Diagnostics and Simulation of Sprays for Automotive Applications

Ronald O. Grover, Jr.
Staff Researcher

Tang-Wei Kuo
Lab Group Manager

Propulsion Systems Research Laboratory
General Motors Global Research and Development
Acknowledgement

GM R&D:

Experiment:
Scott Parrish
Ronald Zink
Kevin Peterson
Jerry Silvas

Modeling:
Xiaofeng Yang
Ramachandra Diwakar
Jian Gao

External University Collaborations:

Experiment:
Profs. Min Xu, David Hung (SJTU)
Prof. Raul Payri (CMT, Valencia)

Modeling:
Prof. David Schmidt (Univ. of Massachusetts- Amherst)
Prof. Rolf Reitz (UW-Madison)
Prof. Chris Rutland (UW-Madison)
Sprays Integral to DI Engine Technology Evolution

Pathway to advanced combustion strategies
1. High resolution experiments (i.e., optical diagnostics)
2. Validated high-fidelity computational models (i.e., CFD)
3. In-depth understanding of complex physics \(\rightarrow\) engine design
DI Engine Combustion Strategies

Gasoline Spray-Guided Combustion

Diesel Combustion

Smyth, et al., FISITA, 2006
Integrated Advanced Engine Development

- Cycle Simulation
- Spray Lab Injector Characterization
- CFD Characterization of Injector
- CFD Intake Calculations
- CFD Engine Spray Analysis
- Engine Test Cell Data
- Optical Engine Diagnostics
- CFD Engine Combustion

Smyth, et al., FISITA, 2006
Advancements in HPC for IC Engine Development

Restricted to large number of simultaneous simulations on LCF Platforms

Desired pathway for enhanced solver scalability to enable high-fidelity simulations with acceptable turnaround time

1-2 day turnaround (future roadmap)

1cpu ~10’s cpus ~100’s cpus

Sub-model development

- Single Cycle RANS
- Empirical spray and combustion
- Reduced chemistry
- Extensive trial and error

Present status

- Multi-cycle LES, cyclic variability
- Resolution of dense spray region
- Large kinetic mechanisms
- Fast flow & chemistry solvers
- Mesh independence
- Optimization

Desired Roadmap

Solver Scalability

Significant opportunity for HPC to lead the advancement in predictive IC engine simulations
1. Injection: $T_{\text{fuel}}$, $P_{\text{inj}}$, turbulence (L/D)
   Sac & after-injection

2. Primary & secondary atomization: drop-size distribution

3. Drop collision & coalescence

4. Turbulence interaction & mixing

5. Drop vaporization
   Local saturation
   Drag (liquid/gas)

6. Air entrainment
   Momentum profile
   Vapor distribution

7. Splashing & Deposition

8. Film Transport & Spread

9. Film Vaporization

**Spray Physical Processes**
Transient Needle Motion with Cavitation

**Lower lifts**
- Swirling flow in nozzle affected by flow in sac
- Transient and asymmetric vapor formation

**Higher lifts**
- Nozzle flow is more ordered with symmetric vapor formation

<table>
<thead>
<tr>
<th>$P_{\text{inj}}$ (bar)</th>
<th>$P_{\text{bck}}$ (bar)</th>
<th>Pulse width (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>782</td>
<td>20</td>
<td>1</td>
</tr>
</tbody>
</table>

Pink sections near nozzle entrance show vapor

Neroorkar, et al., ILASS, 2012
Influence of Nozzle Internal on the External Spray

1. Injector Tip Wetting Mechanisms

- Post-spray spray
- Sac volume fuel mist
- Liquid on tip
- Droplet stripping from tip
- Soot near tip

2. Spray Collapse under Flash-Boiling Conditions

<table>
<thead>
<tr>
<th>Non flash: 100 KPa/20C</th>
<th>Flash: 40 KPa/90C</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Image 1]</td>
<td>![Image 2]</td>
</tr>
<tr>
<td>![Image 3]</td>
<td>![Image 4]</td>
</tr>
</tbody>
</table>

Peterson, et al., Baden-Baden, 2014
1. Injection:
   \( T_{\text{fuel}}, P_{\text{inj}}, \text{turbulence (L/D)} \)
   Sac & after-injection

2. Primary & secondary atomization:
   drop-size distribution
   \textbf{Dense Spray}

3. Drop collision & coalescence

4. Turbulence interaction & mixing

5. Drop vaporization
   Local saturation
   Drag (liquid/gas)

6. Air entrainment
   Momentum profile
   Vapor distribution

7. Splashing & Deposition

8. Film Transport & Spread

9. Film Vaporization

* Including additional atomization, collision, & coalescence
### Measured vs Simulated Sprays

#### Typical spray behavior

<table>
<thead>
<tr>
<th>Measured drops</th>
<th>Calculated drops</th>
<th>Calc drop size</th>
<th>Calc equivalence ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="Image1.png" alt="Image" /></td>
<td><img src="Image2.png" alt="Image" /></td>
<td><img src="Image3.png" alt="Image" /></td>
<td><img src="Image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

#### Flash boiling spray behavior

<table>
<thead>
<tr>
<th>Measured drops</th>
<th>Calculated drops</th>
<th>Calc drop size</th>
<th>Calc equivalence ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="Image5.png" alt="Image" /></td>
<td><img src="Image6.png" alt="Image" /></td>
<td><img src="Image7.png" alt="Image" /></td>
<td><img src="Image8.png" alt="Image" /></td>
</tr>
</tbody>
</table>

*Smyth, et al., FISITA, 2006*
1. Injection: $T_{\text{fuel}}, P_{\text{inj}}, \text{turbulence (L/D)}$
   Sac & after-injection

2. Primary & secondary atomization: drop-size distribution

3. Drop collision & coalescence

4. Turbulence interaction & mixing

5. Drop vaporization
   Local saturation
   Drag (liquid/gas)

6. Air entrainment
   Momentum profile
   Vapor distribution

External Spray
* Including additional atomization, collision, & coalescence

7. Splashing & Deposition

8. Film Transport & Spread

9. Film Vaporization

Spray Physical Processes

Piston

VERIFI Workshop – November 2014
Near Simultaneous Liquid and Vapor Phase Overlays – Mie Scattering / Schlieren Imaging

$P_{\text{inj}} = 20\ \text{MPa}$

Operating Conditions

- Indolene (multi-component gasoline)
- Injected mass: 10 mg
- Fuel pressures: 5, 10, 20 MPa
- Fuel temperature: 90º C
- Ambient pressure: 500 kPa
- Ambient temperature: 800º K

Parrish, Int. Conf. on Eng. & Veh., 2013
High-Speed Mie Scattering & LIF


Individual Cycles
Mie Scattering (liquid only)

25 cycle Average
Mie Scattering (liquid only)

LIF (liquid & vapor)

LIF (liquid & vapor)
**Power of Validated Modeling Toolsets**

**Design Direction**
Upfront design & screening of options
Evidence to support hardware & calibration changes in the engine

**Physical Insight**
In-depth insight of in-cylinder mixture preparation and combustion drivers (also jointly with experimental testing)

**“Out-of-the-Box” Ideas**
Suggest hardware/calibration options outside of the current matrix that could significantly improve the product

**Correlations**
Identify CFD “indicators” that provide a relationship between key measured and computed quantities
Thank you for your attention