Overview of Gasoline Compression Ignition and Background for VERIFI Hands-On simulations

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VERIFI Workshop Hands-on Session (11/13/2014)
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- CSI : Priyesh Srivastava, Shaoping Quan, Keith Richards
Gasoline Compression Ignition (GCI) at Argonne*

- Early direct injection of gasoline - sequential autoignition
- Run engine on 87 octane gasoline over entire speed/load range
- CFD - optimize control knobs for stable combustion

*experiments by Kolodziej et al. SAE 2014-01-1302
## Engine Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinders</td>
<td>4</td>
</tr>
<tr>
<td>Geometric CR</td>
<td>17.8</td>
</tr>
<tr>
<td>Effective CR (CFD)</td>
<td>17.5</td>
</tr>
<tr>
<td>Bore (mm)</td>
<td>82</td>
</tr>
<tr>
<td>Stroke (mm)</td>
<td>90.4</td>
</tr>
<tr>
<td>Connecting Rod Length (mm)</td>
<td>145.4</td>
</tr>
<tr>
<td>IVC/EVO(° aTDC)</td>
<td>-132 / 116</td>
</tr>
<tr>
<td>Number of injector nozzle holes</td>
<td>7</td>
</tr>
<tr>
<td>Nozzle hole diameter (µm)</td>
<td>141</td>
</tr>
<tr>
<td>Nozzle inclusion angle (deg.)</td>
<td>148</td>
</tr>
<tr>
<td>Injection pressure (bar)</td>
<td>250</td>
</tr>
</tbody>
</table>
Traditional Diesel Combustion

Low ignition delay

Non-premixed

High Soot and NOx
Gasoline Compression Ignition

Early injection
SOI at -15 to -40° aTDC

Long ignition delay
Partially premixed
Distributed ignition
Gasoline Compression Ignition

*All visualization done by Joe Insley using ParaView*
Challenges

Low load operation a challenge!

Hard to ignite gasoline at low loads/fueling

Can injection be used to control/enhance reactivity?
Injection timing versus minimum fueling possible

Experiments (SAE 2014-01-1302)

Min. Fueling for 3% COV IMEP

1500 RPM
250 bar $P_{\text{inj}}$

Optimum phasing from experiments is at SOI = -30°

~1.5 – 2.0 bar BMEP

*Experiments : Kolodziej et al, SAE 2014-01-1302
## CFD Simulation setup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base mesh (up to SOI)</td>
<td>0.60 mm</td>
</tr>
<tr>
<td>Embedding/AMR (up to SOI)</td>
<td>2 levels on vel. and temp.</td>
</tr>
<tr>
<td>Minimum cell size (up to SOI)</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>Fixed mesh from SOI (using gridscale)</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>Cells (TDC)</td>
<td>9 million</td>
</tr>
<tr>
<td>Peak cell count</td>
<td>30 million</td>
</tr>
<tr>
<td>Combustion model</td>
<td>SAGE in every cell</td>
</tr>
<tr>
<td>Turbulence Model</td>
<td>LES (Dynamic Structure)</td>
</tr>
</tbody>
</table>

Largest LTC simulation to our knowledge with peak cell count of 30 million cells.
Cell count as a function of crank angle

Switch to uniform 0.15 mm mesh from injection

9 mil. cells

Hands-on ~1 to 1.5 deg. near ignition

SOI = -35 deg.
## CFD Simulation setup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td>1500</td>
</tr>
<tr>
<td>$T_{\text{liner}}$ (K)</td>
<td>380</td>
</tr>
<tr>
<td>$T_{\text{head}}$ (K)</td>
<td>400</td>
</tr>
<tr>
<td>$T_{\text{piston}}$ (K)</td>
<td>400</td>
</tr>
<tr>
<td>Simulation start (°aTDC)</td>
<td>-132</td>
</tr>
<tr>
<td>Simulation end (°aTDC)</td>
<td>45</td>
</tr>
<tr>
<td>Kinetic Mechanism (PRF)</td>
<td>Liu et al. (48 sp. 152 rxn.)</td>
</tr>
<tr>
<td>Fuel Surrogate composition for simulations</td>
<td></td>
</tr>
<tr>
<td>Isooctane (% by mass)</td>
<td>87</td>
</tr>
<tr>
<td>n-heptane (% by mass)</td>
<td>13</td>
</tr>
</tbody>
</table>
Numerical SOI sweep – Effect of injection timing

- Keep fueling constant as well as injection duration
- Constant IVC conditions and boundary conditions
- Only vary SOI timing
- Ignition timing used as metric for low-load reactivity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel mass (mg)</td>
<td>9.68</td>
</tr>
<tr>
<td>Inj. Dur. (deg.)</td>
<td>10.08</td>
</tr>
<tr>
<td>T_{IVC} (K)</td>
<td>397</td>
</tr>
<tr>
<td>P_{IVC} (bar)</td>
<td>1.41</td>
</tr>
<tr>
<td>$\phi$</td>
<td>0.24</td>
</tr>
<tr>
<td>Overall EGR</td>
<td>10%</td>
</tr>
</tbody>
</table>
CFD captures experimental trend

**EXPERIMENTS**

- Fixed Fueling: 9.68 mg /cycle
- Variable Fueling: 9.4 – 11.7 mg /cycle

**CFD SIMULATION**

- Ignition Timing (CA10)
- Optimum injection timing at SOI = -30°

*Experiments: Kolodziej et al, SAE 2014-01-1302

1500 RPM, 250 bar P_{inj}

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CFD Simulation for hands-on

- Start from restarts ~ CA10
- Run 1 to 1.5° in 3 hours
- 2048 processors/case
- 4 cases
- Total: 8192 procs
- 1 mid-plane of MIRA
- 26 participants
- 13 racks on MIRA
Domain partitioning – fluid mechanics
Domain partitioning – fluid mechanics
Running on 2048 processors – do we scale well?

We are at 93% scaling efficiency on 2048 processors (cores) – pretty good…

- Actual Speedup = 3.7 X
  \( \frac{(\text{Solution Time})_{512}}{(\text{Solution Time})_{2048}} \)
- Ideal speedup
  - \( \frac{2048}{512} = 4 \times \)
- Scaling eff.
  - \( \frac{\text{Actual}}{\text{Ideal}} \times 100 = 93\% \)
- Example of “strong scaling”
Role of chemistry load balancing in scaling

Load balance chemistry based on equalizing “computational effort per processor” rather than “number of cells per processor” …and rebalance every timestep!

Better chemistry load balancing by Argonne/CSI was key

More details in Kevin’s presentation…
CFD captures experimental trend

**EXPERIMENTS**

- **Fixed Fueling:** 9.68 mg /cycle
- **Variable Fueling:** 9.4 – 11.7 mg /cycle

**CFD SIMULATION**

- Optimum injection timing at SOI = -30°

**Experiment Data:**

- Experiments (SAE 2014-01-1302)
- Min. Fueling for 3% COV IMEP

**Simulation Results**

- SOI (deg. aTDC)
- CA10 (deg. aTDC)

*Experiments: Kolodziej et al, SAE 2014-01-1302*

1500 RPM, 250 bar P_{inj}
Effect of injection timing

CA: -35.0° aTDC

SOI -36°

SOI -35°

SOI -30°

SOI -24°
Effect of late injection

- Let’s compare -30° with the later injection timing of -24°
Effect of later injection – Reduced residence time

- Less time for fuel to breakdown, and react by TDC
Effect of later injection – Later ignition

- Later CA10 timing is related to delay in SOI
Effect of early injection

- Let’s compare -30° with the earlier injection timings of -35° and -36°
Effect of early injection – Fuel in squish

- Fuel in squish is less reactive – higher rate of heat loss
- Overall reactivity of mixture is reduced – ignite later
Effect of early injection – Later ignition

- Ignite later for the early injection cases (SOI = -36° and -35°)

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Effect of early injection – Burn slower

- Fuel in squish burns slower lowering the overall rate of heat release
- Further reduces combustion stability
Explanation for CA10 vs. SOI trend

- Inject late – less time for fuel to breakdown and autoignite
- Inject early – fuel in squish, less reactive, ignites later, burns slower
Summary of Insights and Future Work

- CFD captures experimental trend in combustion stability vs. SOI

- Optimum SOI timing identified from simulations
  - Injecting earlier than optimum – fuel in squish
  - Injecting later than optimum – reduction in residence time

- Insights
  - Use smaller nozzle angle, say 120°
  - Study effect of injection pressure and swirl

- Future work:
  - Optimization of injection pressure, inclusion angle, swirl using CFD
  - Open-cycle, multi-cylinder, multi-cycle simulations
  - HPC Front: ~ 100 million to 1 billion cells, 1 rack of Mira (16K processors)
Thank you

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