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Flow imbalance and Reynolds number impact on mixing in Confined Impinging Jets

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HIGHLIGHTS

- The flow in a CIJs mixer is studied with the PLIF flow visualization technique.
- Three flow regimes are observed in the range 50 < Re < 600.
- The jets' flow imbalance always influences negatively the mixing quality.
- The mechanism of eddy engulfment is a key aspect in the reduction of mixing scales.

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ABSTRACT

The flow in a Confined Impinging Jets (CIJs) mixer was studied with Planar Laser Induced Fluorescence. Two key aspects influencing the flow regimes and mixing quality were studied: the impact of the jets' Reynolds number (Re) in the range 50 < Re < 600; and the effect of the jets' flow imbalance, maintaining the flow rate of one of the injectors fixed and varying the other. Mixing mechanisms and scales are studied from the acquired flow images, and the mixing degree is quantified from the calculation of the Intensity of Segregation (Danckwerts, 1952). In balanced flow conditions, i.e., equal volumetric feeding rates, when the best mixing performance is observed, three flow regimes are observed: for Re < 103 the flow is steady with complete segregation of the two feeding jet streams; for Re = 104 the flow tends to an oscillatory periodic laminar flow regime; for Re > 104 the flow evolves to a self-sustained chaotic laminar regime with strong mixing dynamics. With the increase of Re it is observed the formation of smaller mixing scales in the flow and an increase on the mixing quality. The visualized mixing scales are compared with theoretical models existing in the literature for the estimation of the striation thickness, leading to the conclusion that, in the studied flow regimes, the statistical theory of turbulent diffusion does not provide a realistic physical description of the flow. Furthermore, the jets' mass flow imbalance is shown to always influence negatively the mixing quality. This is observed even when the flow imbalance results in the increase of the flow rate of one of the jets, increasing the amount of energy supplied to the system for dissipation. Results of this work show that the mechanism of eddy engulfment promoted by the two chaotically oscillating impinging jets, in the laminar regime, is a key aspect in mixing by CIJs.

1. Introduction

Mixing is a unit operation present in many industrial processes that require the contact of reactants for chemical reactions, or the homogenization of solutions or solid particles. Over the last decades, mixing in Confined Impinging Jets (CIJs) mixers has appeared as an alternative to conventional mixing in stirred tanks, and has revealed to be well suited for continuous processes that require a rapid homogenization of streams [2]. In this technology, two or more liquid reactants are injected into a confined space, the mixing chamber, through opposed jets. The jets impinge in the chamber and the resulting mixture flows through the remaining of the chamber until the outlet. Since the first studies on CIJs [3,4], it is known that only above a critical Reynolds number, Re_C, the flow is strongly dynamic with high velocity chaotic fluctuations near the injection point, and rapidly becoming steady and parallel as it moves away from the impingement point until the outlet. This rapid deceleration and quite strong energy dissipation of the two jets at the top of the mixing chamber, after impingement in the

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confined space, allows for a quite effective mixing to be achieved quickly and without movable mechanical parts, such as stirring devices. The hydrodynamic instability generated from the impingement of the two jets, promoting the mixing the two streams, occurs at low Re = $\mathcal{O}(100)$, that is in laminar regime, making CIJs suitable for the mixing of high viscosity liquids.

CIJs mixers/reactors are generally divided into two types, depending on its geometry: jet mixers with cylindrical chamber and injectors [2,5–10] and jet mixers with rectangular cross-section chamber and injectors [11–17]. These devices have a wide range of applications in different industrial processes such as reactive co-precipitation for nanoparticle production or in reactive polymer injection machines.

Since its appearance (Table 1), several authors have used flow visualization techniques with passive tracers to study mixing in CIJs mixers: the main concern has been the study of the mixing mechanisms in opposed jets mixing and evaluating the effect of operational conditions or geometrical parameters on mixing quality.

The first flow visualization experiments were made by Lee et al. [4], who have taken high speed photographs of the flow in a transparent Plexiglas mixing chamber, relying in optical effects of small density variations of the injected solutions to observe mixing patterns. Photographs of the flow were taken at Reynolds numbers Re = 50, 90 and 150. All images showed vortex motion in the flow, more intense around the impingement point and fading away downstream. In the same year, Tucker III and Suh [3] used an ink tracer to detect flow structures in the impingement jets flow, quantifying the mixing quality from the variance of the photographed concentration fields. Tucker III and Suh [3] observed that poor mixing occurs for Re < 150. An increase on mixing quality was observed as Re increased until a value around 1000, from which no further improvements were detected. Tucker III and Suh [3] also studied the impact of flow imbalance in the mixing quality by increasing the flow rate of one of the jets and decreasing the other, but the used experimental technique did not allow identifying any impact. Technological limitations at that time and the rapid motion of the formed vortices hindered the clear visualization of the flow from both methods of Lee et al. [4] and Tucker III and Suh [3] for Re > 150. To overcome this limitation, Sandell et al. [18] adopted a more advanced technique with thymol blue, a pH indicator used as a dye that fades with mixing. Thymol blue in stagnant tap water takes about half an hour to fade, but rapidly fades with agitation. The fading tracer prevents the clouding of the chamber, allowing the visualization of the jets' impingement, and the appearance of zones with higher accumulation of tracer allows the identification of regions of bad mixing in the flow: regions with poor mixing appear as colored, while well-mixed regions become clear. Sandell et al. [18] have shown that, in the studied range of Reynolds number from 250 to 720, there is a continuous and significant improvement on mixing quality up to a Reynolds number of 400. From this value forward, an improvement on mixing quality still occurs, but at a decreasing rate. Wood et al. [19] captured images of CIJs flow seeded with polystyrene particles with an average diameter of 100 μm. The shutter speeds on the camera were varied so that the particles present in the fluid appeared as streaks in the images. In the experiments of Wood et al. [19], a steady flow regime was observed up to Re = 90. The Reynolds number was incrementally increased to study the onset of flow oscillations. The instability of the two impinging jets' interface was observed to grow as Re is increased. A stable impingement point position could not be obtained above Re = 150 in the experiments. Johnson et al. [20] and Johnson and Wood [21] used several flow visualization techniques including the use of a dye, a fluorescent dye and tracer particles. For Re < 90, the flow was observed to be stationary and unaffected even by sudden temporary perturbations in the flow

Table 1
Summary of experiments with flow visualization techniques for the study of mixing in CIJs.

Source	Geometry	Mixing chamber dimension (mm)	Injectors dimension (mm)	Experimental technique	Reynolds number range	Critical Reynolds Number
Lee et al. [4]	Cylindrical	3.18	1	Density variations	50–150	–
Tucker III and Suh [3]	Cylindrical	22	9.5	Ink tracer	50–2000	>150
Sandell et al. [18]	Cylindrical	52	9.5	Fading dye with mixing	250–720	–
Wood et al. [19]	Cylindrical	25.4	2.38	Seeding particles	60–300	135
Johnson et al. and Johnson and Wood [20,21]	Cylindrical, prismatic	20–25	2–4	Seeding particles, dye, fluorescent dye, tracer particles	90–300	Between 90 and 150
Unger and Muzzio [22]	Cylindrical	890	13	PLIF	150–600	–
Bierdel and Piesche and Schütz et al. [23,24]	Cylindrical	10	1	Colored tracer	50–150	Between 50 and 150
Hoffmann et al. [26]	Prismatic	0.4	0.1–0.2	μ-LIF	100–375	Different flow regimes
Santos et al. [25]	Cylindrical	10	1.5	PIV	100–500	120
Sultan et al. [17]	Prismatic	2–6	0.5–2	PLIF	50–500	150–320
This work	Cylindrical	10	1.5	PLIF	50–600	110