Numerical Simulations of Reactive and Non-Reactive Flows in Engine Environments

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Research sponsored by

NASA, National Science Foundation,
the Office of Naval Research, and
the California Energy Commission
Outline of Presentation

1) Reactive Flow Simulations:
   - 1a) Canonical pulsating, overdriven detonation waves in 1D
   - 1b) 1D & 2D Simulations of pulse detonation wave engines (PDWE)

2) Non-Reactive Flow Simulations:
   - 3D vortex element simulations of unforced and forced jets in crossflow
   - Comparisons with experiments on dynamically compensated transverse jets
Research Collaborators

• **Reactive Flow Simulations:**
  – 1D pulsating, overdriven detonations: Peter Hwang and Prof. Ron Fedkiw (both now at Stanford), Prof. Stan Osher and Dr. Barry Merriman (UCLA), Dr. Tariq Aslam (LANL)
  – Simulations of pulse detonation wave engines: Xing He (UCLA)

• **Non-Reactive Flow Simulations:**
  – 3D vortex element simulations of jets in crossflow: Prof. Luca Cortelezzi (McGill Univ.)
  – Experiments on dynamically compensated transverse jets: Prof. Bob M’Closkey, Jon King, and Steve Shapiro (UCLA), Prof. Luca Cortelezzi
PART 1a: Pulsating Detonation Waves

• WHAT IS A DETONATION?
  – “A premixed flame in which the upstream gas is supersonic” (Strahle)
  – “A combustion wave propagating at supersonic speed” (Kuo)
  – “A strong shock wave which triggers and is supported by a coincident chemical reaction” (Fickett and Davis)

![Typical “ZND” detonation structure](image)
Pulsating Detonation Waves

- Pulsating detonation phenomena were suggested in early experiments (Campbell and Woodhead, 1927) and through linear stability analysis (Erpenbeck, 1962)

- Demonstrated to exist for “overdriven” detonations, with the number of instability modes increasing as the overdrive \( f \) approaches unity, where

\[
 f = \left( \frac{D}{D_{CJ}} \right)^2
\]

(\( D = \) detonation speed, \( D_{CJ} = \) speed of Chapman-Jouget detonation)

- Canonical problem against which numerous numerical schemes are compared and validated (Boulioux, et al., 1991, Quirk, 1994, Papalexandris, et al., 1997)
1D Pulsating Detonation Waves: Governing Equations

- 1D reactive Euler equations, single step reaction kinetics:

\[
\begin{align*}
\rho_t + (\rho u)_x &= 0 \\
(\rho u)_t + (\rho u^2 + p)_x &= 0 \\
(\rho E)_t + (\rho u E + up)_x &= 0 \\
(\rho Y)_t + (\rho u Y)_x &= -K \rho Y \exp(-T^+/T) \\
E &= e + q_0 Y + \frac{u^2}{2}
\end{align*}
\]

- Alternative initial conditions considered, for a reaction with \( q_o = 50 \) and \( \gamma = 1.2 \):
  - Propagating shock front generating an overdriven detonation with \( f = 1.6 \)
  - Overdriven ZND detonation front with \( f = 1.6 \)
1D Pulsating Detonations: Numerical Approach

• Third order Essentially Non-Oscillatory (ENO) method for spatial integration, with alternative procedures explored to avoid entropy-violating expansion shocks near sonic points:
  – Local Lax Friedrichs (LLF) scheme, which adds extra numerical viscosity throughout the computational domain at each time step
  – Roe Fix (RF) scheme, which only adds extra numerical viscosity when there is a sonic point locally, i.e., where the eigenvalues change signs

• Third order TVD (total variation diminishing) Runge-Kutta method used for time discretization:

  \[ U_t = f(U) \]

  where \( U = (\rho, \rho u, E, \rho Y) \)

• Scheme validated using “test” problems with exact solutions (shock tube, “bang-bang”) as well as grid resolution studies
Effects of Computational Domain Size

- Computations of reactive interfaces, especially detonation waves become expensive due to the required resolution to obtain accurate wave speeds.

- Reduce cost by employing a computational domain of length $L$ only (truncated):

$L$ can be measured in units of $L^{1/2}$, the detonation reaction half-length.

Tests conducted for the “canonical” overdriven detonation: $f = 1.6$
Effects of Computational Domain Size

- **Computational domain of $$3\;L^{1/2}$$:**
  - Resolution: 20 grid points per $$L^{1/2}$$

- **Computational domain of $$5\;L^{1/2}$$:**
  - Resolution: 20 grid points per $$L^{1/2}$$

Note: Solid line is exact solution

Resolutions:

- Left: 20 grid points per $$L^{1/2}$$
- Right: 20 grid points per $$L^{1/2}$$
Effects of Computational Domain Size

- **Computational domain of $50 \, L_{1/2}$:**

  Resolution: 20 grid points per $L_{1/2}$

  ![Graph showing shock pressure over time with note: Solid line is exact solution.]

Resolution: 20 grid points per $L_{1/2}$
"Erroneous" flow properties behind the shock/detonation catch up with the shock via $u+c$ waves, which are faster than that of the detonation, $D$:

Thus, if the solution at time $t = t_{\text{desired}}$ is sought, the criterion for $L$ is:

$$t_{\text{desired}} < \frac{L}{2.4} + \frac{L}{8.6}$$

$L$ in units of $L^{1/2}$

- e.g., if $t_{\text{desired}} = 40$, the required domain size $L > 75$ (BUT the detonation has traveled a distance $X = 344$, for an elimination of 80% of the grid!)
• Verification of estimate: the shock and the “erroneous” $u+c$ wave will intersect at computational time $t = 40$, for a domain length of $L = 75$:

(Computed via 5\textsuperscript{th} order WENO by Tariq Aslam)
Effects of Computational Domain Size

- Verification of estimate: actual vs. estimated time $T$ at which the solution deviates from the correct one

<table>
<thead>
<tr>
<th>Domain Size ($L^{1/2}$)</th>
<th>$T$ (equation)</th>
<th>$T$ (actual)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.6</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>2.7</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>5.3</td>
<td>19</td>
</tr>
<tr>
<td>50</td>
<td>26.6</td>
<td>55</td>
</tr>
<tr>
<td>75</td>
<td>39.9</td>
<td>78</td>
</tr>
</tbody>
</table>

- e.g., $L = 5L^{1/2}$:

So the estimated time of corruption $T$ is a CONSERVATIVE estimate (this is good!)
Effects of Reaction Zone Resolution

- 5 grid points per $L^{1/2}$:

- 20 grid points per $L^{1/2}$:

Computational Domain: $L = 75L^{1/2}$
Effects of Reaction Zone Resolution

- 40 grid points per $L^{1/2}$:

Computational Domain: $L = 75 \, L^{1/2}$
Comparisons with Other Schemes: Overdrive $f = 1.6$

Relative mesh spacing $= \frac{10}{\text{grid points per } L^{1/2}}$

- Bourlioux et al. (1991)
- Quirk (1993), Superbee Limiter
- Quirk (1993), Minmod Limiter
- Papalexandris et al. (1997), Unsplit Scheme
- ENO2-LLF
- ENO2-RF
- ENO3-LLF
- ENO3-RF
- ENO3-LLF-2ND
Effects of Grid Spacing on Pulsation Period

Average Period

Period vs. Relative Grid Spacing

- ENO2-RF
- ENO2-LLF
- ENO3-RF
- ENO3-LLF-ZND
- ENO3-LLF
Now apply these computational tools to more “practical” problems arising in an engine environment:

The Pulse Detonation (Wave) Engine (PDWE or PDE!)

Part 1b: APPLICATION of Detonation Simulations
Conventional Combustion Engines involve Deflagrations

- Gas turbine engine (Brayton cycle):

- Automobile engine (Otto cycle):
Pulse Detonation Wave Engines involve **Detonations:**

**Components**

- Fuel Inlet
- Ignitor
- Detonator Tube
- Inlet Air
- Rotary Valve (Shutter Type)
- Thrust Wall
- Repeating CJ Detonation Wave

**PDE Cycle**

1. Purge air
2. Fill with fuel and air
3. Ignite
4. Shock coalescence
5. Expansion
6. Blowdown

*Air Intake*
PDWEs involve a Constant Volume Cycle:

a) thrust wall → detonation front

b) propagating detonation

c) detonation

d) reflected expansion wave

e) expansion wave

f) reflected expansion wave

g) expansion wave

h) reflected compression wave

i) compression wave

j) thrust wall → shock/detonation reflection
Focus of Present Studies

- Examination of reactive flow processes in PDWEs using high order numerical schemes with the aim of simulating and understanding:
  - Fundamental flow processes producing improved performance characteristics
  - The impact of PDWE geometry, including nozzle presence and shape, on flow and performance characteristics
  - Whether 1D simulations can accurately replicate 2D planar and/or axisymmetric PDWE flow phenomena and performance characteristics
  - The relationship between PDWE performance and noise characteristics

Diagram: Detonation tube with nozzle and Patm.
PDE Simulations: Reactive Euler Equations

- Both 1D and 2D (planar and axisymmetric) transient simulations were performed, using a 3rd order WENO scheme for spatial integration and 3rd order Runge-Kutta time integration.

- Governing equations (e.g., for 2D planar case):

\[
\frac{\partial U}{\partial t} + \frac{\partial F_x(U)}{\partial x} + \frac{\partial F_y(U)}{\partial y} = S(U)
\]

\[
U = \begin{pmatrix}
\rho \\
\rho u \\
\rho v \\
E \\
\rho Y
\end{pmatrix}, \quad
F_x(U) = \begin{pmatrix}
\rho u \\
\rho u^2 + p \\
\rho uv \\
(E + p)u \\
\rho Yu
\end{pmatrix}, \quad
F_y(U) = \begin{pmatrix}
\rho v \\
\rho uv \\
\rho v^2 + p \\
(E + p)v \\
\rho Yv
\end{pmatrix}, \quad
S(U) = \begin{pmatrix}
0 \\
0 \\
0 \\
- \frac{T_i}{\gamma - 1}
\end{pmatrix}
\]

\[
E = \frac{p}{\gamma - 1} + \frac{\rho (u^2 + v^2)}{2} + \rho q Y
\]

- A minimum of 20 grid points per reaction half length used.
Code Validation: 1D Shock Tube with Open End

- 3rd Order WENO for spatial integration, 3rd Order Runge-Kutta time integration, absence of reaction
- Shock exiting tube (length = 10 m) results in reflected expansion wave, as in pulse detonation engine cycle; same result as analytic solution

\[ t = 0.86 \text{ ms:} \quad \text{t = 12.4 ms:} \]

Computations done without a pressure relaxation length external to the tube
PDWE Pressure field evolution: 2D planar simulations

- CH₄/O₂ reaction, detonation tube length of 1.0 m
- Ignition via computational “spark” at thrust wall

$t = 0.06$ ms  
$t = 0.26$ ms  
$t = 0.49$ ms

$t = 0.76$ ms  
$t = 1.01$ ms  
$t = 2.89$ ms
Centerline pressure evolution: 2D planar simulations

- CH$_4$/O$_2$ reaction, detonation tube length of 1.0 m
- Ignition via computational “spark” at thrust wall

![Pressure Evolution Graphs]

- $t = 0.06$ ms
- $t = 0.26$ ms
- $t = 0.49$ ms
- $t = 0.76$ ms
- $t = 1.01$ ms
- $t = 2.89$ ms
2D planar case: Centerline Pressure Distribution (L=1.25m)
Animation of 2D planar pressure field (L=1.25m)
**PDWE Performance Parameters**

**Impulse I:**

\[ I = A \int \Delta p_{tw}(t) \, dt \]

where \( A = \) thrust wall area,
\( \Delta p_{tw} = \) pressure differential on thrust wall

**Specific impulse Isp:**

\[ I_{sp} = \frac{I}{\rho Vg} \]

where \( \rho = \) initial reactant density, \( V = \) tube volume

**Fuel specific impulse Ispf:**

\[ I_{spf} = \frac{I_{sp}}{Y_f} \]

where \( Y_f = \) fuel mass fraction
2D Planar vs. Axisymmetric Computations

- CH₄/O₂ reaction, ignition via computational “spark” at thrust wall

**Impulse/Area:**

**Specific Impulse:**
Temporal pressure evolution at various locations

- CH₄/O₂ reaction, 2D axisymmetric detonation tube with L = 1.0 m

(a) Thrust wall  (c) Tube end  (d) 1 m downstream
Noise levels may be estimated by examining the Fourier transform of the time-dependent pressure data at various locations:

- (b) Tube center
- (c) Tube end
- (d) 1 m downstream
2D/Axisymmetric Computations: Noise Estimates

- Rough estimate of sound pressure level, SPL, at dominant frequency (around 330 hz, the PDE cycle frequency):

\[
SPL = 20\log\frac{[P]}{[P_{ref}]}
\]

<table>
<thead>
<tr>
<th>Location</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
<th>(f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPL (dB)</td>
<td>211</td>
<td>202</td>
<td>173</td>
<td>174</td>
<td>173</td>
</tr>
</tbody>
</table>
One-Dimensional Simulations

- Explored the attempt by some (Kailasanath & Patnaik, 2000) to replicate 2D phenomena with a 1D simulation using a “pressure relaxation length” exterior to the PDWE tube during subsonic exit flow to artificially reduce the external pressure over a prescribed length when the exit flow is locally subsonic:

  Pressure at thrust wall:

  Pressure at tube exit:

[Graphs showing pressure over time with and without relaxation length]
1D vs. 2D Axisymmetric Computations

- \( \text{CH}_4/\text{O}_2 \) reaction, ignition via computational “spark” at thrust wall

Pressure distribution:  
Exit plane Mach number:

Time \( t = 0.76 \text{ ms} \)
1D vs. 2D Axisymmetric Computations

- CH$_4$/O$_2$ reaction, ignition via computational “spark” at thrust wall

Temporal wall pressure: Specific Impulse:

![Pressure Graph](image1)

![Specific Impulse Graph](image2)
Effects of reaction mechanism: 1D computations

- $\text{H}_2/\text{O}_2$ vs. $\text{CH}_4/\text{O}_2$ reaction, ignition via computational “spark” at thrust wall

PDE Specific Impulse:

1D computations done WITHOUT a pressure relaxation length
Preliminary Conclusions: PDE Simulations

• Important PDE processes can be resolved using either 1D or 2D simulations with only single step kinetics:
  – Temporally evolving pressure, density fields
  – Estimations of important performance parameters such as impulse and specific impulse
  – Estimations of noise emanating from pulsating detonation phenomena

• 1D simulations seen to produce virtually the same behavior as seen in 2D simulations, even without a pressure relaxation length

• ONGOING/FUTURE work to explore complex reaction mechanism effects, more extensive 1D/2D simulation comparisons, effects of nozzle presence on performance and noise generation
PART 2: Simulation of Actively Pulsed Jets in Crossflow

- **Concept:** Active injectant-crossflow mixing and reaction control can be accomplished through strategically pulsing the jet flow (via acoustical excitation or pulsed valve injection)

- **Ongoing studies:**
  - Laboratory scale studies of acoustically controlled gaseous jets in crossflow, with development and testing of a dynamical compensator
  - Numerical simulations, via 3D vortex element modeling, of unforced and forced jets in crossflow
Technological Applications of Transverse Jets

- **Dilution air jet injection** in air-breathing engines, with the aim of temperature pattern factor control (turbine blade cooling):

\[
PF = \frac{T_4^{MAX} - T_3}{T_4^{AVE} - T_3}
\]

(Courtesy of Dr. Jeff Cohen, UTRC)
• Fuel jet injection in air-breathing engines, especially in high speed engines such as a supersonic combustion ramjet (SCRAMJET):

Rapid fuel penetration, mixing, and reaction processes required for supersonic combustion completion within the engine

From McDaniel, et al. (1988)
- Film cooling air injection from high pressure turbine blades in air-breathing engines:
Technological Applications of Transverse Jets

- Thrust vector control via liquid injection within rocket engine nozzle:

Flow in rocket nozzle is deflected via the impulse introduced by TVC jets, with and without reaction.
3D Vortex Simulations of Transverse Jets

- **Assumptions:**
  - 3D vortex blobs/filaments used to characterize the generation and evolution of the vorticity field
  - Jet and crossflow are incompressible
  - Coupling between jet and boundary layer upstream of jet is neglected at present
  - Effect of crossflow on jet flow deep within the nozzle is neglected at present (Soldati and Cortelezzi are exploring this)

- **Problem is made dimensionless using the jet radius (D/2) and crossflow velocity \( U_\infty \)**
- **Mean crossflow is assumed to have a laminar boundary layer upstream of the jet with a cubic velocity profile**
- **Image vortex filaments are imposed in order to represent the jet injection wall boundary**
Since the vorticity in many flows occupies only a small volume of the entire flowfield, it is of interest to attempt to follow the evolution of the vorticity field.

The theorems of Helmoltz and Kelvin suggest that for a uniform-density, inviscid fluid, tubes of vorticity retain their identity and move as material entities; hence we make use of the vorticity transport equation:

\[
\frac{\partial \omega}{\partial t} + \mathbf{u} \cdot \nabla \omega = \omega \cdot \nabla \mathbf{u} + \nu \nabla^2 \omega
\]

The velocity field is related to the vorticity field through the Biot-Savart law, modified here to account for a finite vortex core size (radius \( \sigma \)) and Gaussian vorticity distribution (Rosenhead, 1930; Moore, 1972):

\[
\mathbf{u}(\mathbf{x}, t) = -\frac{\Gamma}{4\pi} \int_C \left[ \mathbf{x} - \mathbf{r}(s') \right] \times \frac{\partial \mathbf{r}}{\partial s'} \, ds'
\]

\[
\left( |\mathbf{x} - \mathbf{r}|^2 + \alpha \sigma^2 \right)^{3/2}
\]
The transverse jet shear layer at the nozzle exit is modeled by introducing a three-dimensional vortex filament (ring) at the jet exit at each time step $dt$

The $i^{th}$ vortex filament is represented by a set of $N_i$ nodes interpolated by a cubic spline

As filaments are stretched and deformed by the flow, additional nodes are added and redistributed to maintain accuracy

The velocity field induced by all vortex elements at a point in space is then computed from the modified Biot-Savart integral:

$$ u(x, t) = -\sum_{i=1}^{N_f} \frac{\Gamma_i}{4\pi} \int_{C_i} \frac{[x - r_i(s', t)] \times \frac{\partial r_i}{\partial s'}}{(|x - r_i(s', t)|^2 + \alpha \sigma_i^2)^{3/2}} ds' $$

where $N_f$ is the total number of vortex filaments and $\Gamma_i \equiv \gamma^2 dt/2$, $\sigma_i$ and $C_i$ are the circulation, the core radius, and the contour of the $i^{th}$ vortex filament, respectively, situated at position $r_i$. 
3D Vortex Simulations of Transverse Jets

\[ \frac{U_{\text{jet}}}{U_{\infty}} = 5.4 \]

- \( t = 1.5 \)
- \( t = 2.0 \)
- \( t = 2.5 \)
- \( t = 3.0 \)
- \( t = 3.5 \)
- \( t = 4.0 \)
Comparison with Experiments: Rollup Phenomena

Vortex rollup and its contribution to the counter-rotating vortex pair (CVP) are consistent with the experiments of Kelso, et al. (JFM, 1996):

An experimental study of round jets in cross-flow

Figure 5. Behaviour of the jet shear layer for velocity ratios (a) 2.2 and (b) 4.0 at $Re = 1600$ and $\delta/D = 0.61$. In these photographs, blue dye is injected from the circumferential slot in the pipe and red dye is released from the dye injection port.

Vortex ring tilting contributes to CVP formation:

Lim, Kelso, & Perry, 1998

Cortelezzi & Karagozian (JFM, 2001)
Comparison with Experiments: Rollup Phenomena

Operating conditions: $U_{jet}/U_\infty = 2.54$, $\delta/D = 0.5$

- Predicted non-dimensional rollup frequency from computations:
  $$f^* = (f) D / (2 U_\infty) = 1$$

- Measured non-dimensional rollup frequency in our experiments:
  $$f^* = (f) D / (2 U_\infty) = 0.97 \quad \text{(measured } f = 620 \text{ hz})$$
3D Vortex Simulations of Transverse Jets

- Ensemble averaging of velocity field over one rollup cycle, then extraction of vorticity isosurfaces, reveals the nearfield formation of the CVP:

\[ \frac{U_{\text{jet}}}{U_\infty} = 5.4 \]

- High magnitude vorticity is contained within two slim columns which resemble the CVP cores
3D Vortex Simulations of Transverse Jets

- The entrainment of the crossflow can be characterized using stream-tracers imposed in the ensemble-averaged flowfield:

\[ \frac{U_{\text{jet}}}{U_{\infty}} = 5.4 \]
3D Simulations of Pulsating Transverse Jets

- Examine now the temporally varying exit plane velocity (vorticity) field, representing the pulsed transverse jet with square wave excitation:

Simulations:

- $f = 80 \text{ hz, } \alpha = 10\%$
- $f = 133 \text{ hz, } \alpha = 10\%$
Similar waveforms are often observed in our laboratory experiments on pulsed transverse jets! 

Experiments:

\[ f = 55.0 \text{ Hz}, 15\% \text{ DC}, Z=0.225 \text{ in.}, X=0.175 \text{ in.} \]
Pulsating Transverse Jets

- Simulations compare reasonably well with our lab’s experimental observations via smoke visualization at or below the “optimal” duty cycle or pulse width:

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity Ratio = 2.54</td>
<td>Velocity Ratio = 2.58</td>
</tr>
<tr>
<td>Input Waveform = Square</td>
<td>Input Waveform = Square</td>
</tr>
<tr>
<td>Scaled Frequency = 0.5</td>
<td>Scaled Frequency = 0.5</td>
</tr>
<tr>
<td>RMS Pert. Amplitude = 80%</td>
<td>RMS Pert. Amplitude = 50%</td>
</tr>
<tr>
<td>Input Duty Cycle = 10%</td>
<td>Input Duty Cycle = 31%</td>
</tr>
</tbody>
</table>
Pulsating Transverse Jets

- Simulations compare reasonably well with our lab’s experimental observations via smoke visualization above the “optimal” duty cycle or pulse width:

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity Ratio = 2.54</td>
<td>Velocity Ratio = 2.58</td>
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<td>Input Waveform = Square</td>
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</tr>
<tr>
<td>Scaled Frequency = 0.5</td>
<td>Scaled Frequency = 0.5</td>
</tr>
<tr>
<td>RMS Pert. Amplitude = 80%</td>
<td>RMS Pert. Amplitude = 50%</td>
</tr>
<tr>
<td>Input Duty Cycle = 30%</td>
<td>Input Duty Cycle = 35%</td>
</tr>
</tbody>
</table>
3D Simulations of Pulsating Transverse Jets

- Time-resolved evolution may be computed:

- Velocity Ratio = 2.54
- Waveform = Square
- Scaled Frequency = 0.5
- RMS Pert. Amplitude = 80%
- Input Duty Cycle = 10%
Smoke Visualization of Jet Excitation

Identification of “Optimal Forcing” Frequencies and Duty Cycles

44 Hz, 13% DC

55 Hz, 15% DC

Compensated, with RMS of net output velocity pert. matched at 1.70 m/s and ‘on-time’ = 2.9 ms

85 Hz, 24% DC

110 Hz, 31% DC
Conclusions

• 3D vortex element simulations are able to capture the essential physical phenomena associated with jets in crossflow, enabling us to study the mechanisms for important features:
  – Formation of the counter-rotating vortex pair (CVP) structure
  – Characterization of natural rollup frequencies

• Simulations of the pulsating jet in crossflow allow comparisons with corresponding experiments and examination of phenomena leading to enhanced jet penetration, spread, and mixing

• Ongoing work relates to closed-loop control of transverse jet mixing processes, both in computations and experiments
Other Cool Projects:

Droplet Combustion during Acoustic Excitation in \( \mu g \)

- termination or second speaker
- burning droplet
- velocity perturbation
- pressure perturbation
- loud speaker

Diagram:
- Micro-valve
- Linear Photodiode Array
- Droplet
- Light Source
Other Cool Projects:

Hydrogen Leak Detection via Micromachined Leaks

![Image of circular orifice](image1.png)

![Image of slit orifice](image2.png)

![Graph showing comparison between actual and predicted H2 mass flow rates](graph.png)

Graph: (Actual H2 mass flow rate)/(Predicted H2 mass flow rate by HST)

- **Circular orifice**
- **Slit orifice**
Other Cool Projects:

Enhanced Mixing via Lobed Fuel Injectors

Tests in Mach number range 0.4 – 1.1 in UCLA/A2I2 Trisonic Wind Tunnel

Simulations

Experiments