Turbulent Wall Fire

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Measurement and Computation of Fire Phenomena – MaCFP
Lund University, 06/10/2017

Contributors

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Wall Fire – A Canonical Problem

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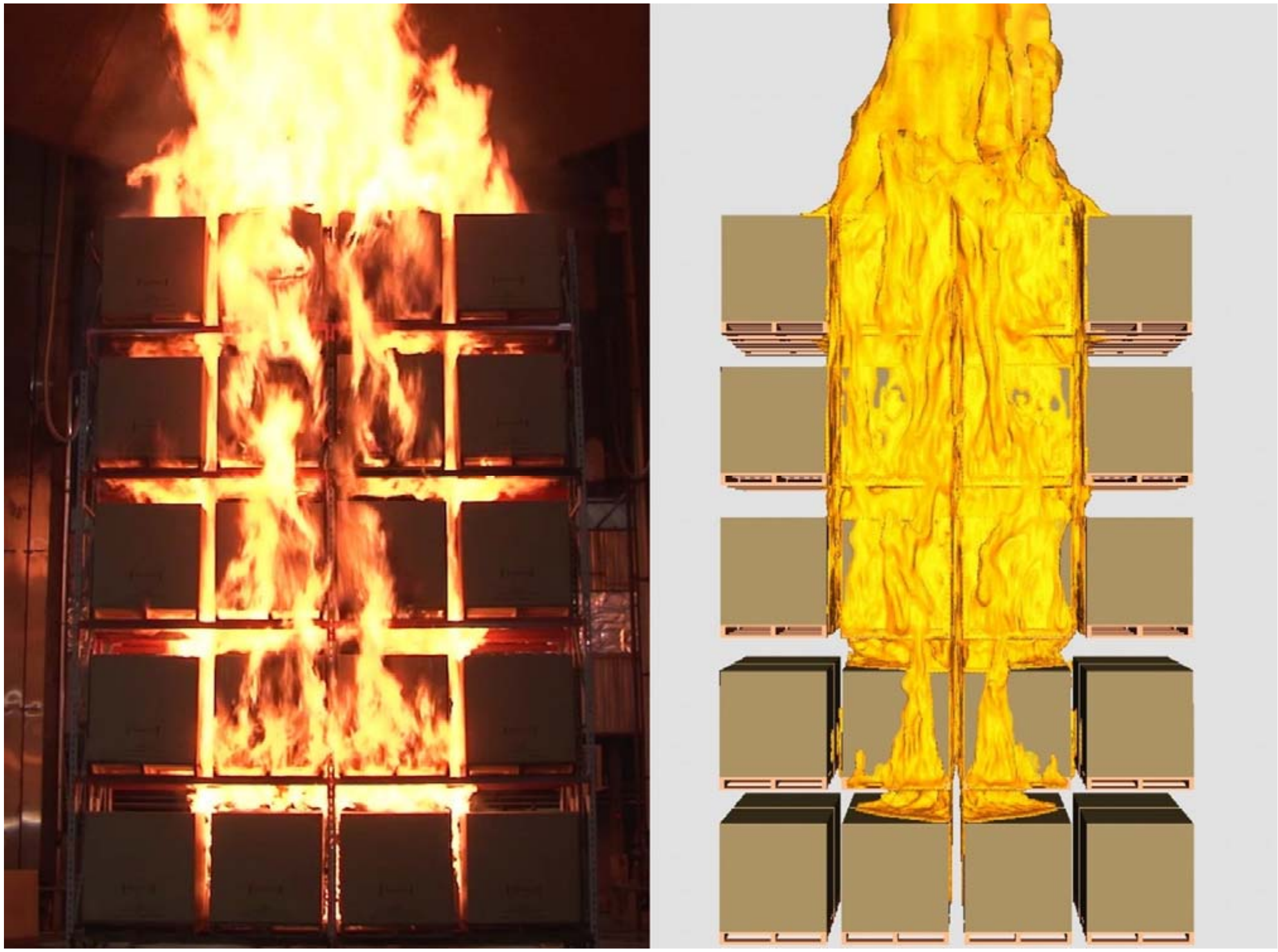
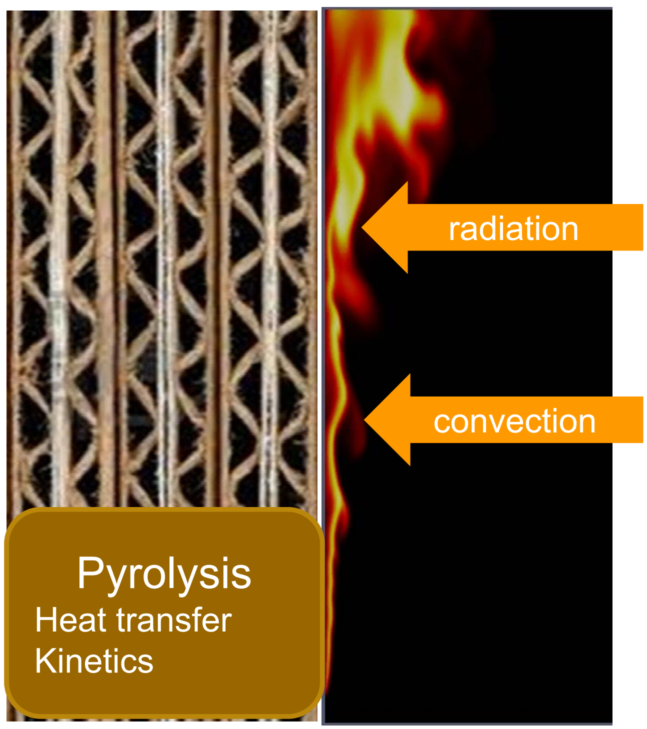
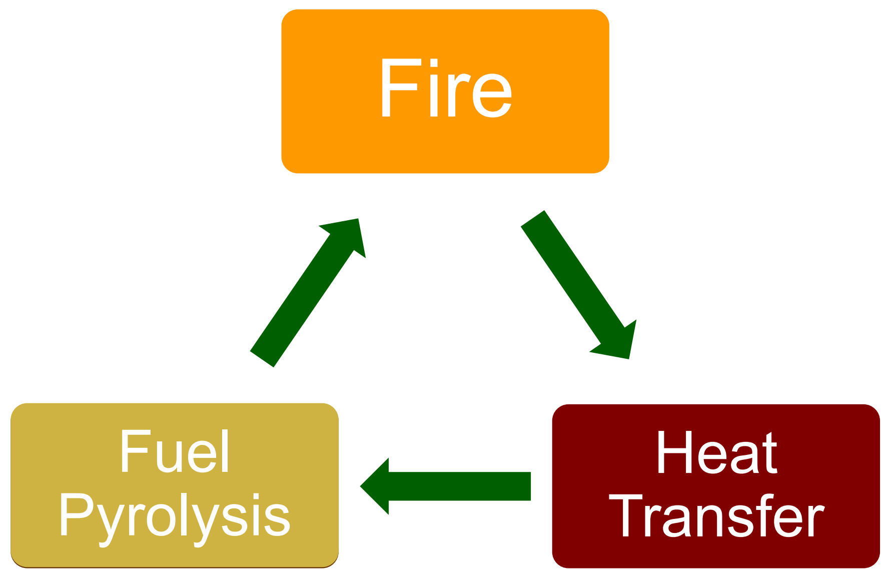


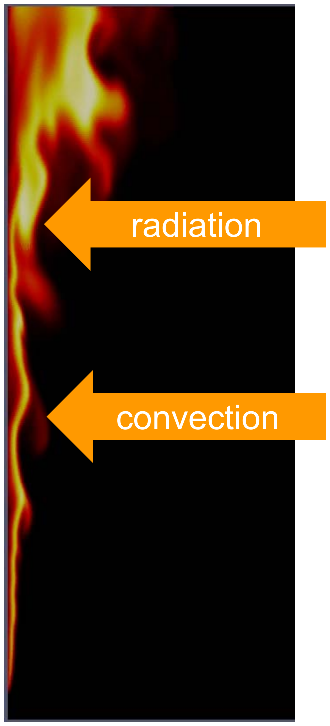
Wall Fire – A Canonical Problem

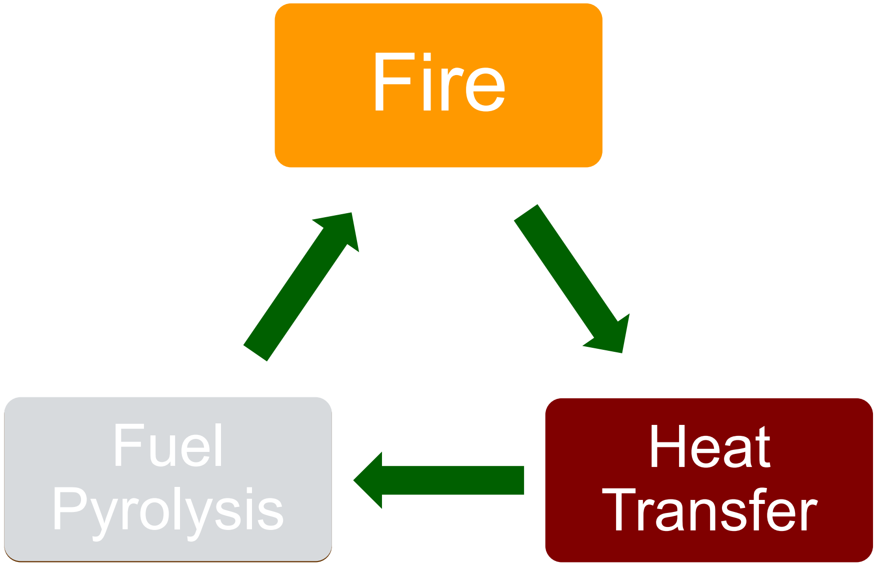
Scope: Wall Fire Heat Transfer





Scope: Wall Fire Heat Transfer



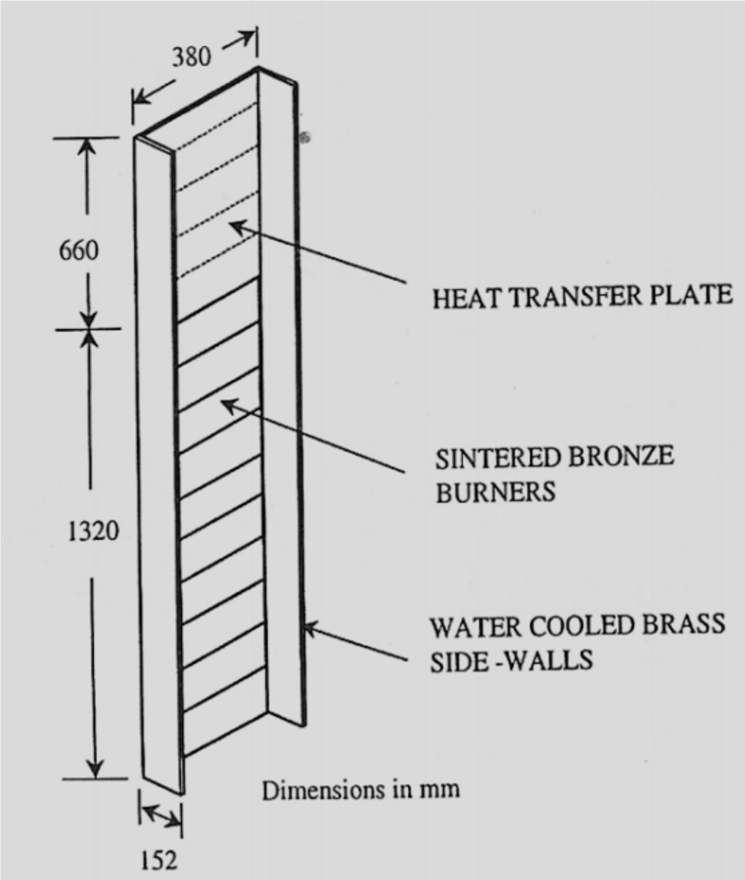


Outline

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

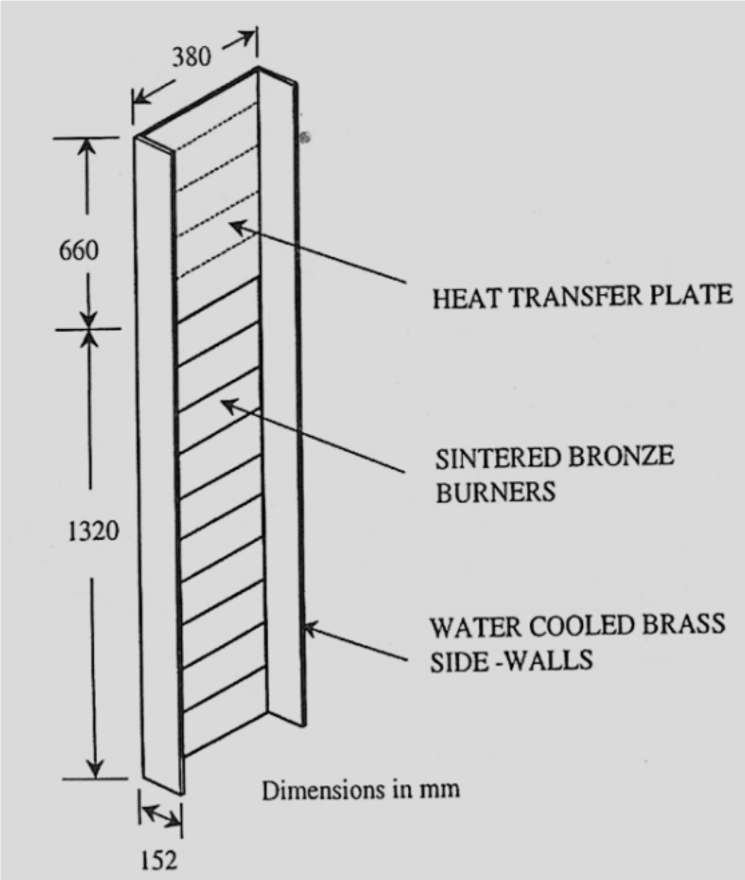
Experiments – (J. de Ris et al., FM report, 1999) (J. de Ris et al., Proc. 7th IAFSS, 2002) (N. Ren et al., C&F 2015)

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

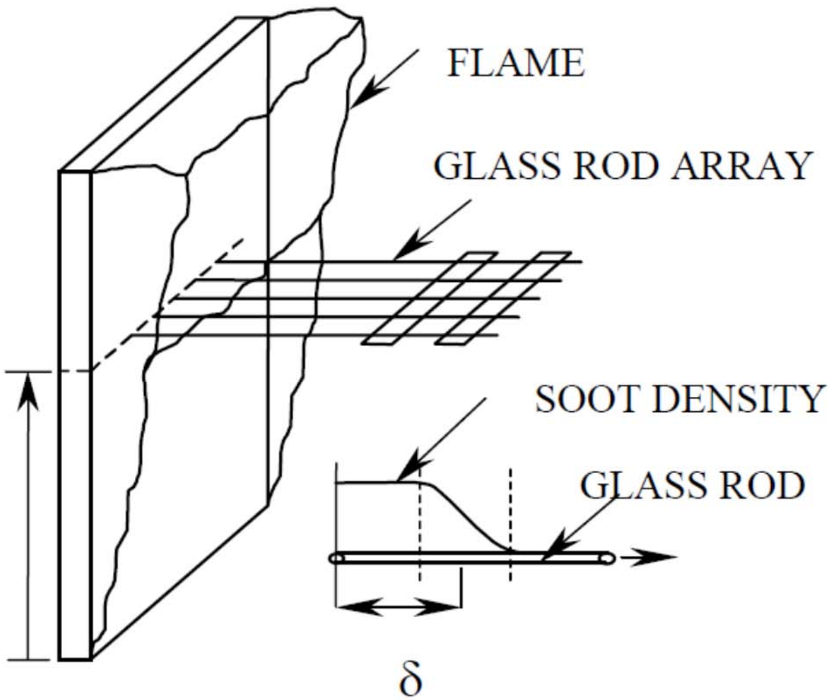


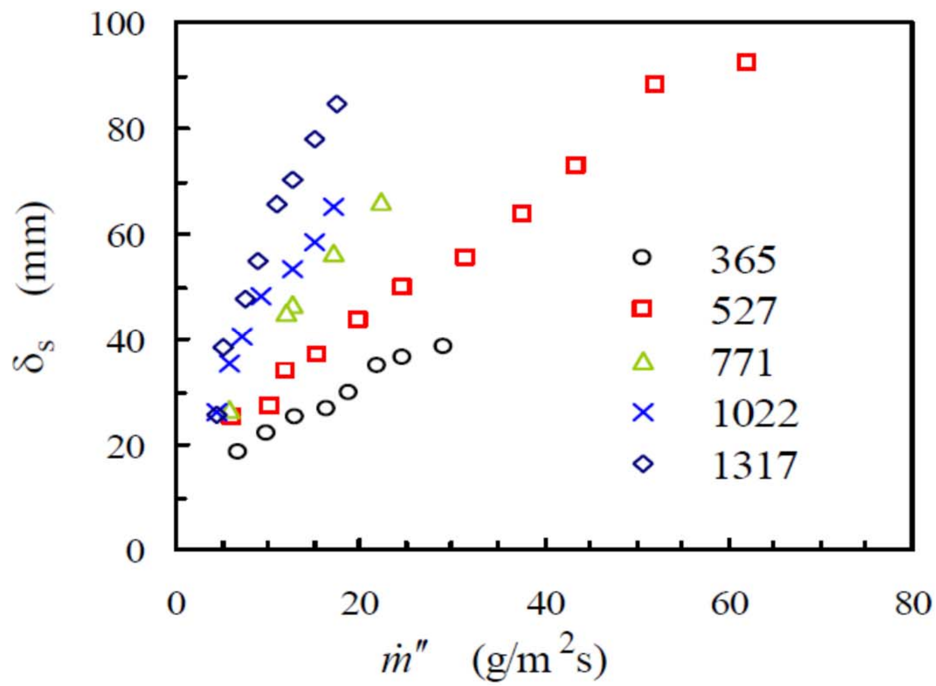
Experiments – (J. de Ris et al., FM report, 1999) (J. de Ris et al., Proc. 7th IAFSS, 2002) (N. Ren et al., C&F 2015)

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



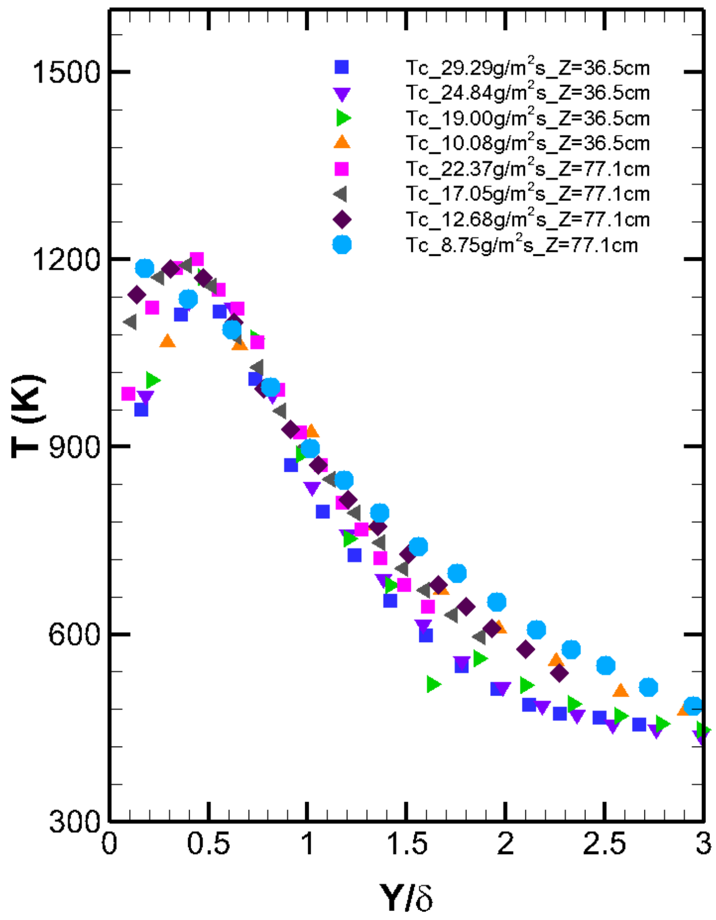
Soot Depth



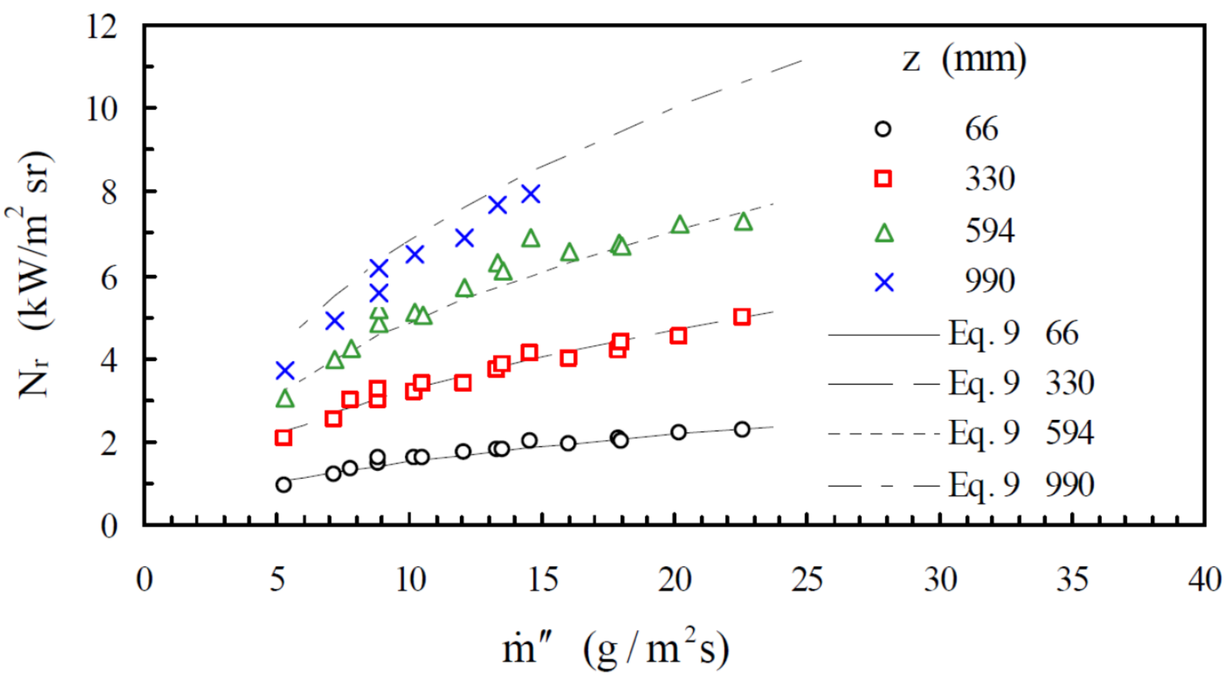


Measured soot depth vs. fuel mass transfer at different heights (mm)

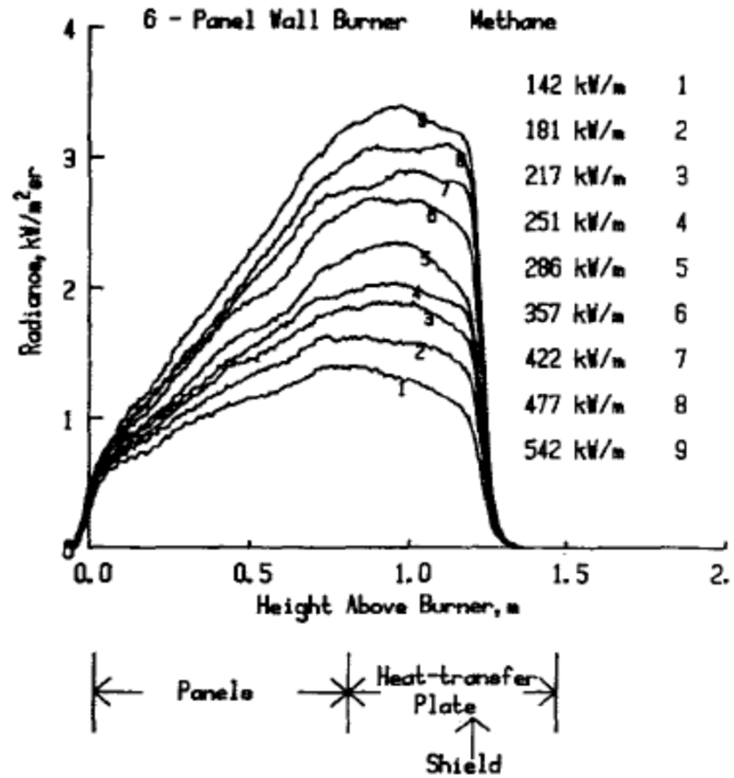
Temperature



Radiance



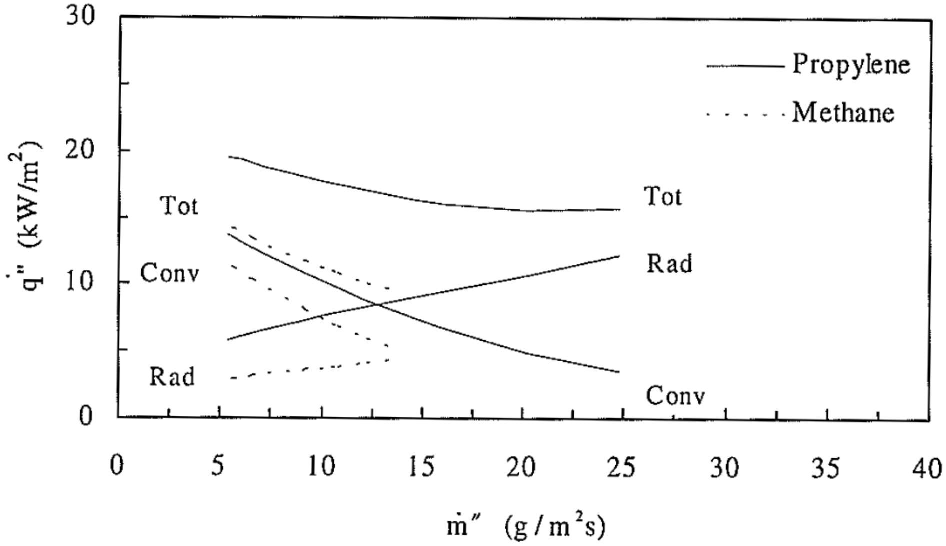
De Ris, et. al, 2003, Fire Safety Science



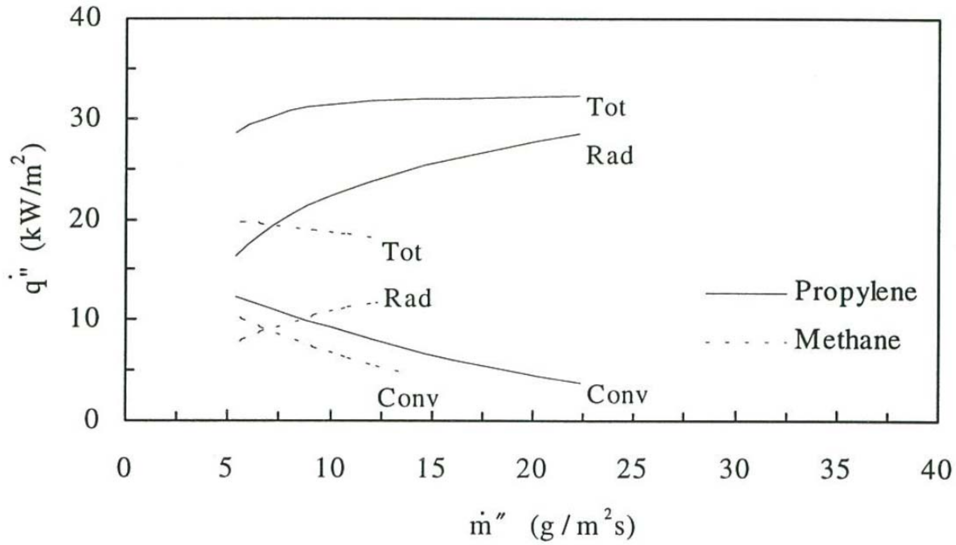
Outward radiance normal to the burner surface

Markstein & de Ris (1992)

Heat Fluxes



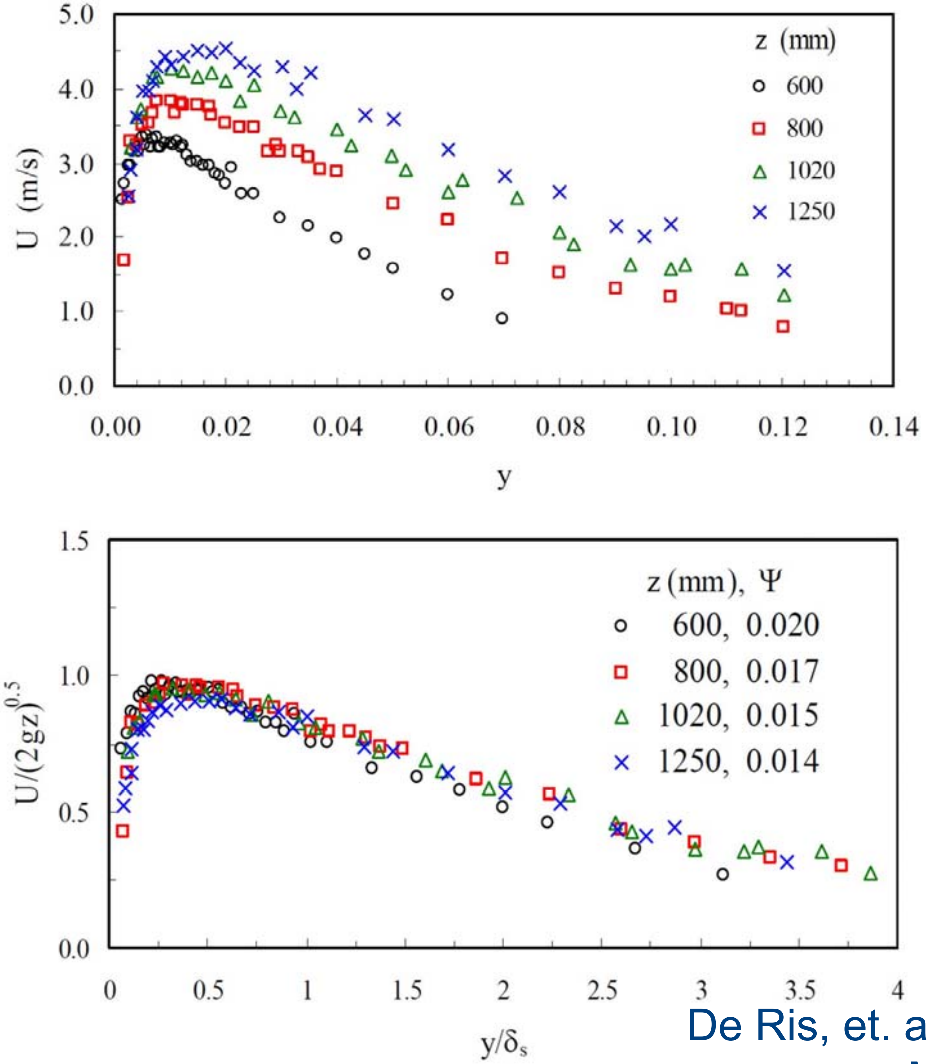
Small wall-fire: z = 198 mm



Large wall-fire: z = 990 mm

de Ris et al. (Unpublished)

Velocity



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

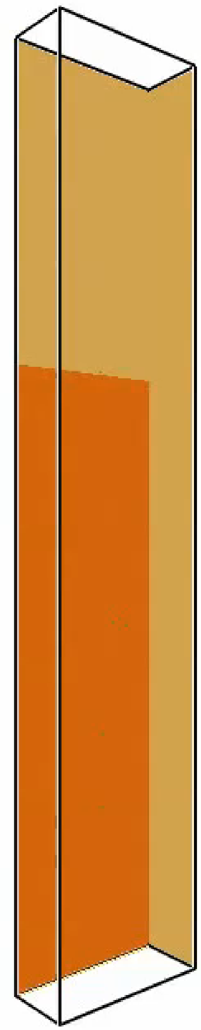
Modeling

Modeling Choices

- Mesh resolution
- Convection treatment: wall functions
- Radiation model
- Turbulence and combustion model

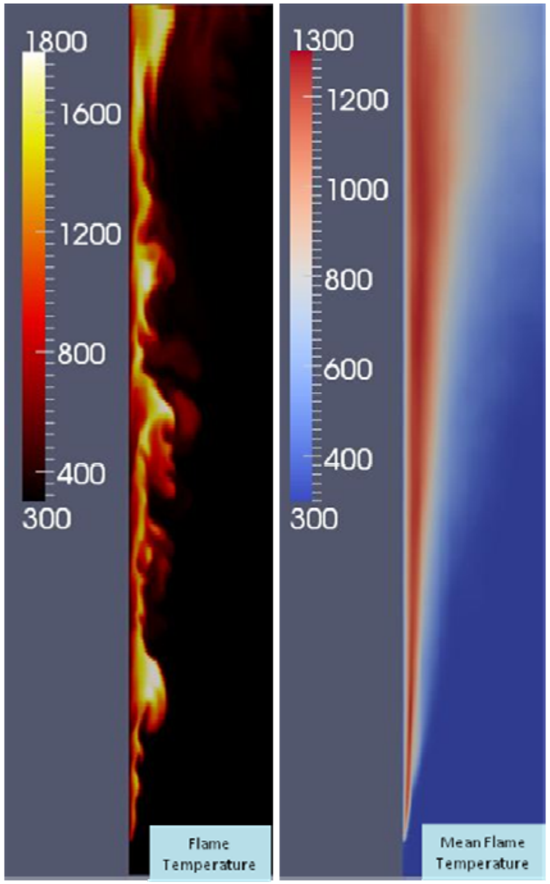
NIST – FDS 6.5.3

- 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



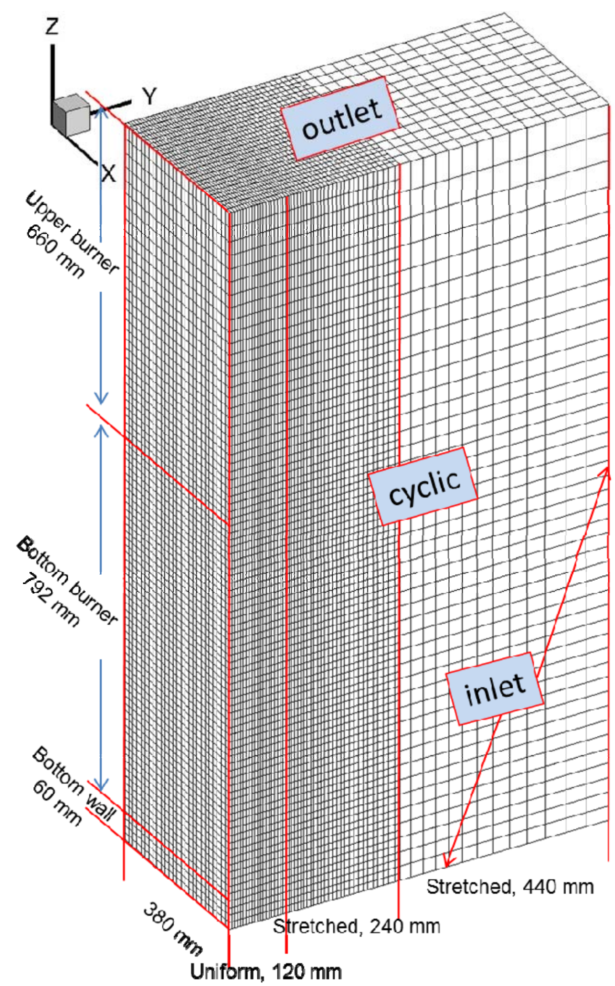
FM Global – FireFOAM 2.2.x

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



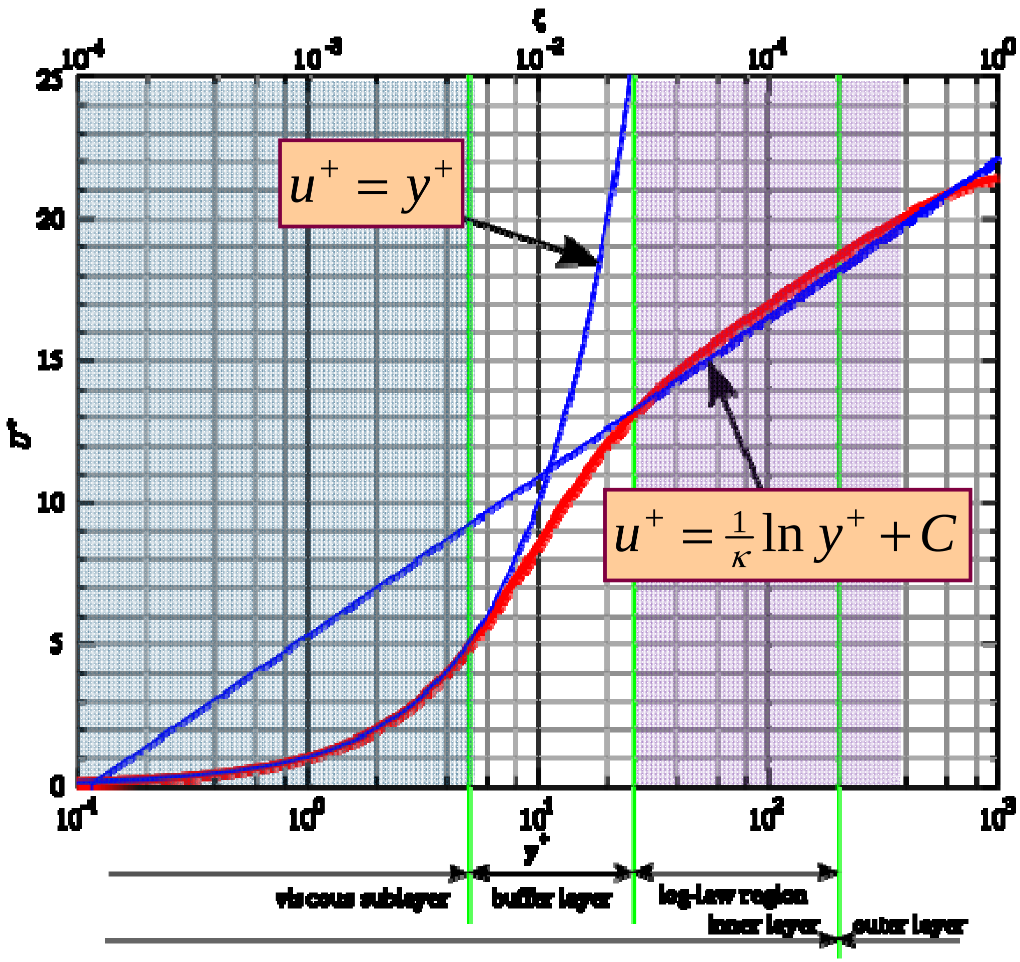
Mesh and B.C.

- Base line – 3 mm grid
  - ΔY ~ 3 mm ΔX ~ 7.5 mm, ΔZ ~ 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 ˚C
  - Fixed flow rates with turbulent fluctuations
    - 8.8, 12.7, 17.1, 22.4 g/m^{2}s
- Schemes:
  - 2nd order fully implicit



Grid Convergence

Law of the Wall: High Re

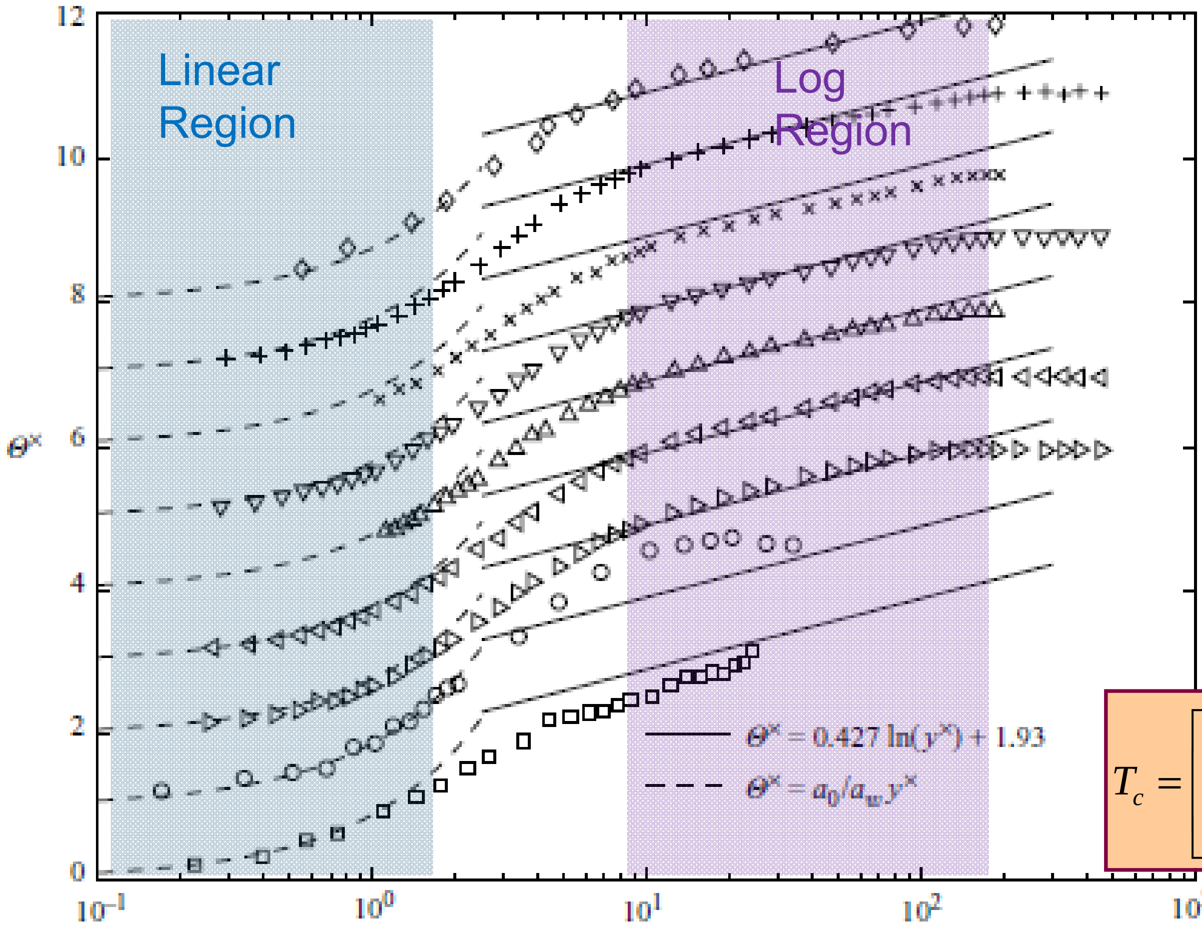


$$u^+ = \frac{u}{u_\tau}$$

$$y^+ = \frac{y u_\tau}{\nu}$$

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

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

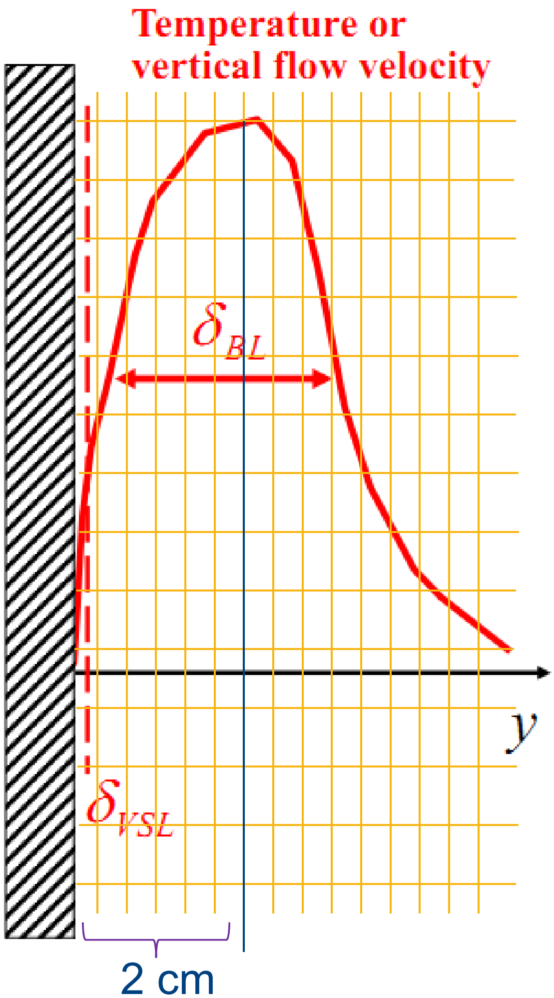
- High Re, momentum driven flow (Piomelli et al., 2002)

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

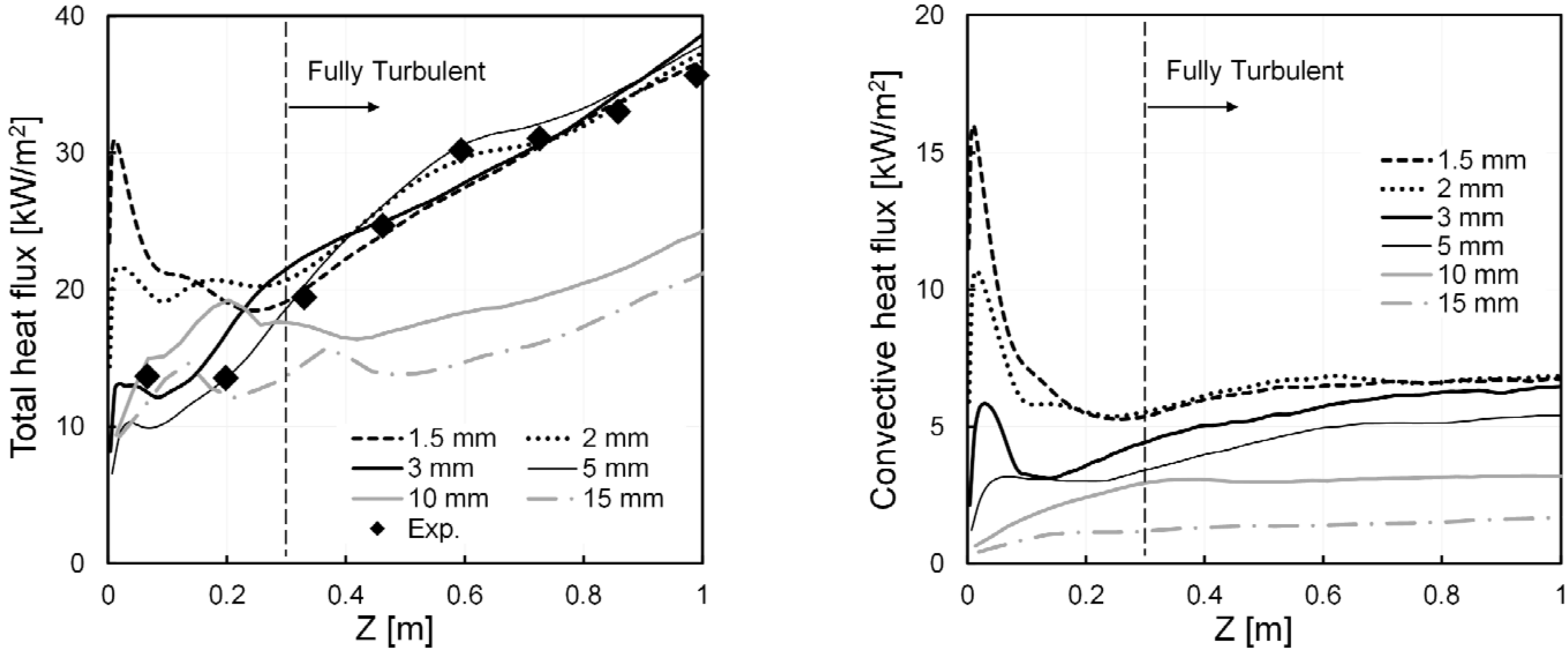
- High Grashof, natural convection (Holling et al., 2005)

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

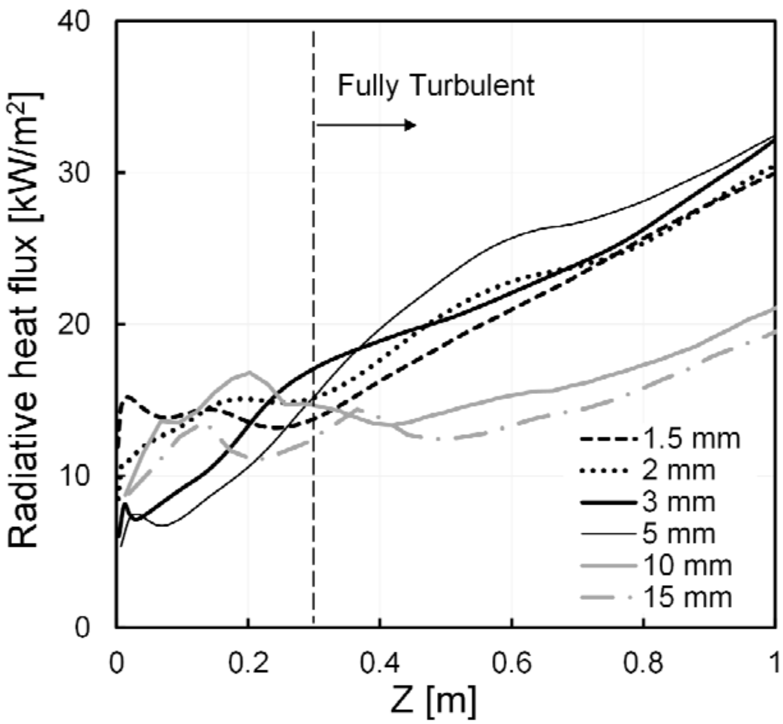
- Wall fire ?
  - 10-20 cells across the flame: 3mm to start



Grid Convergence - FireFOAM

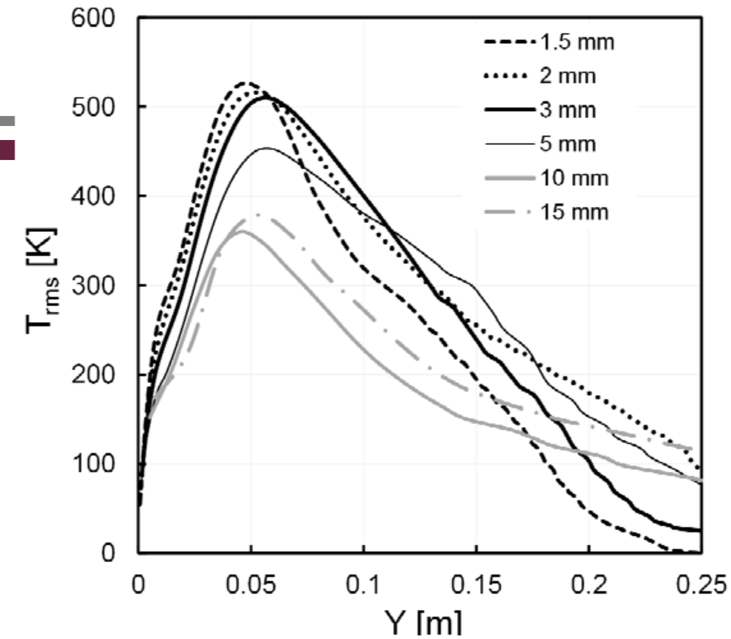


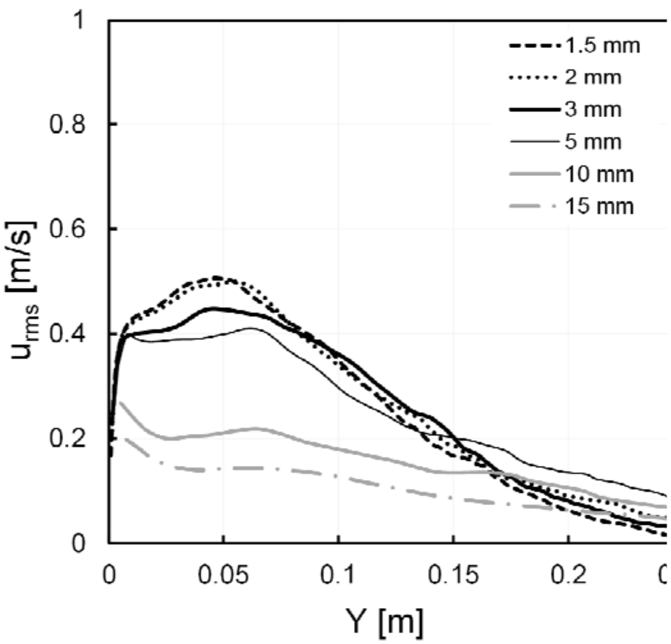
Grid Convergence - FireFOAM

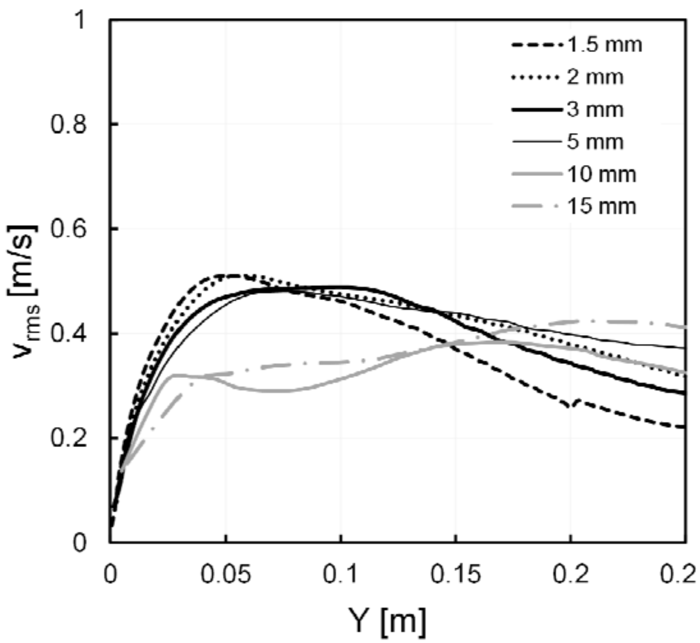


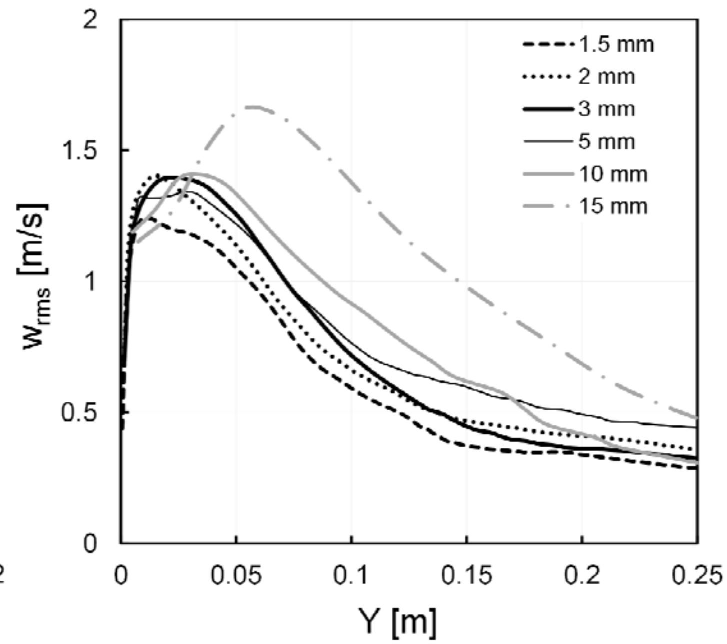
FM Global

Grid Convergence







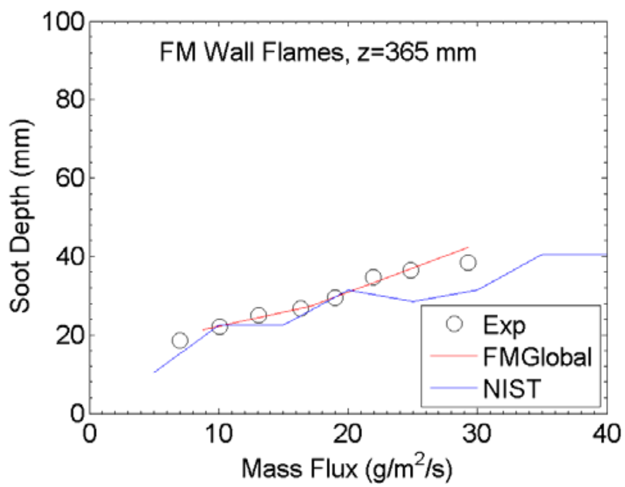


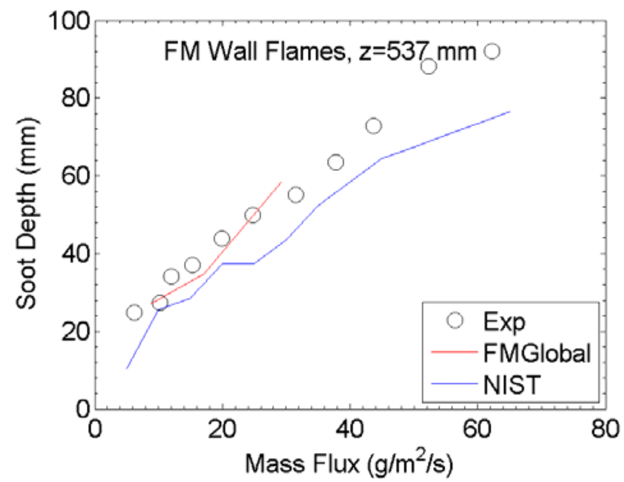
Grid Requirement

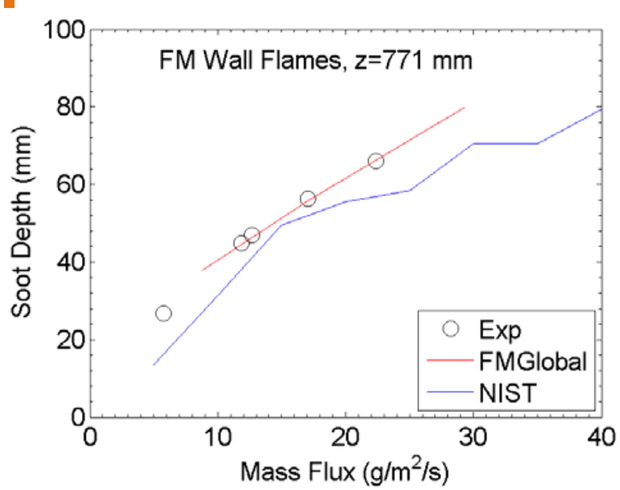
- Larger cell size than
  - Momentum driven shear flow
  - Buoyancy driven natural convection flow
- Because
  - Buoyancy and HRR take place in outer layer
  - Blowing effect

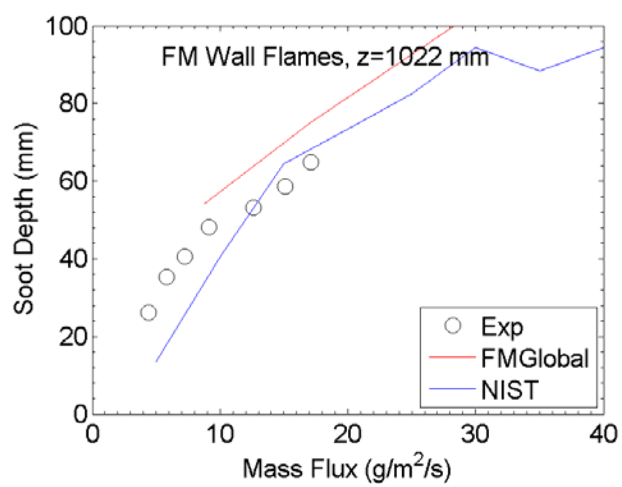
Model Comparison

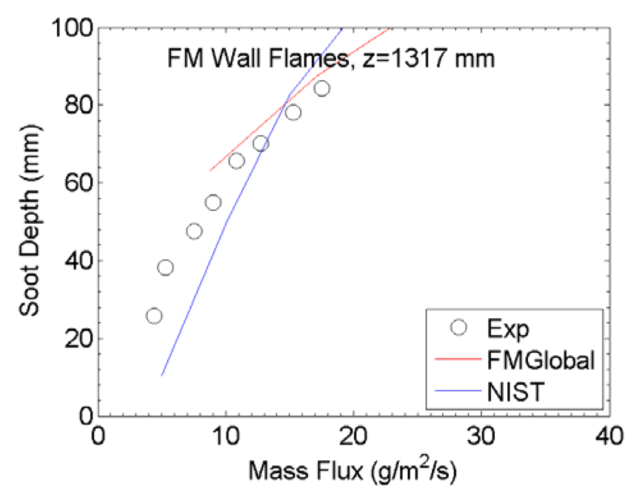
Soot Depth


FM Wall Flames, z=365 mm
Soot Depth (mm)
Mass Flux (g/m²/s)
Exp
FMGlobal
NIST

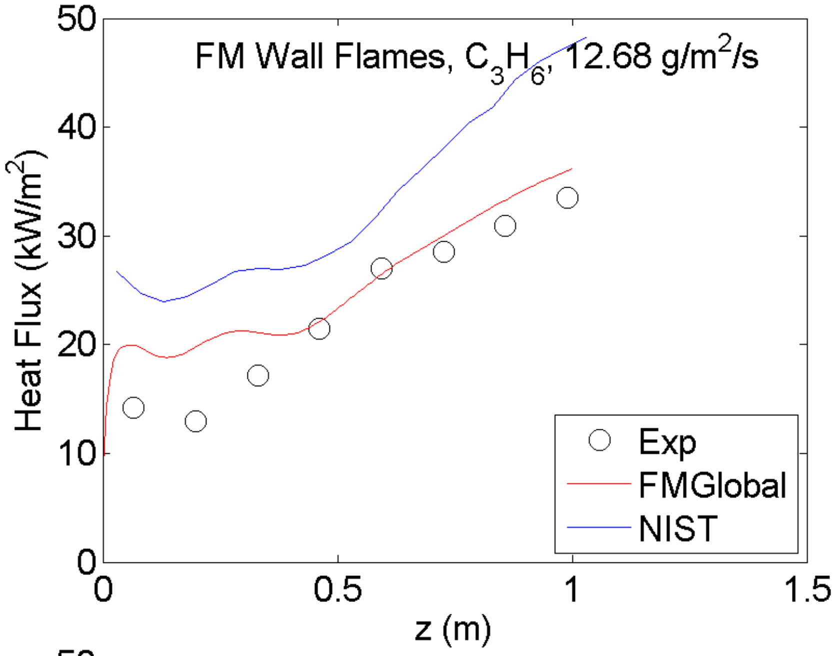

FM Wall Flames, z=537 mm
Soot Depth (mm)
Mass Flux (g/m²/s)
Exp
FMGlobal
NIST

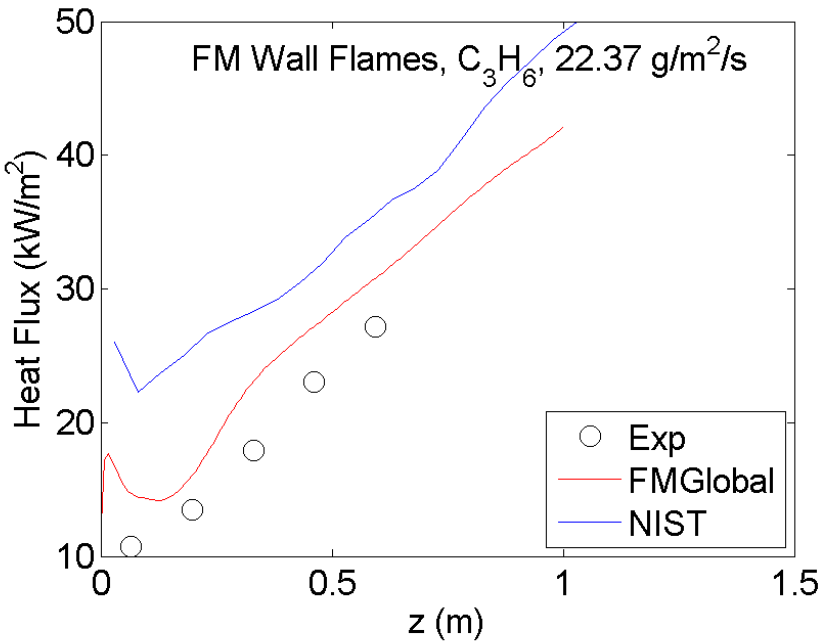

FM Wall Flames, z=771 mm
Soot Depth (mm)
Mass Flux (g/m²/s)
Exp
FMGlobal
NIST

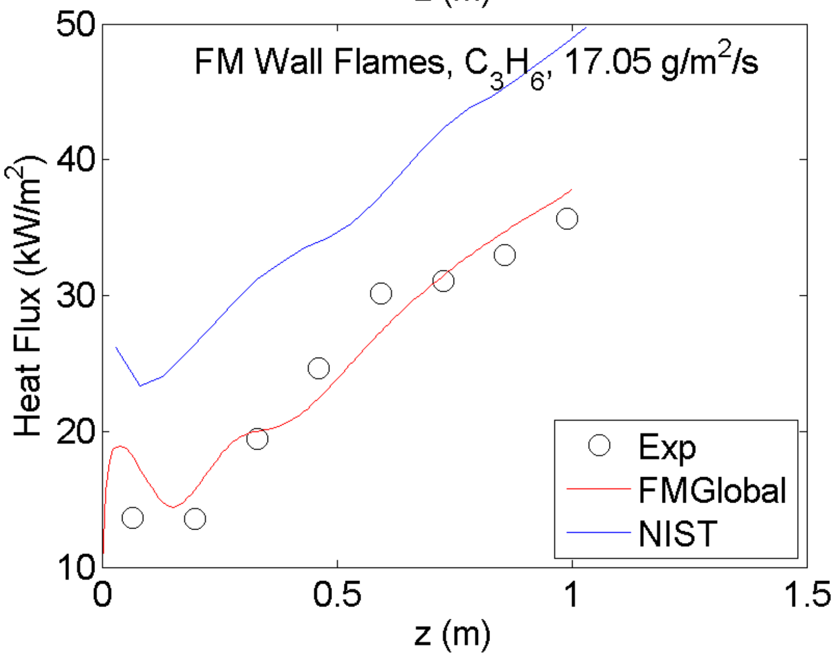

FM Wall Flames, z=1022 mm
Soot Depth (mm)
Mass Flux (g/m²/s)
Exp
FMGlobal
NIST


FM Wall Flames, z=1317 mm
Soot Depth (mm)
Mass Flux (g/m²/s)
Exp
FMGlobal
NIST

Total Heat Flux







Radiation Model – FireFOAM

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

$$\frac{dI}{ds} = \left(\frac{\chi_{rad}\,\dot{q}_c'''}{4\pi}\right)$$

Fuel	Methane CH_4	Ethane C_2H_6	Ethylene C_2H_4	Propylene C_3H_6
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.

Fuel	**Radiative Fraction**	
	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

Table 6.1: Limits of the spectral bands for methane (CH_4).

ω (1/cm): 10000 | 3800 | 3400 | 2400 | 2174 | 1000 | 50

6 Band Model	1	2	3	4	5	6
Major Species	Soot CO_2, H_2O	CO_2 H_2O, Soot	CH_4 Soot	CO_2 Soot	H_2O,CH_4 Soot	H_2O CO_2

λ (μm): 1.00 | 2.63 | 2.94 | 4.17 | 4.70 | 10.0 | 200

Table 6.2: Limits of the spectral bands for ethane (C_2H_6).

ω (1/cm): 10000 | 3800 | 3350 | 2550 | 1650 | 1090 | 50

6 Band Model	1	2	3	4	5	6
Major Species	Soot CO_2, H_2O	CO_2 H_2O, Soot	C_2H_6 Soot	CO_2 CO, H_2O, Soot	C_2H_6 H_2O, Soot	H_2O CO_2, C_2H_6

λ (μm): 1.00 | 2.63 | 2.99 | 3.92 | 6.06 | 9.17 | 200

Table 6.3: Limits of the spectral bands for ethylene (C_2H_4).

ω (1/cm): 10000 | 3800 | 3375 | 2800 | 1650 | 780 | 50

6 Band Model	1	2	3	4	5	6
Major Species	Soot CO_2, H_2O	CO_2 H_2O, Soot	C_2H_4 Soot	CO_2 CO, H_2O, Soot	C_2H_4 H_2O, Soot	H_2O CO_2

λ (μm): 1.00 | 2.63 | 2.96 | 3.57 | 6.06 | 12.82 | 200

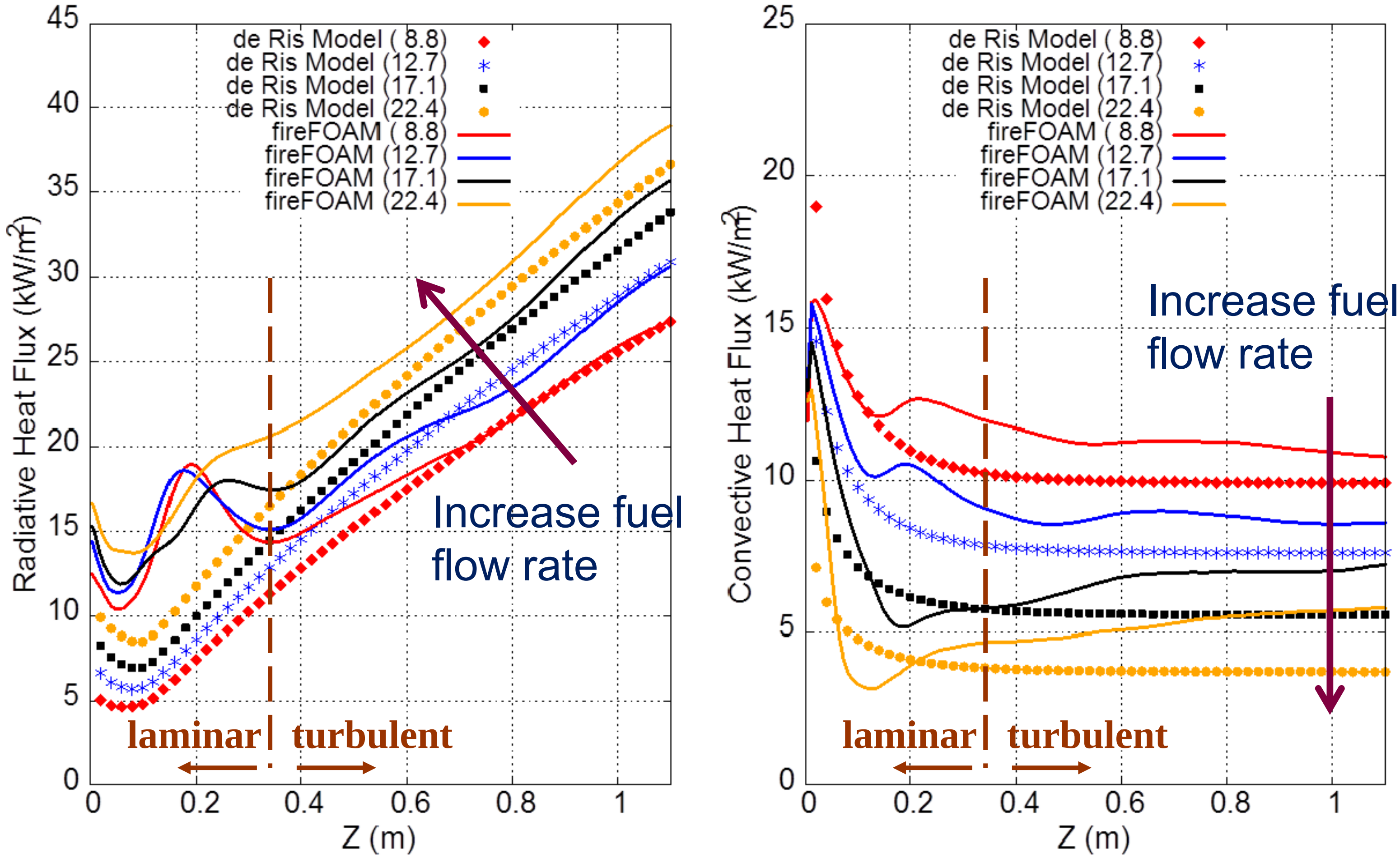
Table 6.4: Limits of the spectral bands for propylene (C_3H_6).

ω (1/cm): 10000 | 3800 | 3250 | 2600 | 1950 | 1175 | 50

6 Band Model	1	2	3	4	5	6
Major Species	Soot CO_2, H_2O	CO_2 H_2O, Soot	C_3H_6 Soot	CO_2 CO, Soot	C_3H_6 H_2O, Soot	C_3H_6, H_2O CO_2

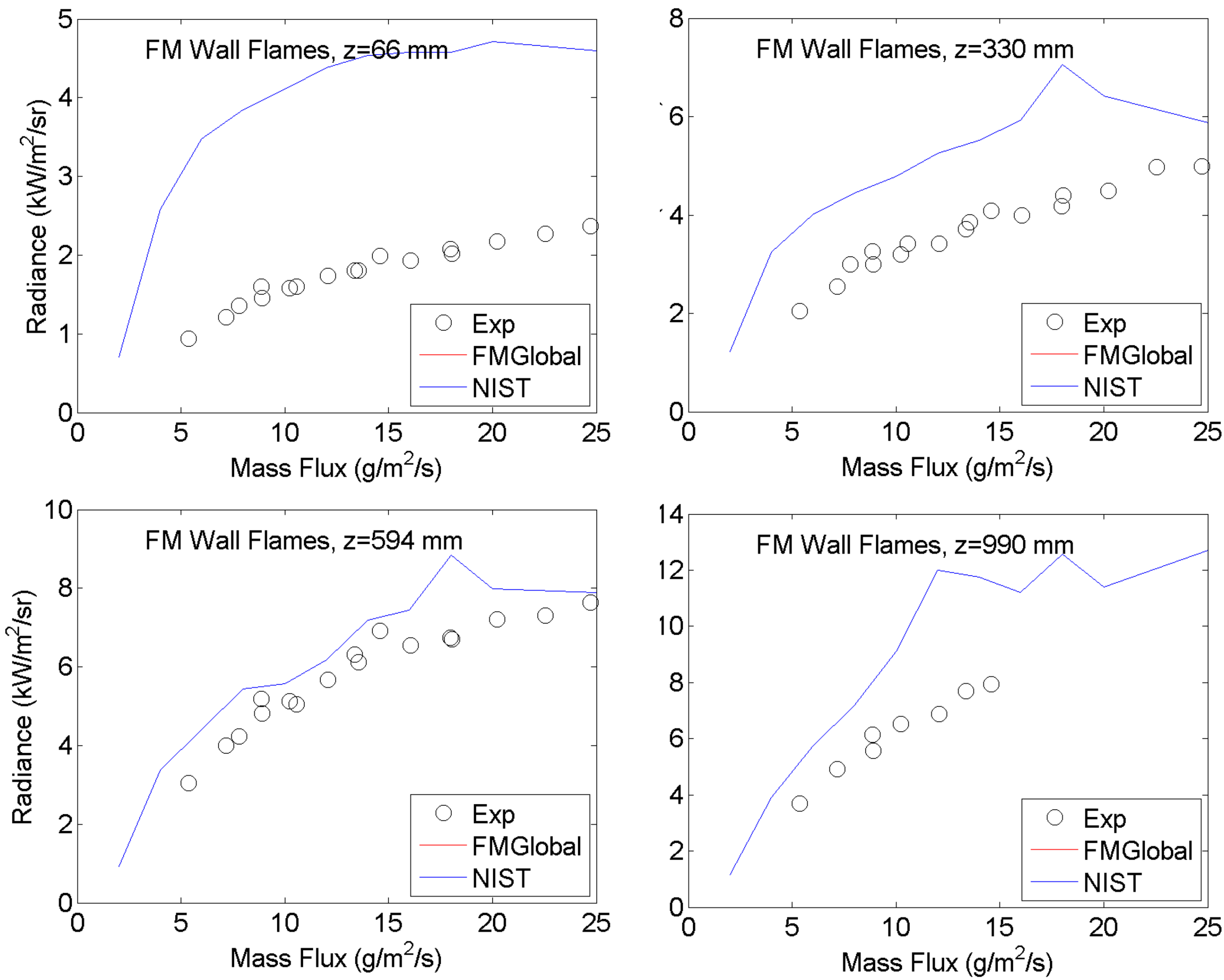
λ (μm): 1.00 | 2.63 | 3.08 | 3.85 | 5.13 | 8.51 | 200

Convective and Radiative Heat Flux

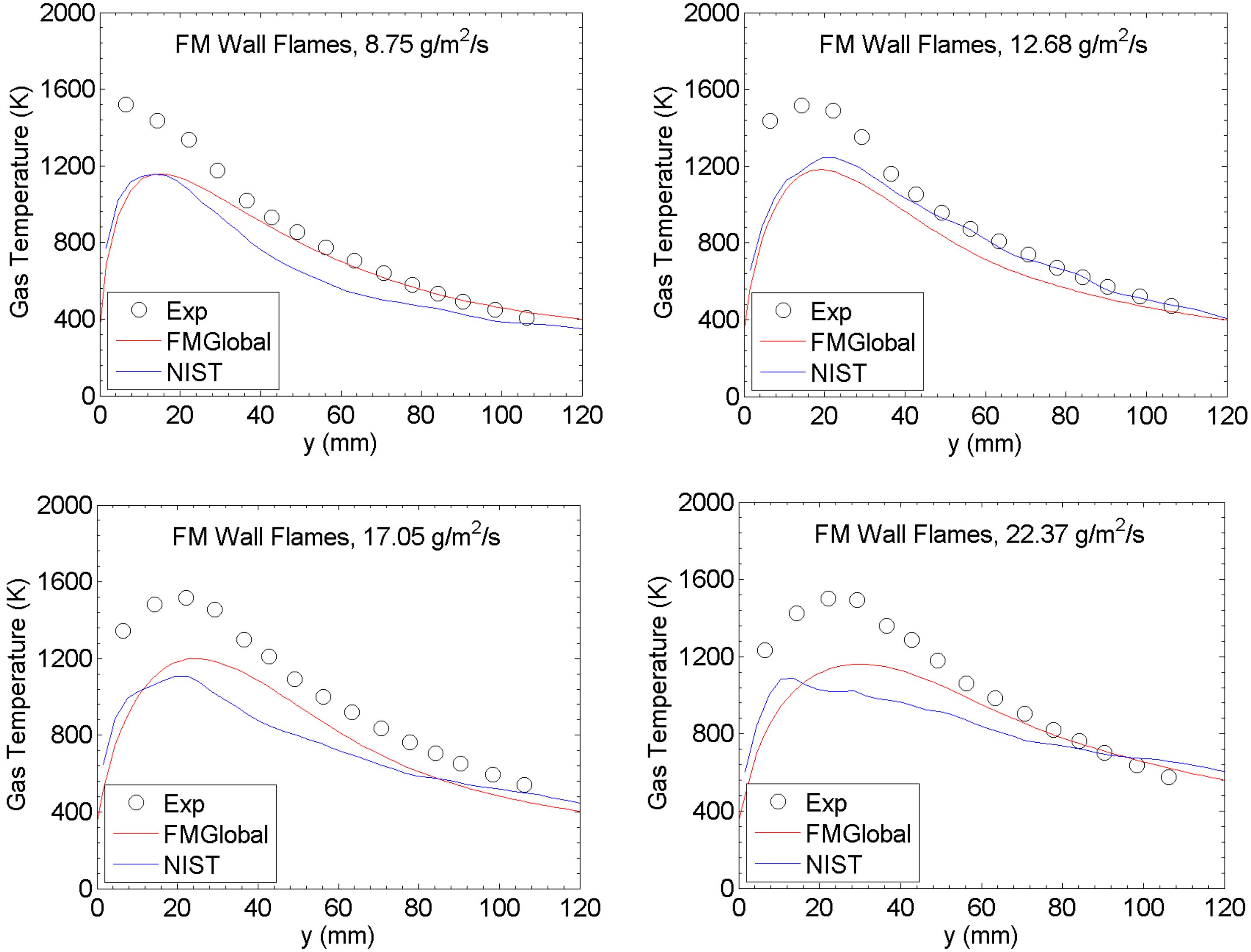


FM Global

Radiance



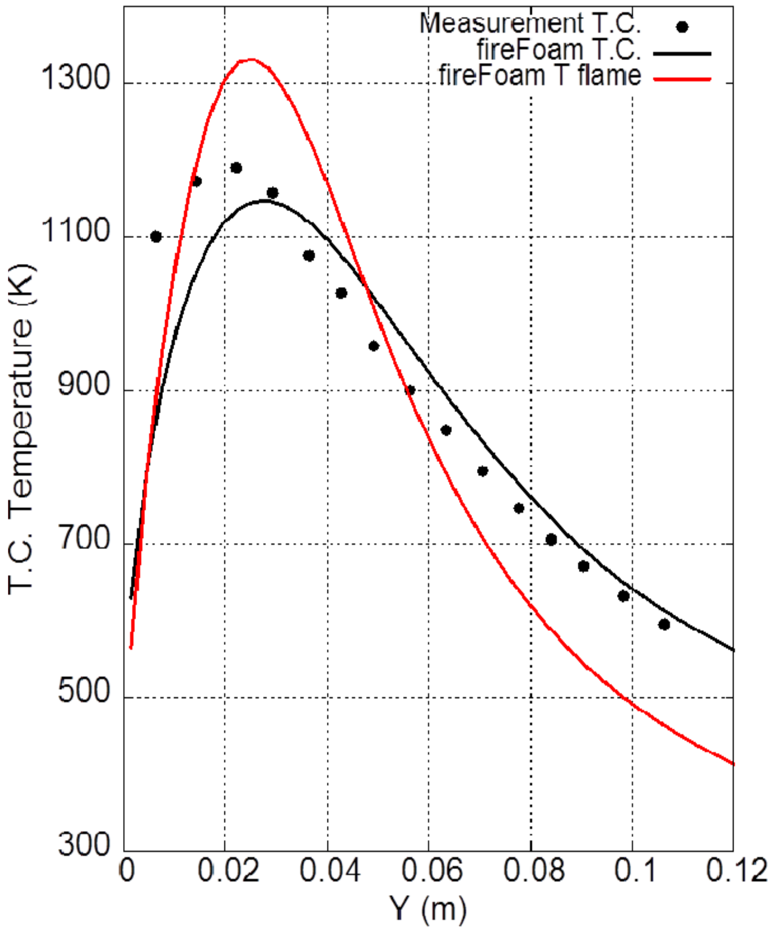
T Gas


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
Gas Temperature (K)
y (mm)
Exp
FMGlobal
NIST
0
400
800
1200
1600
2000
0
20
40
60
80
100
120

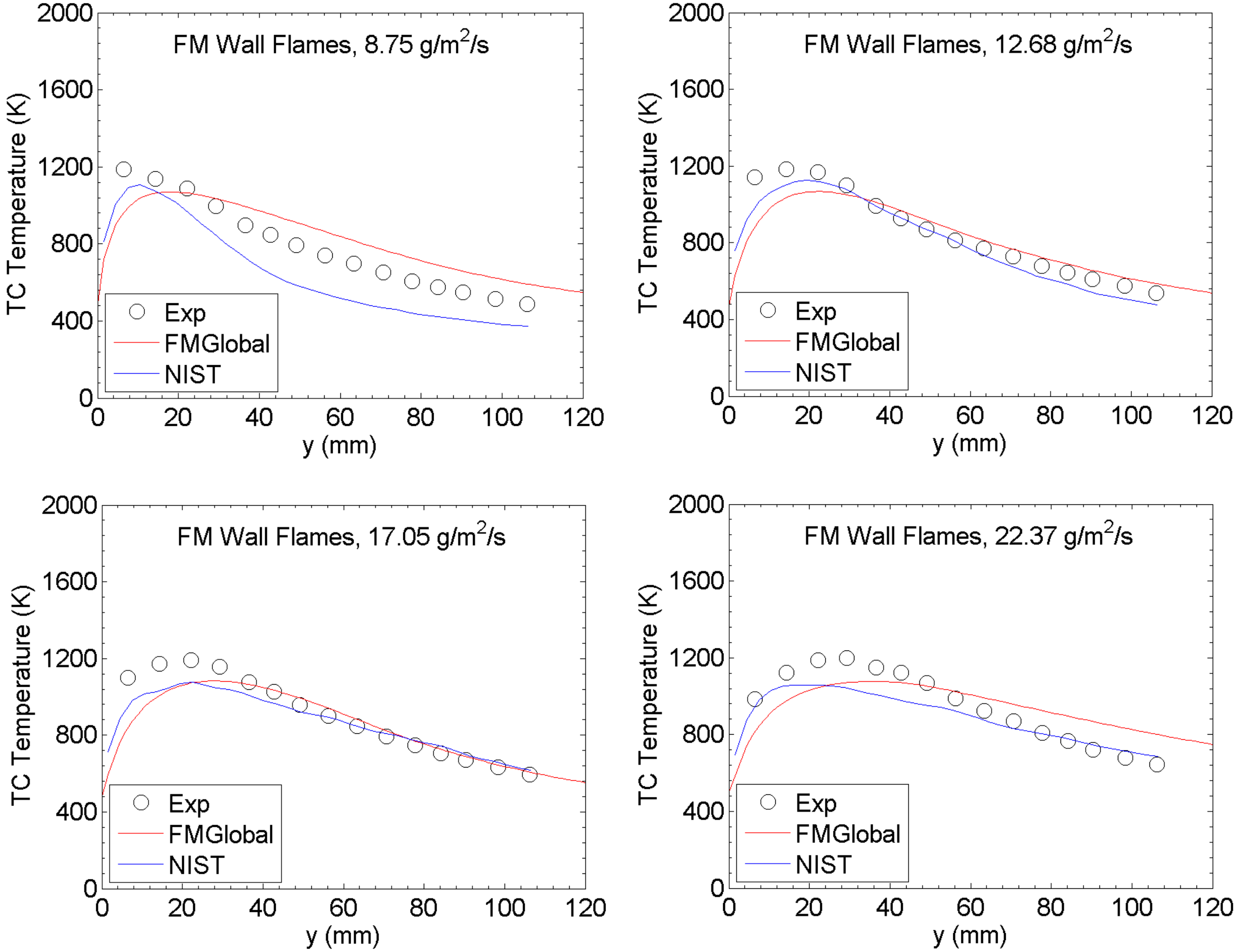
Thermocouple (T.C.) Temperature

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

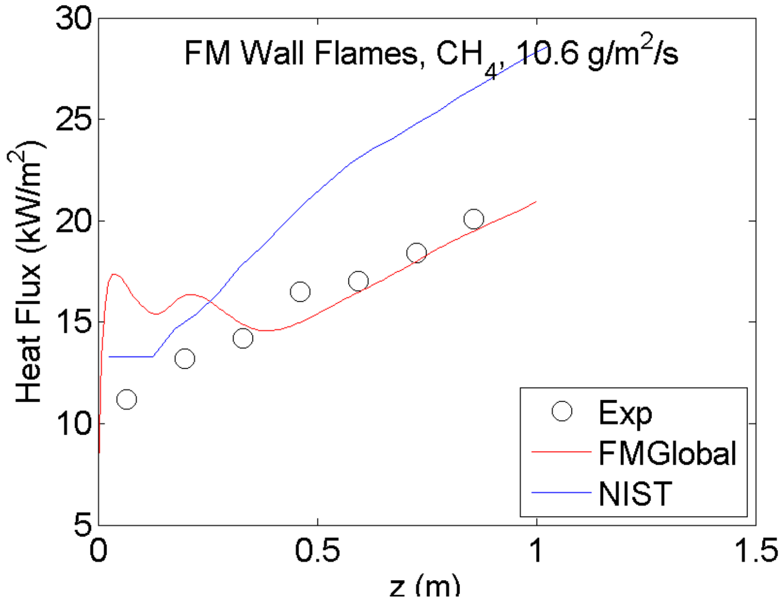
$$\rho_{Tc} C_{Tc} \frac{V_{Tc}}{A_{Tc}} \frac{dT_{Tc}}{dt} = \varepsilon_{Tc}\left(G - \sigma T_{Tc}^4\right) + h\left(T_g - T_{Tc}\right)$$

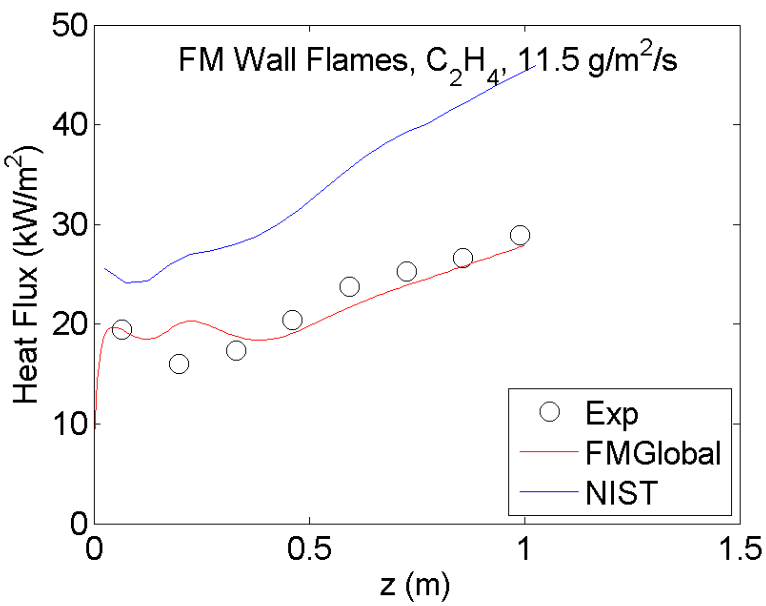


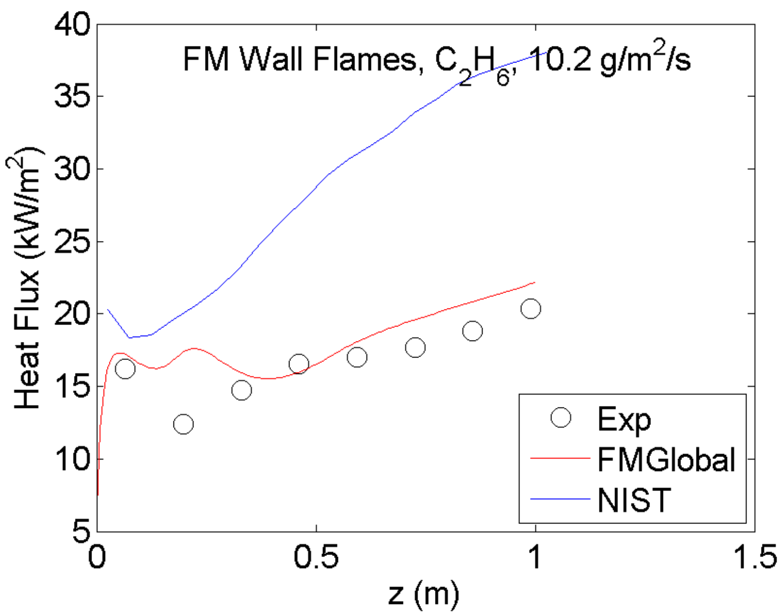
T TC


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
TC Temperature (K)
y (mm)
Exp
FMGlobal
NIST
0
400
800
1200
1600
2000
0
20
40
60
80
100
120

Other Fuels

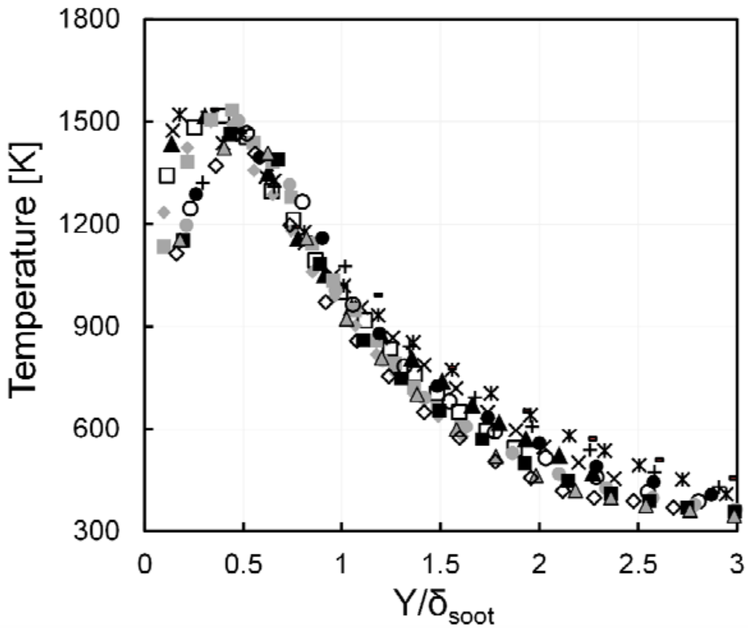

FM Wall Flames, CH_4, 10.6 g/m^2/s
Heat Flux (kW/m^2)
z (m)
Exp
FMGlobal
NIST
30
25
20
15
10
5
0
0.5
1
1.5

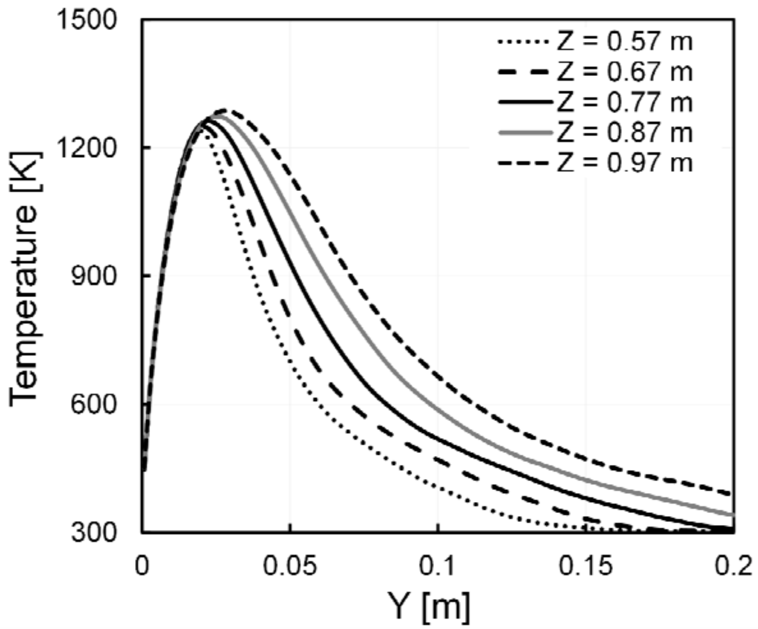

FM Wall Flames, C_2H_4, 11.5 g/m^2/s
Heat Flux (kW/m^2)
z (m)
Exp
FMGlobal
NIST
50
40
30
20
10
0
0
0.5
1
1.5

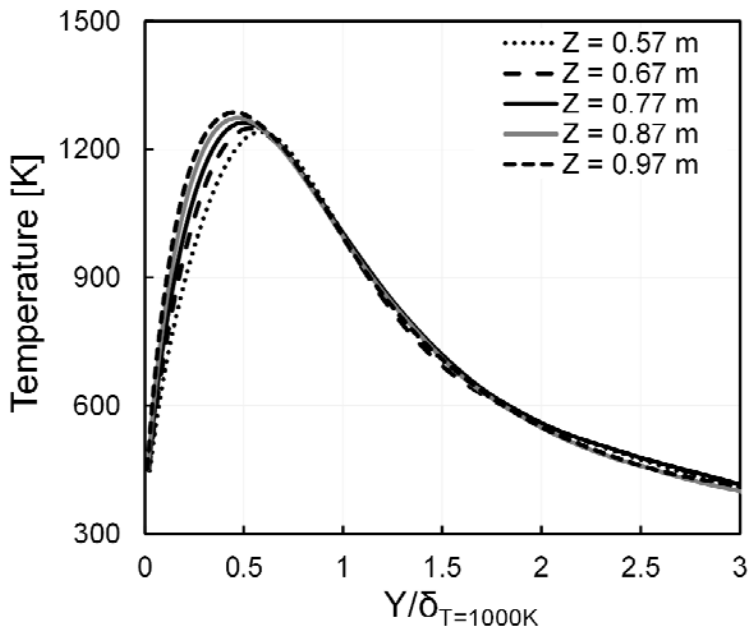

FM Wall Flames, C_2H_6, 10.2 g/m^2/s
Heat Flux (kW/m^2)
z (m)
Exp
FMGlobal
NIST
40
35
30
25
20
15
10
5
0
0.5
1
1.5

Additional Modeling Results

T Similarity

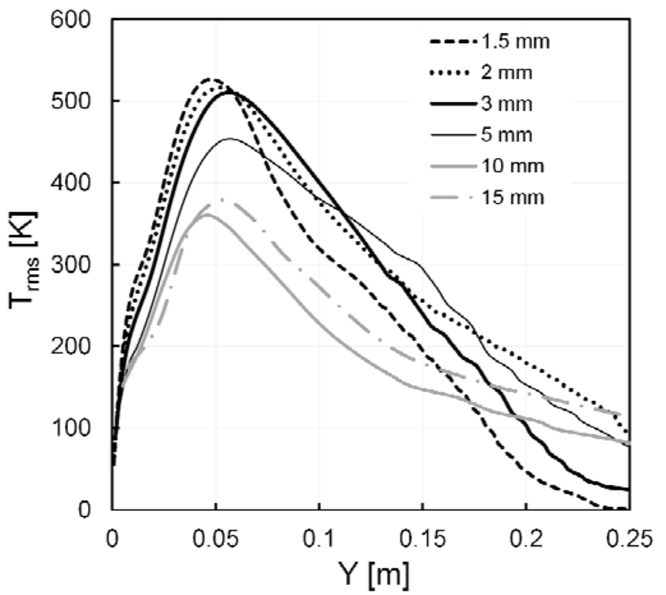


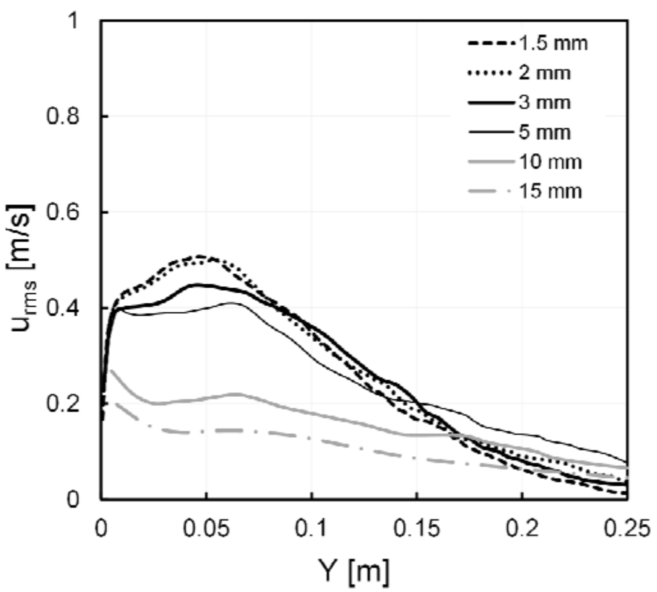


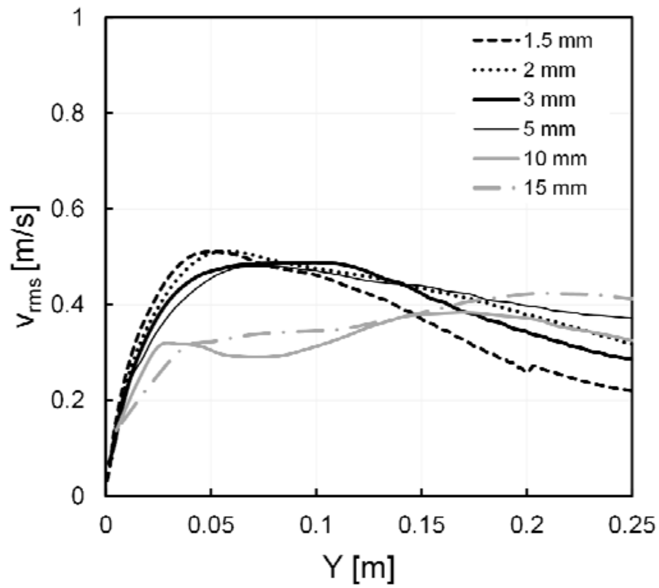


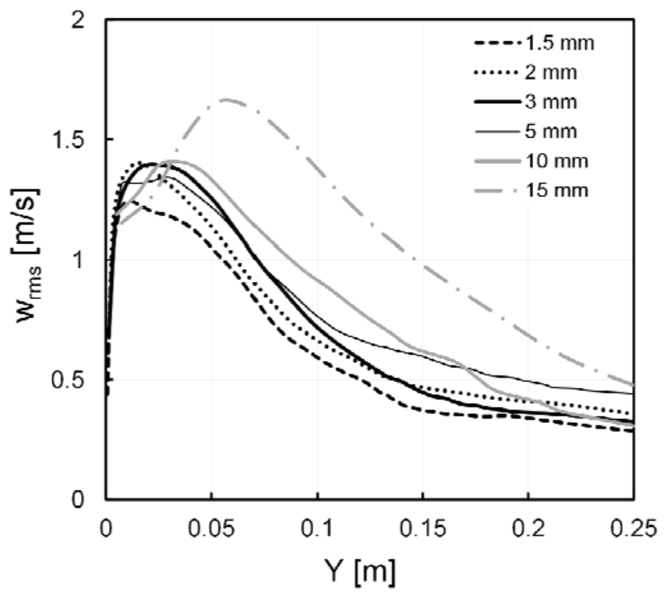
FM Global

T and U Fluctuation

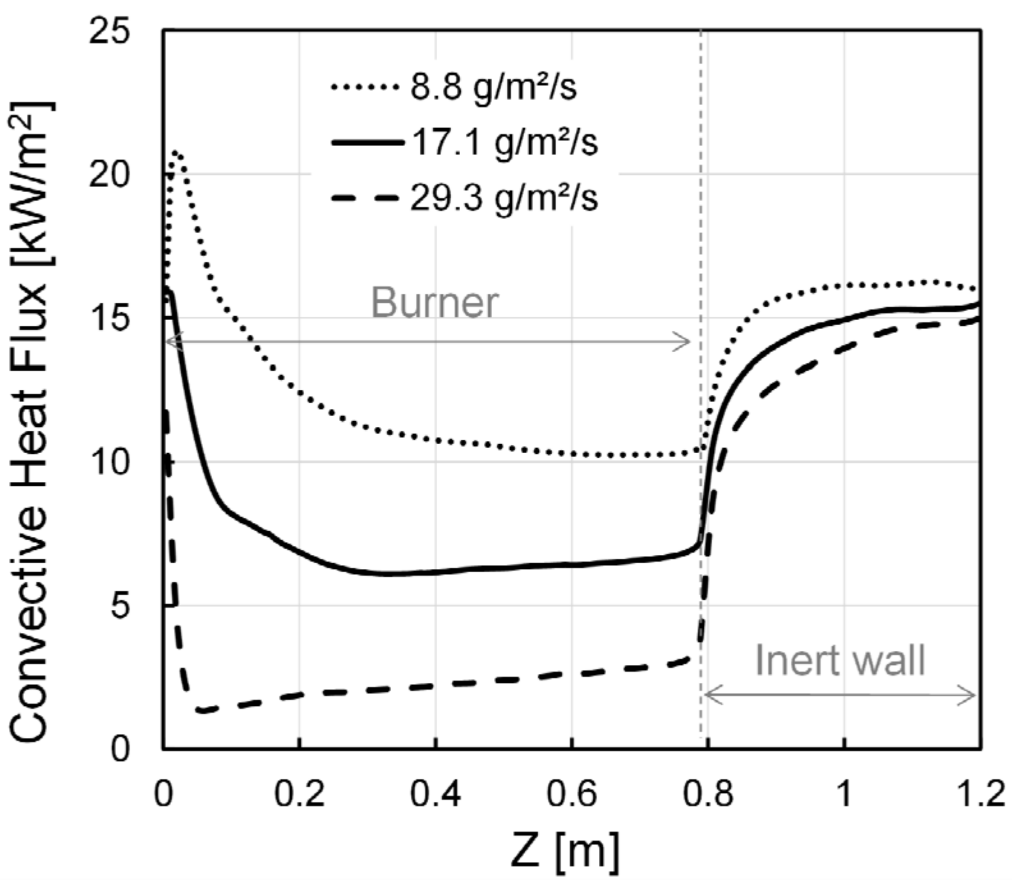


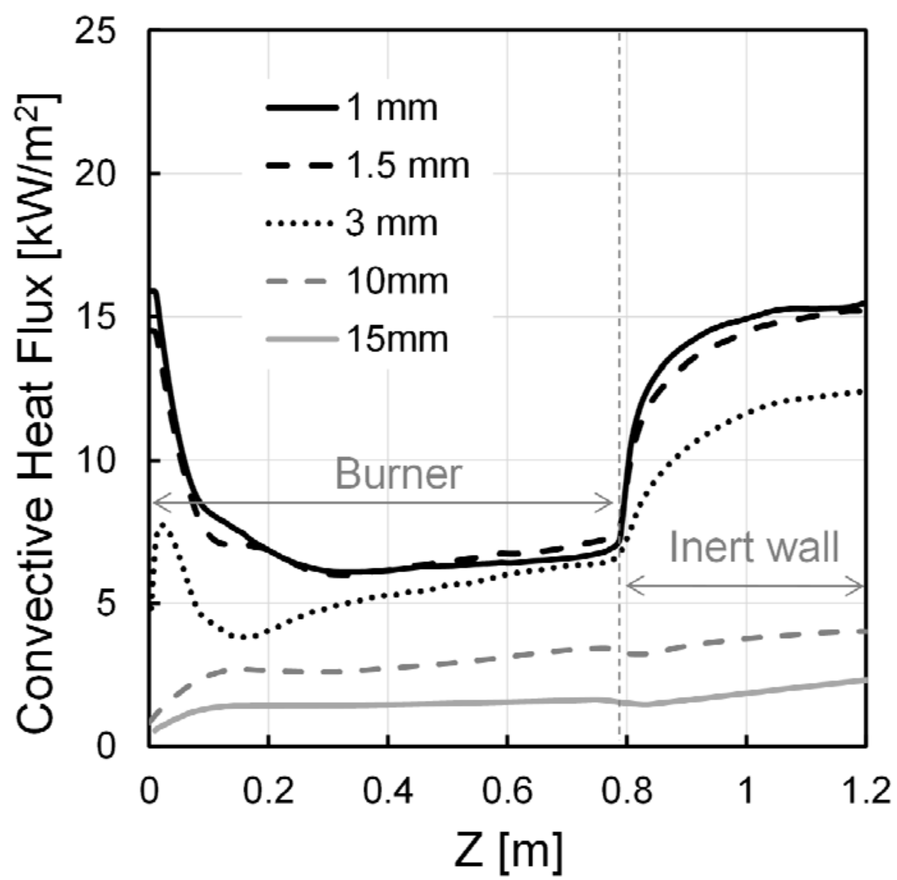






Blowing Effect





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

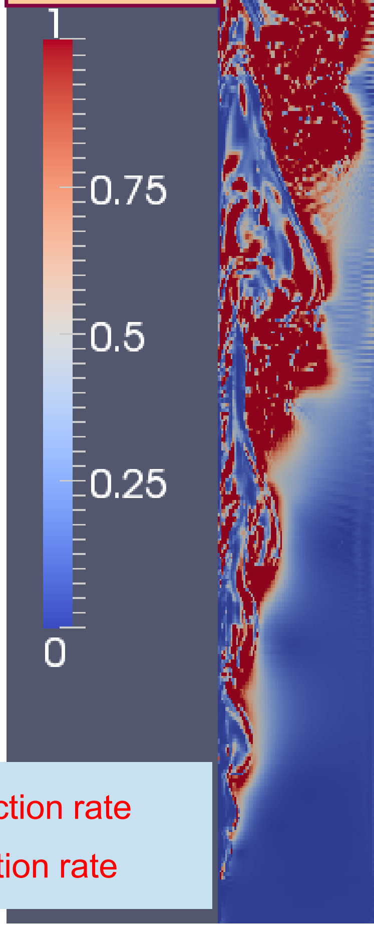
$$\overline{\dot{\omega}_F'''} = \frac{\bar{\rho}}{\min(\tau_T / C_T, \tau_d / C_d)} \min(\tilde{Y}_F, \frac{\tilde{Y}_{O_2}}{r_s})$$

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

$$\tau_d = \frac{\Delta^2}{\alpha}$$

require adequate near wall turbulence model!

$$R = \frac{\tau_d / C_d}{\tau_t / C_{EDC}}$$



Turbulence reaction rate

Diffusion reaction rate

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
2. Wrong scaling at near wall region

   O(1) instead of $O(y^3)$

WALE* model

Wall adaptive local eddy-viscosity

Zero for pure shear flow

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

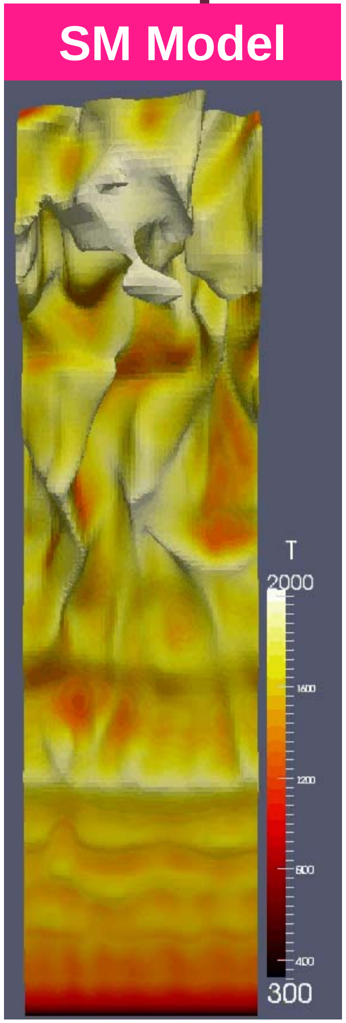
$O(y^3)$ near wall scaling

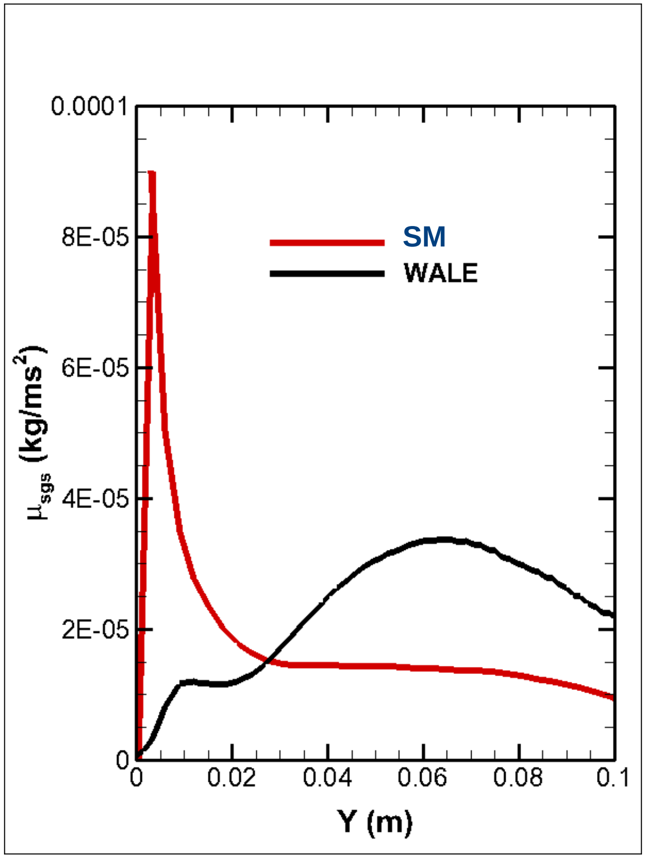
$$S_{ij}^d = \overline{S}_{ik}\overline{S}_{kj} + \overline{\Omega}_{ik}\overline{\Omega}_{kj} - \frac{1}{3}\delta_{ij}\left(\overline{S}_{mn}\overline{S}_{mn} - \overline{\Omega}_{mn}\overline{\Omega}_{mn}\right)$$

$$\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right), \qquad \overline{\Omega}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} - \frac{\partial \overline{u}_j}{\partial x_i}\right)$$

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

Wall-Adaptive Local Eddy Viscosity





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

Discussions