Vorticity dynamics for a spatially developing liquid jet within a co-flowing gas
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- 3D NS equations and VoF interface tracking for transient liquid round jet.
- Delineation of atomization mechanisms on a gas Weber number versus liquid Reynolds number map, consistent with temporal studies and limited experiments.
- Behaviors in the behind-the-cap region (BCR) vs. upstream region (UR).
- Explain the behaviors based on vorticity dynamics.
Parameter Choices

Domain I – 3D lobes form on KH axisymmetric surface waves in an orderly fashion. The lobes elongate into ligaments. These ligaments break into droplets.

Domain II - The lobes thin rapidly, holes and liquid bridges form, the bridges break to give ligaments which break further into droplets.

Domain III – The lobes are more highly corrugated but ligaments form from the lobes and then break into droplets.

-- Cases 1, 2, and 3 in the plot show Re and We values based on the relative liquid-gas velocity.

-- Based on the absolute single-phase velocities, Re and We are the same for all cases.

-- A case 4 has the same position as Case 2 in the map but with substantially different absolute velocities.
Numerical Method

QUICK for spatial discretization – 2 μm mesh;

Crank-Nicolson time marching; SIMPLE Algorithm;

Volume of Fluid (VoF) with piecewise linear interface calculation (PLIC);

λ₂ method for post-process identification of vortex structures.
Starting Behavior

- The liquid velocity is higher than the gas velocity.
- A cap forms at the downstream end of the liquid jet.
- There is recirculation in the gas behind the cap.
- An indentation occurs near the cap.
- Downstream of the cap, Kelvin-Helmholtz (KH) waves form due to relative motion of the gas in the downstream direction (for the liquid).
- Upstream, KH waves form due to relative gas velocity in the upstream direction.
Behaviors in Different Domains

- Similarities of Cases 2 and 4 show relevance of relative velocity rather than velocity or momentum ratios.

- Hairpins, lobe thinning, and hole puncture appear earlier in Domain II.

- Slower development in the more viscous Case 3, i.e., with the lower Re value based on relative velocity.

- The larger relative velocity results in faster cap growth and breakup.
Comparisons of three cases at later time

- (a) Case 1; (b) Case 2; (c) Case 3.
- Relative velocity decreases from Case 1 to Case 3.
- Wavelength increases from Case 1 to Case 3.
- Cap size decreases with relative velocity decrease.
Periodicity and Non-periodicity of KH waves

- Periodic KH waves on the upstream portion of the KH wave with non-periodic behavior downstream for both Case 1 (upper) and Case 3 (lower).

- Periodic vortex structures of both rotational directions where surface wave is periodic.

- Downstream non-periodic surface waves and vortex structures are influenced by the recirculation.

- The length of the upstream periodic portion grows in time and becomes the dominant character.

- The waves in Case 1 (Domain II) grow much faster and stretch outward farther in the radial direction.
Appearance of Hairpin Vortices

• Axisymmetric KH surface waves with associated vortex rings grow with downstream flow.

• Corrugation (i.e., 3D lobes) appear downstream with emerging hairpin vortices and their associated pairs of counter-rotating streamwise vorticity, one for each lobe.

• Two layers of hairpins appear at first with a phase difference of 180°. They correlate with the lobe structure. The layer outside the lobe stretches downstream and becomes an inner layer for the next downstream lobe.

• The inner layer stretches upstream and becomes the outer layer for the next upstream lobe.

• Further downstream, three layers appear. The new middle layer has weaker streamwise vorticity, is more chaotic, and relates to a slightly deflected vortex ring.
Hairpin Interactions

- Hairpins have opposing rotation to major KH rollers.

- Case 1 (upper sketch) has overlapping hairpins from upstream braid and downstream lobe.

- Resulting streamwise vorticity promotes perforations in the lobe.

- Case 3 (lower sketch) has wrapping of hairpins around KH roller with appearance of third hairpin from downstream.

- Upstream and downstream hairpins do not overlap to cause perforations. Rather, stretching into ligaments results.
Concluding Remarks

- Distinct behaviors occur in downstream Behind-the-Cap region vs. Upstream Region: i.e., non-periodic vs. periodic, effect of recirculation on local flow and rotation.
- $We_g$ and $Re_l$ are key parameters in distinguished different domains for three-dimensional liquid-structure formations; i.e., lobes, holes, bridges, ligaments, and droplets.
- At lower $We_g$ and lower $Re_l$ (Domain I), the atomization cascade involves sequential formation of lobes, stretching to ligaments, breaking into droplets.
- At higher $We_g$ and higher $Re_l$ (Domain II), the atomization cascade involves sequential formation of lobes, thinning and perforating of lobe, bridge formation and tearing to ligaments, breaking into droplets.
- In the upstream region, structure formations follow the same pattern found for temporal jet analysis.
- The surface-wave formation and associated liquid-structure formations correlate well with development of the vortex structures.
- Hairpin vortices and the resulting stream wise vorticity are important in explaining liquid structure development.
Thank you.