WSGG and wide band gas radiation models for pool fires in FireFOAM

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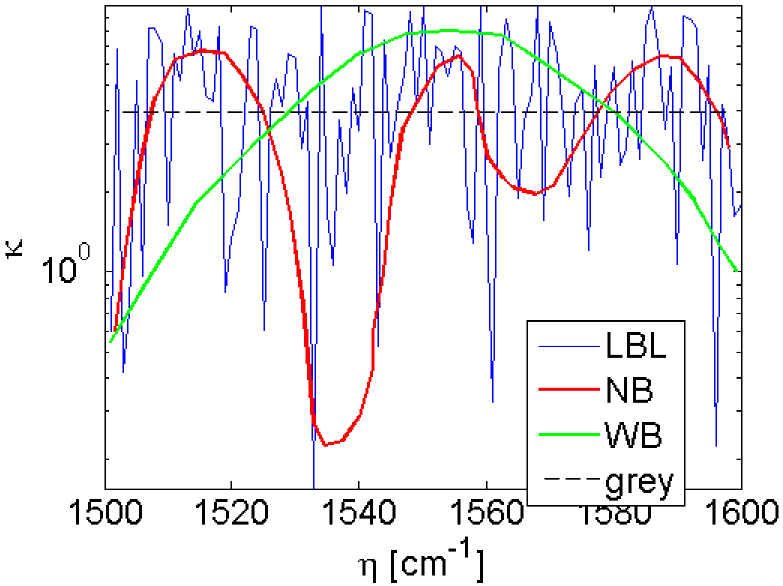
Motivation

- Built-in OpenFOAM gas radiation models are limited (no spectral treatment).
- Many weighted-sum-of-grey-gases models (WSGG) in the radiation literature but few comparative studies available in CFD context.
- WSGG are suitable for gas radiation, but does not retain spectral information.
- Spectral band widths and band locations are needed to predict radiation in simulations of water spray quenched fires.
- The Exponential Wide Band (EWB) model coupled with a ‘Box’ model yields the adequate spectral information, while being more cost effective than detailed radiation models.

Gas radiation models for CFD

- Extreme dependence of absorption coefficient on wavelength ($\kappa = f(\eta)$).
- Grey models have very limited accuracy.
- Line-by-line (LBL) calculations for benchmarking only.
- Narrow and (most) wide band (NB, WB) models too costly for CFD.
- Wide band model acceptable if implemented as step-wise grey (e.g. ‘box’ model).



Radiative Transfer Equation (RTE)

General form with wavelength **λ**, position **r** and solid angle **s** :

$$\frac{\partial I_\lambda(\vec{r},\mathbf{s})}{\partial s} = -\left[\kappa_\lambda(\vec{r}) + \sigma_\lambda(\vec{r})\right] I_\lambda(\vec{r},\mathbf{s}) + \kappa_\lambda I_{b,\lambda}(\vec{r}) + \frac{\sigma_\lambda}{4\pi}\int_0^{4\pi} I_\lambda(\vec{r},\mathbf{s}')\phi\lambda(\mathbf{s}',\mathbf{s})\,d\Omega'$$

Negligible scattering ⇔ RTE simplifies to ODE with constant member :

$$\frac{\partial I_\lambda(\vec{r},\mathbf{s})}{\partial s} = \kappa_\lambda(\vec{r})\left[I_{b,\lambda}(\vec{r}) - I_\lambda(\vec{r},\mathbf{s})\right]$$

Radiant flux divergence (source term) :

$$\nabla.\dot{q}_r'' = \int_0^\infty \kappa_\lambda \left(4\pi I_{b,\lambda} - \int_0^{4\pi} I_\lambda \, d\Omega'\right) d\lambda$$

Source term in sensible enthalpy equation :

$$\frac{\partial \bar{\rho}\tilde{h}_s}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j\tilde{h}_s}{\partial x_j} = \frac{D\bar{p}}{Dt} + \frac{\partial}{\partial x_j}\left\{\bar{\rho}\left\{\alpha + \frac{\nu_t}{\mathrm{Pr}_t}\right\}\frac{\partial \tilde{h}_s}{\partial x_j}\right\} + \dot{q}''' - \nabla.\dot{q}_r''$$

Banded and grey RTE

Grey RTE : 1 solution per direction

$$\frac{\partial I}{\partial s} = \kappa\left[I_b(T) - I\right], \kappa = -\frac{\ln(1-\varepsilon)}{S}, S = 3.6V / A$$

$$\varepsilon = \sum_{j=1}^{N} a_j(T)\left[1 - \exp\left(-k_j pS\right)\right] \longleftarrow \text{Transmissivity along homogeneous path}$$

Banded RTE : N solutions per direction

WSGG (N = 4 or 5):

$$\frac{\partial I_j}{\partial s} = \underset{\substack{\uparrow \\ \text{cst}}}{k_j}\left[\underset{\substack{\uparrow \\ \text{f(T)}}}{a_j} I_b(T) - I_j\right]$$

Wide band 'box' model (N = 7 for CO_2-H_2O mixture):

$$\frac{\partial I_n}{\partial s} = \underset{\substack{\uparrow \\ f(\vec{r}, S)}}{\kappa_n}\left[\underset{\substack{\uparrow \\ \text{Fractional blackbody power function}}}{\Delta F(n, \Delta\lambda_n, T)_n} I_b(T) - I_n\right]$$

Weighted-sum-of-grey-gases (WSGG)

- Cost effective and ideal for CFD application.
- Replace real gas properties with 3 or 4 fictitious “grey gases” (absorption coefficient constant for given pressure and path length).
- Total emissivity data for water vapour and carbon dioxide fitted with polynomials.
- Tabulated absorption coefficients κ and weights *a(T).*
- p_{CO2}/p_{H2O} generally must be known.

$$\varepsilon_{tot} = \sum_{j=1}^{J} a_j(T)\left[1 - \exp\left(-\kappa_j p_a S\right)\right]$$

$$S = 3.6V / A \qquad p_a = p_{CO_2} + p_{H_2O}$$

Wide band 'box' model

- Band absortance A_n from EWB calculations over path length S

•Obtain equivalent band width $\Delta\eta_{eq}$

- Obtain band absorption coefficient κ_n

$$\Delta\eta_{eq} = \frac{A_n}{1-\tau_n} \qquad (3)$$

$$(1) \quad A_n = \Delta\eta_{eq}\left(1-e^{-\kappa_n S}\right)$$

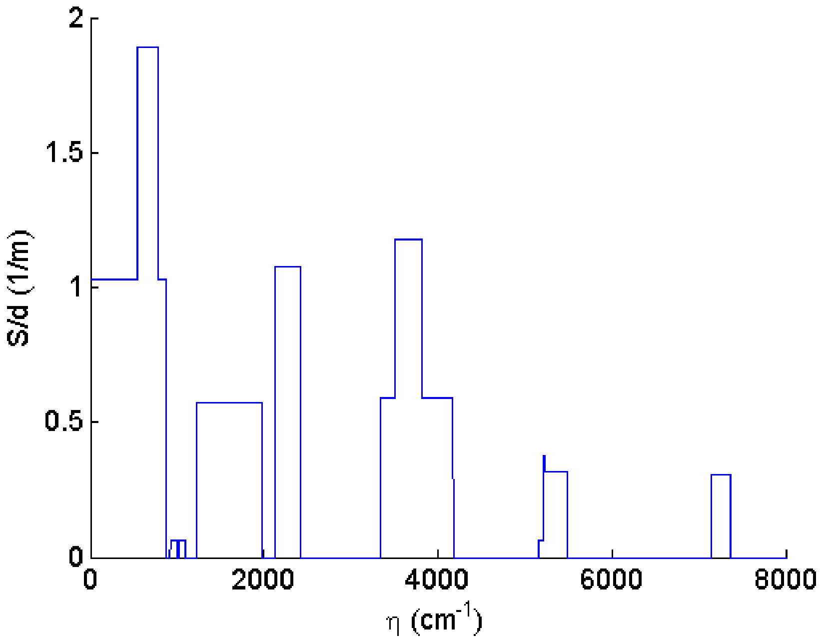
$$(2) \quad \kappa_n = \rho\alpha / \Delta\eta_{eq}$$

$$\kappa_n = -\ln(\tau_n)/S \qquad (4)$$

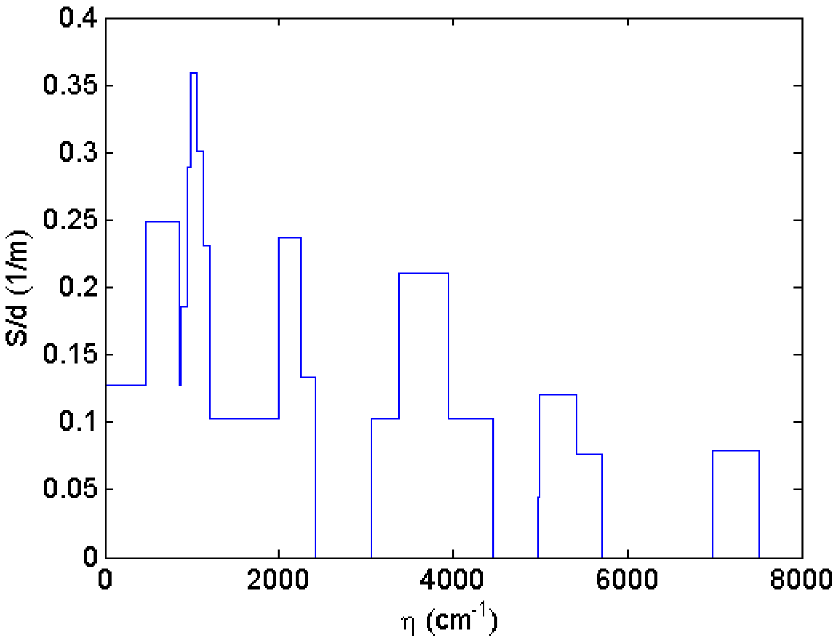
▪ Eq. 1 & 2 ⬄ "Modest" model, Eq. 3 & 4 ⬄ "Beer" model
▪ Eq. 1 is only valid for a homogeneous path length ⬄ medium must be homogeneous
▪ **For inhomogeneous media a scaling method must be used e.g. Curtis-Godson**

Box model absorption spectrum

Low *p.S*



High *p.S*

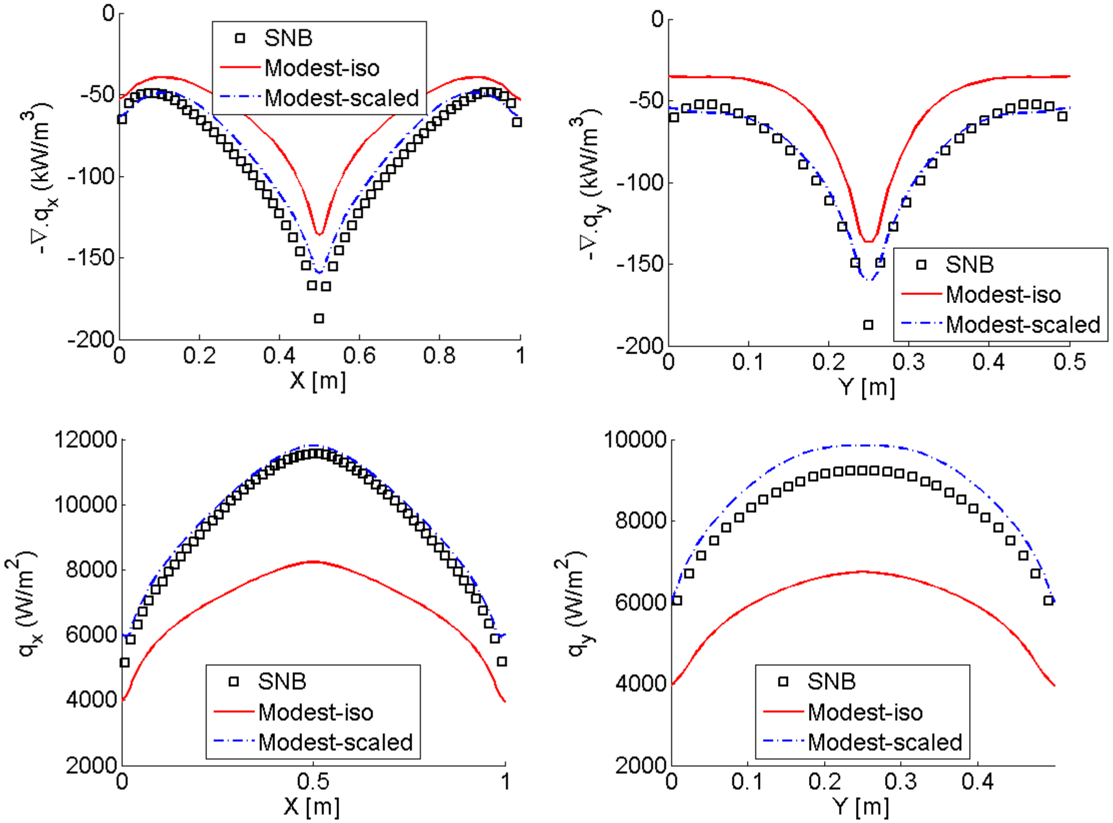


- High pressure-path lengths in CO_2-H_2O mixtures cause band overlaps : challenging for wide range of scenarios (e.g. large fires or furnaces)
- Bands in fringe spectral regions can be neglected to save time

Box model for non-uniform CO_2

Source terms along x and y :

Fluxes along x and y :



- SNB = Statistical Narrow Band (bench)
- Scaling significantly improves source terms and fluxes (works best with “Modest” approach)

Comparison of radiation models in LES of 30cm pool fires

116 kW heptane fire based on experiment by Klassen & Gore (1994)

- Comparison of 1 grey and 2 banded WSGG models

20 kW methanol fire based on experiment by Klassen & Gore (1994) completed by LDV data from Weckman & Strong (1996)

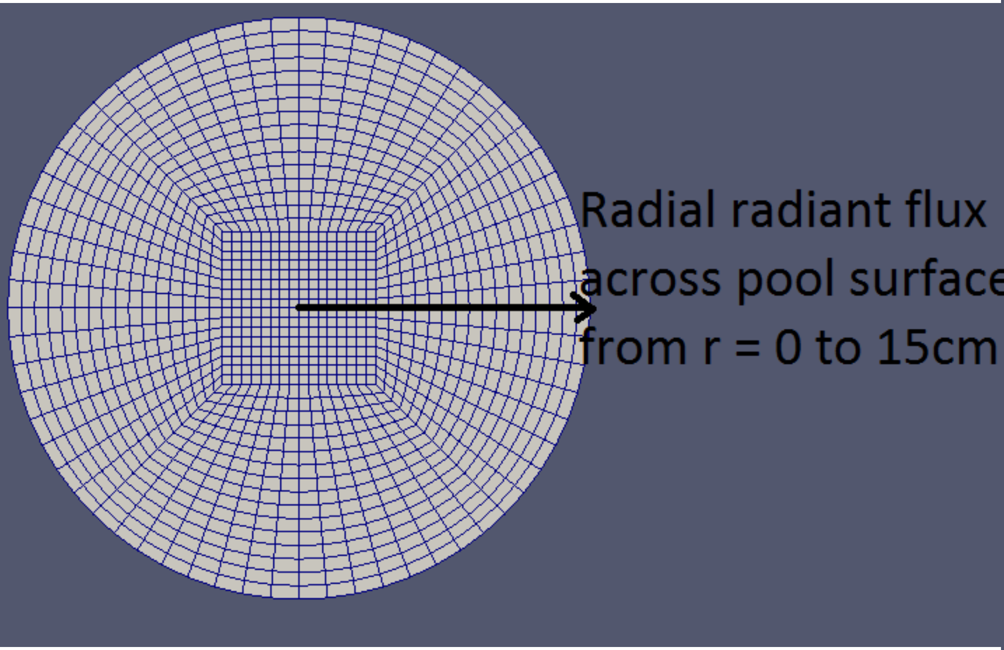
- Comparison of 2 grey, 3 banded WSGG models + “Modest” box model

Combustion and soot models : Eddy Dissipation Concept and Smoke Point Height extended for LES by Chen et al. (2014)

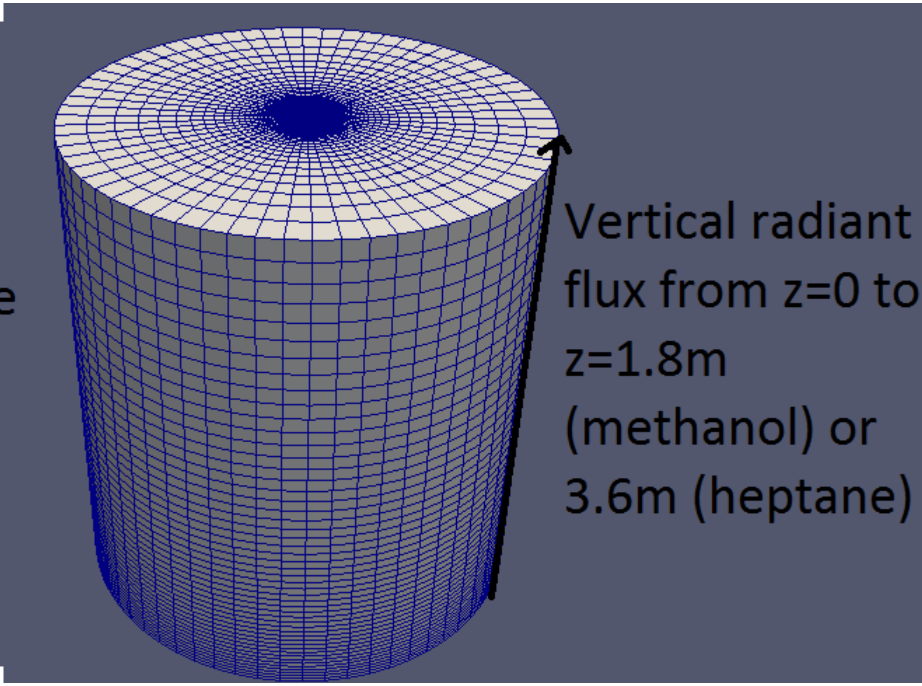
High angular resolution for FVM radiation solver

Non uniform mesh

- Cylindrical domain with r = 15cm, R = 82.5cm, H = 180cm or 360cm
- Grid nodes clustered towards pool surface
- Smallest cell resolution of 7.11mm, 48 cells across pool surface

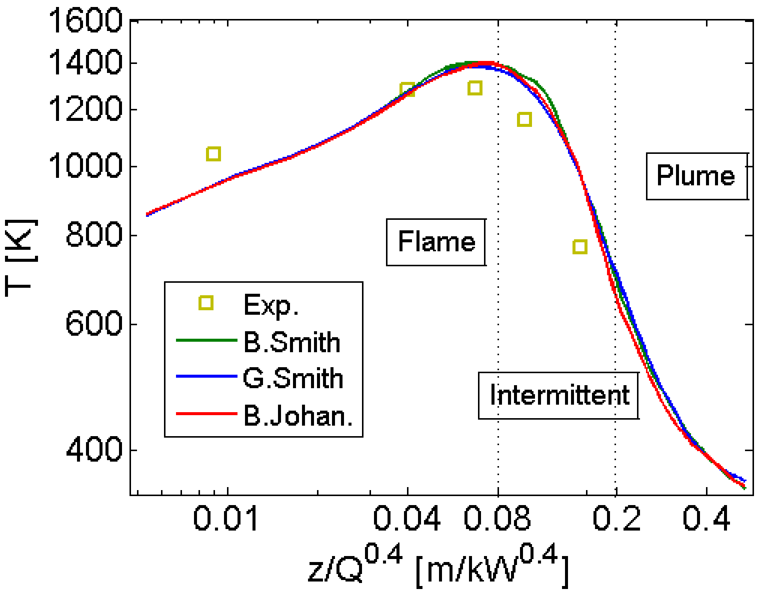


Radial radiant flux across pool surface from r = 0 to 15cm

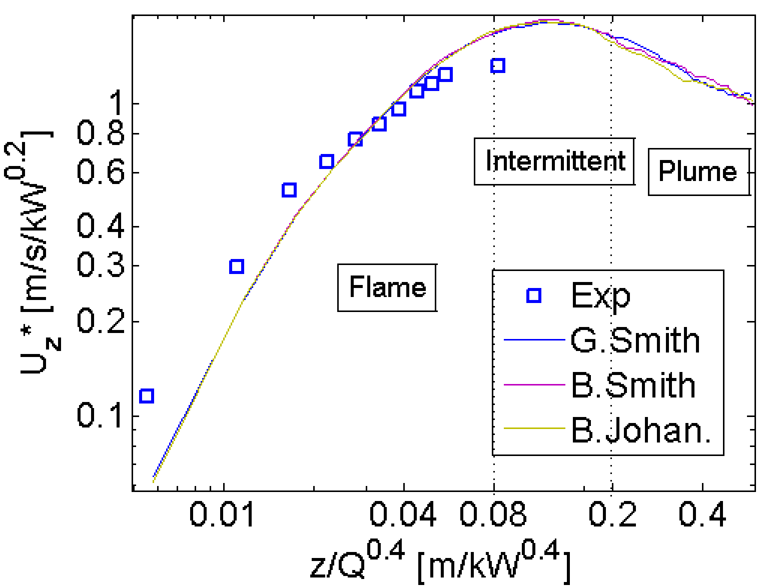


Vertical radiant flux from z=0 to z=1.8m (methanol) or 3.6m (heptane)

Heptane pool fire (WSGG)



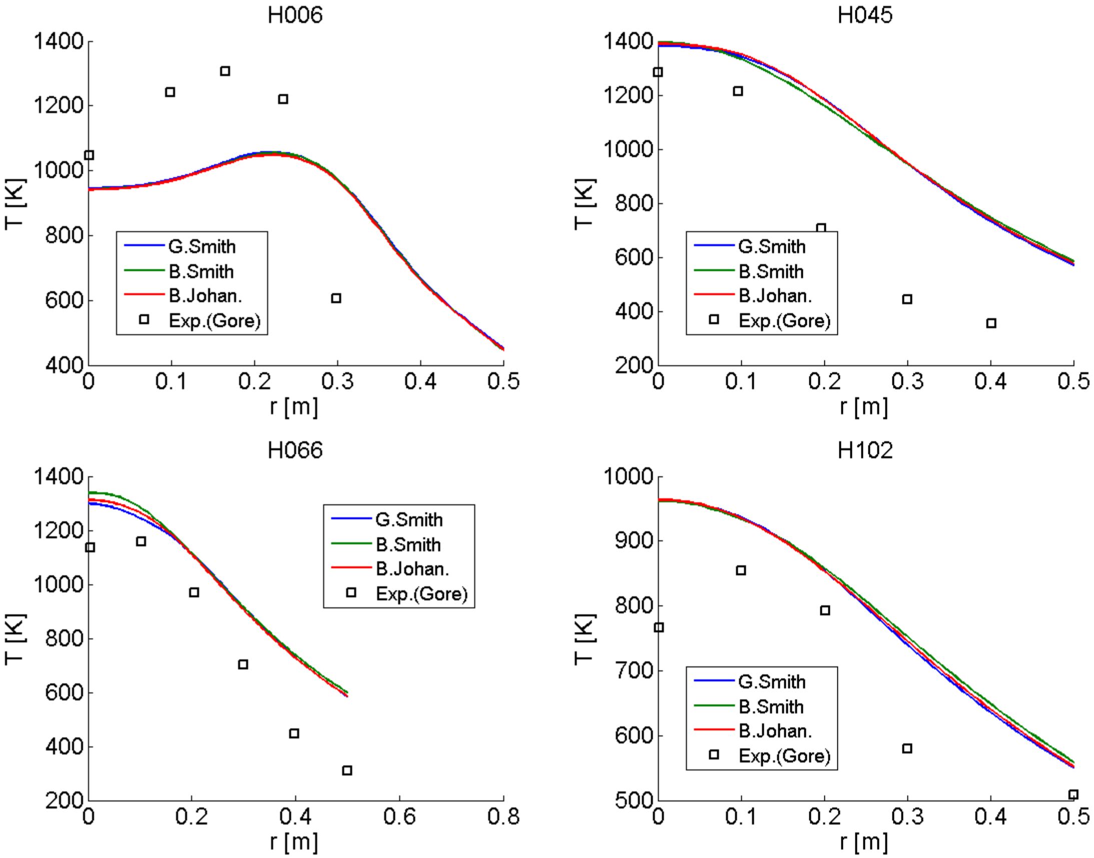
Centreline temperature



Nondimensional centreline velocity

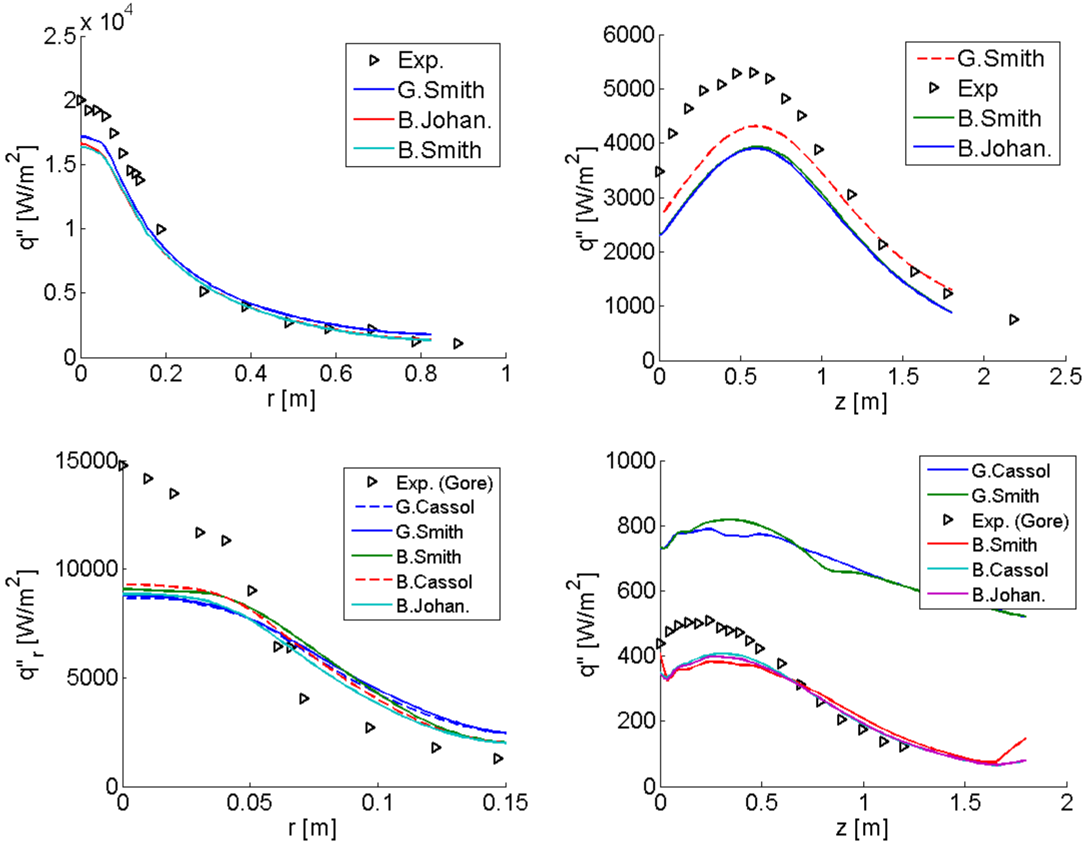
- ”G.Smith” = grey WSGG formulation based on Smith et al. (1982)
- Little differences between various WSGGs
- Prediction is better in the continuous flame zone (where most radiation occurs)

Heptane pool fire



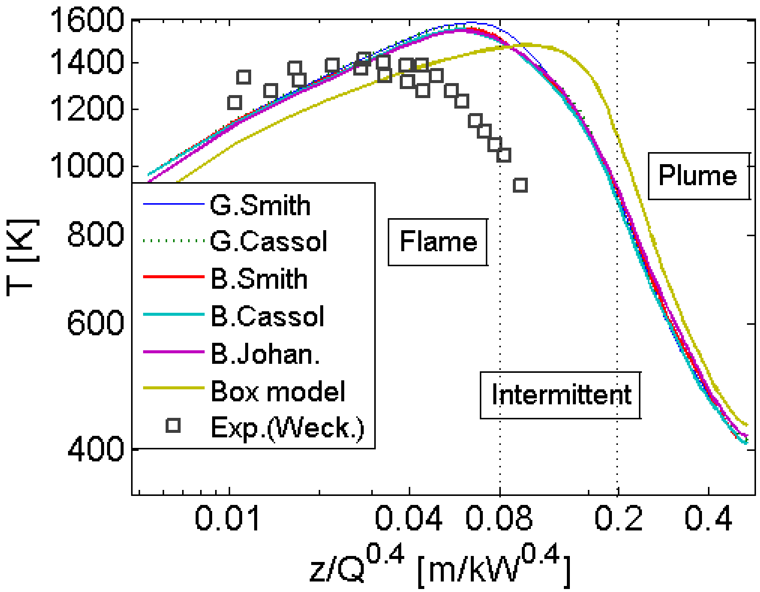
- Radial temperatures at elevations 6cm, 45cm, 66cm and 102cm (experimental errors within 15%)
- Good overall agreement within flame zone

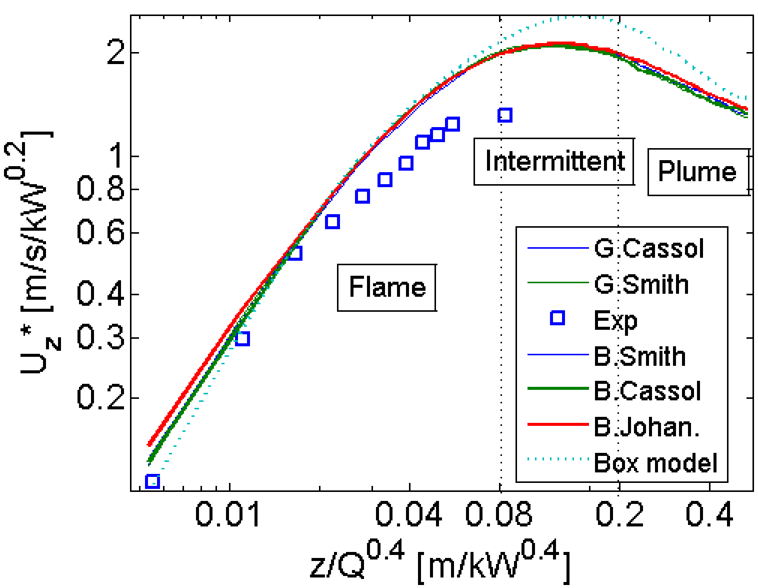
Heptane and methanol pool fire



- Radiant flux feedback to pool surface (radially, left) and domain’s side wall (vertically, right)
- Methanol more difficult to reproduce but banded WSGG better for side wall

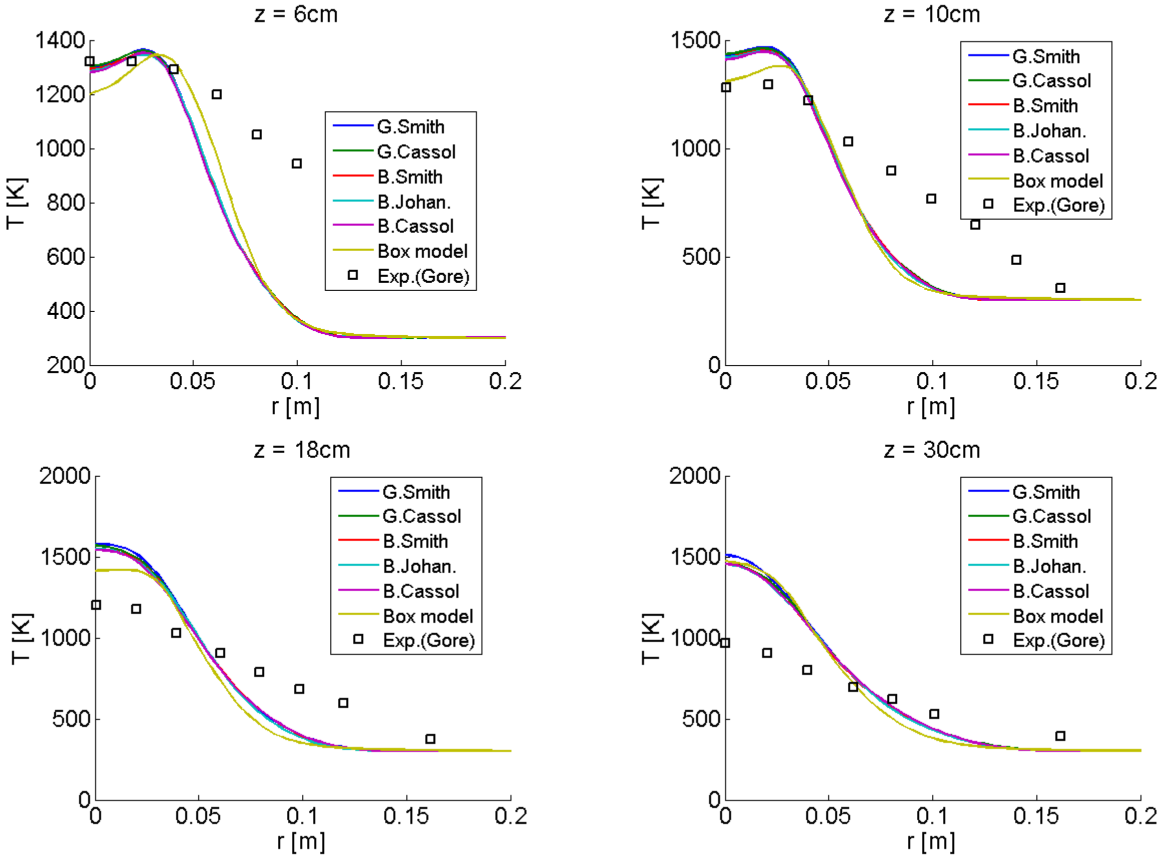
Methanol pool fire





- Little differences between various WSGGs
- Prediction is better in the continuous flame zone (where most radiation occurs)
- Preliminary wide band box model temperature result is encouraging

Methanol pool fire



- Radial temperatures at elevations 6cm, 10cm, 18cm and 30cm
- Box model temperatures quite close to WSGG

Heptane and methanol pool fires

Fuel	WSGG	Radiant fraction (Xr)
Methanol	**Experiment**	**18.0%**
Methanol	Grey Smith	15.1%
Methanol	Grey Cassol	14.6%
Methanol	B’d Smith	17.1%
Methanol	B’d Cassol	16.4%
Methanol	B’d Johansson	16.1%
Heptane	**Experiment**	**31%**
Heptane	Grey Smith	35.6%
Heptane	B’d Smith	37.3%
Heptane	B’d Johansson	37.8%

Future work

- Improvement of band overlaps in box model.
- Larger scale pool fires.
- Sooty pool fire with box model (heptane).
- Box model coupling with Mie theory model for droplet radiation.
- Water curtain encircling pool fire (radiation blocking).
- Fire suppression simulations.

Acknowledgements

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Thank you for your attention!