Simulation of combustion in porous media

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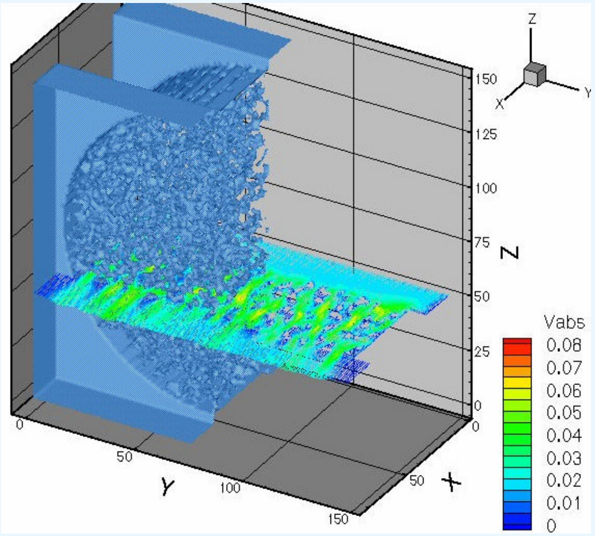
Outline

- Numerical simulation of combustion in porous media
- Numerical modeling
- Pseudo-homogeneous model
- Results pseudo-homogeneous model
- Heterogeneous model
- Results heterogeneous model
- Summary

Direct simulation:

Lattice-Boltzmann

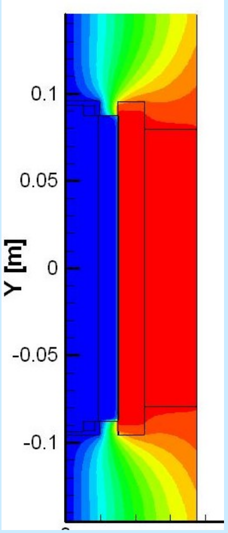
- no heat transfer (ongoing work)
- simple kinetics



Simulation with homogeneous approach:

Finite-Volume-Method

- Effective properties of porous media
- Model for heat transfer necessary



$$\frac{\partial(\rho v_j)}{\partial x_j} = 0$$	**mass**
$$\frac{\partial}{\partial x_j}\left(\rho v_j v_i - \mu \frac{\partial v_i}{\partial x_j}\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial v_j}{\partial x_i}\right) + \rho g_i$$	**momentum**
$$\frac{\partial}{\partial x_j}\left(\rho v_j c_P T_g - \lambda_g \frac{\partial T_g}{\partial x_j}\right) = \sum_{k=1}^{N_S} \dot{\omega}_k \Delta h^0_{j,k} + \frac{\partial}{\partial x_j}\left(\sum_{k=1}^{N_S} \rho h_k D_k \frac{\partial Y_k}{\partial x_j}\right)$$	**energy**
$$\frac{\partial}{\partial x_j}\left(\rho v_{s,j} Y_k - \rho D_k \frac{\partial Y_k}{\partial x_j}\right) = \dot{\omega}_k$$	**species**

Modification of transport equations

$$\frac{\partial(\rho v_{s,j})}{\partial x_j} = 0$$

Mass balance, s: „superficial velocity“

$$\frac{dp}{dx_i} = -\frac{\mu}{k_{1,ij}} v_{s,j} - \frac{\rho}{k_{2,ij}} \left| v_{s,j} \right| v_{s,j}$$

additional pressure loss

$$\frac{\partial}{\partial x_j}\left(\rho v_{s,j} Y_k - \rho \varepsilon D_{k,eff} \frac{\partial Y_k}{\partial x_j} \right) = \dot{\omega}_k$$

conservation of species, influence of dispersion

Pseudo-homogeneous model

Energy equation for artificial fluid phase:

$$\frac{\partial}{\partial x_j}\left(\rho v_{s,j} c_P T_g - \lambda_{eff,j}\frac{\partial T_g}{\partial x_j}\right) = \sum_{k=1}^{N_S}\dot{\omega}_k \Delta h^0_{j,k} + \frac{\partial}{\partial x_j}\left(\sum_{k=1}^{N_S}\rho h_k \varepsilon D_k \frac{\partial Y_k}{\partial x_j}\right)$$

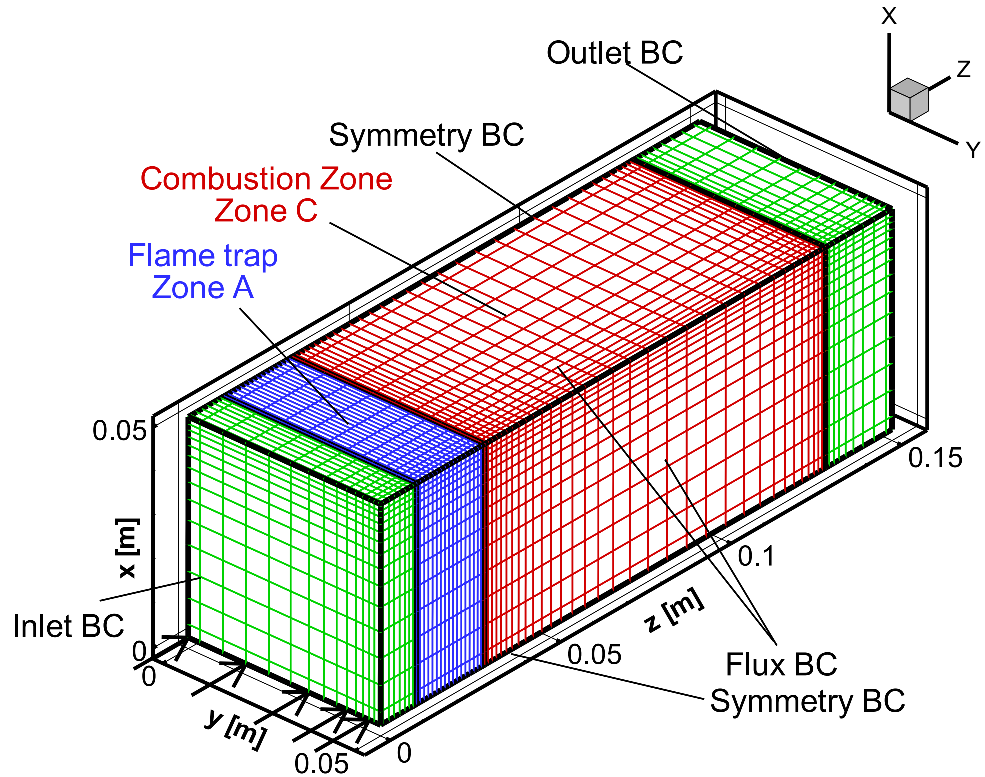
Effective heat conductivity:

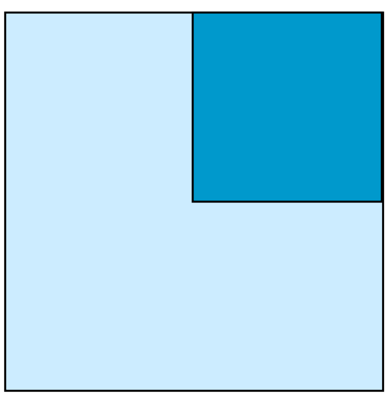
- heat conductivity in fluid
- heat conductivity in solid
- radiation
- increased convective transport due to dispersion

$$\Lambda_{eff,j} = \Lambda_{eff,0} + \frac{\rho U_0 c_{p,f} d}{K_j} \qquad \text{with} \qquad j = ax, rad$$

$\lambda_{eff,0}$ and K_j are measured

Geometry and boundary conditions

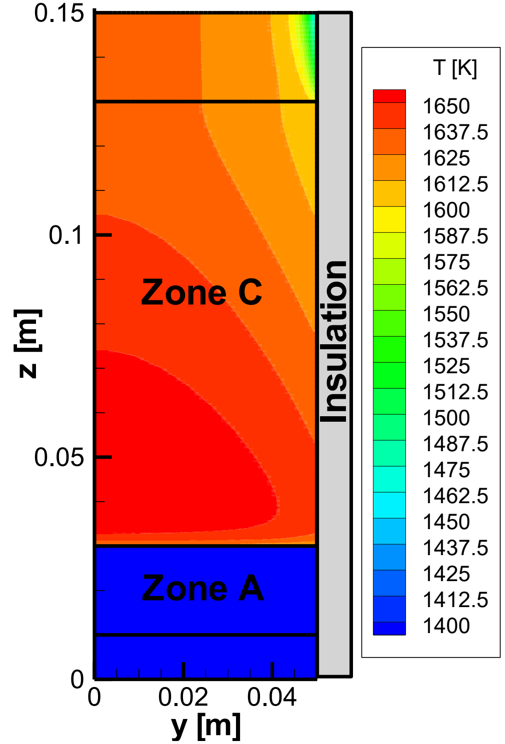


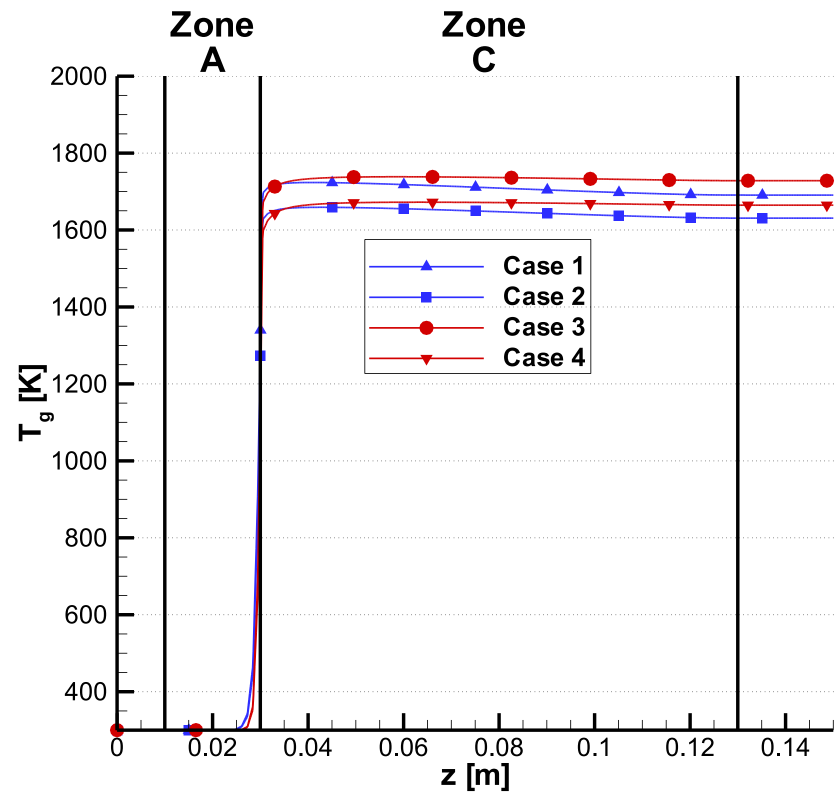


Boundary conditions for combustion of a low calorific CH_4-mixture:

T_{Inlet}	= 300 K
u_{Inlet}	= $f(p,\lambda,CO_2)$
c_{Inlet}(Spezies)	= $f(\lambda,CO_2)$
Mechanism	= Gri-Mech 1.2

Results





Case	p [kW]	CH_4 [Vol.%]	CO_2 [Vol.%]	Model
1	5	40	60	p-h
2	5	30	70	p-h
3	10	40	60	p-h
4	10	30	70	p-h

p-h = Pseudo-homogeneous

Gas phase:

$$\frac{\partial}{\partial x_j}\left(\rho v_{s,j} c_P T_g - \lambda \varepsilon \frac{\partial T_g}{\partial x_j}\right) = \sum_{k=1}^{N_S} \dot{\omega}_k \Delta h^0_{j,k} + \frac{\partial}{\partial x_j}\left(\sum_{k=1}^{N_S} \rho h_k \varepsilon D_k \frac{\partial Y_k}{\partial x_j}\right) - \alpha A_V \left(T_g - T_s\right)$$

exchange

Solid phase:

$$\frac{\partial}{\partial x_j}\left(-\lambda_s (1-\varepsilon)\frac{\partial T_s}{\partial x_j}\right) = \alpha A_V \left(T_g - T_s\right) + S_R$$

Source-/Sink term from radiation model

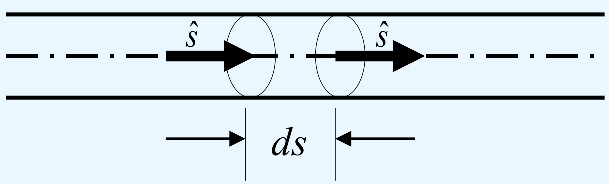
Radiation transfer equation

Radiation transfer equation:

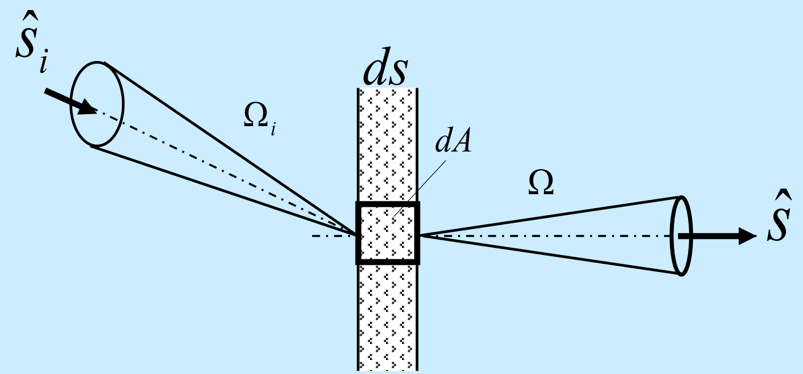
$$I_\eta\left(s+ds,\hat{s},t+dt\right)-I_\eta\left(s,\hat{s},t\right)=$$

$$\underbrace{\kappa_\eta I_{b\eta}(s,t)ds}_{\text{Increase due to emission}} - \underbrace{\kappa_\eta I_\eta\left(s,\hat{s},t\right)ds}_{\text{Decrease due to absorption}} - \underbrace{\sigma_{s\eta} I_\eta\left(s,\hat{s},t\right)ds}_{\text{Decrease due to outgoing radiation}} + \underbrace{\frac{\sigma_{s\eta}}{4\pi}\int_{4\pi} I_\eta(\hat{s}_i)\Phi_\eta(\hat{s}_i,\hat{s})d\Omega_i ds}_{\text{Increase due to incoming Dispersion}}$$

Bilanzierung über Strahlungsrichtungen:



Balance of radiation energy in one direction $\hat{s}$

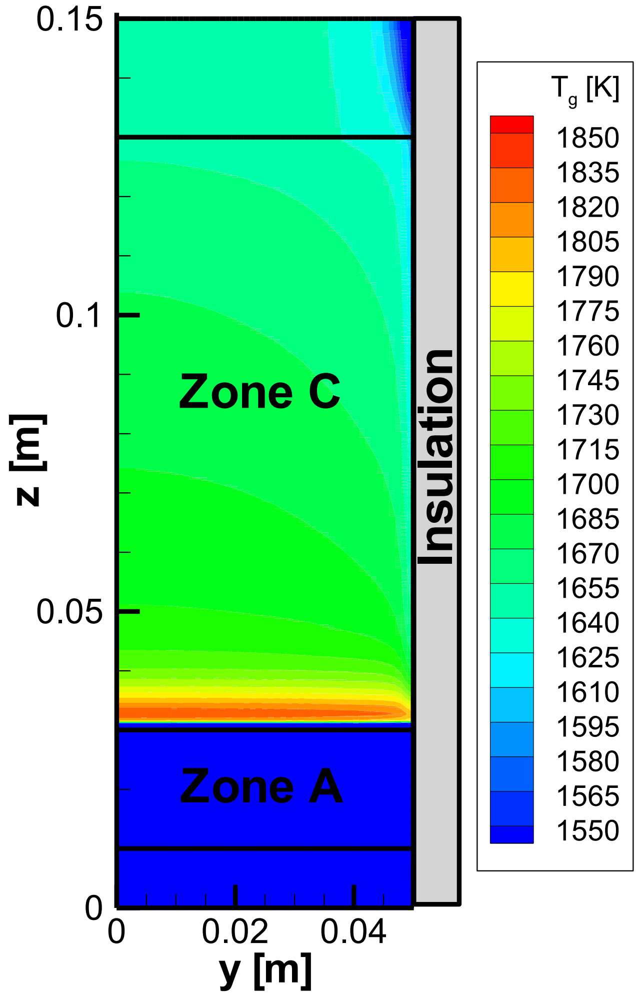


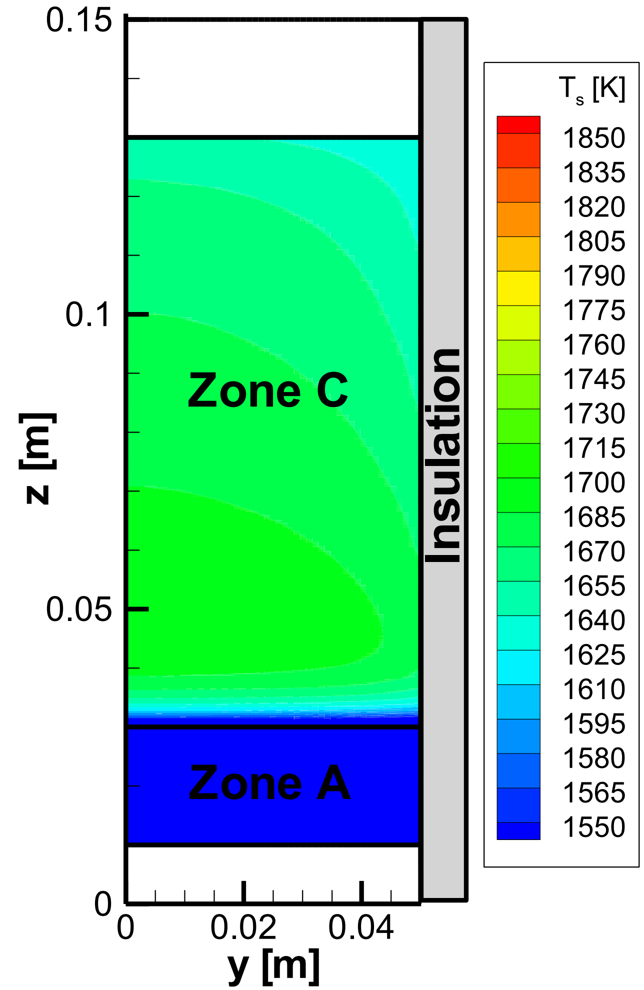
Change of direction due to dispersion

Source term for energy equation:

$$S_R = \nabla \cdot q_R\left(\vec{r}\right) = k(4\pi \cdot I_b - G)$$ mit $$I_b = \frac{\sigma T_b^4}{\pi}$$ und $$G\left(\vec{r}\right) = \int_{4\pi} I\left(\vec{r},\hat{s}\right)d\Omega$$

Results

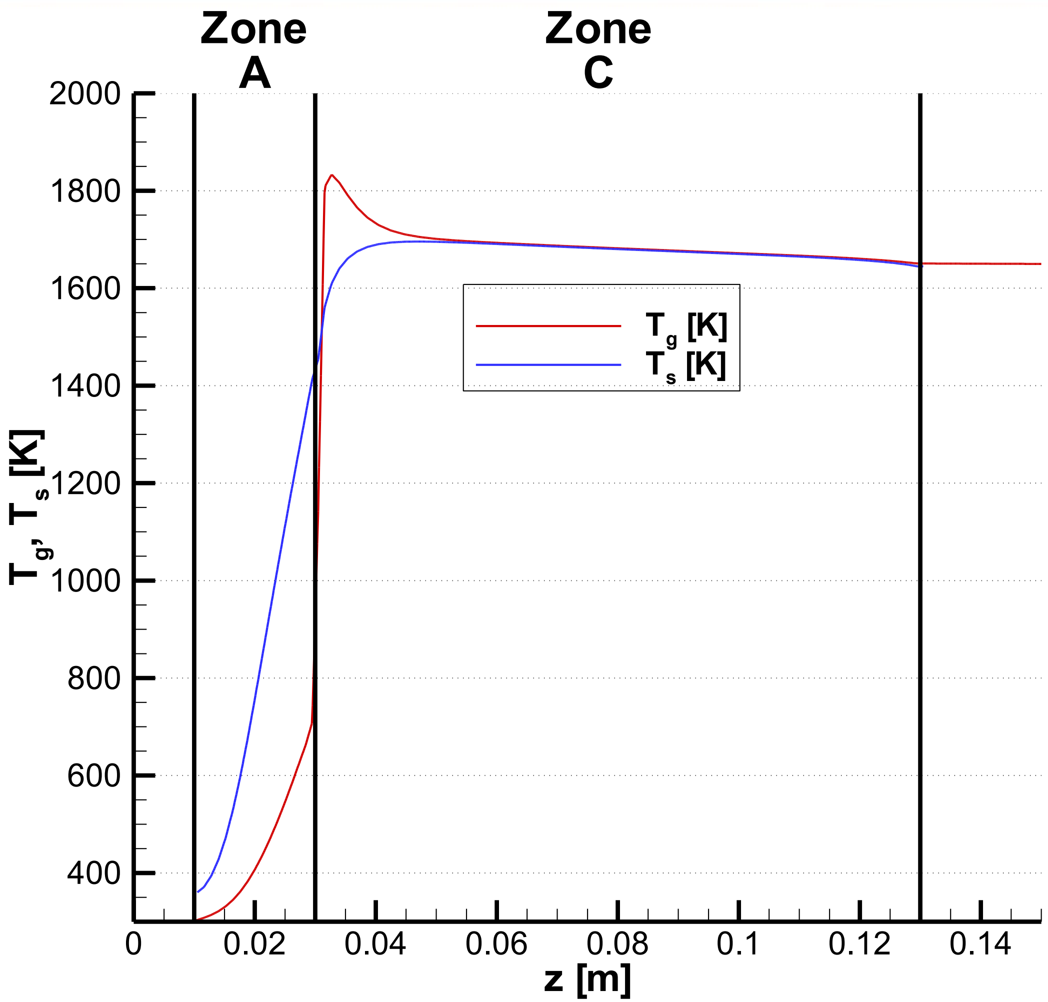




Case	p [kW]	CH_4 [Vol.%]	CO_2 [Vol.%]	Model
5	5	40	60	het

het = heterogeneous

Results



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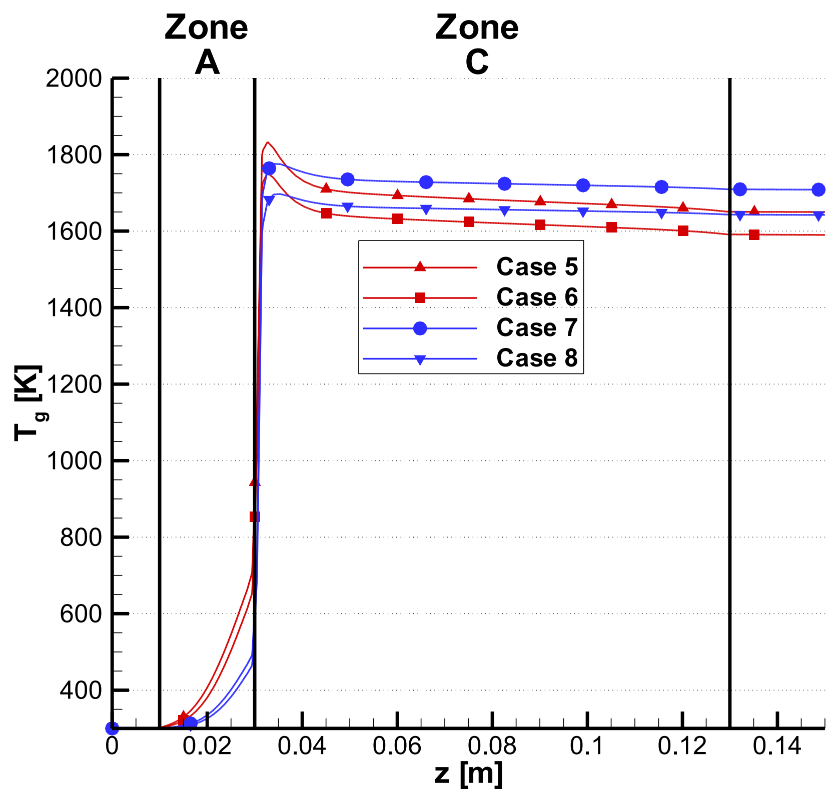
Results



Case	p [kW]	CH_4 [Vol.%]	CO_2 [Vol.%]	Model
5	5	40	60	het
6	5	30	70	het
7	10	40	60	het
8	10	30	70	het

het = heterogeneous

Summary

- Numerical simulation of combustion in porous media
- Modification of the transport equations
- Introduction to pseudo-homogeneous model with results for low calorific combustion
- Introduction to heterogeneous model with results for low calorific combustion
- Comparison pseudo-homogeneous / heterogeneous models:

pseudo-homogeneous model gives reasonable results for:

- global values: Outlet temperature, reaction rate, etc.
- „stable“ operation conditions

pseudo-homogenes Modell does **not** give reasonable results for:

- detailt investigation of heta transport (superadiabatic temp.)
- investigation of temperature distribution in flame trap
- simulation in the region of flash back or blow off of the burner