Vorticity dynamics for a spatially developing liquid jet within a co-flowing gas

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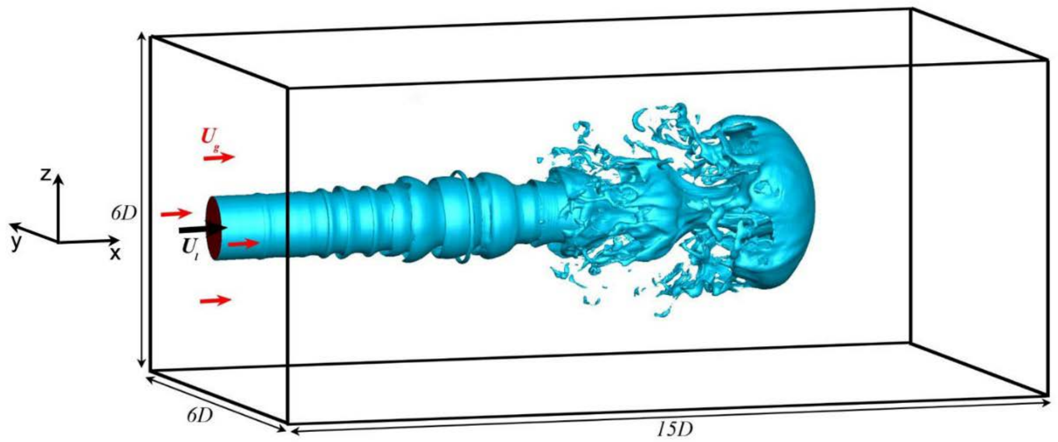


- 3D NS equations and VoF interface tracking for transient liquid round jet.
- Delineation of atomization mechanisms on a gas Weber number versus liquid Reynolds number map, consistent with temporal studies and limited experiments.
- Behaviors in the behind-the-cap region (BCR) vs. upstream region (UR).
- 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.

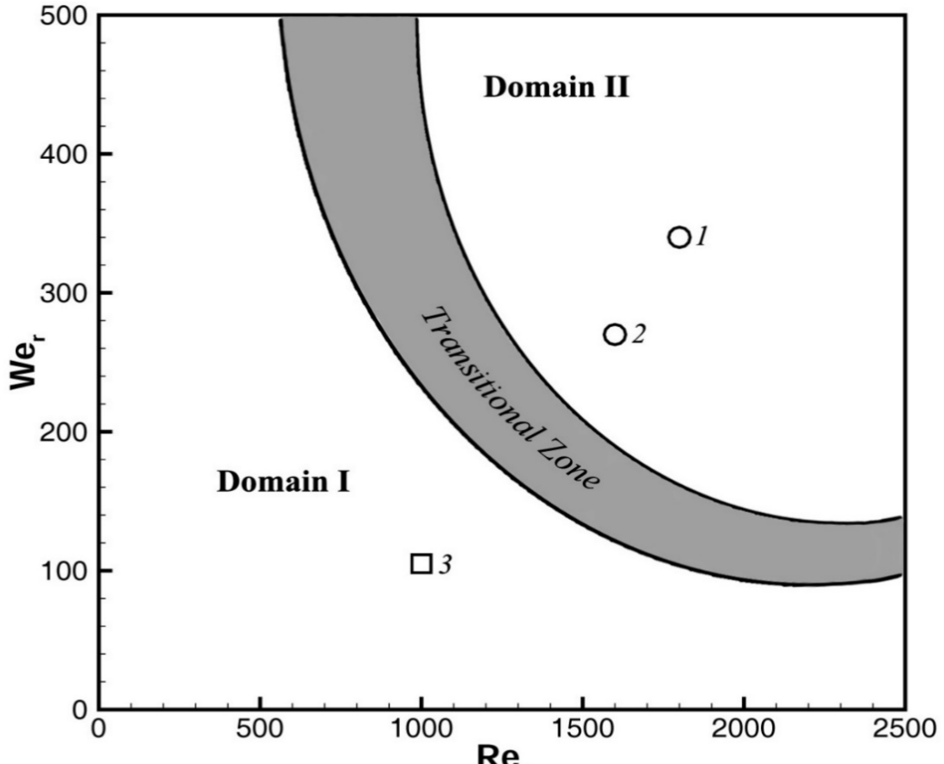
Domain II - The lobes thin rapidly, holes and liquid bridges form, the bridges break to give ligaments which break further into droplets.

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.



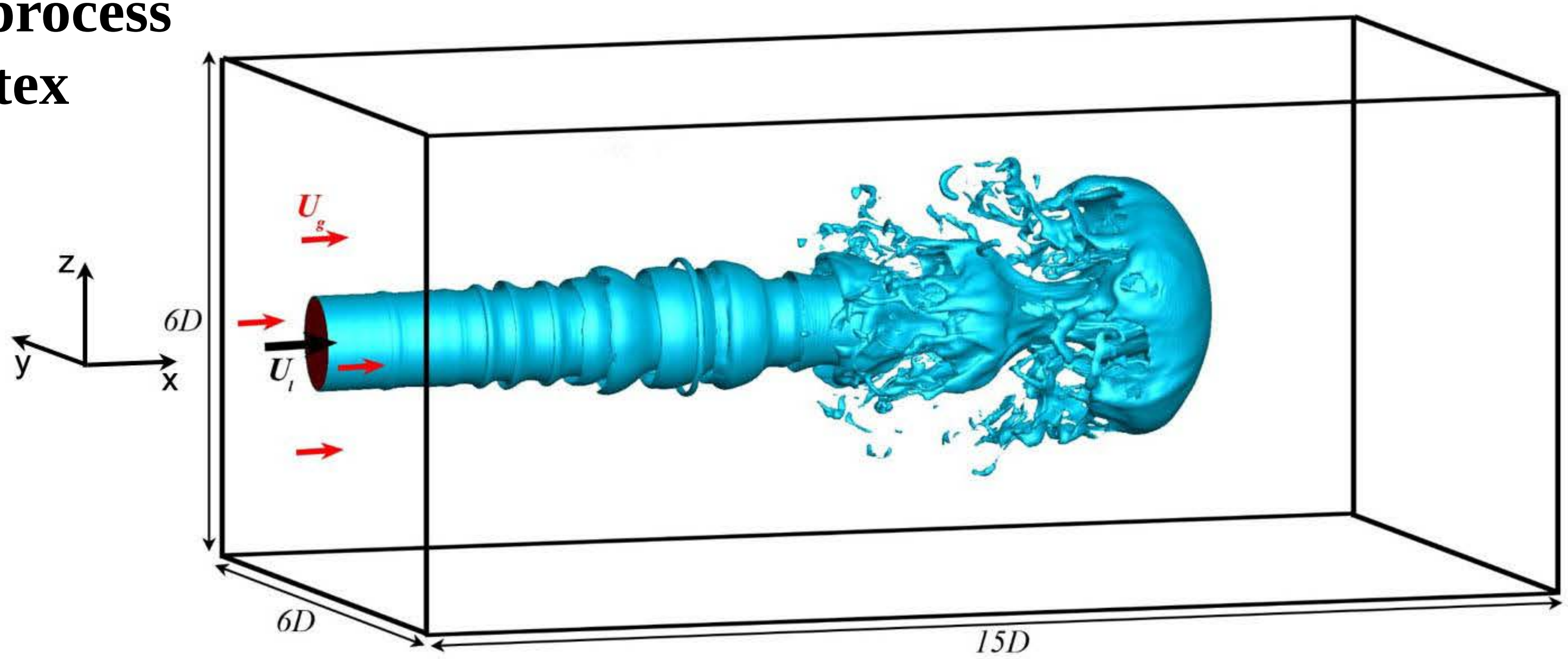
Numerical Method

QUICK for spatial discretization – 2 μm mesh;

Crank-Nicolson time marching; **SIMPLE Algorithm;**

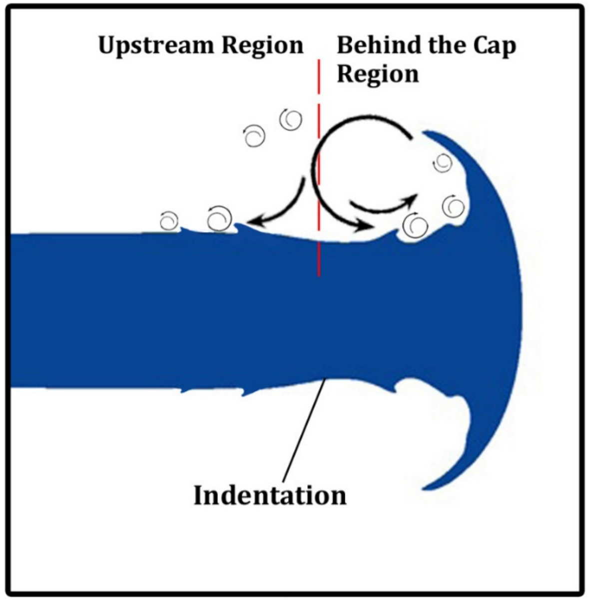
Volume of Fluid (VoF) with piecewise linear interface calculation (PLIC);

λ_2 method for post-process identification of vortex structures.

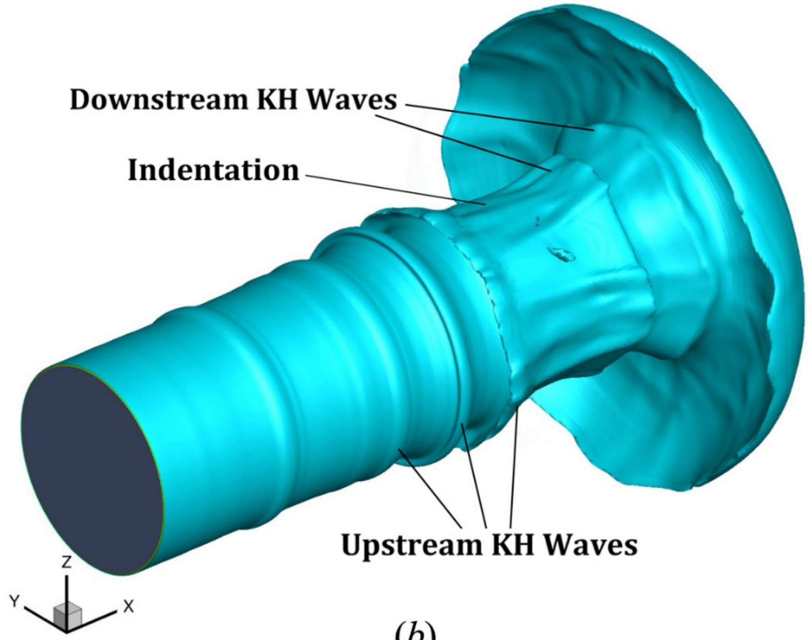


Starting Behavior

- 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.



(a)



(b)

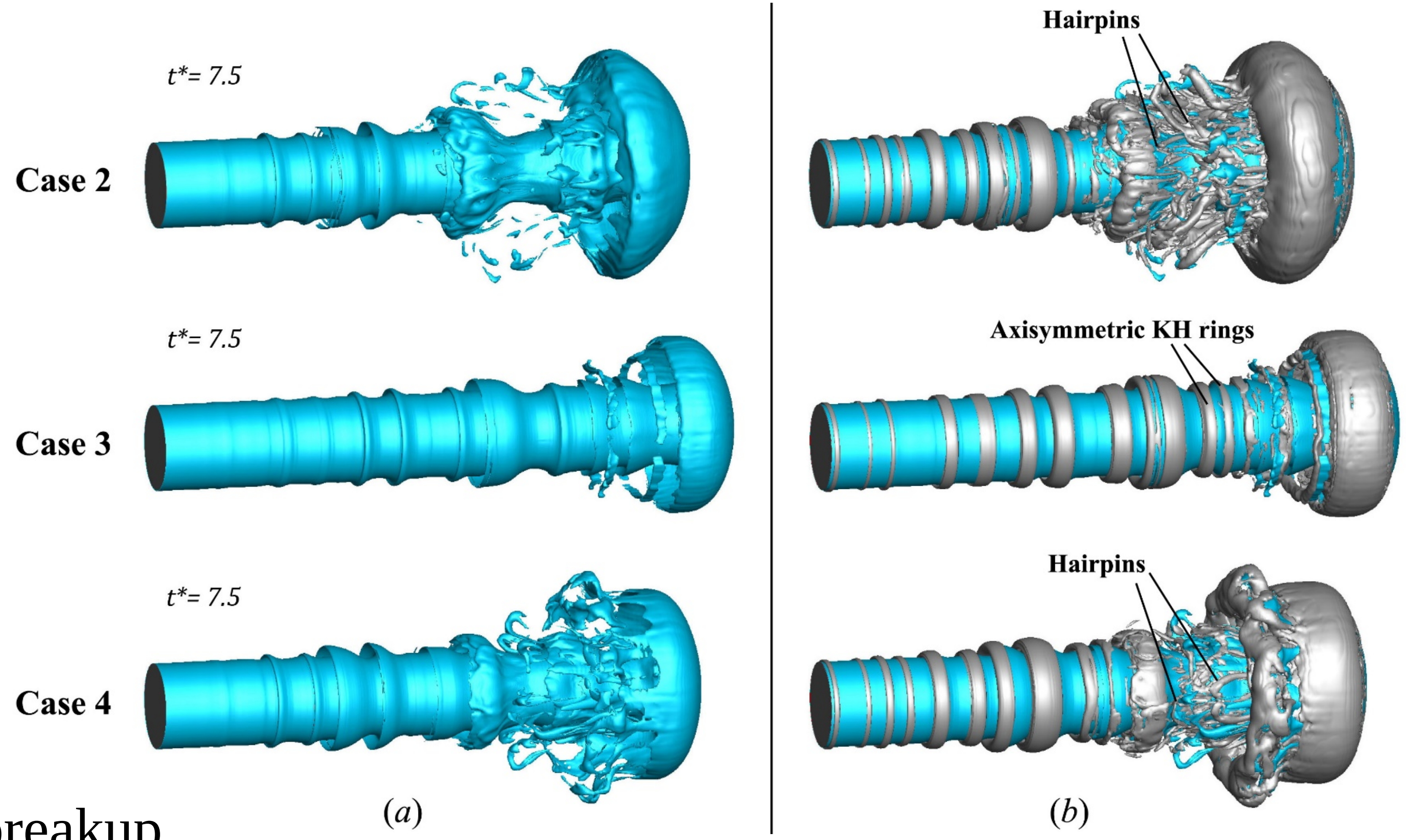
Behaviors in Different Domains

- 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.

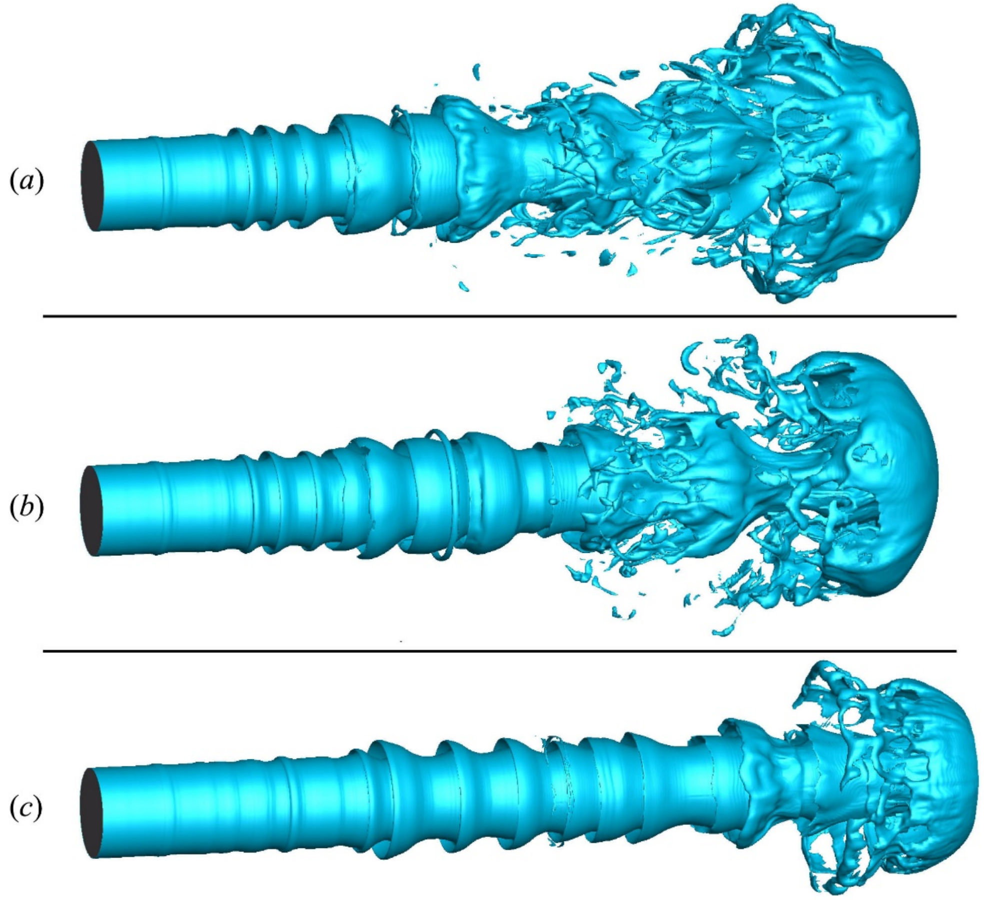
- Slower development in the more viscous Case 3, i.e., with the lower Re value based on relative velocity.

- 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

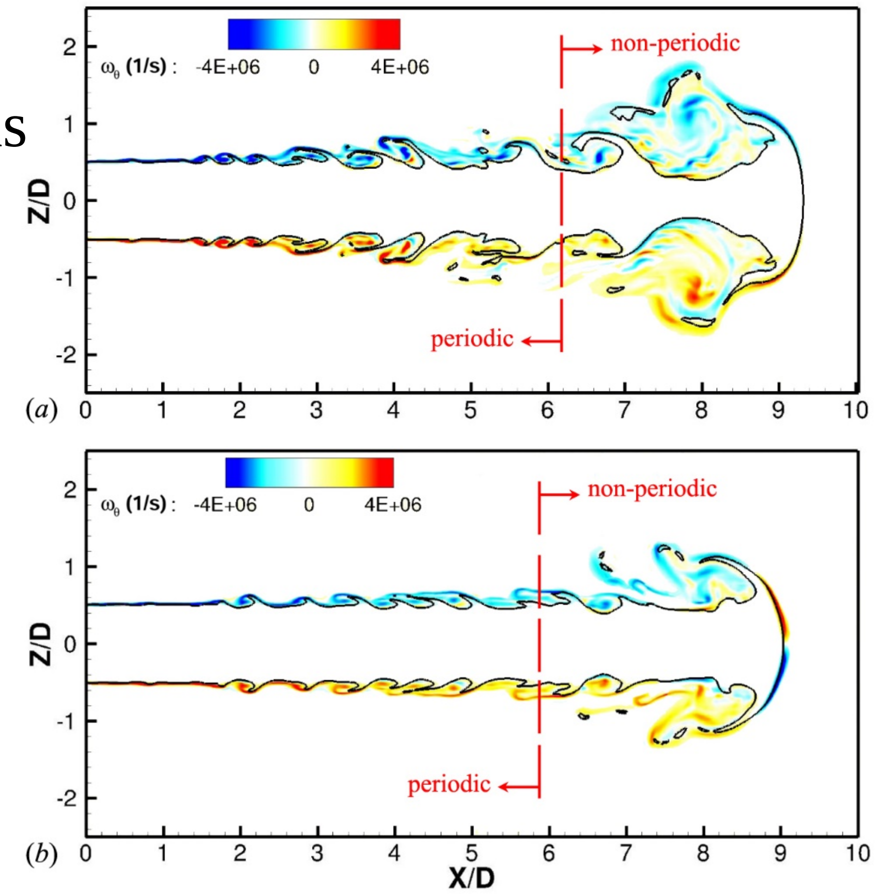
- Periodic KH waves on the upstream portion
of the KH wave with non-periodic behavior downstream for both Case 1 (upper) and Case 3 (lower).

- 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

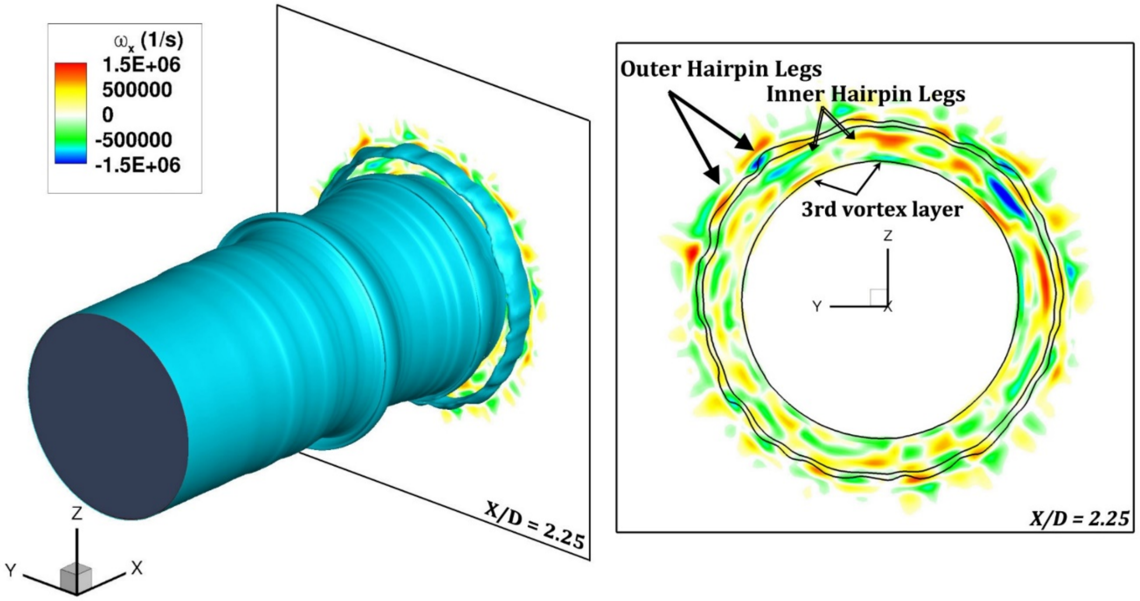
- Axisymmetric KH surface waves with associated vortex rings grow with downstream flow.

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

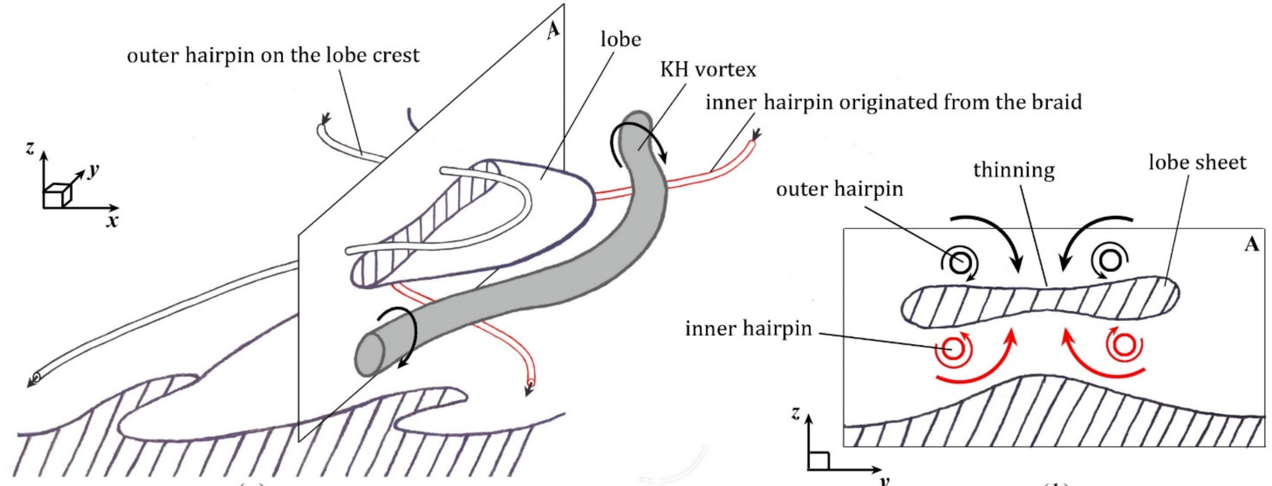
- Two layers of hairpins appear at first with a phase difference of 180°. They correlate
with the lobe structure. The layer outside the lobe stretches downstream and becomes
an inner layer for the next downstream lobe.

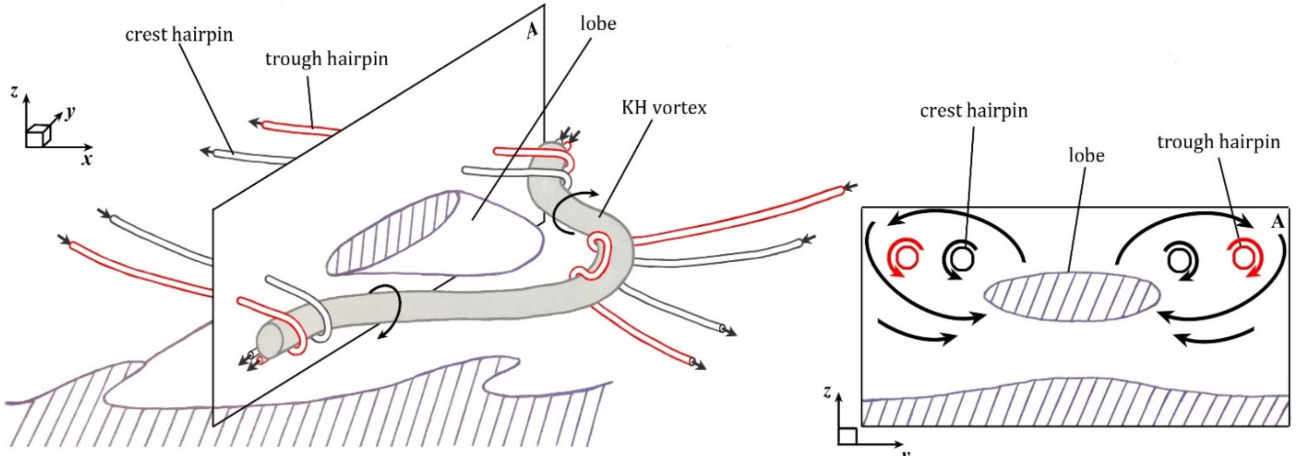
- The inner layer stretches upstream and becomes
the outer layer for the next upstream lobe.

- 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



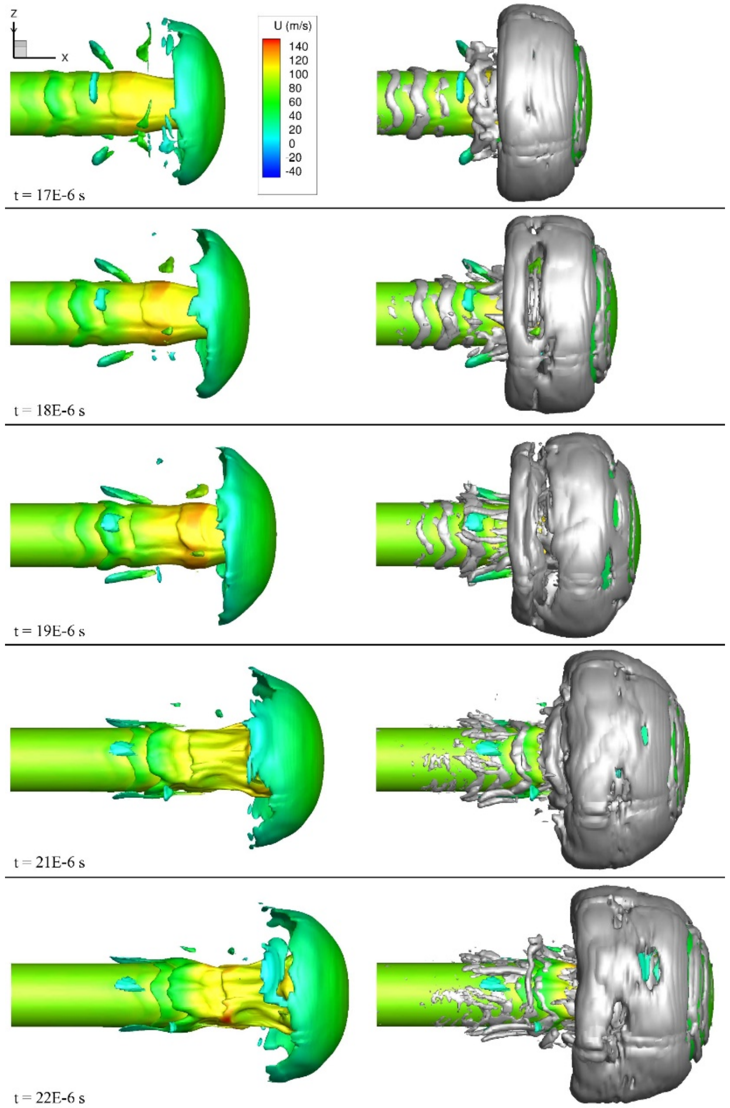


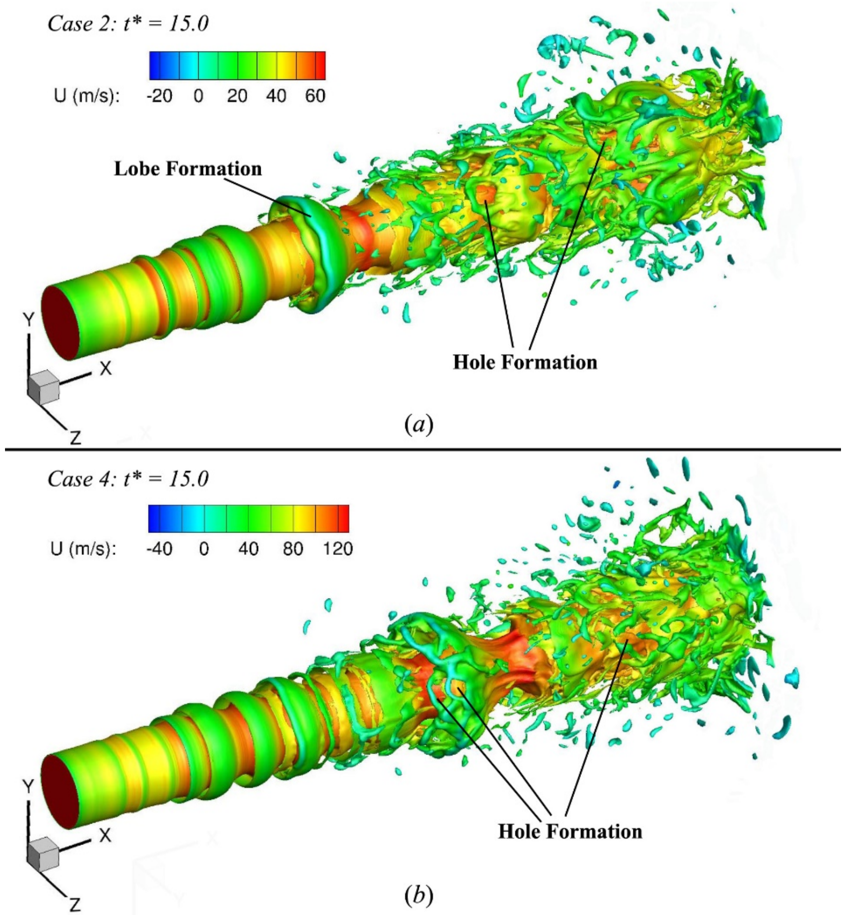
- Hairpins have opposing rotation to major KH rollers.
- Case 1 (upper sketch) has overlapping hairpins from upstream braid and downstream lobe.
- Resulting streamwise vorticity promotes perforations in the lobe.
- Case 3 (lower sketch) has wrapping of hairpins around KH roller with appearance of third 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.


z
x
U (m/s)
140
120
100
80
60
40
20
0
20
-40
t = 17E-6 s
t = 18E-6 s
t = 19E-6 s
t = 21E-6 s
t = 22E-6 s


Case 2: t* = 15.0
U (m/s): -20 0 20 40 60
Lobe Formation
Hole Formation
Y
X
Z
(a)
Case 4: t* = 15.0
U (m/s): -40 0 40 80 120
Hole Formation
Y
X
Z
(b)