LES analysis of knock in downsized direct injection spark ignition engines

Summary

- Engine configuration without taking into account direct injection
  - Wall temperature boundary conditions
  - Comparisons of knock tendencies on a spark timing sweep
  - LES analysis of different autoignition behaviors

- Direct injection engine configuration
  - Wall temperature boundary conditions
  - Comparisons of knock tendencies on a spark timing sweep

- Conclusions & Outlooks
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Numerical models for piston engine

- The AVBP solver (CERFACS/IFPEN) is used in this study
- Numerical scheme is Lax-Wendroff and turbulence model is Smagorinsky

- Injection: Lagrangian Approach

- Spark ignition: ISSIM-LES

- Premixed flame propagation: ECFM-LES

- Auto-ignition: TKI-LES


The ICAMDAC configuration

- The configuration is a four valves single cylinder
- Direct injection is not taken into account in LES calculations

Spark timing sweep:

<table>
<thead>
<tr>
<th>Spark timing (CAD)</th>
<th>-4</th>
<th>-2</th>
<th>0</th>
<th>6</th>
<th>8 (Réf)</th>
<th>10</th>
<th>12</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. (500 cycles)</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>LES (15 cycles)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

### Engine capacity

- Engine capacity: 400 cm³
- Compression rate: 10,5
- RPM: 1800
- IMEP: 19 bars
- Fuel: Isooctane
- Kinetic scheme for TKI table: Jerzembeck
Thermal boundary conditions at walls

- Wall temperatures have to be estimated as precisely as possible to study knock.
- In this case, they are extracted from a 1D model and imposed as boundary conditions.

However, this estimation is simple and cylinder head temperature is constant in space for example.
Local in-cylinder pressure over the spark timing sweep

- Numerical sensor at the same location in the cylinder head
- Good coherence between LES and experiment whatever the spark timing
- The number of knocking cycles decreases when spark timing increases
Knock intensity

- A MAPO (Maximum Amplitude Pressure Oscillation) is used to determine the knock intensity both in experiment and in LES.
- The methodology is based on the local in-cylinder pressure at cylinder head.

In-cylinder pressure signal

<table>
<thead>
<tr>
<th>CAD</th>
<th>P&lt;sub&gt;cyl&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>-360,0</td>
<td>1,620</td>
</tr>
<tr>
<td>-359,5</td>
<td>1,621</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td>360,0</td>
<td>1,5</td>
</tr>
</tbody>
</table>

Selection of the desired angular interval

Filtering of the knock frequency [5kHz, 9kHz]

Rectification of a signal and low-pass filtering operation

The same analysis is conducted for LES and experiment results.
Percentage of knocking cycle

Methodology
- The knock intensity defined previously for each cycle is used
- A threshold is defined by the operator of the real engine test bench
- If the knock intensity of a cycle is superior to this threshold, the cycle is considered as knocking cycle

Results :
- Spark Timing ≤ 0 CAD : knock at all cycles
- Spark Timing ≥ 11 CAD : no knock
- Experimental tendencies well reproduced by LES

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Graph:
- Experiment (Min)
- Experiment
- Experiment (Max)
- LES

Knocking cycles [%]

Spark timing [CA]
Maximum knock intensity

The experimental level and tendency are well reproduced by LES.
Different knock behavior depending on the spark timing

- LES allows to analyze in details knock development:
  - One cycle in the low knock intensity region
  - One cycle in the high knock intensity region

- Details results are available in articles already published


Auto-ignition at late spark timing (+8 CAD after Top Dead Center)

- Highly temporally refined simulations (one image every 0.02 CAD or 1.85 µs) allows to follow autoignition and pressure wave interactions

- Low amplitude of pressure fluctuations results from:
  - Late timing of autoignition spots
  - Only local pockets of fresh gases are consumed by autoignitions

![Graph showing mean cylinder pressure and crank angle with a peak at 25.02 CA]
Auto-ignition at early spark timing (4 CAD before TDC)

- Very high amplitude of pressure fluctuations results from:
  - Early autoignition spots, 20% of the fresh gases remain into the combustion chamber
  - Coupling between autoignition and pressure waves: deflagration to detonation transition
  - All the fresh gases are consumed by autoignition in less than 1 CAD

In-cylinder pressure [bar]

Crank angle [°]

Time = 13.02 CA
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The PSA Peugeot Citroën engine configuration

- A real industrial engine configuration
- All following results are normalized
- Only one of the three cylinder is simulated in LES

<table>
<thead>
<tr>
<th>Engine capacity</th>
<th>400 cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression rate</td>
<td>10,3</td>
</tr>
<tr>
<td>RPM</td>
<td>5500</td>
</tr>
<tr>
<td>IMEP</td>
<td>19 bars</td>
</tr>
<tr>
<td>Fuel</td>
<td>SP95-E10</td>
</tr>
<tr>
<td>Timing of injection</td>
<td>Early in the cycle</td>
</tr>
<tr>
<td>Spark timing sweep</td>
<td>From reference spark timing to 7,5 before this reference</td>
</tr>
</tbody>
</table>
Combustion modeling

- Models ECFM-LES / ISSIM-LES / TKI-LES
  - Same set-up as the previous configuration

- Generation of the autoignition delay table for gasoline:
  - Chemical kinetic scheme: Lawrence Livermore National Lab
    - 1388 species
    - 5935 reactions

- A Toluene Reference Fuel is used:
  - iso-octane = 42.8%
  - n-heptane = 13.7%
  - toluene = 43.5%
Wall temperatures for intake, exhaust and cylinder head

One of the main hypothesis of the ICAMDAC simulations presented previously

A coupled fluid/structure calculation has been achieved by PSA Peugeot Citroën

Values are imposed as boundary conditions in LES calculations

Temperatures are constant during the whole cycle
Wall temperatures for valves

- Values extract from the fluid/structure calculation for valves are not coherent
  - Exhaust valves are too hot
  - Temperature repartition does not correspond to thermal images

- The contact between closed valves and cylinder head was well modelled

- Values extract from thermal images where imposed manually as LES boundary conditions

- A radial evolution is imposed to take into account heat exchange with cylinder head when the valves are closed
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Simulation of the spark timing chosen as a reference

- The latest spark timing is chosen as a reference
- All the spark timings of the sweep are relative to the reference angle

<table>
<thead>
<tr>
<th>Spark timing</th>
<th>-18.38</th>
<th>-11.38</th>
<th>-7.51</th>
<th>-6.76</th>
<th>-6.01</th>
<th>-5.26</th>
<th>-4.51</th>
<th>-3.76</th>
<th>-3</th>
<th>-2.25</th>
<th>-1.13</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
<tr>
<td>LES</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</table>

- No knock observed at this spark timing on the real engine test bench
- 15 consecutive LES cycles are generated
In-cylinder pressure analysis

- The numerical sensor is located at the same location than the experimental pressure sensor

- The LES sample of 15 cycles is limited but allow to well describe all the experimental envelope
- One cycle is out of the envelope, with a slow ignition and combustion
Injection analysis

- The injection timing occurs early during the intake to obtain at the spark timing a premixed mixture.
- All the liquid droplets are evaporated before TDC.

- The global equivalence ratio is $\Phi = 1.2$.
- The aerodynamic well mixed the mixture.
- At TDC, the PDF (green) is centered on the target equivalence ratio.
  - But stratifications seems very different from one cycle to another.

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**Injection Analysis**

- Injection timing: Early intake.
- Premixed mixture at spark timing.
- Liquid droplets evaporated before TDC.
- Global equivalence ratio: $\Phi = 1.2$.
- Aerodynamic well mixed.
- PDF centered at TDC.
- Stratifications vary from cycle to cycle.
Equivalence ratio fields at Top Dead Center

Cycle 2

Cycle 3

Cycle 4

Cycle 5

Cycle 6

Cycle 7

Cycle 8

Cycle 9

Cycle 10

Cycle 11

Cycle 12

Cycle 13

Cycle 14

Cycle 15

Cycle 16
Simulation of the experimental spark timing sweep

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<th>-7,51</th>
<th>-6,76</th>
<th>-6,01</th>
<th>-5,26</th>
<th>-4,51</th>
<th>-3,76</th>
<th>-3</th>
<th>-2,25</th>
<th>-1,13</th>
<th>Ref</th>
</tr>
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<tbody>
<tr>
<td>Experiment</td>
<td>❌</td>
<td>❌</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
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<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

- Several common spark timings between LES and experiment are simulated
- 15 LES cycles are simulated for each spark timing
  - Only combustion phases are recomputed
In-cylinder pressure comparisons

Spark Timing (ST) = -18,38 CAD

ST = -4,13 CAD

ST = -6,76 CAD

ST = -5,26 CAD

ST = -3,75 CAD

ST = -2,25 CAD

Reference
Method to compare LES with experimental results

For an easy comparison, the number of the LES cycle (abscissa) is multiplied by 10

- Cycle 2 ➔ Cycle 20
- Cycle 3 ➔ Cycle 30
- ... Etc
Knock analysis based on MAPO analysis

ST = -18.38 CAD

Reference spark timing

ST = -2.25 CAD

ST = -7.51 CAD

ST = -6.76 CAD

ST = -3.76 CAD
The knock intensity depends strongly on the position of the pressure sensor.
Maximum knock intensity over spark timing

- Only the intensity of the extreme cycle with the maximum knock intensity is plotted for each spark timing.

- The order of magnitude is quite well reproduced by the LES:
  - At the relative spark timing = - 7.5 CAD:
    - The experimental intensity decrease
    - The predicted LES intensity increase
  - Only one cycle is analyzed

- The sharp increase predicted on the single cylinder engine is not visible in this configuration.
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Conclusions & Outlooks

- Two different configurations have been studied:
  - A single cylinder and an industrial configuration
  - With and without direct injection modelling
  - Two different fuels

- LES is able to reproduce experimental pressure envelope on a full spark timing sweep

- Knock tendencies are well captured by the LES even if the sample of LES cycles has to be increased

- Analyze in the future the link of flow parameters (stratification or temperature gradients, velocity ...) to the occurrence of autoignition spots

- A new industrial engine configuration by Renault is under calculation to validate once more our methodology
• Thanks to ANR (Agence Nationale de la Recherche), GSM (Groupe Scientifique Moteur) and ADEME to partially fund these research works

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