Overview & Perspectives for Internal Combustion Engine using STAR-CD

Marc ZELLAT
TOPICS

- Quick overview of ECFM family models
- Examples of validation for Diesel and SI-GDI engines
- Introduction to multi-component fuels
- Application and validation of multi-component fuel to SI-GDI and Dual fuel engines
  - Real multi-component gasoline
  - Influence of anti-knock additive in the fuel mixture
  - Dual fuel: Diesel/Natural gas combustion
- Conclusion and perspectives
A General Schematic View of Spray and Combustion

- Large scales: $\tau = k/\varepsilon$ (integral length)
- Small scales: $\tau = (\nu/\varepsilon)^{0.5}$ (Kolmogorov length)

Auto-Ignition
Temperature fluctuations

Post-oxidation
Kinetic controlled

Fuel vapor

Mixture fluctuations
Diffusion reaction zone

Temperature fluctuations

Mixture partially burnt gases

Auto-Ignition

Fig. 3. Instantaneous representation of the combustion brush on a small scale for a diffusion spray flame reproduced from Ref. [1]

THERETICAL ECFM-CLEH MODEL DESCRIPTION:
ECFM-3Z / ECFM-CLEH models: conceptual framework

‘EXTENDED COHERENT FLAME - 3 ZONE’
possible fluid states in computational cell

Fuel injection into charge (air + egr)

Mixing of fuel and charge

Ignition in mixed zone

Combustion in mixed zone
+ Un-mixed in burnt gases

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THOERETICAL ECFM-CLEH MODEL DESCRIPTION:
ECFM-3Z / ECFM-CLEH concept: **Flame structure**

**ECFM-3Z**
- Zf/unmixed
- Zf/premixed
- Zf/diffusion

Transfer is function of c only
Transfer if Phi > Phi.crit.

**ECFM-CLEH**
- Passive mixing zone
- Premixed flame zone
- Passive mixing zone
- Diffusion flame zone
- Post-oxidation zone

The diffusion zone is **unmixed burnt gases**
The post-oxidation is **mixed burnt gases**
The transfer between zones is from turbulent mixing and the combustion progresses

\[ Z_F = Y_F \left|_{UM} + Z_F \left|_{PM} + Z_F \left|_{DIFF} + Z_F \right|_{PSTOX} \right. \]

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THOERETICAL ECFM-CLEH MODEL DESCRIPTION:
ECFM-CLEH model : Fundamental approach of 4 reaction rates

Auto-ignition
TKI-PDF model

Propagation
ECFM model

Diffusion flame
Mixing PDF model
P.D.F : Mixture Fraction FLUCTUATION

Post-Oxidation
Chemical Kinetics

Flame surface density
ITNFS Function

Tables for LFS

Mixing controlled reaction rate
Distributed flame with Pdf on mixing scalar (look-up table)

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Automotive DIESEL ENGINE B : RESULTS

5 operating conditions

point 1 : Full load

point 2 : Mid-load

point 3 : Mid-load

point 4 : Low-load

point 5 : Low-load

Swirl Level : Flap open/closed

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Automotive DIESEL ENGINE B : RESULTS

Emissions

NOx-NORA

SOOT

CO

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Automotive DIESEL ENGINE C: Injector 1 versus Injector 2
Injection timing variation comparison: SOOT

Injector 1

Injector 2

Retarded Injection

SOOT
The Soot Sectional Method is capable to differentiate Soot diameter and Distribution between injector 1 and injector 2

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GDI-GASOLINE: Real Engine
Wall Guided Multi-hole injector

Spray and mixture @ 440 °CA ABDC

Equivalence ration around TDC
Red is above ER 1.

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In-cylinder pressure history (left) - Apparent Heat Release (right)
A single component representative fuel has been used in the examples and validations shown in the previous section.

SI-GDI engines are very sensitive to the fuel composition (evaporation process, stratification, Octane number calibration using additives ...)

Dual fuel combustion is emerging, especially in combination with Diesel and Natural gas.

To get better simulation of the system including combustion chamber, fuel composition and mixture preparation strategy.

CD-adapco has extended existing combustion models in STAR-CD to multi-component fuel.

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The refiner must implement processes to improve the gasoline octane number from natural crudes.

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American Society for Testing and Materials Cooperative Fuel Research: Distillation process

ASTM procedure

Heated Multi-component Droplet STAR-Simulation

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The liquid is represented using $N$ components

Vaporization is treated using the discrete approach

**For combustion:**
- The molecular weight is computed according to local component concentration taking into account the number of C, H and O in each component
- Same treatment for the Enthalpy of formation and Laminar Flame speed

**For Auto-Ignition:**
1. **When correlation is used:**
   - Ignition delay and auto-ignition rate are balanced by the Octane (cetane) number of each component
2. **When tables are used:**
   - Tabulated Kinetic for Ignition technique is used, extracting information directly from the tables
Gasoline represented by 4 components

Pressure : full cycle

Pressure : zoom around TDC

A.R.O.H.R : full cycle

Experiment STAR-CD

A.R.O.H.R : zoom around TDC

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Comparison with baseline gasoline: Same amount of energy is introduced due lower L.HV for Ethanol

- **E85 – Combustion**
- Better homogenization around stoichiometry
- Higher Laminar Flame Speed for Ethanol
- **Higher I.M.E.P**

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SPRAY
40 CA after start of injection

4 components

E85 (Gasoline / Ethanol Mixture)

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Operating point 1 **KNOCK** : Spark Timing VARIATION

Reduced Anti-knock Agent

S.T=20 btdc
Mean In-cylinder & Local sensor

S.T=13btdc

**Chemical Heat Release**
- Total Chemical Heat Release
- Premixed Propagation
- Post-oxidation
- Premixed Auto-Ignition
- Diffusion

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Static (728 °CA) Knock onset (space and time)

AI + PM iso-surfaces of Chemical Heat release

Chemical Heat Release
- Total Chemical Heat Release
- Premixed Propagation
- Post-oxidation
- Premixed Auto-Ignition
- Diffusion

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CFD Simulations of a Dual Fuel Engine *
Premixed Natural Gas (methane) + Diesel Pilot injection

Tabulated Kinetic for Ignition is used for Auto-Ignition delay and rate of Auto-ignited consumed fuel

*prepared by J.Lim
Pressure Trace – for case 1 and 2

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG</td>
<td>%</td>
</tr>
<tr>
<td>Diesel [mg]</td>
<td>27.26</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG</td>
<td>%</td>
</tr>
<tr>
<td>Diesel [mg]</td>
<td>156.90</td>
</tr>
</tbody>
</table>

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### Chemical heat Release for case 1 and 2

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG %</td>
<td>2.20</td>
<td>1.72</td>
</tr>
<tr>
<td>Diesel [mg]</td>
<td>27.26</td>
<td>156.90</td>
</tr>
</tbody>
</table>

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Conclusion and Perspectives

Single component using a representative specie

- Well established in ECFM combustion models (ECFM-3Z and ECFM-CLEH)
- Good level of prediction for pressure, heat release, wall heat fluxes
- Good level of prediction in emissions: NO, CO and Soot
- The soot sectional method is able to predict soot diameter and distribution

Emergence of multicomponent for mixture preparation and combustion

- ECFM-3Z has been extended to multi-component fuel
- Combustion and fuel composition are seen now as a system
- Ethanol blended duel and Dual duel combustion has extensively been validated
- Possibility to take into account the detailed mechanism – Introducing different fuel (via External tables)
- CD-adapco is working to provide a tool for tables generation using DARS chemistry solver
- ECFM-CLEH will extended to multi-component fuel in STAR-CD V4.22 (next release)