LES of a spark ignition engine using artificial thickening and flamelet generated manifolds

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Outline

1. LES of non-reacting turbulent flow in motored ICE
   1.1 Turbulence model validation
   1.2 LES of the non-reacting flow in motored TUD-Engine for 50 cycles

2. LES of turbulent reacting flow using FGM & ATF
   2.1 FGM & ATF for ICE
   2.2 First LES of ignition and flame propagation in TUD-Engine

3. Summary and outlook
1. LES of non-reacting turbulent flow in motored ICE

1.1 Turbulence model validation (Smagorinsky):

LES of turbulent non-reacting flow around bluff body in VOLVO burner

<table>
<thead>
<tr>
<th>Geometry parameters &amp; boundary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel length $l$</td>
</tr>
<tr>
<td>Channel width $w$</td>
</tr>
<tr>
<td>Channel height $h$</td>
</tr>
<tr>
<td>Bluff body position</td>
</tr>
<tr>
<td>Inlet velocity</td>
</tr>
<tr>
<td>Temperature / Pressure</td>
</tr>
<tr>
<td>Flow property</td>
</tr>
</tbody>
</table>
1. LES of non-reacting turbulent flow in motored ICE

1.1 Turbulence model validation (Smagorinsky):

3.8 mio cells
Δx ≈ 0.8mm
1. LES of non-reacting turbulent flow in motored ICE

1.1 Turbulence model validation (Smagorinsky):

\[
\begin{align*}
\mathbf{u} &= 0.0000\text{ m} \\
\mathbf{x} &= 0.0000\text{ m} \\
\mathbf{z} &= 0.0000\text{ m} \\
\mathbf{y} &= 0.0000\text{ m}
\end{align*}
\]

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1. LES of non-reacting turbulent flow in motored ICE

1.2 LES of the non-reacting flow in motored TUD-Engine for 50 cycles:

<table>
<thead>
<tr>
<th>Engine properties</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>86</td>
<td>mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>86</td>
<td>mm</td>
</tr>
<tr>
<td>Connecting rod length</td>
<td>148</td>
<td>mm</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>800</td>
<td>1/min</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>8.5</td>
<td>(-)</td>
</tr>
<tr>
<td>Intake / Exhaust port diameter</td>
<td>60</td>
<td>(mm)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Valve timing</th>
<th>CA (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake valve opening time (IVO)</td>
<td>325 (aTDC)</td>
</tr>
<tr>
<td>Intake valve closing time (IVC)</td>
<td>125 (bTDC)</td>
</tr>
<tr>
<td>Exhaust valve opening time (EVO)</td>
<td>105 (aTDC)</td>
</tr>
<tr>
<td>Exhaust valve closing time (EVC)</td>
<td>345 (bTDC)</td>
</tr>
</tbody>
</table>
1. LES of non-reacting turbulent flow in motored ICE

1.2 LES of the non-reacting flow in motored TUD-Engine for 50 cycles:

Number of cells: 2.1 mio (over all structured)
Grid resolution: $\frac{3}{\text{cell volume}} \sim 1 \text{ mm (in-cylinder)}$
Number of CPUs: 12 * 2.6 Ghz
(Intel® Xeon® Processor E5-2670)
1 cycle (720 crank angle degree) $\sim 60 \text{ hours}$
50 cycles (cycle parallelisation) $\sim 3 \text{ weeks}$
1. LES of non-reacting turbulent flow in motored ICE

1.2 LES of the non-reacting flow in motored TUD-Engine for 50 cycles:

Experiment (600 cycles) .........
Kiva4_mpi (50 cycles) .........

90 °CA (bTDC)

Elias Baum, Brian Peterson, Carl-Phillipp Ding, Benjamin Böhm, Andreas Dreizler
1. LES of non-reacting turbulent flow in motored ICE

1.2 LES of the non-reacting flow in motored TUD-Engine for 50 cycles:

Experiment (600 cycles) ............
Kiva4_mpi (50 cycles)

270 °CA (bTDC)

\[ V_{\text{mean}} \quad (\text{m/s}) \]

\[ u_{\text{mean}} \quad (\text{m/s}) \]
\[ w_{\text{mean}} \quad (\text{m/s}) \]
\[ u_{\text{rms}} \quad (\text{m/s}) \]
\[ w_{\text{rms}} \quad (\text{m/s}) \]
2. LES of turbulent reacting flow using FGM & ATF

2.1 FGM & ATF for ICE:

2.1.1 Flamelet Generated Manifolds (FGM):

Chemistry reduction technique: precomputed chemical states (1D-flame) are mapped onto a small number of controlling variables and stored in a lookup table (FGM-table), chemical reactions are described by these transported controlling variables.

Flamelet computation in Chem1D (TU Eindhoven)

- Input: pv
- FGM table
- Output: dynamic viscosity, molecular mass, cp, source term for heat and pv
2. LES of turbulent reacting flow using FGM & ATF

2.1 FGM & ATF for ICE:

2.1.1 Flamelet Generated Manifolds (FGM):

Flamelet computation in Chem1D (TU Eindhoven)
Table dimension: pressure * unburnt temperature * progress variable($Y_{co_2}$)
10(pressure)*19 (unburnt temperature) = 190 flamelets
10 levels for pressure: from 0.7 bar to 32 bar
19 levels for $T_{unburnt}$: from 280 K to 760 K
101 levels for progress variable: from 0 to 1 (normalized)

Input:
- pressure
- temperature
- pv($Y_{co_2}$)

Pressure dependent FGM table

Output:
- dynamic viscosity
- molecular mass
- cp
- source term for heat and pv
2. LES of turbulent reacting flow using FGM & ATF

2.1 FGM & ATF for ICE:

2.1.1 Flamelet Generated Manifolds (FGM):

<table>
<thead>
<tr>
<th>Unburnt temperature</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>...</th>
<th>P10</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Input:**
- pressure (p)
- unburnt temp. (T_u)
- pv (Y_{CO_2})

**Output:**
- dynamic viscosity, molecular mass, cp, source term for heat and pv
2. LES of turbulent reacting flow using FGM & ATF

2.1 FGM & ATF for ICE:

2.1.2 Artificial Thickening (ATF):

The principle of the ATF model is based on a coordinate transformation that is applied to the scalar transport equation to thicken the flame front by the thickening factor $F$ to make it resolvable on coarse grids.

\[
\frac{\partial}{\partial t} (\bar{\rho} c) + \frac{\partial}{\partial x_i} (\bar{\rho} \bar{u}_i c) = \frac{\partial}{\partial x_i} \left( \bar{\rho} \left( \bar{D} + D_t \right) \frac{\partial \tilde{c}}{\partial x_i} \right) + \omega \\
\frac{\partial}{\partial \tau} (\bar{\rho} c) + \frac{\partial}{\partial \xi_i} (\bar{\rho} \bar{u}_i c) = \frac{\partial}{\partial \xi_i} \left( \bar{\rho} F \left( \bar{D} + D_t \right) \frac{\partial \tilde{c}}{\partial \xi_i} \right) + \frac{\omega}{F}
\]

\[\delta = F \delta\]

\[F = \frac{\Delta x}{\Delta x, opt}\]
2. LES of turbulent reacting flow using FGM & ATF

2.1 FGM & ATF for ICE:

2.1.2 Artificial Thickening (ATF):

Grid adaptive / dynamic (flame sensor) / pressure dependent (flame thickness and flame speed are also tabulated) ATF was implemented in Kiva4_mpi

\[ F = \frac{\Delta x}{\Delta x_{opt}} \]

LES grid size

optimal grid size

Source: H.M. Heravi et al. 3th. European Combustion Meeting, 2007
2. LES of turbulent reacting flow using FGM & ATF

2.2 FGM & ATF model validation:
LES of bluff body stabilized turbulent premixed flame in VOLVO burner:

FGM table for propane
Grid adaptive / dynamic (flame sensor) ATF

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<tr>
<td>Channel width ( w )</td>
</tr>
<tr>
<td>Channel height ( h )</td>
</tr>
<tr>
<td>Bluff body position ( x ) = 0.315 m</td>
</tr>
<tr>
<td>Inlet velocity</td>
</tr>
<tr>
<td>Inlet Temperature / Pressure</td>
</tr>
<tr>
<td>Flow property</td>
</tr>
<tr>
<td>Equivalence ratio</td>
</tr>
</tbody>
</table>

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2. LES of turbulent reacting flow using FGM & ATF

2.2 FGM & ATF model validation:

LES of bluff body stabilized turbulent premixed flame in VOLVO burner:

2. LES of turbulent reacting flow using FGM & ATF

2.3 First LES of ignition and flame propagation in TUD-Engine:

- Number of cells 3.8 mio. $\Delta x \approx 0.3 \text{ mm}$
- Number of CPUs: 8*2.6 Ghz (Intel® Xeon® Processor E5-2670)
- 80 crank angle degree $\sim 48$ hours

Pressure dependent FGM table for iso-octane

Dynamic (flame sensor) / Grid adaptive / Pressure dependent ATF
2. LES of turbulent reacting flow using FGM & ATF

2.3 First LES of ignition and flame propagation in TUD-Engine:

2.3.1 Source term for progress-variable ($co_2$):

![Diagram showing progress-variable distribution]
2. LES of turbulent reacting flow using FGM & ATF

2.3 First LES of ignition and flame propagation in TUD-Engine:

2.3.2 Temperature in cylinder:
3. Summary and outlook

Summary (non-reacting flow):

- Implementation of Smagorinsky model in Kiva4_mpi was successful
- First LES for motored TUD-Engine was performed for 50 cycles:
  - Phase averaged & rms velocity during compression
  - Phase averaged velocity during intake
  - Rms velocity during intake stroke

Outlook (non-reacting flow):

- Second LES of TUD Engine (50 cycles) is being performed:
  - Fine grid resolution for intake stroke
  - Crevice volume is considered
  - Heat transfer through cylinder wall is included
3. Summary and outlook

Summary (reacting flow):

- Pressure dependent FGM table for IC Engine was created / method for multidimensional interpolation was developed and verified
- Dynamic ATF model (grid adaptive & flame sensor & pressure dependent) was implemented in Kiva4_mpi and validated
- First LES of ignition and flame propagation in TUD Engine was carried out

Outlook (reacting flow):

- Detailed validation (in-cylinder pressure & mass & temperature & velocity ...
Thanks for your kind attention!

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2. LES of turbulent reacting flow using FGM & ATF

2.2 Verification & validation:
2.2.1 Multidimensional interpolation in pressure dependent table:

Results from FGM table + multidimensional interpolation:
dynamic viscosity, molecular mass, cp, source term for heat and pv

Results from Chem1d:
dynamic viscosity, molecular mass, cp, source term for heat and pv
2. LES of turbulent reacting flow using FGM & ATF

2.1 Pressure dependent FGM table (p, T, pv):

Table generation
10(pressure)*19 (unburnt temperature) = 190 flamelets are calculated in Chem1d (mechanism for isoocan -> TU Eindhoven)
10 levels for pressure: 0.7 – 1 – 2 – 3 – 4 – 5 – 7 – 11.5 – 18 – 24 – 32 (bar)
101 levels for progress variable: from 0 to 1 (normalized)
Table dimension: 10*19*101 (3.1 MB)
Chemie-Turbulenz-Interaktionsmodell