Simulation of Mixture Formation and Combustion for Gasoline Direct Injection Engine Using OpenFOAM

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Outline

- Goals

- Simulation of gasoline-ethanol hollow-cone sprays
  - Modifications of spray sub-models
  - Validations

- On-going work: premixed turbulent combustion

- Conclusions
**Goals**

Main goal: Assess the potential of OpenFOAM and further develop it.

Another goal: Assess the applicability of various spray models to simulating sprays discharged by a pintle-type injector (not develop new spray models).
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Illustration of modelling a hollow-cone spray using Lagragian approach

A fuel atomization jet*.

Illustration of how a hollow-cone spray is modeled numerically.

*Fantasy of flow: the world of fluid flow captured in photographs. By Kashika Jōhō Gakkai

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CFD simulation of I.C. engines by OpenFOAM, Milano, 2011/07/11
## Spray models in OpenFOAM

<table>
<thead>
<tr>
<th>Function</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector model</td>
<td>Rosin-Rammler</td>
</tr>
<tr>
<td>Primary breakup model</td>
<td>LISA</td>
</tr>
<tr>
<td>Secondary breakup model</td>
<td>TAB</td>
</tr>
<tr>
<td>Collision model</td>
<td>O’Rourke</td>
</tr>
</tbody>
</table>

Pintle

VSB2 spray model.

The physical properties of gasoline.*

The KHRT Model

Kelvin-Helmholtz

RT instability grows and cause droplets breakup after a certain time.

Rayleigh-Taylor

Droplets’ size decreases gradually.

New parcel was introduced.

The parent droplets’ size was updated.

"breakup" only once when the size of the new parcel is bigger than the parent parcel.
## Modifications of KHRT model

<table>
<thead>
<tr>
<th>Description</th>
<th>KHRT-2</th>
<th>Standard KHRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>The mass of the liquid stripped of the parent droplets</td>
<td>$4\pi N_0 \rho_f \left( r_0^3 - r^3 \right)/3$</td>
<td>$\sum \left( 4\pi N \rho_f r_{KH}^3 /3 \right)$</td>
</tr>
<tr>
<td>The radius of parent droplets after breakup</td>
<td>$N r^2 \left( r - r_{KH} \right)$</td>
<td>unchanged</td>
</tr>
<tr>
<td></td>
<td>$N_0 r_b^2 \left( r_b - r_{KH} \right)$</td>
<td></td>
</tr>
<tr>
<td>The number of child droplets</td>
<td>$n = \frac{N r^3 - N r_b^3}{r_{KH}^3}$</td>
<td>not calculated</td>
</tr>
<tr>
<td>Breakup criteria</td>
<td>$m_s = 0.03 m_{inj}$, and $n &gt; N_0$</td>
<td>$m_s = 0.20 m_{inj}$</td>
</tr>
</tbody>
</table>

Correct version in OpenFOAM-2.0.0
src/lagrangian/spray/submodels/BreakupModel/ReitzKHRT
KHRT-2 vs. standard KHRT

Comparison of measured (symbols) and calculated (lines) gasoline liquid penetration and SMD. $T_a=350\text{K}$, $T_f=243\text{K}$, $p_a=6\text{bar}$.

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Injector Models

**Injection direction**: randomly distributed within inner cone angle and outer cone angle

**Injection position**: randomly distributed over the circle

**Injection direction**: randomly distributed within inner cone angle and outer cone angle

**Injection position**: along the ring, depending on injection direction
Comparison of liquid penetration and downstream velocity components $U_z$ calculated using unit and pintle injector model along the central line of the spray.

OpenFOAM-2.0.0
src/lagrangian/intermediate/submodels/Kinematic/InjectionModel/ConeNozzleInjection/
**Experimental and Computational Setup**

**Experimental setup**
(Hemdal et al. SAE 2009-01-1496)

- High-speed camera: spray imaging
- PDA: droplet size
  - $T_{fuel} = 243$ K, $T_{air} = 350$ K, $p_{inj} = 50, 125, 200$ bar

**Computational mesh**
- 1,754,400 cells
- Size 0.78 x 0.78 x 0.85 mm (center)
Validation, Rosin-Rammler + VSB2 model

Effect of fuel and $p_{inj}$

Comparison of measured (symbols) and calculated (lines) ethanol liquid penetration and SMD for different injection pressures. Rosin-Rammler distribution ($r_m=7.5\mu m$, $q=3$), VSB2 model. $T_a=350K$, $T_f=243K$.
Validation, Uniform droplet size + KHRT-2

Comparison of measured (filled symbols) and calculated (lines) liquid penetration and SMD of gasoline.

\( p_{inj} = 50 \text{ bar} \)
\( p_{inj} = 125 \text{ bar} \)
\( p_{inj} = 200 \text{ bar} \)
Comparison of measured (filled symbols) and calculated (lines) liquid penetration of gasoline for different ambient and fuel temperatures.

- $T_a = 350 \, \text{K}, \, T_f = 243 \, \text{K}$
- $T_a = 295 \, \text{K}, \, T_f = 295 \, \text{K}$
- $T_a = 350 \, \text{K}, \, T_f = 320 \, \text{K}$
- $T_a = 295 \, \text{K}, \, T_f = 243 \, \text{K}$
Comparison of spray shapes
Uniform droplet size + KHRT-2

0.18 ms  0.36 ms  0.64 ms  0.82 ms

Gasoline spray shapes measured (first row) and calculated using KHRT-2 model (second row) at different instances. \( T_{\text{air}}=350 \, \text{K}, \ T_{\text{fuel}}=243 \, \text{K}, \ p_{\text{inj}}=200 \, \text{bar}. \)
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Basics on premixed turbulent combustion

- $c$: progress variable
- $b$: regress variable ($b=1-c$) used in OpenFOAM.
- Favre-averaging (equations become more compact)

$$\bar{c} = \frac{\rho c}{\bar{\rho}} \quad \bar{T} = \frac{\rho T}{\bar{\rho}}$$
Which way is correct in calculating $\tilde{T}$?

<table>
<thead>
<tr>
<th>Premixed turbulent combustion theory</th>
<th>Standard OpenFOAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>By BML concept</td>
<td>Solving the following eq. which seems like Janaf eq.</td>
</tr>
<tr>
<td>$\tilde{T} = T_u \tilde{b} + T_b (1 - \tilde{b})$</td>
<td>$\frac{\tilde{h} W_m}{R} = a_{1m} \tilde{T} + \frac{a_{2m}}{2} \tilde{T}^2 + \frac{a_{3m}}{3} \tilde{T}^3 + \frac{a_{4m}}{4} \tilde{T}^4 + \frac{a_{5m}}{5} \tilde{T}^5 + a_{6m}$</td>
</tr>
</tbody>
</table>

www.openfoamworkshop.org/6th_OpenFOAM_Workshop_2011/Program/Abstracts/ehsan_yasari_ab.pdf
Why is approach in OpenFOAM wrong?

- In OpenFOAM, unburned and burned gases are treated like a multi-component mixture.
  - But totally different phenomenon.

- Janaf eq. was averaged with error in OpenFOAM.

\[ \bar{T}^n \neq \bar{T^n} \]
Conclusions

- A number of modifications of the implementation of various spray models in OpenFOAM were done in order to follow the description of these models in the original papers.
- Pintle injector model was implemented in OpenFOAM to simulate sprays discharged by pintle injector.
- Among these modifications, the change of the implementation of the KHRT model had the most important effect on the computed penetration length and especially SMD at high injection pressures.
- Problem of calculating $\tilde{T}$ for premixed turbulent combustion in OpenFOAM was addressed.
Thank you for your attention!

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