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FROM PASSIVE TRACER TO BUBBLES DISPERSION IN TAYLOR-COUETTE FLOWS

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Summary: We investigate dispersion of passive tracer and bubble preferential accumulation in the flow between two concentric cylinders. The dispersive characteristics are analysed for Taylor Vortex Flow, Wavy Vortex Flows and fully Turbulent Taylor-Couette flows. Experiments based on flow visualization, PIV and PLIF measurements are compared to direct numerical simulations of Navier-Stokes equations coupled to Lagrangian tracking of fluid elements and bubbles. In vortical flows, bubble accumulation is driven by a competition between added-mass effect, lift and buoyancy forces. At low to moderate Reynolds numbers, the flow is strongly coherent and bubble accumulation patterns can be predicted theoretically (stability analysis of fixed points). When turbulence sets in, small scale structures enhance dispersion. This complex situation where large-scale coherent structures interact with fine scale turbulence leads to bubble mixing which have been analyzed by numerical simulations. Several distributions of bubbles are observed depending on the respective magnitude of turbulence and buoyancy force.

INTRODUCTION

The flow between two concentric rotating cylinders has many industrial applications (mixing, emulsion production, reactors). Moreover, it is an academic configuration (simple geometry) to study dispersion of passive tracers and bubbles because the transition to turbulence is progressive through successive instabilities and bifurcations of the flow. The flow dynamics is controlled by two dimensionless numbers when the outer cylinder is fixed $Re=\omega r_i(r_o-r_i)/\nu$ and $\eta=r_i/r_o$ (see fig. 1 for geometry and ν is the fluid kinematic viscosity). We investigate dispersion mechanisms for all the following configurations of the flow: TVF (Taylor vortex flow), WVF (wavy vortex flow), MWVF (modulated wavy vortex flow, see fig. 2) and TTC (turbulent Taylor-Couette flow). Both numerical simulations (using direct solution of the Navier-Stokes equations coupled to Lagrangian tracking of fluid elements or bubbles) and experiments will be compared.

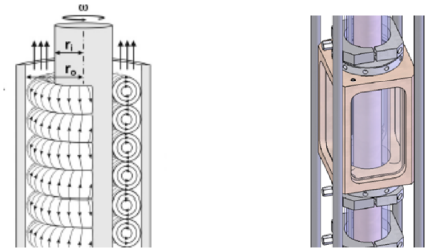

Figure 1: (Left) Geometry of Taylor-Couette vortices – (Right) Sketch of experimental device.

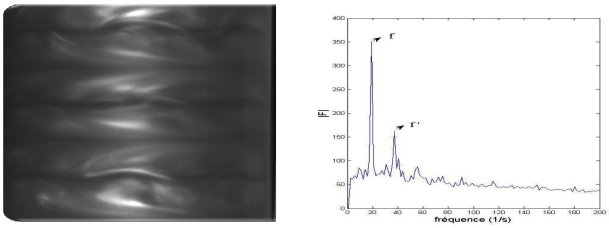

Figure 2: (Left) Visualization of modulated wavy vortex flow (Re=2000).(Right) Spectrum with two peaks related to modulated waves

AXIAL DISPERSION OF A TRACER

When a passive tracer is injected in the flow, predicting its axial dispersion is a key point for modelling the mixing efficiency of the device. For pure Couette azimuthal flow, axial dispersion is a molecular phenomenon characterized by the Schmidt number (ν/D_{mol}). TVF is a cellular flow leading to intra-vortex mixing but weak inter-vortex diffusion. As Re increased azimuthal symmetry is broken yielding to higher values of the effective axial diffusion coefficient D_{eff}. We defined the Schmidt number as $Sc=\nu/D_{eff}$. In fig. 3, we compare the effective axial diffusion obtained from simulations to experiments based on light attenuation of coloured tracers. In simulations, the flow is seeded with 10,000 Lagrangian particles whose mean square displacement evolution in time gives the diffusion coefficient.

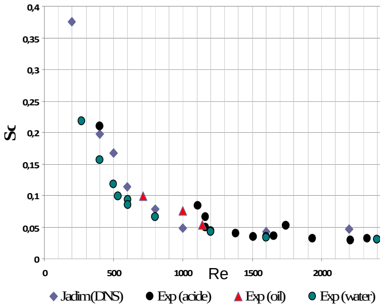

Figure 3: Evolution of effective Schmidt number $Sc=\nu/D_{eff}$ *vs.* Reynolds number Re.

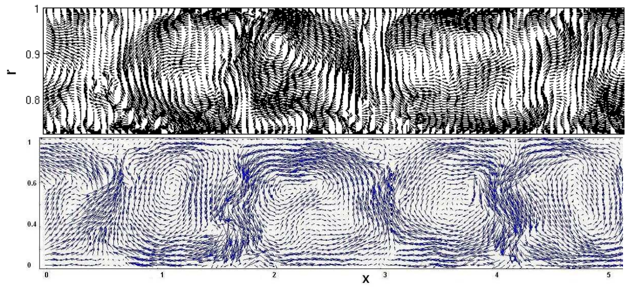

Figure 4: Snapshots of velocity field for Re=6000 from simulations (top) and experiments (bottom).

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The agreement between simulations (DNS with our code Jadim) and experiments (with different fluids: oil, acid and water and η=0.85) is very good although data are more scattered for WVF and MWVF. When the vortices become wavy, the flow is characterized by two wavenumbers: axial and azimuthal wavenumbers (m,n). Both n and m are related to the flow history to reach a particular Re value. We confirm that this have a significant effect on diffusion as suggested by Rudman [1]. Modulation of wavy vortices (detected by a second frequency in the temporal spectrum of the velocity – fig. 2) enhances inter-vortex fluid exchange. Our experimental visualizations (η=0.69) coupling PIV and PLIF measurements emphasize inter-vortex mixing leading to enhanced axial diffusion for large azimuthal wavenumbers.

BUBBLE DISPERION IN A TURBULENT FLOW

When Re is further increased, small scale flow structures feed the coherent structures (see fig. 4 for PIV experiments and DNS simulations). This corresponds to turbulence progressive onset. Our direct numerical simulation results have been successfully compared to referenced data [2, 3]. Grid invariance in simulations has been achieved when herringbone-like patterns are finely meshed near the wall. The flow is complex as it is composed simultaneously of reminiscent coherent WVF vortices and small scale sheared turbulence (fig 5). We investigated bubble dispersion in such flows for various Re (ranging from 5,000 to 10,000) and η numbers (from 0.5 to 0.9). Bubble tracking is numerically achieved by solving force balance including buoyancy, drag, added-mass, dynamic pressure gradient and lift forces. When bubbles reach the wall, we assume that an elastic rebound occurs.

Bubbles do not follow fluid pathlines because of inertia effects (centripetal migration towards the inner cylinder and towards the core of vortices) and lift force. Bubble dynamics in TVF, WVF and MWVF has been described in [4] and compared to experiments [5]. This study was based on finding fixed points of a dynamical system and stability analysis. We move on turbulent regime where mixing is strong and such theoretical prediction impossible.

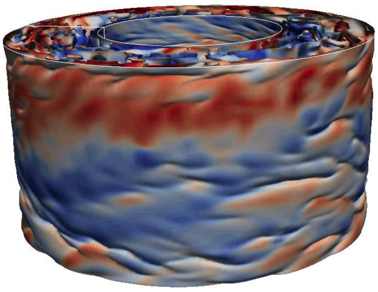

Figure 5: Flow visualization of simulations (Re=8000 η=0.5).

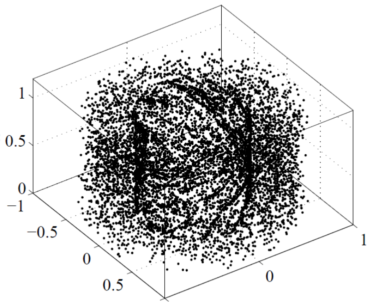

Figure 6: Instantaneous positions of bubbles (Re=8000 η=0.5).

Because bubbles are massless, they are attracted towards the inner cylinder. They interact both with large scale wavy vortices and small scales turbulence leading to fine accumulation patterns (fig. 6). Depending on the respective magnitude of added-mass, lift and buoyancy forces the accumulation pattern is modified. For large values of η, bubbles remain within the core of vortices while weakly sheared flows (low η) force the bubble to accumulate in the close vicinity of the inner wall. Buoyancy effects drive the bubbles vertically while they leave vortices. Under such conditions, spiral patterns can be observed. All those regimes of accumulation will be presented and analyzed in terms of radial profiles of void fraction and other Eulerian and Lagrangian statistics.

CONCLUSION

We have highlighted several features of dispersion mechanisms (fluid elements and bubbles) within the flow between two concentric cylinders (inner cylinder rotating). Both direct numerical simulations of the flow and trajectories have been compared to optical measurements (PIV and PLIF).

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