# **Turbulent Wall Fire**



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### Wall Fire – A Canonical Problem





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## Scope: Wall Fire Heat Transfer



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## Outline

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

# Experiments –

(J. de Ris et al., FM report, 1999) (J. de Ris et al., Proc. 7<sup>th</sup> IAFSS, 2002) (N. Ren et al., C&F 2015)

- Porous vertical burners
  - Propylene
  - Methane
  - Ethane
- Water cooled vertical wall



# Experiments –

(J. de Ris et al., FM report, 1999) (J. de Ris et al., Proc. 7<sup>th</sup> IAFSS, 2002) (N. Ren et al., C&F 2015)

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



### Soot Depth



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

### Temperature



### Radiance



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

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

1

2

3

5

6

7

8

9

2.0

### Heat Fluxes



de Ris et al. (Unpublished)



### 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 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 – 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
  - $-\Delta Y \sim 3 \text{ mm} \Delta X \sim 7.5 \text{ mm}, \Delta Z \sim 7.7 \text{ mm}$
  - 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 °C
  - Fixed flow rates with turbulent fluctuations
    - 8.8, 12.7, 17.1, 22.4 g/m<sup>2</sup>s
- Schemes:
  - 2<sup>nd</sup> order fully implicit





# Grid Convergence





### Natural Convection, High Gr Number



### Grid Requirement

 High Re, momentum driven flow (Piomelli et al., 2002)

$$\delta_{VSL} \approx \frac{V_w}{\left(\tau_w / \rho_w\right)^{1/2}} \approx 0.2mm$$

 High Grashof, natural convection (Holling et al., 2005)

$$\delta_{VSL} \approx \frac{(V_w / \Pr)^{3/4}}{(\dot{q}_{w,c}'' / \rho_w c_{p,w})^{1/4} (g\beta)^{1/4}} \approx 0.5mm$$

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



### Grid Convergence - FireFOAM





### Grid Convergence - FireFOAM





## 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





### Radiation Model – FireFOAM

- Fixed radiant fraction
- Finite volume implementation of Discrete
  Ordinate Method (fvDOM)
- Optically thin assumption



Soot/gas blockage (χ<sub>rad</sub> is reduced by 25%)

Fuel	Methane CH₄	Ethane C <sub>2</sub> H <sub>6</sub>	Ethylene C <sub>2</sub> H <sub>4</sub>	Propylene C <sub>3</sub> H <sub>6</sub>	
Wall Fire (de Ris measurement)	15%	17%	24%	32%	
Simulation (account for blockage)	12%	13%	18%	25%	

### 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.

	Radiative Fraction				
Fuel	Tewarson (SFPE Handbook)	FDS Prediction			
Ethane	0.25	0.31			
Ethylene	0.34	0.38			
Methane	0.14	0.22			
Propylene	0.37	0.39			

ω (1/cm)	10000	3800 34	00 24	00 21	74 10	00 50
6 Band Model	1	2	3	4	5	6
Major Species	Soot CO <sub>2</sub> , H <sub>2</sub> O	$\begin{array}{c} \text{CO}_2\\ \text{H}_2\text{O}, \text{Soot} \end{array}$	CH <sub>4</sub> Soot	CO <sub>2</sub> Soot	H <sub>2</sub> O,CH <sub>4</sub> Soot	H <sub>2</sub> O CO <sub>2</sub>
λ (µm)	1.00	2.63 2.	94 4.1	4.7	70 10	.0 200

Table 6.1: Limits of the spectral bands for methane (CH<sub>4</sub>).

#### Table 6.2: Limits of the spectral bands for ethane (C<sub>2</sub>H<sub>6</sub>).

ω (1/cm)	10000	3800 33	350 255	50 165	50 109	90 50
6 Band Model	1	2	3	4	5	6
Major Species	Soot	CO <sub>2</sub>	C <sub>2</sub> H <sub>6</sub>	CO <sub>2</sub>	C <sub>2</sub> H <sub>6</sub>	H <sub>2</sub> O
Major species	CO <sub>2</sub> , H	$_2O$ H <sub>2</sub> O, Soot	Soot	CO, H <sub>2</sub> O, Soot	H <sub>2</sub> O, Soot	$CO_2, C_2H_6$
$\lambda$ ( $\mu$ m)	1.00	2.63 2.	99 3.9	2 6.0	6 9.1	7 200

Table 6.3: Limits of the spectral bands for ethylene (C<sub>2</sub>H<sub>4</sub>).

	ω (1/cm)	1000	0 380	00 337	75 280	00 165	50 780	) 50
	6 Band Model		1	2	3	4	5	6
	Major Spacias		Soot	CO <sub>2</sub>	C <sub>2</sub> H <sub>4</sub>	CO <sub>2</sub>	$C_2H_4$	H <sub>2</sub> O
Major 5	Major species	0	$CO_2, H_2O$	H <sub>2</sub> O, Soot	Soot	CO, H <sub>2</sub> O, Soot	H <sub>2</sub> O, Soot	CO <sub>2</sub>
	$\lambda$ (µm)	1.00	2.6	3 2.9	6 3.5	7 6.0	6 12.	82 200

Table 6.4: Limits of the spectral bands for propylene (C<sub>3</sub>H<sub>6</sub>).

	ω (1/cm)	100	000 380	00 325	50 260	00 195	50 117	75 50
	6 Band Model		1	2	3	4	5	6
	Major Species		Soot	CO <sub>2</sub>	C <sub>3</sub> H <sub>6</sub>	CO <sub>2</sub>	C <sub>3</sub> H <sub>6</sub>	$C_3H_6$ , $H_2O$
			$CO_2, H_2O$	H <sub>2</sub> O, Soot	Soot	CO, Soot	H <sub>2</sub> O, Soot	CO <sub>2</sub>
	λ (µm)	1.0	0 2.6	3 3.0	8 3.8	5 5.1	3 8.5	1 200

### **Convective and Radiative Heat Flux**







### Thermocouple (T.C.) Temperature

- Gas temperature measurement
  - Fluctuation
  - Radiation
- Numerical description of thermocouple temperature
  - Thermocouple Model

$$\rho_{Tc}C_{Tc}\frac{V_{Tc}}{A_{Tc}}\frac{dT_{Tc}}{dt} = \varepsilon_{Tc}\left(G - \sigma T_{Tc}^{4}\right) + h\left(T_{g} - T_{Tc}\right)$$







# Additional Modeling Results





### **Blowing Effect**



### **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



 $R = \frac{\tau_d / C_d}{1 + C_d}$ 

 $\tau_t / C_{EDC}$ 

E0.75

E0.5

E0.25

0

# **Turbulence Model**

### Smagorinsky model

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

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

Two deficiencies:

- 1. Laminar region with pure shear
- Wrong scaling at near wall region O(1) instead of O(y<sup>3</sup>)

### WALE\* model

Wall adaptive local eddy-viscosity Zero for pure shear flow

$$\mu_{sgs} = \rho (C_{w} \Delta)^{2} \underbrace{\left( \underbrace{S_{ij}^{d} S_{ij}^{d}}_{ij} \right)^{5/2}}_{\left( \underbrace{\overline{S_{ij}} \overline{S_{ij}}}_{ij} \right)^{5/2} + \left( \underbrace{S_{ij}^{d} S_{ij}^{d}}_{ij} \right)^{5/4}}_{\bullet}$$

O(y<sup>3</sup>) near wall scaling

$$\begin{vmatrix} S_{ij}^{d} = \overline{S_{ik}} \overline{S_{kj}} + \overline{\Omega_{ik}} \overline{\Omega_{kj}} - \frac{1}{3} \delta_{ij} \left( \overline{S_{mn}} \overline{S_{mn}} - \overline{\Omega_{mn}} \overline{\Omega_{mn}} \right) \\ \overline{S_{ij}} = \frac{1}{2} \left( \frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right), \qquad \overline{\Omega_{ij}} = \frac{1}{2} \left( \frac{\partial \overline{u_i}}{\partial x_j} - \frac{\partial \overline{u_j}}{\partial x_i} \right)$$

\* Nicoud, Ducros, Flow Turb. Combst. 1999



### Summary

- Grid Requirement
  - O(2-3mm)
  - Capable to direct 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

