Turbulent Wall Fire

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Contributors

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Wall Fire – A Canonical Problem
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Scope: Wall Fire Heat Transfer

Pyrolysis
Heat transfer
Kinetics

radiation

convection

Fire

Fuel Pyrolysis

Heat Transfer
Scope: Wall Fire Heat Transfer

- Radiation
- Convection

Fire

Fuel Pyrolysis

Heat Transfer
Outline

- Experiment
- Modeling results
  - Approach
  - Comparisons
- Discussions
  - Modeling practices
  - Future experiment
Experiments –

- Porous vertical burners
  - Propylene
  - Methane
  - Ethane

- Water cooled vertical wall

(J. de Ris et al., FM report, 1999)
(J. de Ris et al., Proc. 7th IAFSS, 2002)
(N. Ren et al., C&F 2015)
Experiments –

- Measurement
  - Temperature
  - Radiance
  - Total Heat flux
  - Soot depth
  - Velocity

(J. de Ris et al., FM report, 1999)
(J. de Ris et al., Proc. 7th IAFSS, 2002)
(N. Ren et al., C&F 2015)
Soot Depth

Measured soot depth vs. fuel mass transfer at different heights (mm)
Temperature

![Temperature plot]

- Tc_29.23g/m³s_Z=36.5cm
- Tc_24.84g/m³s_Z=36.5cm
- Tc_19.00g/m³s_Z=36.5cm
- Tc_10.08g/m³s_Z=36.5cm
- Tc_22.37g/m³s_Z=77.1cm
- Tc_17.05g/m³s_Z=77.1cm
- Tc_12.68g/m³s_Z=77.1cm
- Tc_6.75g/m³s_Z=77.1cm
Radiance

Outward radiance normal to the burner surface
Markstein & de Ris (1992)

De Ris, et. al, 2003, Fire Safety Science
Heat Fluxes

Small wall-fire: $z = 198$ mm

Large wall-fire: $z = 990$ mm

de Ris et al. (Unpublished)
Ethane

De Ris, et. al, 2003, Fire Safety Science
Most, et. al, 1984
Experiments – Summary

- Carefully designed and conducted data set
  - Reveal physics, build analytical models
- Limitations
  - First order turbulent statistics only
  - Operating conditions varies for different measurement
  - Not ideal for CFD model development and validation
Modeling
Modeling Choices

- Mesh resolution
- Convection treatment: wall functions
- Radiation model
- Turbulence and combustion model
NIST – FDS 6.5.3

- Propylene
- 3 mm resolution, 4.2 million cells, 160 MPI processes
- Six band radiation model using RadCal
- Mixing-controlled fast chemistry, EDC model
- Soot yield: 0.095
- CO yield: 0.017 (Tewarson, *SFPE Handbook*)
- Open boundaries, front, bottom, top
- Burner surface and side walls, ambient temperature
- Nusselt number based convective heat transfer model
FM Global

FM Global – FireFOAM 2.2.x

- Propylene
- 3 mm resolution, 0.8 M cells, 36 cores
- Modified EDC model
- Radiant fraction based radiation model
- Direct resolving convective heat flux
Mesh and B.C.

- **Base line – 3 mm grid**
  - $\Delta Y \sim 3$ mm, $\Delta X \sim 7.5$ mm, $\Delta Z \sim 7.7$ mm
  - 0.8 M cells, CFL = 0.5
  - 36 CPUs, 45 hrs for 30 s

- **B.C.**
  - Cyclic (periodic) in span-wise
  - Entrainment BC at the side
  - Fixed temperature, $T = 75 \, ^\circ C$
  - Fixed flow rates with turbulent fluctuations
    - 8.8, 12.7, 17.1, 22.4 g/m$^2$s

- **Schemes:**
  - 2$^{nd}$ order fully implicit
Grid Convergence
Law of the Wall: High Re

\[ u^+ = y^+ \]

\[ u^+ = \frac{1}{\kappa} \ln y^+ + C \]

\[ u^+ = \frac{u}{u_\tau} \]

\[ y^+ = \frac{y u_\tau}{\nu} \]

\[ u_\tau = \frac{\tau_w}{\rho} \]
Natural Convection, High $Gr$ Number

$T_c = \left[ \frac{1}{\alpha g \beta \left( \frac{q_w}{\rho c_p} \right)^3} \right]^{1/4}$

Holling & Herwig, JFM 2005
Grid Requirement

- High Re, momentum driven flow (Piomelli et al., 2002)
  \[ \delta_{VSL} \approx \frac{\nu_w}{(\tau_w / \rho_w)^{1/2}} \approx 0.2mm \]

- High Grashof, natural convection (Holling et al., 2005)
  \[ \delta_{VSL} \approx \frac{(\nu_w / \Pr)^{3/4}}{(\dot{q}_{w,c} / \rho_w c_{p,w})^{1/4} (g \beta)^{1/4}} \approx 0.5mm \]

- Wall fire?
  - 10-20 cells across the flame: 3mm to start
Grid Convergence - FireFOAM
Grid Convergence - FireFOAM

Radiative heat flux [kW/m²] vs. Z [m]

Fully Turbulent

- 1.5 mm
- 2 mm
- 3 mm
- 5 mm
- 10 mm
- 15 mm
Grid Convergence

![Graphs showing grid convergence metrics](image)
Grid Requirement

- Larger cell size than
  - Momentum driven shear flow
  - Buoyancy driven natural convection flow

- Because
  - Buoyancy and HRR take place in outer layer
  - Blowing effect
Model Comparison
Soot Depth

FM Wall Flames, z=365 mm

FM Wall Flames, z=537 mm

FM Wall Flames, z=771 mm

FM Wall Flames, z=1022 mm

FM Wall Flames, z=1317 mm
Total Heat Flux

FM Wall Flames, $\text{C}_3\text{H}_6$, 22.37 g/m²/s

Heat Flux (kW/m²)

z (m)

FM Wall Flames, $\text{C}_3\text{H}_6$, 17.05 g/m²/s

Heat Flux (kW/m²)

z (m)
Radiation Model – FireFOAM

- Fixed radiant fraction
- Finite volume implementation of Discrete Ordinate Method (fvDOM)
- Optically thin assumption
- Soot/gas blockage ($\chi_{rad}$ is reduced by 25%)

\[
\frac{dI}{ds} = \left(\frac{\chi_{rad} \dot{q}_c}{4\pi}\right)
\]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Methane $\text{CH}_4$</th>
<th>Ethane $\text{C}_2\text{H}_6$</th>
<th>Ethylene $\text{C}_2\text{H}_4$</th>
<th>Propylene $\text{C}_3\text{H}_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Fire (de Ris measurement)</td>
<td>15%</td>
<td>17%</td>
<td>24%</td>
<td>32%</td>
</tr>
<tr>
<td>Simulation (account for blockage)</td>
<td>12%</td>
<td>13%</td>
<td>18%</td>
<td>25%</td>
</tr>
</tbody>
</table>
Radiation Model – FDS

- Six band radiation model using RadCal
- Soot yield: 0.095

RadCal has radiative properties for methane, ethane, ethylene, and propylene (and a few other fuels). FDS has a 6 band option for radiative transport. This option is expensive, requiring about 56% of total CPU time. It is not normally used for routine fire protection calculations.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Tewarson (SFPE Handbook)</th>
<th>FDS Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethane</td>
<td>0.25</td>
<td>0.31</td>
</tr>
<tr>
<td>Ethylene</td>
<td>0.34</td>
<td>0.38</td>
</tr>
<tr>
<td>Methane</td>
<td>0.14</td>
<td>0.22</td>
</tr>
<tr>
<td>Propylene</td>
<td>0.37</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Table 6.1: Limits of the spectral bands for methane (CH₄).

<table>
<thead>
<tr>
<th>Band</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ (µm)</td>
<td>1.00</td>
<td>2.63</td>
<td>2.94</td>
<td>4.17</td>
<td>4.70</td>
<td>10.0 200</td>
</tr>
<tr>
<td>λ (µm)</td>
<td>1.00</td>
<td>2.63</td>
<td>2.94</td>
<td>4.17</td>
<td>4.70</td>
<td>10.0 200</td>
</tr>
</tbody>
</table>

Table 6.2: Limits of the spectral bands for ethane (C₂H₆).

<table>
<thead>
<tr>
<th>Band</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ (µm)</td>
<td>1.00</td>
<td>2.63</td>
<td>2.99</td>
<td>3.92</td>
<td>6.06</td>
<td>9.17 200</td>
</tr>
<tr>
<td>λ (µm)</td>
<td>1.00</td>
<td>2.63</td>
<td>2.99</td>
<td>3.92</td>
<td>6.06</td>
<td>9.17 200</td>
</tr>
</tbody>
</table>

Table 6.3: Limits of the spectral bands for ethylene (C₂H₄).

<table>
<thead>
<tr>
<th>Band</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ (µm)</td>
<td>1.00</td>
<td>2.63</td>
<td>2.96</td>
<td>3.57</td>
<td>6.06</td>
<td>12.82 200</td>
</tr>
<tr>
<td>λ (µm)</td>
<td>1.00</td>
<td>2.63</td>
<td>2.96</td>
<td>3.57</td>
<td>6.06</td>
<td>12.82 200</td>
</tr>
</tbody>
</table>

Table 6.4: Limits of the spectral bands for propylene (C₃H₆).

<table>
<thead>
<tr>
<th>Band</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ (µm)</td>
<td>1.00</td>
<td>2.63</td>
<td>3.08</td>
<td>3.85</td>
<td>5.13</td>
<td>8.51 200</td>
</tr>
<tr>
<td>λ (µm)</td>
<td>1.00</td>
<td>2.63</td>
<td>3.08</td>
<td>3.85</td>
<td>5.13</td>
<td>8.51 200</td>
</tr>
</tbody>
</table>
Convective and Radiative Heat Flux

- Increase fuel flow rate

Increase fuel flow rate

Laminar | Turbulent

Laminar | Turbulent

FM Global
Radiance

FM Wall Flames, z=66 mm

FM Wall Flames, z=330 mm

FM Wall Flames, z=594 mm

FM Wall Flames, z=990 mm
T Gas

- FM Wall Flames, 8.75 g/m²/s
- FM Wall Flames, 12.68 g/m²/s
- FM Wall Flames, 17.05 g/m²/s
- FM Wall Flames, 22.37 g/m²/s
Thermocouple (T.C.) Temperature

- Gas temperature measurement
  - Fluctuation
  - Radiation

- Numerical description of thermocouple temperature
  - Thermocouple Model

\[
\rho_{Tc} C_{Tc} \frac{V_{Tc}}{A_{Tc}} \frac{dT_{Tc}}{dt} = \varepsilon_{Tc} \left( T_g - \sigma T_{Tc}^4 \right) + h \left( T_g - T_{Tc} \right)
\]
Other Fuels

FM Wall Flames, C\textsubscript{2}H\textsubscript{4}, 11.5 g/m\textsuperscript{2}/s

Heat Flux (kW/m\textsuperscript{2})

z (m)

FM Wall Flames, CH\textsubscript{4}, 10.6 g/m\textsuperscript{2}/s

Heat Flux (kW/m\textsuperscript{2})

z (m)

FM Wall Flames, C\textsubscript{2}H\textsubscript{6}, 10.2 g/m\textsuperscript{2}/s

Heat Flux (kW/m\textsuperscript{2})

z (m)
Additional Modeling Results
FM Global

T Similarity

Temperature [K] vs. $Y$ [m]

Temperature [K] vs. $Y/\delta_{soot}$

Temperature [K] vs. $Y/\delta_{T=1000K}$

Symbols indicate different $Z$ values:
- $Z = 0.57$ m
- $Z = 0.67$ m
- $Z = 0.77$ m
- $Z = 0.87$ m
- $Z = 0.97$ m
T and U Fluctuation
Blowing Effect

Convective Heat Flux [kW/m²] vs. Z [m]

- 8.8 g/m²/s
- 17.1 g/m²/s
- 29.3 g/m²/s

Burner
Inert wall

Convective Heat Flux [kW/m²] vs. Z [m]

- 1 mm
- 1.5 mm
- 3 mm
- 10 mm
- 15 mm

Burner
Inert wall
Convective Heat Flux

- Wall function implication
  - Blowing effect controls the heat flux in the pyrolysis region
  - Flaming non-pyrolysis region has constant convective heat flux
  - Plume region should have reduced heat flux depending on T, and wall function should account for grid size automatically

- Should compare convection and radiation separately with other models
Combustion Model

- Eddy Dissipation Concept (EDC model)
  - Mixing controlled reaction

\[
\dot{\omega}_F = \frac{\bar{\rho}}{\min(\tau_T/C_T, \tau_d/C_d)} \min\left(\tilde{Y}_F, \frac{\tilde{Y}_{O_2}}{r_s}\right)
\]

\[
\tau_T = \frac{k_{sgs}}{\varepsilon_{sgs}} \sim \frac{\Delta}{k_{sgs}}^{1/2}
\]

\[
\tau_d = \frac{\Delta^2}{\alpha}
\]

require adequate near wall turbulence model!

Turbulence reaction rate
Diffusion reaction rate
Turbulence Model

Smagorinsky model

\[ \mu_{sgs} = \rho (C_s \Delta)^2 \left( 2 \overline{S_{ij} S_{ij}} \right)^{1/2} \]

\[ \overline{S_{ij}} = \frac{1}{2} \left( \frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) \]

Two deficiencies:
1. Laminar region with pure shear
2. Wrong scaling at near wall region
   O(1) instead of O(y^3)

WALE* model

Wall adaptive local eddy-viscosity

\[ \mu_{sgs} = \rho (C_w \Delta)^2 \frac{\left( S_{ij}^d S_{ij}^d \right)^{3/2}}{\left( \overline{S_{ij} S_{ij}} \right)^5} + \frac{\left( S_{ij}^d S_{ij}^d \right)^{5/4}}{\left( \overline{S_{ij} S_{ij}} \right)^{5/4}} \]

Zero for pure shear flow

O(y^3) near wall scaling

\[ S_{ij}^d = \overline{S_{ik} S_{kj}} + \Omega_{ik} \Omega_{kj} - \frac{1}{3} \delta_{ij} \left( \overline{S_{mn} S_{mn}} - \Omega_{mn} \Omega_{mn} \right) \]

\[ \overline{S_{ij}} = \frac{1}{2} \left( \frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right), \quad \Omega_{ij} = \frac{1}{2} \left( \frac{\partial \overline{u_i}}{\partial x_j} - \frac{\partial \overline{u_j}}{\partial x_i} \right) \]

Wall-Adaptive Local Eddy Viscosity

SM Model

WALE Model

![Graph showing comparison between SM and WALE models](image)

- SM Model
- WALE Model

- Graph showing comparison between SM and WALE models.
Summary

- Grid Requirement
  - $O(2-3\text{mm})$
  - Capable to directly calculate convective heat flux
  - Blowing effect reduces resolution requirement

- Near-wall turbulence model and combustion model important for HRR and T distribution
  - Model can be grid dependent
Summary (cont’d)

- Wall heat flux prediction sensitive to model choices
  - Over prediction of heat flux for soot yield and wide band radiation model
  - Separating convection/radiative heat flux, also soot and gas radiation contributions should help understand model deficiency

- Wall function might be simplified recognizing constant convective heat flux in the flaming region
Discussions