

Flame Speed Sensitivities for Modeling Launch Vehicle Explosion Risk

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Motivation

- Large, explosive failures are dangerous and cause significant damage
- A lot of research has gone into studying accident risk for hydrogen storage facilities and petrochemical sites
- Interest here is on uncontained failures in rocket engine bays
- Need to be able to model the explosion risk for launch vehicles

Modeling Options

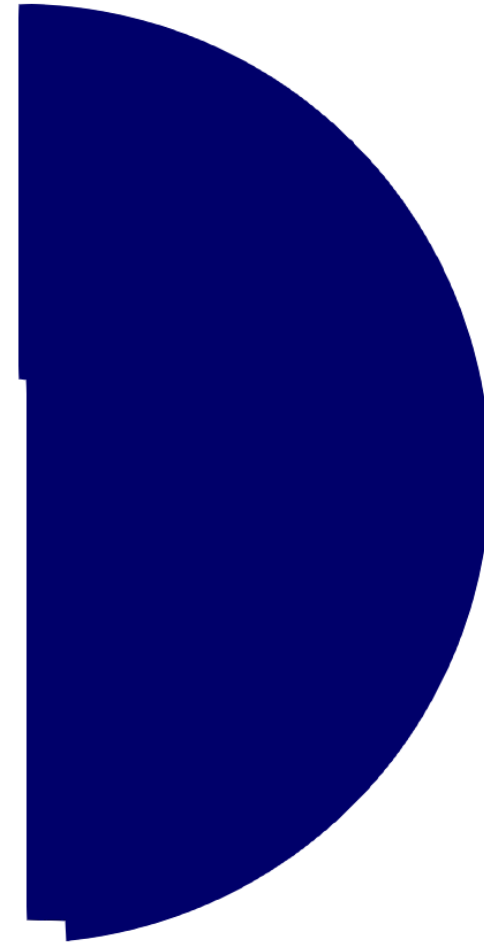
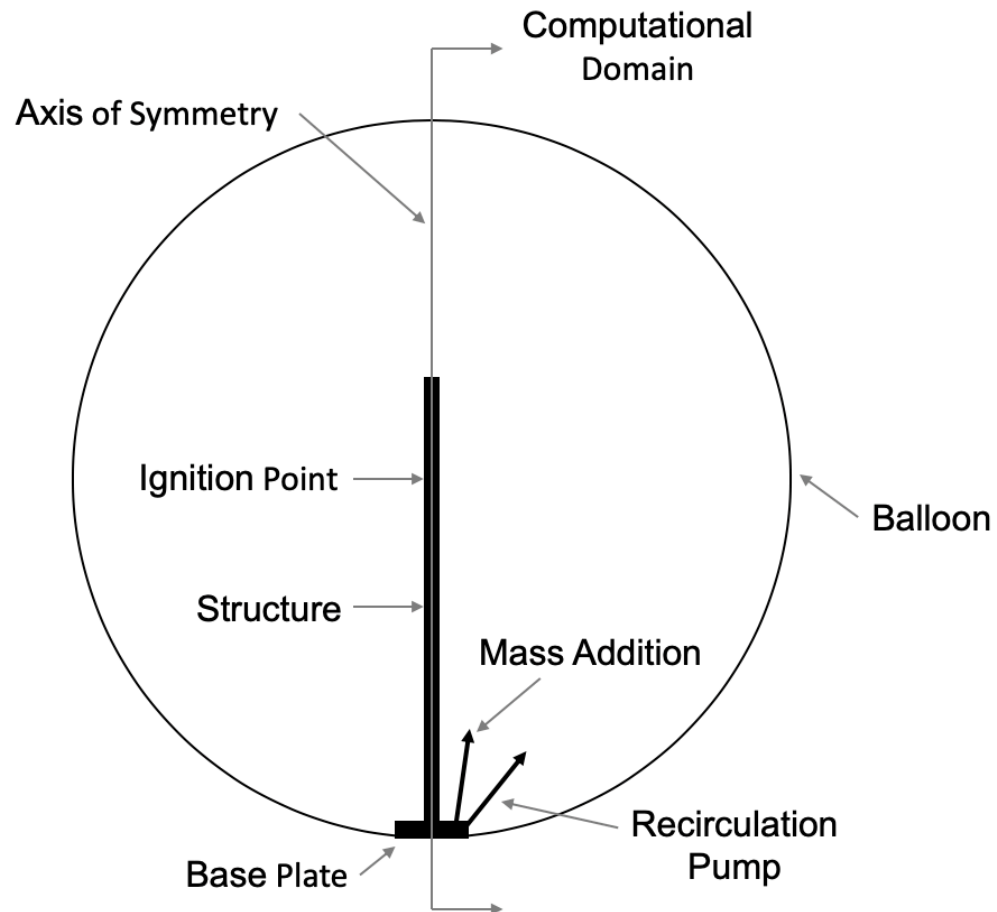
- Options for characterizing physical environment to perform risk assessments
 - Computational fluid dynamics (CFD) simulations
 - Running physical experiments
 - Developing an engineering risk model
- Engineering risk models have the fastest turnaround time
 - Typically used to support large vehicle design and certification
 - Informed by CFD and experiments

Study Goals

- Perform numerical simulations over a range of initial conditions
- Compare to experimental and model results
- Provide an understanding of flame speed sensitivities
- Determine when engineering models may need higher fidelity inputs to anchor model results

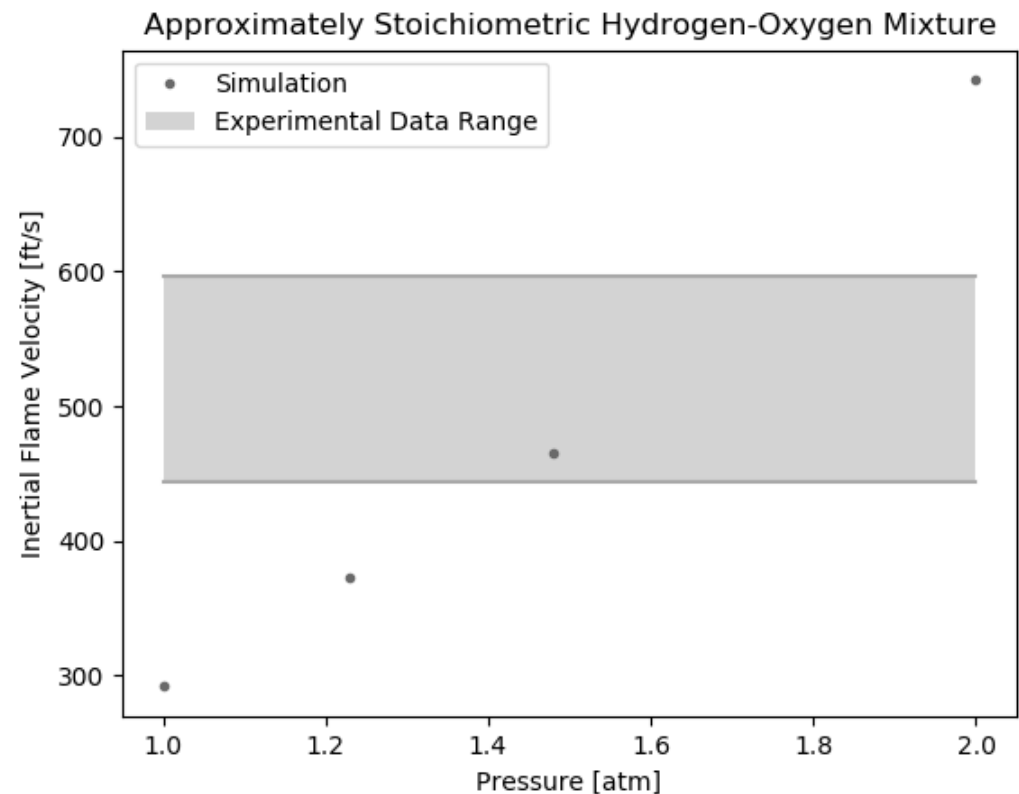
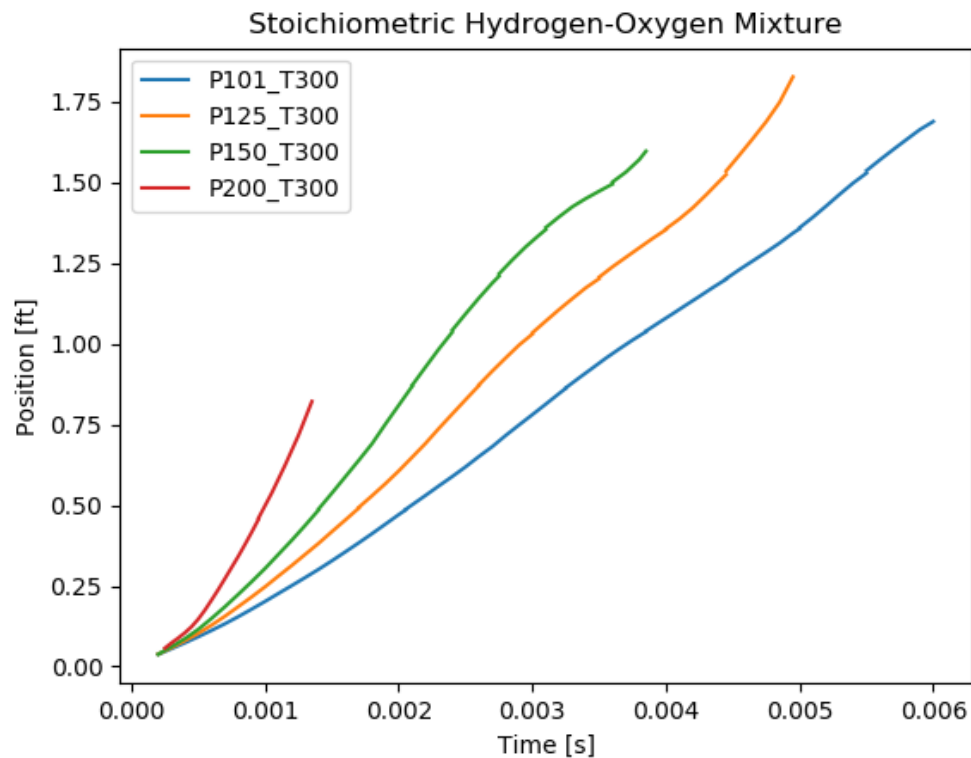
Geometry

- Geometry representative of Hydrogen Unconfined Combustion Test Apparatus experiments

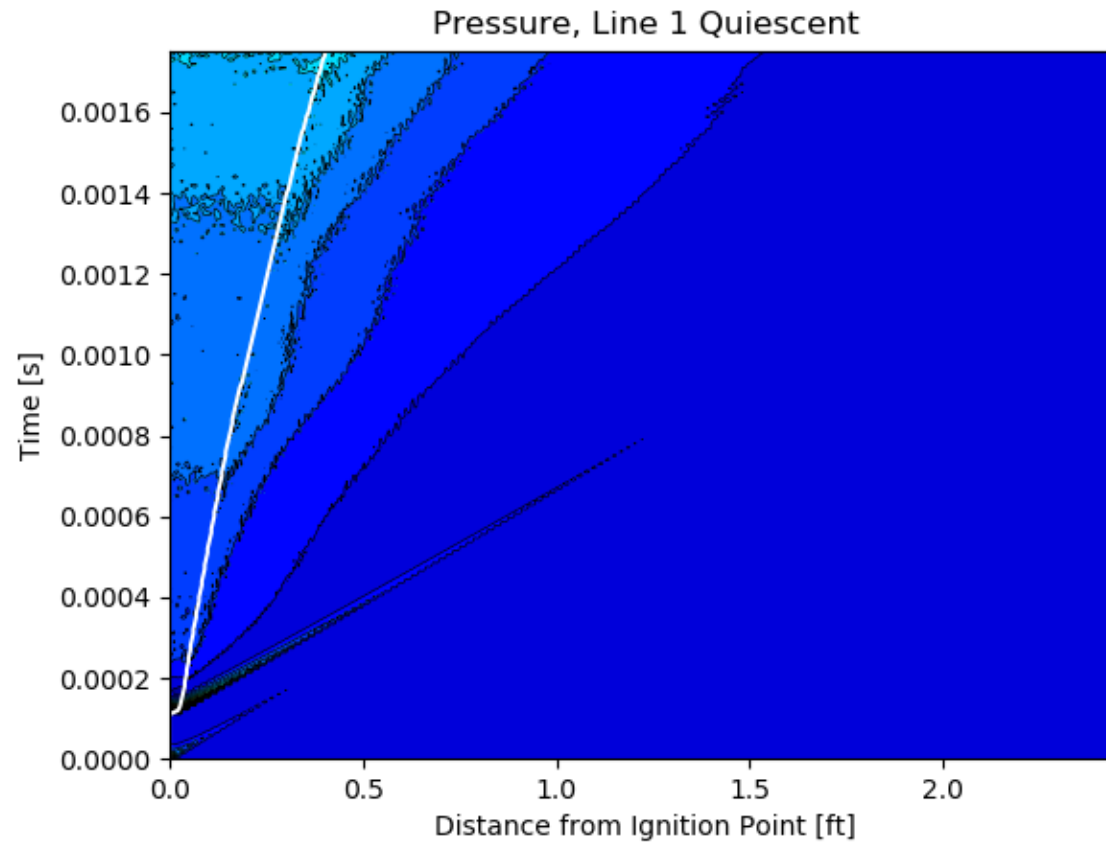


Initial Pressure Variation

- Quiescent flow (no velocity)
- Vary initial pressure from 1 to 2 atm
- Constant initial temperature, density varies with pressure

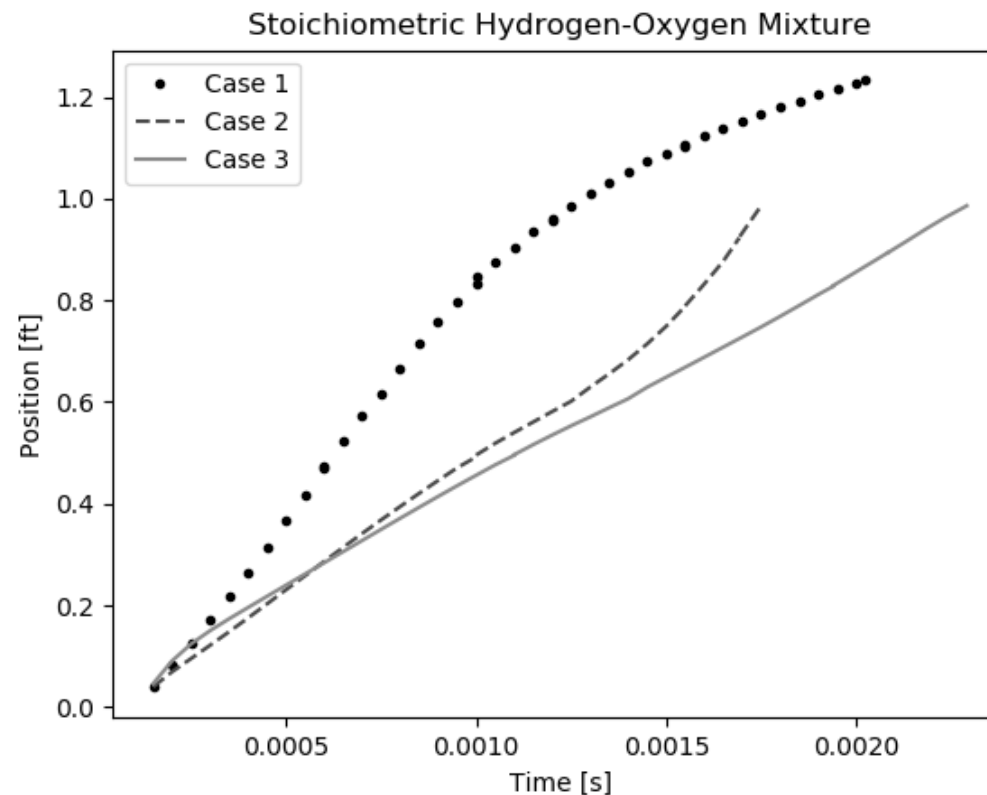


Initial Pressure Variation



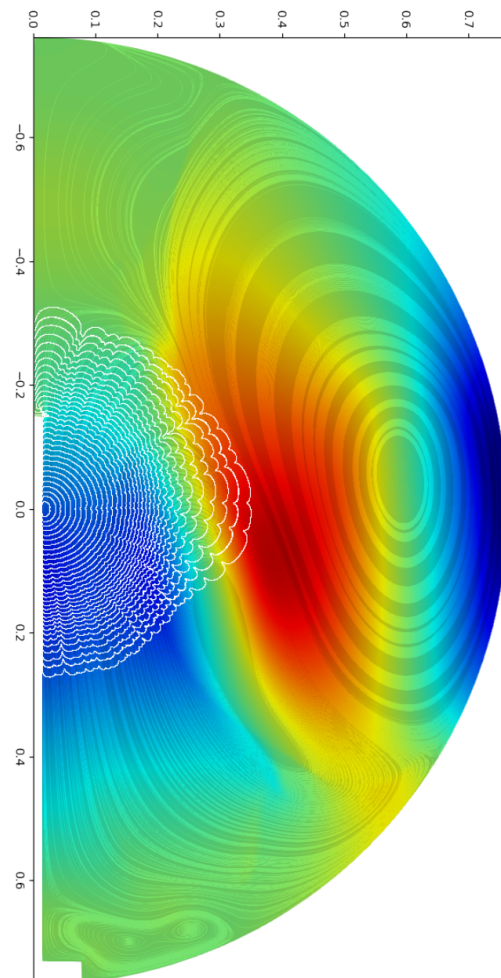
Initial Velocity Variation

- Simulate adding mass from base plate
- Introduces velocity into the balloon
- Simulate 3 distributions using different settling times

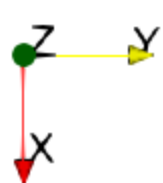
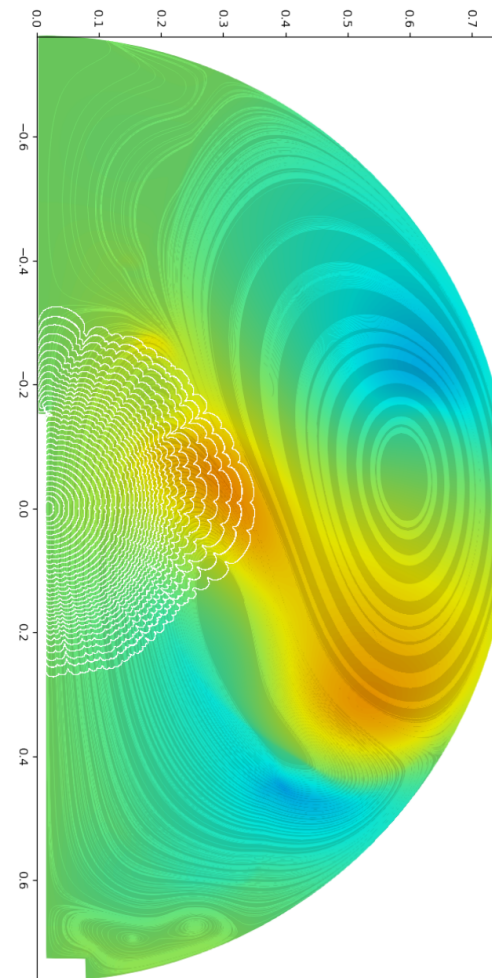


Initial Velocity Variation

x-velocity

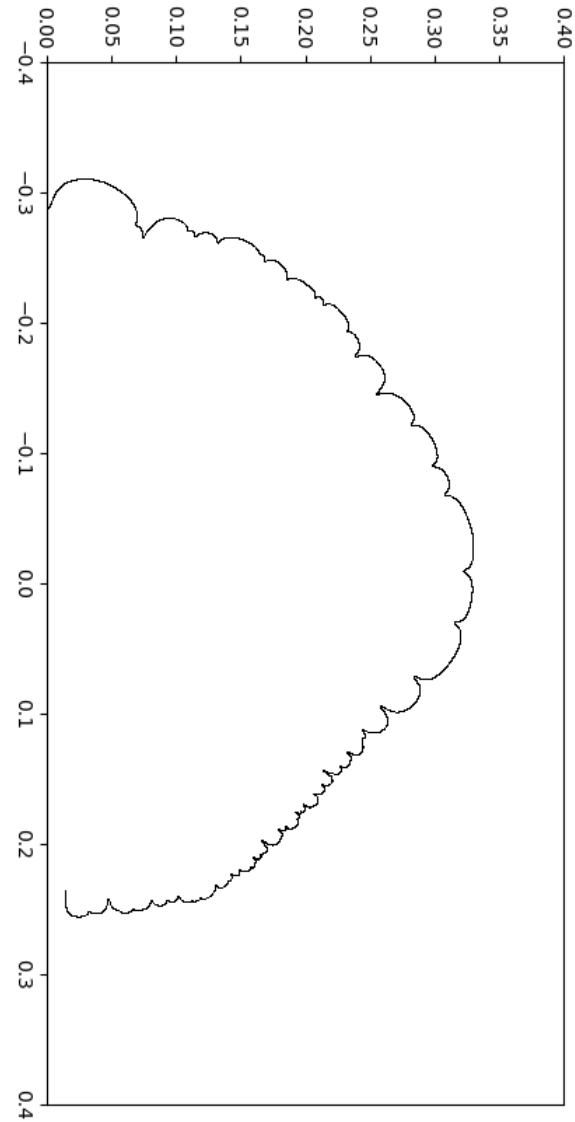


y-velocity

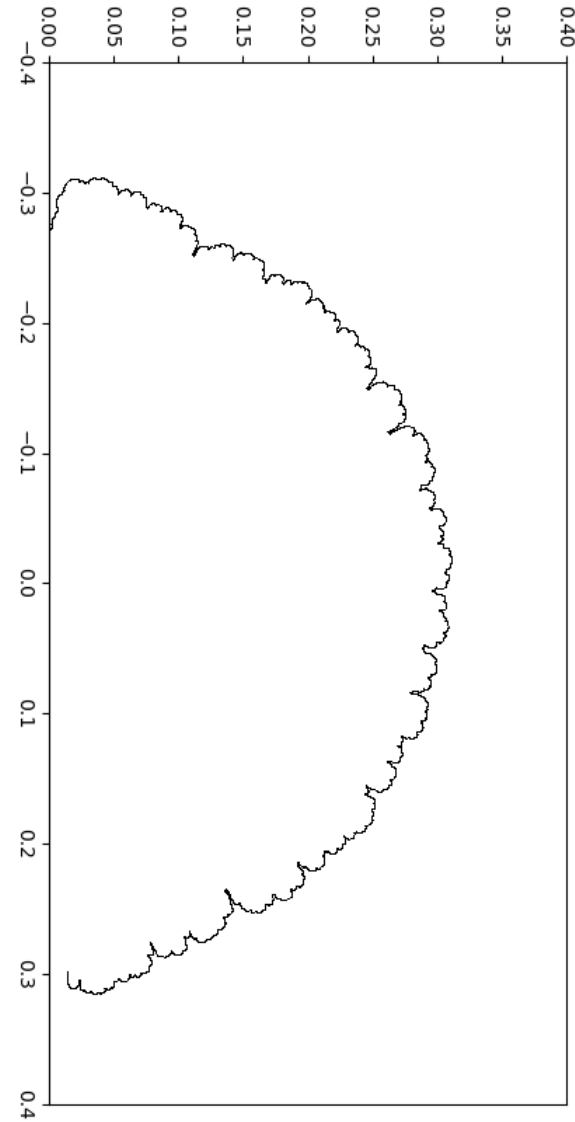


Initial Velocity Variation

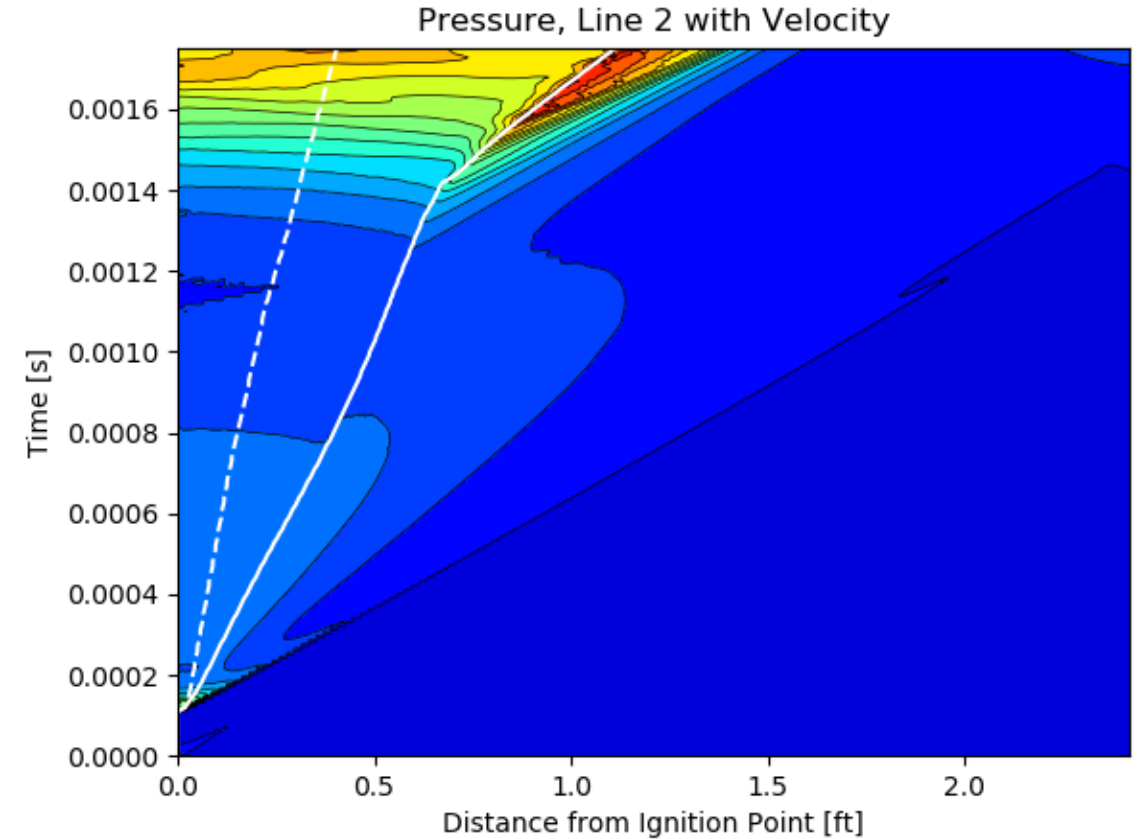
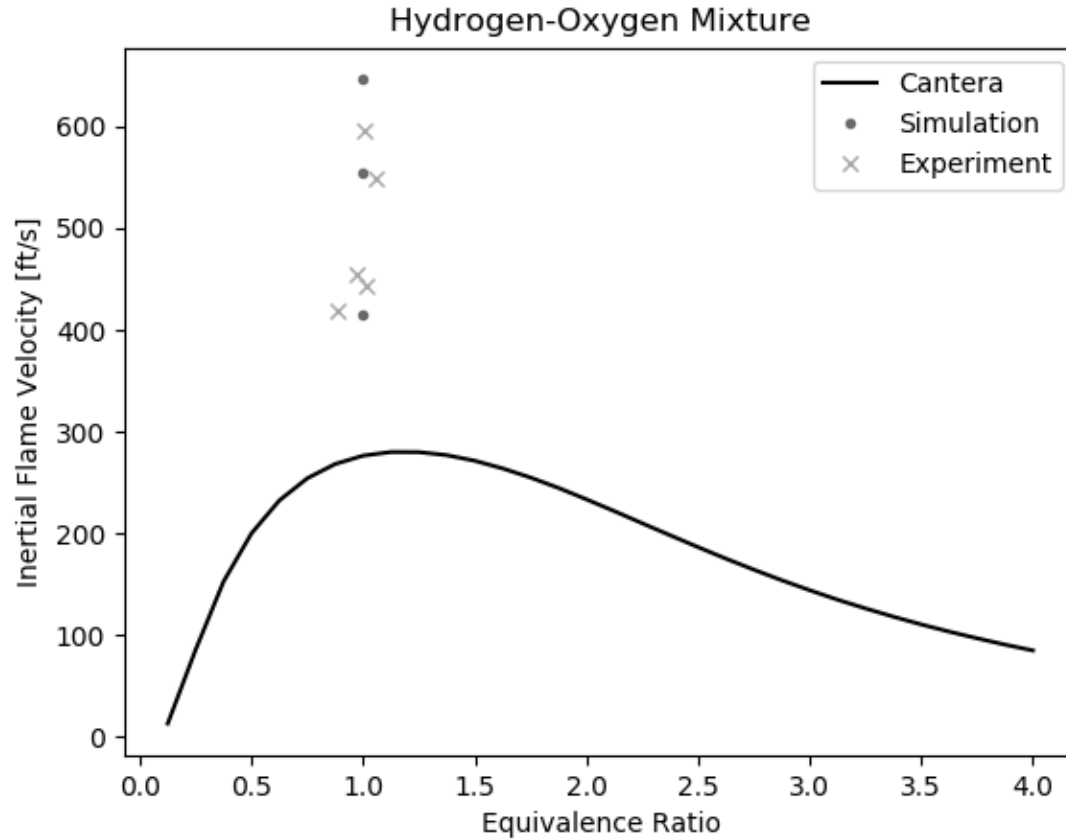
Non-Quiescent,
Stoichiometric,
Case 2



Quiescent,
Stoichiometric,
 $P = 125$ kPa



Initial Velocity Variation



Mixture Ratio Variation

- Considered fuel lean and fuel rich scenarios
- Mass was added for same amount of time to get similar velocity distributions
- Densities were different so pressure and temperature varied small amounts

Average Velocity [ft/s] and standard deviation for the initial flow fields

	Phi = 0.5		Phi = 1		Phi = 1.5	
	Mean	SD	Mean	SD	Mean	SD
Case 1	13.88	6.60	10.67	7.01	12.56	10.18
Case 2	9.83	4.39	10.19	5.09	9.19	4.41
Case 3	8.49	3.95	7.41	3.83	5.12	2.25

Mixture Ratio Variation

- Similar type of propagation seen with the additional mixtures
- Flame speeds presented as average flame speeds, not always locally a perfect fit
- Prior to interactions with distinct features in the flow, trends are as expected

Average velocity [ft/s] for total propagation

	Phi = 0.5	Phi = 1	Phi = 1.5
Case 1	452	646	405
Case 2	397	554	658
Case 3	452	416	573

Average velocity [ft/s] for initial propagation

	Phi = 0.5	Phi = 1	Phi = 1.5
Case 1	593	959	802
Case 2	353	538	470
Case 3	405	452	425

Flame Acceleration and Distortion

- From the variations considered, velocity distribution dominated the flame speed determination
- Considered strain rate, vorticity magnitude, and radial velocity gradients of initial field
- Simplified to 2D

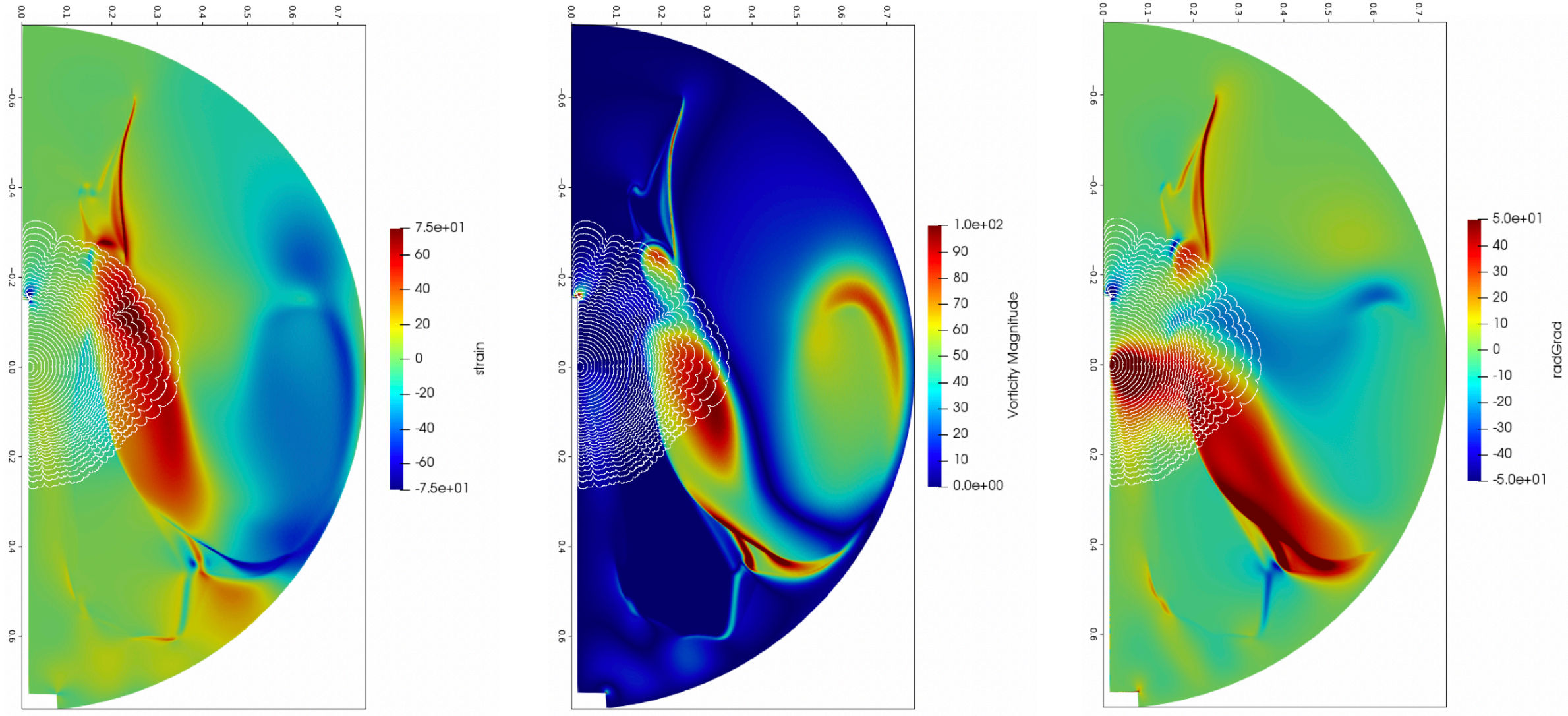
$$\epsilon_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$$

$$\frac{1}{r} \frac{\partial v_r}{\partial \theta} = \frac{x}{r^2} \left(x \frac{\partial u}{\partial y} - y \frac{\partial u}{\partial x} + v \right) + \frac{y}{r^2} \left(x \frac{\partial v}{\partial y} - y \frac{\partial v}{\partial x} - u \right)$$

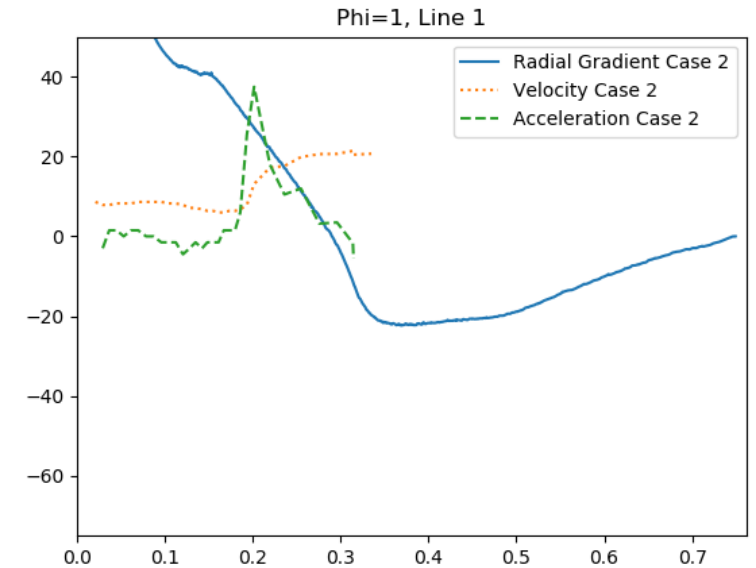
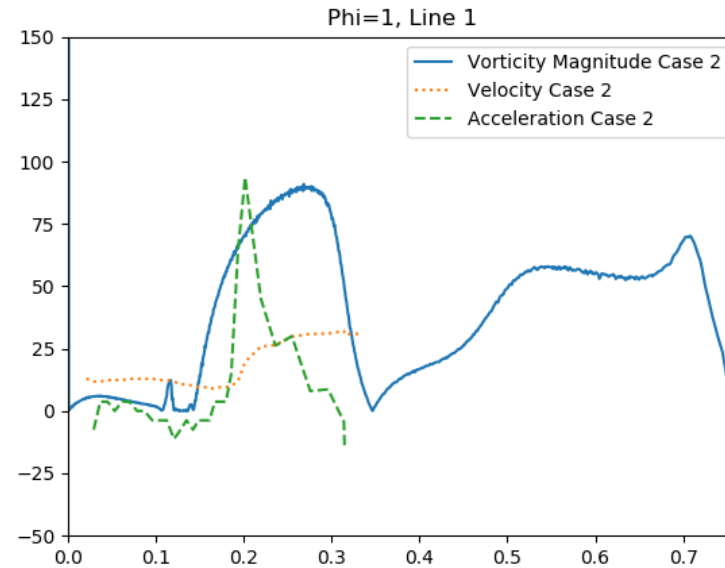
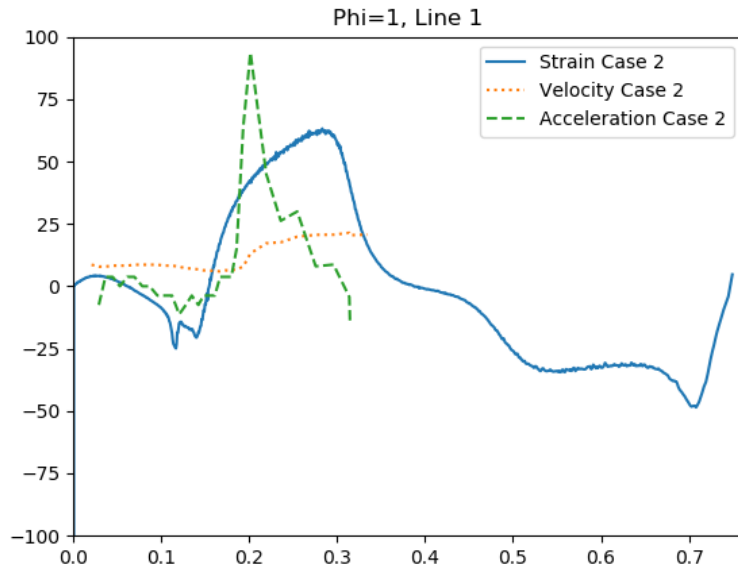
$$\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

$$r = \sqrt{x^2 + y^2}$$

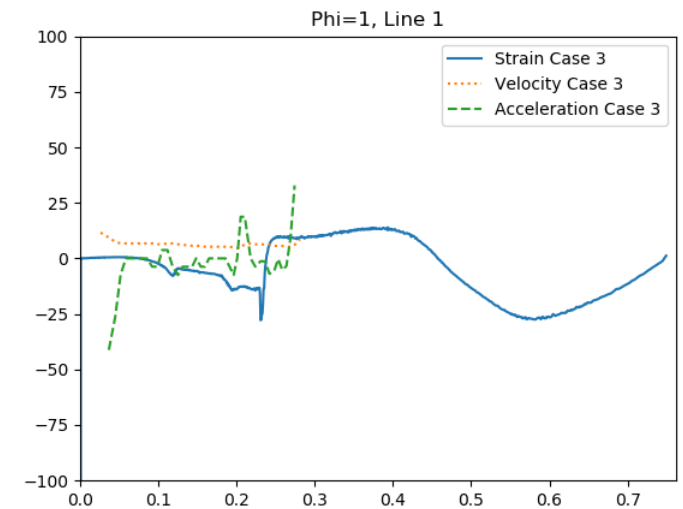
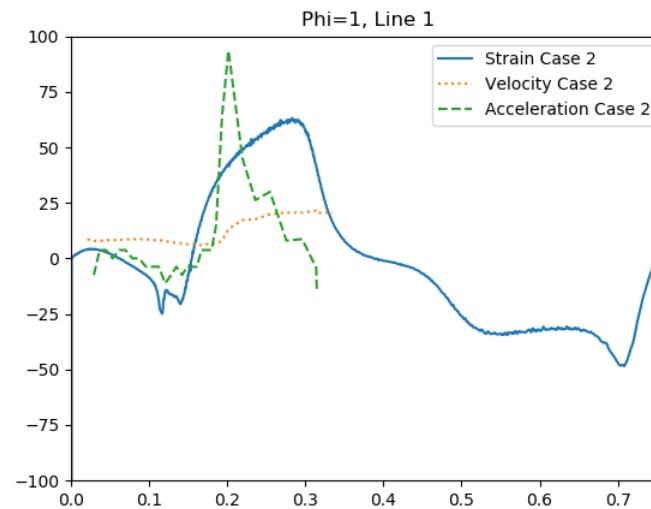
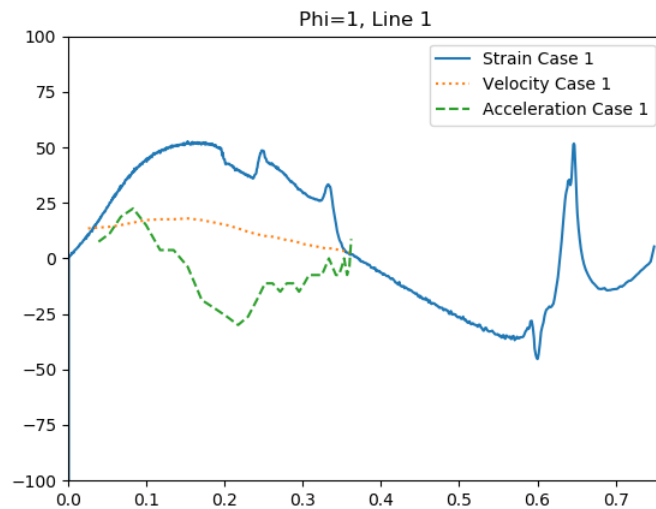
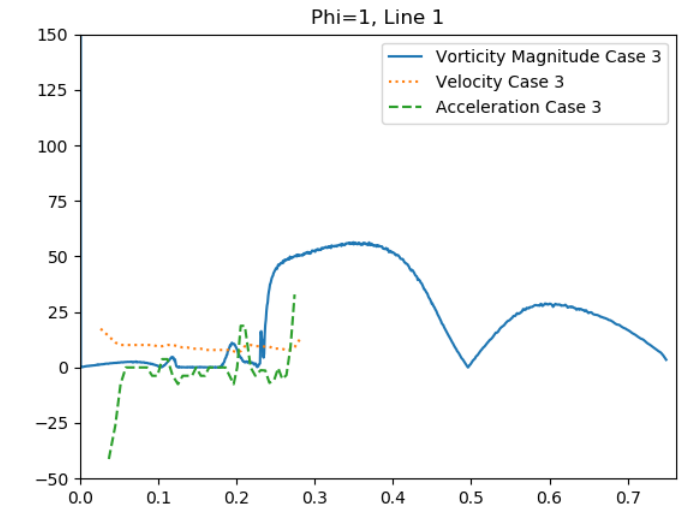
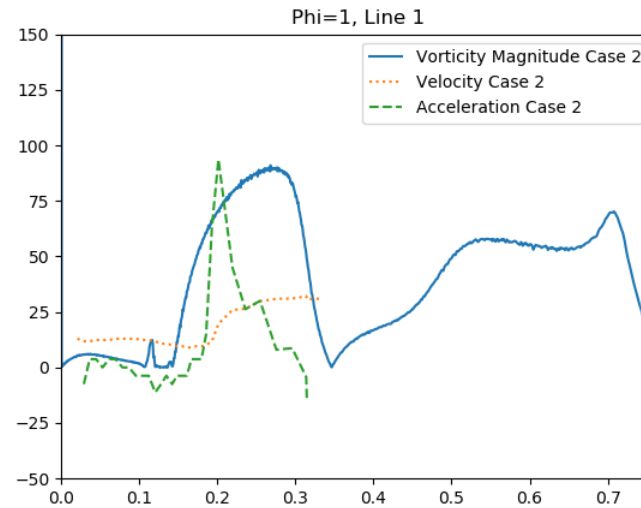
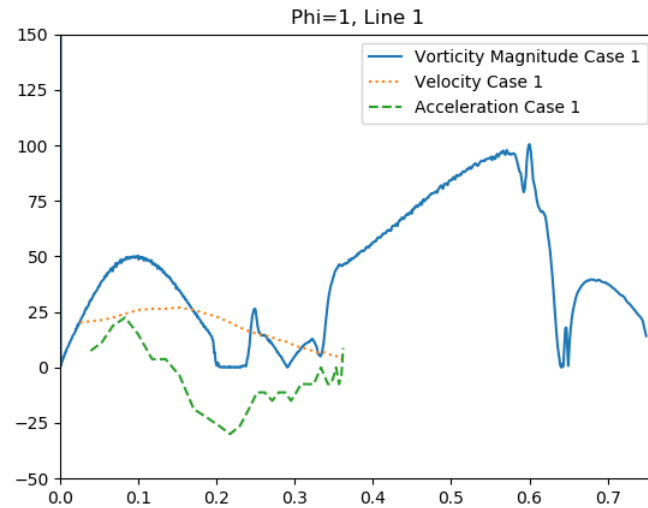
Flame Acceleration and Distortion



Flame Acceleration and Distortion



Flame Acceleration and Distortion



Flame Acceleration and Distortion

- Classified the flow using elementary flow patterns determined by invariants of the gradient tensor of the velocity field
- Simplified to 2D

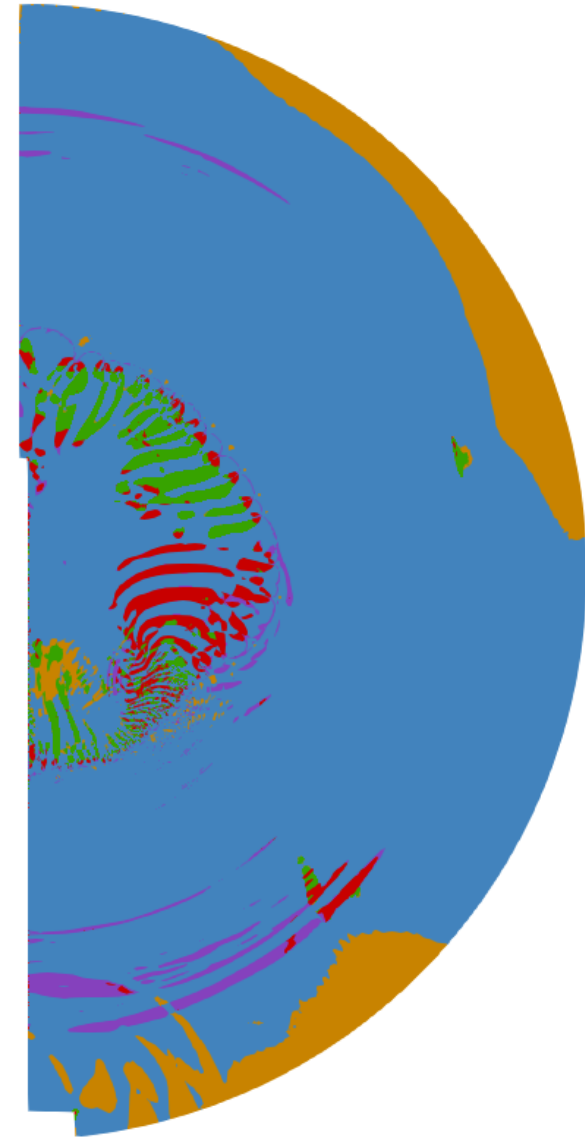
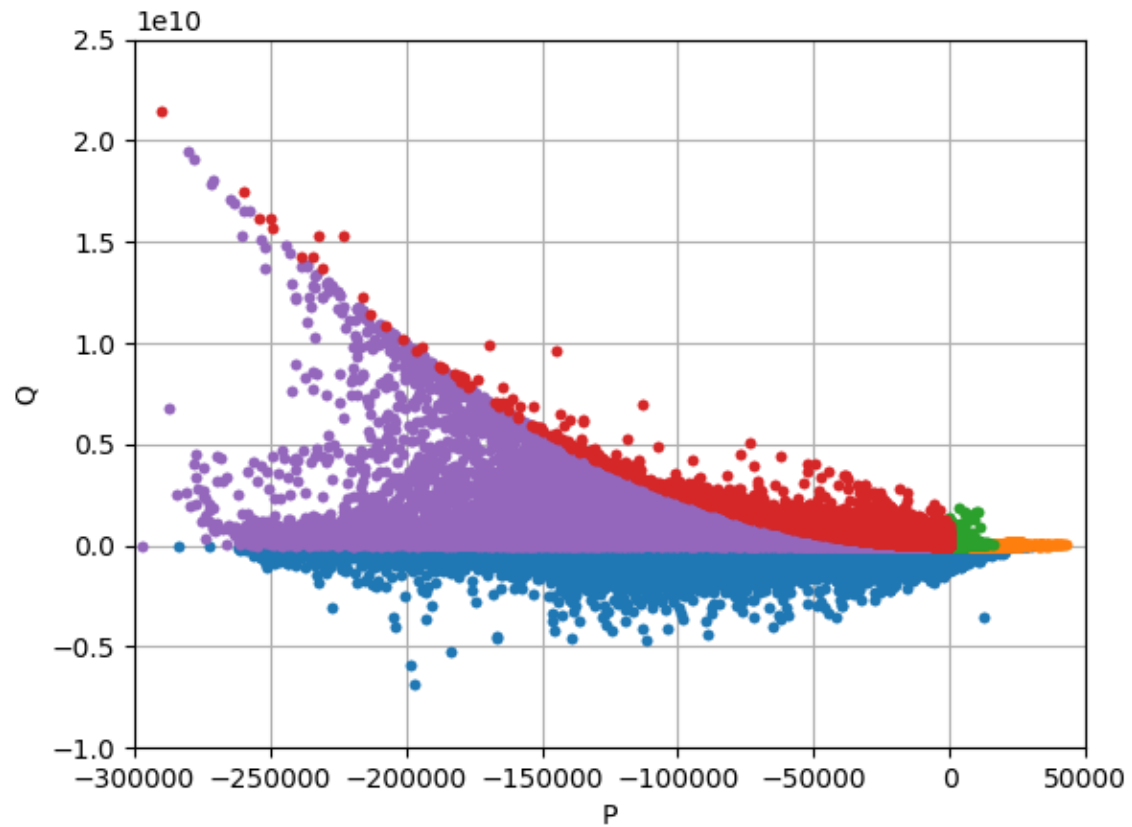
$$A_{ik} = \frac{\partial U_i}{\partial x_k}$$

$$P = -A_{ii}$$

$$Q = \text{Det}(A_{ik})$$

$$D = Q - \frac{P^2}{4}$$

Flame Acceleration and Distortion



Conclusions

- Initial pressure, velocity magnitude, and mixture ratio produce clear trends
- Flame speed was much more sensitive to initial velocity distribution
- Interactions of the flame front with the underlying velocity distribution result in flame acceleration and distortion
- Acceleration appears to be tied to vorticity magnitude
- Based on invariants, flow becomes unstable rotational flow where accelerating and deforming
- Much less likely to produce distorted flames if large bulk features in the underlying flow can be eliminated
- Engineering model works well for quiescent unconfined flows, needs higher fidelity inputs to anchor when features in the flow
- Analyses should report all initialization processes since they make a difference

Questions?