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Experimental study on oscillation behaviors in T-jets reactor with excitation

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HIGHLIGHTS

- New oscillation behaviors in T-jets reactors with excitation are observed.
- Different oscillation behaviors are identified and investigated.
- Influence factors on flow behaviors are investigated.

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ABSTRACT

The oscillation behaviors in T-jets reactors with excitation are experimentally studied by a flow visualization technique. The images of the smoke-seeded flow are captured by a particle imaging velocimetry (PIV) system and a high-speed camera. The effects of the Reynolds number, the excitation frequency and the excitation amplitude on the oscillation behaviors in T-jets reactors have been investigated. The impingement plane flaps periodically caused by the pulsed inflow, and the excited flapping frequencies of the impingement planes are equal to the excitation frequencies. Different oscillation behaviors in T-jets reactors with excitation are identified, and the interaction between the self-sustained oscillations and the excited flapping oscillations is investigated and discussed. Results show that the excitation as well as the geometry parameters of T-jets reactors has significant effects on oscillation behaviors. The excited oscillation amplitudes of impingement planes increase with Reynolds numbers and excitation amplitudes, but non-monotonically decrease with excitation frequencies.

1. Introduction

The mixing principles can be divided into passive and active mixing relying either on the pumping energy or provision of other external energy (Hessel et al., 2005). Impinging jets reactors are effective for passive mixing, and have been applied for increasing industrial processes, e.g., combustion, gasification, absorption, extraction, drying and nanoparticle synthesis. The most common types of impinging jets reactors are confined impinging jets reactors (CIJR) and T-jets reactors (Santos and Sultan, 2013), and the latter ones are commonly used as micromixers and attract much attention in recent years (Yang et al., 2004; Wong et al., 2004; Hoffmann et al., 2006; Soleymani et al., 2008a, 2008b; Sultan et al., 2012, 2013; Tu et al., 2014b). The flow regimes and mixing mechanism are key issues for the design and operation of T-jets reactors.

The flow dynamics and mixing characteristics in T-jets reactors have been studied for different geometry parameters. Different flow regimes, i.e., the segregated or stratified flow, the vortex flow, the engulfment flow, the oscillation and turbulent flow in the typical T-jets reactors with the width-to-height ratios of jets of $w/h=1$ and the normalized jets separations of $L/h=2$ have been distinguished depending on jet Reynolds numbers (Engler et al., 2004; Thomas and Ameel, 2010; Dreher et al., 2009; Schwarzer et al., 2006). For new-type T-jets reactors with some headspace, larger width-to-height ratios and separations of jets, a self-sustained chaotic flow regime has been reported (Sultan et al., 2012), which indicates the geometry parameters have significant effects on flow dynamics in T-jets reactor. The mixing performance is improved significantly in T-jets reactors under the oscillation flow regime (Dreher et al., 2009; Sultan et al., 2012, 2013), and the vortices resulting from the

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oscillation in the chamber are essential for the mixing performance enhancement (Soleymani et al., 2008a, 2008b; Sultan et al., 2013). In our recent investigation (Tu et al., 2014b), a half deflecting oscillation has been observed in T-jets reactors at $w/h > 8$ and $L/h > 8$, and the influence factors and the critical parameters have been investigated. Due to small geometry dimensions of T-jets reactors, the typical operating Reynolds number is in laminar flow and mixing quality is poor, and thus proper measures are needed to improve mixing in T-jets reactor.

Adding external excitation is one of active mixing technologies, and has been employed in impinging jets reactors to enhance mixing performance (Santos and Sultan, 2013). Erkoç et al. (2007) have studied numerically the effect of pulsation on the flow dynamics in a 2D RIM, and simulation results show that the frequency and the amplitude of the pulsation have a strong effect on the flow field. Sun and Sie (2010) have investigated the mixing performance in the diverging channel with pulsatile pressure, and found mixing performance is best with a phase difference between 0.25π and 0.5π. Previous studies (Ito and Komori, 2006; Oberti et al., 2009; Glasgow and Aubry, 2003; Qiu et al., 2012) show that the periodic oscillations caused by the excitation can generate vortexes in the impinging plane, which are then stretched and folded within the chamber. Consequently the interfacial area between two mixing fluids is increased and mixing performance in micromixers is improved. However, these studies are mainly centered on the effects of the excitation on the ultimate mixing performance, and less attention has been focused on the oscillation behaviors in micromixers. To our knowledge, experimental investigations about the oscillation behaviors in T-jets reactor with excitation of pulsed inflow have not been reported.

Results of our previous studies show that the impingement plane of axisymmetric and unrestricted opposed jets under modulated airflow exhibits periodic oscillations, and the excitation frequency, the excitation amplitude and the jet separation have substantial effects on the amplitude of the excited oscillation (Li et al., 2013a). For planar and unrestricted opposed jets with acoustic excitation, the acoustic excitation results in a horizontal periodic oscillation at $L/h \leq 4$, and the transition from the deflecting oscillation to horizontal oscillation occurs with asynchronous excitation at high amplitude and $L/h > 4$ (Li et al., 2013b). Our recent studies indicate that the confined boundaries have significant effects on the flow behaviors in T-jets reactor (Tu et al., 2014a, 2014b), so the results of the unrestricted opposed jets with excitation cannot be directly applied to the T-jets reactor.

Motivated by the contributions of above studies, we perform a study of flow behaviors in T-jets reactors with excitation based on our recent experimental investigation (Tu et al., 2014b). Our main objectives are to identify the oscillation behaviors in T-jets reactors with excitation, and to investigate the effects of the Reynolds number, the excitation frequency, the excitation amplitude and the geometry parameters of T-jets reactors on the oscillation behaviors.

2. Experimental set-up

The schematic diagram of experimental apparatus is drawn in Fig. 1(a). The working fluid was air from a steel cylinder. The flux was controlled by two precise gas flow controllers with accuracy of $\pm 0.25\%$ of full scale deflection. The modulated airflows were generated by additional gas from another steel cylinder, and they were controlled by the periodic open and close of the electromagnetic valves with very short response time (less than 5 ms). The electromagnetic valves were controlled by an asynchronous controller to adjust the phase displacement of the instantaneous flowrate waveforms of the opposed jets. The sketch map of the flowrate controlling in T-jets reactors with pulsation is shown in Fig. 1(b). In current experiment, the phase displacement was set to π. The excitation frequency (f_e) was in the range of 1–25 Hz. The excitation amplitude (a_e) was defined as the ratio of the pulsed flow (Q_p) to the base flow (Q_b), and it was in the range of 5–40%.

The sketch map of the T-jets reactor is drawn in Fig. 1(c). The original point o is the intersection of the axes of injectors and the chamber. Three T-jets reactors with different geometries were investigated in the experiment, in which Reactor I is a typical T-jets reactor, while Reactor II and III are new-type T-jets reactors with large jet separation and some headspace. The geometry parameters and dimensions of the T-jets reactors are listed in Table 1, where h and w are the height and width of the injector, L is the jet separation, d is the depth of the reactor chamber, and H is the height of the headspace above the injectors.

The Reynolds number is defined as

$$Re = \frac{\rho u_0 h}{\mu} \quad (1)$$

where u_0 is the bulk mean exit velocity of the injector, ρ and μ are the density and dynamic viscosity of air, which are 1.21 kg/m^3 and 18.1×10^{-6} Pa s under experimental conditions. The Reynolds numbers are in the range of 35–210 in current study.

The Strouhal number is defined as

$$St = \frac{fh}{u_0} \quad (2)$$

where f is the oscillation frequency.

The flow in the T-jets reactor was visualized by the white smoke generated by some small fuming tablets in the smoke generator, as shown in Fig. 1(a). In the experiment, the smoke was only introduced to left jet in order to observe the structures of the flow field more clearly. A pulsed Nano Nd: YAG-laser ($\lambda = 532$ nm, pulse energy 200 mJ, pulse frequency 10 Hz) with integrated light-sheet optics was used to illuminate the smoke-seeded flow, and the viewing plane was x–z plane, as shown in Fig. 1(a) and (c). The images of the smoke-seeded flow in the laser "sheet" were recorded by a charge coupled device CCD camera (*FlowSense*, EO 4M camera) with a frame rate of 10 Hz. The CCD camera of PIV system can capture the slices of flow visualization images with high spatial resolution, but cannot capture the high-frequency dynamic flow for its limit of laser pulse frequency (less than 15 Hz). Therefore, a high-speed camera (*Photron*, APX-RS) was used to record the dynamic flow with a frame rate of 1000 fps (frames per second) and resolutions of 1024×1024 pixels. A continuous halogen spot light (2000 W) was used to illuminate the smoke-seeded flow.

In current study, the visualization images of flow dynamics were captured by the CCD camera of the PIV system, and the values of oscillation periods, frequencies, Strouhal numbers and oscillation amplitudes were analyzed from the visualization images captured by the high-speed camera. The mean values and their standard deviations were obtained via analysis of 10 periods, and the uncertainty of data analysis is less than 5%. Image processing software of ImageJ (Abramoff et al., 2004) was used to analyze and process the recorded digital images captured by the high-speed camera. As the images were acquired at an interval of 0.001 s, the time series of locations of the impingement planes can be obtained conveniently using the image processing software. The detailed method of image processing can be found in our previous paper (Li et al., 2013a).

3. Experimental results and discussion

Fig. 2 shows the typical visual images of flow patterns in Reactor I with various Reynolds numbers and excitation frequencies. For the