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Gallery of Fluid Motion

# Rico and the jets: Direct numerical simulations of turbulent liquid jets

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The breakup of an interface into a cascade of droplets and their subsequent coalescence is a generic problem of central importance to a large number of industrial settings. Examples of these applications include the atomization of propellants in engines, the formation of droplets in injectors, mixers, and separators, and the generation of droplets in multiphase flow regime transitions [1–3]. In all of these situations, it is important to predict the evolving droplet size distribution that results from a competition between breakup and coalescence, which are influenced by a range of multiscale physics; this includes the interaction of turbulence with interfaces, capillarity, viscosity, and gravity. Therefore, it is unsurprising that the breakup of liquid jets during injection (i.e., atomization) has received great scientific interest [4–8].

The transient dynamics of turbulent liquid/liquid systems have not received the attention they deserve in the literature. Temporal instabilities and the resulting spatiotemporal interfacial structures are predicted by solving the full three-dimensional two-phase Navier-Stokes system in the context of a hybrid front-tracking/level-set method [9–11]. We consider a cylindrical nozzle with diameter $D = 4$ mm injecting water with density $\rho_w$ and dynamic viscosity $\mu_w$. This water jet enters progressively into the computational domain of size $20D \times 4D \times 4D$, initially filled with a stagnant viscous silicone oil of density $\rho_{so}$ and viscosity $\mu_{so}$. The surface tension is taken to be that of oil and water (e.g., $\sigma = 35.1$ mN/s) [12]. The Reynolds number is defined as $\mathrm{Re} = \rho_w U_{\mathrm{jet}} D/\mu_w$ and fixed to the value of $\mathrm{Re} = 6530$. The domain has been divided into $48 \times 6 \times 6$ subdomains where each subdomain contains a Cartesian structured grid of $64^3$ cells, accounting for a global structured mesh grid of $3072 \times 384 \times 384$. This mesh is sufficiently large to resolve all relevant turbulent length scales and interfacial singularities (e.g., pinch-off and coalescence).

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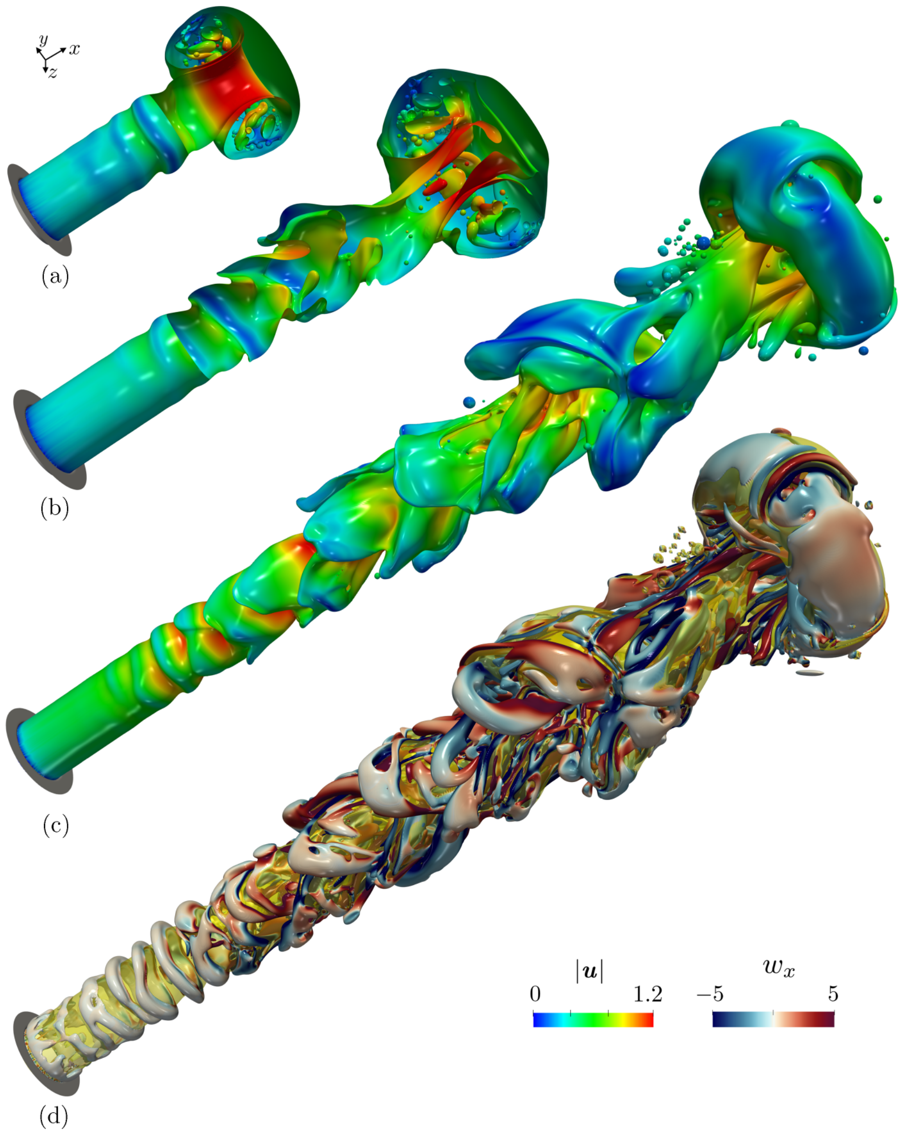


FIG. 1. Spatiotemporal evolution of the interface in the injection of a water jet into a stagnant viscous silicone oil at $t = (7.25, 12.05, 28.97)$ corresponding to (a), (b), and (c), respectively, with $\mathrm{Re} = 6530$. (d) Illustration of the coherent vortical structures through the $Q$ criterion close to the free surface (in yellow) at $t = 28.97$. The vortical structures have been colored by the value of the vorticity in the streamwise direction. In the vorticity representation, blue and red represent vortical structures with counterclockwise and clockwise rotation, respectively. All variables are dimensionless quantities.

We use a solver for massively parallel simulations of fully three-dimensional multiphase flows [10], able to run on a variety of computer architectures, wholly written in FORTRAN 2008 and adopting an algebraic domain decomposition strategy for parallelization with MPI. The fluid interface solver is based on a parallel implementation of the Level Contour Reconstruction Method (LCRM), which is an adaptation of our high-fidelity hybrid front-tracking/level-set method, able to handle highly deforming interfaces with complex topology changes [13–15]. This code uses parallel GMRES and multigrid iterative solvers suited to solve the linear systems arising from the implicit solution of the fluid velocities and pressure. More details on the numerical techniques can be found in Shin *et al.* [10,11].

The spatiotemporal evolution of the interfacial dynamics is shown in Fig. 1. At early injection times, large capillary pressure is generated near the leading edge, due to local interfacial curvature, leading to a radially-driven flow. This capillary-induced flow together with the viscous resistance from the stagnant phase yields the formation of a leading-top mushroom-like structure [see Fig. 1(a)]. This structure covers an internal interfacial toroidal sheet whose thickness reduces over time to generate the formation of holes, which expand radially to form ligaments and eventually entrapped droplets. As time evolves, the free surface behind the leading structure adopts the shape of a "cylinder" which undergoes a Kelvin-Helmholtz instability (KH) to form the initial corrugations observed to occur on the free surface. The KH instabilities on the free surface are triggered by the parallel motion of fluids at different velocities and are amplified by the pulsatile injection.

The interfacial dynamics of the jet can be explained by coupling the vorticity $\boldsymbol{\omega} = \nabla \times \mathbf{u}$ with the interfacial location. During the early stages and close to the injection point, the streamwise vorticity field $\omega_x$ is characterized by values which are two orders of magnitude smaller than the azimuthal vorticity $\omega_\theta$. As the flow evolves downstream, $\omega_x$ becomes comparable in magnitude with $\omega_\theta$, leading to the deformation of axisymmetric KH vortex rings in the streamwise direction adopting a new hairpin shape. These hairpin vortices trigger the formation of interfacial lobes which are stretched downstream (from outer hairpin vortices) and upstream (from inner hairpin vortices) to eventually obtain a hairpin shape [see Figs. 1(b) and 1(c)]. We have used the $Q$ criterion to visualize the three-dimensional nature of the vortical structure [shown in Fig. 1(d)] [16]. The topological shape of the vortex resembles the instantaneous hairpin-like vortical structures reported in experiments and numerical simulations of [17,18]. Outer hairpin vortices are observed clearly, whereas the inner hairpin vortices are localized underneath the interface. Additionally, a vortex-cap covers the leading mushroom structure.

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