Large-Eddy Simulations with Conjugate Heat Transfer of a Reacting Flow in an Internal Combustion Engine

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Large-Eddy Simulation for Energy Conversion in electric and combustion Engines

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Motivation

- Engine heat transfer affects efficiency, performance, and emissions.
- Convective heat transfer controlled by the boundary layer development.
- Periodic changes in thermodynamic states throughout the cycle and large cycle-to-cycle variation (CCV) prevents a well-established boundary layer.

[1] greencarcongress.com
Heat Transfer Measurements

Engine heat transfer varies spatially and temporally [1].

Cycle-to-cycle variation in surface temperature [2].

IC engine modeling typically uses steady, isothermal boundary conditions.

Conjugate Heat Transfer (CHT)

- Spatially and temporally varying temperatures
- Heat transfer between fluid and solid
- Shortcomings:
  - Reynolds-Averaged Navier-Stokes (RANS) models
  - Fixed engine components
  - Validation needed
- Large-eddy simulations (LES) CHT performed by Misdariis et al. [1]:
  - Some cyclic and spatial variations
  - Shortcomings: fixed valves, valve motion on in-cylinder flow not simulated

**Previous study** [2]: Multi-cycle LES with CHT with moving solid components, validated with near-wall flow, temperature, and heat flux measurements.

**This study**: extend to fired operating condition.

Objectives

• Integrate CHT with LES for improved heat transfer predictions for fired engine operating condition to capture spatial, temporal, and cyclic variations in surface temperatures.

• Validate and assess CHT method in near-wall flow and temperature predictions with particle-image velocimetry (PIV) and planar laser-induced fluorescence (PLIF) data of the transparent combustion chamber (TCC-III) engine.

• Compare CHT to LES with uniform temperature boundary conditions.
# TCC-III Engine

## Extensive database on Deepblue

- **Engine operation**: Fired (stoichiometric propane/air mixture)
- **Bore**: 92 mm
- **Stroke**: 86 mm
- **Clearance at TDC**: 9.5 mm
- **Compression ratio**: 10:1
- **Intake valve opening**: 352.8 CAD aTDCc
- **Intake valve closing**: -119.2 CAD aTDCc
- **Exhaust valve opening**: 124.8 CAD aTDCc
- **Exhaust valve closing**: -347.2 CAD aTDCc
- **Spark plug**: AC Delco R44LTS
Near-Wall Velocity and Temperature Measurements

Engine conditions:
- 1300 RPM
- 40 kPa intake and 98 kPa exhaust manifold absolute pressure (MAP)
- 80 °C intake temperature

Note: Uncertainty of ensemble average velocity less than 10% (P. C. Ma, et al. Intl. J. Engine Research (2017)).

PIV dataset: [1]
- S_2016_03_25_09
- Resolution: 0.125 mm

PLIF dataset: [2]
- Resolution: 0.1 mm

3D CFD Simulations with CONVERGE

**LES model**: Dynamic structure model

**Number of cycles**: 11 cycles, first cycle discarded

**Wall models**
- Werner and Wengle wall model
- Han and Reitz heat transfer model

**Thermal boundary condition**
- Uniform and constant surface temperature
- CHT, with supercycling

**Combustion and Emissions Modeling**
- G-equation model
- Laminar flame speed: Gülder correlation for propane
- Turbulent flame speed: Pitsch model, $b_1$ tuning
- Spark: energy source equal to 32 mJ at -18 CAD
- Extended Zel’dovich NOx model
Thermal Boundary Conditions for the Fired Uniform Temperature Model
Computational Domain CHT model

Intake

Exhaust

|V| (m/s)

40
30
20
10
0

Cylinder head

Cooling jacket

Valve seat

Piston

Liner

Valves

Spark plug
LES Model Validation

• Note: $b_1$ tuning was required, which affects the turbulent flame speed (Pitsch model)

\[
s_t = s_l \left( 1 - \frac{b_3^2 s_l \mu_t}{2 b_1 \mu u'} + \sqrt{\left( \frac{b_3^2 \mu_t s_l}{2 b_1 \mu u'} \right)^2 + \frac{b_3^2 \mu_t}{\mu}} \right)
\]

  – LES with uniform temperature BCs: $b_1 = 5.5$, CONVERGE 2.4
  – LES CHT: $b_1 = 8$, CONVERGE 3.0

• More tuning of $b_1$ is required for LES CHT, need to simulate all 10 cycles
Bulk temperature field and early flame kernel differences due to varying surface temperatures and differences in turbulent flame speed

- CHT has a larger $b_1$ value than uniform temperature LES, which affects turbulent flame speed
- Surface temperature also affects combustion process
Near-wall flow fields show improvements are still needed in wall modeling approach of engine LES

- CHT: accurate flow direction at -100 and -35 CAD, but opposite flow at -20 CAD, comparable velocity magnitude
- Uniform T LES: opposite flow with higher velocity magnitude at -100 and -35 CAD, and perpendicular and stronger flow at -20 CAD
- Flow field comparisons need to be done with caution
  - Abraham [1] found flow pattern switching in the TCC engine
  - Low number of simulated cycles

Near-wall temperature fields also need wall modeling improvements

- Simulations predict higher temperatures than measured
- Measurements show smaller structures and the need for mesh refinement
- Simulated temperatures increase with wall distance
- Higher near-wall temperatures predicted by CHT than uniform T LES except at -100 CAD

PLIF: 145 cycles
LES: 10 cycles
CHT Surface Temperature Predictions

- Dynamics are captured
- Level of CCV after 40 CAD was overpredicted

13 K or -3% difference
Temporal and cyclic variations in surface heat flux

Note: experimental data filtered to reduce noise, but lowered peak heat flux from 990 kW/m²K to 579 kW/m²K

- CHT predicts largest peak heat flux of 1191 kW/m²K
- Uniform T model predicts peak heat flux of 949 kW/m²K
- CHT predicts a level of CCV closer to the measurement due to more consistent ΔT from cycle to cycle
CHT model predicts spatial, temporal, and cyclic variation of surface temperature at the spark plug.
Spark plug temperature varies with time, space, and from cycle to cycle, and increases over cycles as engine warms up, even with supercycling.

<table>
<thead>
<tr>
<th></th>
<th>exp</th>
<th>CHT cycles 2-11</th>
<th>CHT cycles 5-11</th>
<th>Uniform T LES</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMEP ensemble avg</td>
<td>302 kPa</td>
<td>284 kPa</td>
<td>169 kPa</td>
<td>317 kPa</td>
</tr>
<tr>
<td>IMEP COV</td>
<td>0.85%</td>
<td>2%</td>
<td>0.86%</td>
<td>0.44%</td>
</tr>
</tbody>
</table>
Conclusions

• Near-wall predictions show improvements are needed in wall models, even with improved surface temperature boundary conditions from LES CHT. However, comparisons should be done with caution.
• CHT model predicted surface temperatures within 3% of measured cylinder head temperature.
• CHT model overpredicted peak heat flux but comparable level of CCV as the measurement.
• CHT model predicts large spatial, temporal, and cyclic variations in spark plug surface temperature ranging from 350 to 1000 K.
• Spark plug temperature increased gradually from cycle 2 to 4 even with supercycling.
Thank you for your attention

Questions?