Gallery of Fluid Motion

Atomization of the optimally disturbed liquid jets

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Atomization process is a disintegration of a liquid stream or a chunk of fluid blobs into discrete small droplets and particles. This process is ubiquitous in a wide range of industrial applications, such as metal manufacturing process, powder production of a solid, combustion engines, DNA sampling, medical surgeries, and pharmaceutical applications, among others [1–3]. The elucidation of fundamentals of atomization process is crucial to better design and control of these applications and thus maximizing their utility.

Recently, Hwang *et al.* [4] identified a new mechanism to significantly amplify the magnitude of the optimized inlet disturbances, which eventually leads to efficient atomization of liquid jets as shown in Fig. 1. A multiphase Orr mechanism, a reorientation of initially tilted perturbation structures by the mean shear inside liquid jets, drives the amplification process even without exponentially growing instabilities (see Fig. 2). Depending on the operating conditions, the liquid jet with the optimized inlet disturbance can amplify interfacial disturbances at a faster pace than modal mechanisms.

This new pathway to distort the interface of liquid jets differs from earlier studies [5–7] mainly in three aspects. First, Hwang *et al.* [4] applied a partial norm that only extracts the surface tension energy of disturbances from the full norm as opposed to a norm commonly based on the perturbation kinetic energy. Second, the multiphase Orr mechanism extracts the perturbation energy from the mean shear in stream-wise direction, and transfers it to the surface tension energy [4]. Therefore, the material interface, which is kinematically coupled to the radial perturbations velocity, is directly affected and amplified. Third, azimuthal instability, or transverse instability, is directly triggered from the beginning of the amplification process rather than induced by a preceding exponential instability, e.g., the Kelvin-Helmholtz instability.

The realizability of the multiphase Orr mechanism is demonstrated using fully nonlinear simulations. We employ a semi-implicit compressible solver CHARLES, which is developed at Cascade Technologies Inc.. The solver is based on finite volume formulation, and it performs on unstructured grid. For the interface capturing method, an algebraic volume of fluid method is applied [8]. We

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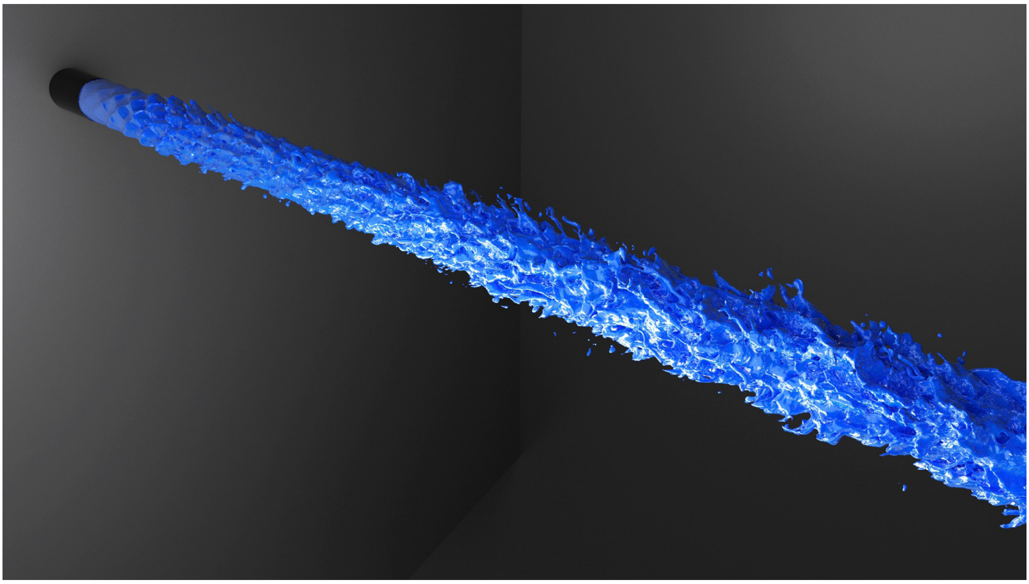

FIG. 1. Image rendering of isosurface of the liquid jet atomization triggered by the optimal inlet disturbances with parameters Re = 8000, We = 7500, $m = 0.0404$, and $\eta = 0.0319$, where Re, We, m, and η are the Reynolds number, Weber number, viscosity ratio, and density ratio, respectively. All parameters are normalized by the centerline velocity and the radius of the liquid jet.

consider a cylindrical simulation domain with a length of $60R$ in the streamwise direction and radius of $5R$, where R is a radius of the liquid jet. A cylindrical mesh is employed. The grid near the interface is refined to capture the small disturbance amplitude growth rate. At the inlet, we prescribe an optimized disturbance following Hwang *et al.* [4]. Additionally, the homogeneous Neumann boundary condition is imposed on the side wall and the outlet. For more details on the simulation setup, readers are referred to Hwang [9].

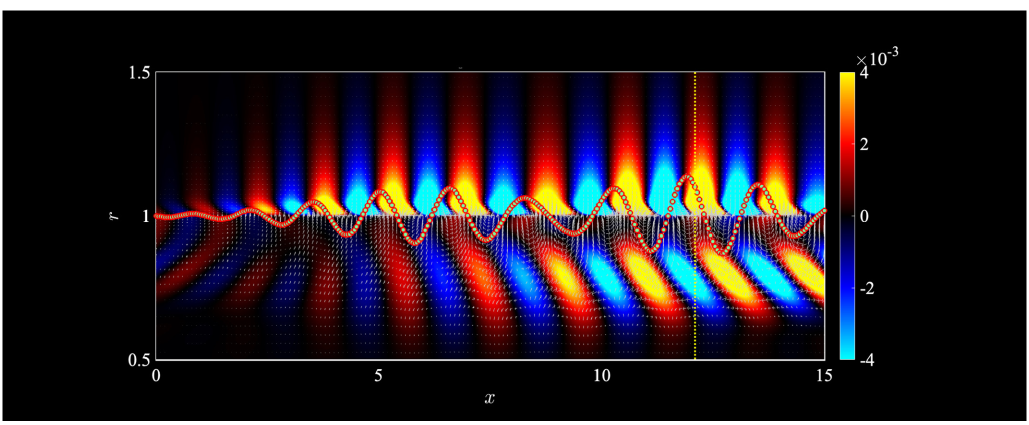

FIG. 2. Side view of the stream-wise evolution of the optimal inlet disturbance. Vectors of the stream-wise and radial disturbance perturbation velocity fields with color contours of the azimuthal disturbance field. The circles indicate material interface. The yellow dashed line marks the target location. Parameters are Re = 8000, We = 7500, $m = 0.0404$, and $\eta = 0.0319$.

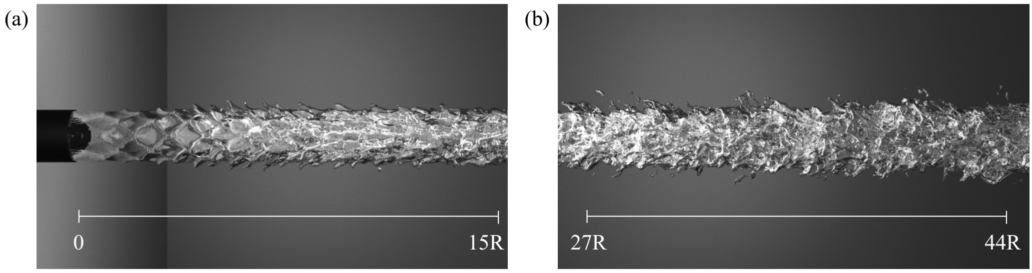

FIG. 3. Image rendering of the isosurface of the liquid jet atomization triggered by the optimal inlet disturbances at (a) the near field and (b) the far field with Re = 8000, We = 7500, $m = 0.0404$, and $\eta = 0.0319$.

The isosurface of the optimally disturbed liquid jets are shown in Fig. 3. The optimized inlet disturbance is amplified as predicted by the linear theory in the region near the nozzle exit [see Fig. 3(a)]. The small-scale structures begin to emerge at the downstream region as depicted in Fig. 3(b) as the inlet disturbances quickly grow to the level that the nonlinear terms become significant. The density of the small-scale structures are evaluated using a surface density (Σ) of the liquid jet, which is defined by the ratio of the interface surface area to the liquid volume within a control volume in the stream-wise direction. A comparison of the surface density of the optimally disturbed liquid jet and the randomly disturbed liquid jet shows that the ratio of the two increases in the stream-wise direction, indicating the optimal inlet disturbances more effectively distort the interface (see Fig. 4). In both cases, the initial perturbation energy of less than 0.1% of the kinematic energy of the base flow was used.

In this work, we demonstrated the multiphase Orr mechanism as a new pathway for the amplification of small disturbances on liquid jets using the fully nonlinear multiphase solver CHARLES. Liquid jets are intrinsically unstable and their breakup is often ascribed to the exponentially growing instabilities. Alternatively, it was shown that the small optimized inlet disturbances can grow at a faster pace by the multiphase Orr mechanism than that of the classical modal growth mechanism.

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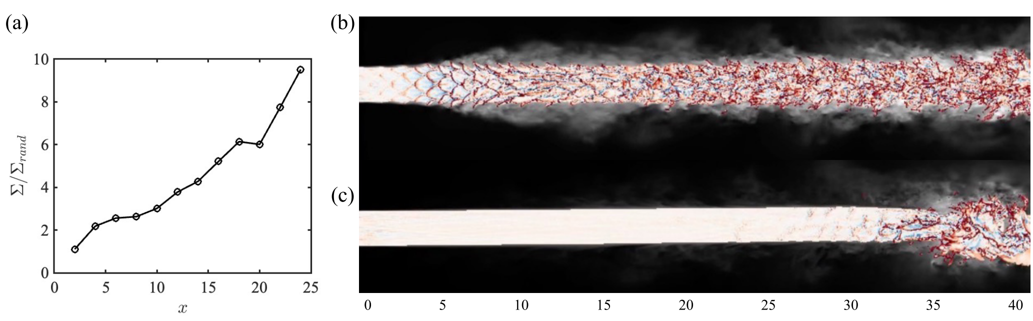

FIG. 4. (a) Ratio of the surface density of the optimally disturbed liquid jet and a randomly disturbed liquid jet. Color maps of surface curvature are used to highlight small-scale structures and velocity magnitude with (b) the optimal disturbance at $t = 0.23$ and (c) the random disturbance at $t = 0.2$. The color map for surface curvature is saturated and it ranges from $\kappa = -5000$ (blue) to $\kappa = 5000$ (red). The color map for velocity magnitude ranges from $|\mathbf{u}| = 0$ (black) to $|\mathbf{u}| = 1.5$ (white). All parameters are nondimensionalized.

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