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

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Outline

• Introduction to the problem and general approach
• Experimental activities
• Computational activities
Overarching objectives

• **Use laser diagnostics to:**
  – Develop canonical systems for RDE investigation
  – Understand the physics of RDE in lab- and full-scale configurations
  – Provide data for validation

• **Use high-fidelity simulations to:**
  – Understand basic detonation physics
  – Simulate full scale RDEs
Overarching goal: investigate non-idealities and their link to 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

From:
(top) Nordeen et al., AIAA 2011-0803
Objectives and tasks

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

**Objective 1**
Develop canonical RDE flowfield for laser-diagnostic study of non-idealities in RDE

- Task 2.1
  Investigate degree of unmixedness due to injection and how it affects shock propagation and leakage

- Task 2.2
  Investigate the structure of the detonation wave under non-uniformly mixed, turbulent mixtures

**Objective 2**
Understand the physics of non-idealities in RDEs and how they impact performance and operability

- Task 3.1
  Investigate and determine how non-idealities affect RDE performance and operability

- Task 3.2
  Investigate how fuel reactivity in non-uniform mixtures affect RDE performance and operability

**Objective 3**
Develop DNS/LES combustion models for prediction of detonation wave propagation

- Task 4.1
  Develop DNS capability for turbulent detonation of fuel/air mixtures

- Task 4.2
  Conduct DNS of configurations replicating the linearized RDE analogue

- Task 4.3
  Develop LES models for turbulence generation and combustion in the presence of detonation waves

- Task 4.3
  Conduct LES analysis of RDEs to understand the effect of non-idealities on performance and operability

---

**RDE physics**
- Non-idealities
- Performance
- Operability

---

**Experimental tools**

**Computational tools**

✓ Ongoing

✓ Completed
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
- Multiple injection mixing
- 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
Today we will discuss

• **Experimental component:**
  – Initial investigation of shock-induced mixing
  – Development of lab- and full-scale RDE systems

• **Computational component:**
  – Effect of nonequilibrium on detonation cell size
  – Effect of injector mixing on detonation propagation
Outline

• Introduction to the problem and general approach

• Experimental activities

• Computational activities
Planned 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

• Important parameters
  – Wave speed $D$ (Mach number)
  – Jet-to-ambient (induced flow) density and velocity ratios
  – Injection pressure and configuration

From: Schwer D. A. and Kailasanath K., AIAA 2010-6880
Shock-induced mixing: detonation/shock analogy

Detonation

Shock analogy

Temperature

Pressure

Burnt

Unburnt

Open questions:
- Does the analogy hold?
  - In what ways mixing in a non-detonating flow captures mixing in detonation
- Impact of shock compression on turbulent mixing and structure

From: Schwer D. A. and Kailasanath K., AIAA 2010-6880
Shock-induced mixing: detonation/shock analogy

- We answer the questions by combining:
  - Experimentation in canonical flow
  - High-fidelity simulations of detonating and non-detonating flowfield (multiple-injectors)

From: Schwer D. A. and Kailasanath K., AIAA 2010-6880
Scaling of detonation/shock analogy

- Normal Shock
- Det H₂/Air (φ = 1)
- Det CH₄/Air (φ = 1)
Scaling of detonation/shock analogy

\[ \frac{\rho_2}{\rho_j} \]

\[ \frac{u_2}{u_j} \]

\[ \dot{m}'' : \text{Mass flux} \]
Scaling of detonation/shock analogy

<table>
<thead>
<tr>
<th>Case</th>
<th>Ambient</th>
<th>Jet</th>
<th>Wave Mach</th>
<th>Detonation</th>
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<tr>
<td>A</td>
<td>Air</td>
<td>Helium</td>
<td>1.9</td>
<td>H₂/Air</td>
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<tr>
<td>B</td>
<td>Air</td>
<td>Methane</td>
<td>1.4</td>
<td>CH₄/Air</td>
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<tr>
<td>C</td>
<td>Air</td>
<td>DME</td>
<td>2.1</td>
<td>C₂H₂/Air</td>
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<tr>
<td>D</td>
<td>Air</td>
<td>DME</td>
<td>1.5</td>
<td>C₃H₈/Air</td>
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</table>

![Graph showing density ratio and velocity ratio for different cases.](image-url)
## Scaling of detonation/shock analogy

<table>
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<td>1.9</td>
<td>H$_2$/Air</td>
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<td>C$_2$H$_2$/Air</td>
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<tr>
<td>D</td>
<td>Air</td>
<td>DME</td>
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<td>C$_3$H$_8$/Air</td>
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<table>
<thead>
<tr>
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<th>$d$, mm</th>
<th>$S$, mm</th>
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<tr>
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<td>2</td>
<td>--</td>
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<tr>
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<tr>
<td>3</td>
<td>0.8</td>
<td>3.5</td>
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</table>

Note: non-reacting cases
Shock-induced mixing in turbulent jets

- Flexible configuration
  - Single isolated injector
  - Multiple isolated injectors

- Well-suited for controlled unit-physics experiments
  - Quantitative mixing measurements
  - Flexibility in range of conditions
    - Shock strength
    - Injection details (speed, configuration, molecular weight)
Shock-induced mixing in turbulent jets

- Flexible configuration
  - Single isolated injector
  - Multiple isolated injectors

- Well-suited for controlled unit-physics experiments
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  - Flexibility in range of conditions
    - Shock strength
    - Injection details (speed, configuration, molecular weight)
Shock tube facility
Interaction of shock wave with turbulent jet

- Detonation-induced mixing analogue
- Visualization data
  - 100 kHz movie with 300 ns exposure (shock smears by 0.13 pixel)
  - Injection of $\text{H}_2$ into still air subject to a Mach 1.39 shock wave
  - Played back at 5 frames/second
  - Elapsed time 0.5 ms (50 frames)

From initial work presented at UTSR 2015 Workshop
Interaction of shock wave with turbulent jet

From initial work presented at UTSR 2015 Workshop

\[ M = 1.39 \]

\[ u_j/D \sim 1/12 \]
\[ u_j/u \sim 1/5 \]
\[ \rho_j/\rho_2 \sim 1/24 \]
\[ \rho_2/\rho_1 = 1.7 \]

\[ u = 194 \text{ m/s} \]
\[ u_j \sim 40 \text{ m/s} \]
Interaction of shock wave with turbulent jet

From initial work presented at UTSR 2015 Workshop

Pure ambient fluid

LIF signal $S \sim f(\chi, p, T)$

Pure jet fluid

$H_2$

$N_2$

$10d$

$20d$

shock

$D$

$D$

$I$

$II$

$III$

$I$

$II$

$III$
Example of diagnostic application: Making LIF measurements quantitative

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

$M = 2.3$
$T = 500 \, K$
$p = 1 \, \text{atm}$
Seeded $\text{N}_2$

$H_2$ injection

$\text{N}_2$ injection
Interaction of shock wave with multiple turbulent jet

Case B1-2: $M = 1.4$

- Detonation-induced mixing analogue
- Visualization data
  - 82 kHz movie with 300 ns exposure (shock smears by 0.13 pixel)
  - Injection into still air subject to a shock wave
  - Played back at 5 frames/second
  - Elapsed time 0.5 ms (50 frames)
Strong jet density variation
Impact on:
- Shock propagation speed across jets
- Shock front curvature

Shock strength variation
Impact on:
- Jets compression
- Jets instabilities
- Jets structure and scale orientation
- Mixing
Strong jet density variation
Impact on:
- Shock propagation speed across jets
- Shock front curvature

Shock strength variation
Impact on:
- Jets compression
- Jets instabilities
- Jets structure and scale orientation
- Mixing
Ongoing work on interaction of shock wave with turbulent jet array: Mixing study using tracer PLIF

- Shown is a qualitative flow visualization
- Nearly the same density ratio, but case B-4 has 4x the velocity ratio of case B-1
- Velocity ratio affects post-shock mixing field
  - More rapid mixing behind the shock wave as velocity ratio increases
- Why?
Ongoing work on interaction of shock wave with turbulent jet array: Parametric study and outcome

- **Parameters to be varied**
  - Shock strength (Mach #)
  - Injectant/ambient species
    - Light/heavy vs heavy/light
    - Injectant-to-ambient density and velocity ratios
  - Injection pressure ratios
  - Injection configuration

- **Performance metrics**
  - Degree of mixing (spatial measurement)
  - Plume shape
    - Width, corrugation, deflection
  - Length and time scales of injector response
  - Scaling with working parameters
    - Density & velocity ratios
    - Plume compression rate
    - Injector size and spacing

\[ M = 1.39 \]
Planned 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
Development of a flexible RDE hardware at U-M
Development of a flexible RDE hardware at U-M

- Modular configuration
- Multiple injection schemes
  - AFRL design (radial injection)
  - Semi-impinging jets (ONERA\textsuperscript{1})
  - Pintle injector (NRL\textsuperscript{2})

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Development of a flexible RDE hardware at U-M

Radial injection (AFRL) (shown to work)

Pintle injector (NRL) (not a very good performer)

Semi-impinging (ONERA) (good mixer)

From Gaillard et al., Acta Astronautica, 111:334-344 2015
Gaillard et al. (2015) evaluated different jet configurations

**Shared**

**Impinging**

**Semi-impinging**

**Fig. 4**

1. **Shared**
   - a: periodic
   - b: symmetric

2. **Impinging**
   - a: periodic
   - b: symmetric

3. **Semi-impinging**
   - a: periodic
   - b: symmetric

From Gaillard et al., Acta Astronautica, 111:334-344 2015
Gaillard et al. (2015) evaluated different jet configurations in terms of mixing efficiency. They studied three types of configurations: Shared, Impinging, and Semi-impinging. The graphs show the mixing efficiency as a function of the normalized height, indicating that the Shared configuration generally performs better than the Impinging and Semi-impinging configurations. The figures illustrate the different configurations and their respective mixing qualities, with the Shared configuration showing the highest efficiency across the range of normalized heights.
Schwer & Kailasanath evaluated a pintle-like design

- Azimuthal stratification
- Detonation could not be stabilized

Flexible RDE hardware (Round RDE)

Afterburner assembled

Assembled RDE

Top view showing detonation channel

View of the injector (pintle design)
Testing of the afterburner
Next steps on the development of RDE system

- Evaluate flow properties (non-reacting) produced by RDE
- Integration of RDE with exhaust, supply and control systems
- Testing of integration, control system and test sequence under unfueled operation
- Testing under fueled operation
How it will look like after integration is completed

Gas sampling (exhaust emission measurements)

Supply and control

To exhaust

RDE

Dump exhaust

Optical access
Planned 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/CH₂O/CH/NO PLIF imaging
    • e.g., Simultaneous OH/CH₂O PLIF imaging for flame structure and heat release distribution study in premixed combustion
  – Rayleigh scattering imaging (thermometry in reacting flows)

• But we need an optically accessible system

Simultaneous OH/CH₂O PLIF imaging in inverted oxy-fuel coaxial non-premixed CH₄ flames
Development of linearized RDE (what originally planned)

- Designed after AFRL design (radial injection)
- Pre-detonator to generate a planar detonation designed
- Designed, but not built yet
Development of linearized RDE (what originally planned)

- **Benefits**
  - Simple configuration to study and model
  - Allows for optical access for laser diagnostics

- **Drawbacks**
  - Intermittent operation (2 or 3 detonation cycle)
  - Unclear if a fully-developed detonation wave can be achieved (due to limited length and intermittent operation)
  - May not allow to reach stationary parasitic combustion
Proposed hybrid RDE

• Designed with features similar to our RDE configuration
• Feasibility design study almost completed
  •Awaiting verification of optical components
Proposed Hybrid RDE (Race Track RDE, or RT-RDE)
Proposed Hybrid RDE (Race Track RDE, or RT-RDE)
Proposed Hybrid RDE (Race Track RDE, or RT-RDE)
Proposed Hybrid RDE (Race Track RDE, or RT-RDE)

Gap

Illumination plane

15"

3"
Proposed Hybrid RDE (Race Track RDE, or RT-RDE)

Our design:

- Resolves optical access limitations of round RDE
- But optical access through curved wall is required
- We have designed an optical arrangement to access the detonation chamber through curved wall
Proposed Hybrid RDE (Race Track RDE, or RT-RDE)

Our design:

- Resolves optical access limitations of round RDE
- But optical access through curved wall is required
- We have designed an optical arrangement to access the detonation chamber through curved wall
Next steps for experimental program

• Detailed studies of shock-induced mixing in single and multiple injector configurations
  – All systems operational
  – Complete mixing measurements on parametric study

• RDE
  – Complete integration of RDE and testing
  – Investigation of performance of different injectors
  – Inform future work on RT-RDE

• RT-RDE
  – Verify optical access design (prototype window should be delivered this month)
  – Fabrication and instrumentation (design is complete, shop selected)
  – Investigate detonation structure and the link between unmixedness, detonation structure and pressure gain
    • Speciation distribution
    • Detonation speed and height, pressure time history
    • Transition and stabilization to deflagration mechanisms
Outline

• Introduction to the problem and general approach

• Experimental activities

• Computational activities
Computational Study of Non-idealities in RDEs

Venkat Raman
University of Michigan
Outline of Simulation Results

• Effect of nonequilibrium on detonation cell size
• Effect of injector mixing on detonation propagation
  ➡ Blast wave/detonation comparison
  ➡ Multi-injector DNS
  ➡ Detonation structure analysis
Thermal equilibrium is not preserved through shocks, resulting in underpopulated vibrational states.

- Relaxation depends on species and collision timescales.
- Relevant if relaxation is comparable to reacting and mixing scales, i.e.,

\[ \tau_{relax} \approx \min(\tau_{react}, \tau_{flow}) \]
Vibrational Nonequilibrium: Ab-initio Derived Rates

- QCT-based state-specific reaction rates used to calibrate model
  - Model matches QCT results at high temperatures
  - Nonlinear/higher-order model required at lower temperatures

\[ \text{H} + \text{O}_2(v) \rightarrow \text{O} + \text{OH} \]
**Detonation Wave Simulation: Equilibrium Case**

- **Baseline solution simulated assuming thermal equilibrium**
  - Stoichiometric hydrogen-air mixture initially at 300 K and 1 atm
  - Ignition length near $2.1 \times 10^{-4}$ m from the shock front ($\approx 1 \times 10^{-4}$ s)
  - Temperatures pre-shock, post-shock, and post-combustion are 300, 1510, and 2920 K

**Properties**

- Mass Fraction
  - $H_2$, $O_2$, $H_2O$, $H_2O_2$, $OH$, $HO_2$

**Mass Fraction**

- Detonation Wave Simulation: Equilibrium Case
  - Shock and Ignition markers

---

**Graphs**

- Properties
  - Mass fraction of various species
  - X-axis: $x$ (m) × $10^{-4}$
  - Y-axis: $M$, $T/T_o$

- Mass fraction
  - X-axis: $x/m$ × $10^{-4}$
  - Y-axis: $10^0$, $10^{-2}$, $10^{-4}$, $10^{-6}$
Recall the nonequilibrium relaxation factor:

\[
\frac{\tau_{relax}}{\min(\tau_{reac}, \tau_{flow})}
\]

Consider two simulations:

- **A** Reactive simulation with thermal equilibrium
  - \(O_2\) relaxes to a quasi-steady state within \(2 \times 10^{-5}\) m
  - \(H_2\) and \(N_2\) relax more slowly

- **B** Inert simulation with vibrational nonequilibrium

\[
\frac{\tau_{relax}}{\min(\tau_{reac}, \tau_{flow})} \approx O(1)
\]
Detonation Wave Simulation: Nonequilibrium Case

Nonequilibrium simulation demonstrates necessity for species-specific vibrational temperatures

- $O_2$ rapidly approaches quasi-steady-state via T-V exchange
- Induction length is comparable to equilibrium case

Temperature of detonation wave with vibrational nonequilibrium
2D Detonation Wave Simulation

- 2D detonation wave simulated to assess vibrational nonequilibrium effects on detonation cell-pattern regularity
  
  ➡ Initial conditions based on the 1D simulation at equilibrium conditions, then simulated along channel until stable
  
  ➡ Simulated on 5000 cores over 10 hours

![Pressure History]

- Temperature (T):
  - 3000 K
  - 2700 K
  - 2400 K
  - 2100 K
  - 1800 K
  - 1500 K
  - 1200 K
  - 900 K
  - 600 K
  - 300 K

- Pressure (P, atm):
  - 10 atm
  - 9 atm
  - 8 atm
  - 7 atm
  - 6 atm
  - 5 atm
  - 4 atm
  - 3 atm
  - 2 atm
  - 1 atm

Pressure History
2D Detonation Wave Simulation

Ignition length is thin compared to bulk flow.

H2 relaxation is slow after shock.

Cell structure formed after detonation.
The pressure history shows that modeling vibrational nonequilibrium significantly modifies detonation cell size

- Delayed relaxation of H\textsubscript{2} plays a critical role in this process
- In both cases, detonation cells are unstable
Blast Wave/Detonation Analogy

• Can blast waves with appropriate conditions used to understand mixing in detonations?
  ➡ Easier experiment to do
  ➡ Access to better laser diagnostic tools

• Numerical study
  ➡ Conduct blast wave and detonation studies
  ➡ Identify mixing parameters
### Blast wave conditions

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<th>1</th>
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<th>jet</th>
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<td>P (Pa)</td>
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<td>226880</td>
<td>66700</td>
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<tr>
<td>T (K)</td>
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<td>486.42</td>
<td>298</td>
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<td>rho (kg/m³)</td>
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<td>1.77</td>
<td>5.4274-02</td>
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<tr>
<td>U (m/s)</td>
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<td>418</td>
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<tr>
<td>comp (H₂-O₂-Ar mole)</td>
<td>2-1-7</td>
<td>2-1-7</td>
<td>1-0-0</td>
</tr>
</tbody>
</table>

**Diagram:**
- **u**: A symbol for velocity or wave velocity.
- **S**: A symbol for shock wave.
- **u_j**: Velocity of the jet.
- **j**: A symbol for a specific region or point.
## Detonation conditions

<table>
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<td>comp (H₂-O₂-Ar mole)</td>
<td>2-1-7</td>
<td>burnt products</td>
<td>1-0-0</td>
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</tbody>
</table>
3 Jet mixing comparison: blast wave/detonation

- Premixed H\textsubscript{2}-O\textsubscript{2}-Ar at 298K, 6670Pa and pure H\textsubscript{2} injectors
- Conserved properties: $\rho_{\text{jet}}/\rho_2$ and $u_{\text{jet}}/u_2$
Preliminary Mixing Metrics

- Scalar variance seems to decay in a similar manner
  - Density change the primary driver for enhanced mixing

- Post-wave mixing is driven only by decaying turbulence
  - Similar for both blast waves and detonations
Multi-Injector Configurations

- RDEs employ discrete injectors
  - Premixed or non-premixed

- In non-premixed injectors
  - Level of mixing can control detonation propagation

- How does injector mixing affect detonations?
  - Influence of small-scale mixing
  - Large scale impact
  - Distance between injectors

- Goal: Develop a canonical linear RDE setup for studying mixing effects
Numerical Study of Multi-injector Configurations

- For all simulations
  - Injection zone $L_j = 10\text{cm}$
  - Fuel mass flow rate $F_j$
- Variables
  - $N_j =$ number of injectors
  - $D_j =$ injectors diameter
  - $dX_j =$ distance between injectors centerline
  - $M_j =$ injector exit Mach number

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$N_j$</th>
<th>$D_j$ [mm]</th>
<th>$dX_j$ [Dj]</th>
<th>$M_j$</th>
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<tr>
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<td>24</td>
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<td>L</td>
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<td>8</td>
<td>3.55</td>
<td>4.03</td>
<td>0.53</td>
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</table>
**Configuration S**

- Isocontours of:
  - $H_2 = 0.1$
  - $T = 800K$ (black)
  - $\log(|q|) = 9.5$

- Colored by temperature
Configuration L

- Isocontours of
  - H$_2$ mass fraction of 0.1
  - Temp. of 800K (black)
  - $\log(|q|) = 9.5$
  - Q-criterion

- Colored by temperature
Post-detonation Explosions

- **Shock wave interactions**
  - Regular high-pressure spots
  - Creates regular post-detonation explosions

- **Frequency is independent of the injector configuration**
  - Independent of ambient conditions
    - [To be discussed next]
Effect of Ambient Conditions

- **Simulations so far**
  - Consider first passage of detonation wave
  - Cold oxidizer as ambient condition

- **RDE conditions**
  - Some pre-burnt mixture from prior detonations will be present

- **How does ambient composition affect detonations?**
  - Can there be pre-ignition and loss of efficiency?
Variation of downstream mixture

- **Case I** represents the first passage of the detonation
  - Clean Ar-O2-H2 mixture
  - Low temperature and pressure

- **Case II** represents a second passage of the detonation
  - Partially burnt Ar-H2O-O2-H2 mixture
  - Higher temperature and pressure

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$P_{\text{jet}}/P_{\text{ambient}}$ (Pa)</th>
<th>$T_{\text{jet}}$ (K)</th>
<th>$T_{\text{ambient}}$</th>
<th>Ambient composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>6670</td>
<td>298</td>
<td>298</td>
<td>O$_2$ / Ar (1/7)</td>
</tr>
<tr>
<td>Case II</td>
<td>33350</td>
<td>298</td>
<td>2200</td>
<td>H$_2$O / O$_2$ / Ar (1/2/14)</td>
</tr>
</tbody>
</table>
Initial indication is that ambient conditions do not significantly affect detonation process

- Mass consumption rates are unaltered
- Additional conditional statistics being analyzed currently
Front-tracking and Induction Length

- Pressure jump used to identify detonation location
  - Normal constructed from surface data
- Mass fraction data extracted along the normal
Detonation Velocity Variation

Pure oxidizer

Ambient

Vitiated Ambient

injector center locations
Induction Length

Pure oxidizer

Vitiated Ambient

S

M

L

induction length (m)

induction length (m)

induction length (m)

induction length (m)

x (m)

x (m)

x (m)

x (m)
Conditional Scalar Plots

- Conditional plots are useful in determining flame structure
  - Obtained on the normal vector
Outlook for Year 2 & 3

- **Current progress**
  - Basic physics studies are close to completion
  - Next step is to extract combustion models based on DNS data

- **Year 2 - Full scale simulations**
  - Move to complex geometries and full-scale RDE simulations
  - OpenFOAM with AMR chosen as solver base

- **Year 3 - Optimization using inverse design**
  - Inverse design solver is being constructed