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Numerical study of active mixing over a dynamic flow field in a T-jets mixer—Induction of resonance

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ABSTRACT

The flow field in a 2D T-jets mixer was simulated to study the effect of the pulsation/modulation of the jets flow rate on the dynamics of mixing. Different strategies, frequencies and amplitudes of the opposed jets flow rate modulation were tested. The modulation frequencies were set as multiples of the natural oscillation frequencies of the dynamics flow field. The natural flow frequencies are determined from the unforced flow, i.e., when the jets are not modulated. It is found that out phase modulation of the opposed jets, with frequencies close to the natural frequencies, cause resonance of the flow enhancing the order of the system, which results in a flow field with a well-defined repetitive generation of vortices. Conversely, when the pulsation frequencies were different from the natural frequencies the flow disorder was enhanced, i.e., the vortices evolution throughout the T-jets mixers is less repetitive. The impact of the jets flow rate modulation on the flow field dynamics increases with the modulation amplitude up to the extreme case where it completely drives the dynamics of the system. A design equation for the most energy efficient pulsation of the jets feed streams in opposed jets mixers is proposed.

1. Introduction

Mixing is the critical step for many industrial processes, particularly when the rate of the chemical reaction is faster than the mixing rate, and the reactions are competitive and/or consecutive reactions, e.g., crystallization and reactive polymerization. For those reactions, the history of mixing sets the product properties, namely cristallinity or Particle Size Distribution (PSD), or the mechanical properties of polymers obtained by reactive processes (Kolodziej et al., 1982, 1986; Schwarzer et al., 2006). Schwarzer et al. (2006) and Pieper et al. (2011) demonstrated that the Reynolds number of the jets in a T-jets precipitator has direct impact on the PSD of barium sulphate nanoparticles. The Reynolds number is associated with mixing in T-jets mixers, and thus mixing is an important design parameter for the development of specific products.

The particular case of opposed jets reactors has been often studied for controlled mixing of two liquids, namely for the production of nanoparticles. Marchisio et al. (2006) and Johnson and Prud'homme (2003) used cylindrical mixing chambers with round injectors (Confined Impinging Jets (CIJ)) for precipitation of nanoparticles and observed both the operation Reynolds number and the geometry of the CIJs influence the nanoparticles PSD. Liu and Fox (2006) used CIJs and observed that the conversion of a second order competitive reaction varied three orders of magnitude when the Reynolds

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numbers at the jets ranged between 1 and 5000. Nunes et al. (2012) also observed the critical role of mixing in a CIJ, reporting the selectivity of a second order competitive reaction that varied three fold over a range of Reynolds numbers less than 300. Schwarzer et al. (2006), Gradl et al. (2006) and Gradl and Peukert (2009) used a prismatic T-jets mixing chamber for the precipitation of barium sulphate; at turbulent or laminar chaotic flow regimes; these authors also observed that the Reynolds number affected the PSD of the nanoparticles. Santos et al. (2005) reported, in a 2D T-jets geometry, that the conversion of a second order chemical reaction depends on the Reynolds number of the jets. Soleymani et al. (2008a) used a micromixing test reaction and varied the reactor geometry and the operation Reynolds number; both factors influenced the chemical reaction conversion. Krupa et al. (2012, 2014) used a competitive consecutive chemical reaction to assess micro-mixing in T-jets reactors and also reported a clear effect of the mixer geometry on the flow regime, which had an impact on the selectivity of the chemical reaction.

Other authors studied mixing in opposed jets mixers, without chemical reaction, using mainly flow or mass transfer data. Engler et al. (2004) studied several T-jets mixers geometries and reported results of mixing obtained from tracer visualization in the range of Reynolds 6–200. In this range of Reynolds numbers, Engler et al. (2004) identified three flow regimes: stratified flow, vortex flow and engulfment flow. The regimes were characterized as follows:

- Stratified/segregated flow is a regime where two streams, each fed by one jet, flow without mixing side by side through the mixing chamber. The axis of the mixing chamber defines a symmetry line between both streams. Mixing between the two streams relies solely on diffusion.
- Vortex flow is a regime where there are vortices in the streams flowing side by side without breaking the symmetry line between the streams. At this flow regime, mixing between the two streams still relies solely on diffusion.
- Engulfment flow is a regime where vortices engulf both the streams fed by each jet. Mixing is now mainly promoted by the convective mechanisms—the vortices.

The transition between the flow regimes was not only a function of the Reynolds number; the geometry of the mixers was also influencing the flow regimes transition. Soleymani et al. (2008b) also observed that the transition between the three flow regimes was a function of both geometry and Reynolds number. The three flow regimes reported in Engler et al. (2004) and Soleymani et al. (2008b) are laminar, even at Reynolds numbers 489; Wong et al. (2004) also reported laminar flow regimes.

In CIJs, only two laminar flow regimes are reported: the stratified flow that is generally referred as steady flow regime in CIJ and above a transition Reynolds number in the range of 90–120, a regime referred in CIJ literature as self-sustainable chaotic flow regime (Lee et al., 1957; Tucker and Suh, 1980; Wood et al., 1991; Johnson and Wood, 2000; Teixeira et al., 2005; Santos et al., 2008). The chaotic flow regime is characterized by oscillations of the jets impingement point and by the formation of vortices immediately downstream the jets impingement point. This flow regime differs from the engulfment flow regime on the orientation of the flow rotation, i.e., in the engulfment flow regime the flow rotation is aligned with the mixing chamber axis and in the chaotic flow regime the vortices rotation is perpendicular to the mixing chamber axis (Santos and Sultan, 2013). Santos et al. (2009) related the formation rate of the vortices in chaotic flow regimes with the frequency of oscillation of the jets impingement point.

The chaotic flow regime was also observed in 2D opposed jets geometries studied with CFD simulations by Santos et al. (2005, 2010), which studied a geometry having a head space and larger chambers in comparison to the jets widths. The head space is a free space above the injectors where vortices are formed, and these vortices have a key role on the operation at self-sustainable chaotic flow regimes. If the mixing chamber top is directly above the injectors the wall will hinder the flow oscillations and the chaotic flow is not reached, as shown from 2D CFD simulations of Santos et al. (2002). Sultan et al. (2012, 2013) made PLIF experiments with deeper mixing chambers than in previous works on T-jets, and considered a head space above the jets and mixing chamber width to jets width larger than six. The deeper chamber, at least 0.5 times the chamber width was also necessary condition for a chaotic flow, on shallow chambers strong wall effect also rendered the flow steady. The flow expansion ratio with the mixing chamber width being at least fourfold the injectors yield was also proven to be a must have condition to onset the vortex street typical of the chaotic flow regime (Sultan et al., 2012). The PLIF experiments corroborated the numerical results of the 2D CFD model. The transition between the two flow regimes in 2D geometries was reported at a Reynolds number of 250. Tu et al. (2014a,b) provided further experimental evidence of the existence of a chaotic flow regime with the same vorticity pattern of the 2D CFD model. In this work the 2D CFD model is used at chaotic flow regimes. Further experimental validation is provided in this paper regarding the oscillatory behaviour of opposed jets under chaotic flow regimes.

If the properties of a product depend on the mixing history inside the reactor, which variables can be used to control those properties in a continuous static mixer? The most obvious variable, as proven by Schwarzer et al. (2006) and Kolodziej et al. (1986) is the Reynolds number, and reactor design can also play a key role (Johnson and Prud'homme, 2003; Sultan et al., 2012). Although, in term of complex products, such as nanoparticles, the final product properties to be targeted go beyond the average particle size, other important properties can be the shape of the PSD or the crystal morphology, which depend in a complex fashion of the mixing history (Silva et al., 2008; Marchisio et al., 2006). In this paper, additional control of the mixing history and hence on the product properties is targeted using active mixing.

Active mixing is the use of a "disturbance generated by an external field for the mixing process" (Nguyen and Wu, 2005), where this disturbance can be of several types, from electrical to mechanical. In this work, the external stimulus is applied to the flow rate of the two feed streams that enter as opposed jets in a mixing chamber, so that the flow rate of each feed stream has a sinusoidal variation over its average value. Active mixing was previously tested on opposed jets mixers, namely: Ito and Komori (2006) on Y-mixers by using a mechanical flow pulsator; Komori and Ito (2005) and Deshmukh et al. (2000) using a bubble micro-pump; Fujii et al. (2003) using fast switching of the pumps; Zhongliang et al. (2002) using an electrokinetic flow control for Y- and T-jets micro-mixers; Li et al. (2008) using a dual syringe pump and Sun and Sie (2010) using a dynamic pressure signal obtained by varying the level of the feeding liquid in the feeding bottles of two opposed jets. Bierdel and Piesche (2001) studied the effect of the pumps flow pulsation on mixing in an opposed jets mixing chamber of a