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3D CFD modelling of solid biomass combustion in grate furnaces

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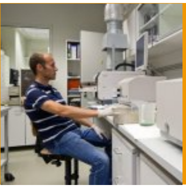
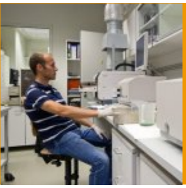


Contents

- Scope of work
- Methodology
- Model overview
  - Thermal conversion of solid biomass in packed beds
  - Hydrodynamics of a packed bed
- Results
  - Particle motion on the grate
  - Thermal conversion of particles and particle temperature
  - Gas phase temperature and species concentrations at the bed surface
- Summary and conclusions
- Outlook



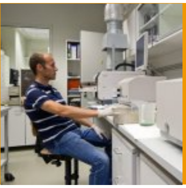
Scope of work

- Development of a CFD based model for packed bed combustion in biomass grate furnaces
- A model for the thermal conversion of the packed bed should include models for
  - the particle movements in the fuel bed
  - the thermal conversion of the particles
- Link of the packed bed model and link with an in-house developed CFD model for the turbulent reactive flow in the combustion chamber
- Application and test of the model with a 20 kW underfeed stoker grate furnace and a pilot-scale moving grate furnace (180 kW)

Methodology

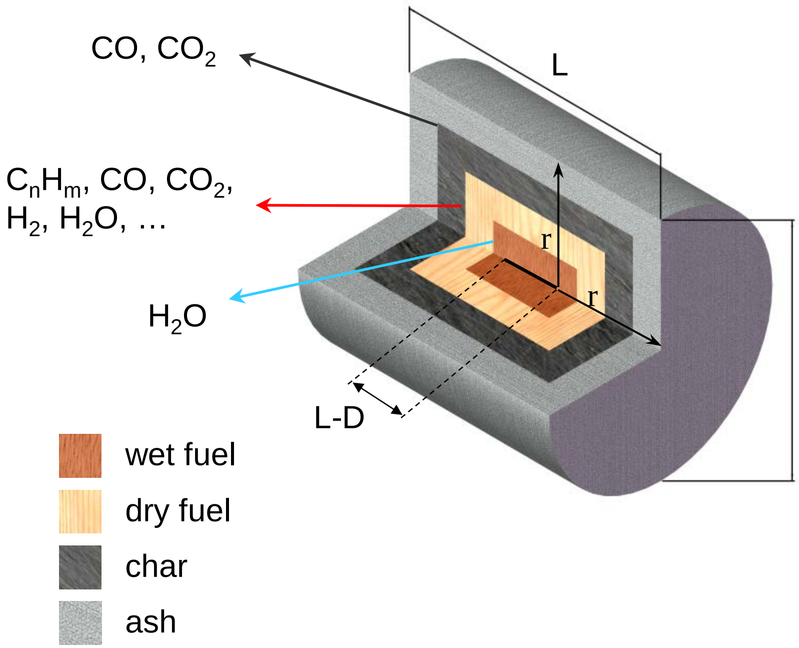
Modelling of the thermal conversion of packed beds can be divided into two parts:

1. Thermal conversion of particles
    - A layer model, implemented as UDF in ANSYS FLUENT, has been developed to consider the biomass particles as thermally thick particles with intra-particle gradients.
2. Hydrodynamics of packed beds
    - The Euler-Granular model of ANSYS FLUENT is used, since it allows to consider particle-particle collisions.
    - The Euler-Granular model does not enable to hook the layer model.
    - The velocity field of the particle phase from the Euler-Granular simulation without chemical reactions is saved and is then used in the subsequent simulation of particle combustion with the Discrete Phase Model.

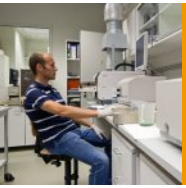


Thermal conversion of particles (layer model) (I)

- Spherical and cylindrical particles can be modelled by the layer model
- A particle is discretised in four layers
- Each layer corresponds to a conversion stage (wet fuel, dry fuel, char, ash)
- Boundaries between the layers correspond to the conversion fronts of the sub-processes (drying, pyrolysis, char burnout), which move towards the particle centre during conversion
- Simultaneous progress of the sub-processes is possible



- Advantage: the consideration of the intra-particle gradients improves the results of particle conversion rates
- The model is published in Fuel Processing Technology, 95 (2012), pp. 96-108.



Thermal conversion of particles (layer model) (II)

- Drying is assumed to take place at a constant temperature (the boiling temperature of water). Therefore, the drying rate is limited by the heat transfer.
- Pyrolysis is described by three independent competitive reactions for cellulose, hemicellulose, and lignin.
  - The kinetic rate of each reaction is calculated by an Arrhenius equation.
  - The empirical constants are obtained from fuel specific fast heating rate TGA experiments.
- Char oxidation and gasification reactions are assumed to be limited by the mass transport rate.
  - CO and CO_2 are the products of char oxidation.
  - Char gasification with H_2O, CO_2 and H_2 is also considered.

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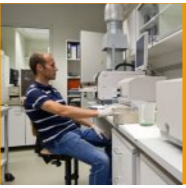
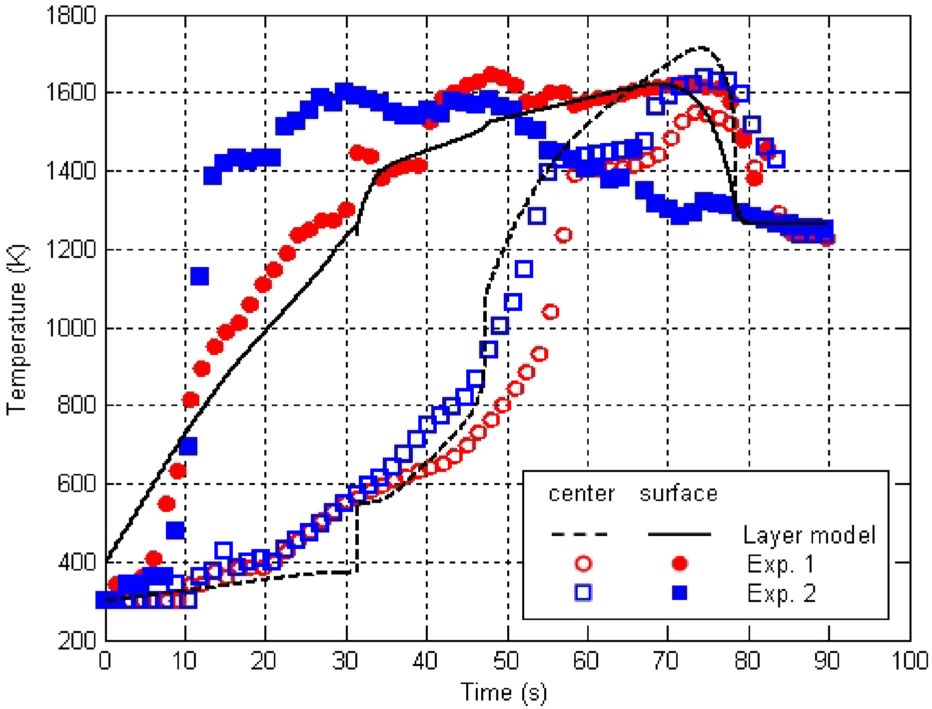
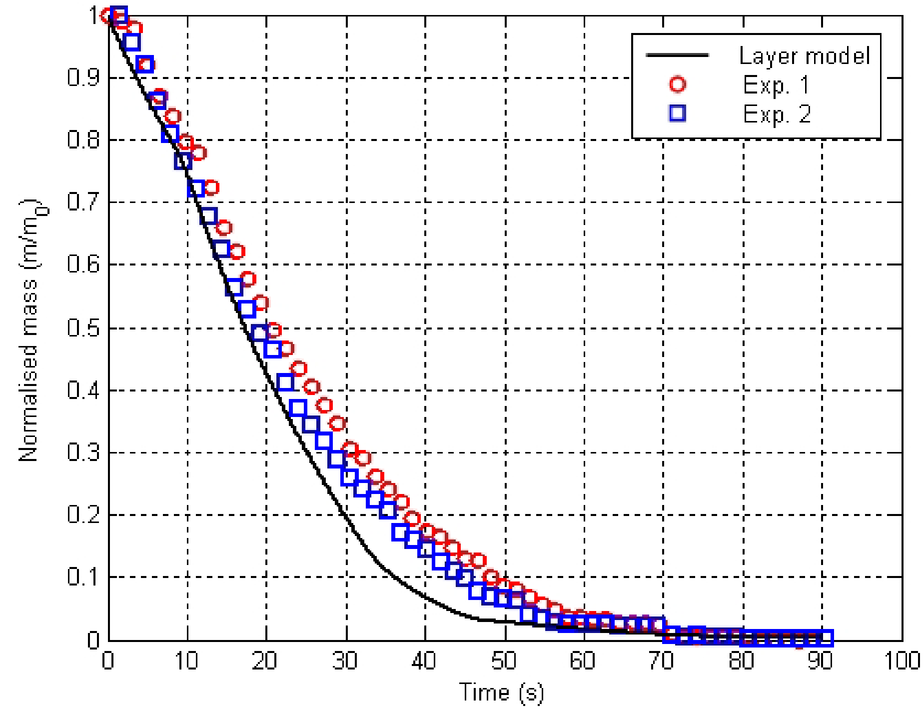


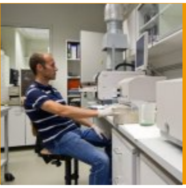
Validation of the layer model





- Experimental setup:
  - Single particle reactor, oxidising conditions
  - Fuel: poplar wood (cylindrical particle)
  - Water content: 40 (wt% w.b.)
  - Diameter: 9.5 (mm); length = 9.5 (mm)
  - Reactor wall temperature: 1276 (K)
  - Air temperature: 1050 (K)

Exp. data: Lu H., *Experimental and modeling investigation of biomass particle combustion*, Ph.D. thesis, 2006, Brigham Young University.

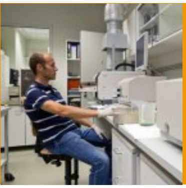


Hydrodynamics of the packed bed

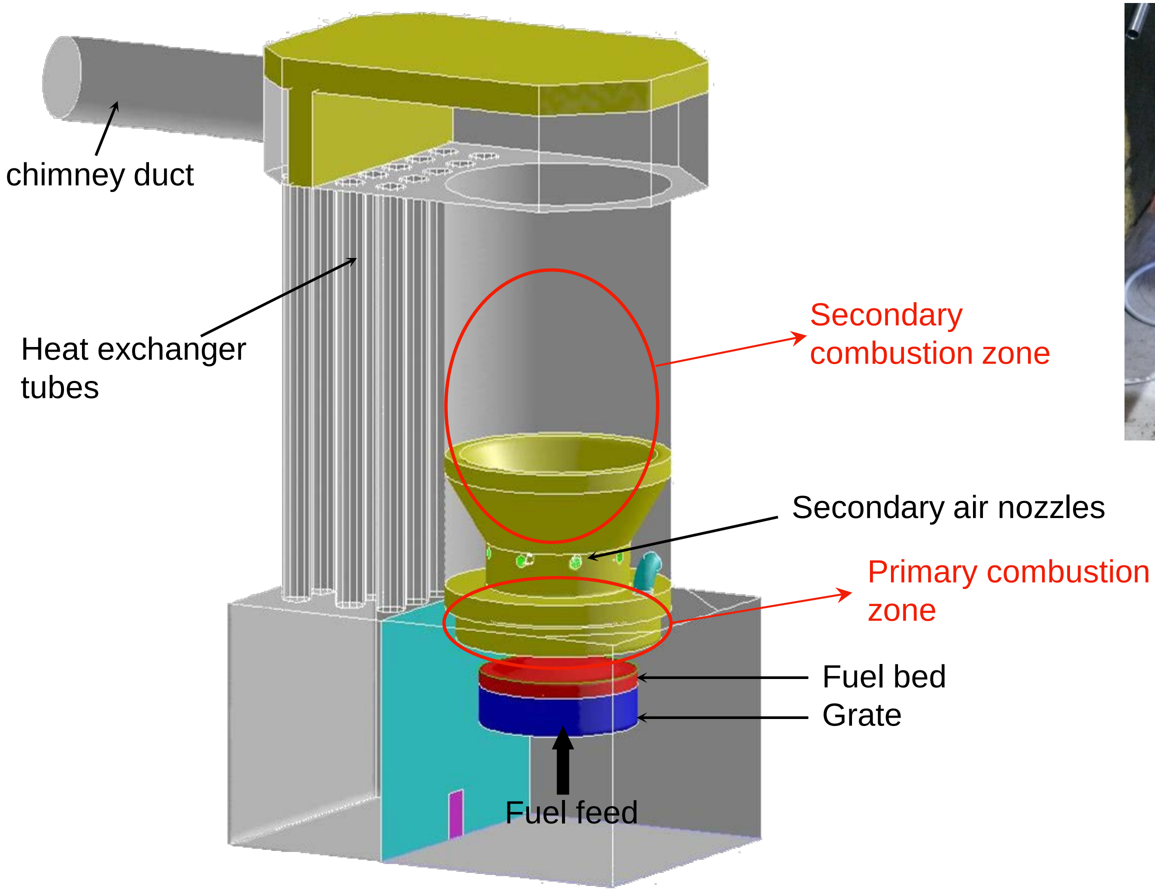
- The Euler-Granular model assumes that the particle phase behaves as a fluid. Therefore, the continuity and momentum equations are solved for both gas and particle phases:
- An additional conservation equation is formulated for the granular temperature:

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\alpha_s\rho_s T_G)+\nabla\cdot(\alpha_s\rho_s\vec{u}_s T_G)\right]=\overbrace{\left(\overline{\tau}_s-p_s\overline{I}\right):\nabla\vec{u}_s}^{\text{Production}}+\overbrace{\nabla\left(\kappa\nabla T_G\right)}^{\text{Diffusion}}-\overbrace{\gamma}^{\text{Dissipation}}-\overbrace{3K_{gs}T_G}^{\text{Exchange}}$$

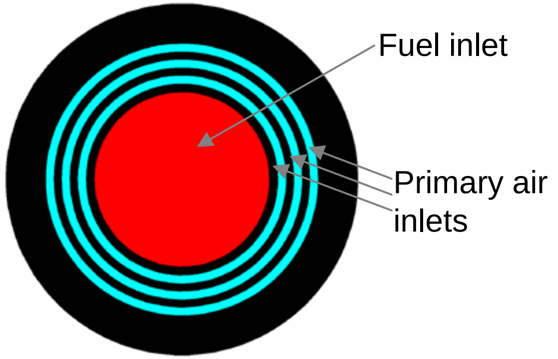
- The granular temperature T_G is associated with the kinetic energy of the particle fluctuation around the mean velocity.
- To close the governing equations the constitutive equations are required for the following parameters: solid stress tensor $\overline{\tau}_s$, solid pressure p_s, diffusion coefficient κ, collisional dissipation γ and momentum exchange coefficient K_{gs}.



Example 1: simulation of 20 kW underfeed stoker furnace



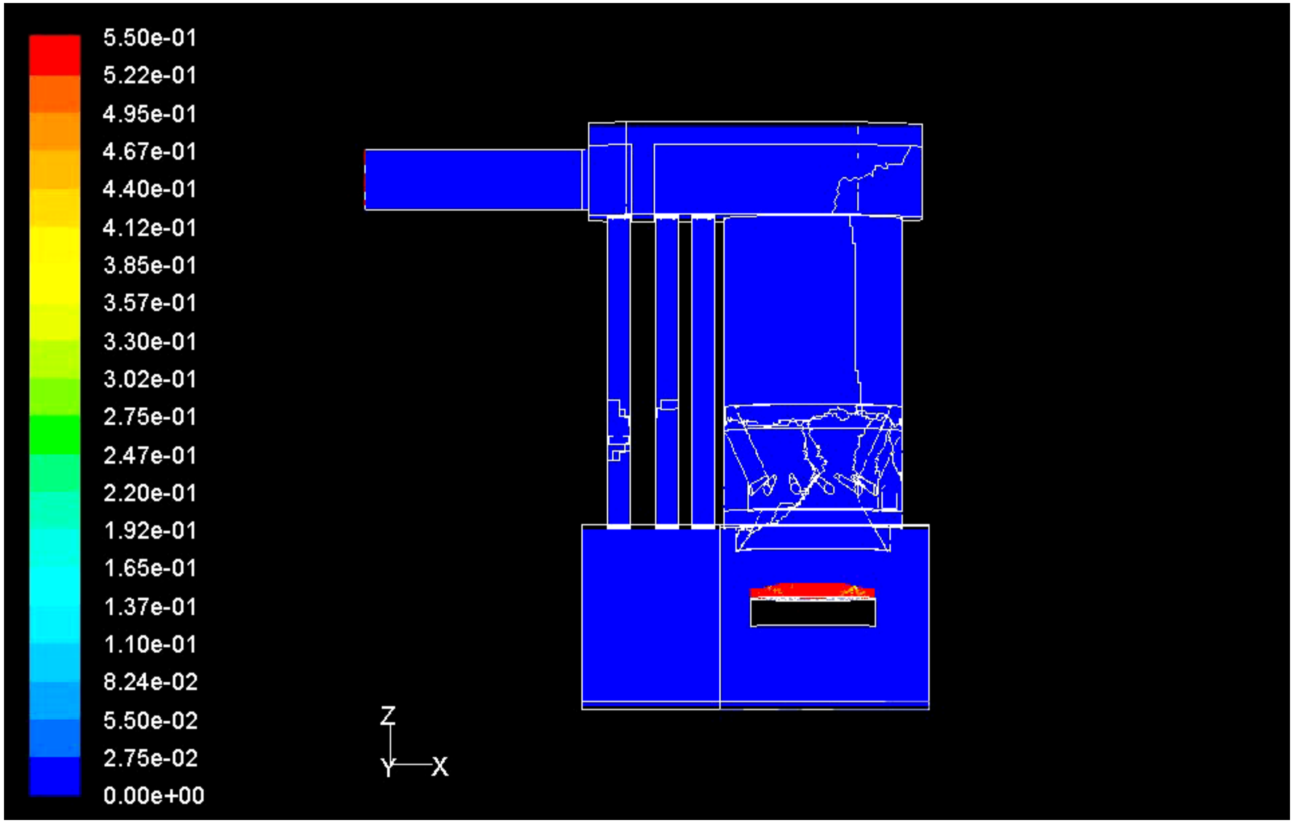
Picture of the grate



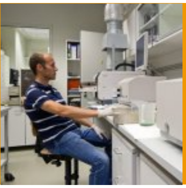
Scheme of the grate used for simulations

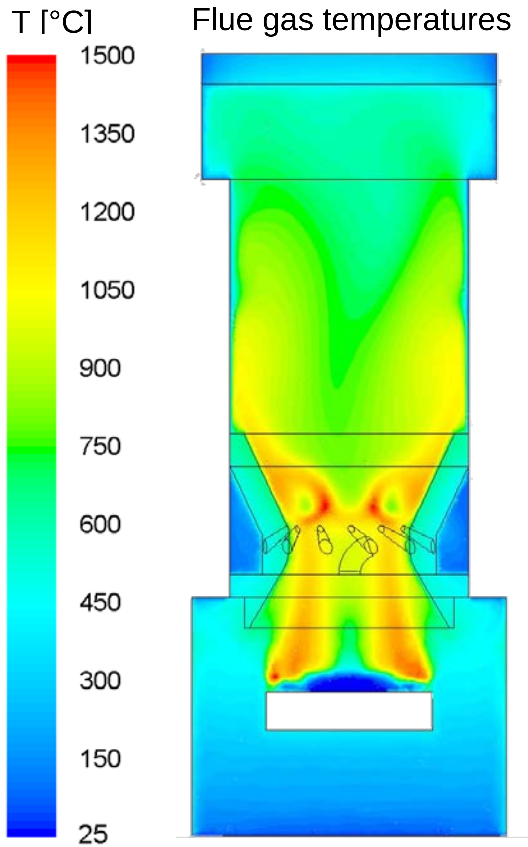
<u>Operating data:</u> Biomass fuel: softwood pellets;
Moisture content= 8.1 wt.% (wet base); λ_{total}= 1.58; λ_{prim}= 0. 64, no flue gas recirculation

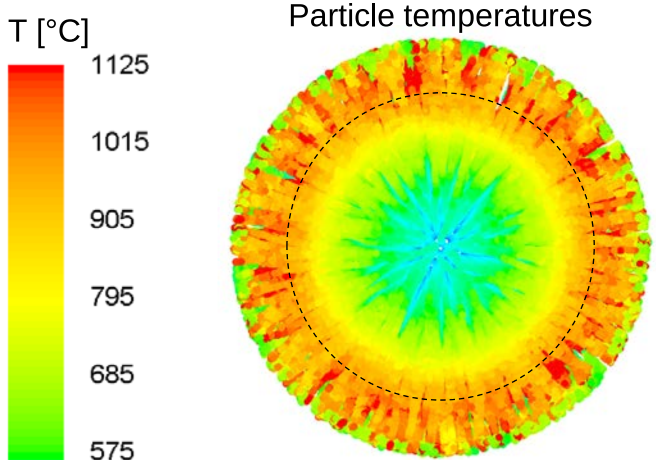
Particle motion on the grate



Particle and flue gas temperatures [°C]







Visual observation

Explanations: Biomass fuel: softwood pellets;
Moisture content= 8.1 wt.% (wet base); λ_{total}= 1.58; λ_{prim}= 0. 64, no flue gas recirculation

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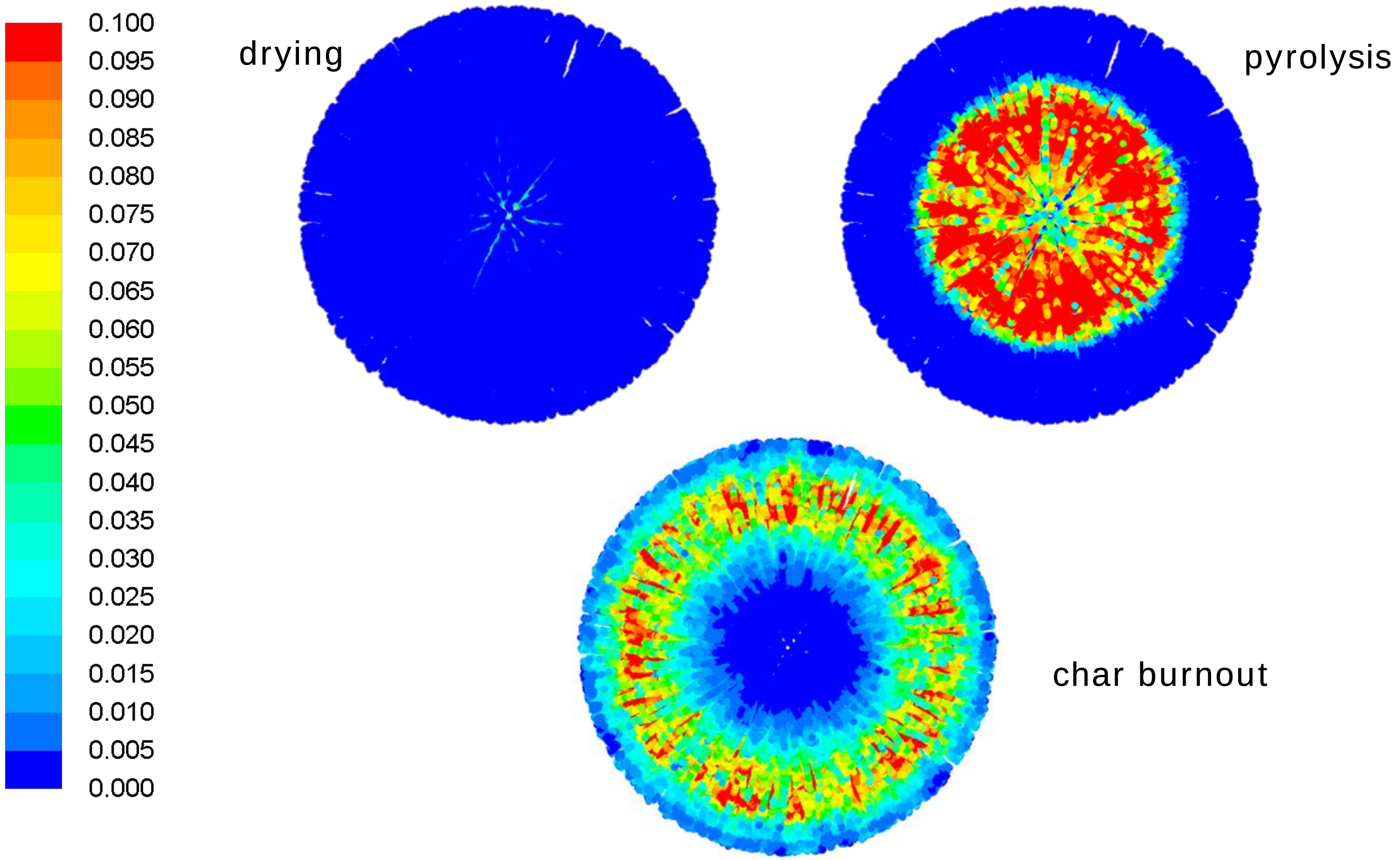
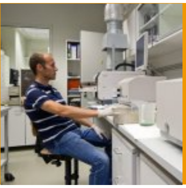
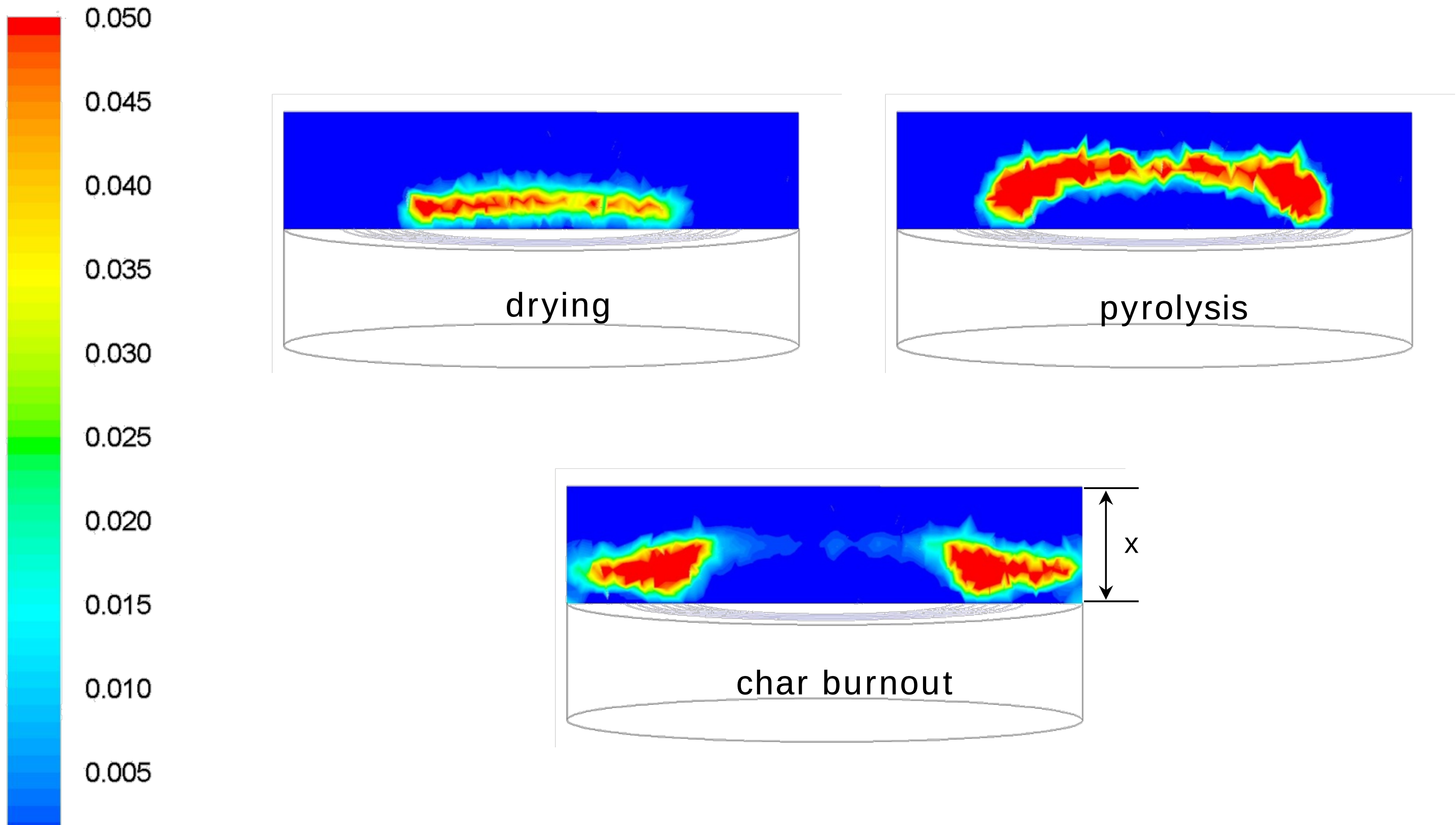
Particle tracks coloured by release rates [mg/s]



The concentration of unburned char in the ash is less than 1 wt.% (d.b.), which is in good agreement with experimental results.

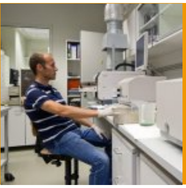


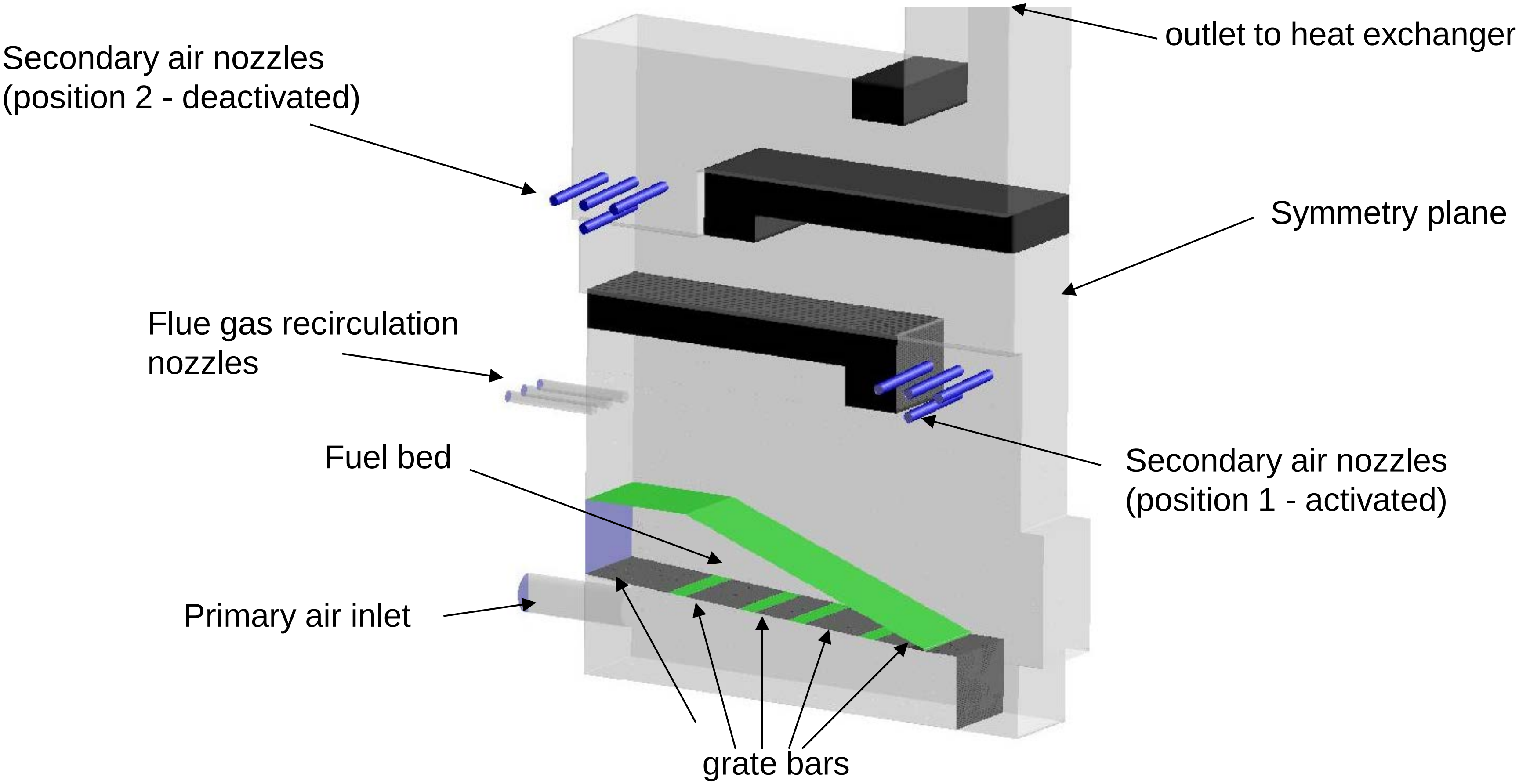
Contours of release rates [mg/s]



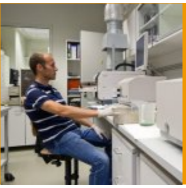
Contours of release rates at a vertical cross section through the grate axis; x= 5cm bioenergy2020+

Example 2: simulation of a 180 kW moving grate furnace



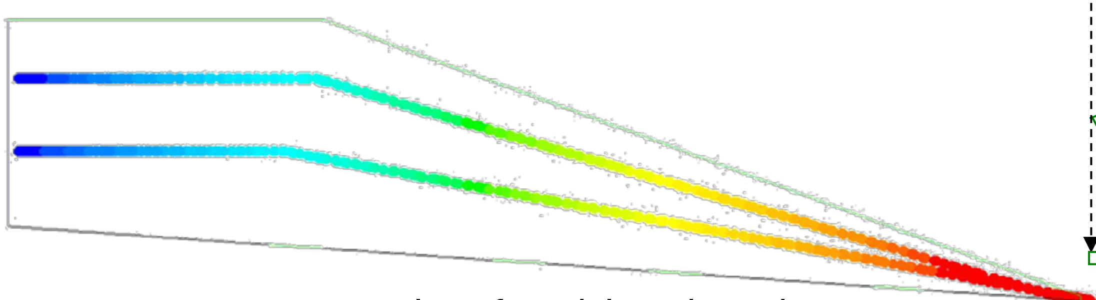


Operating data: Biomass fuel: spruce wood chips;
Moisture content= 21.8 wt.% (wet base); λ_{grate}= 0.69; $\lambda_{PCC\ incl.\ FGR}$ = 0. 9; λ_{total}= 1.67

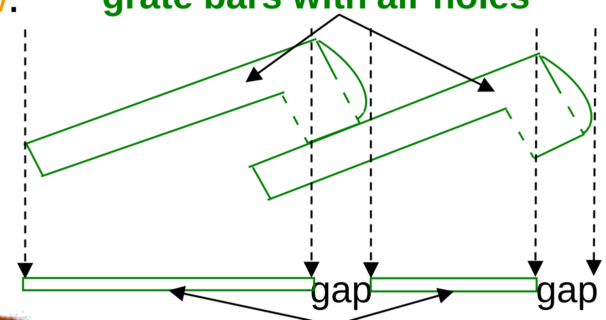


Methodology
Grate position & simplification

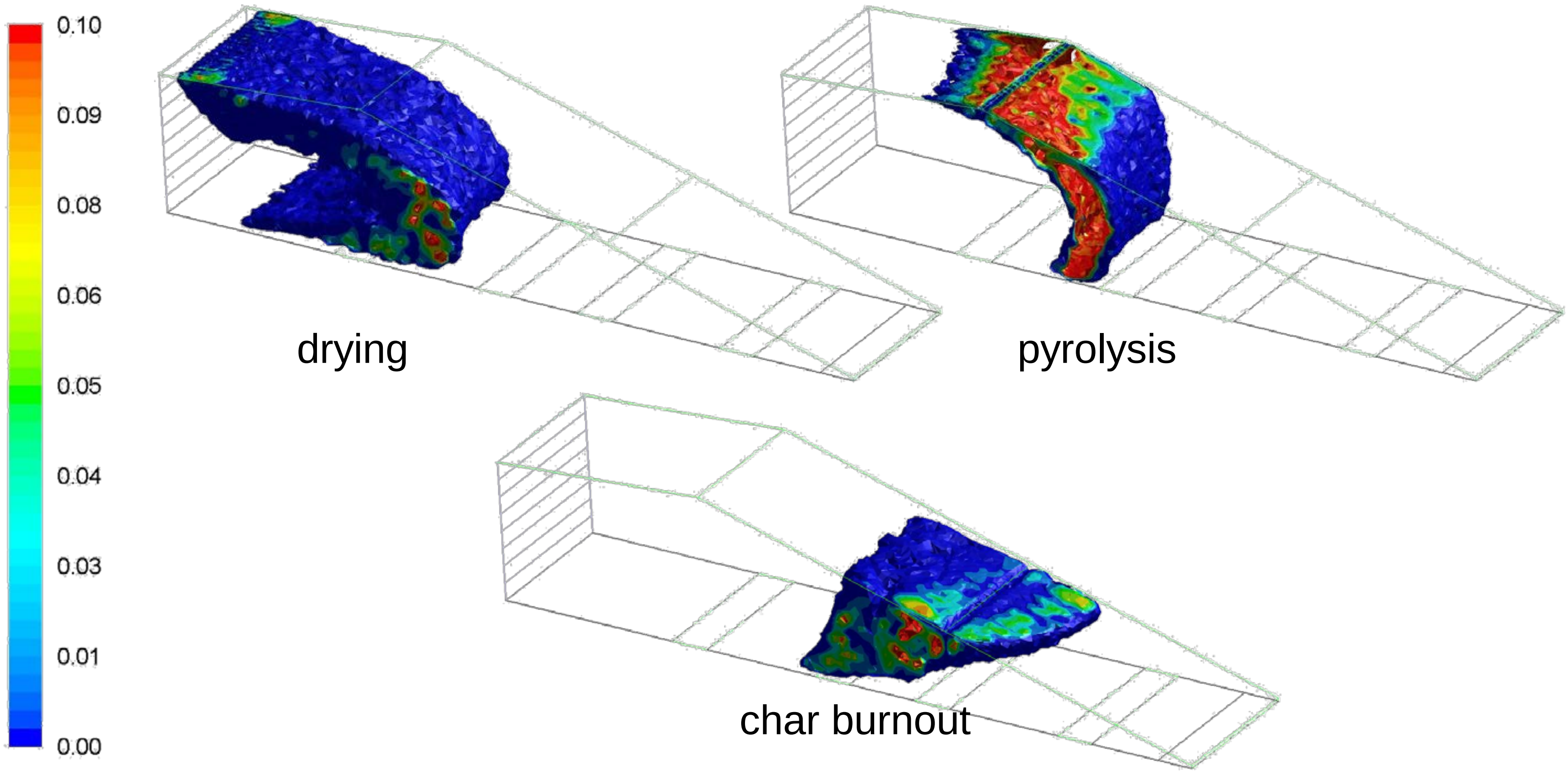
- Even in steady state operations, a time-dependent variation of fuel conversion is taking place due to the grate movements. For the selected test run, a grate position has been chosen, where the conversion was at its average value.
- After the position of the grate was chosen, its geometry was simplified by projecting it to a plane, as it is shown below.
- Due to the simplification of grate bars, the particle velocities are pre-defined and together with their trajectories are included in a UDF and coupled to ANSYS Fluent. Two particle paths are shown below.
- Primary air is introduced below the grate, where it is distributed and passes through the gaps in the grate. During the flow through the gaps, the air is heated by the grate bars.
- The pressure drop through the bed was also modelled by treating it as a porous medium. The coefficients were defined according to Ergun’s law.



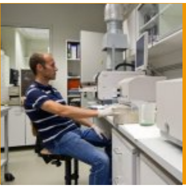
Two examples of particle trajectories



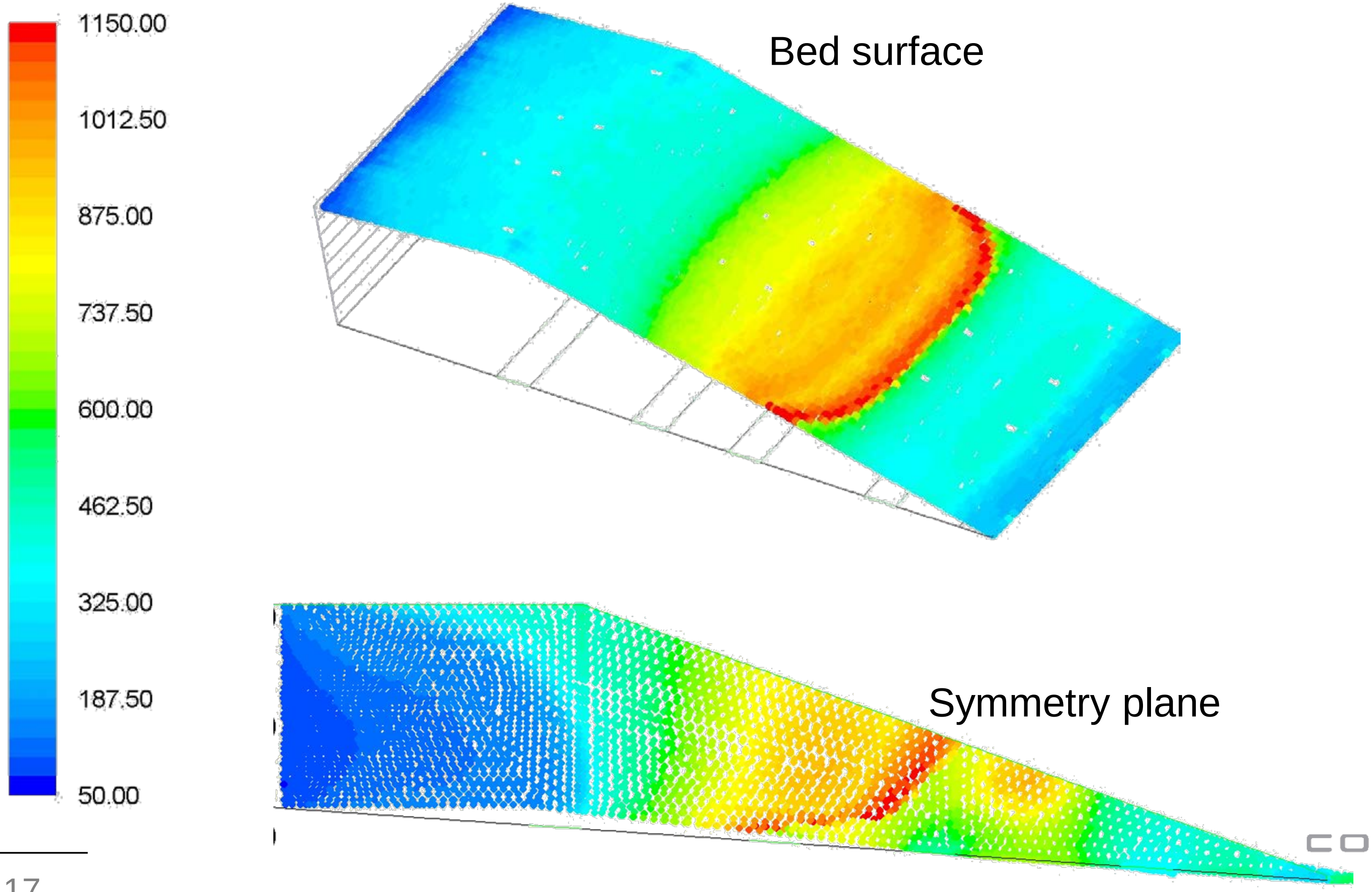
Release zones inside the fuel bed coloured by the release rates [mg/s]



Half of the grate width is shown; from the wall to the symmetry plane.



Particle temperature at the surface of the fuel bed and in the symmetry plane [°C]



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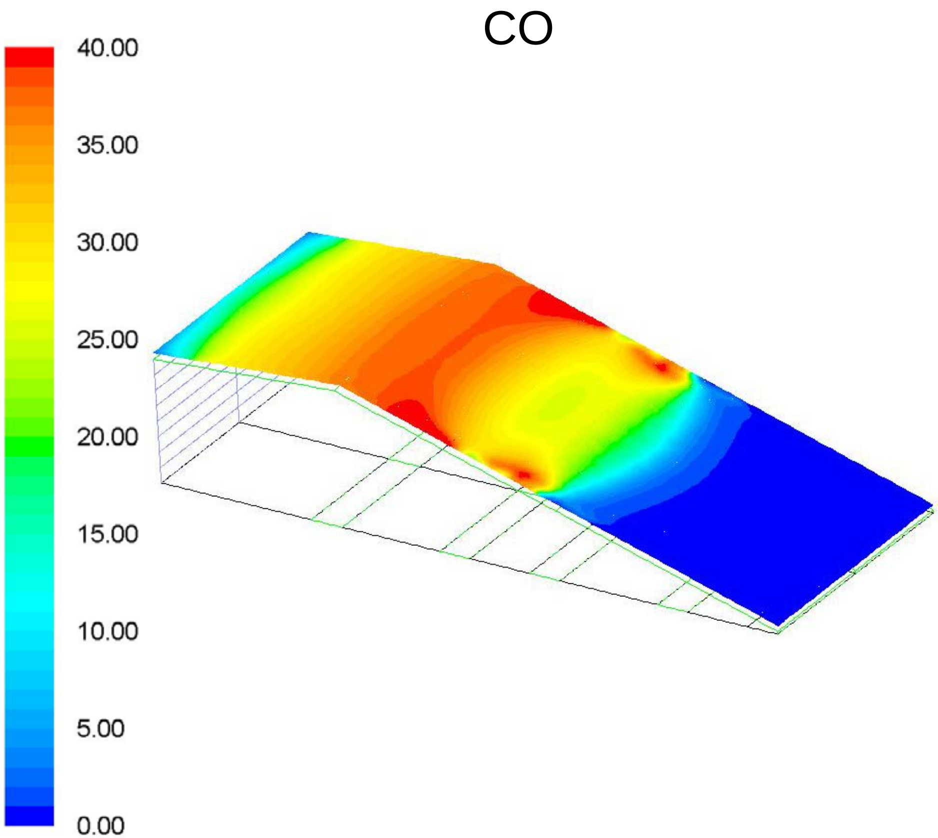
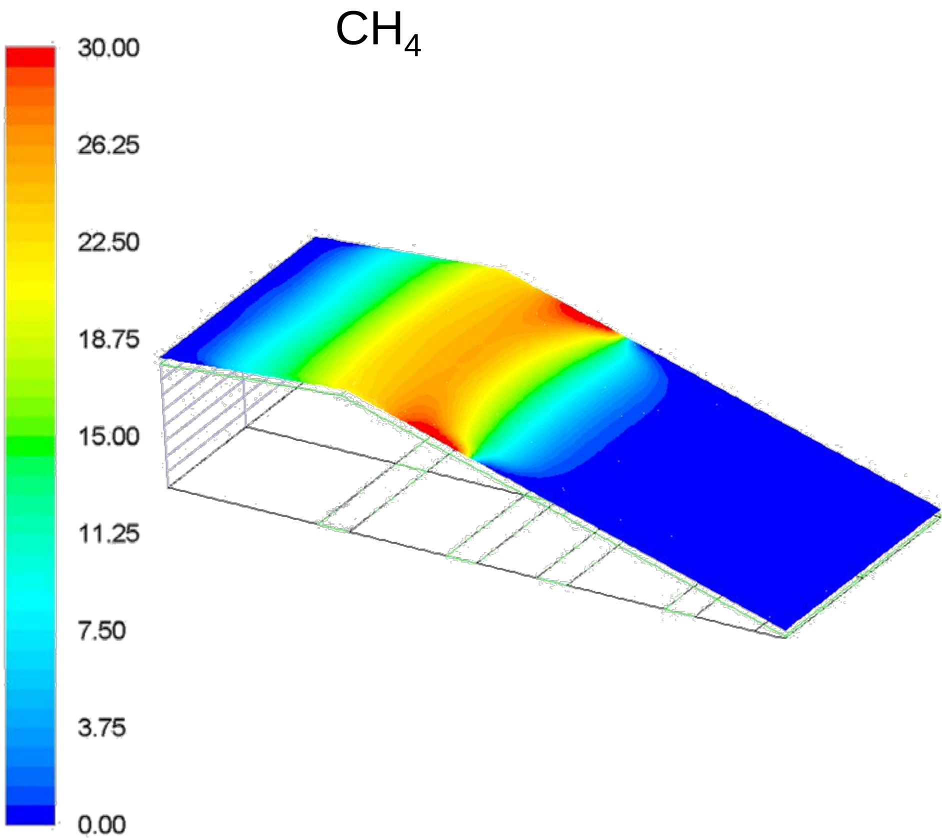
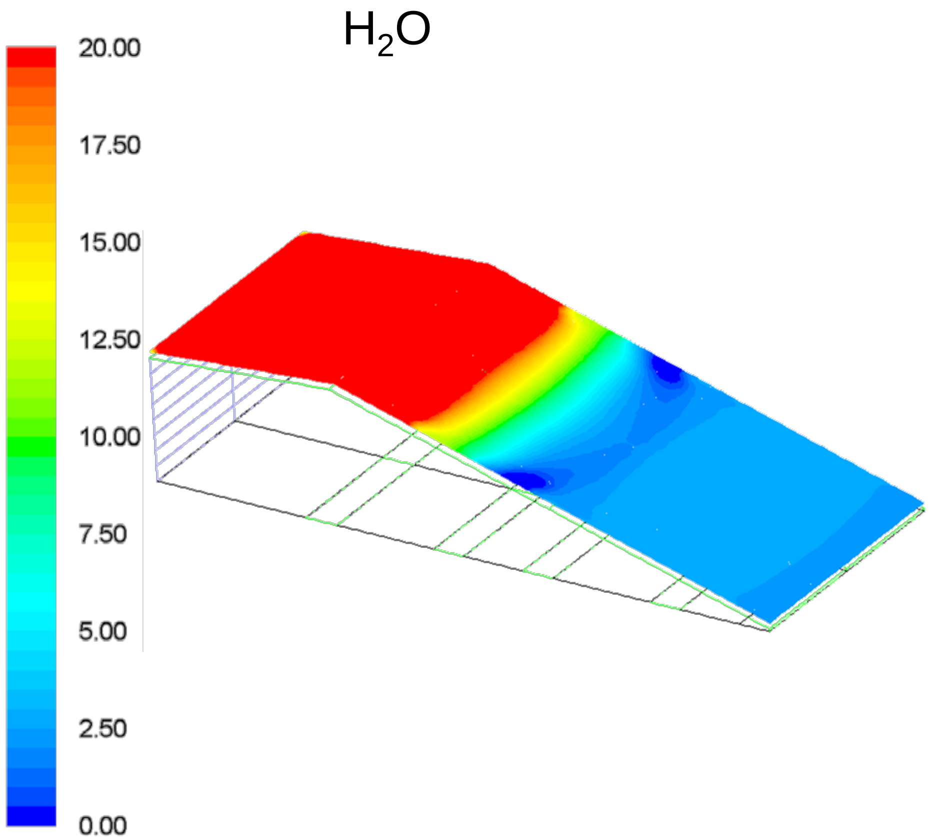
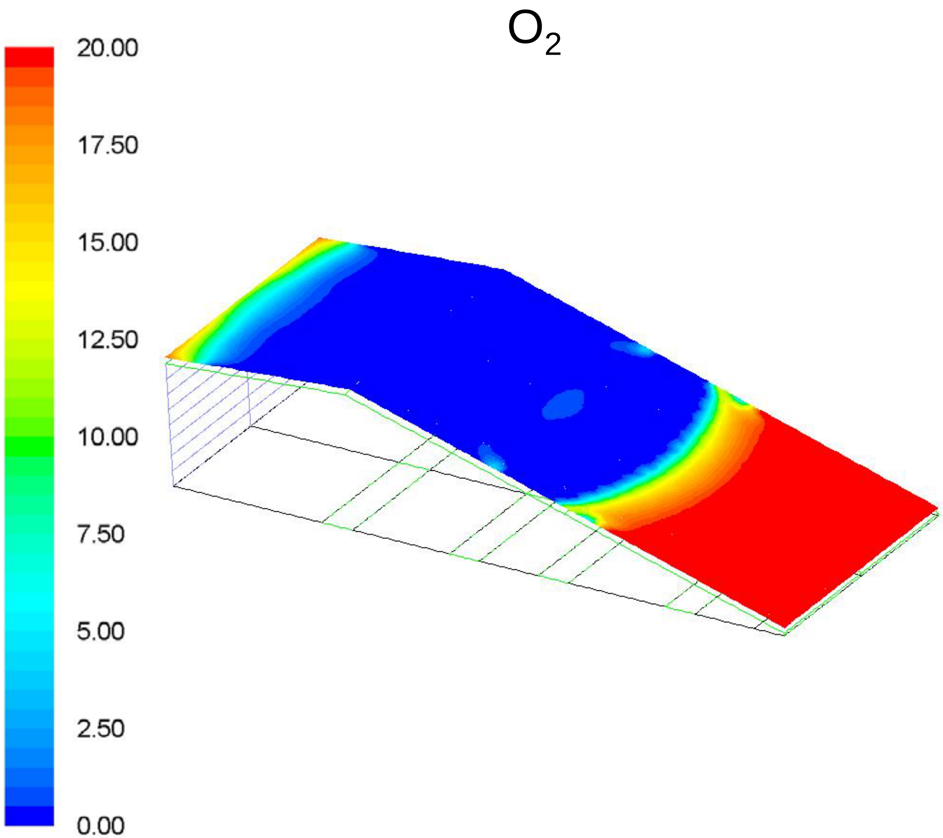
CO and CH_4 (vol.% d.b.) concentrations at the surface of the fuel bed

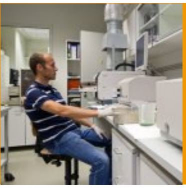




H_2O (vol.% w.b.) and O_2 (vol.% d.b.) concentrations at the surface of the fuel bed



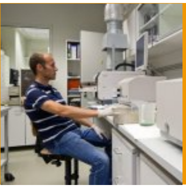




Summary and conclusions

A CFD based model for packed bed combustion in biomass grate furnaces has been developed and successfully tested. The model has the following advantages:

- Approximating the particle movements on the grate under consideration of particle-particle collisions (already applied for the fixed grate and is on-going for the moving grate).
- Due to the consideration that the particles are thermally thick, the particle temperatures and consequently the mass loss rate during the thermal conversion of the particles can be better predicted.
- The effect of particle related parameters (size, physical properties and moisture content) as well as operating conditions (air distribution below the grate, air pre-heating, flue gas re-circulation and air staging) can be investigated.
- The packed bed modelling has been linked with an in-house developed gas phase CFD model for turbulent reactive flows in the combustion chamber. Hence, also the influence of flow, gas phase combustion and heat transfer from the combustion chamber on packed bed conversion is considered.



Outlook

Further developments planned:

- Development of an enhanced heat transfer model for the packed bed (considering particle-particle radiation and conduction)
- Application of an appropriate gas-solid multiphase model to simultaneously simulate the movement and the thermal conversion of the particles.

Thank you for your attention

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