Gas Optical Properties of Oxy-Fuel Combustion and Implications on Radiative Heat Transfer

3rd Oxyfuel Combustion Conference

Ponferrada, 9th - 13th of September 2013

Sebastian Rehfeldt

Process Engineering & Design Firing Systems

Hitachi Power Europe GmbH

Introduction

HITACHI
Inspire the Next

- **Oxy-fuel combustion: high concentration of CO_2 and H_2O in flue gas**
  - Influence on flue gas emissivity?
  - Influence on radiative transfer?
  - Gray modeling sufficient?
  - Global emissivity models suitable?
  - Absorption coefficient?
  - Path length?
- **Gray modeling (required computation time is low)**

Emissivity modeling (I)

HITACHI
Inspire the Next

- **Most commonly used global emissivity model by Smith et al. (1982)**
  - Sum of u gray gases $\varepsilon = \sum_u a_{\varepsilon,u}[1 - e^{-\kappa_u pL}]$ (3 gray, 1 transparent)
  - $a_{\varepsilon,u}$ weighting factors of gray gas u which are temperature polynomials $\sum_\upsilon b_{\varepsilon,u,\upsilon} T^{\upsilon-1}$ with υ being 4
  - κ_u is the absorption coefficient of gray gas u
  - pL is the pressure path length
  - Lallemant and Weber (1993) found best agreement with exponential wide band model over wide range of pressure path lengths
  - Khare and Wall (2007) found deviation to accurate emissivity model for high CO_2 and H_2O concentrations

Emissivity modeling (II)

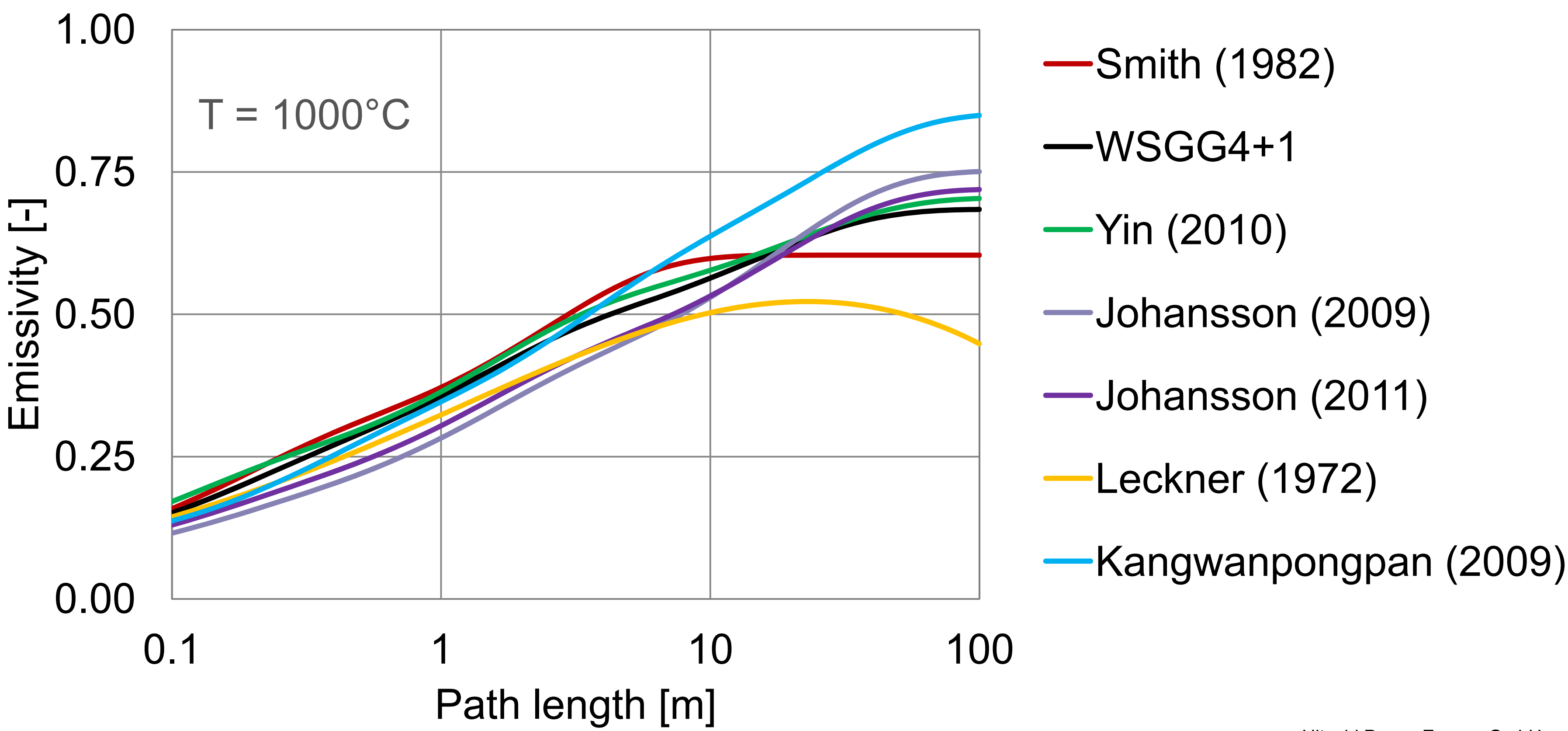
HITACHI Inspire the Next

➢ Emissivity model for high concentration of CO_2 and H_2O

- Consideration of actual mole fraction ratio $\Psi = {}^{\sigma_{H_2O}}/_{\sigma_{CO_2}}$ as proposed by Johansson et al. (2009)
- $a_{\varepsilon,u}(T,\Psi)$ weighting factors $\sum_{\upsilon} \sum_{w} \left(c_{\varepsilon,u,\upsilon,w} \Psi^{w-1} \right) T^{\upsilon-1}$
- $\kappa_u(\Psi)$ function of the form $\sum_p \left(d_{u,p} \Psi^{p-1} \right)$
- WSGG4+1 – four gray and one transparent gas (u = 5)

Emissivity modeling (III)

- **Different global emissivity models have been developed recently**
  - $\sigma_{CO_2} = 0.7$, $\sigma_{H_2O} = 0.25$



Absorption coefficient (I)

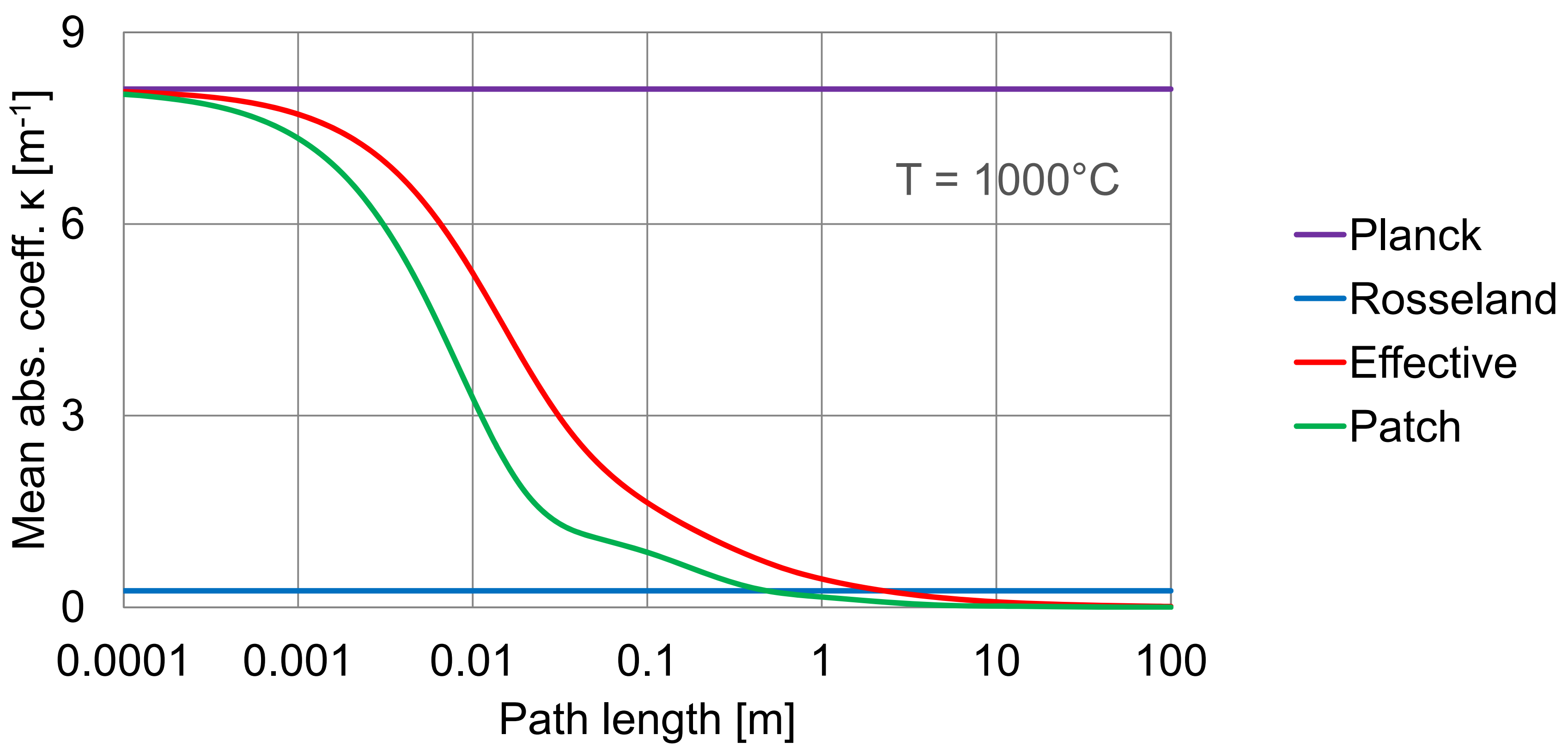
HITACHI
Inspire the Next

- **Intensive quantity**
- **Required for coupling with Radiative Transfer Equation (RTE)**
  - $\frac{dI}{ds} = \kappa_g (I_b - I)$ (gray formulation of the RTE without scattering)
- **Planck mean, Rosseland mean, u solutions of RTE**
- **Effective absorption coefficient**
  - $\kappa_e = -(1/L) \cdot ln(1 - \varepsilon_g)$
- **Patch (1967) absorption coefficient**
  - $\kappa_{pa} = L \cdot \frac{\delta \kappa_e}{\delta L}$

Absorption coefficient (II)

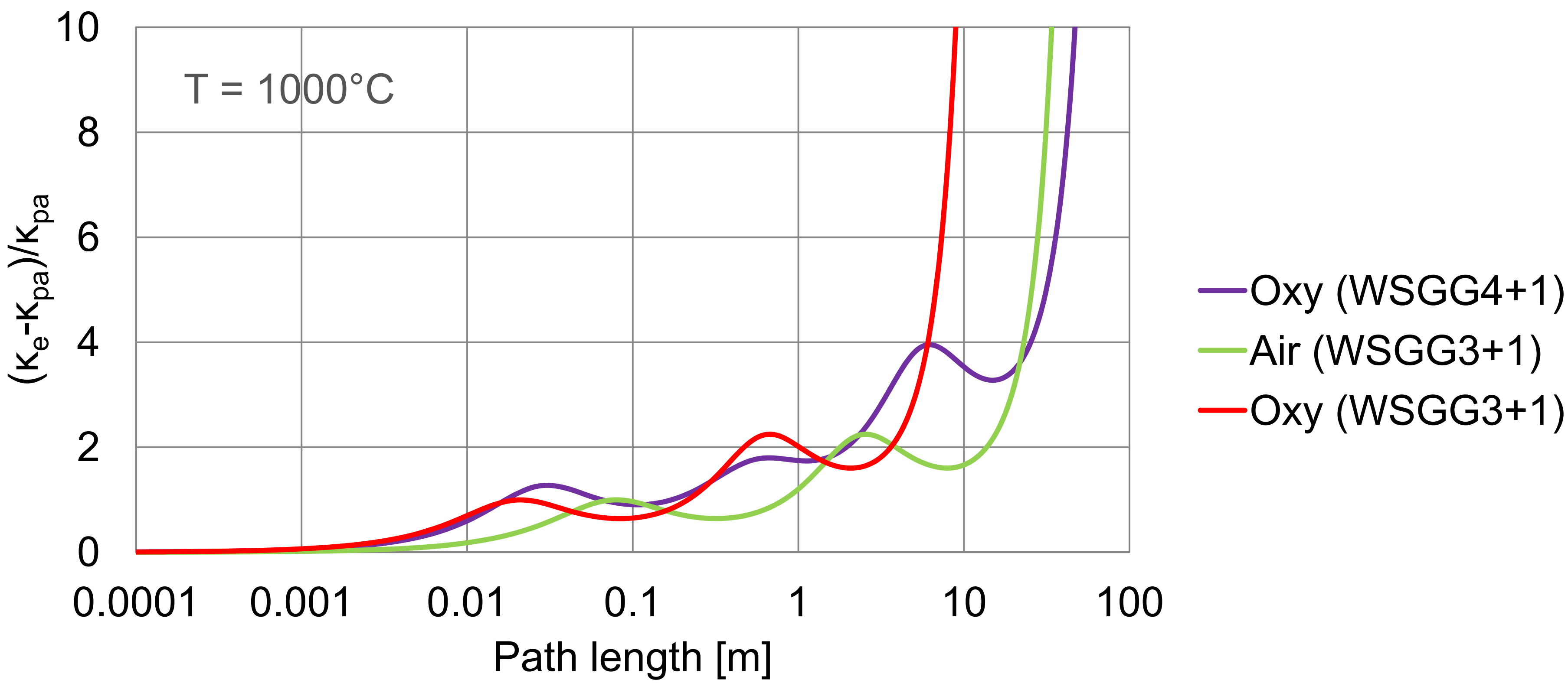
Planck mean, Rosseland mean, Patch and effective absorption coefficient

- $\sigma_{CO_2} = 0.7$, $\sigma_{H_2O} = 0.25$



Absorption coefficient (III)

- **Effective and Patch absorption coefficient similar at path lengths < 1m (Lallemant et al. 1996)**



Radiative Transfer Simulation (I)

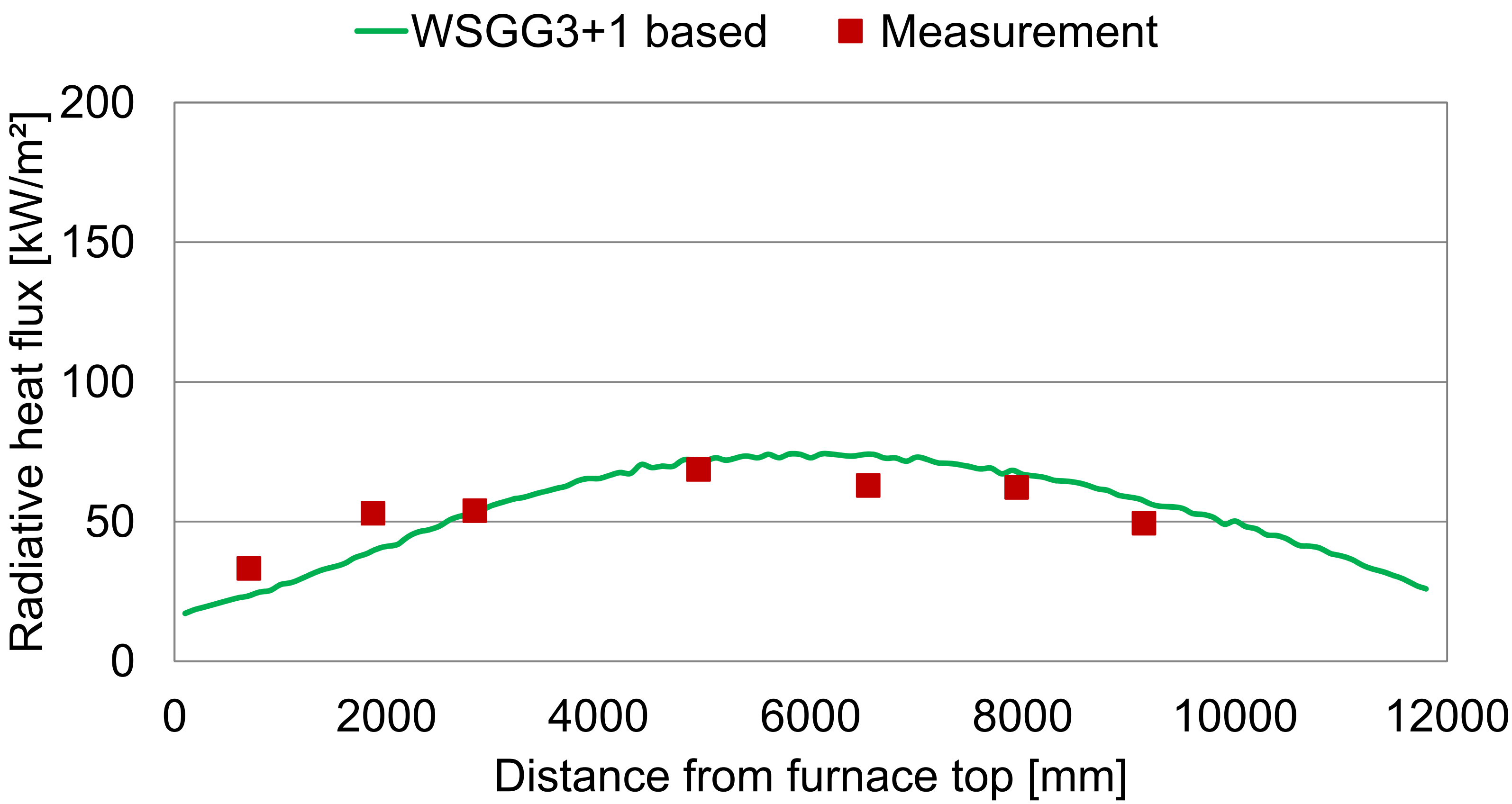
HITACHI Inspire the Next

➢ Monte Carlo Ray Tracing

- 30 MW_{th} Oxy-fuel boiler
- Mean beam length L = 3.21 m, wall reflectivity 0.15
- Temperatures and gas concentration known from measurement (no iterative solution required)
- One billion beams from 208.152 volume elements
- 10.000 beams from each of 23.352 surface element
- Two size fractions of ash particles, monodispersed soot and coal particles
- Isotropic, gray scattering; scattering by soot is neglected

Radiative Transfer Simulation – Air Firing

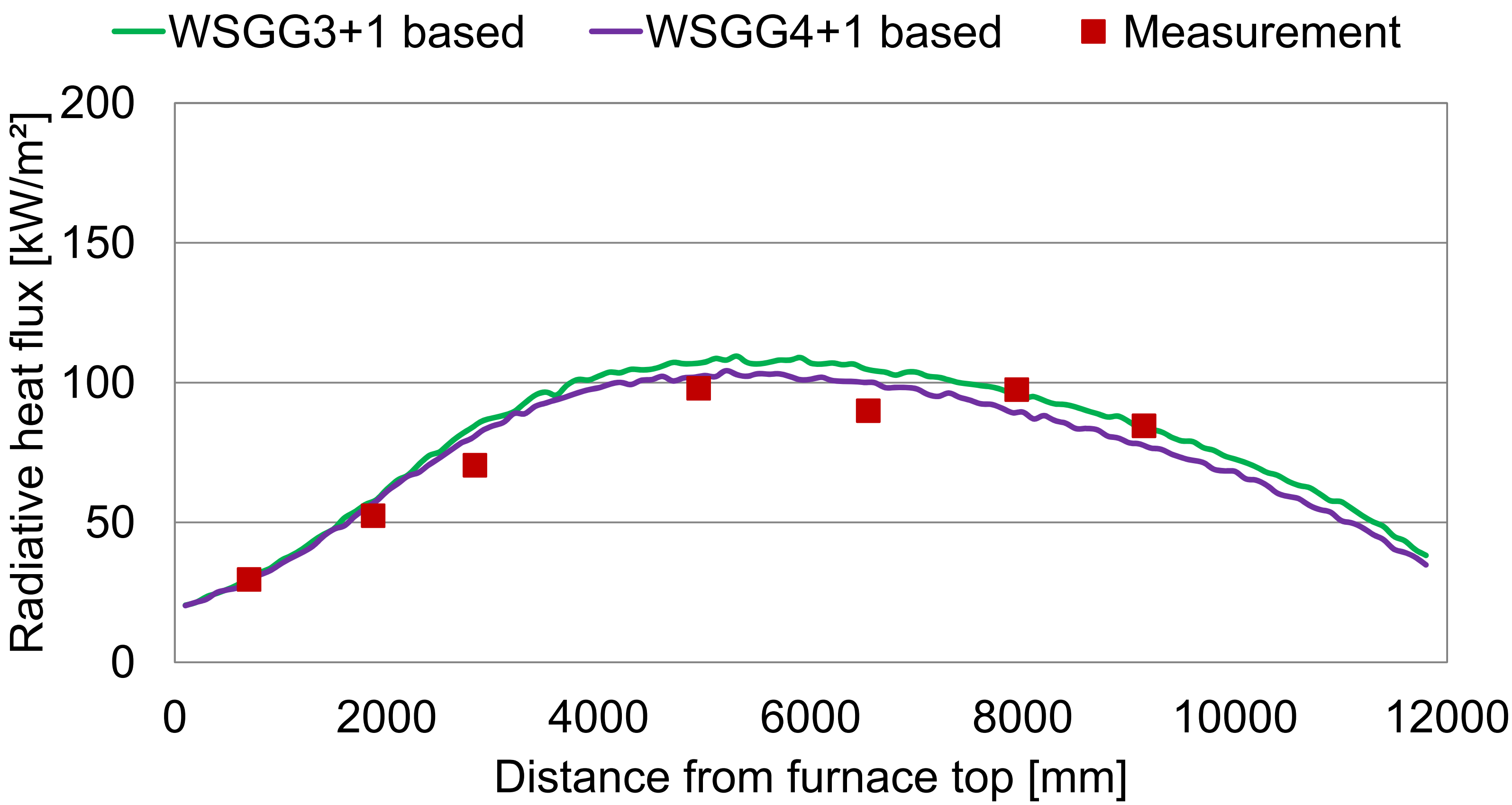
- **Heat flux results (centerline of furnace front wall), Patch absorption coeff.**



Radiative Transfer Simulation – Oxy (30 % O_2)

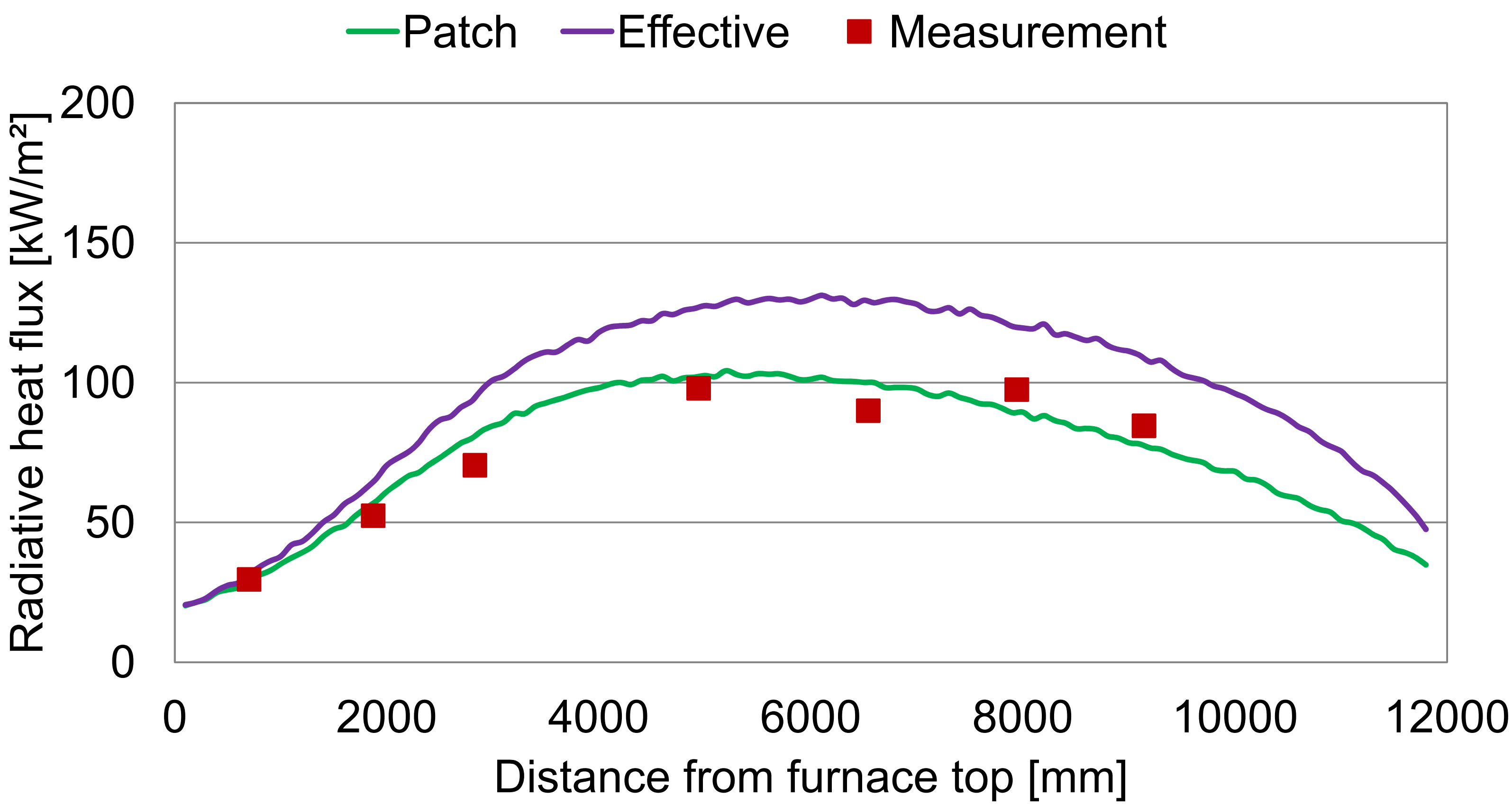
HITACHI
Inspire the Next

- **Heat flux results (centerline of furnace front wall), Patch absorption coeff.**



Radiative Transfer Simulation – Oxy (30 % O_2)

- **Heat flux results (centerline of furnace front wall), WSGG4+1 based**



Radiative Transfer Simulation – Summary

HITACHI
Inspire the Next

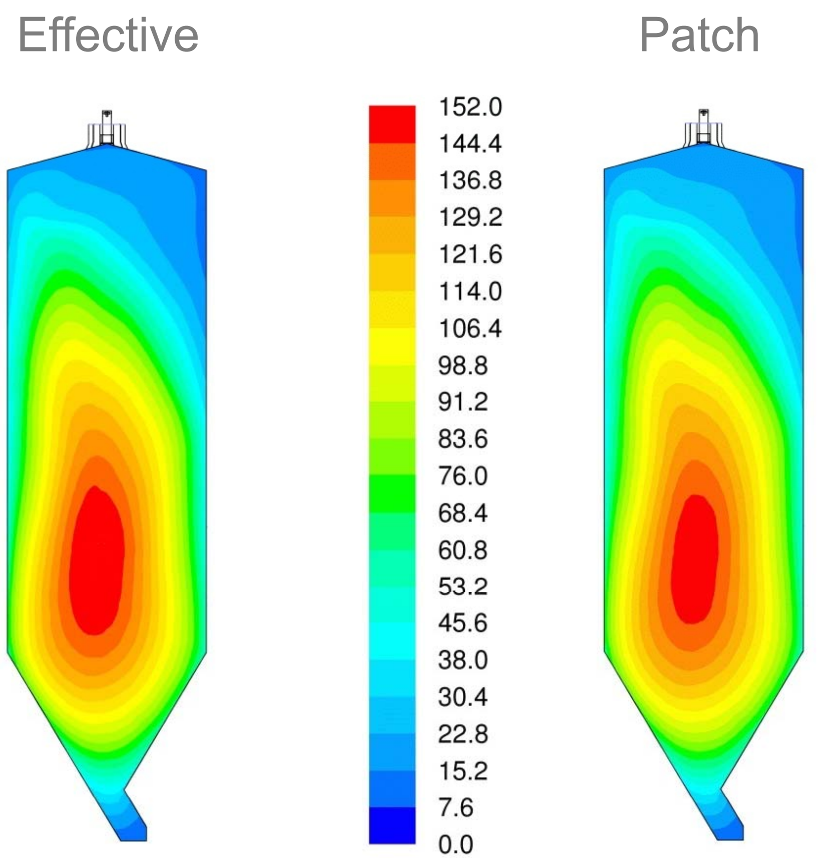
- **Influence of gas emissivity on heat flux results rather low**
- **Influence of gas emissivity model on heat flux results rather low**
- **Influence of absorption coefficient appears to be high, but …**
  - No iterative solution of radiative transfer equation (temperatures known)
  - Just „calibration“ model
  - Regarding iterative solution, absorption coefficient influences heat flux ***and*** temperatures
  - Emission term of RTE is function of fourth power of temperature
  - Influence on heat flux results much lower in iterative solution

Radiative Transfer Simulation with FLUENT

HITACHI
Inspire the Next

➢ **Incident radiative heat flux at furnace front wall [kW/m²]**

- WSGG4+1
- Oxy-fuel
- 30 % O_2
- Particle emissivity 0.7
- Wall reflectivity 0.3



Summary

- **Simplefied modeling of gas optical properties allows results with similar quality as for air-fired systems**
  - Several gas emissivity models suitable for oxy-fuel combustion available
  - Coupling with RTE (absorption coefficient) is also important
  - Effective absorption coefficient possibly leads to higher error
- **Influence of gas emissivity / gas absorption coefficient is limited**
  - Especially if particles (soot, ash, coal) are present
- **General short-comings of global emissivity models unaffected**
  - There are more sophisticated models available
  - Computational effort must me justified

References

- ❑ Lallemant, N.; Weber, R.; IFRF Doc. no. G 08/Y/2 (1993).
- ❑ Smith, T. F.; Shen, Z. F.; Friedman, J. N.; ASME Journal of Heat Transfer 104 (1982) 602-8.
- ❑ Khare, S.; Wall, T.; Technical Note No. 27, Australian Black Coal Utilisation Research Ltd. (2007).
- ❑ Leckner, B.; Combustion and Flame 19 (1972), 33-48.
- ❑ Johansson, R.; Leckner, B., Andersson, K.; 6th Mediterranean Combustion Symposium (2009).
- ❑ Johansson, R.; Leckner, B.; Andersson, K.; Johnsson, F.; Combustion and Flame 158 (2011) 893-901.
- ❑ Kangwanpongpan, T.; França, F. H. R.; Corrêa da Silva, R.; Smith Schneider, P.; Krautz, H. J.; Proceeding of the 9th International Conference on Greenhouse Gas Control Technologies (2009).
- ❑ Yin, C.; Johansen, L. C. R.; Rosendahl, L. A.; Kær, S.; Energy Fuels 24 (2010) 6275-82.
- ❑ Lallemant, N.; Sayre, A.; Weber, R.; Progr. Energy Combust. Sci. 22 (1996) 543-74.
- ❑ Patch, R. W.; Journal of Quantitative Spectroscopy and Radiative Transfer 7 (1967) 611-37.

HITACHI
Inspire the Next