A Joint Experimental/Computational Study of Non-idealities in Practical Rotating Detonation Engines

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Co-I: Venkat Raman

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Kickoff meeting October 5, 2015

UTSR/NETL

Summary

- **Title:**
  - A Joint Experimental/Computational Study of Non-idealities in Practical Rotating Detonation Engines
- **Funding agency:**
  - University Turbine Systems Research/NETL
  - Funding Opportunity Number: DE-FOA-0001248
  - Topic Area 2: Pressure Gain Combustion R&D
  - Project manager: David Lyons
- **Personnel:**
  - PI: Mirko Gamba, University of Michigan
  - Co-I: Venkat Raman, University of Michigan
  - Students currently involved:
    - Fabian Chacon
    - Yasin Abul-Huda
    - TBD
  - Key external collaborators:
    - Dr. John Hoke, Innovative Scientific Solution, Inc. (ISSI)
    - Drs. Adam Holley and Peter Cocks, United Technology Research Center (UTRC)
    - Dr. K. Kailasnath, Navy Research Labs (NRL)

Outline

- Programmatic overview
- Introduction to the problem and general approach
- Experimental activities
- Computational activities
- Interactions and collaborations

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Overarching objectives

- **Objective 1:**
  Develop canonical and operational RDE configurations, as well as imaging-based laser diagnostics for understanding fuel stratification, leakage, parasitic combustion and detonation structure under non-ideal conditions in RDEs.

- **Objective 2:**
  Develop a comprehensive picture of the fundamental physics governing non-idealities and how they impact RDE performance and operability from both experiments and simulations.

- **Objective 3:**
  Develop detailed computational tools (DNS & LES) for studying detonation wave propagation processes in RDEs.

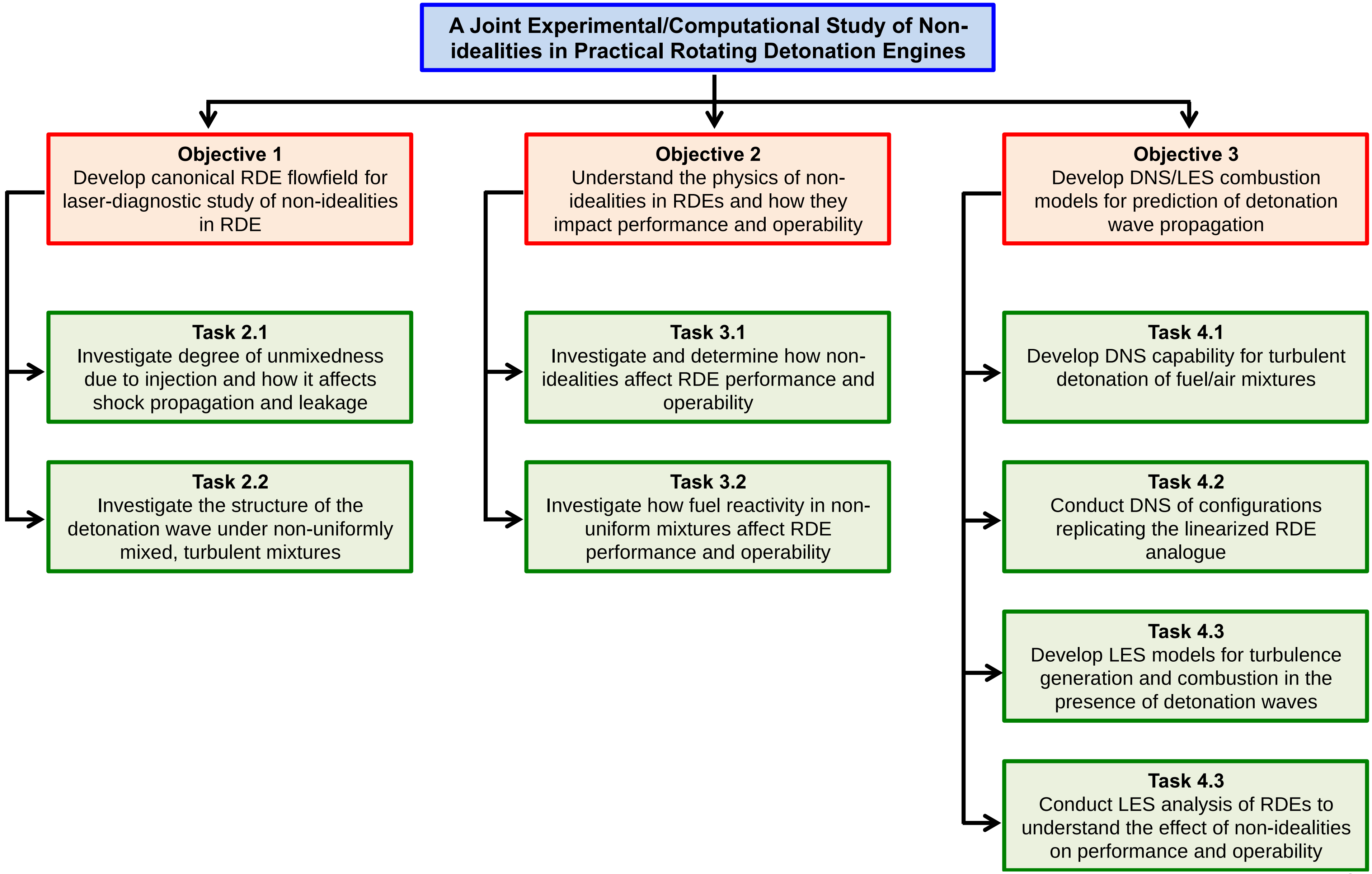
Expected outcomes

- **Outcome 1:**
  Identify the sources and properties of non-idealities in RDEs, their contribution to loss in pressure gain, and potential design limitations

- **Outcome 2:**
  Detailed experimental tools and measurements (databases) about fundamental aspects of RDEs will become available to the RDE design community.
  - e.g., transfer of techniques and data to UTRC, ISSI, NRL

- **Outcome 3:**
  Detailed computational tools (DNS/LES) as well as combustion models with detailed chemistry for pressure gain combustion will be made available to the RDE design community.
  - e.g., openFoam development of RDE modeling
  - e.g., transfer of detonation computational models to UTRC, ISSI, NRL

Objectives and tasks



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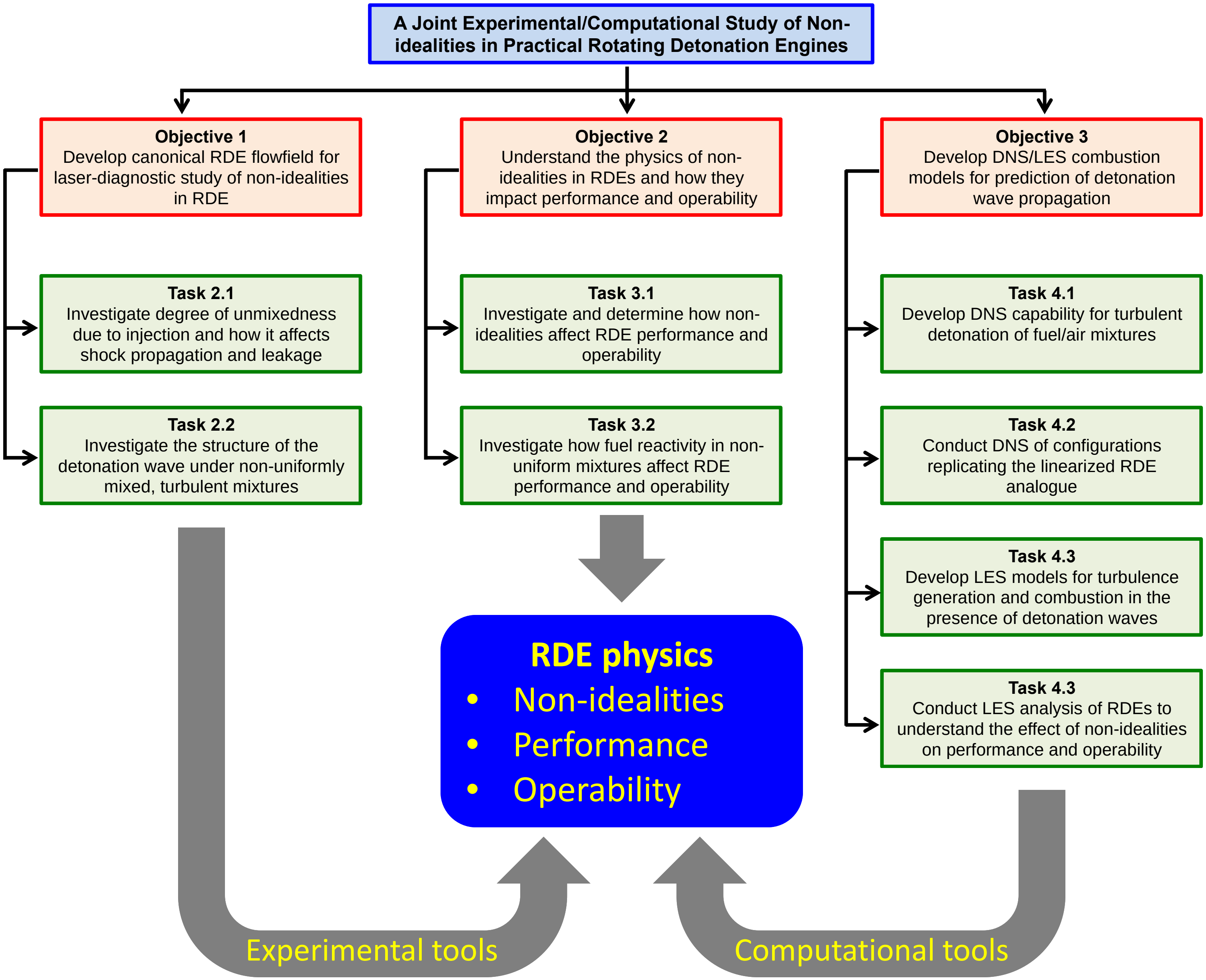

Timeline of the project

	Task	Name	Start	Finish		2016				2017				2018		
					Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Task 1	**1.0**	**Project meeting and planning**	10/15	09/18												
	1.1	Project meetings and progress report	10/15	09/18												
Task 2	**2.0**	**Study of non-idealities in detonation waves**	10/15	12/17												
	2.1	Mixing study due to injection and shock interaction	10/15	12/16												
	2.2	Detonation wave structure	04/16	12/17												
Task 3	**3.0**	**RDE performance and operability under non-idealities**	10/15	09/18												
	3.1	Effects on non-idealities in RDE operability	10/16	09/18												
	3.2	Effect of fuel reactivity and non-idealities	07/16	09/18												
Task 4	**4.0**	**Develop LES combustion models for detonations**	10/15	09/18												
	4.1	DNS for turbulent detonation	10/15	12/16												
	4.2	DNS replicating detonation in linearized RDE	04/16	06/17												
	4.3	LES models for turbulent detonation	07/18	09/17												
	4.4	LES analysis of RDE performance	04/18	09/18												

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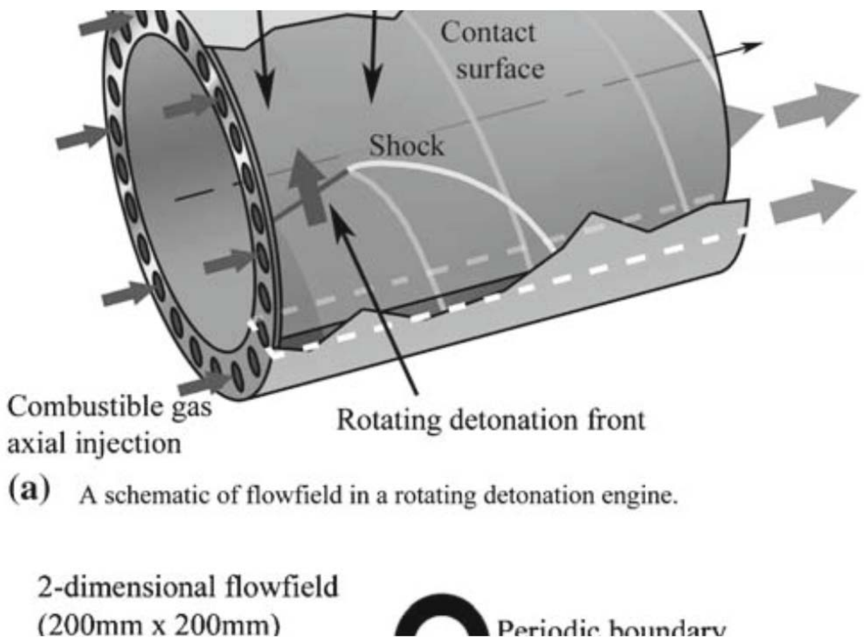
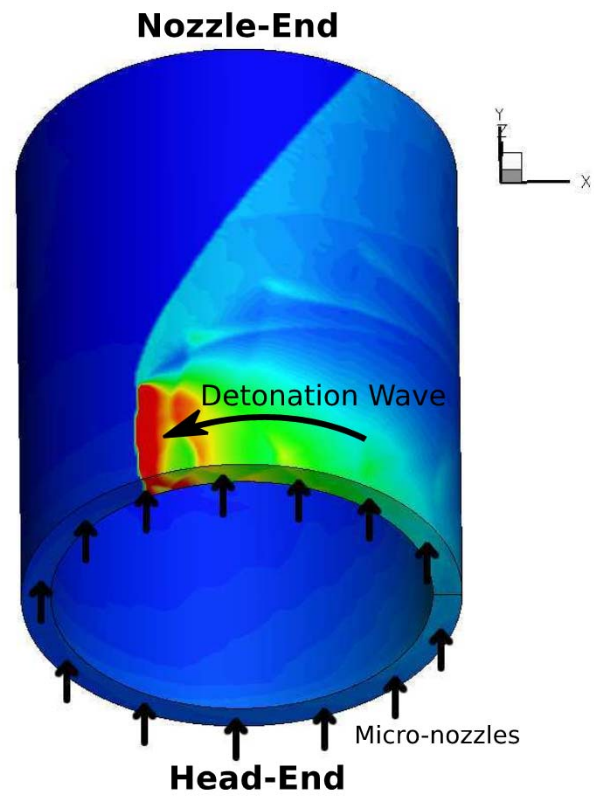
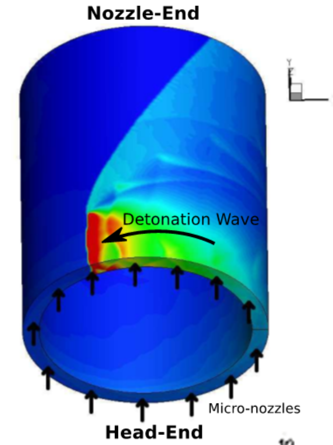
Overview of RDE operation and Pressure Gain (PG)

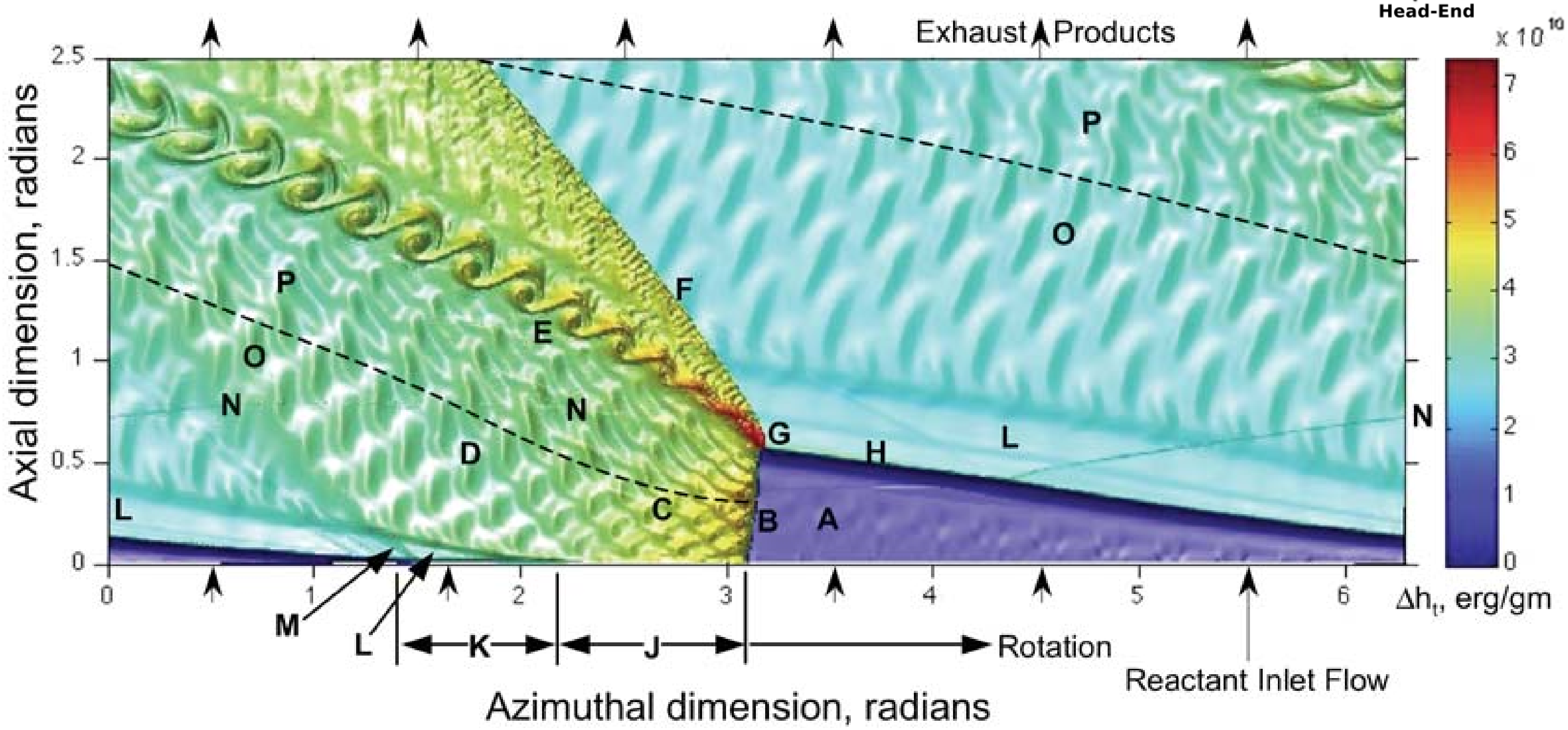




From:
Hishida M., Fujiwara T. and Wolanski P., Shock Waves, 19:10-10, 2009
Schwer D. A. and Kailasanath K., AIAA 2010-6880

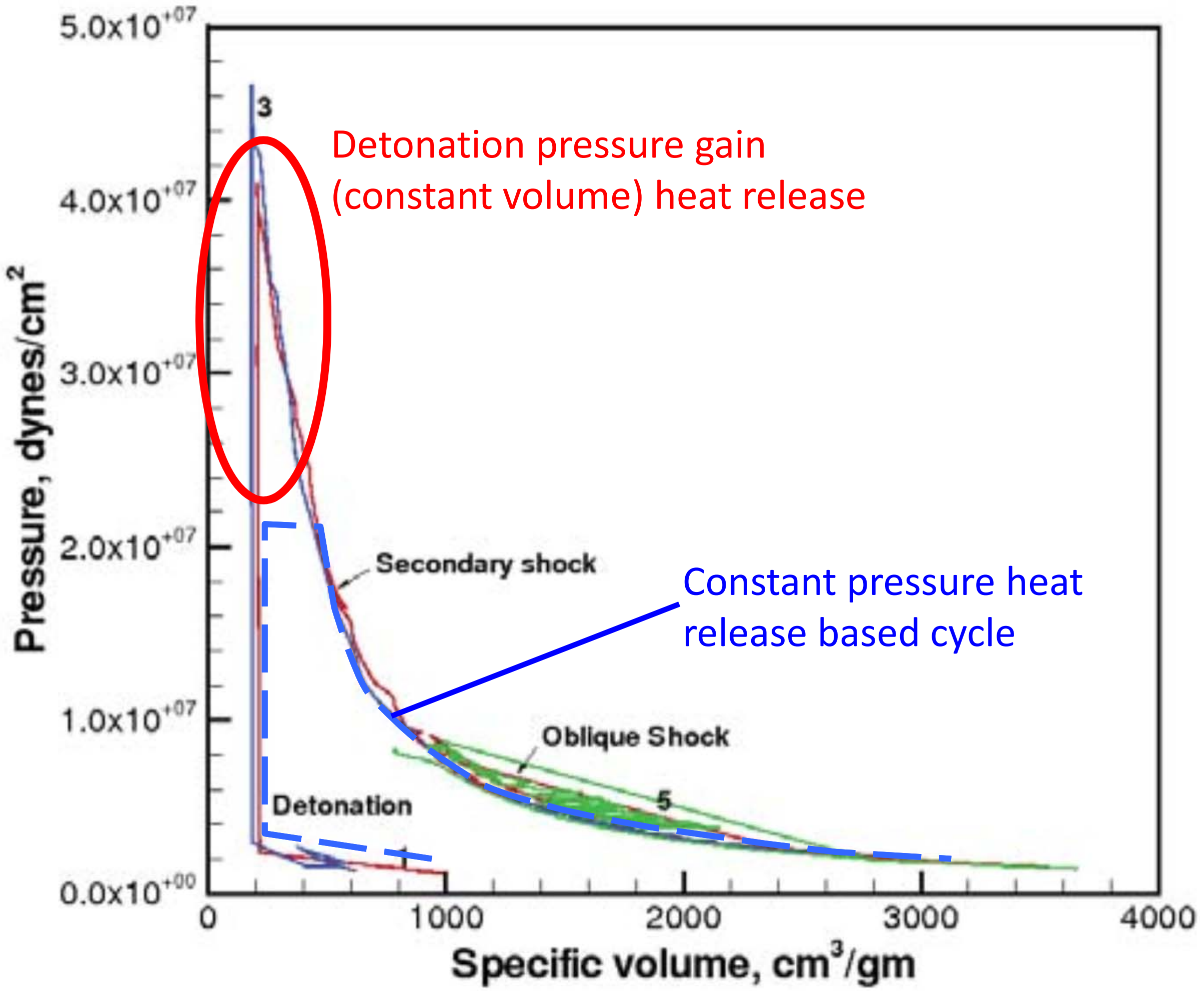
RDE flowfield (unwrapped)





From: Nordeen et al., AIAA 2011-0803

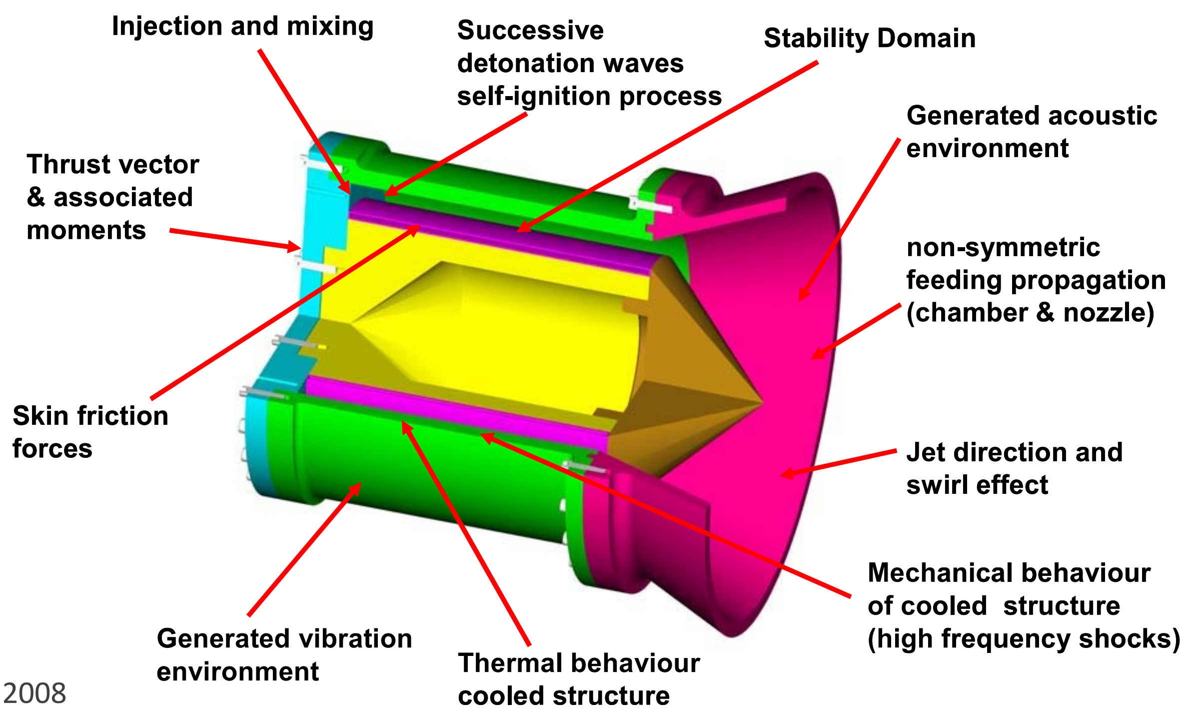
Thermodynamics of RDE and Pressure Gain



From: Schwer D. A. and Kailasanath K., AIAA 2010-6880

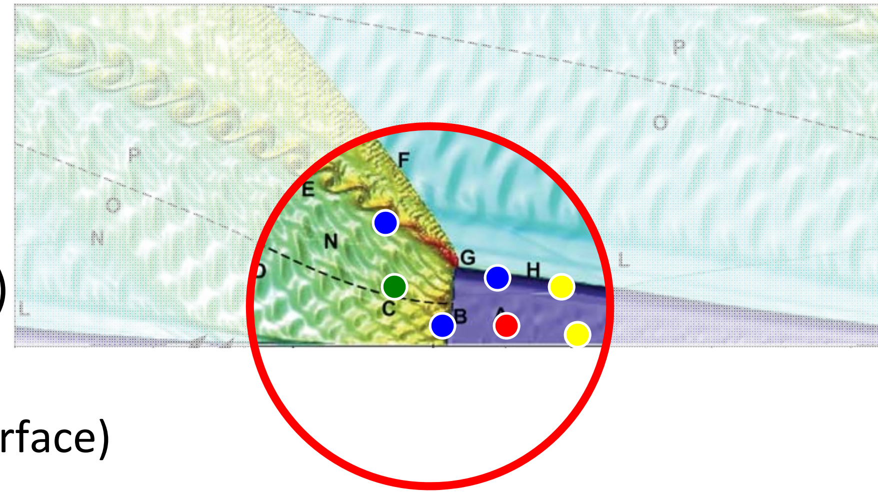
(Some) Practical challenges

- Detonation initiation
- Detonation sustainment
- Produce and maintain pressure gain
- Injector design
  - Mixing, minimize pressure drop, prevent back-flow
- Integration with turbomachinery (compressor/turbine)
  - Unsteady operation
- (High-frequency) unsteady loads (mechanical/thermal)

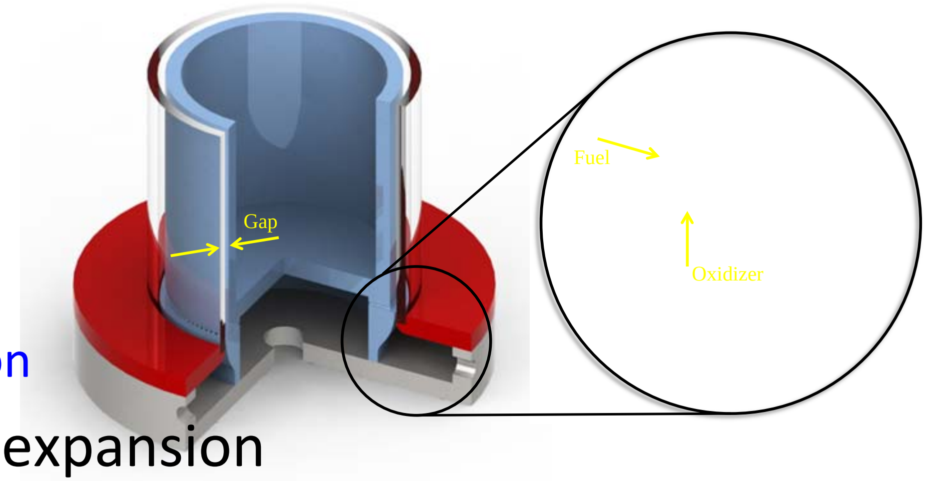


From: Falempin F., EN-AVT 2008

Non-idealities and loss of pressure gain



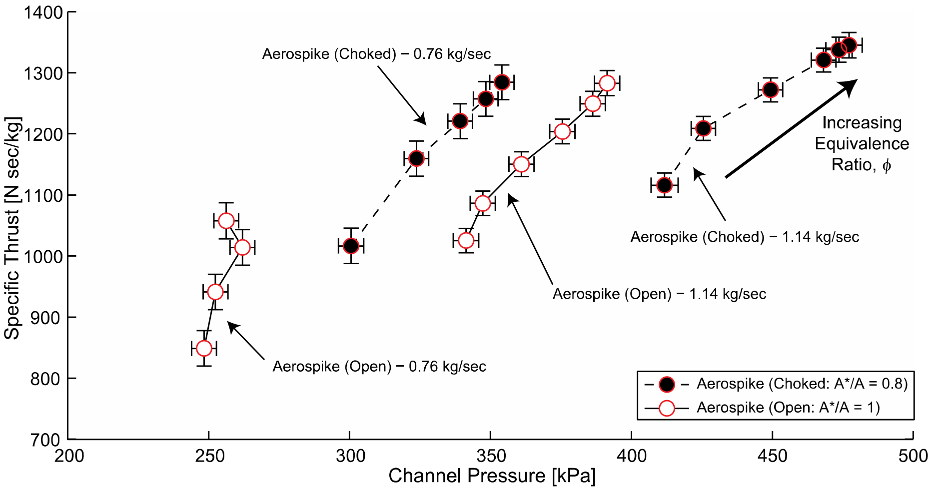
- Detonation non-idealities
  - – Incomplete fuel/air mixing
  - – Fuel/air charge stratification
  - – Mixture leakage (incomplete heat release)
  - – Parasitic combustion:
    - Premature ignition (e.g., burnt/unburnt interface)
    - Stabilization of deflagration (flame)
  - – Detonation-induced flow instabilities
    - Richtmyer-Meshkov (R-M) instability
    - Kelvin-Helmholtz (K-H) instability



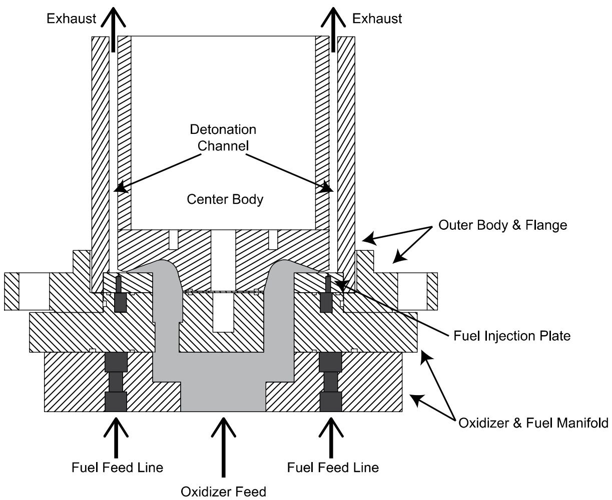
- They lead to loss in pressure gain
  - – Linked to loss of detonation propagation
- Additional losses exist during flow expansion
  - – Secondary shock and (multiple) oblique shock
  - – Flow instabilities (e.g., K-H instability)
  - – Mixture leakage through burn/unburnt interface

Past/current analysis/investigation approach

- Past/current approach is based on global performance assessment
- Experimentally:
  - Global performance assessment
  - Low-fidelity and/or global metrics
    - Pressure measurements
    - Luminosity-based analysis (optical access is a challenge!)



  - Parametric study
    - Variation with flow rate, (global) equivalence ratio, fuel, pressure
    - Injector design / annulus / exhaust flowpath testing



- Prediction/computation
  - Euler solver or limited viscous effects modeling
  - One-dimension, perfect mixture
  - Single-step reaction
  - Induction-time based combustion models
  - Neglect mixing, three-dimensional viscous effects and turbulence

Our approach: a multi-level physics study

Practical RDE

↓

Unit-physics decomposition

Diagnostics

- Laser-based imaging
- Mixing measurement
- Detonation structure
- Temperature and species imaging

Injection & mixing

- Free single injector
- Free multiple injection
- Confined multiple injection
- Shock-induced mixing
- DNS/LES modeling
- Experiments

Turbulence & detonations

- Linear analogue
- Detonations in stratified mixtures
- DNS/LES modeling
- Experiments

Detailed modeling

- Variable mixture ignition model
- Homogeneous reactor model with tabulated ignition times
- Non-equilibrium

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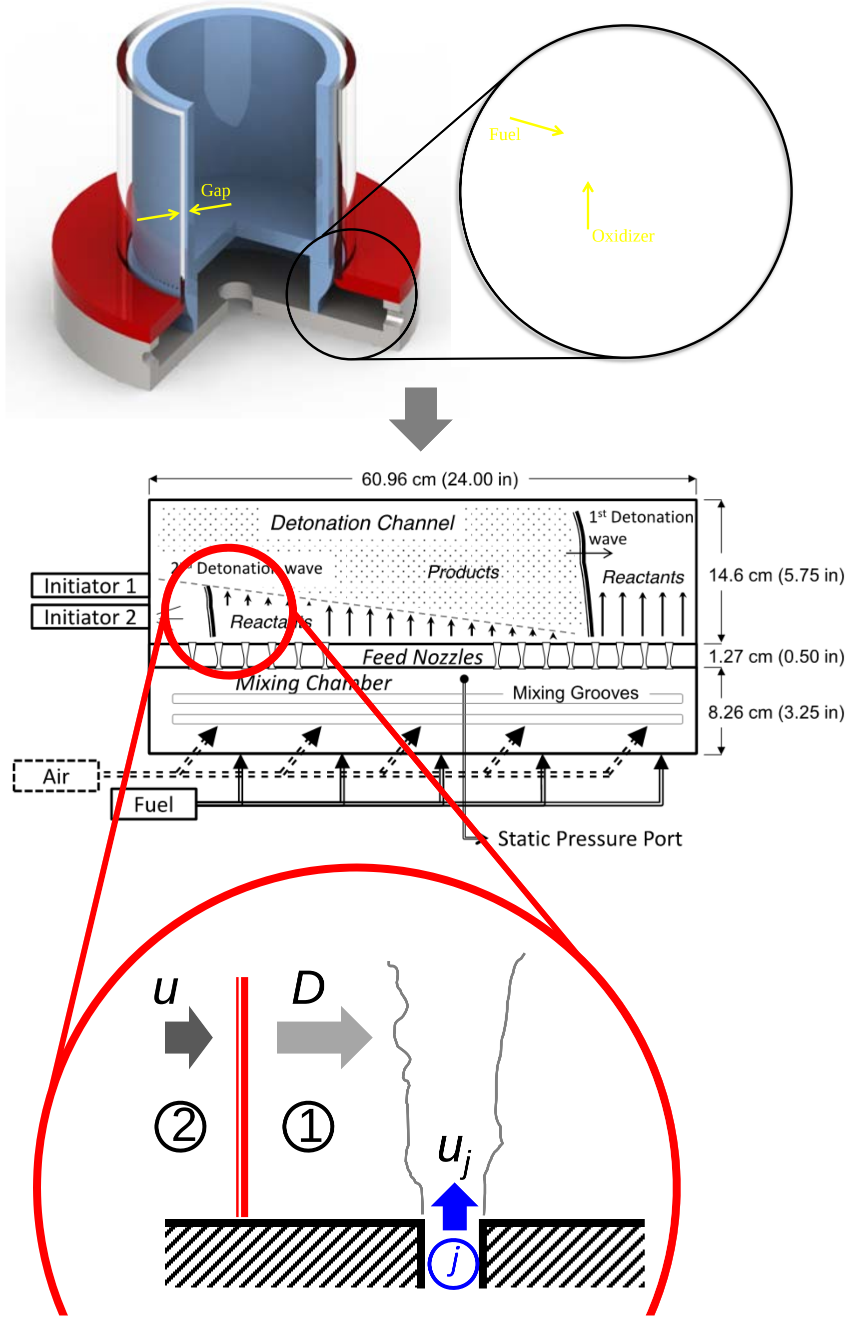
Experimental multi-level approach

RDE full system:
- Link between mixing and performance
- Design from ISSI/AFRL

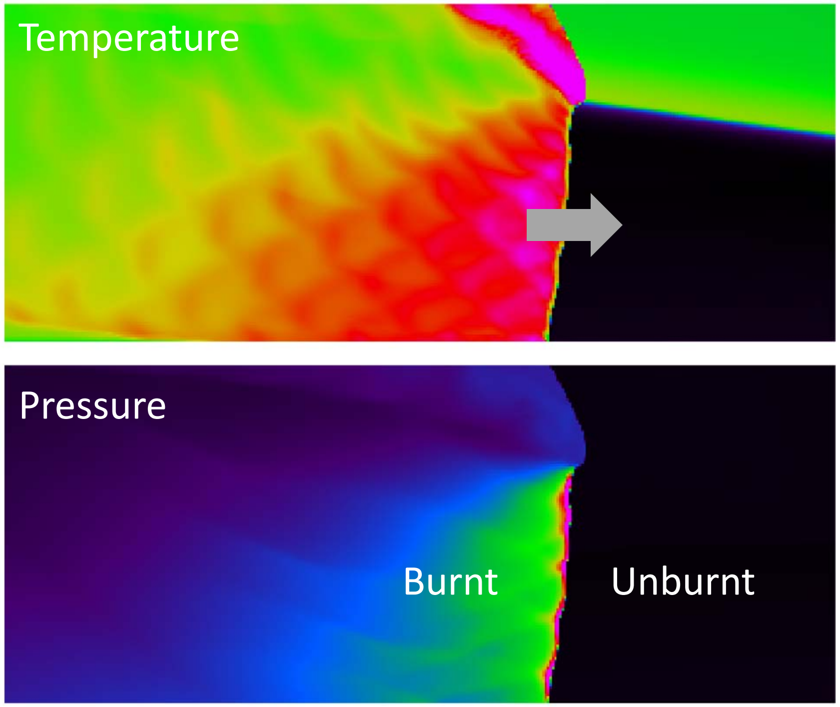
Linearized analogue:
- Detonation structure
- Detonation/turbulence interaction
- Detonation in stratified mixtures
- Design from ISSI/AFRL

Single or multiple injectors:
- Mixing studies
- Shock-induced mixing
- Our starting point

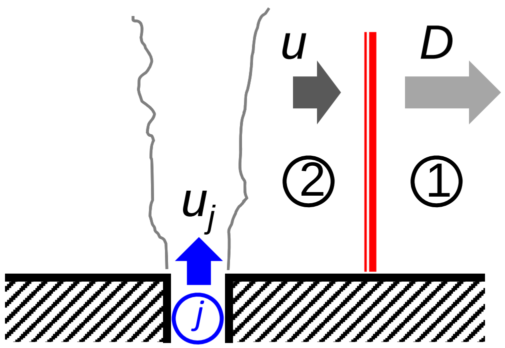


Shock-induced mixing: detonation/shock analogy

Detonation

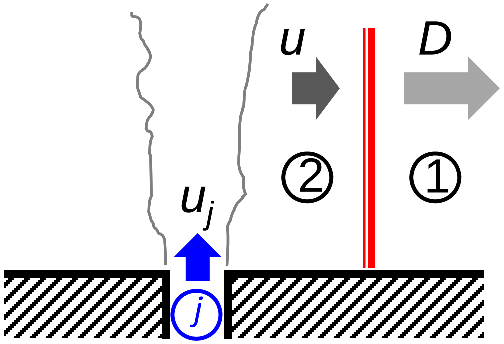


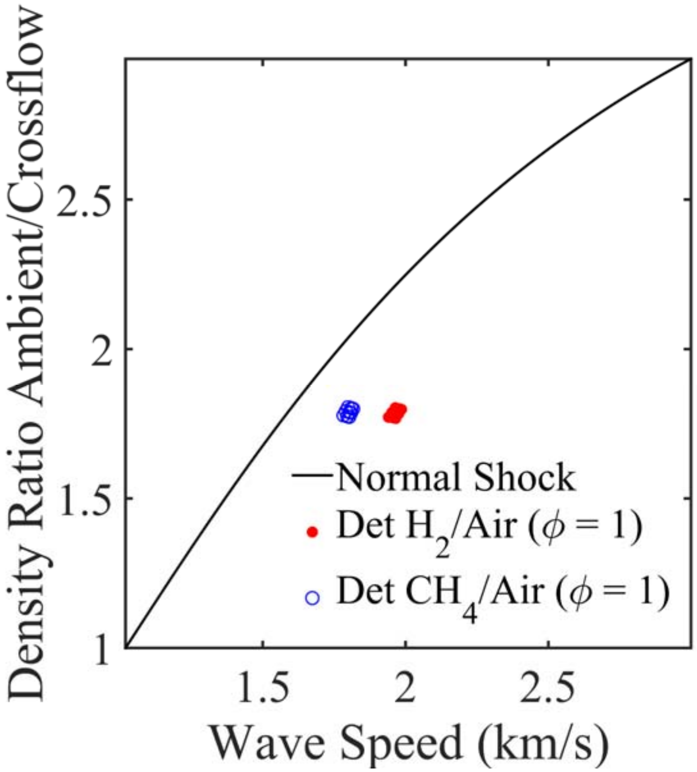
Shock analogy

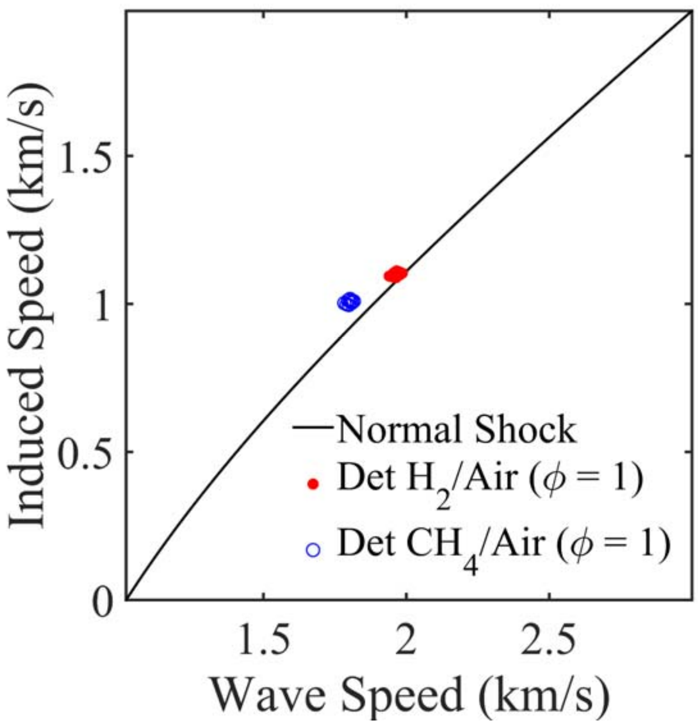


From: Schwer D. A. and Kailasanath K., AIAA 2010-6880

Scaling of detonation/shock analogy







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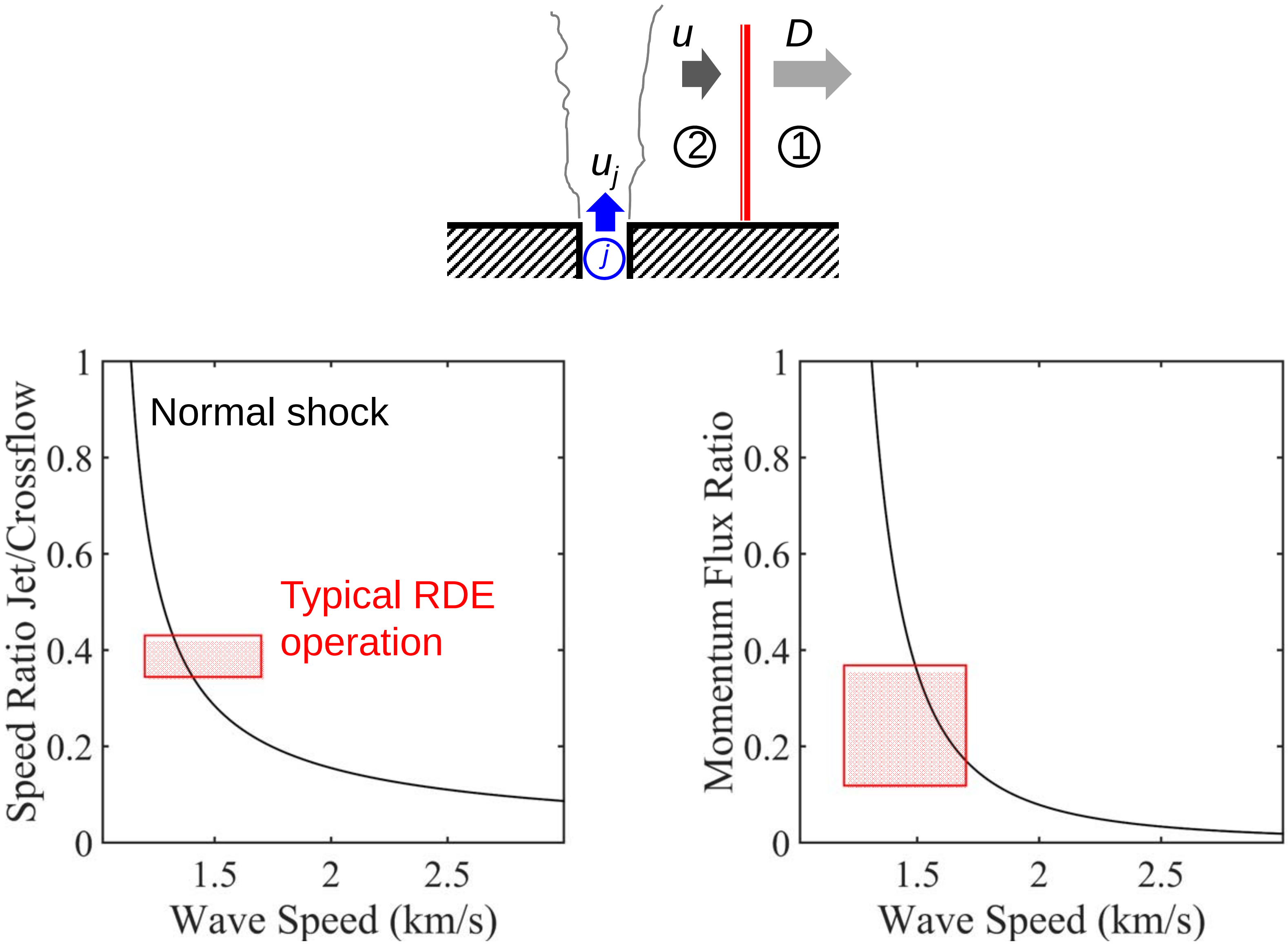
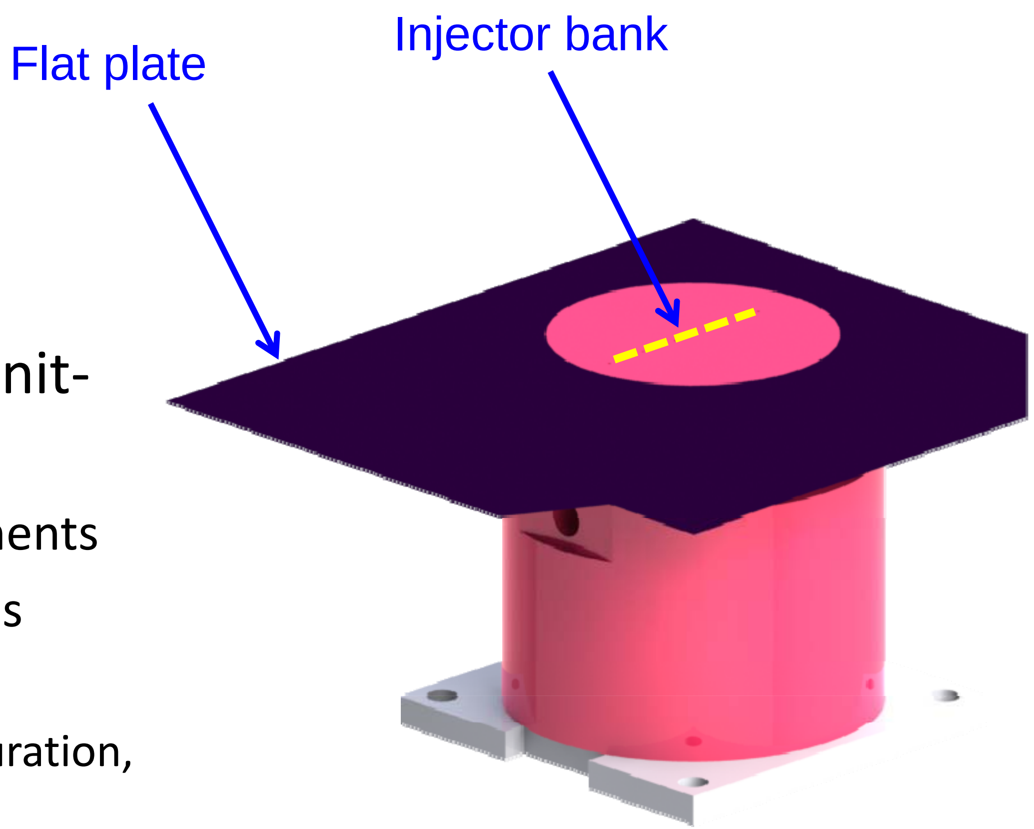


Shock-induced mixing in turbulent jets

- Flexible configuration
  - Single isolated injector
  - Multiple isolated injectors
  - Confined multiple injectors
  - Different injector configurations can be tested conveniently



- Well-suited for controlled unit-physics experiments
  - Quantitative mixing measurements
  - Flexibility in range of conditions
    - Shock strength
    - Injection details (speed, configuration, molecular weight)
  - What learnt here can be extended to the linearized RDE

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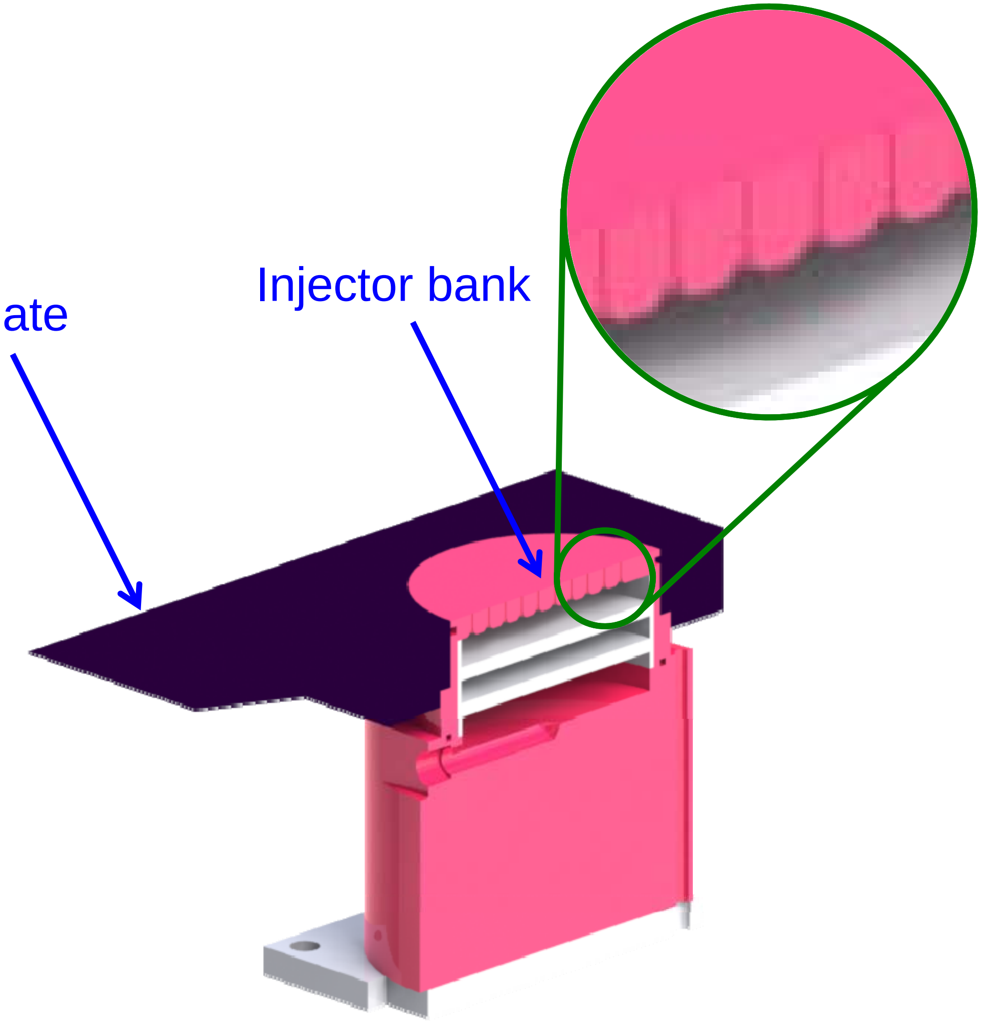

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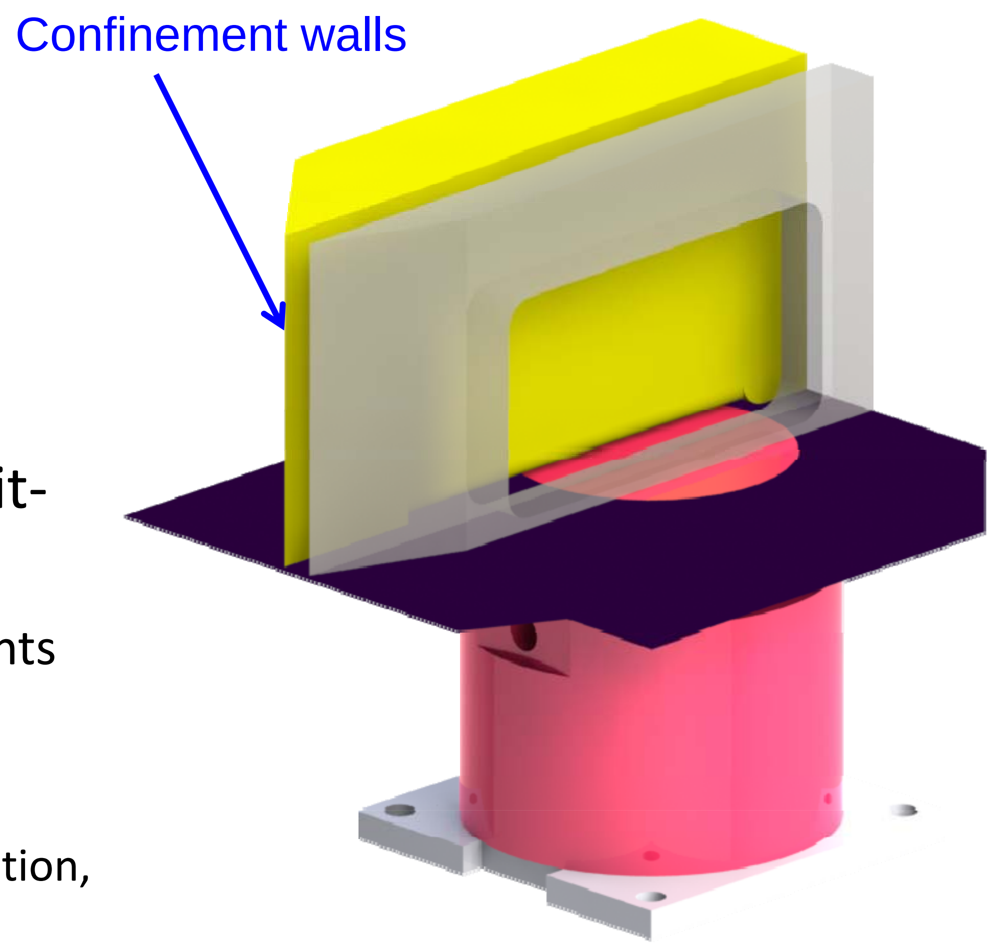

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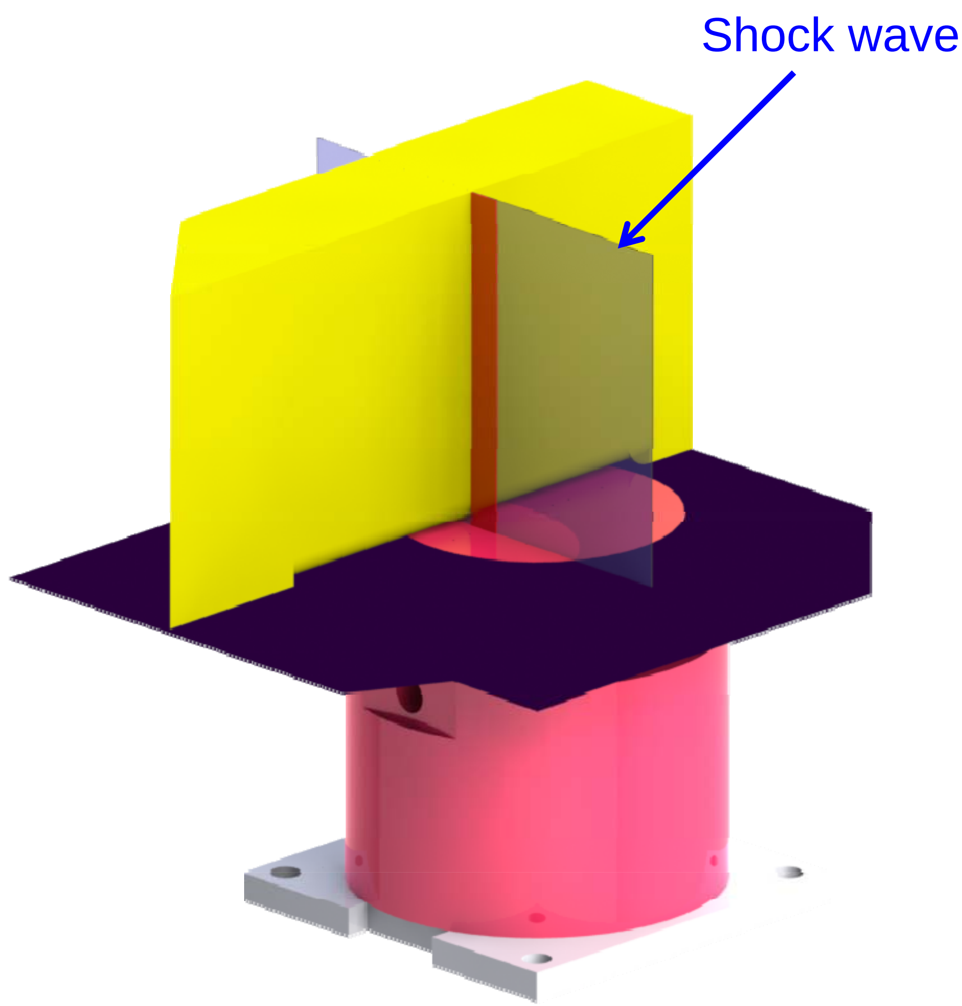

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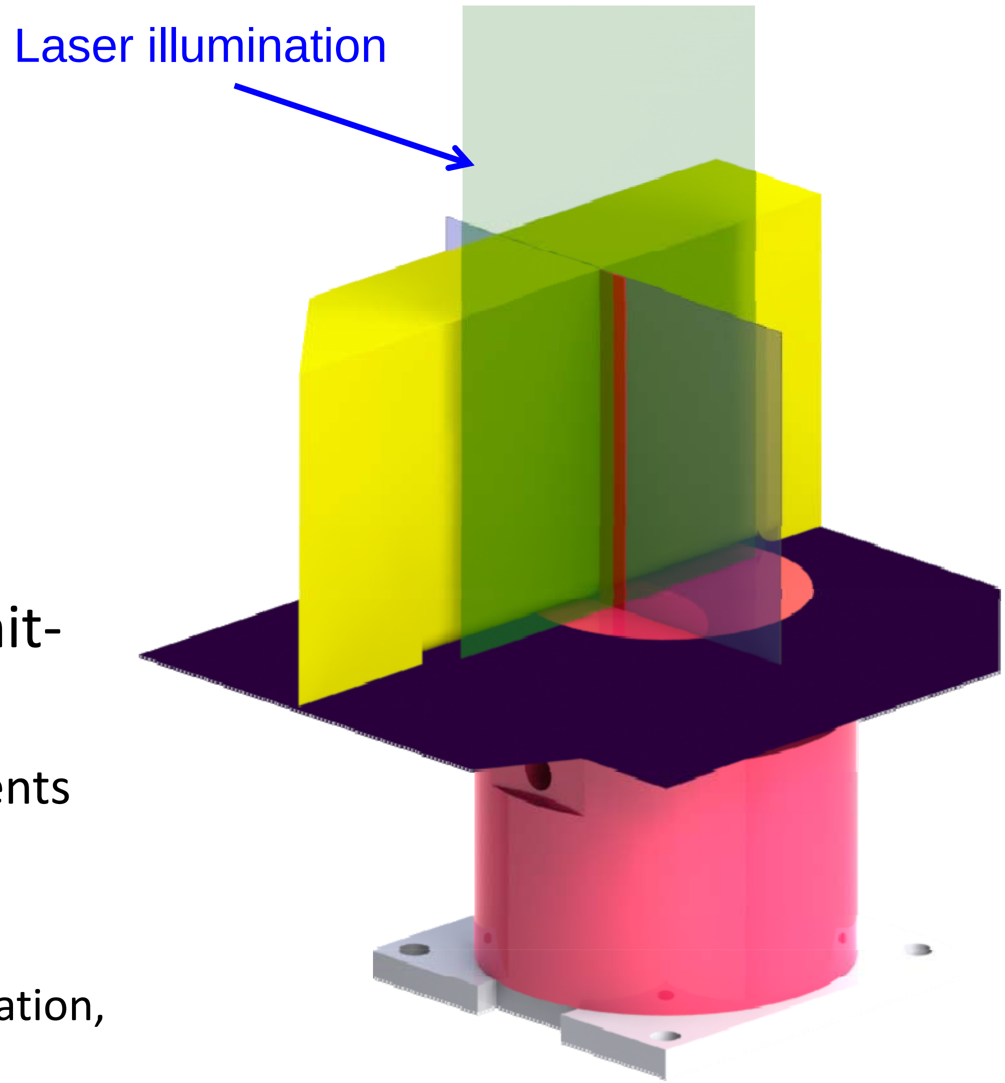

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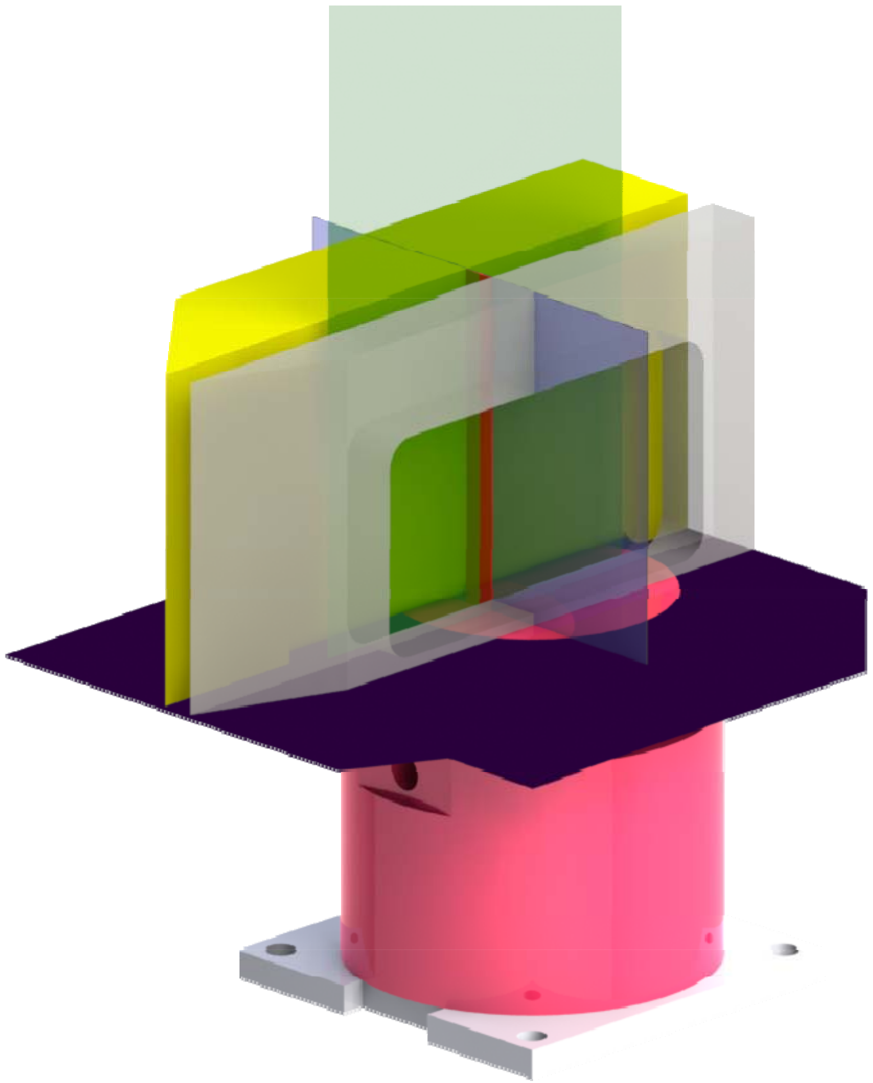

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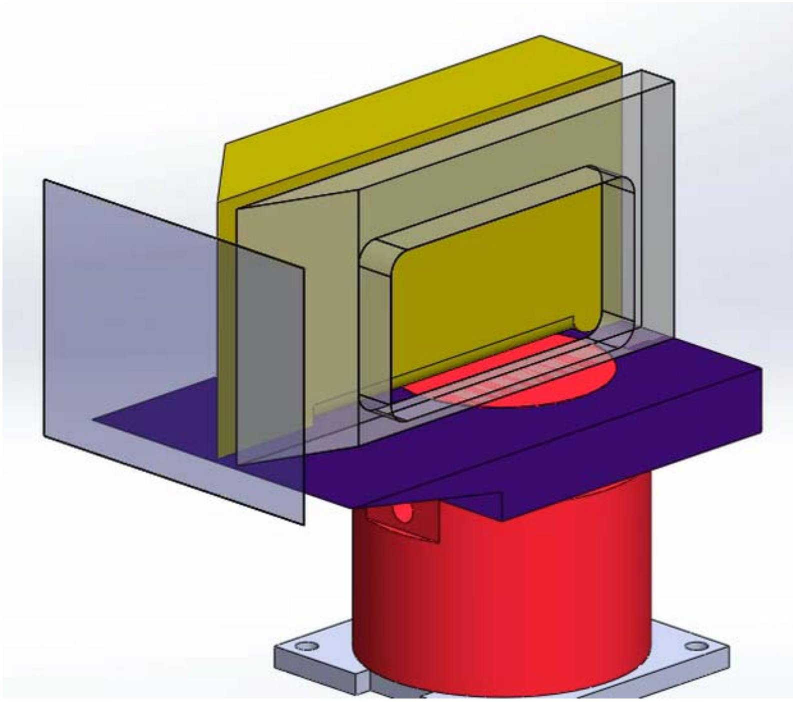
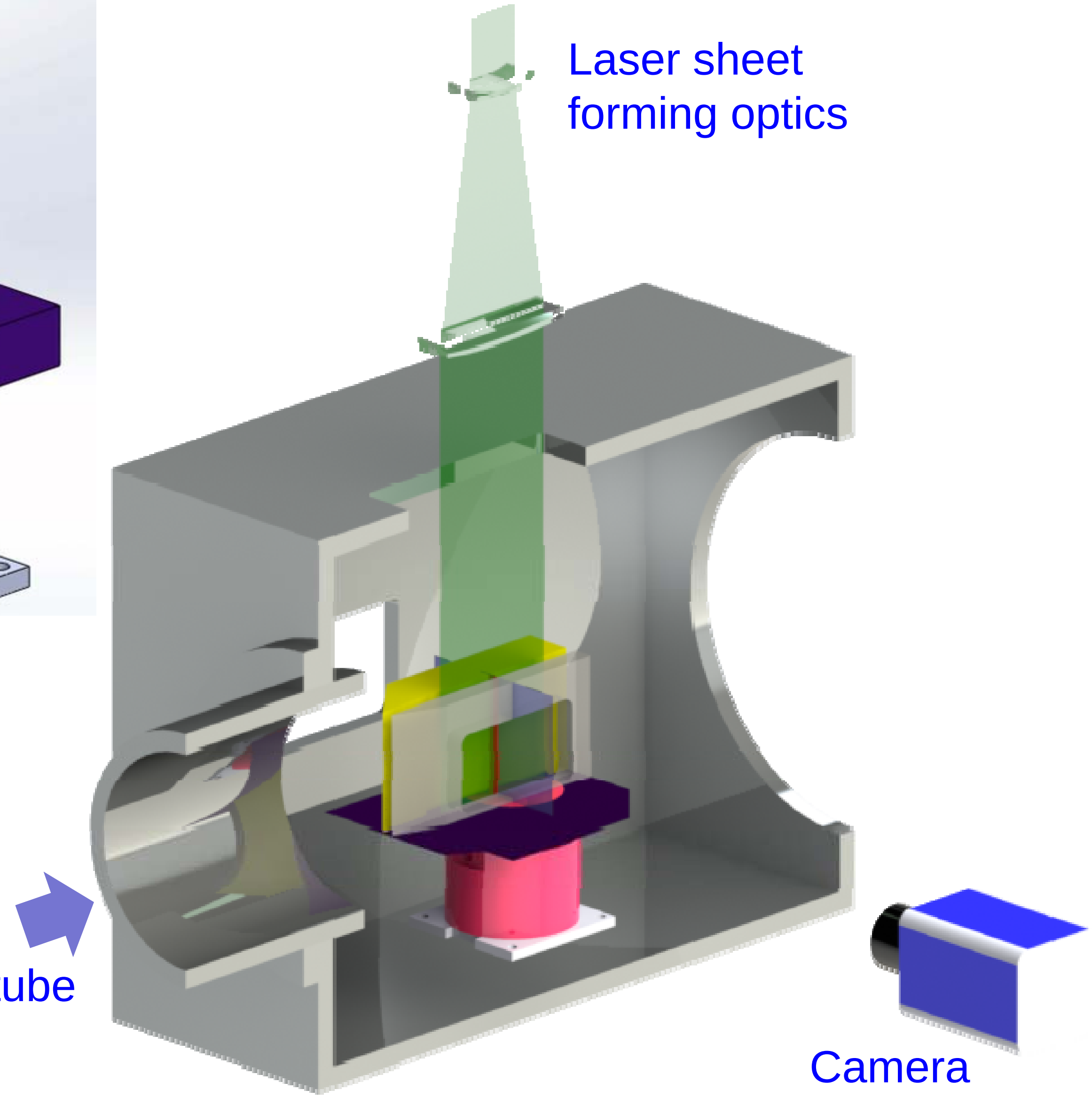
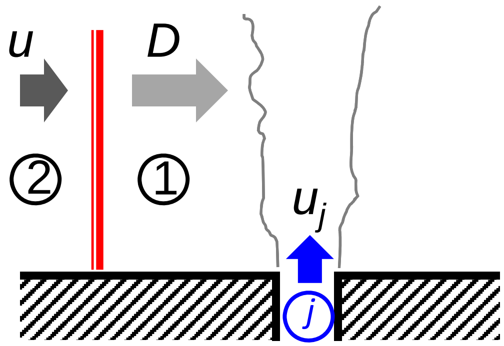
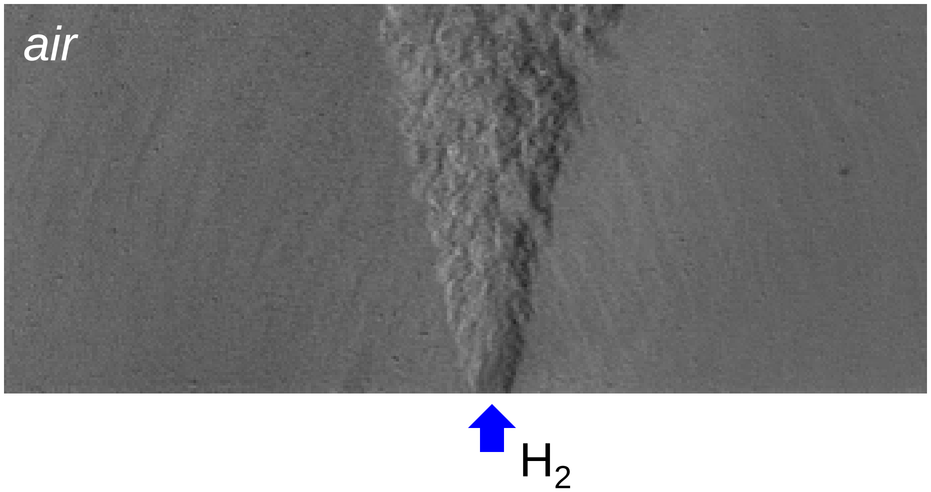




Interaction of shock wave with turbulent jet

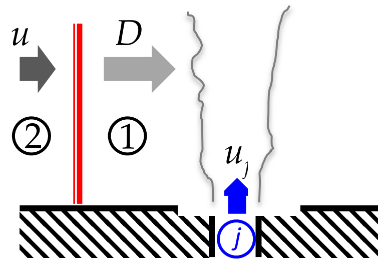


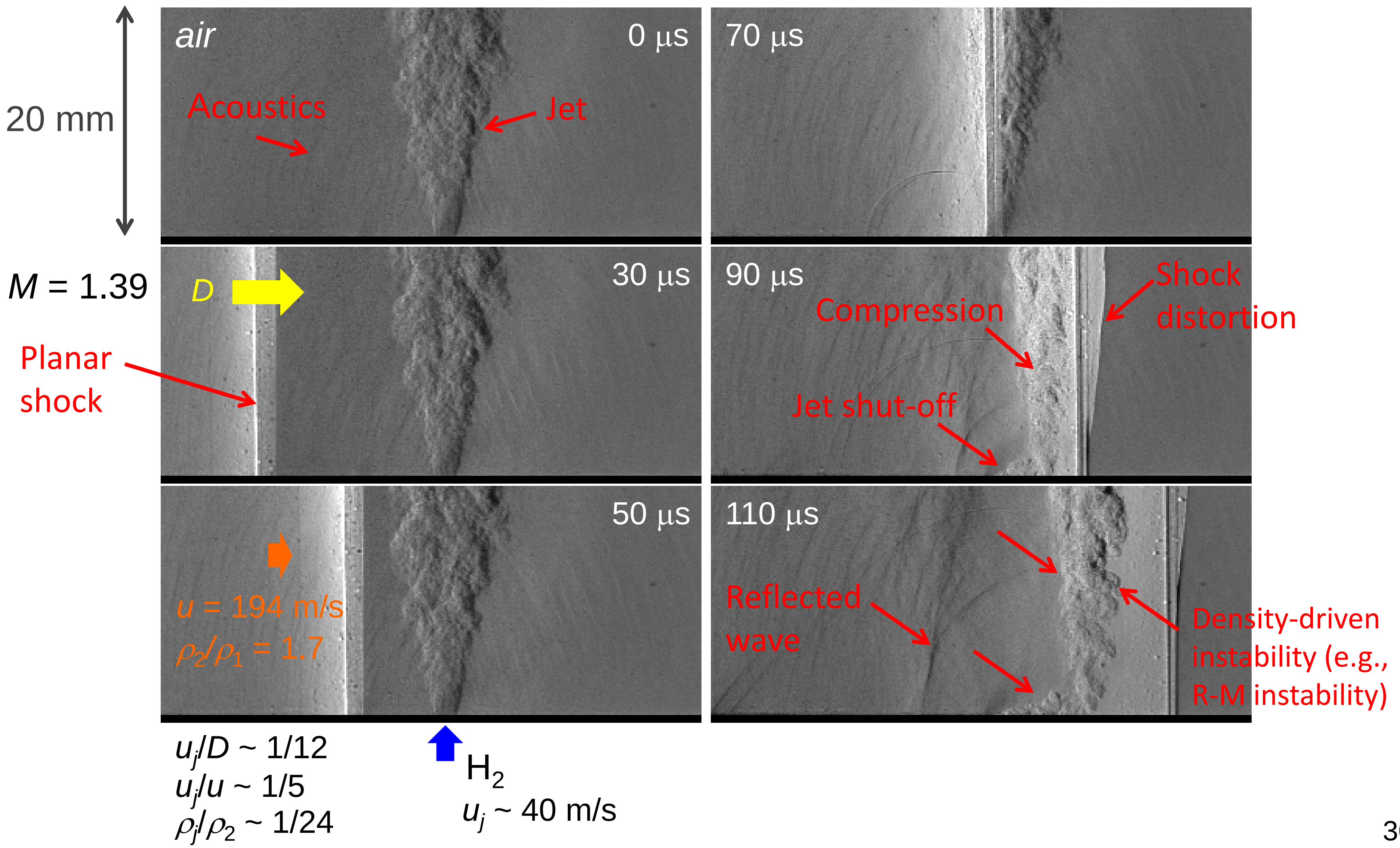
M = 1.39



- Detonation-induced mixing analogue
- Visualization data
  - 100 kHz movie with 300 ns exposure (shock smears by 0.13 pixel)
  - Injection of H_2 into still air subject to a Mach 1.39 shock wave
  - Played back at 5 frames/second
  - Elapsed time 0.5 ms (50 frames)

Interaction of shock wave with turbulent jet





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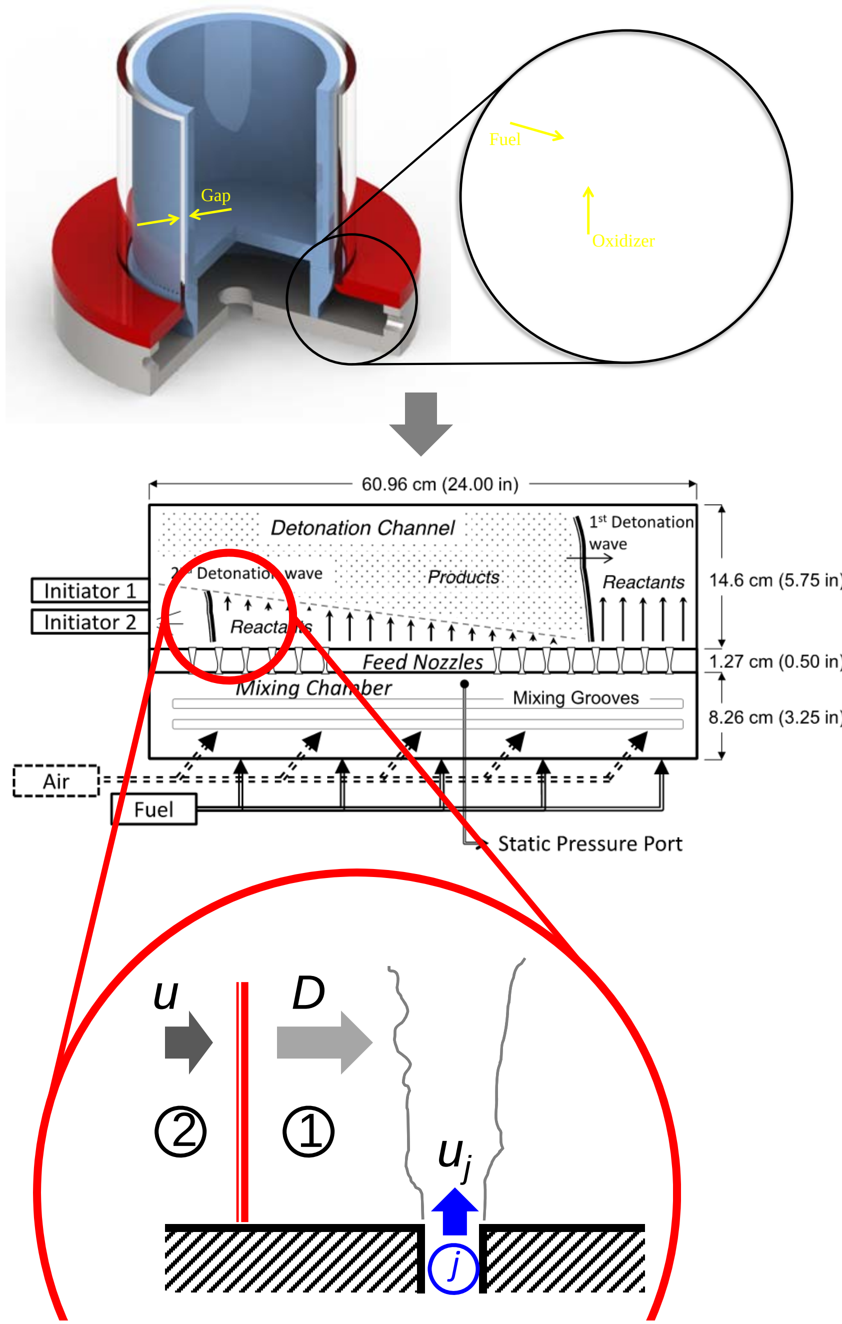
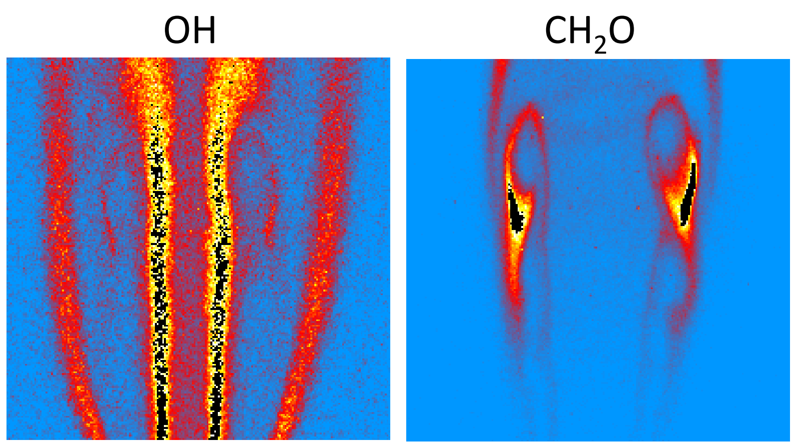


Suite of diagnostic techniques for the study of RDE physics

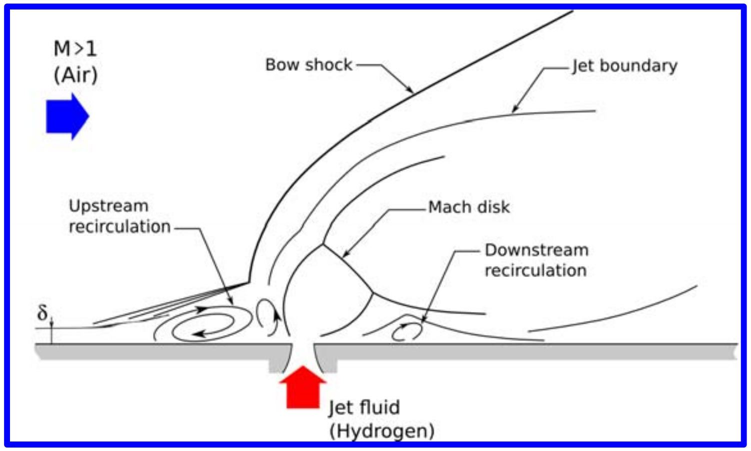
- Traditional techniques:
  - Pressure, heat flux, flame chemiluminescence
  - Schlieren imaging
- Laser-based imaging diagnostics:
  - Planar laser-induced fluorescence (PLIF) mixing and flame marker
  - Two-color toluene PLIF thermometry and mixing (non-reacting) imaging
  - $OH/CH_2O/CH/NO$ PLIF imaging
    - e.g., Simultaneous OH/CH_2O PLIF imaging for flame structure and heat release distribution study in premixed combustion
  - Rayleigh scattering imaging (thermometry in reacting flows)
- Some examples follow

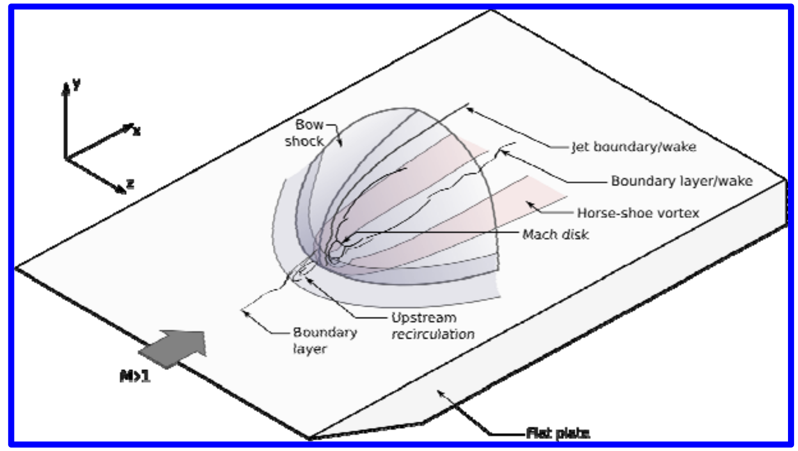


Simultaneous OH/CH_2O PLIF imaging in inverted oxy-fuel coaxial non-premixed CH_4 flames

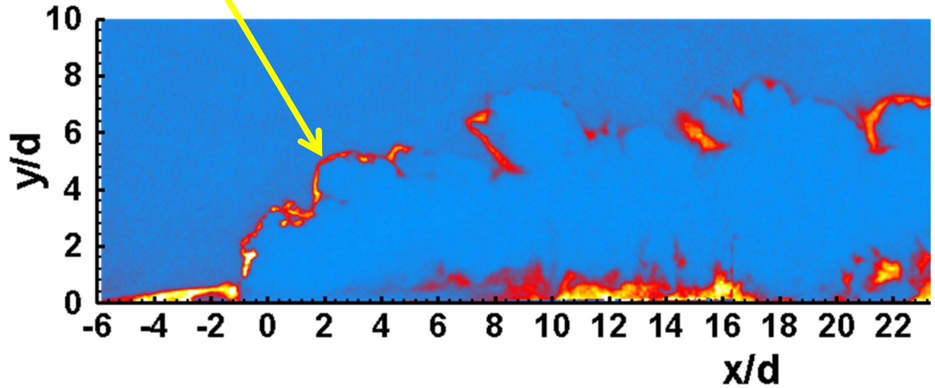
Mixing and combustion measurements in compressible turbulence

Study of transverse jets in supersonic crossflow - reacting

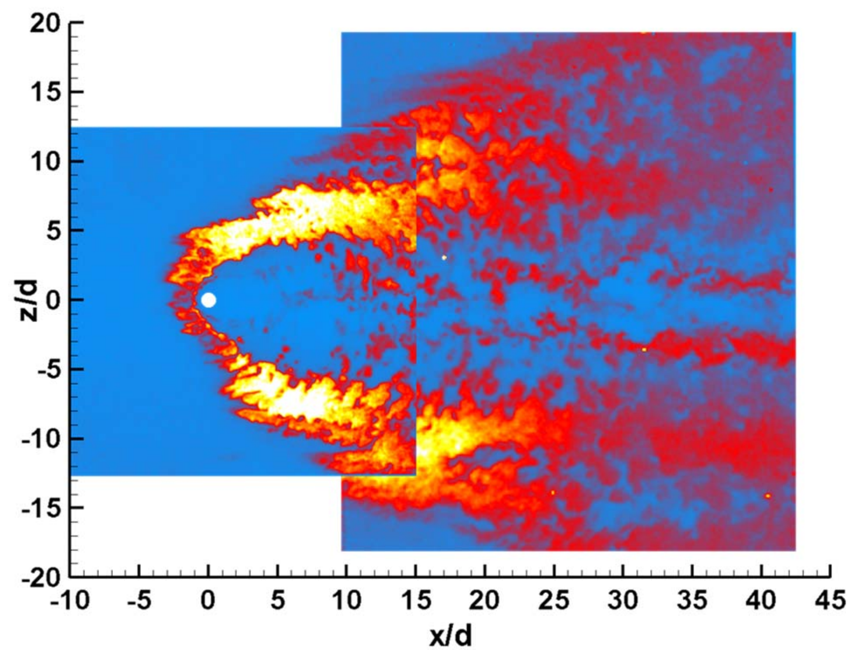




Distribution of OH radical (flame marker)



Side-view centerplane

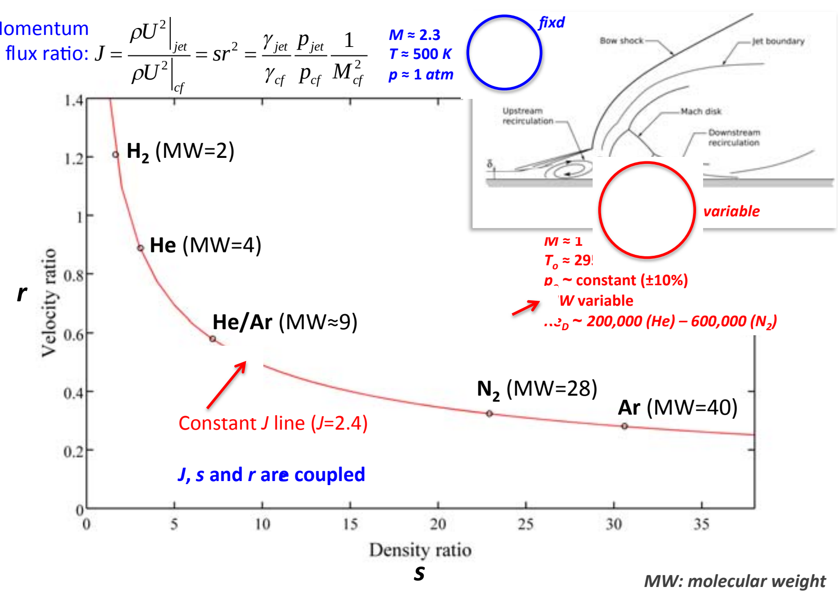


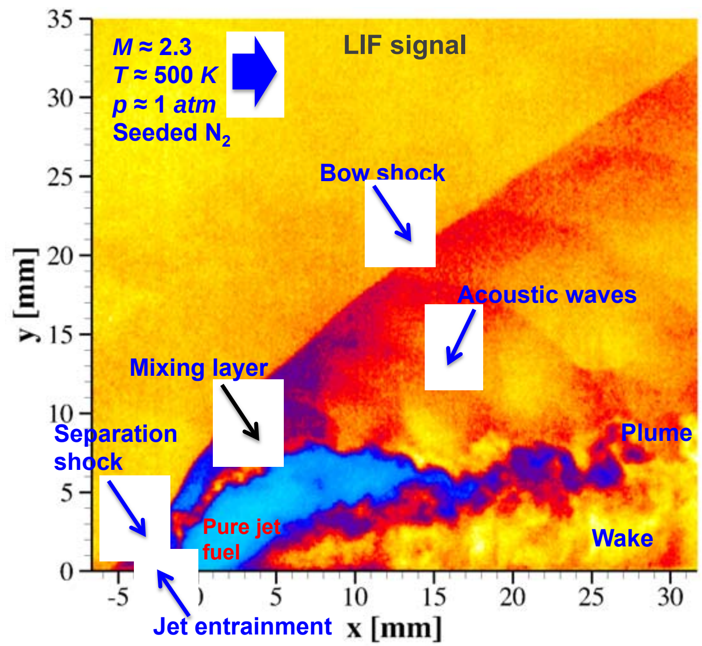
Plan-view 1mm off the wall

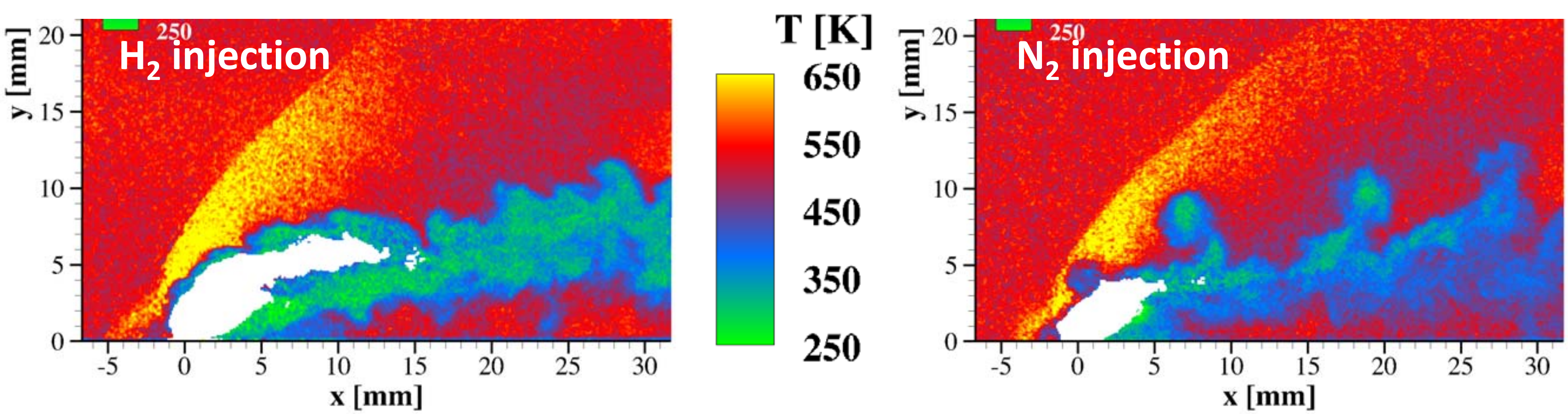
Mixing and combustion measurements in compressible turbulence

Study of transverse jets in supersonic crossflow – non-reacting mixing using toluene PLIF thermometry

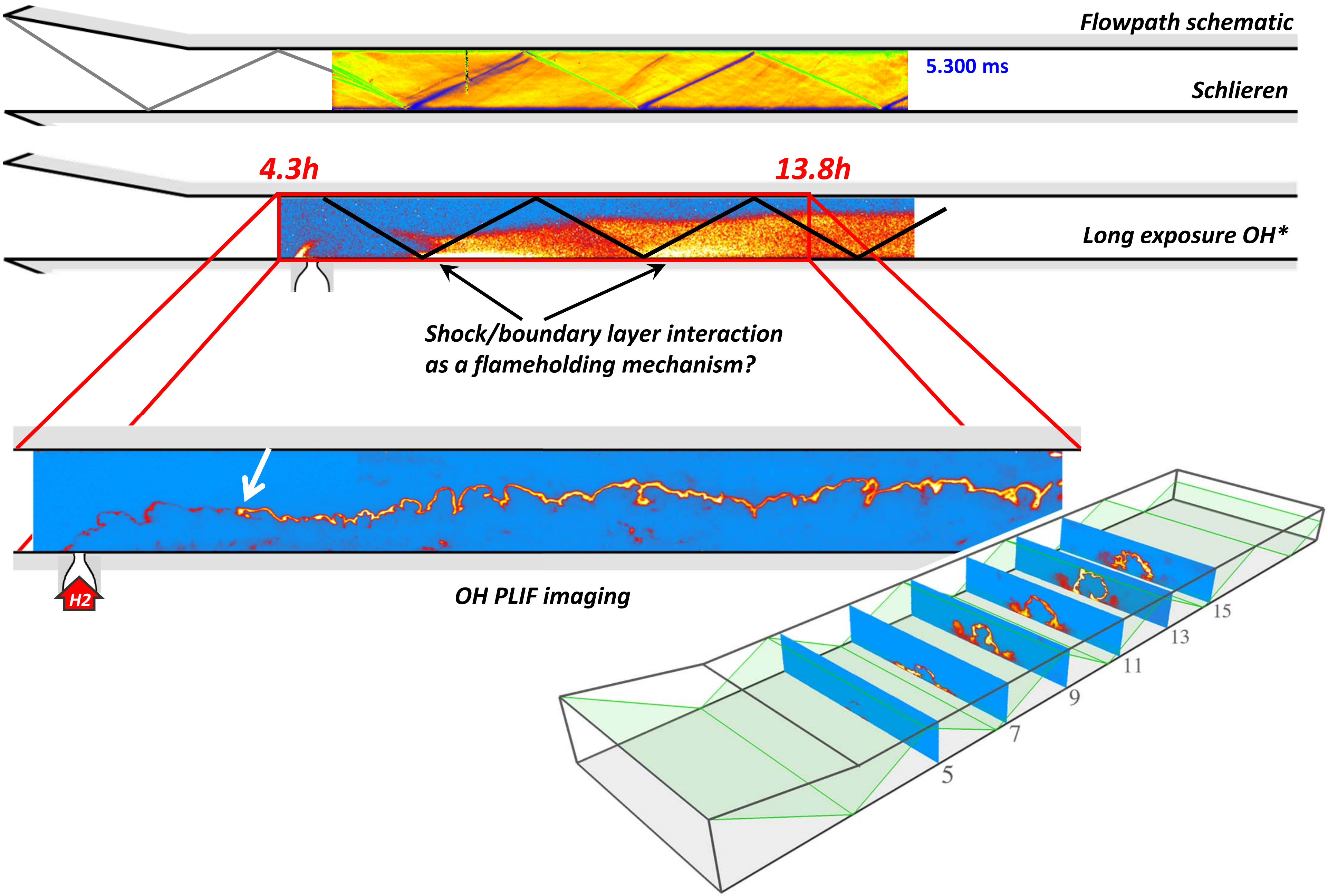
Momentum flux ratio: $J = \frac{\rho U^2|_{jet}}{\rho U^2|_{cf}} = sr^2 = \frac{\gamma_{jet}}{\gamma_{cf}} \frac{p_{jet}}{p_{cf}} \frac{1}{M_{cf}^2}$







Flame structure in scramjet model, (H2/air at $\phi = 0.23$)



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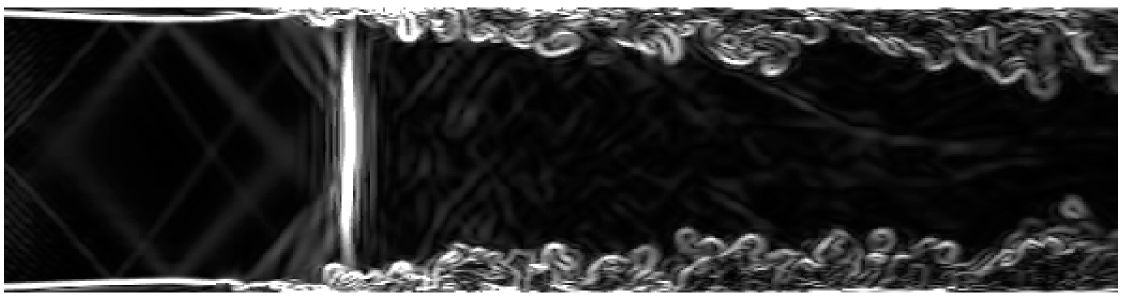
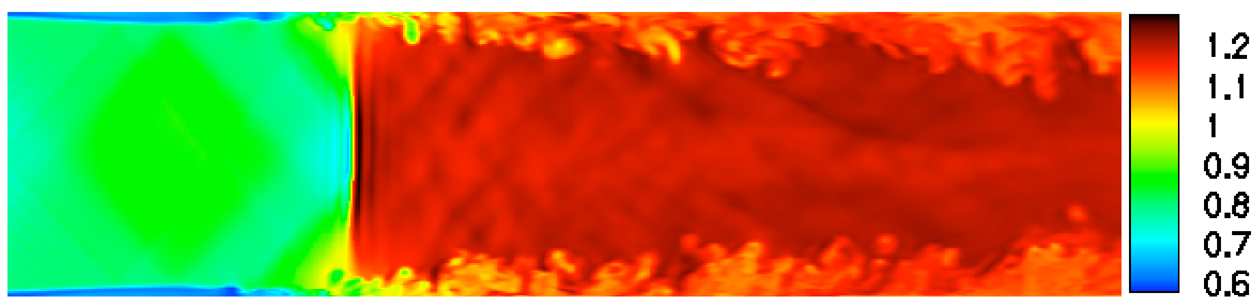
Computational issues in RDEs

- RDEs driven by strong discontinuities
  - Shocks, pressure jumps, strong velocity gradients
  - Numerically challenging
- Coupling to turbulence and inhomogeneities
  - Small-scale gradients in concentration, temperature etc.
  - Ability to capture strong jumps and small-scale features
    - Low dispersion and dissipation in numerical tools
- Combustion modeling
  - How to describe combustion in detonation-based devices?

Numerical capabilities

- Prior work in high-speed shock-containing flows
  - Low dispersion numerics
  - Near-shock resolution using specialized non-oscillatory schemes
  - Central schemes to preserve turbulent kinetic energy away from shock
  - Shock region determined using numerical "sensors"
    - Strain rates and pressure gradients used as sensors





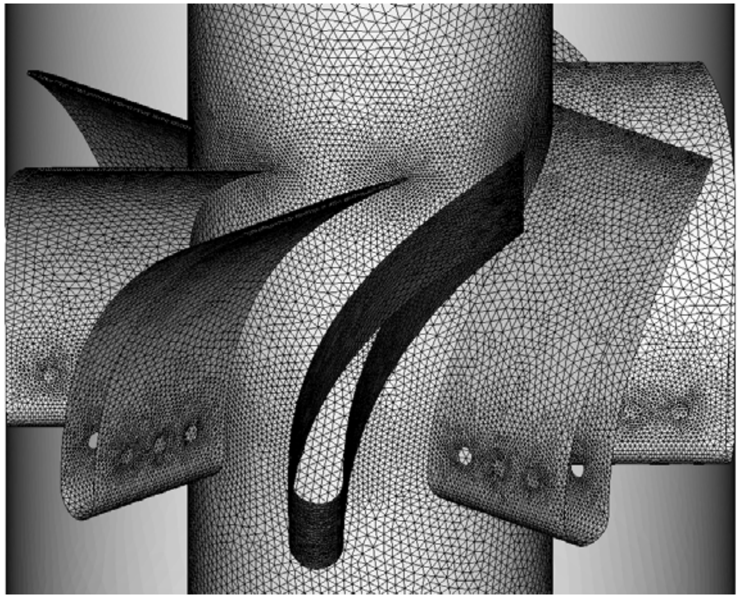
Current focus

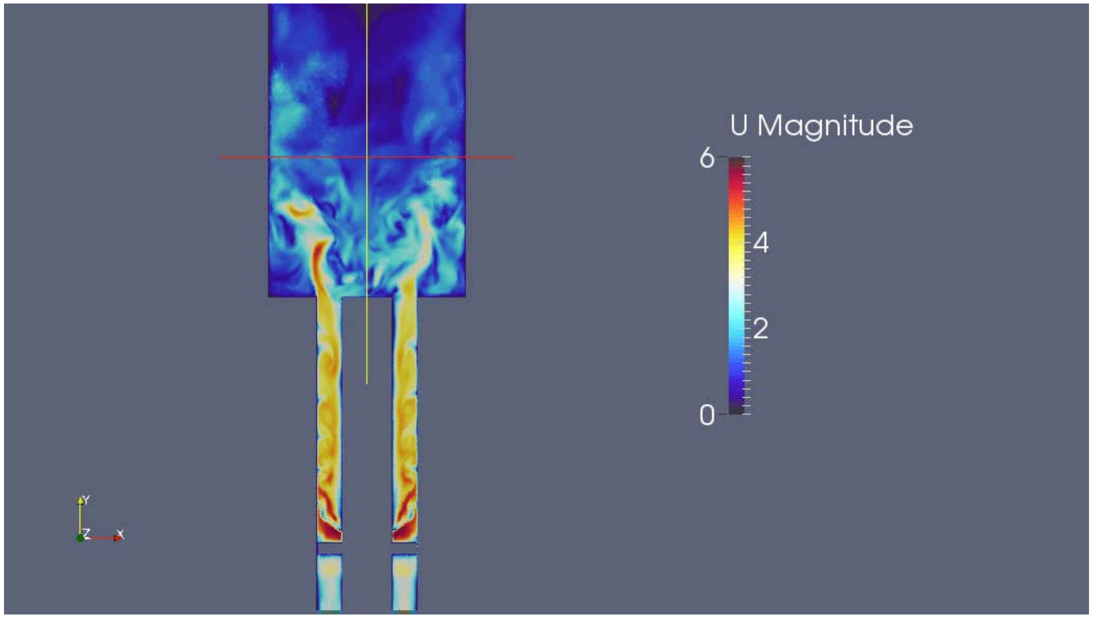
- Need to use complex geometries to model injectors
  - Need unstructured and complex mesh capabilities

- Current work
  - Move solvers to open source framework
  - Ability to directly import CAD files
  - Easily portable across machines
  - **Most importantly, can be easily shared with researchers**
    - **No IP issues on code transfer**
    - **Preliminary solvers developed using NETL-funded work**

OpenFOAM capabilities

- Used for low-speed reacting flows
  - Multiple combustion models implemented
  - Ability to handle detailed chemical kinetics
  - Tested for Euler-type high-speed flows
  - Currently being ported to Siemens Inc.; Collaborations with GE and Rolls Royce





Combustion modeling

- If detonation is uniform, only time-lag model is needed
  - Only valid under ideal conditions
  - Injection leads to spatially non-uniform mixing
  - Variations in fuel/air composition
    - Leads to non-uniform detonation
    - Generation of baroclinic torque and vorticity generation
    - Enhances the effect of non-uniform mixtures

- Combustion modeling focus
  - Develop a variable mixture ignition model

Combustion modeling focus

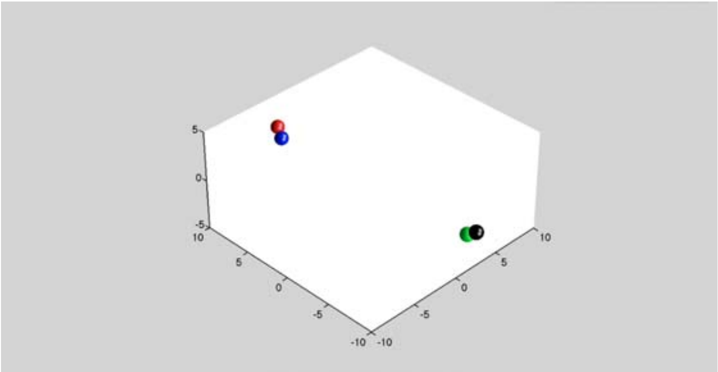
- Low-speed models are not accurate
  - Turbulent mixing dominated ignition

- RDEs
  - Pressure-driven detonation
    - Induction time dependent on pressure response of fuel
  - Response of variable equivalence ratio mixing
    - Non-uniformity in fuel-air ratio can lead to variable delays in ignition
    - Formation of cellular shock structures
    - Loss of efficiency and fuel leakage

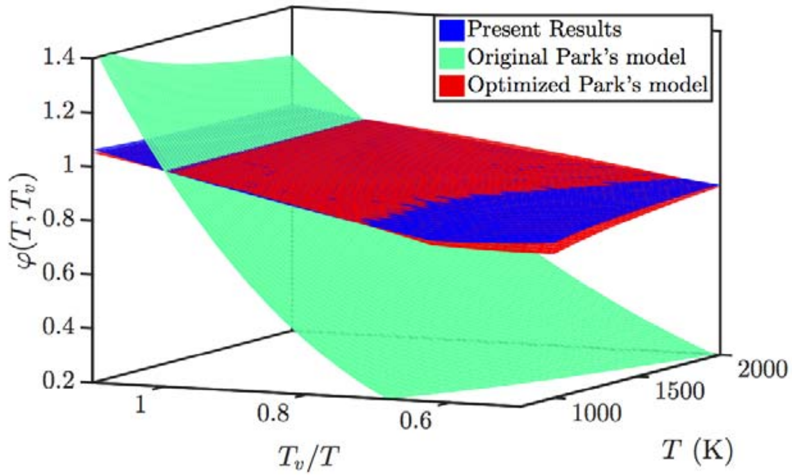
- First approach
  - A local mixture dependent ignition time
  - Use homogeneous reactor configuration to tabulate ignition times

Additional issues

- Strong detonation waves can introduce internal energy nonequilibrium
  - Internal modes cannot be described by Boltzmann distribution
  - Strongly affects ignition and combustion processes



- Our group has been working on nonequilibrium effects through a simultaneous AFOSR-funded effort
  - Use ab-initio computational chemistry to understand effect of nonequilibrium
  - This effort will be leveraged here
  - Strong interest from NRL (Dr. Kailasnath)



External collaborations

- Initiating collaboration with NRL
  - Get input on code development
  - Provide information on nonequilibrium and combustion modeling
- University of Maryland (Prof. Yu)
  - Use existing experimental data for initial validation
  - Provides stop-gap validation data until UM experiments come online
- UTRC and ISSI/AFRL
  - Develop and transfer code and modeling expertise
  - Interact to work on injector modeling

Outline

- Programmatic overview
- Introduction to the problem and general approach
- Experimental activities
- Computational activities
- Interactions and collaborations

Interactions, collaborations and synergies

- Strong coupling between experiments and computations
  - Model development and validation
  - Experiment design and understanding
  - Combined investigation of the physics of detonations under turbulent mixing, incomplete fuel/air mixing, stratification

- Key external collaborations
  - ISSI/AFRL (Dr. John Hoke) on RDE and linearized RDE analogue operation, performance and modeling
  - UTRC (Drs. Adam Holley and Peter Cocks) on modeling and non-ideal behavior
  - Initiating collaboration with NRL (Dr. Kailasnath) on code and combustion model development

- Other collaborations/interactions
  - University of Maryland (Prof. Yu) on initial use of existing experimental data for initial validation
  - Interested in establishing interaction with NETL (Dr. Ferguson)

Questions?