3W), and the emitted fluorescence light was captured by a high-sensitive CCD camera (Baumer, TXG14NIR) with the image size of 1392 × 1040 pixels. The distribution of fluorescence intensity in the measurement plane can be converted to the tracer concentration distribution. Detailed setup of the experimental system and the calibration procedure can be found in our previous work [23].

3. Results and Discussion

3.1. Temporal and spatial unmixedness of the process

The mixing process was visualized by pseudo-color images converted from gray-level images of the PLIF experiments. In this work, the initial dimensionless concentrations of Stream B (jet flow) and Stream A (crossflow) are set to be one and zero, respectively. Fig. 2 shows instantaneous and time-averaged mean concentration of the mixing process in the mixers, M16-1Φ8 and M16-2Φ5.6. In turbulent flow, the local instantaneous concentration, $f_{t,loc}$, can be described by the time-averaged mean concentration, $\bar{f}_{t,loc}$, plus the temporal fluctuation of the local concentration, $f'_{t,loc}$, *i.e.*,

$$f_{t,loc} = \bar{f}_{t,loc} + f'_{t,loc}. \tag{3}$$

When two streams are mixed, two common indices to evaluate the mixing state are the spatial and temporal unmixedness indices [25]. In general, the spatial unmixedness index is calculated from the time-averaged mean concentration distribution, whereas the temporal unmixedness index considers turbulent fluctuation of the local concentration. In our previous work [23], the mixing process was evaluated by the spatial variation of concentration within the defined mixing region. In this work, we make a further comparison between these two indices to find which one is more appropriate, in particular in the evaluation of the turbulent mixing process represented by the instantaneous concentration distribution.

The spatial unmixedness index, I_{spat}, was calculated based on the time-averaged mean concentration distribution. At the defined mixing zone with m sub-zones, I_{spat} is

$$I_{spat} = \sqrt{\frac{\sigma_s^2}{\left(\sum_{i=1}^{m} \bar{f}_{t,loc(i)}/m\right)\left(1-\sum_{i=1}^{m} \bar{f}_{t,loc(i)}/m\right)}}, \quad y_1 = \ldots = y_i = \ldots = y_m \tag{4}$$

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