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Experimental study of enhanced mixing induced by particles in Taylor–Couette flows

D. Dherbécourt[a], S. Charton[a,*], F. Lamadie[a], S. Cazin[b], E. Climent[b]

[a] CEA, DEN, DTEC, SGCS, F-30207 Bagnols-sur-Cèze, France
[b] Institut de Mécanique des Fluides, Université de Toulouse, CNRS-INPT-UPS, F-31400 Toulouse, France

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ABSTRACT

Local mixing dynamics was recently investigated experimentally in Taylor–Couette single-phase flow, thanks to simultaneous Particle Image Velocimetry (PIV) and Planar Laser-Induced Fluorescence (PLIF) techniques. The results highlighted the influence of the successive flow bifurcations and the role of azimuthal wave states on the dispersion of dye injected in Taylor–Couette flows.

The present work extends this study to two-phase configurations with spherical solid particles. The respective effect of particle size and concentration on the vortices size and transition thresholds between the various flow regimes has been examined thanks to flow visualizations and PIV measurements. These hydrodynamic features have been complemented with PLIF experiments, that revealed a drastic enhancement of mixing due to the presence of particles regardless of the flow regime, highlighting the existence of significant particle-induced mixing in Taylor–Couette flows.

1. Introduction

Following the fundamental work of Taylor (1923), flow patterns between two concentric cylinders, depicted in Fig. 1, have been extensively studied. In practical applications involving Taylor–Couette flows (bio and chemical reactors, filtration, etc.), the inner cylinder usually rotates while the outer one stays at rest. Annular centrifugal contactors based on such geometry showed their great potential in the nuclear industry where they are particularly suitable for small-scale studies of solvent liquid–liquid extraction processes, as shown by Davis and Weber (1960). This flow is known to exhibit multiplicity of stable regimes, ranging from laminar Couette flow to turbulence through a sequence of successive hydrodynamic instabilities (Fig. 1), as the rotation rate of the inner cylinder is increased (Andereck et al., 1986).

Beyond a critical Reynolds number (Eq. (1)) based on the gap width e, the rotation rate of the rotor Ω and the fluid viscosity ν (for the case of two-phase flow see mixture viscosity correlations in Einstein (1956) for dilute regime and Stickel and Powell (2005) for dense suspensions), pure Couette flow evolves to toroidal vortices called Taylor Vortex Flow (TVF), which regularly ripple at higher Reynolds numbers. This flow state, designated as Wavy Vortex Flow (WVF) is characterized by an axial wavelength λ and an azimuthal wave number m. As the rotation further increases, this wavy flow becomes modulated by additional frequencies and finally turbulence occurs (Turbulent Taylor Vortex Flow, TTVF). As evidenced by Coles (1965), the occurrence of these flow states and the related hydrodynamic properties depend on the acceleration ramp used to access a given Reynolds number.

$$Re_\Omega = \frac{\Omega R_i e}{\nu} \qquad (1)$$

Axial diffusion is an important phenomenon in reactor design, as the amount of mixing within the vortices greatly influences the efficiency of separation processes. In Taylor–Couette flows, mixing results from both intra-vortex

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* *Corresponding author*. Tel.: +33 466796229.
E-mail address: sophie.charton@cea.fr (S. Charton).

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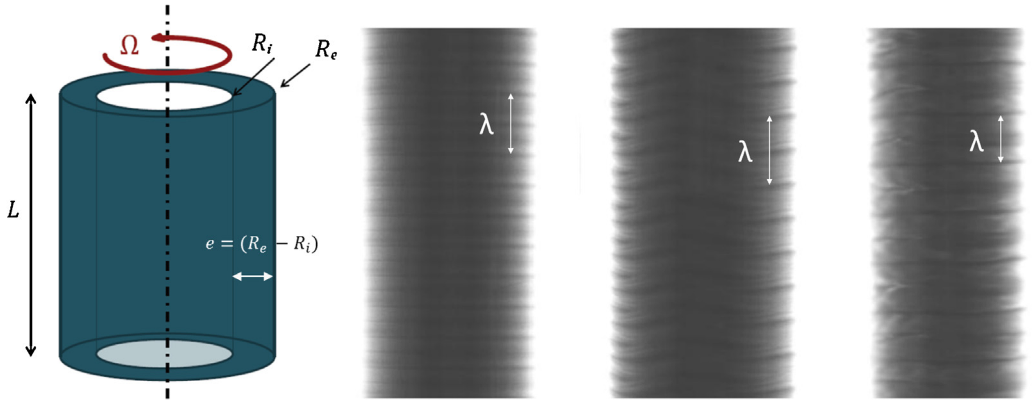

Fig. 1 – Left: Sketch of the Taylor–Couette flow between two concentric cylinders. Right: Flow states visualization, increasing rotation from left to right: TVF, WVF, MWVF, and their corresponding axial wavelengths λ.

mechanisms, related to the rotational flow within each vortex, and inter-vortex mechanisms, controlled by the global flow topology. Our previous study (Nemri et al., 2014) investigated the relation between the dynamics of the single-phase flow and the mixing mechanisms, using simultaneous PIV–PLIF measurements.

In TVF regime, the PLIF measurements revealed a weak intra-vortex mixing, and confirmed the occurrence of dye inter-vortex transport at the vortices outer boundaries. The tracer remains confined in outer layers before being convected towards the separation between vortices, where it can be further transported to the neighboring vortices by diffusion. The weak velocity in the vortices cores carries the tracer very slowly, and mixing in these regions is basically achieved by molecular diffusion across streamlines. Dye transport by both diffusion and convection is well depicted by the 2-zones model proposed by Desmet et al. (1996) to describe mass transfer in TVF.

As the rotation rate increases, the occurrence of wavy motion was shown to enhance mixing noticeably, as a consequence of the local velocity field properties (Akonur and Lueptow, 2003). This was also observed from the more usual dye tracer technique by Ohmura et al. (1997). Indeed, the apparition of traveling waves in WVF breaks the boundaries (closed streamlines) between adjacent vortices and enhances fluid exchange, thus increasing inter-vortex mixing. Wavy motion also yields an enhanced transport of the tracer to the vortex core, supplemented by diffusion, thus increasing intra-vortex mixing as well. The resulting global mixing is therefore noticeably more efficient in WVF than in TVF (Nemri et al., 2014). Moreover, many studies confirmed that mixing properties are very sensitive to the azimuthal wave state (λ, m) in wavy flow, as shown by axial dispersion coefficients determined by DNS and dye tracer experiments by Rudman (1998) and Nemri et al. (2013, 2015).

Regarding liquid–solid flow configurations and taking into account the sensitivity of mixing to hydrodynamics, the influence of the particles on the flow properties is studied. Particle-induced mixing is indeed an important research topic, although very few studies are related to Taylor–Couette flows. Experimental evidence of particle induced mixing was reported by Ajuha (1975) while studying heat transfer in sheared polystyrene suspensions. More recently, Metzger et al. (2013) investigated the effect of shear-induced particle agitation on heat transfer across suspensions, through experiments and numerical simulations in a Couette cell. They highlighted a significant enhancement (>200%) of the suspension transport properties with particles, but concluded that the driving mechanism for this enhanced transport is the translational particle diffusivity. Investigating the influence of particle size, d, particle volume fraction ϕ and applied shear γ, the effective thermal diffusivity α was found to be proportional to the Peclet number $Pe = \gamma d/\alpha$ for $Pe \leq 100$, exhibiting a linear increase of the effective thermal transport properties with the particle concentration for $\phi \leq 40\,\%$. Besides these numerous experimental works, self-diffusion of particles has also been studied theoretically and numerically, as in Abbas et al. (2009) who considered inertial particles in a pure shear flow.

Few studies are dedicated to two-phase Taylor–Couette flows. Most of them are dedicated to bubbly flows, as in the work of Djeridi et al. (2004). Although mixing characterization was not their objectives, the authors investigated the bubbles trajectories and their effects on the flow structure. Modification of the transition thresholds and of the vortices wavelength was highlighted, as well.

This study is part of a more general research program aiming at demonstrating the relevance of Taylor–Couette devices for solvent extraction. One of the most important features of Taylor–Couette flows regarding liquid–liquid extraction is their very low axial mixing, enabling high separation efficiency to be achieved (Lanoë, 2002). In this paper, mixing is investigated in a liquid–solid configuration. Density-matched spherical polymethylmethacrylate (PMMA) particles are used, thus preventing coalescence and breakage events occurring in liquid–liquid dispersions, as well as any sedimentation or creaming phenomena. The particle size (800–1500 μm diameter) and concentration (1–8%) are chosen to be representative of typical laboratory-scale two-phase flow operations.

After a description of the experimental setup of coupled PIV/PLIF experiments, the twofold influence of the particles on the mixing is investigated, considering both the variations of hydrodynamic properties and the particles-induced mixing, depending on the volume fraction.

2. Material and experimental techniques

2.1. Experimental setup

The geometric parameters of the experimental device are given in Table 1 and a picture of the setup is presented in Fig. 2. The inner cylinder (rotor) is driven by a speed regulator system. Indeed, because of the flow sensitivity to its transient evolution, the acceleration must be carefully controlled.

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