CAUSALITY IN DROP-TURBULENCE INTERACTIONS: IDENTIFYING THE DRIVER OF DROP DEFORMATION AND BREAKUP

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Binary mixtures of inmiscible fluids in turbulent conditions are ubiquitous in natural phenomena and industrial applications. The physical properties of these flows depend strongly on the structure of the disperse phase, in which the breakup of fluid particles—drops or bubbles—plays a fundamental role. Understanding and modelling turbulent breakup is essential to predict and control the dynamics of inmiscible mixtures, but this remains a challenge to theoretical and empirical approaches. Fluid-particle breakup is often viewed from an energetic perspective, in which the surface energy of the particle is a marker of its degree of deformation. This approach is very convenient, but requires isolating the mechanisms that lead to the effective increments of the surface energy, and thus to breakup. Fluid-particle deformation occurs when turbulent kinetic energy is transformed into surface energy, but the opposite mechanism is also possible; fluid-particle relaxation produces turbulent kinetic energy through oscillatory motions in which the surface energy may increase locally (although not on average). Only the former mechanism can cause breakup, but distinguishing it from the latter is difficult because of the complexity of surface-turbulence interactions.

In this talk, we address this problem by resorting to causality analysis applied to drops embedded in isotropic turbulence. We leverage our recent findings on the mechanism that causes the increments of the surface energy, which may be locally described as the stretching of the drop surface by the local rate-of-strain tensor [1]. We decompose this quantity into local and non-local components, which describe the contribution to surface-energy increments due to eddies far from the drop surface (outer stretching), and close to it or inside the drop (inner stretching). We average these quantities over the surface of single drops, and construct temporal signals of the contribution to the surface energy due to inner and outer stretching that cover the evolution of drops until breakup. We study the causal relation between these signals in massive ensembles of time-resolved independent single-drop simulations at different Weber numbers (see figure 1(a)). First, we show that the temporal auto-correlation of the outer stretching scales with turbulence quantities, while that of the inner stretching scales with the characteristic relaxation time of the interface. Moreover, their cross-correlation shows that negative inner stretching (surface relaxation) occurs on average after positive outer stretching (surface deformation due to turbulence) with a time delay that scales with the relaxation time, suggesting that the latter is the cause of the former (see figure 1(b)). We corroborate this hypothesis by applying convergent cross mapping [2], a non-linear test of causality, to the signals. These results indicate that the causes of drop breakup may be largely identified by analysing the outer stretching; it depends mostly on turbulence dynamics, it is the main source of surface-energy increments, and drives the inner stretching, which acts as a rather 'passive' surface-energy dissipation mechanism.

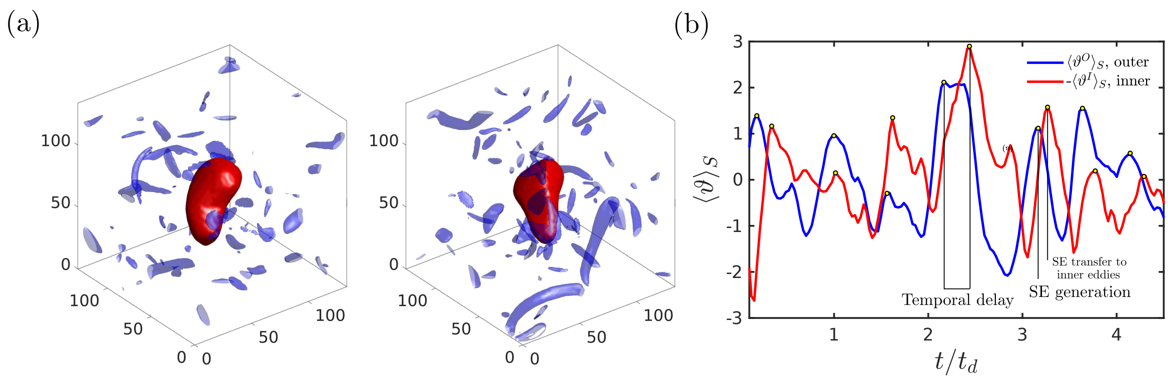

Figure 1. (a) A drop embedded in isotropic turbulence at Weber numbers $\mathrm{We} = 1.8$. The frame is fixed at the centre of the drop, blue isosurfaces mark intense vorticity. The size of the computational box is marked in Kolmogorov units. (b) Temporal evolution of the contributions to surface energy (SE) of (blue) outer and (red) inner eddies in the evolution of a single drop in isotropic turbulence.

References

[1] Vela-Martin, A, Avila, M, *J. Fluid Mech.* **929** (2021).
[2] Ye, H. and Deyle, E.R. and Gilarranz, L.J. and Sugihara, G., *Sci. Rep.* **5**, 1–9 (2015).