An Experimental and Simulation Study of Early Flame Development in a Homogeneous-Charge Spark-Ignition Engine

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Overview

- Why this study?
- Key approaches
- Simulation details
- Results
- Conclusions
Why this study?

- Even for homogeneous mixture, spark-ignited combustion exhibits unexplained variations
- Root causes?
- Baseline study for further analysis of less stable operating conditions
  - TCC-III engine
  - Propane, $\phi=1$

https://deepblue.lib.umich.edu/handle/2027.42/108382
Combustion data to be released in the future
Key aspects of this work

• Large Eddy Simulations
  • Identical mesh, boundary conditions
  • Different ignition and combustion models

• Experiments
  • Multi-parameter imaging

• Data mining and post-processing tools
  • Identical for experiments and simulations
TCC-III Engine: Specifications and Operation

- 92mm x 86 mm BxS, 10:1 CR
- 1300 RPM, 40kPa Intake, 101.5 kPa Exhaust
- Propane, $\Phi = 1$, SOIgn = 342 aTDCe
Key LES details (1)

- STAR-CD v4
- Domain includes details up to intake and exhaust plenums
- Average in-cylinder mesh size ~ 0.75 mm; finer meshes near the spark-plug tip and in the valve-curtain regions
- Smagorinsky subfilter-scale turbulence model
- Time-dependent pressure and temperature boundary conditions from GT Power model prescribed at the plenum inlet/outlet, with no cycle-to-cycle variations
- 60 cycles

Ignition and Turbulent Flame Propagation Model

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- Ignition: Simple energy deposition model for flame initiation
- Combustion: Modified thickened flame model
  - $F \sim 0.1 \delta^0_l$: increases flame thickness
  - $\Xi$: accounts for wrinkling at sub-filter scale; applied to diffusive and reaction terms
- Near-wall treatment

\[
\frac{\partial \rho Y_m}{\partial t} + \frac{\partial \rho u_i Y_m}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \rho \Xi F D_m \frac{\partial Y_m}{\partial x_i} \right)
\]

\[
\Xi = \left( 1 + m \left( \frac{\Delta}{\delta^0_l} \left( \frac{u'_\Delta}{s^0_l} \right) \right)^\beta \right)
\]

\[
u'_\Delta = c u'_\Delta \Delta x^3 (\nabla \times \mathbf{u})
\]


Ignition and Turbulent Flame Propagation Model

- Ignition: Imposed Stretch Spark-Ignition (ISSIM-LES)\(^1\)
- Combustion: ECFM-LES\(^2\)
- Flame surface density (FSD) approach
  - Includes sub-filter stretch effects during ignition
  - transition from subfilter-scale-only to resolved-scale contributions
  - efficiency function \( \Gamma \) (sub-scale velocity fluctuations)

\[
\frac{\partial \bar{\Sigma}}{\partial t} = T_{res} + T_{sgs} + S_{sgs} + \alpha C_{sgs} - \nabla \\
\cdot (\alpha S_d N \bar{\Sigma}) + \alpha (C_{res} + S_{res}) \\
+ (1 - \alpha) \frac{2}{r_b} (1 + \tau) \bar{\Sigma} \bar{\Sigma} + \dot{\omega}_{\Sigma}^{ign}
\]

\[
\frac{2}{r_b} (1 + \tau) \bar{\Sigma} \bar{\Sigma}
\]

\[
\alpha = 0.5 \left[ 1 + \tanh \left( \frac{r_b^+ - 0.75}{0.15} \right) \right] \quad , r_b^+ = r_b / \bar{\Delta}
\]

\[
\Gamma \left( \frac{\Delta}{\delta_i}, \frac{u'}{s_i} \right) = 0.75 \cdot \exp \left( - \frac{1.2}{(u' \cdot s_i)^{0.3}} \right) \cdot \left( \frac{\Delta}{\delta_i} \right)^{2/3}
\]


In-cylinder pressure data

- Compression polytropic suggests bulk temperature is 30 – 40°C colder at SOIgn for LES
- Suggests long and late combustion ➔ AHR analysis
- Importance of logP-logV presentation
Apparent heat release rate

- \[ q_i = \frac{n*p_i*(v_i-v_{i-1})+v_{i}(p_i-p_{i-1})}{n-1} \]

- Model 1: earlier combustion than measurements; highest early-combustion CCV

- Model 2: delayed and slower combustion
Combustion Phasing

- Overall combustion phasing variability largely established before CA10
  - relevance of ignition model
  - focus on early flame growth
Cycle-to-cycle variability established by CA01

- AHRR measurements from in-cylinder pressure data
  - for experiments
  - for models
- Measurements still sufficiently precise to use CA01 as standard of comparison with models
- How to study timings with smaller CA(MBF)?
Flame size as metric for early combustion times

- 2-D projection of OH* (Experiments)
- 2D projection of flame surface (Models)
Cycle-to-cycle variability in flame growth

- Model 1: Average growth as in experiments prior to CA01, but greater variability
- Model 2: Average early growth slower than experiments, and greater variability
- Correlations established early
  - $0.5 < t_{\text{flame}} < 1.5$ ms
  - $5\text{mm} < L_{\text{flame}} < 15\text{mm}$
- This is the period which need be captured by the simulation ignition model and transition to the flame.

Dotted lines indicate highest and lowest values
Note: Experiments roll of due to limited field of view
Early flame area development

- Model 1 shows an average growth equal to the measurements but shows far more variability.

- Can this be related to flow properties?
Cycle variation of spatially averaged velocity

- Experiments show larger variation of velocity magnitude at start of ignition

- Large-scale directional distribution more similar
Analysis of velocity gradients

• PIV-data do not resolve largest gradients at the resolved scale (1mm)
  • not a good standard for comparison

• Focus attention on model results
  • volume-averaged 3-D, 3C gradient distributions around the spark plug
Relevance of velocity gradients

- Conditionally sampled by phasing: CA 10
- Example:
  - Model 1 shows more samples with large $\frac{du}{dx}$ than Model 2
  - Both models show that fast-burning cycles (red) are associated with large $\frac{du}{dx}$.

- Overview
  - More in paper
Conclusions

- Impact of early flame development in homogeneous-charge spark-ignition combustion on cycle-to-cycle variations in engine performance

- Integrated experimental and LES studies
  - 2 LES setups: same numerical methods and computational mesh; different ignition and turbulent combustion models
  - Imaging and pressure-based experiments
  - Analysis of LES and experimental data used the same procedures

- Results
  - Both models over-predict cycle-to-cycle variations in combustion
  - Relevance of flow near spark plug region highlighted, in particular, velocity gradients
  - Key timing determining phasing is around the transition from laminar to turbulent flame growth, before CA01
  - Guidance for future studies
Re-start strategy to obtain 60 cycle results

- After the first fired cycle, the combustion difference between Models 1 & 2 will present a different flow and residual to the subsequent cycles, especially since there is significant “back flow” during the valve overlap at TDC exhaust, due to the 40kPa vs 101.5 kPa intake and exhaust plenum pressures.

Model 1
3 sets of 20 cycles

Model 2
4 sets of 15 cycles
Apparent heat release rate analysis

• Correspondence between the cumulative AHR from the simulation $P_{cyl}$, and the MFB sampled from the cylinder volume of the simulation.

\[ q_i = \frac{n * p_i * (v_i - v_{i-1}) + v_i * (p_i - p_{i-1})}{n-1} \]

\[ n_i = -\frac{\ln p_i - \ln p_{i-1}}{\ln v_i - \ln v_{i-1}} \]
Transition from laminar to turbulent flame growth

• Data and early models show a change in flame-growth rates, producing a notional change from laminar to turbulent time scales of the burning rate (Abraham, Reitz and Bracco).

• A quantifiable transition is shown in the measured data.
Correlation of $\tau_{\text{spark}}$ & $\tau_{\text{lam-turb}}$ with CA10

- Cycle by cycle spark discharge current and voltage measurements plasma discharge nearly until CA10, and

- Far longer than the “laminar to turbulent” transition.

  ➔ initial dependence of the spark must transition to dominance by heat of combustion.

  ➔ Plasma continues to act as flame-holder for combustion in the wake of the spark plug electrodes.

- Very poor correlation between $\tau_{\text{lam-turb}}$ and CA10. ➔ correlation must evolve after $\tau_{\text{lam-turb}}$
- Gradient distributions showing low gradient values, and inadequacy of the linear axis to reveal differences in large-gradient region of the distributions.