

Numerical and experimental investigation of flow instabilities in the presence of a viscosity gradient

SAND2016-12169C

American Physical Society,
Division of Fluid Dynamics
Portland, OR

Ryan Keedy
Alberto Aliseda

November 20-22, 2016

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.



Effect of Viscosity Gradient

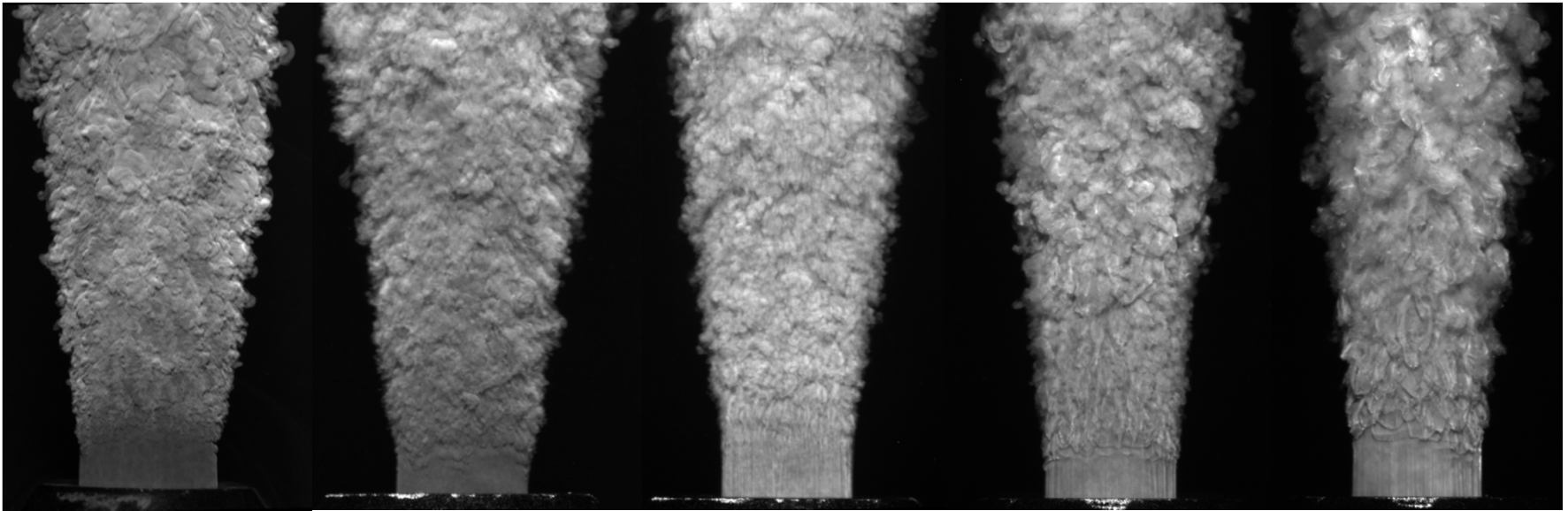
$$\mu_a / \mu_j = 2$$

$$\mu_a / \mu_j = 1$$

$$\mu_a / \mu_j = 0.5$$

$$\mu_a / \mu_j = 0.1$$

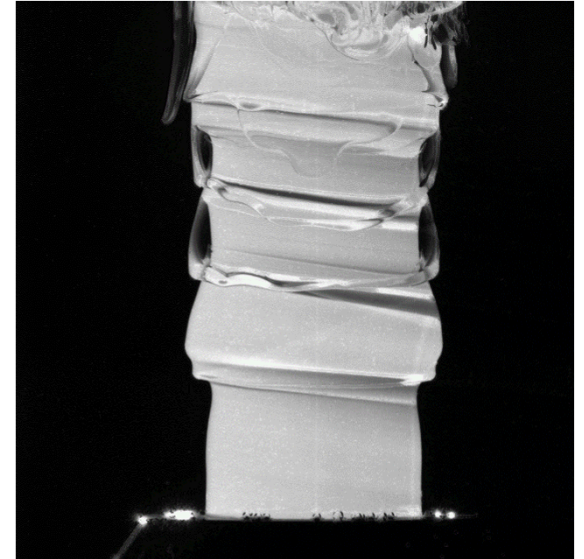
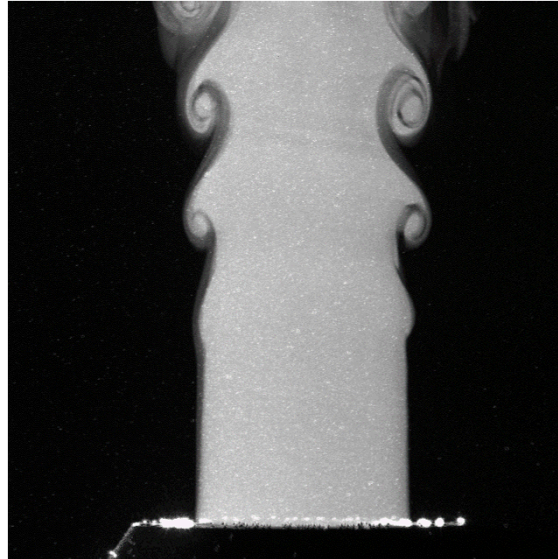
$$\mu_a / \mu_j = 0.01$$



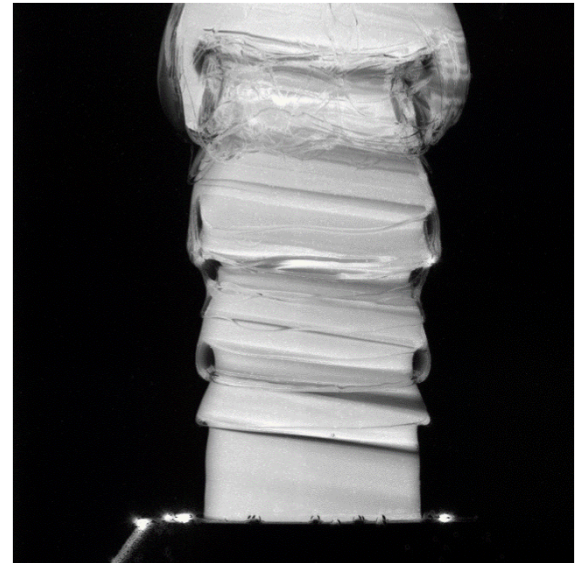
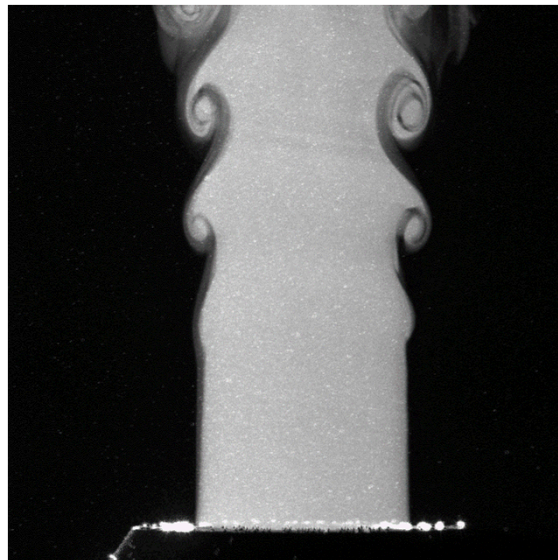
Jet viscosity has a significant effect on the nature of the jet breakup and its spreading rate

Viscosity Ratio Becomes Important

Constant Velocity

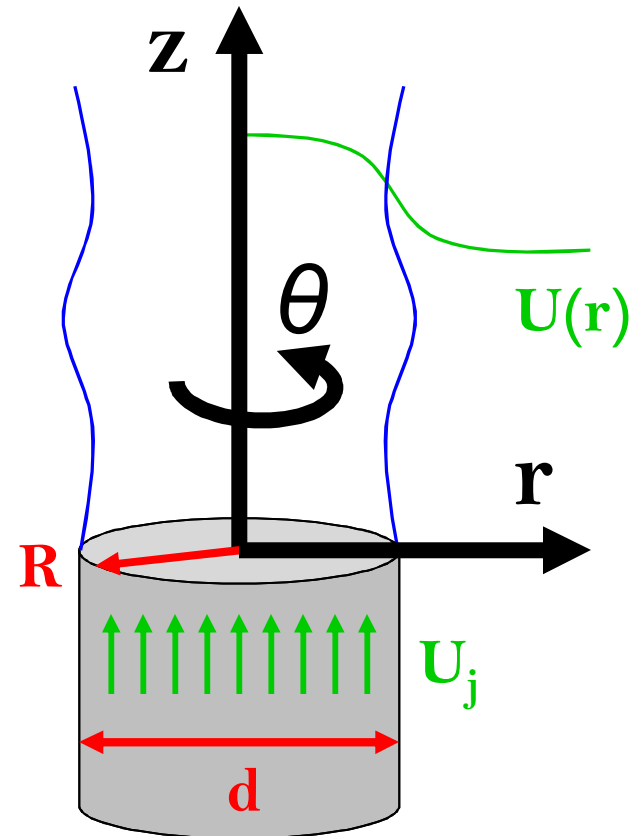


Constant Jet Re #



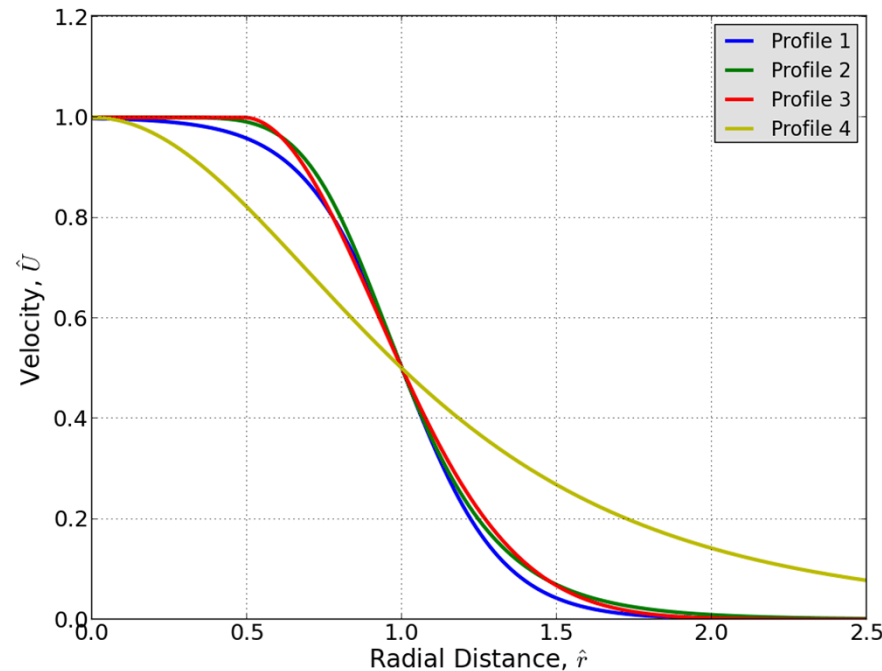
Stability Analysis Approach

- Domain with cylindrical coordinates
- Unperturbed flow is assumed to be axisymmetric
- Spatial stability analysis most appropriate for spatially developing free shear flow
 - Temporal stability analysis is easier/more common in the literature
- Focus initially on axisymmetric disturbances
- Spectral analysis using Chebyshev polynomials to discretize the derivatives
- Gauss-Lobatto collocation points help to avoid numerical issues at the boundary



Stability Analysis Approach

- Several different velocity profiles have been used in the literature

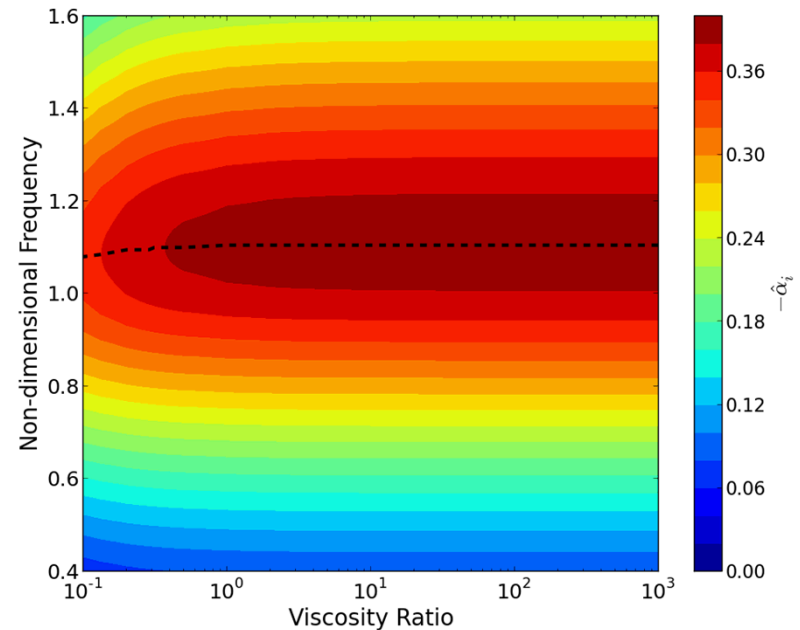
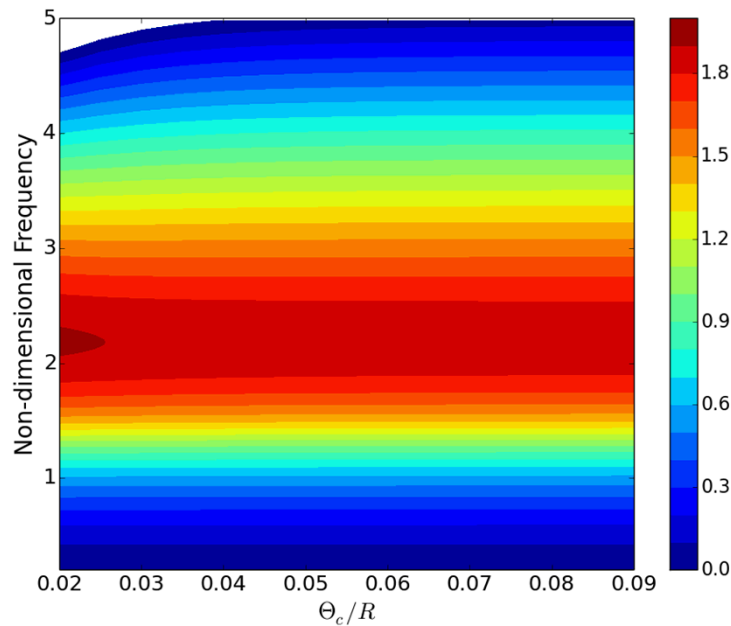


- Early jet development velocity/concentration profile approximation:

$$U = 0.5 \left\{ 1 + \tanh \left[\frac{R}{4\Theta} \left(\frac{R}{r} - \frac{r}{R} \right) \right] \right\}$$

Initial Results

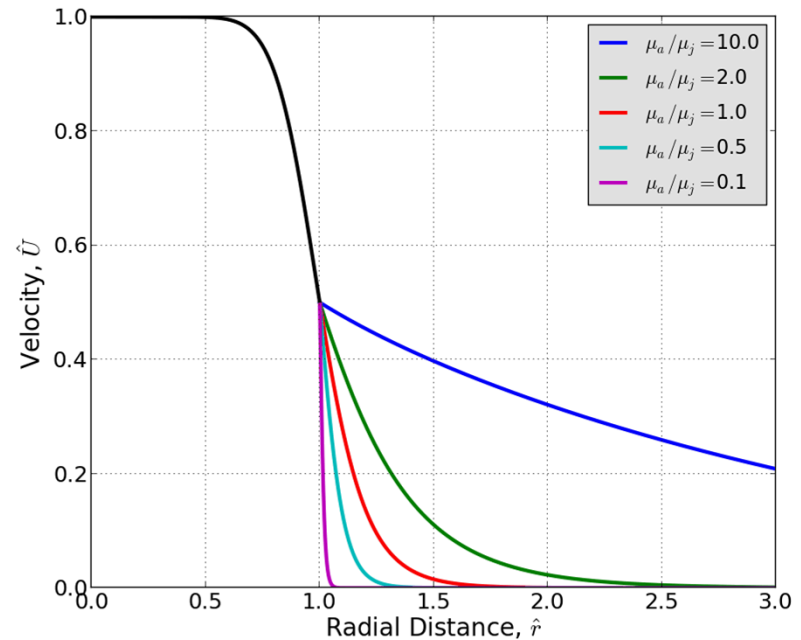
Contour plots of most unstable eigenvalues



- Stability characteristics are fairly insensitive to considerable range of concentration ratios and gradients

Approximate Velocity Profile

- Variations in stability are inconsistent with experimental observations (too small)
- Velocity profile likely does not reflect modified velocity due to viscosity
- Piecewise profile used to reflect different viscosities, matching shear at interface

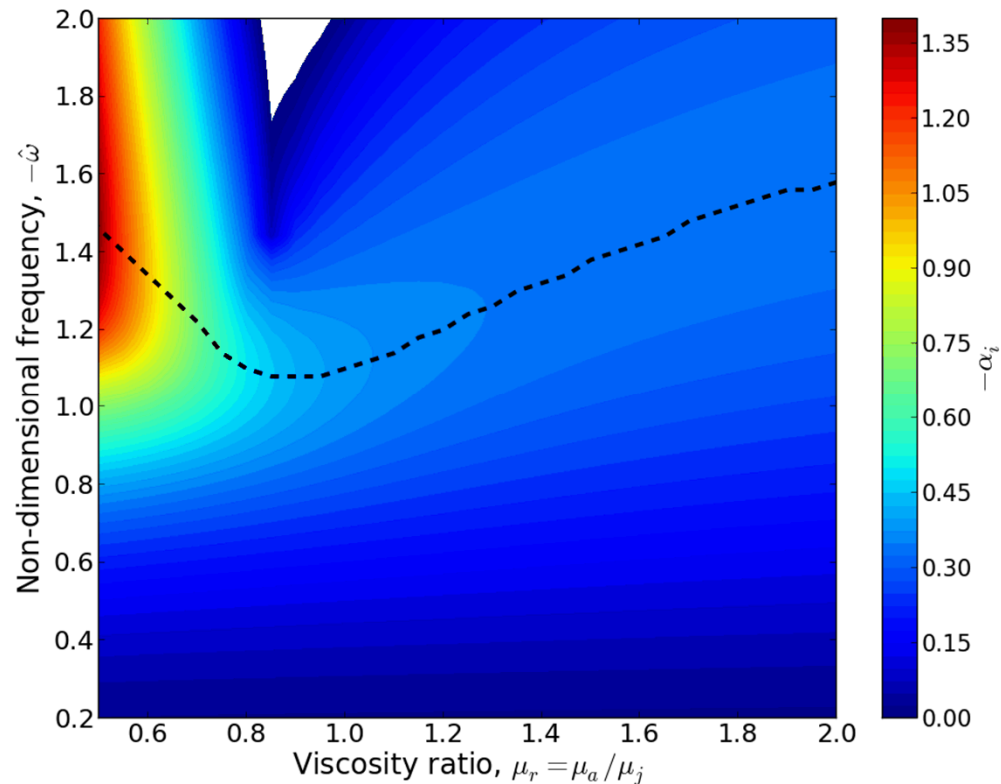


$$U_1 = 0.5 \left\{ 1 + \tanh \left[\frac{R}{4\Theta_1} \left(\frac{R}{r} - \frac{r}{R} \right) \right] \right\} \quad r \leq R$$

$$U_2 = 0.5 \left\{ 1 + \tanh \left[\frac{R}{4\Theta_2} \left(\frac{R}{r} - \frac{r}{R} \right) \right] \right\} \quad r > R$$

Results

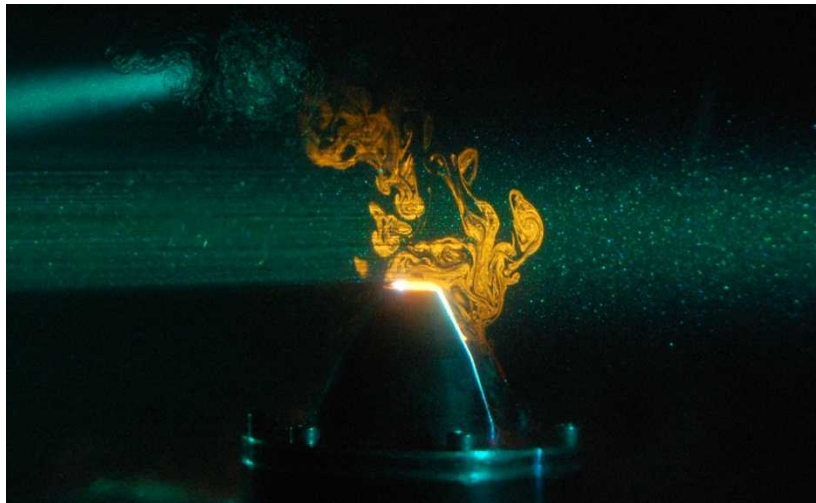
- Concentration terms/equations are disregarded (their effect is manifest in the velocity/viscosity terms)
- Most unstable frequency increases as viscosity ratio deviates from ~ 1



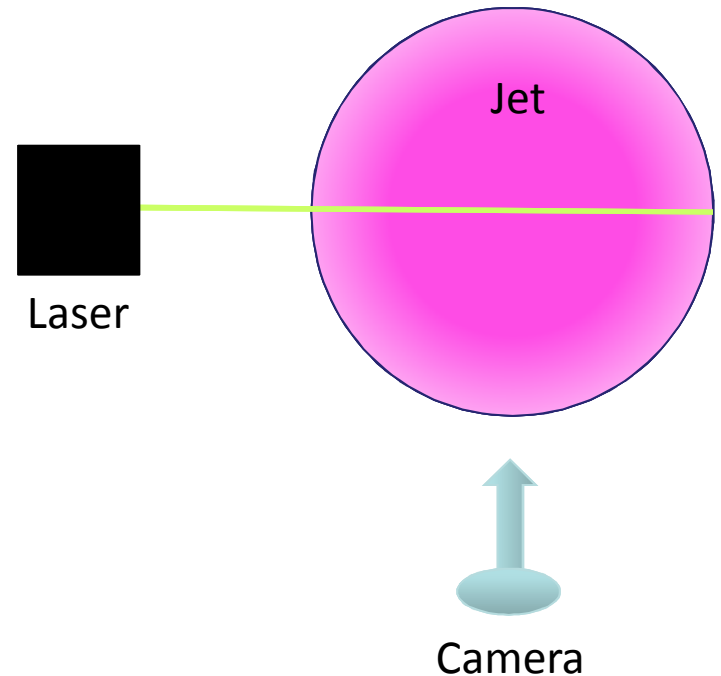
Instability magnitude contours

Experimental Setup

- Jet was dyed with Rhodamine
- Laser was used to create a plane of illumination within the jet
- Fluorescence intensity from the sharp scalar concentration interface delimits the jet interior



Top-down view

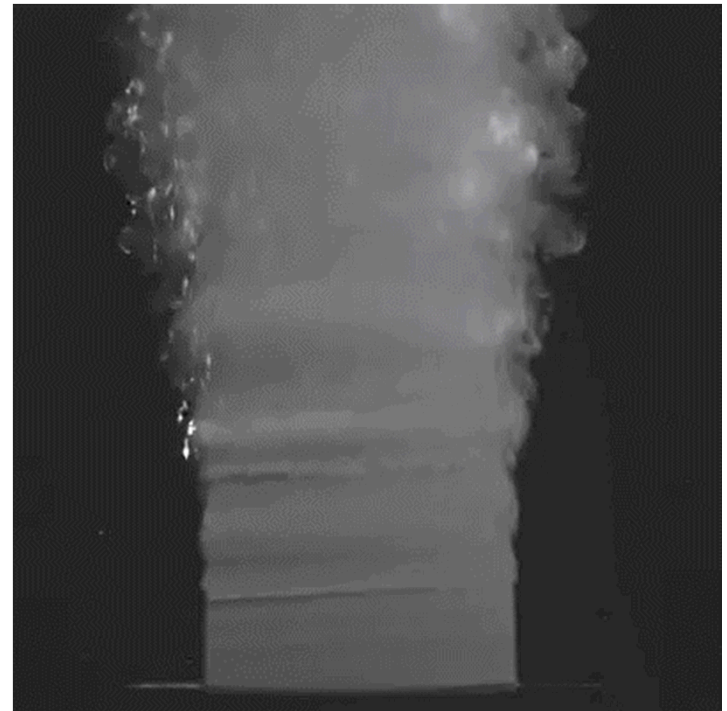


Experimental High Speed Video

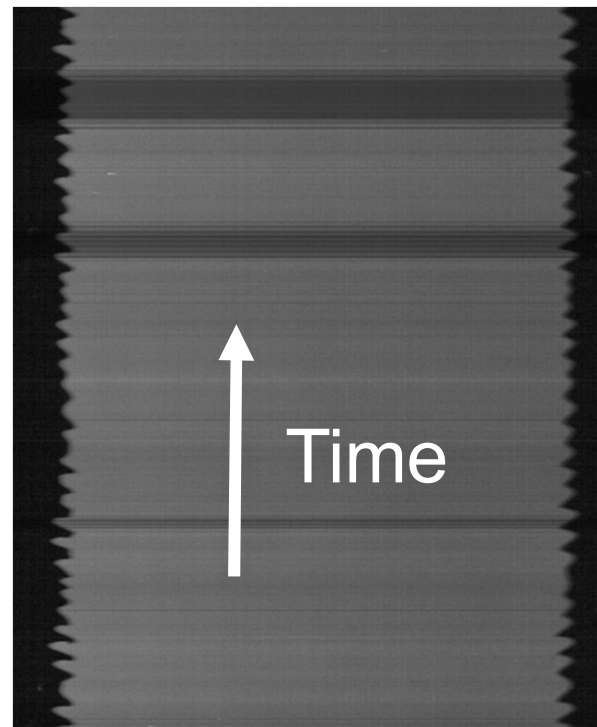
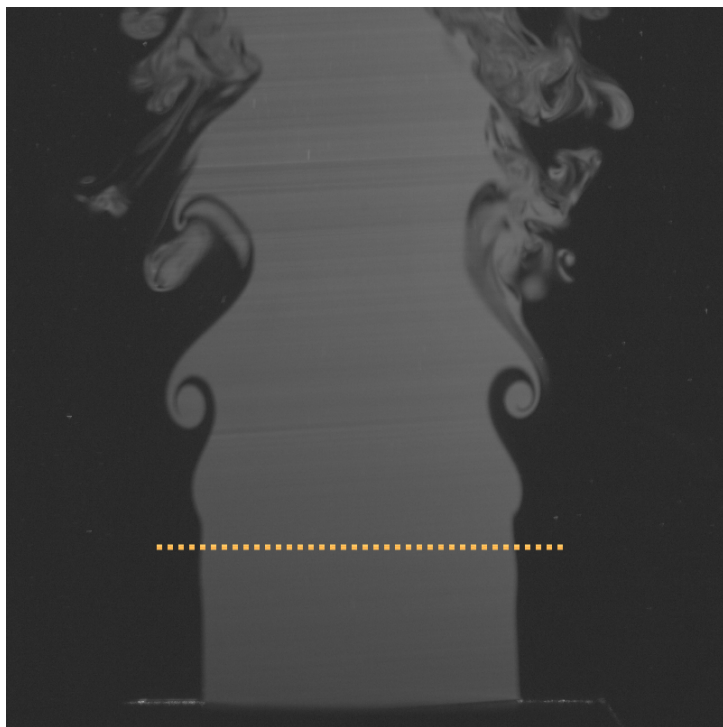
0.8 cP jet viscosity



2 cP jet viscosity



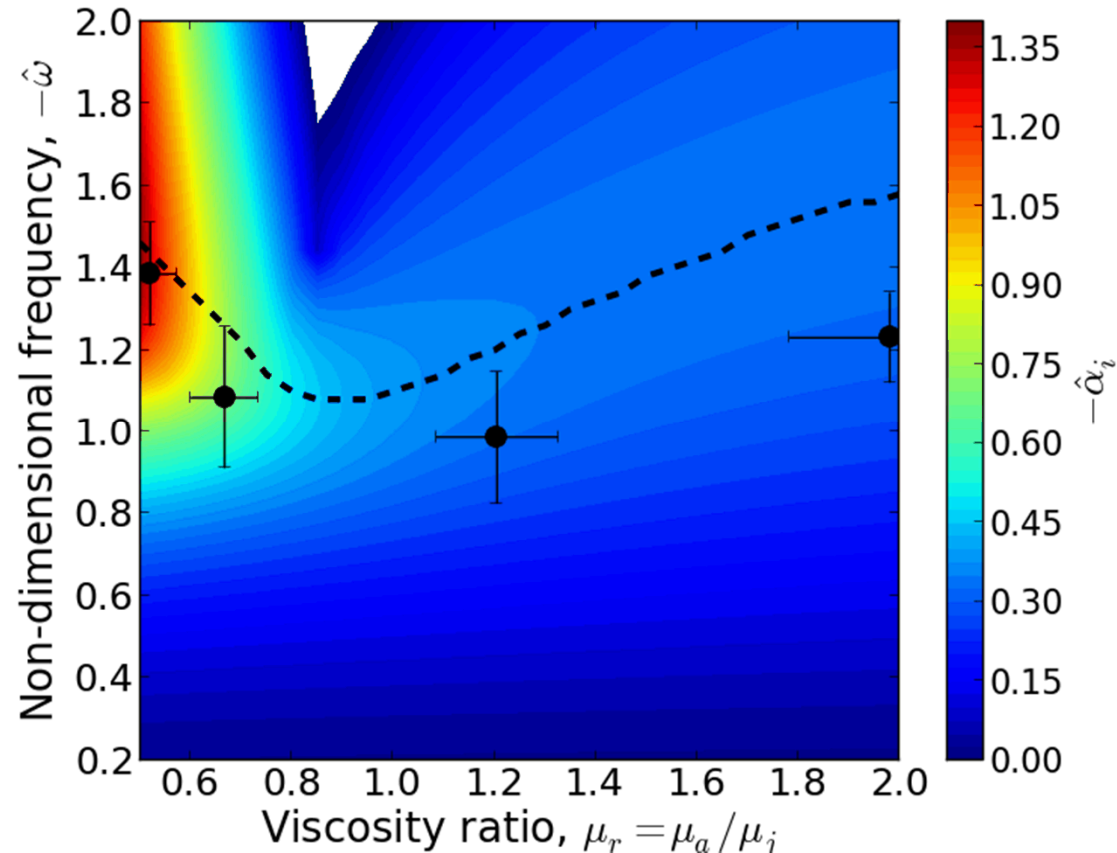
Measuring Frequency



- Single pixel-wide row for each frame
- Stitched together from successive frames

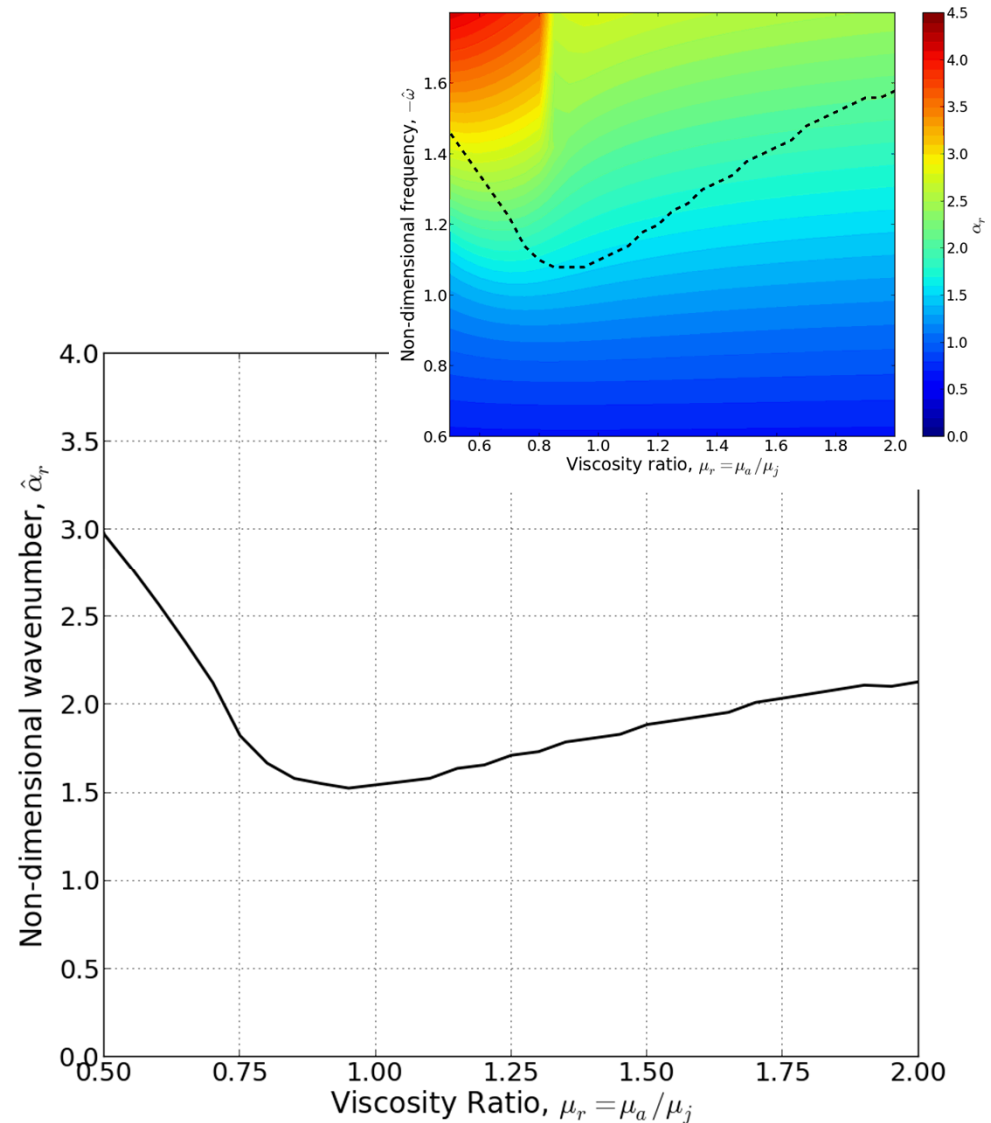
Frequency Response Comparison

- The predictions from the stability analysis are consistent with measured frequencies of experiments for a range of viscosity ratios

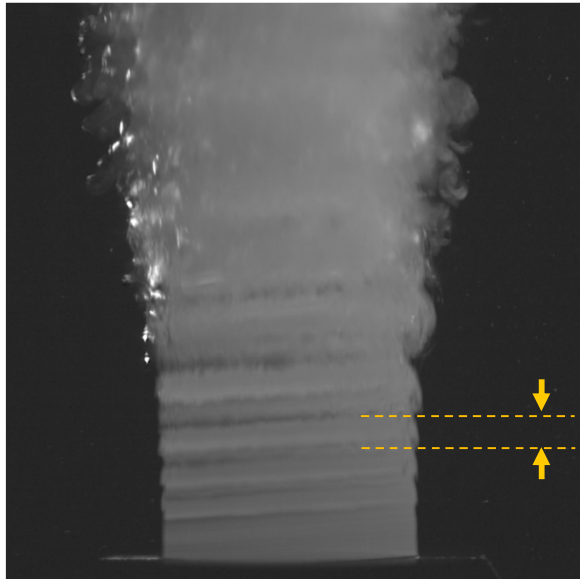


Results (Wavenumber)

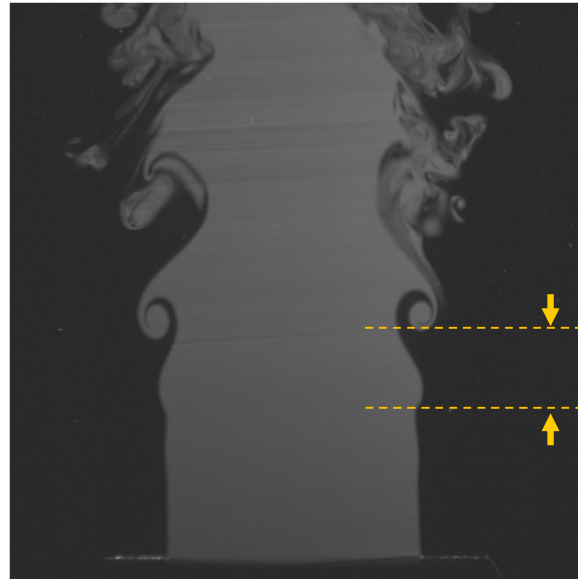
- Wavenumber also increased away from viscosity ratio of ~ 1
- Expect smaller instability features, especially at lower viscosity ratios (relatively high jet viscosity)



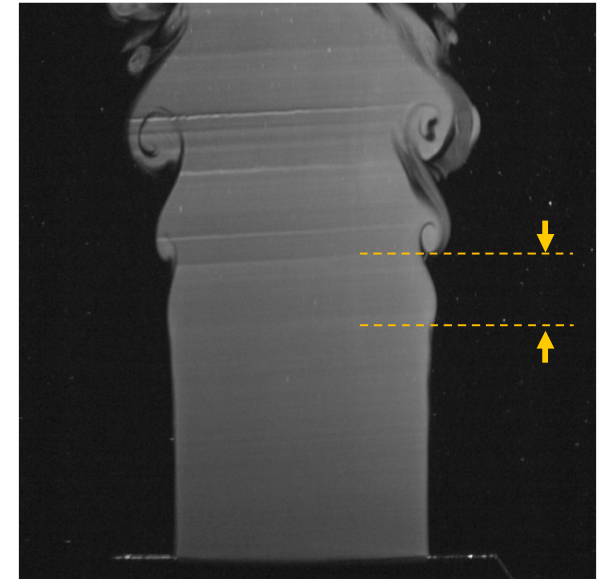
Instability Scale



$$\mu_a / \mu_j = 0.5$$

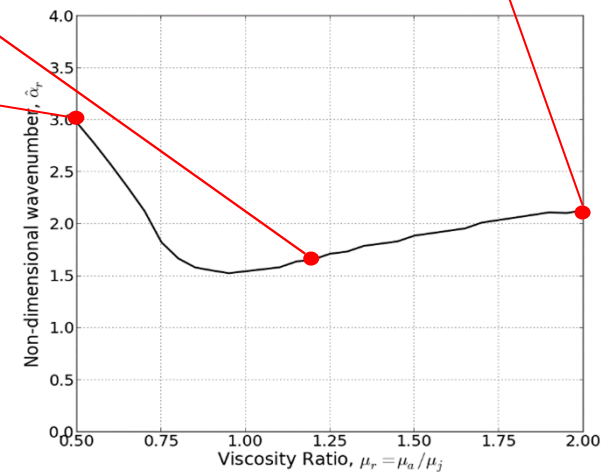


$$\mu_a / \mu_j = 1.2$$

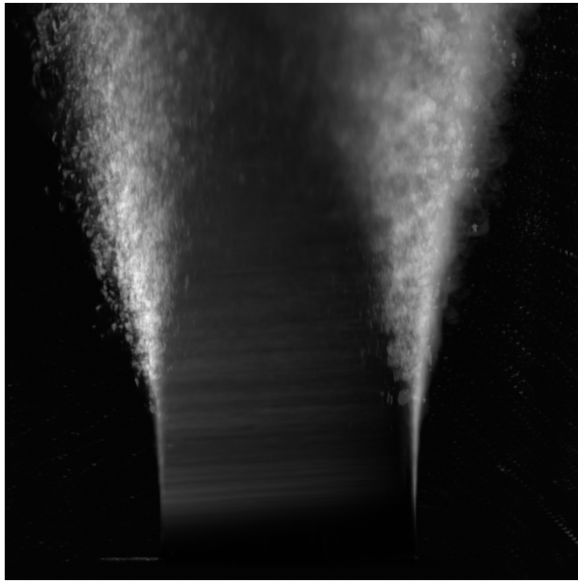


$$\mu_a / \mu_j = 2$$

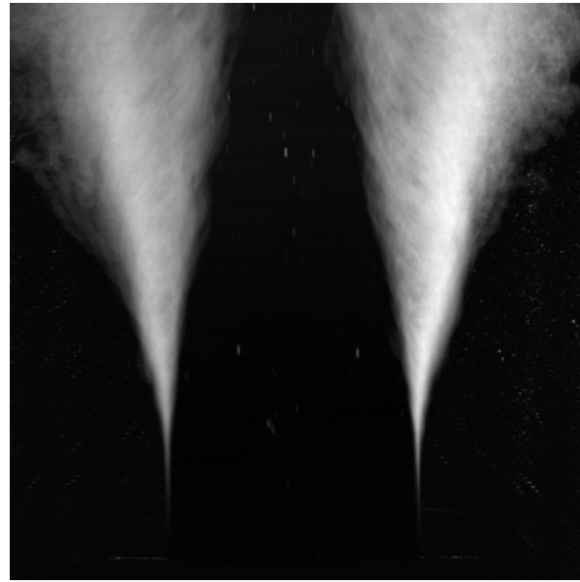
- High viscosity jet shows much smaller disturbances



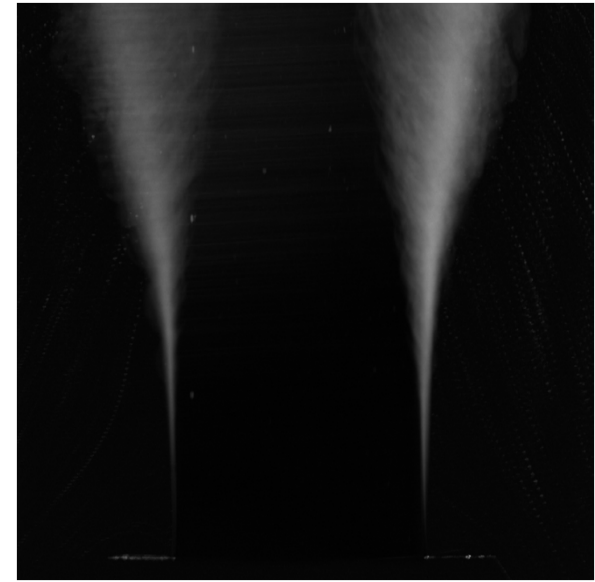
Standard Deviation Plots



$$\mu_a / \mu_j = 0.5$$



$$\mu_a / \mu_j = 1.2$$



$$\mu_a / \mu_j = 2$$

- (Nearly) Uniform viscosity jet experiences the most spreading
 - Viscosity differences seem to inhibit entrainment
 - Likely due to size of instabilities

Conclusions

- For high viscosity jets, engulfment is significantly inhibited by smaller instabilities
- Low viscosity jets have comparably large disturbances, but they will have more trouble straining/entraining more viscous ambient fluid
- Maximum entrainment/spreading is achieved near viscosity ratio of unity