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14. ABSTRACT In this study a series of three-dimensional unsteady reacting flow simulations are used to investigate the effect of swirl on the instability amplitude of a single-element gas-gas rocket combustor. The baseline combustor of interest is unstable because of a fuel cut-off event caused by the high-pressure waves in the combustor. Previous two-dimensional simulations have shown that swirl reduces the amplitude of the pressure oscillations compared with that of the baseline configuration. The current three-dimensional simulations show that swirl is indeed able reduce the amplitude of the instabilities, albeit not to the same extent observed in the two-dimensional simulations. We further observe that the enhanced mixing due to the swirling flow leads to a reduction in the recovery time associated with the fuel cut-off event, thereby allowing the combustor to experience a more continuous heat release. Nevertheless, unlike the two-dimensional case, the three-dimensional simulations show that the flame does not stay anchored to the dump-plane, which explains the higher relative amplitudes in this case.					
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Effect of Swirl on an Unstable Single-Element Gas-Gas Rocket Engine



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and Douglas G. Talley

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Outline



- Introduction
- Overview of the instability mechanism present in the current configuration
- Prior results form a 2D parametric study
- Results from the series of 3D simulations
- Summary



History



Combustion instability is an organized, oscillatory motion in a combustion chamber sustained by combustion.

CI caused a four year delay in the development of the F-1 engine used in the Apollo program

- > 2000 full scale tests
- > \$400 million for propellants alone (2010 prices)

Irreparable damage can occur in less than 1 second.



Damaged engine injector faceplate caused by combustion instability

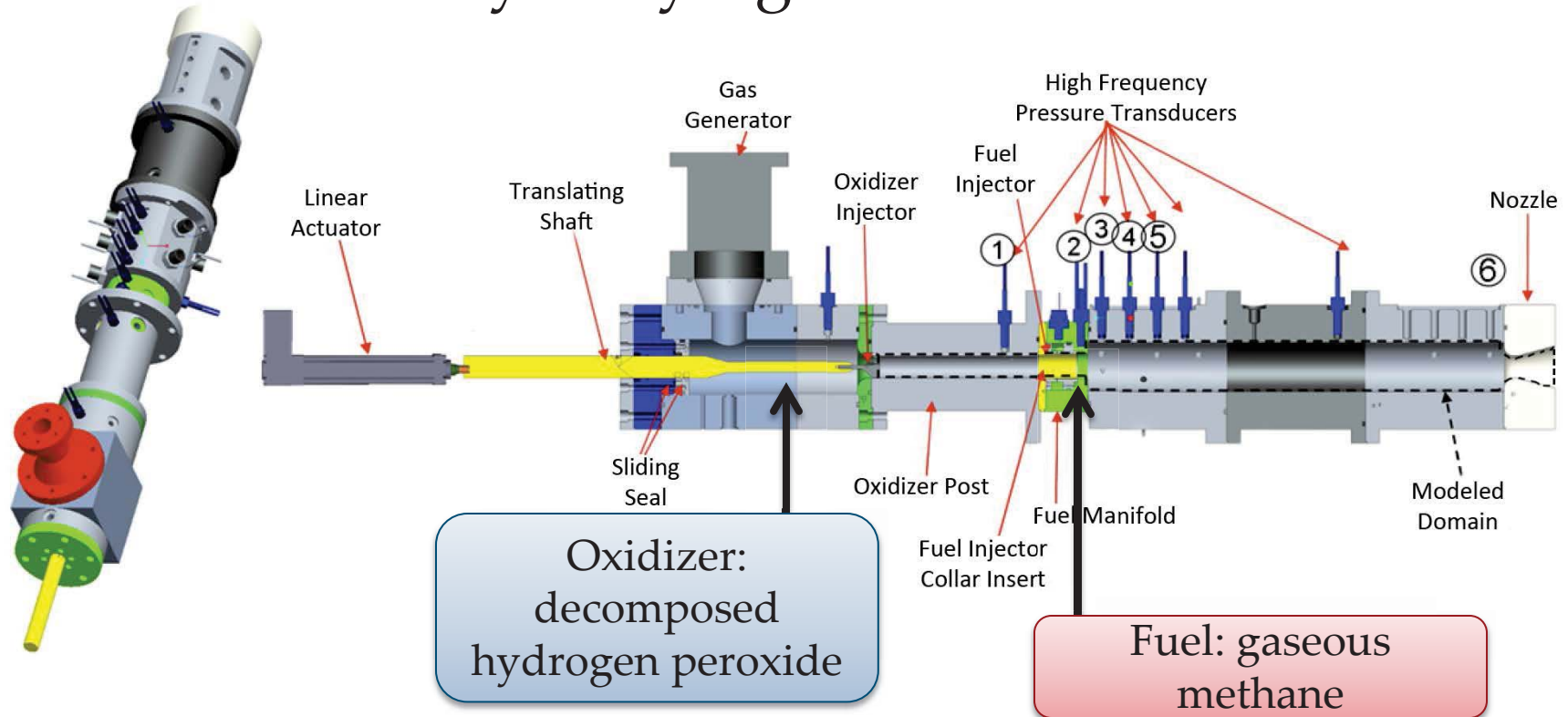
“Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs”

– JANNAF Stability Panel Draft (2010)



Longitudinal Experiment

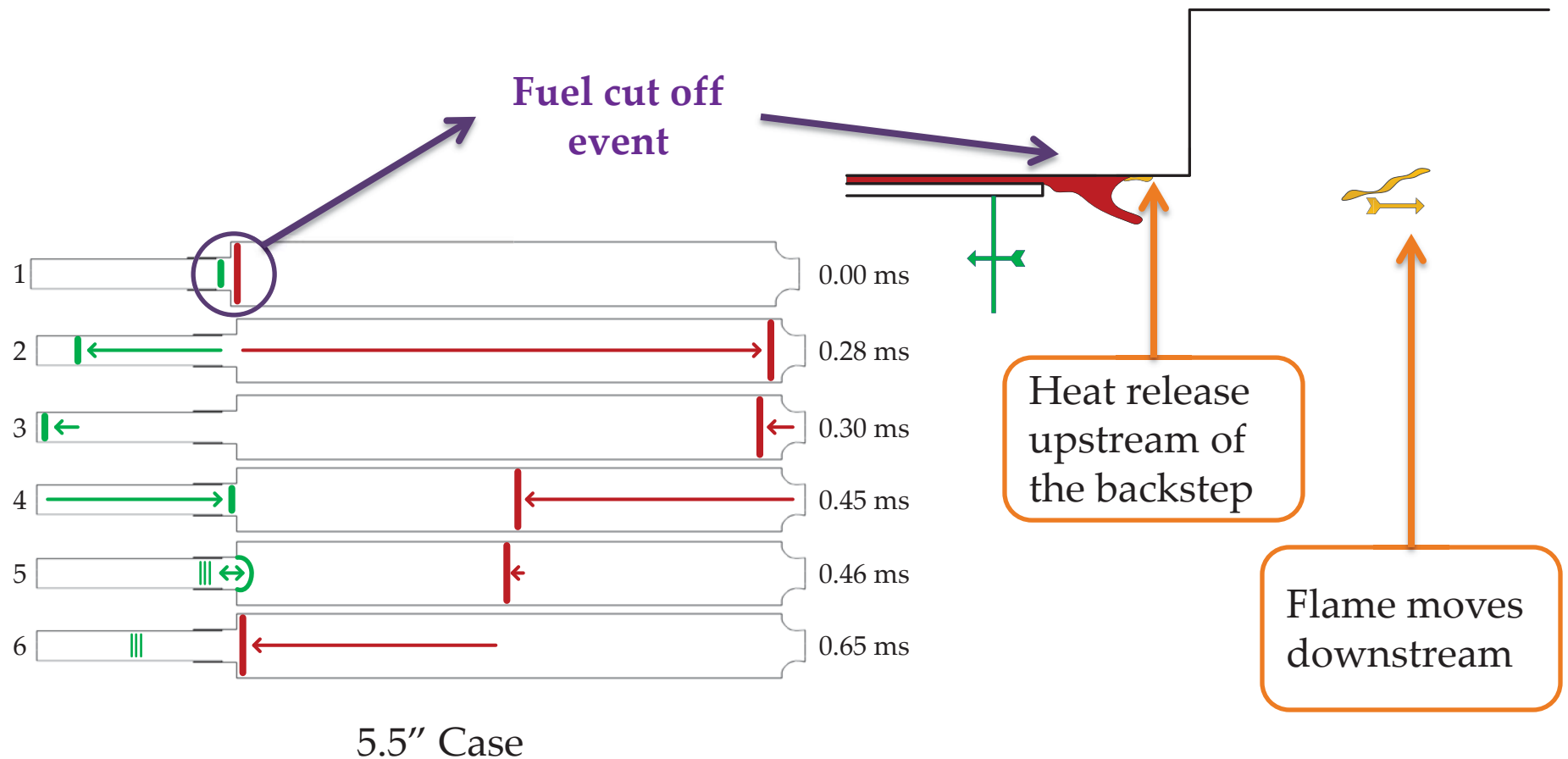
Continuously Varying Resonance Chamber



Mean pressure, 1.37 MPa (200 psi)



Pulse Timing I



- In the 3.5" case the returning pulse arrives sooner in the cycle
- In the 7.5" case the returning pulse arrives later in the cycle

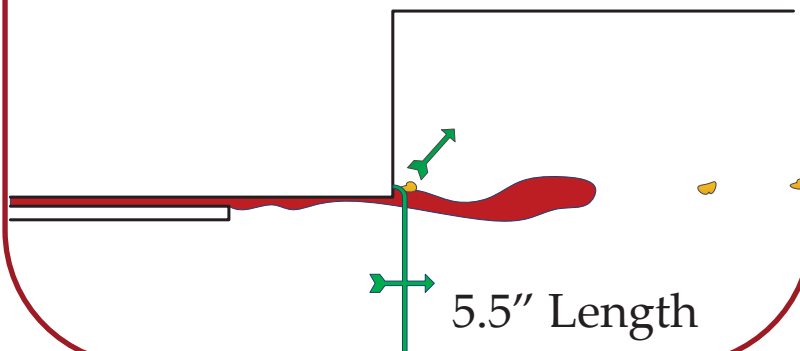


Pulse Timing II

After the fuel cutoff event the combustion restarts through one of two identified mechanisms

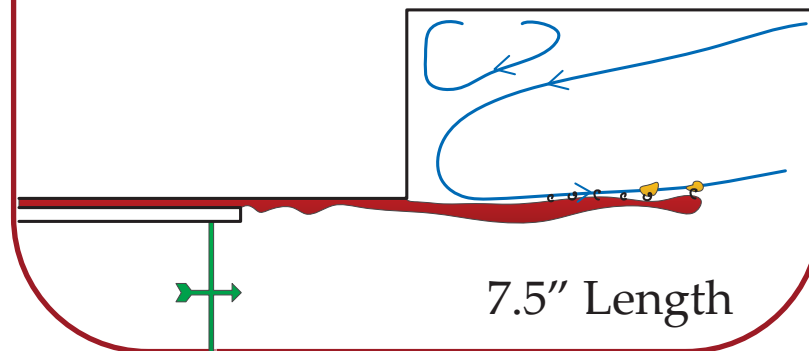
Post-coupled Ignition

Mechanism: The returning wave in the oxidizer post pushes unburnt fuel into the warm recirculating gases at the backstep where ignition takes place



Vortex Transport Mechanism:

The post wave arrives later in the cycle, the unburnt fuel slowly mixes with the recirculating gases in the shear layer. Ignition takes place in the shear layer downstream of the backstep





Baroclinic Torque

$$\frac{d\omega}{dt} = (\omega \cdot \nabla) u - \omega (\nabla \cdot u) + \frac{1}{\rho^2} (\nabla \rho \times \nabla p) + \nabla \times \left(\frac{1}{\rho} \nabla \cdot \tau \right)$$

Generation of vorticity due to misaligned density and pressure gradients

In the CVRC pressure pulses in the oxidizer post interact with the shear layer and generate vorticity



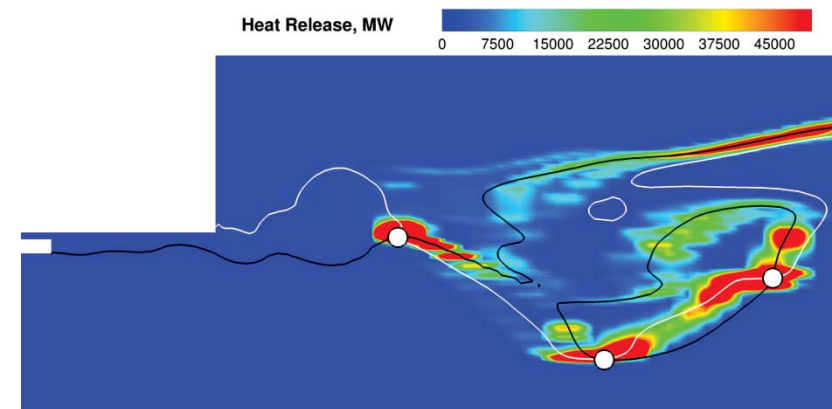
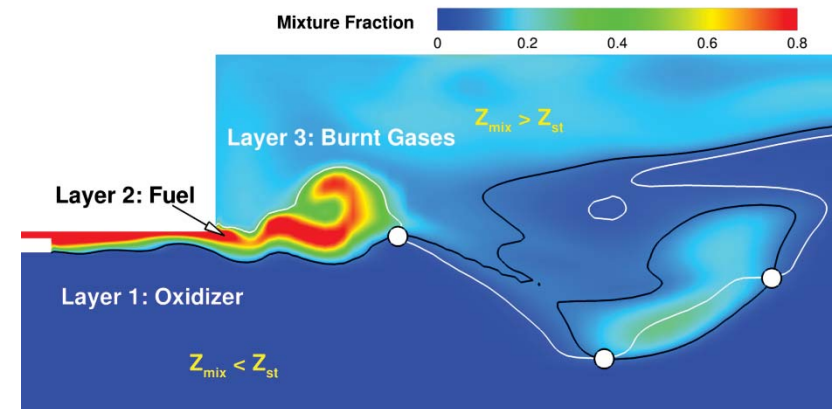
Increased vorticity results in increased mixing and generates partially premixed regions susceptible to combustion



Tibrachial Flame



- Intersection of:
 - Diffusion flame
 - Partially premixed fuel rich flame
 - Partially premixed fuel lean flame
- Location of intense heat release
- Observed in the CVRC by Garby et. al. and Guézennec et. al



White line, $T = 2000$ K

Black line, $Z = Z_{st} = 0.095739$

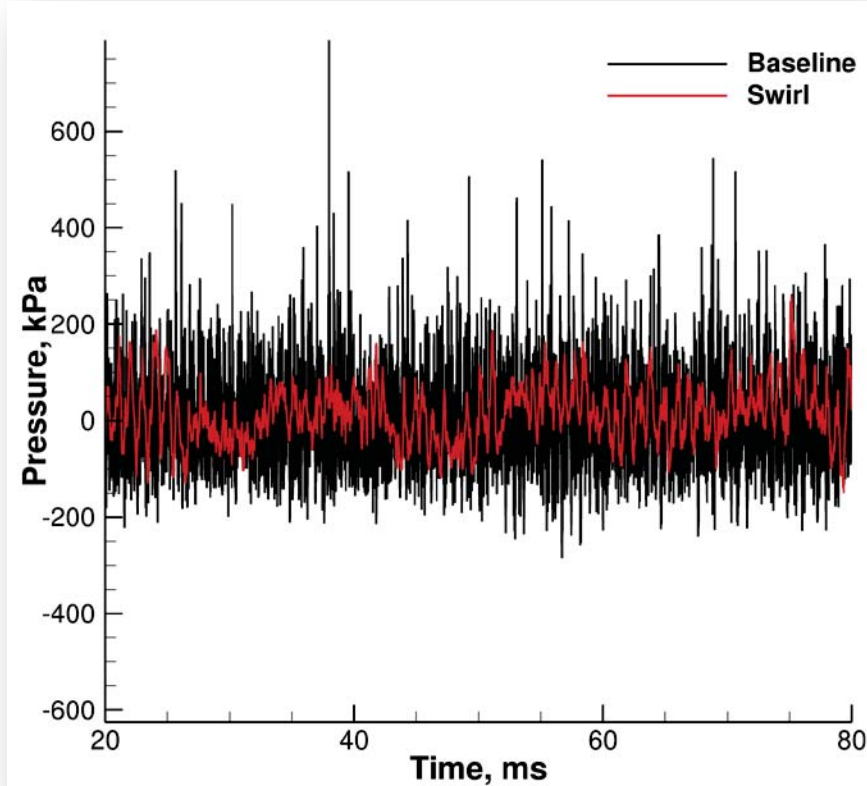
$$Z = \frac{\nu_{st} Y_{CH_4} - Y_{O_2} + Y_{O_2}^0}{\nu_{st} Y_{CH_4}^0 + Y_{O_2}^0}$$



2D Parametric Study



2D Swirl shows substantial reductions in amplitude



Case	p'_{ptp} , kPa	Frequency, Hz
Experiment	387.15	1324
BL	135.19	1460
S-1	78.82	1480
S-2	65.00	1480
S-3	40.72	1480
S-4	60.61	1480

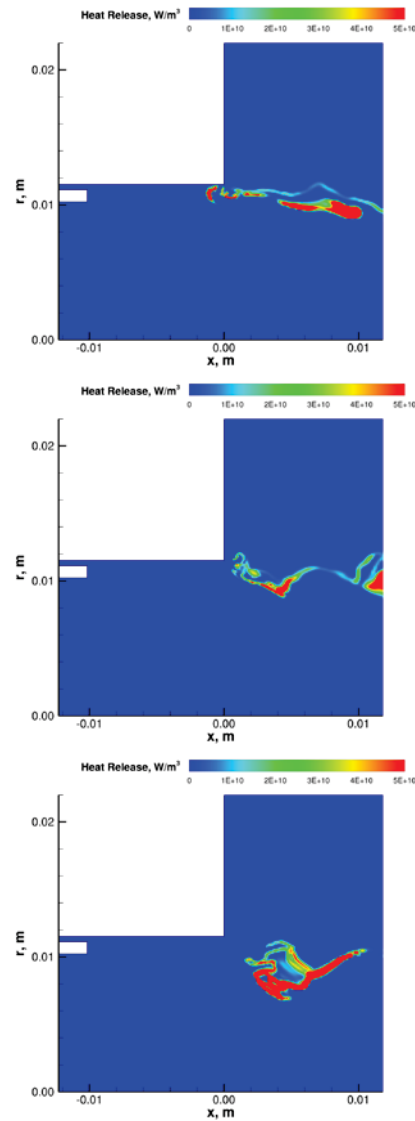
Concerns:

- Total amplitudes in 2D are lower compared with 3D
- Swirl component is assumed axisymmetric and may be stronger than 3D

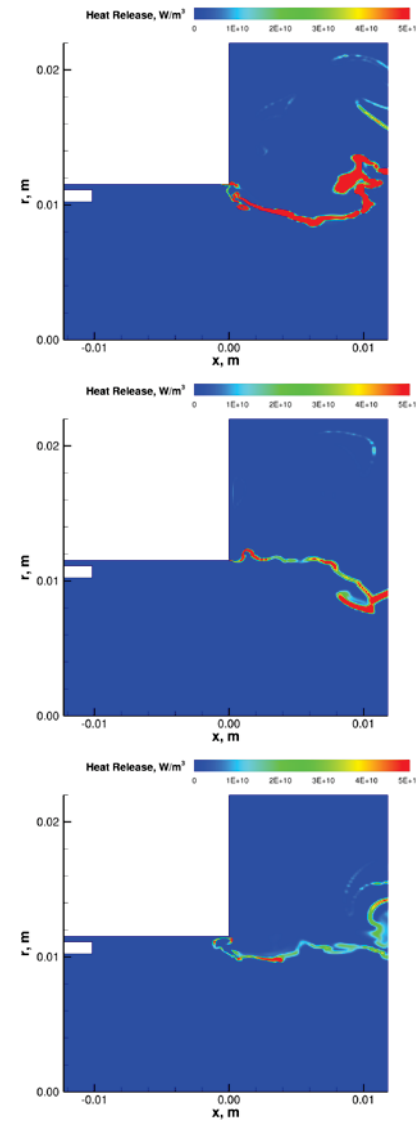


2D Shows Attached Flame

No
swirl



Swirl





Three-dimensional Study

Examine the effect of swirl when exposed to the larger amplitude consistent with the experimental results

Remove the axisymmetric assumption

Swirl is imposed using a boundary condition, not geometry

$$u_{\theta}(r) = u \cdot \left(\frac{r}{R_s} \right) \sin(\theta_S)$$

Four cases:

Baseline

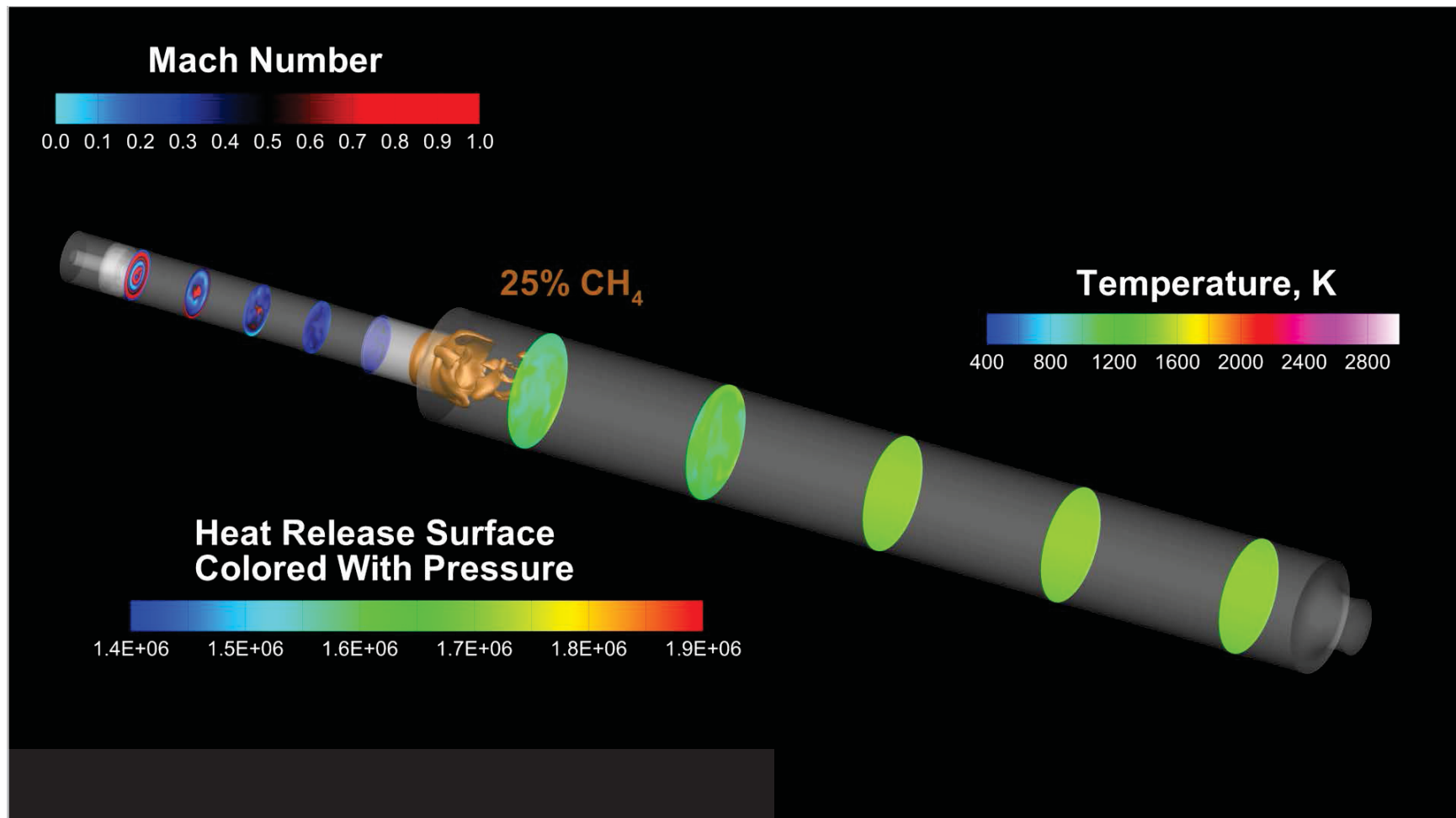
3° Swirl

9° Swirl

15° Swirl

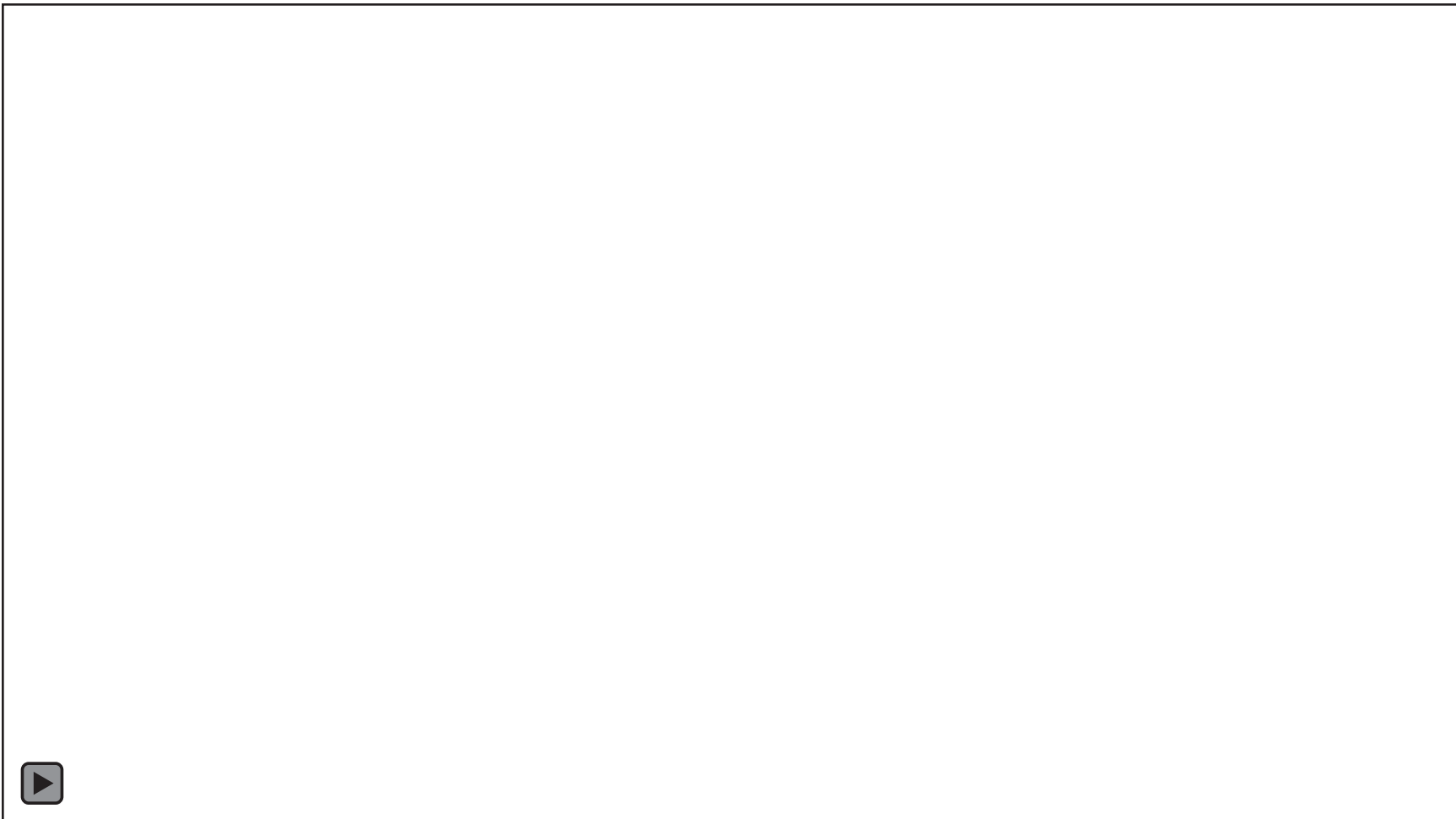


Simulation without Swirl





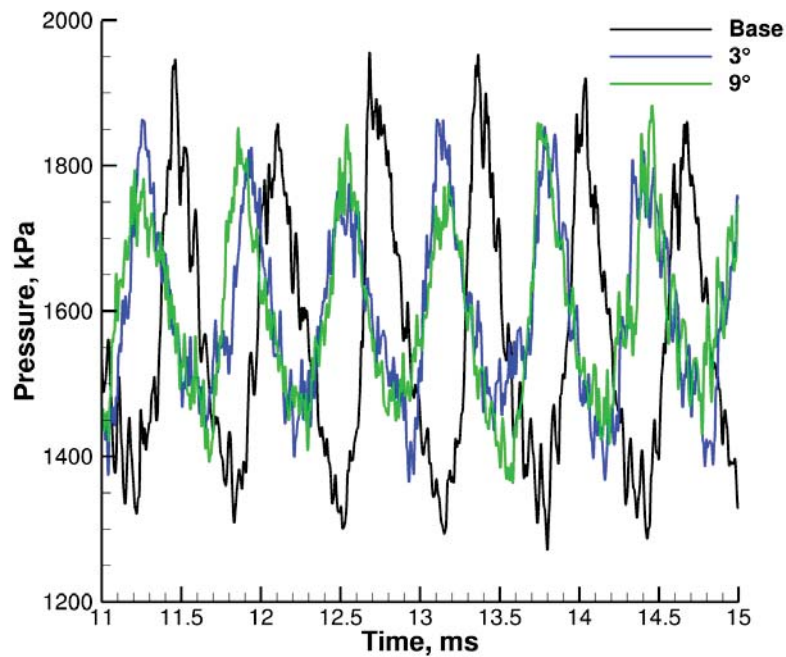
Simulation with Swirl



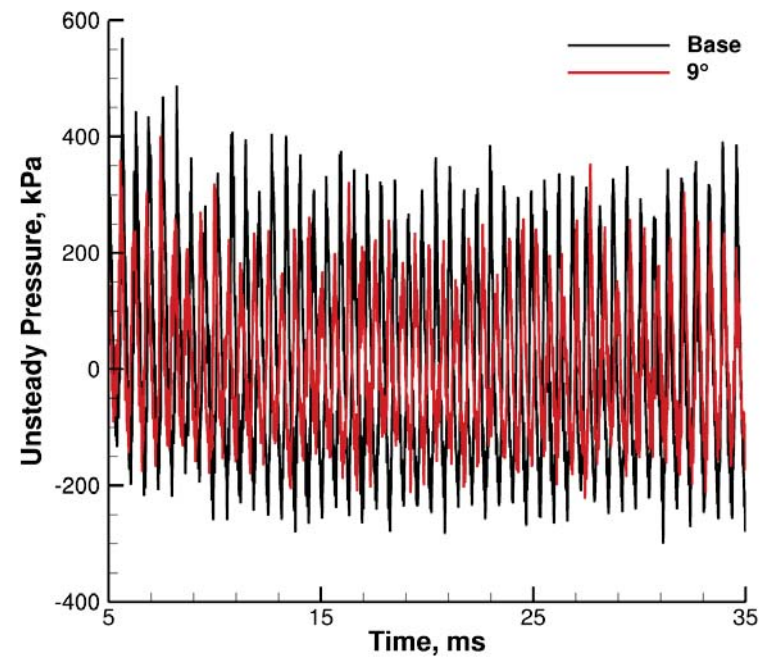


Pressure Amplitude

Swirl has a wider trough with more unsteady fluctuations

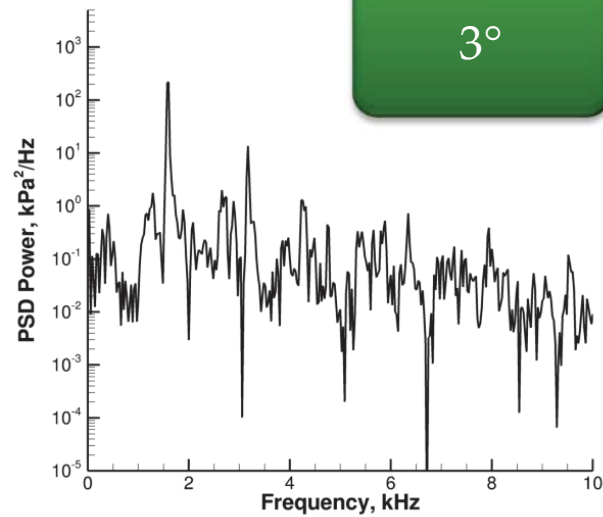
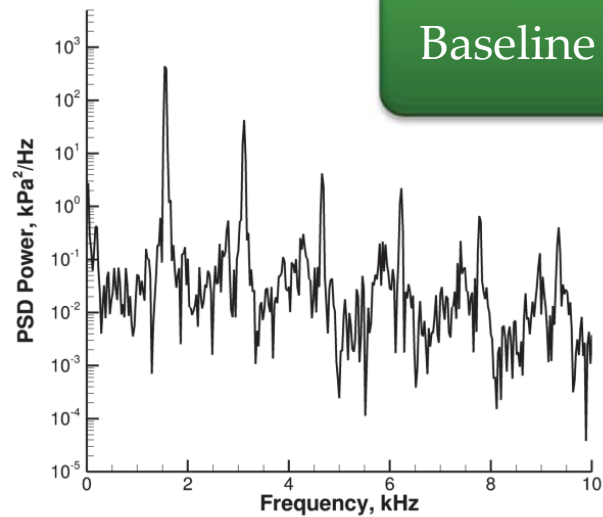


Swirl has a lower amplitude.



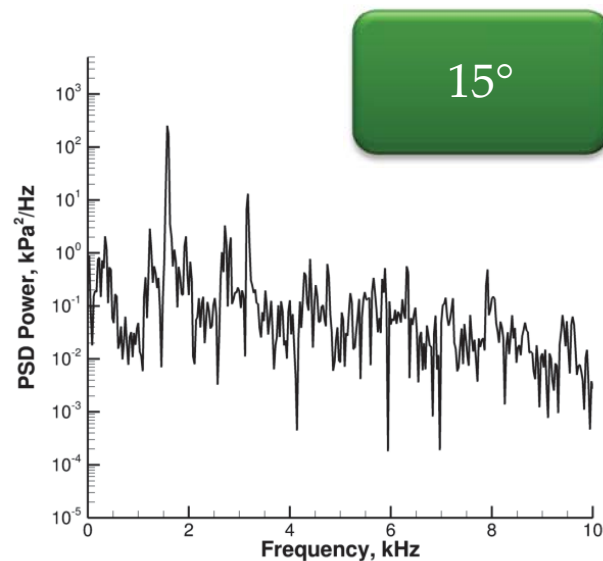
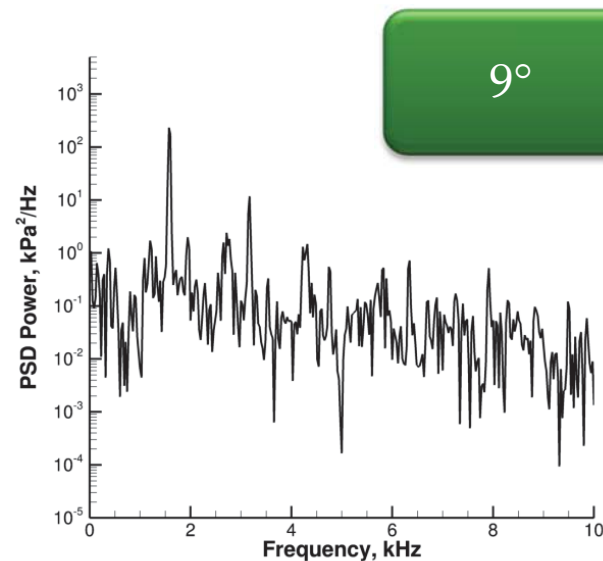


Power Spectral Density Analysis



Swirl has lower amplitudes

Higher order modes are more difficult to identify with swirl



Unknown mode between L1 and L2 for each swirl case



Amplitudes

PSD data is integrated using the FWHM method to determine the peak-to-peak pressure for each mode.

Mode	Baseline		3°		9°		15°	
	f , Hz	p' , kPa	f , Hz	p' , kPa	f , Hz	p' , kPa	f , Hz	p' , kPa
1	1543	349.10	1600	265.88	1571	248.80	1571	251.77
Unknown	—	—	2886	17.37	2714	29.72	2714	21.55
2	3114	87.55	3171	61.19	3171	60.66	3171	66.19
3	4629	36.25	4723	28.47	4723	25.59	4723	27.65

9° of swirl had the greatest reduction, about 30%

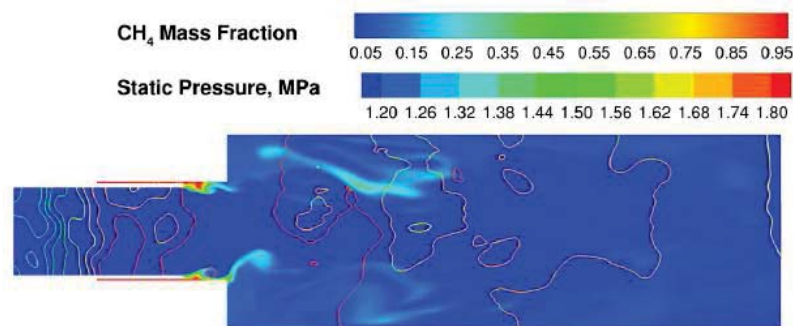
Amplitude reduction is less than the 2D prediction

The unknown mode has a weak amplitude.

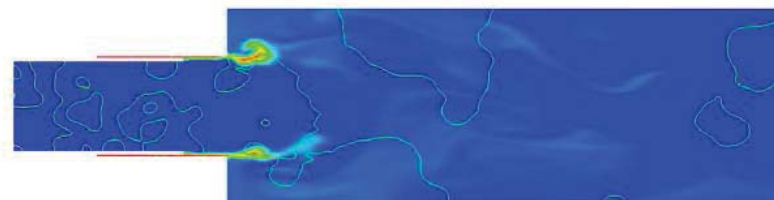
Baseline compares well with experimental results



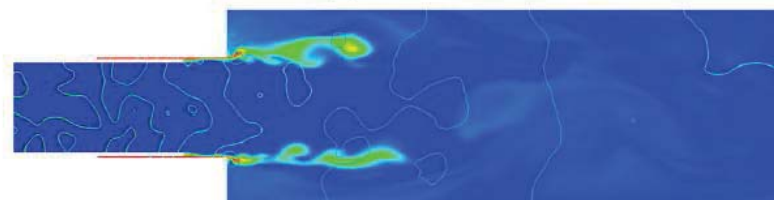
Methane Cycle



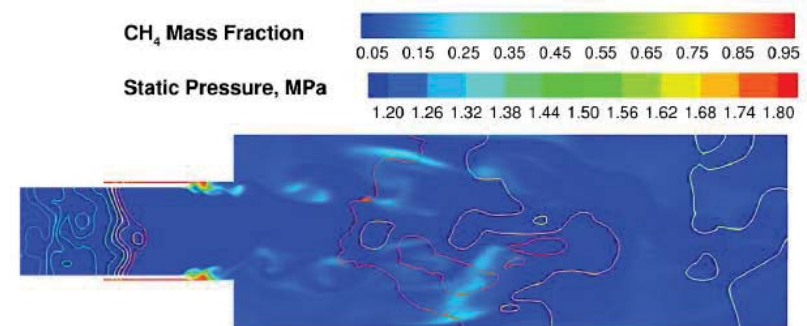
(a) Time 1.



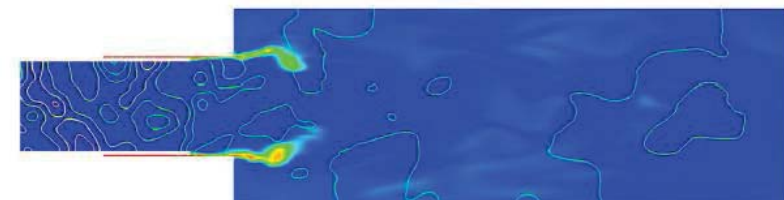
(c) Time 2.



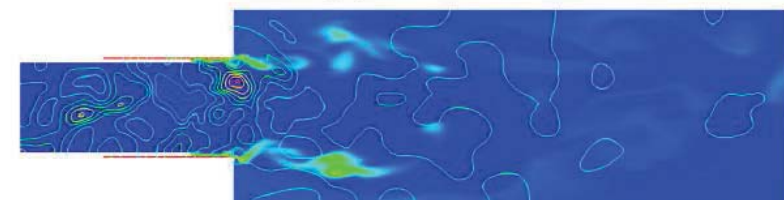
(e) Time 3.



(b) Time 1.



(d) Time 2.



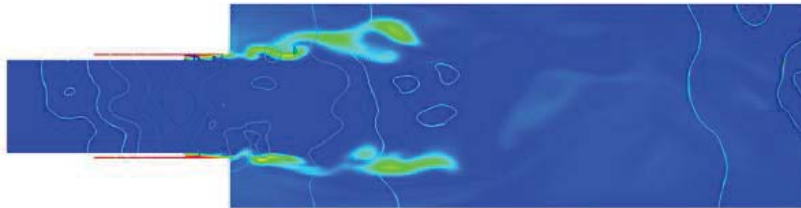
(f) Time 3.

No Swirl

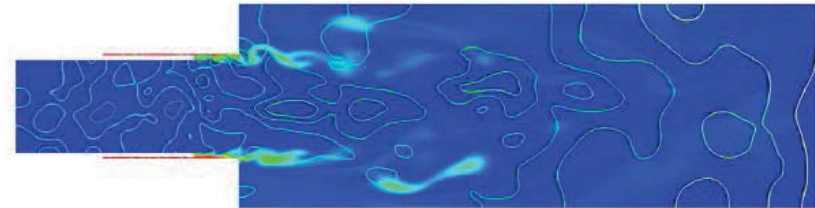
9° Swirl



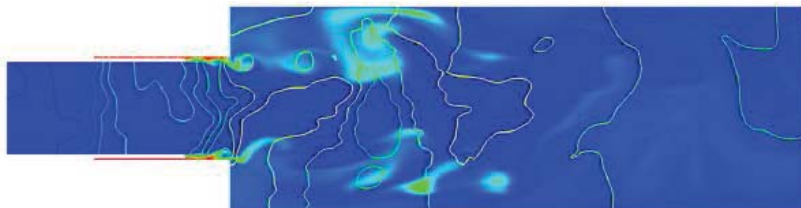
Methane Cycle II



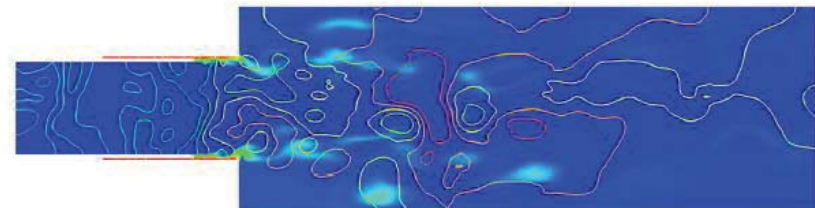
(g) Time 4.



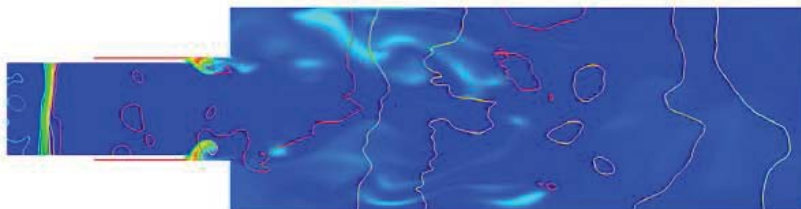
(h) Time 4.



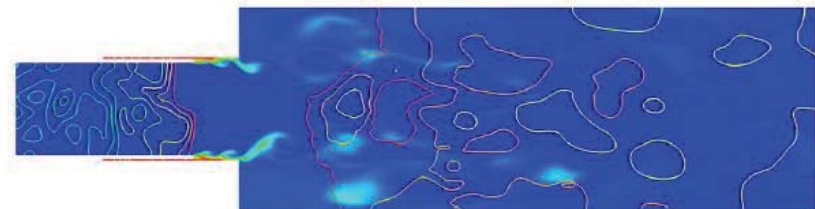
(i) Time 5.



(j) Time 5.



(k) Time 6.



(l) Time 6.

No Swirl

9° Swirl



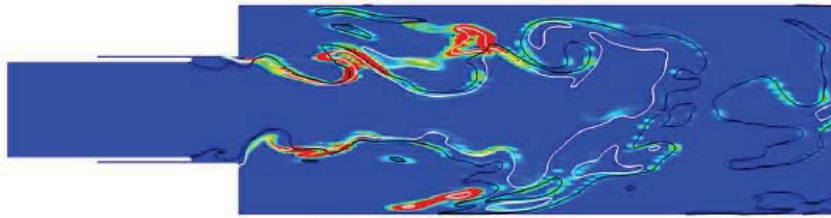
Heat Release Cycle



Heat Release, MW/m³



0 15000 30000 45000 60000 75000 90000

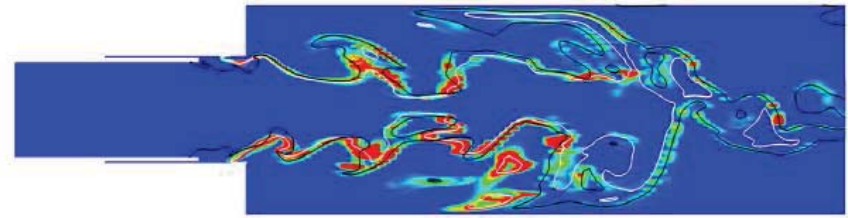


(a) Time 1.

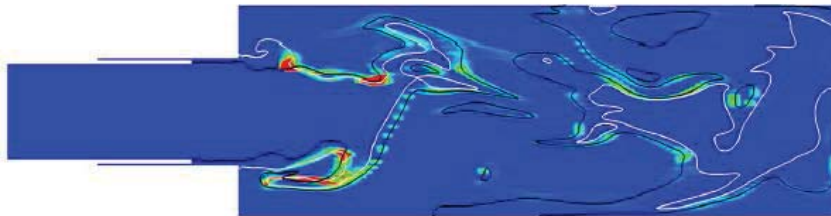
Heat Release, MW/m³



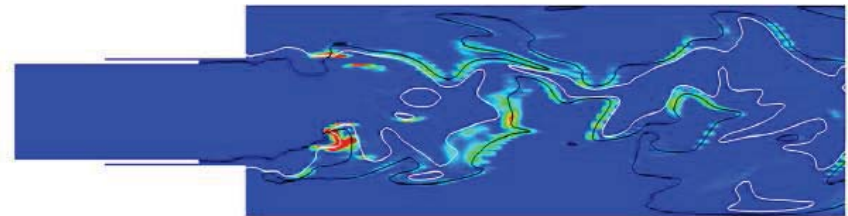
0 15000 30000 45000 60000 75000 90000



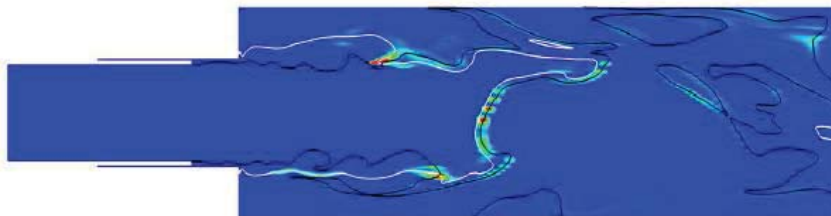
(b) Time 1.



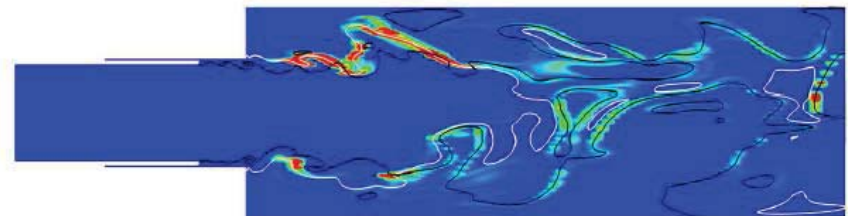
(c) Time 2.



(d) Time 2.



(e) Time 3.



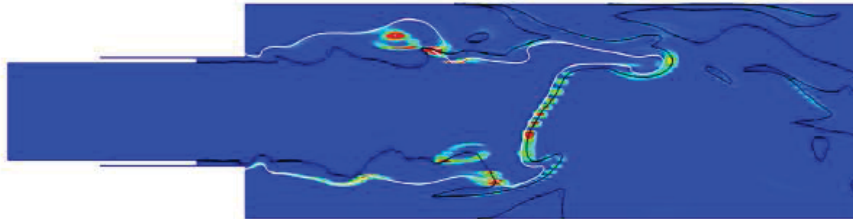
(f) Time 3.

No Swirl

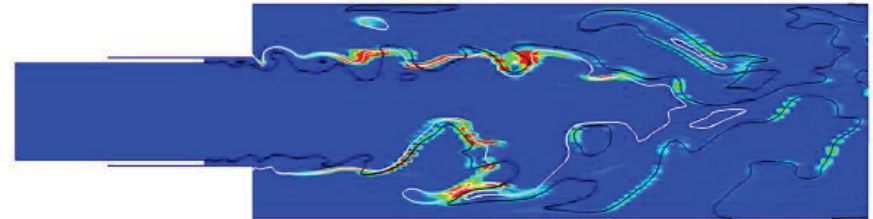
9° Swirl



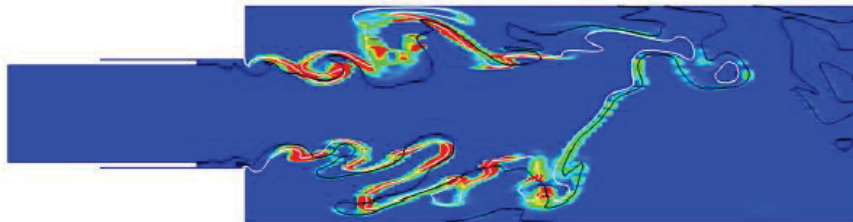
Heat Release Cycle II



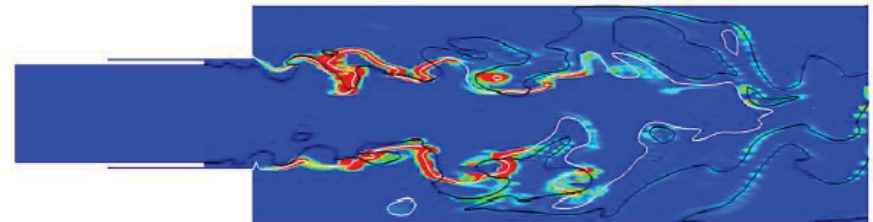
(g) Time 4.



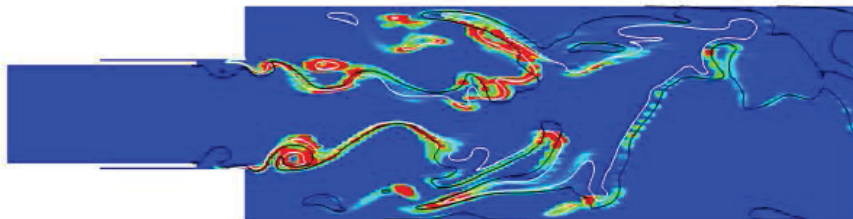
(h) Time 4.



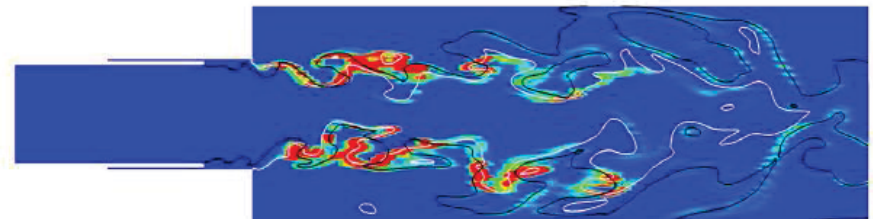
(i) Time 5.



(j) Time 5.



(k) Time 6.



(l) Time 6.

No Swirl

9° Swirl

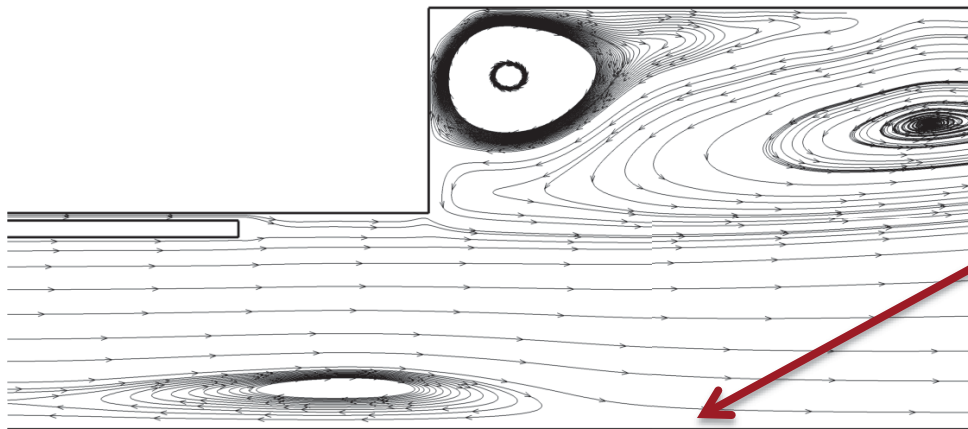


Lack of a CTRZ

Central toroidal recirculation zones can be found in flows with swirl.

The CTRZ has a stabilizing effect

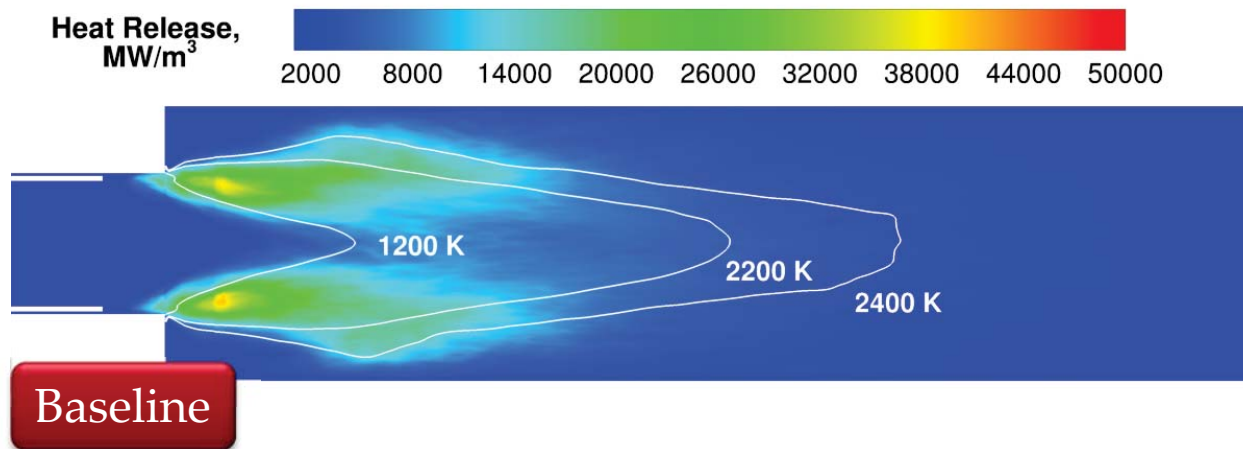
A CTRZ was found in 2D but not 3D



Possibly a result of
the artificial
centerline boundary
condition

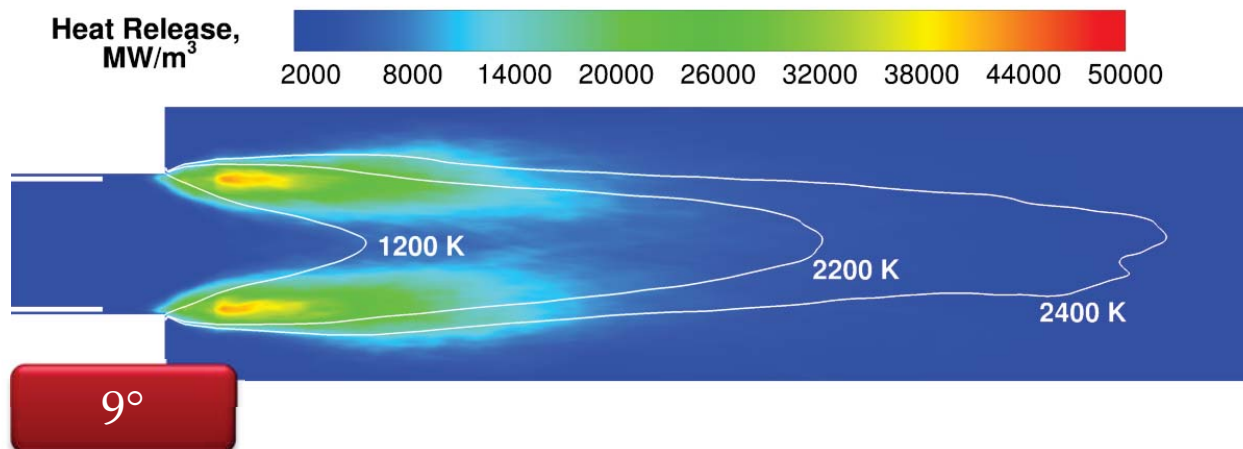


Time Averaged Flowfield



Heat release is similar for all three swirl cases

Swirl shows that the heat release that is confined to the shear layer



No “bump” in heat release

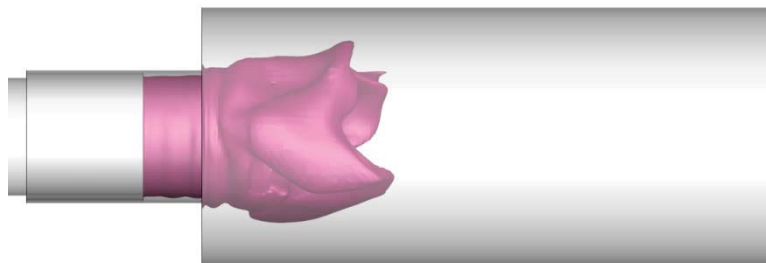
No evidence of a CTRZ in 3D!



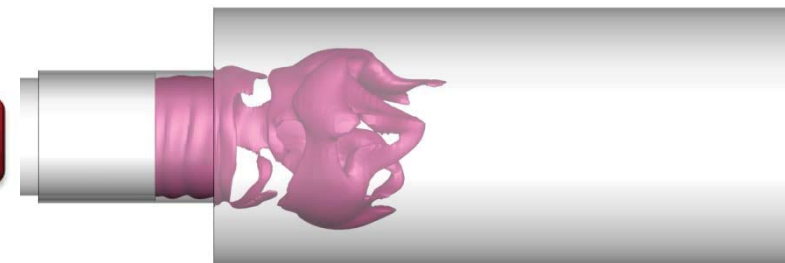
Accumulation of Fuel

Cycle analysis showed that heat release resumes quickly in the swirl case compared to the baseline

There is less fuel accumulation in the cycle and evidence of consumption sooner



50%



75%



Baseline

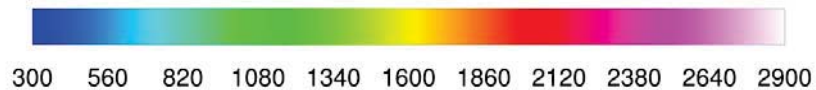
9°



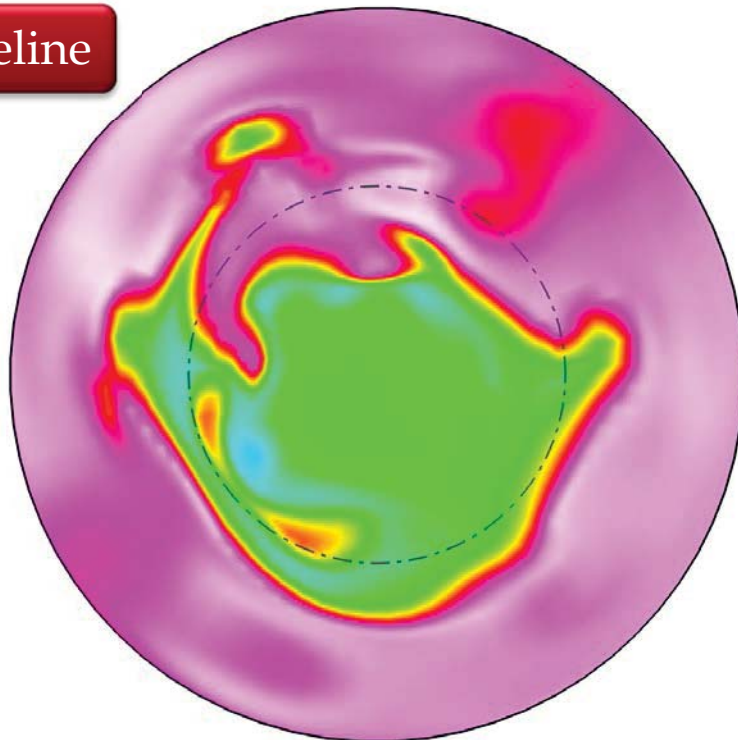
Injection Differences



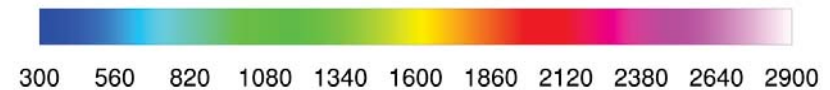
Temperature, K



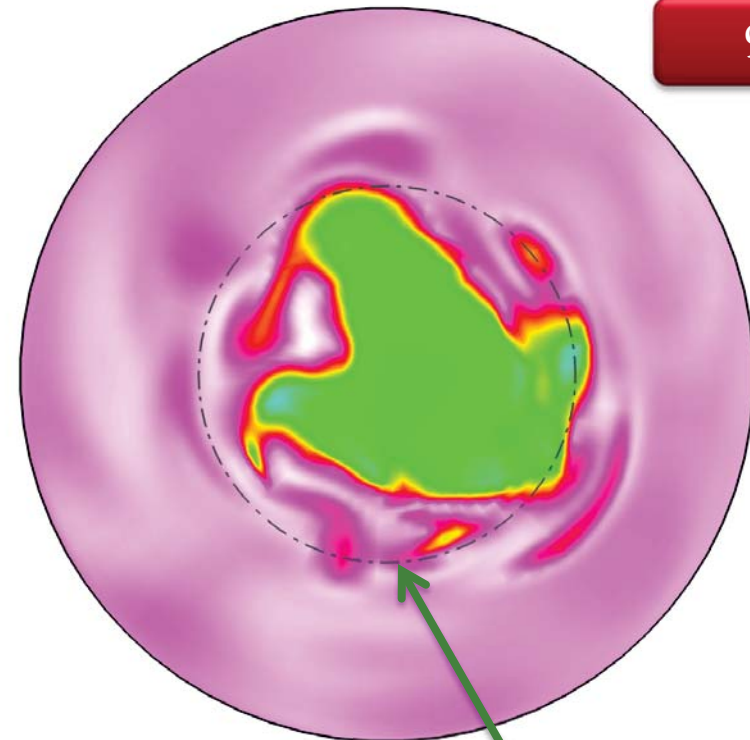
Baseline



Temperature, K



9°



Ox post diameter

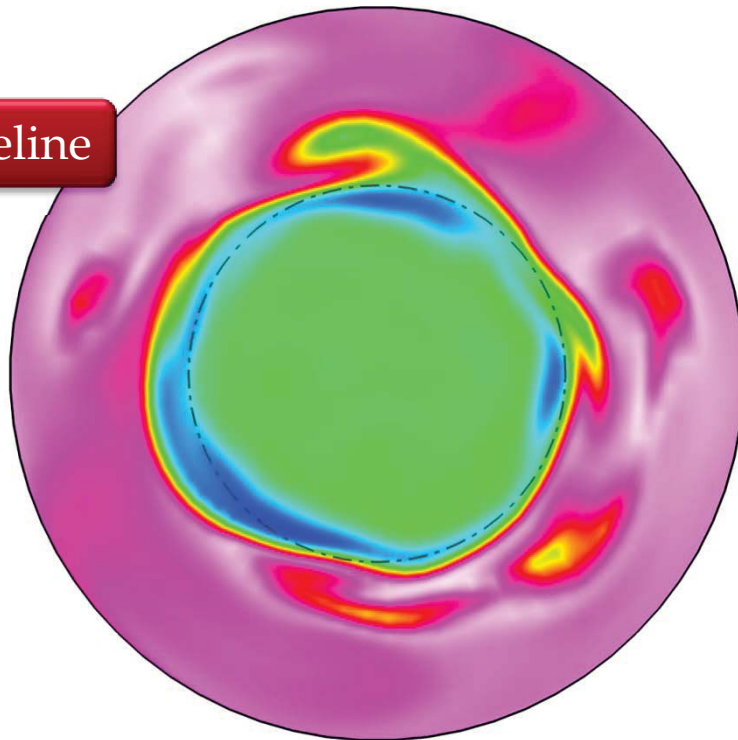
20%



Injection Differences

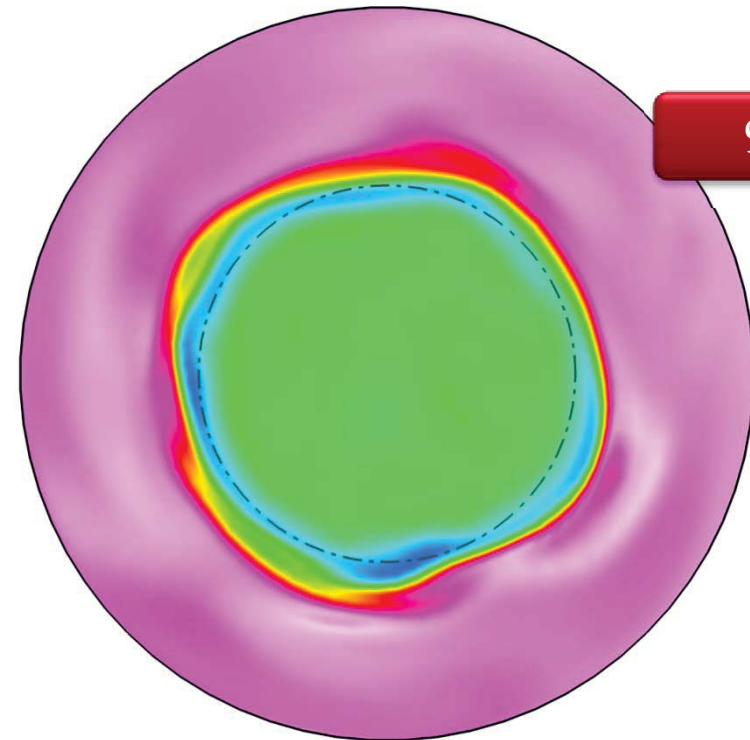


Baseline



More radial
expanse

9°



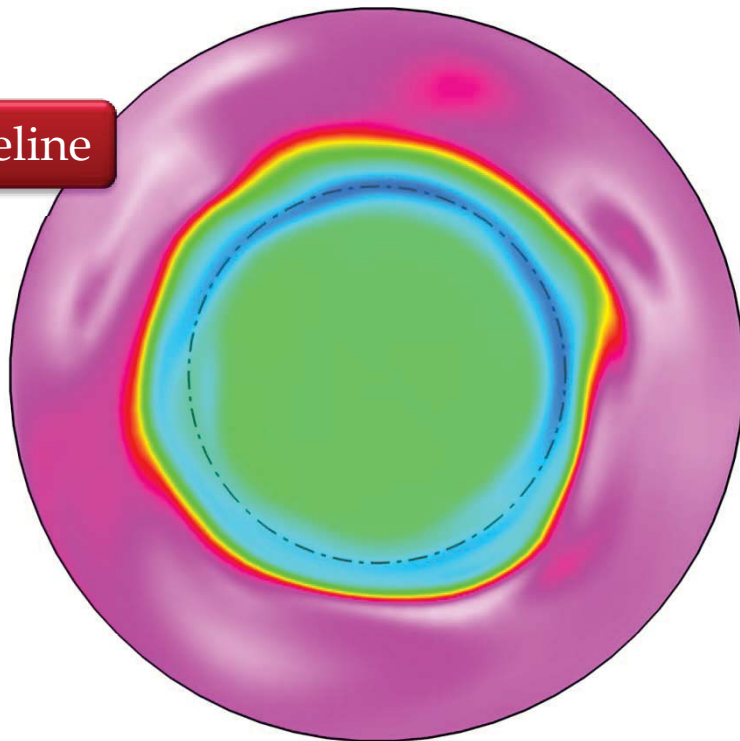
Less pure fuel
regions

40%



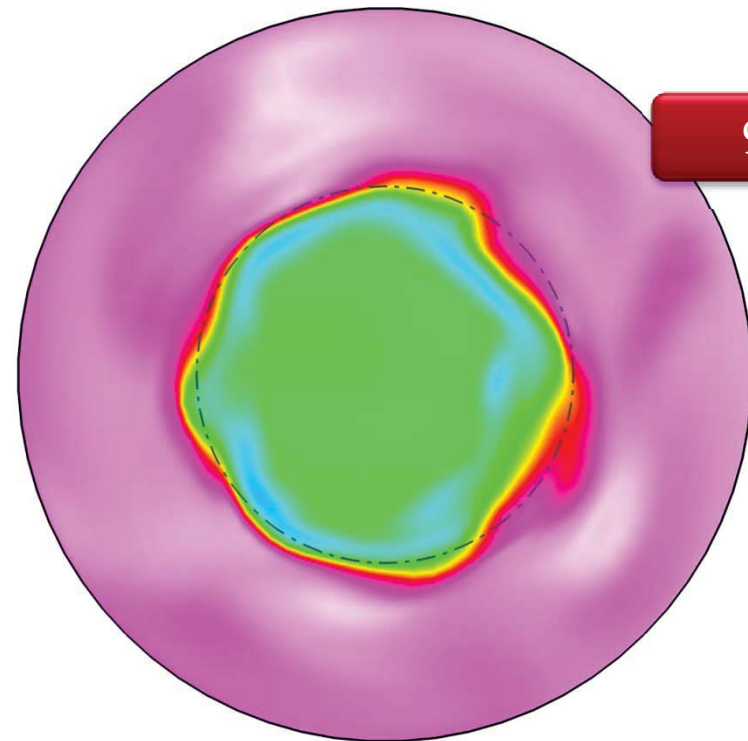
Injection Differences

Baseline



More radial
expanse

9°



Less evidence of
fuel

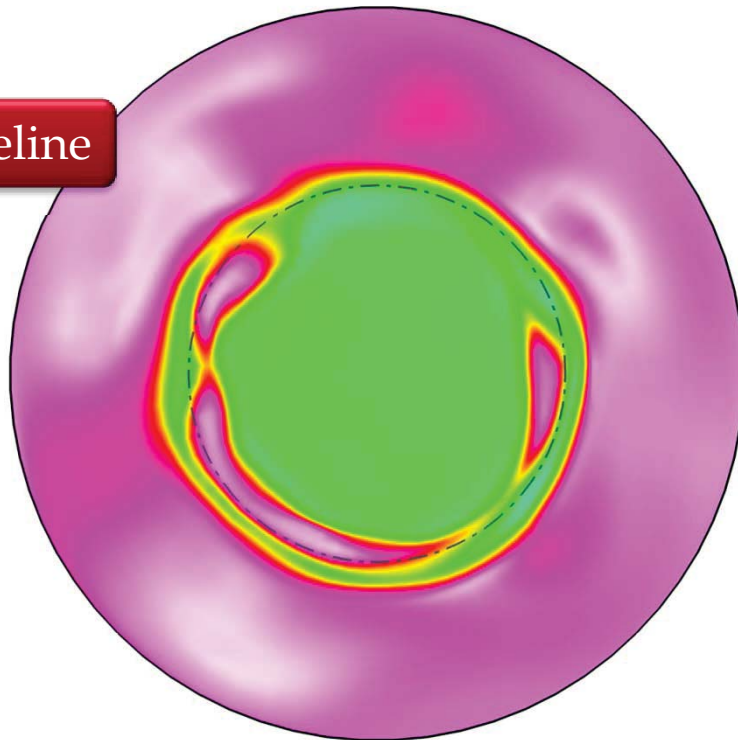
70%



Injection Differences

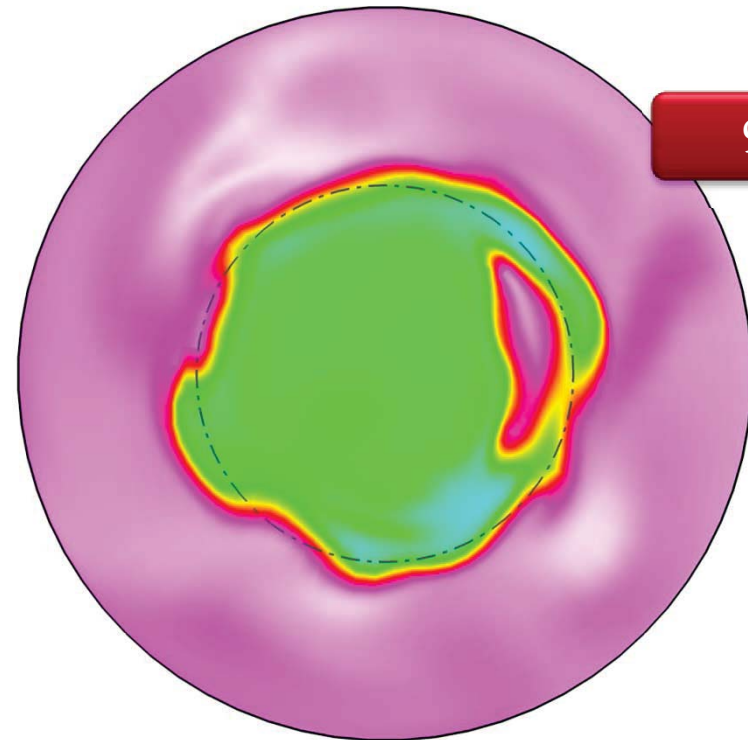


Baseline



More radial
expanse

9°



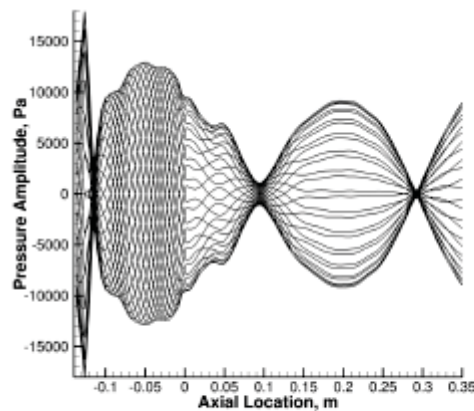
Less evidence of
fuel

80%

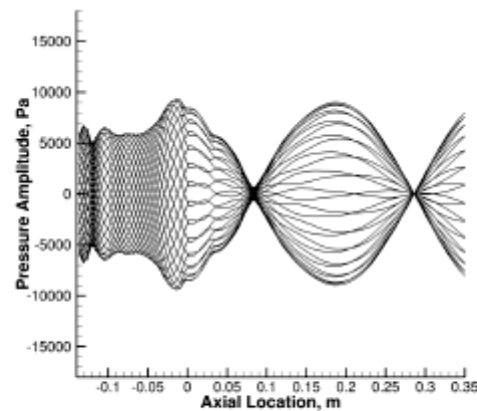


Unknown Mode

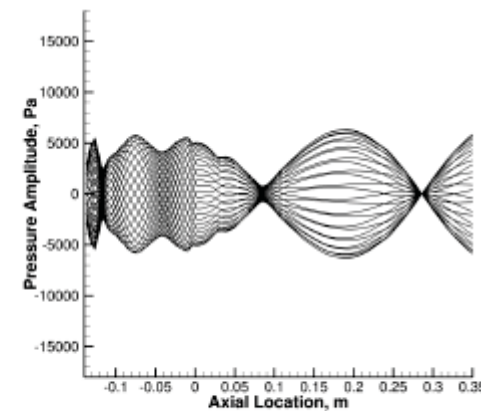
Unknown mode was found in the swirl cases with a frequency between the first and second longitudinal modes



(a) 3° swirl, pressure.



(b) 9° swirl, pressure.



(c) 15° swirl, pressure.

No evidence of a PVC mode or spinning mode

A similar mode was found in a 3.5" simulation which had a similar amplitude to the swirl cases.



Summary

A numerical investigation of the effect of swirl on an unstable single-element gas-gas rocket engine was undertaken

The addition of swirl to the fuel reduced the amplitude by 30%

The reduction of amplitude was a result of:

Improved mixing
between the fuel
and oxidizer

Shorter recovery
time of the fuel
cut off event

More continuous
heat release
throughout the
cycle

The percent amplitude reduction in 3D was not as great as 2D, but had a similar absolute reduction in amplitude

2D simulations should be used to reduce the number 3D simulations



Effect of Swirl on an Unstable Single-Element Gas-Gas Rocket Engine



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