Chapter 9: Flame wall interactions in canonical configurations

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Technische Universität Darmstadt
Literature

Flame-wall interaction (FWI)

- Topical subject with relevance for
  - Safety technology: flame arresters
  - Catalytically assisted combustion
  - Micro-combustion
  - Gas turbine combustion (lean, low NOx)
  - Internal combustion engines (cold start, downsizing)

J. Hermann et al., TU Darmstadt
Pressurized combustor
Interaction of flame-flow-effusion cooling
Flame-Wall Interaction

- Example: Spark ignition engines

- Large heat loss to wall
- Flame quenching = termination of chemical reactions
- Sources of UHC and CO

→ Complex problem with high practical relevance

Burned gas: 1500~2500 K
Wall surface: 350~700 K
General properties of FWI

• When flame approaches closer than a few flame thicknesses to the wall (for premixed combustion)
  → Intense coupling between flame and wall
    • Large heat fluxes (exceeding 1 MW/m² for HC-fuels at 1 bar)
    • Flame quenching causing incomplete combustion
      • Emission of unburned hydrocarbons and CO
      • Relevant especially for engine combustion
        • Contribution to heat loss ~30%
        • Contribution to unburned hydrocarbons ~40%
Dynamics of HOQ: 1D-simulation
Source: T. Meier, G. Künne; A. Ketheheun, J. Janicka (Darmstadt)
FWI for turbulent conditions

Source: T. Poinsot and D. Veynante, Theoretical and Numerical Combustion 2005
FWI for turbulent conditions

Studied by DNS in simplified configurations and mostly simplified chemical kinetics

Very limited number of comprehensive experimental studies going beyond quenching distances and heat transfer

→ Requirement for more detailed insights into practically relevant configurations
Parameters of interest to better understand FWI

- Quenching distances, visualization of flames near walls
- Wall temperature and heat flux $\dot{Q}$
- Flow fields near walls
  - Velocity boundary layers $u$
- Thermo-chemical states during FWI
  - Thermal boundary layers $T$
  - Concentration boundary layers $X$
- Local heat release rates near walls

Focus today
Outline

- Motivation
- Multi-dimensional laser diagnostics for studying flame-wall interactions
  - Side-wall quenching of flames
  - Flame-wall interaction in IC engines
- Summary
Burner setup – Side-wall Quenching

- Premixed V-flame (fuel: methane, DME)
- $\Phi = 0.83, 1, 1.2$
- $\text{Re} = 5000$
- Laminar and turbulent (by turb. grid)
- Temperature controlled wall
### High-speed PIV/OH-PLIF: Experimental setup

<table>
<thead>
<tr>
<th>Gas velocity</th>
<th>Flame front position</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Particle Image Velocimetry (PIV)</strong></td>
<td><strong>Planar LIF of OH radical</strong></td>
</tr>
<tr>
<td>2 D/2 C</td>
<td>Flame front from OH gradient</td>
</tr>
<tr>
<td>Rep. Rate: 10 kHz and 10 Hz</td>
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</tr>
</tbody>
</table>

- Two fields of view (18x18 mm²)
- 2C-PIV (Al₂O₃ particles)
- OH-PLIF
  - High-speed dye laser system (35 µJ/pulse)
  - Q₁(6)-line
  - Canny-edge filter for flame front detection
Visualization of flow field and flames near walls

- Extraction of flow features: Boundary layers, turbulence fields, … (not shown)
CARS/ CO-LIF/ OH-PLIF/ Phosphor Thermometry
Experimental setup

<table>
<thead>
<tr>
<th>Gas Temperature</th>
<th>CO Concentration</th>
<th>Wall Temperature</th>
<th>Flame front position</th>
</tr>
</thead>
<tbody>
<tr>
<td>ro-vibrational ns-CARS</td>
<td>Two Photon LIF of CO molecule</td>
<td>Phosphor thermometry</td>
<td>Planar OH-LIF</td>
</tr>
<tr>
<td>0 D Rep. Rate: 10 Hz</td>
<td>0 D Rep. Rate: 10 Hz</td>
<td>2 D Rep. Rate: 10 Hz</td>
<td>2 D Rep. Rate: 10 Hz</td>
</tr>
</tbody>
</table>

Front view

Side view

Phosphor Coating
OH-LIF Laser Sheet
OH-LIF
Flow master
CARS Signal
CARS Stokes
Burner Nozzle

Crossing Point CARS and CO-LIF Beams
Flame

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Gas phase and wall surface temperature (Re = 5000, Φ = 1.0, laminar)

- **DME** flames: quench further upstream than methane flames due to increased laminar burning velocity.
- Higher $T_{\text{wall}}$ → increased $T_{\text{gas}}$ within boundary layer → flame burns further upstream due to increased laminar burning velocity.
Wall-heat flux
(Re = 5000, Φ = 1.0, laminar)

\[ q = \lambda \frac{(T_{\text{gas}} - T_{\text{wall}})}{\Delta y} \]

Methane

DME

- \( T_{\text{wall}} = 330 \text{ K} \)
- \( T_{\text{wall}} = 450 \text{ K} \)
- \( T_{\text{wall}} = 540 \text{ K} \)
- \( T_{\text{wall}} = 670 \text{ K} \)
Quenching distance and wall-heat flux
(Re = 5000, Φ = 1.0, laminar)

With higher $T_{\text{wall}}$

- **Maximum heat flux** increases due to decreasing **quenching distances**
- **Heat flux in post-flame region** decreases as expected for non-reacting flows
Temperature & wall-normal CO-profiles
(Re = 5000, Φ = 1.0, laminar)
CO-temperature correlations: State space

- Spatial **conditioning** (axial & wall-normal)
- Flame tip **fluctuates** up and down (± 150 µm)
→ Different **thermo-kinetic states** at one measurement location

\[
z = 48 \text{ mm, laminar}
\]
Upstream quenching position, various y-positions

\[
\begin{align*}
X_{CO} & \\
T [\text{K}] & 
\end{align*}
\]
Thermo-chemical states for $z = 49.5$ mm @ quenching position ($Re = 5000, \Phi = 1.0,$ laminar)

- **CO formation** branch: strongly influenced for $y < 0.3$ mm for methane flame
- **CO consumption** branch: shifted to lower temperatures for entire near-wall region with both fuel types
Time scale analysis
(Re = 5000, Φ = 1.0, laminar)

Time scales of CO formation

Time scales of CO oxidation

**Time scale of heat transfer**

\[
\tau_H = \frac{L^2}{\lambda \rho c_p},
\]

- \(L\) represents the wall-normal distance \(y\)
- \(\lambda\) heat conductivity

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Time scale analysis
(Re = 5000, Φ = 1.0, laminar)

- **CO-formation**: slower than heat transfer for y ≤ 0.2 mm (methane), y < 0.1 mm (DME)
  → Only for methane at y ≤ 0.2 mm influence of wall heat loss
- **CO-oxidation**: both fuels are influenced by heat loss in near-wall region

\[ \tau_H = \frac{L^2}{\lambda \rho c_p}, \quad L \text{ represents wall-normal distance} \]
Thermo-chemical states for $z = 42.5 \text{ mm}$
(Re = 5000, $\Phi = 1.0$, turbulent)

- Both branch are influenced for entire near-wall region
- Intermediate states between both branches are observed
  $\rightarrow$ Increased wall heat transfer due to turbulence
Heat release imaging – Scope

- Measurement of relative heat release rate (HRR) for premixed flames interacting with cold walls
- Investigation of flame structures during flame-wall interactions
- Use of correlation between HRR and $X_{\text{OH}} \times X_{\text{CH}_2\text{O}}$
Correlation between HRR and \(S_{\text{CH}_2\text{O}} \times S_{\text{OH}}\)

- Correlation between the product of \(S_{\text{CH}_2\text{O}} \times S_{\text{OH}}\) and HRR derived from premixed flame calculations for stoichiometric methane/air and DME/air flames
- Curvature (horizontal axis), strain (area along the line) and the case of \(L_e = 1\) (no variation of strain) are considered
Experimental setup for heat release imaging
Results – laminar flame (1)

- Ensemble average, 1000 samples

![Diagram showing results for methane and DME flames with CH$_2$O and OH concentrations, and HRR (heat release rate) profiles.](image)
Results – laminar flame (2)

- Wall-normal profiles at quenching height
Results – turbulent flame (1)

- Single realization
Results – turbulent flame (2)

- **Left:** Wall-normal profiles of curvature (averaged) vs. wall-normal distance
- **Right:** Normalized profiles of the HRR against curvature. HRR values are normalized by the value at curvature = 0.
Results – turbulent flame (3)

Correlation analysis

- Curvature close to wall approaches to zero due to laminarization
- Mean positive curvature (convex flame front towards unburnt gases) in the FWI region
- Mean negative curvature for flames approaching the wall \((y = 1.5 – 4 \text{ mm})\)
- Increase in HRR particularly with negative curvature observed for both fuels, this is in accordance with one-dimensional flame calculations using a detailed transport model

→ Indication that Lewis number effects are important for turbulent premixed flames interacting with walls
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Experimental setup

Flow field

- Planar laser-induced fluorescence (PLIF) of SO₂
- Inert tracer
- High temperature sensitivity

Flame position

- 200 cycles, $\lambda = 1$

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition (°CA)</td>
<td>-14.2</td>
<td>-22.2</td>
<td>-22.2</td>
<td>-27.2</td>
</tr>
<tr>
<td>imep (bar)</td>
<td>5.7</td>
<td>1.9</td>
<td>6.2</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Acusto optical deflector

- Nd:YAG @ 266 nm
- Nd:YAG @ 532 nm
Physical Processes in IC Engines

- Wall-resolved Particle Tracking Velocimetry
- Significant deviations from log-law

Flame propagation

Flame front

Probability „burnt“
200 cycles

A
800 1/min
0.95 bar

B
800 1/min
0.40 bar

C
1500 1/min
0.95 bar

D
1500 1/min
0.40 bar

Flame-flow-interaction

- 15°CA: similar flow structures for A-C (confirmed by bulk flow characteristics)
- Case A: Strong acceleration of flow
- Case D: Deceleration of flow

Different flame-flow interactions dependent on operation condition
Boundary layer, cases A – D

× $\delta_{50} = y_{piston}(0.5 \cdot U_{x,max})$

➢ Strong changes for A

➢ Correlation between flow and combustion?

Conditional statistics

$U_x$:  
- Closely above the piston
- -9°CA

$P_{max}$ (bar)  
- $r = 0.61$  
- Strong / weak flow

$U_x$ (m/s)  
- $4.3 \text{ m/s}$

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Conditional statistics, case A

\[ \delta_{50} \approx 170 \, \mu m \]
\[ \delta_{50} \approx 110 \, \mu m \]
\[ \delta_{50} \approx 80 \, \mu m \]
\[ \delta_{50} \approx 140 \, \mu m \]

- **A_S**: Strong - Early acceleration
- **A_W**: Weak - Later acceleration
- **A_M**: Motored - Reduced velocity magnitudes

\[ \times \delta_{50} = y_{Kolben}(0.5 \cdot U_{x,max}) \]
- Similar development over °CA
- Differences in gradients
Conditional statistics, case A

Conclusions

- Boundary layer flows strongly influenced by turbulent flame (flow magnitudes, gradients)
- Boundary layer flows strongly correlated with combustion performance (PMI)
- Variation with operating conditions
- Open issue: Scaling law
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Summary

- Chemically reacting flows such as combustion processes are multi-dimensional in nature
- Chemical and physical processes acting at similar time-scales cause a strong mutual interaction
- Multi-parameter diagnostics are mandatory to disclose reaction-transport coupling
- Advanced laser diagnostics are unrivalled, for example
  - Spatial resolution of 20 µm in IC engine
  - Simultaneous measurement of wall & gas temperatures, heat flux, CO-concentration and flame front position in generic FWI-burner
Thank you for your kind attention