Investigation of the unsteady wall heat transfer under engine relevant conditions using Direct Numerical Simulation.

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Outline:

- Experiments and modeling of the ICE wall heat transfer
- Numerical approach
- Results
  - Wall heat transfer
  - Velocity and thermal boundary layer
- Conclusion & Outlook
ICE wall heat transfer

Experiments:

Heat flux:
- Thermocouples [1]
- Phosphor coating [2]

Velocity boundary layer:
- LDV [3]
- Near wall 2D-PIV [4]

⇒ Very few information about the boundary layers on the gas side are available [1]

3D RANS/LES engine simulations:

Wall modeling based on:
- Wall function approach (based on law of the wall)
- Wall resolved calculations

⇒ Need for improved ICE wall heat transfer models

Aims of our work:
⇒ Provide an improved understanding of wall boundary layers in ICEs
⇒ Provide a highly resolved validation platform

Part 1: Intake and exhaust stroke
- 11 consecutive cycles
- Comparison with experimental LDA data (Morse et al., 1979)
- Cycle-to-cycle variations

Part 2: Close the valve at BDC and simulate the compression stroke
- Thermal stratification
- Boundary layers
- Unsteady wall heat transfer

Overview


Operating conditions:
⇒ Engine speed 560 rpm
⇒ Compression ratio = 12

Mesh:
⇒ 90 Mio. nodes (mesh 1)
⇒ 135 Mio. nodes (mesh 2)
⇒ Wall resolution ≈ 10 μm

<table>
<thead>
<tr>
<th>mesh 1</th>
<th>range [°CA]</th>
<th>Δr⁺</th>
<th>Δrφ⁺</th>
<th>Δz⁺</th>
<th>Δw⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 – 306</td>
<td>&lt; 5</td>
<td></td>
<td>&lt; 5</td>
<td>&lt; 2</td>
<td>&lt; 0.4</td>
</tr>
<tr>
<td>mesh 2</td>
<td>306 – 360</td>
<td>&lt; 6</td>
<td>&lt; 6</td>
<td>&lt; 3</td>
<td>&lt; 0.9</td>
</tr>
</tbody>
</table>


Boundary conditions:

- Piston velocity at the piston
- Zero velocity on all other boundaries
- Thermal boundaries fixed at 500K
- Zero flux species boundary conditions

Numerics:

- Spectral element solver: Nek5000 (ANL)
- LAV plugin for low Mach number combustion including detailed transport and chemistry
- 9th order spatial discretization
- 3rd order time integration
Temperature [K]

- Intake channel:
  - Air/H₂ (500K)
- Cylinder:
  - EGR (900K)

Velocity magnitude [m/s]

- Engine speed:
  - 560 rpm
- Calculation time:
  - 600,000 CPUh per intake stroke
The thermodynamic loss angle is 1.54 °CA.

\[ \rho = \rho R T \]
\[ \nu = \frac{\mu(T)}{\rho(p,T)} \]
\[ Re = \frac{u l}{\nu} \]
Heat flux: $q = k \frac{\partial T}{\partial \nu}$

Heat transfer coefficient:

$\alpha = \frac{q}{(T_{av} - T_W)}$

$\alpha_{Woschni} = 3.26 d^{-0.2} \times p^{0.8} \times T^{-0.55} \times (2.28 s_p)^{0.8}$

$\alpha_{Hohenberg} = 130 V^{-0.06} \times p^{0.8} \times T^{-0.53} \times (T^{0.163}(s_p + 1.4))^{0.8}$


$y^+ = 180.2$
WD = 3.75 mm

$y^+ = 45.9$
WD = 0.9375 mm

$y^+ = 23.2$
WD = 0.375 mm

$\mathcal{U}_z$ [m/s]

$y^+ = 180.2$
WD = 3.75 mm

$y^+ = 45.9$
WD = 0.9375 mm

$y^+ = 23.2$
WD = 0.375 mm

$\mathcal{U}_z$ [m/s]
Velocity and thermal boundary layer:
\[ y^+ = \frac{y}{\nu_W \sqrt{\rho_W}} \quad u^+ = \bar{u} \sqrt{\frac{\rho_W}{\tau_W}} \]

\[ y^* = \frac{y}{\nu(y) \sqrt{\rho(y)}} \quad u^* = \bar{u} \sqrt{\frac{\rho(y)}{\tau_W}} \]

\[ T^+ = \frac{(T_W - T) \rho_W c_p u_{\tau,W}}{q_W} \]

\[ T^* = \frac{(T_W - T) \rho(y) c_p u_{\tau}(y)}{q_W} \]

Same behavior can be observed at liner and piston surfaces
\[ y^* = 9.2 \]
Summary and conclusions (compression):

- Model free DNS simulation of the compression stroke under engine relevant conditions

- Wall heat transfer
  - Globally:
    - Strongly influenced by decreasing kinematic viscosity
  - Locally:
    - Correlated with the wall normal velocity
    - Highly fluctuating due to ejection streams close to the wall

- Boundary Layer
  - Deviates from the law-of-the-wall in the log law region [Jainski et al. (2013)]
  - Basis for many existing wall models in engines
  - In density weighted wall-normal units fully collapsing profiles can be observed
Current work & Outlook:

- Use the DNS results as validation platform for LES turbulence & wall heat transfer models
- Use the fields as initial conditions for detailed reactive calculations
- Simulate higher turning speeds and more realistic engine geometries

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Thank you very much for your attention!

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