5-23-2016

# Analysis of fluctuations in velocities, voidage and gas concentration in cfb conditions

Timo Niemi
*VTT Technical Research Centre of Finland , Finland*, timo.niemi@vtt.fi

Sirpa Kallio
*VTT Technical Research Centre of Finland , Finland*, sirpa.kallio@vtt.fi

Juho Peltola
*VTT Technical Research Centre of Finland , Finland*


# Analysis of fluctuations in velocities, voidage and gas concentration in CFB conditions

Fluidization XV 2016

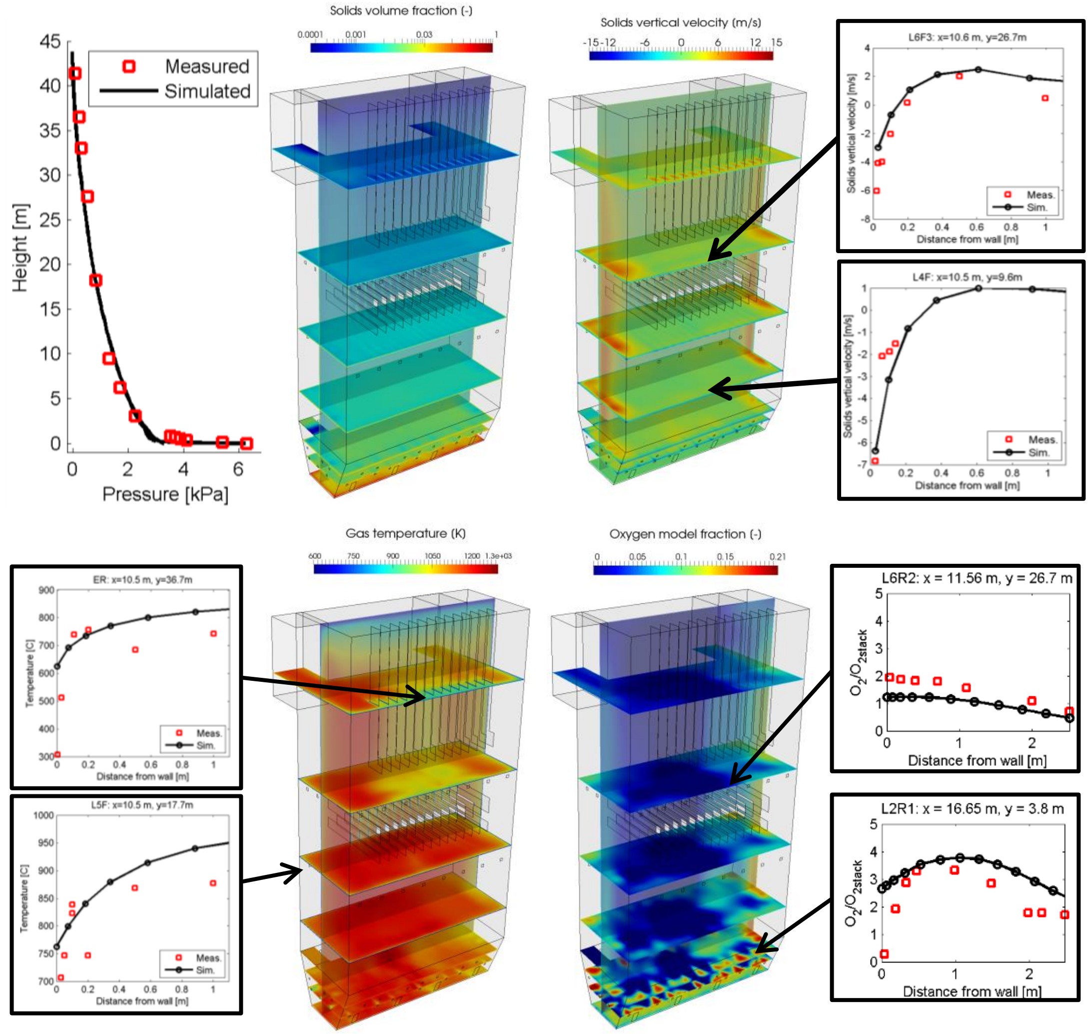
Timo Niemi, Juho Peltola, Sirpa Kallio
VTT Technical Research Centre of Finland

# Background and motivation

- CFBs can be simulated reasonably well using CFD and fine mesh resolution
  - Computational requirements limit applicability
- Industrial scale applications require coarse meshes or time-averaged simulation
  - Closure models are needed for the time and length scales of the flow field that are not resolved
- Development of the closure models requires good understanding of the characteristics of the process

# Background and motivation

- At VTT we have concentrated on the time-averaged approach for CFB combustion
- Filtered closure models for drag, solid pressure, volume fraction–pressure gradient correlation, inter-phase heat transfer
- A fluidization specific Reynolds stress turbulence model
- Promising results, however further development needed for e.g. chemistry
- **Aim of the present study:** gain more understanding of the fluctuation characteristics of chemical species in CFB conditions
- **Method:** simplified CFD simulation of combustion in a pseudo-2D riser




Turow No. 3 235 MWe CFB boiler

# Time-scales, length-scales and diffusion coefficients

- Turbulent diffusion is a product of standard deviation of velocity fluctuation and **Lagrangian** length-scale

$$D_{T,i} = v_{\sigma,i} L_{L,i} \qquad v_{\sigma,i} = \sqrt{\overline{v_i' v_i'}} \qquad v_i = \overline{v_i} + v_i{}'$$

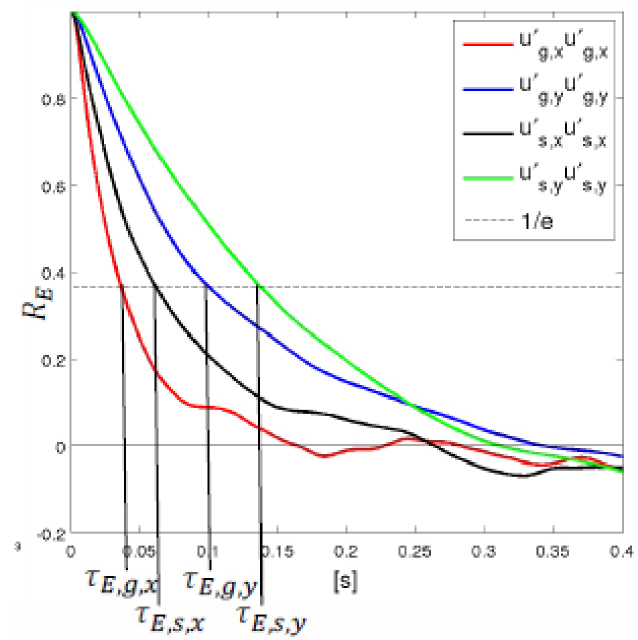
- The length-scale can be calculated from **Lagrangian** time-scale, defined with auto-correlation function $R_{L,i}$

$$L_{L,i} = v_{\sigma,i} \tau_{L,i} \qquad \tau_{L,i} = \int_0^\infty R_{L,i}(t)dt = \int_0^\infty \frac{\overline{v_i'(\tau) v_i'(\tau - t)}}{v_{\sigma,i}^2} dt$$

- In this work the time-scales are calculated using **Eulerian definition**

- Eulerian and Lagrangian time-scales are not the same! Different ratios have been reported in even in single phase flows

$$v_\sigma \tau_L / \bar{u} \tau_E = 0.15 \dots 2 \qquad \tau_L / \tau_E = 1.7 \dots 4$$



# Numerical case setup

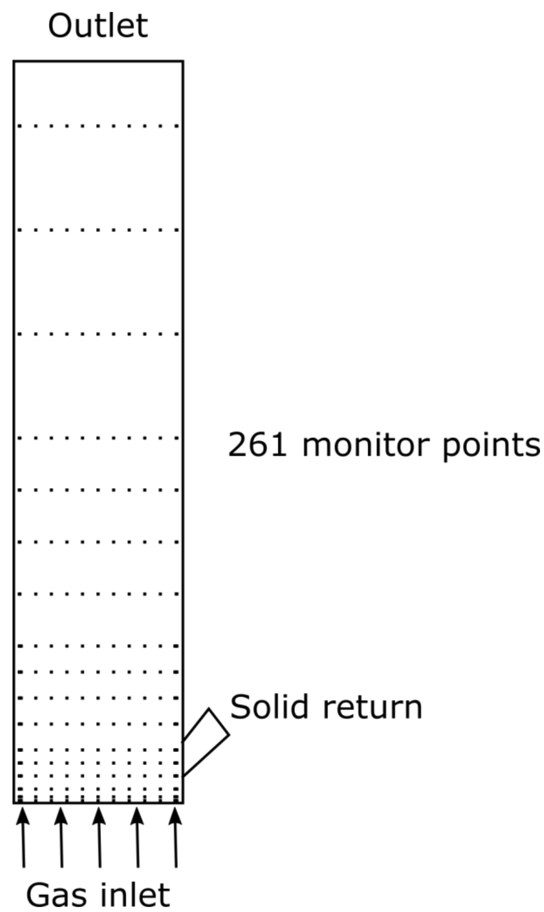
- Simulation carried out with OpenFOAM®, twoPhaseEulerFoam
- Included species $O_2$, CO, $CO_2$, $N_2$
- Single step combustion reaction

$$\mathrm{CO}(g) + \frac{1}{2}\mathrm{O}_2(g) \rightarrow \mathrm{CO}_2(g)$$

- CO released directly proportional to local solid volume fraction, global $\lambda = 1.0$
- Reaction rate limited by reaction kinetics and EDM turbulent rate ($k, \epsilon$ from Smagorinsky LES)

$$R_{kin} = A_r e^{-\frac{E}{RT}} [\mathrm{CO}][\mathrm{O}_2]^{1/2} [\mathrm{H}_2\mathrm{O}]^{1/2} M_{CO}$$

$$R_{turb} = \alpha \rho_g \frac{\epsilon}{k} A \min\left(\frac{Y_{CO}}{M_{CO}}, 2\frac{Y_{O_2}}{M_{O2}}\right) M_{CO}$$



# Numerical case setup cont.

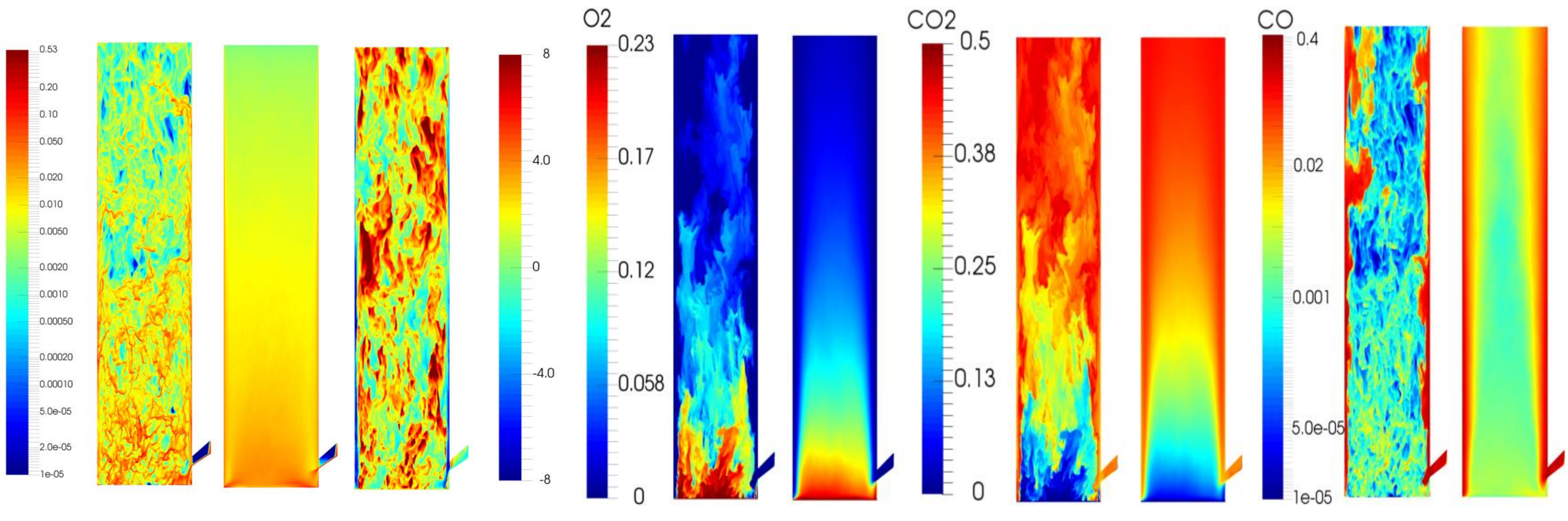
| Physical parameters | |
|---|---|
| Dimensions | 14x3x0.05 m |
| Fluidization velocity | 2.5 m/s |
| Particle diameter | 200 μm |
| Particle density | 2500 kg/m3 |
| Temperature | 1170 K |
| Mesh resolution | 12.5 mm |
| Cell count | 800 k |
| Time step | <0.25 ms |
| Simulated time | 80 s |

| Numerical Models | |
|---|---|
| Granular viscosity | Syamlal |
| Granular conductivity | Syamlal |
| Granular pressure | Lun |
| Frictional stress | Schaeffer |
| Radial Distribution | SinclairJackson |
| Drag | Gidaspow |

# Results: transient and time-averaged fields

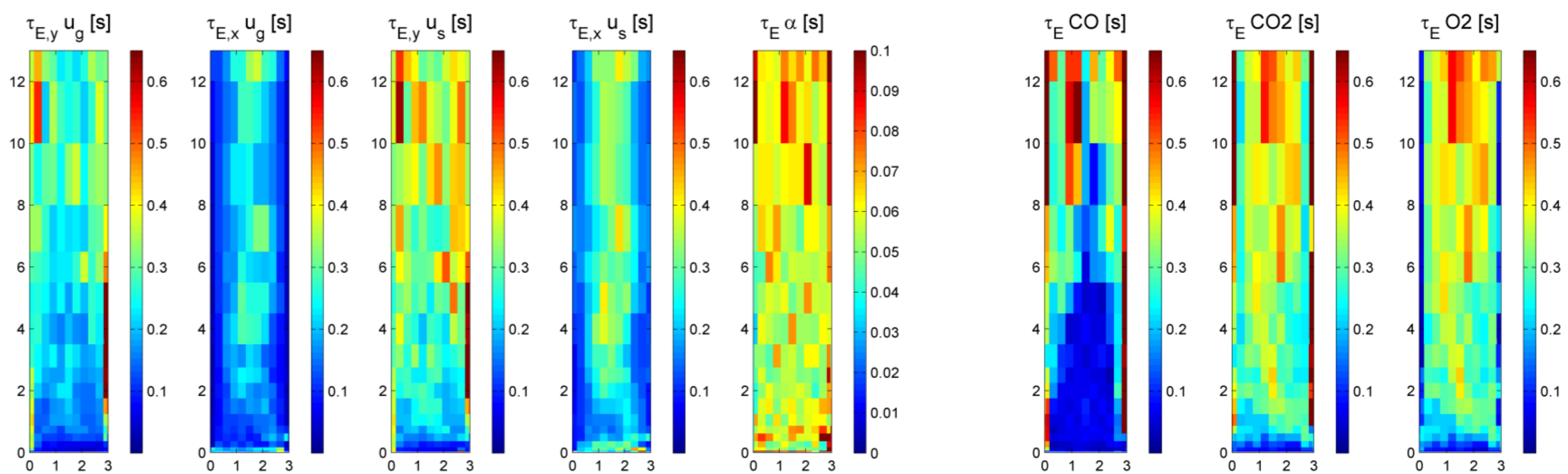
- $O_2$ concentration is high at the bottom, small near walls
- $CO_2$ and $O_2$ have opposite behavior
- Concentration of CO is mostly small, high near walls
- Length scales of $O_2$ and $CO_2$ similar to velocity field, CO similar to volume fraction field

Solid volume fraction Gas velocity Species mass fractions



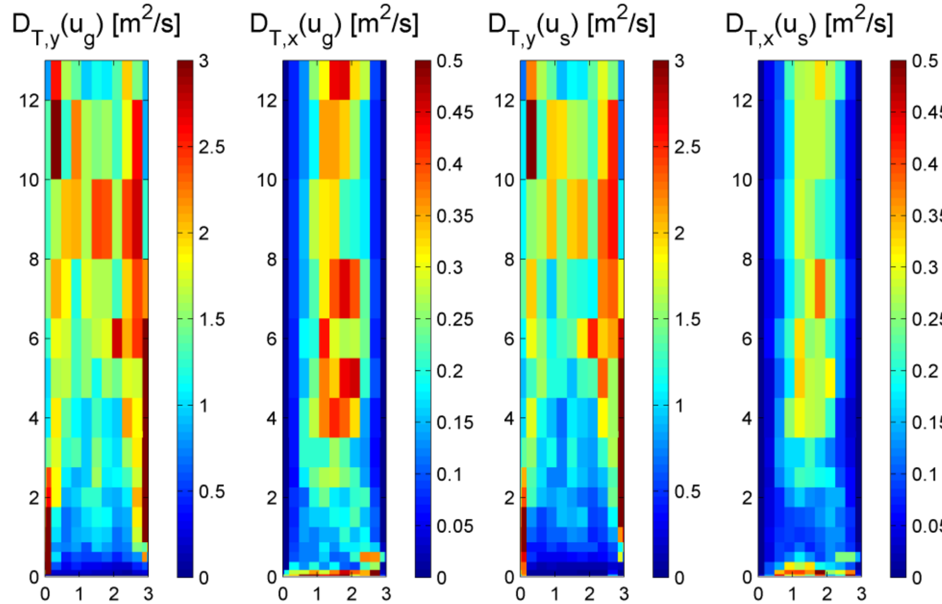
# Eulerian time scales

- Anisotropic and large locational dependence
- Solid phase time scales are longer than gas phase
- Fluctuation time scales of volume fraction are relatively uniform, shorter than those of velocity
- O2 and CO2 time scales roughly equal to velocity time scales
- CO has large spatial variance in the time scales; small time scales at the bottom, large near walls



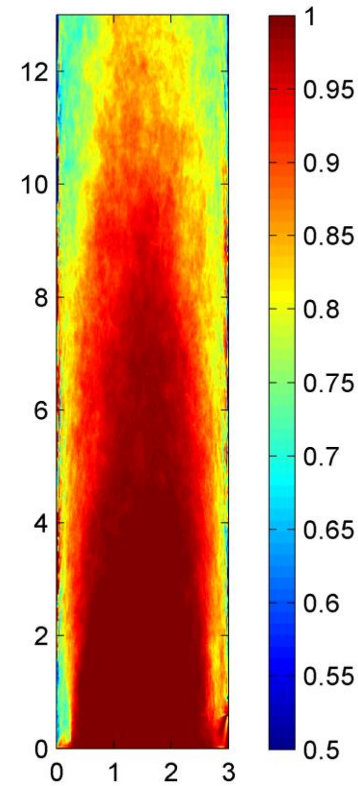
# Diffusion coefficients

- Horizontal diffusion is large at the very bottom, overall vertical diffusion is larger
- Vertical diffusion increases with height, horizontal diffusion is largest at the center
- Gas phase diffusion larger than solid phase

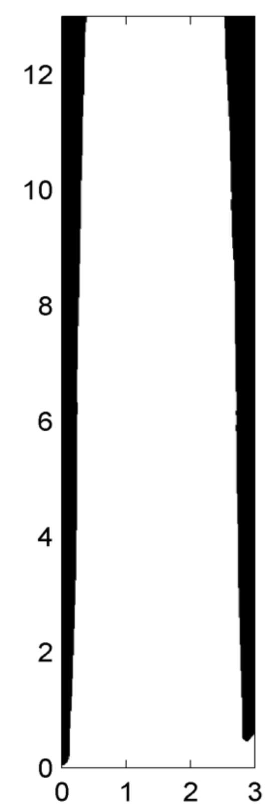


# Time averaged reaction rates

- In most parts of the riser the turbulent reaction rate has limited the reactions
- Based on the averaged concentrations, CO has usually limited the reaction rate
- Overall reactions have been fast compared to the source




The ratio of the average reaction rate to the local scale turbulent reaction rate

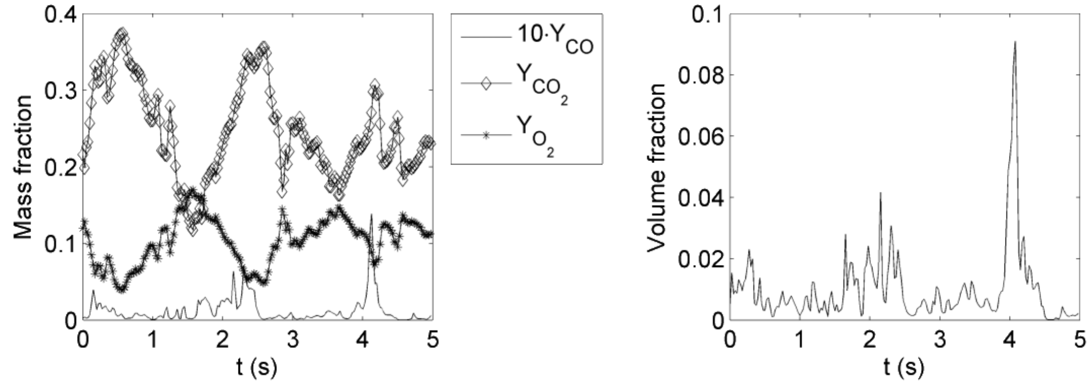



$O_2$ limited areas

# Examples of fluctuation patterns

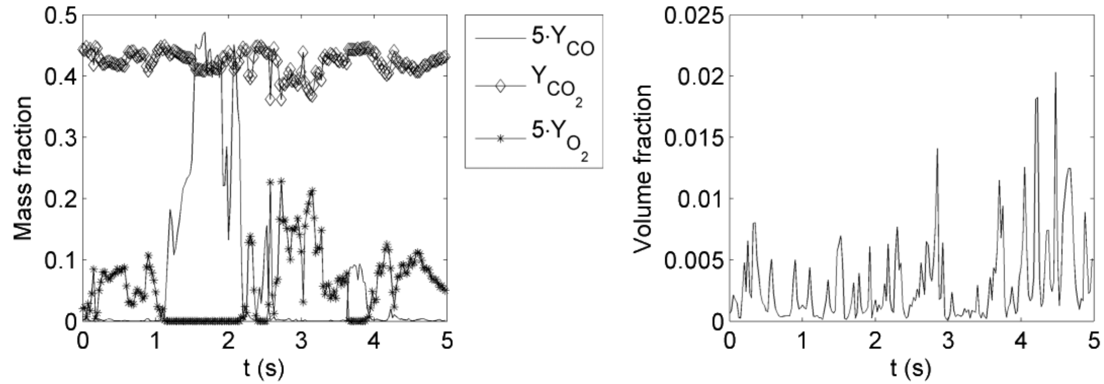
- At the bottom CO concentration closely follows solid volume fraction

3 m height



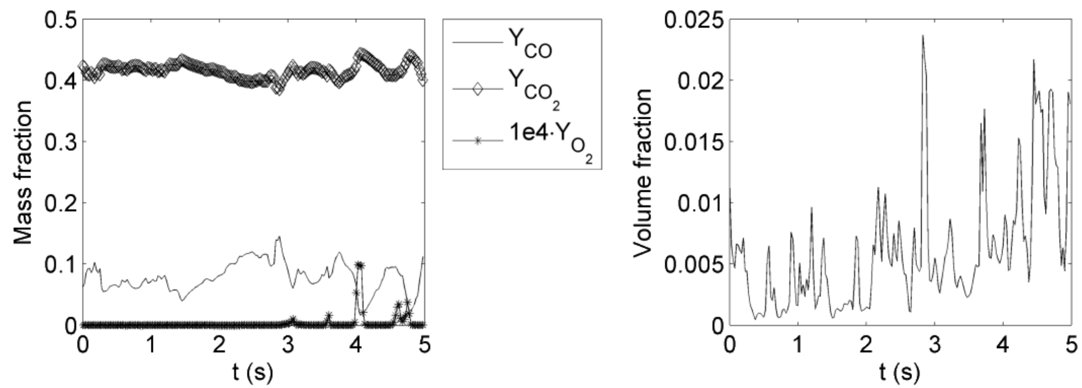

- Higher up the CO no longer follows solid volume fraction, $O_2$ and CO are linked

11 m height



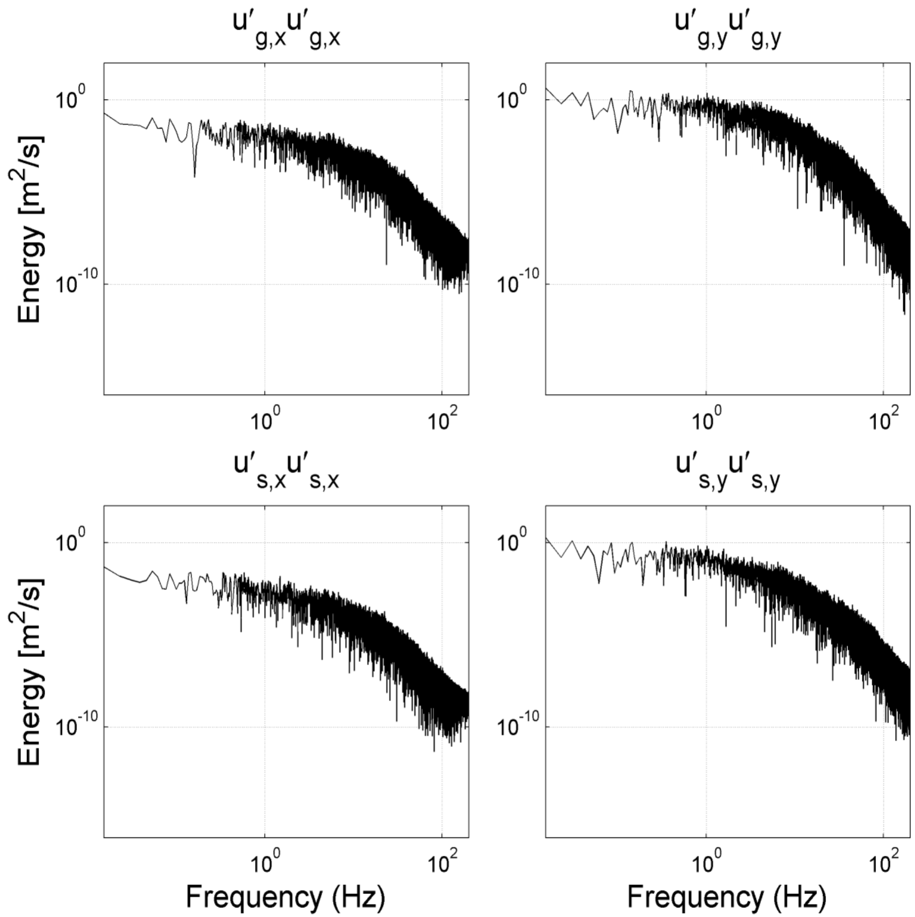

- Near to the wall $O_2$ only occasionally spikes

11 m height, near wall



# Results: example energy spectrum

- Largest energy at small frequencies, no clear peaks
- Typically gas velocity has larger fluctuations than solid, vertical fluctuations larger than horizontal
- Depend on position, eg. near walls horizontal fluctuations are small
- Species fluctuation spectrums are similar



# Reaction rate in time-averaged simulation

- How to calculate reaction rate from time-averaged variables?
- Simplest approach Eddy-Dissipation model

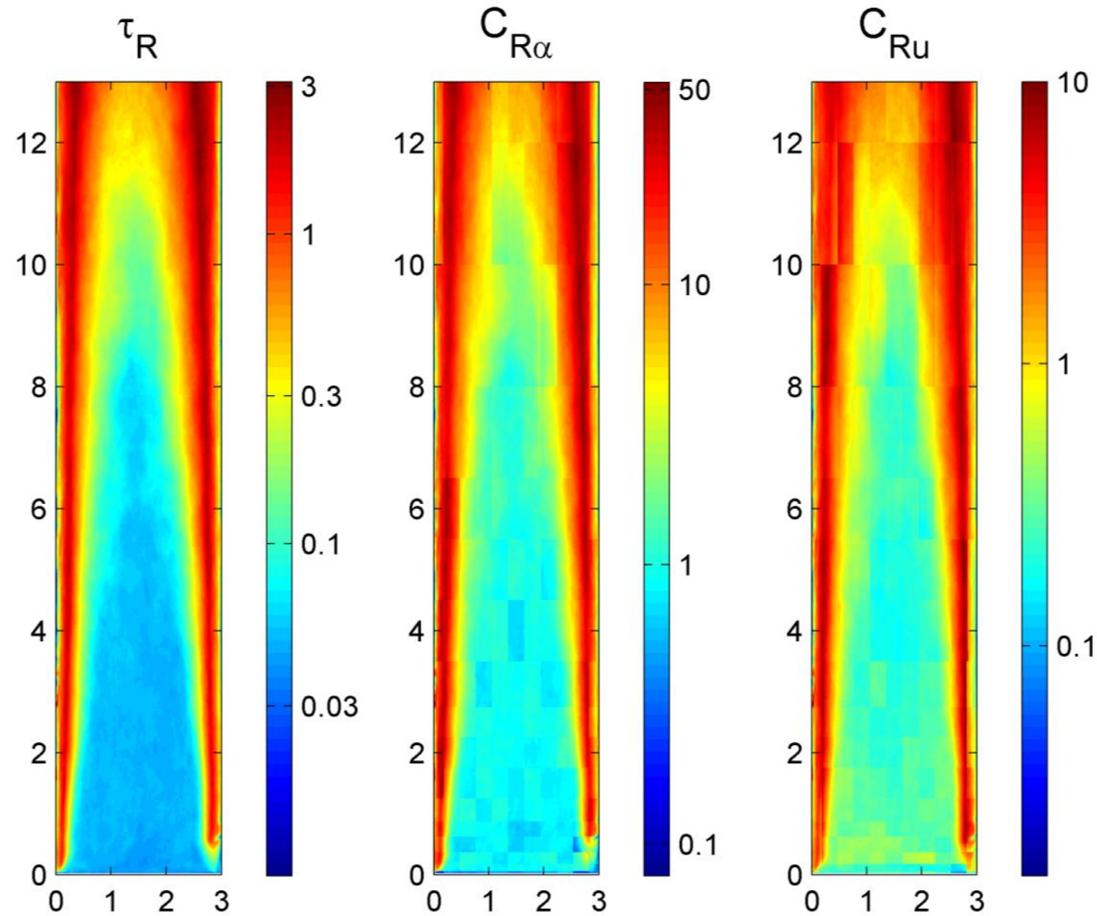
$$R_{eff} = \bar{\alpha}\,\overline{\rho_g}\frac{1}{\tau_R} A \min\left(\frac{\overline{Y_{co}}}{M_{CO}}, 2\frac{\overline{Y_{O_2}}}{M_{O2}}\right) M_{CO}$$

- Ideally $R_{eff} = \bar{R}$
- Question 1: what $\tau_R$ should we use?
- Question 2: can $\tau_R$ be obtained easily from the flow time scales?

$$\tau_R = C_{R\alpha}\tau_\alpha \qquad\qquad \tau_R = C_{Ru} \max\left[\tau_{E,x}\left(u_g\right), \tau_{E,y}\left(u_g\right)\right]$$

# Time scales for EDM-type reaction rate

- Required reaction time scale is not uniform
- Time scale does not directly resemble flow time scales -> constant correction does not work
- At the middle, the volume fraction time scales work quite well, near walls velocity scales are slightly better



# Future work

- More simulations with varying conditions are needed
  - Different stoichiometric ratios, secondary air inlets
- Sensitivity studies for reaction rate
  - How the situation changes if reactions are slower or faster?
  - Effect of the turbulent reaction rate assumptions

For time averaged reaction rate model:

- Validation of the transient reaction rates in small scale/pilot scale
- Include varying temperature and $H_2O$ concentration, CO release from fuel particles

# Summary

- Simplified CFD simulation of combustion in a CFB was performed
- Fluctuation time scales were determined for velocity, voidage and gas species concentrations
- The  time scales strongly depend on the location in the riser and on flow conditions
- Applicability of Eddy-Dissipation type reaction model for time-averaged simulation was investigated

# Acknowledgements


**CLIFF-project**

Clustering Innovation Competence of Future Fuels in Power Production

July 2014 - June 2017

TEKES

TOP ANALYTICA

UPM

CLYDE BERGEMANN Power Group

INTERNATIONAL PAPER

Valmet

amec foster wheeler

ANDRITZ

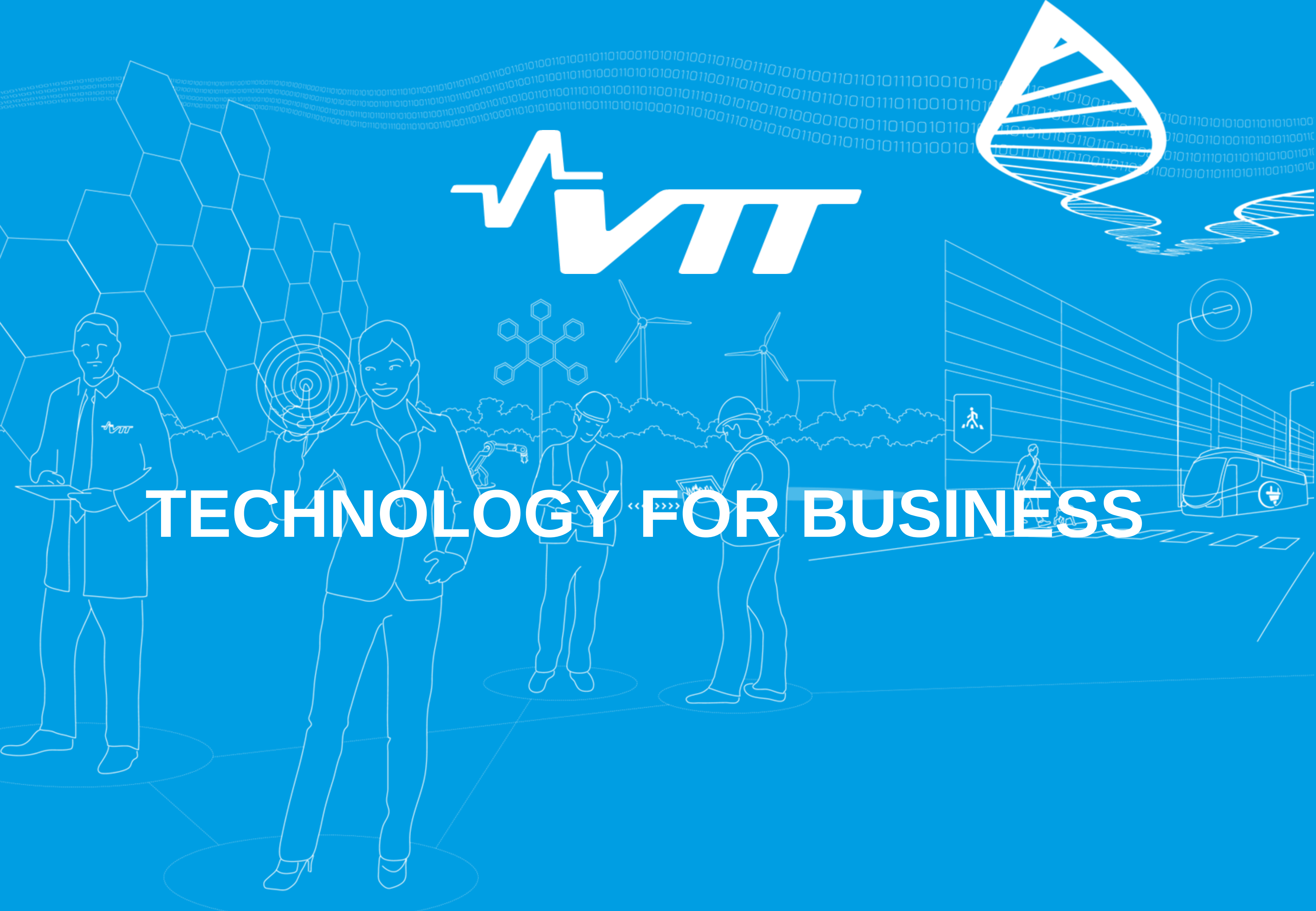
Aalto University

Open your mind. LUT.
Lappeenranta University of Technology

Åbo Akademi

TAMPERE UNIVERSITY OF TECHNOLOGY

VTT



# TECHNOLOGY FOR BUSINESS