Numerical simulation of lime shaft kilns with particle size distribution

Robin Gröpler[1], Prof. Dr. Gerald Warnecke[1], Prof. Dr. Eckehard Specht[2]
[1]Institute for Analysis and Numerics, Faculty of Mathematics, Otto-von-Guericke-University Magdeburg
[2]Institute of Fluid Mechanics and Thermodynamics, Faculty of Process and Systems Engineering, Otto-von-Guericke-University Magdeburg

Introduction. The numerical simulation of a one-dimensional mathematical model is developed describing the lime calcination process in normal shaft kilns. The model comprises a system of ordinary differential equations derived from mass and energy balances. A particle model for the chemical reaction is used and is connected to the energy balance equations for the gas and the solid inside the kiln taking into account the size distribution of solid particles. The model is used to simulate the core and surface temperatures of solid particles of every individual size class, the gas temperature and the lime conversion degree. The model is also used to investigate the influences of the size distribution of solid particles on the lime calcination process. The results of this study can be transferred directly to the praxis for design, operation, regulation and optimization of normal shaft kilns.

Problem Definition

- **A very stiff and unstable numerical behavior** of the given equations inside the kiln is observed
- **A system of boundary value problems** for the energy balance equations has to be solved
- **Nonlinear and nonsmooth terms** complicate the calculation of the chemical reaction

Objectives

- **Develop a stable numerical code** calculating the temperature profiles with particle size distribution
- **Investigating the influence of parameters** by performing extensive parameter variations
- **Transfer the results to the lime industry** creating a program with interface for input and output data

Cooperation

- **Bassem Hallak,** Institute of Fluid Mechanics and Thermodynamics, PhD student
- **Gourisankar Sandaka**, Institute of Fluid Mechanics and Thermodynamics, member of the GK
- **Mubashir Hussain**, Institute of Thermal Process Engineering, member of the GK

Mathematical model

For the production of quicklime (CaO) the raw material limestone ($CaCO_3$) is decomposed by heating splitting off carbon dioxide (CO_2).

Thermal resistances model the sub-processes

- heat convection to the surface (α)
- heat conduction to the reaction front (λ)
- chemical kinetics at the front (k)
- diffusion of CO_2 to the surface (D)
- convection of CO_2 to the surroundings (β)

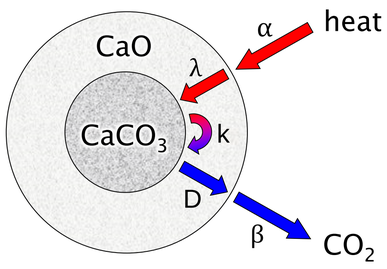


Figure 1. Shrinking core model

From energy and mass balance equations the following differential equations can be derived for the conversion degree X(t) of a single particle

$$\frac{dX}{dt}\left(R_\alpha + R_\lambda\, f_1(X)\right) = 1,$$

$$\frac{dX}{dt}\left(R_\beta + R_D\, f_1(X) + R_k\, f_2(X)\right) = 1,$$

with nonlinear form functions $f_1(X)$ and $f_2(X)$.

This calcination process takes place at very high temperatures in a shaft kiln.

- limestone is fed into the top of the kiln
- exhaust gas with CO_2 flows out at the top
- combustion of fuel injected from the side
- hot gases flow counter currently upwards
- lime is drawn out of the bottom

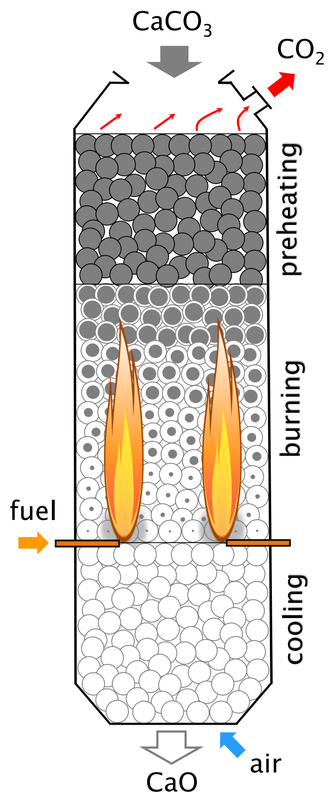


Figure 2. Scheme of a shaft kiln

We make the following assumptions

- ▹ homogeneous heat supply in the layers
  → one-dimensional model
- ▹ particles are spheres

For the temperatures of gas T_g and solid T_s the following energy balance equations are valid

$$\frac{d}{dz}\left[\dot{M}_{g(z)} \cdot c_{pg} \cdot T_{g(z)}\right] = -\alpha_{(z)} \cdot A \cdot \left(T_g - T_{sw}\right) + \frac{d\dot{M}_{f(z)}}{dz} - \frac{d\dot{Q}_{w(z)}}{dz}, \qquad T_g(L) = T_{gL}$$

The change of thermal energy of the gas is equal to the heat transferred from the gas to the solid plus the heat produced by the combustion of fuel minus the wall heat loss.

$$\frac{d}{dz}\left[\dot{M}_{s(z)} \cdot c_{ps} \cdot T_{s(z)}\right] = \alpha_{(z)} \cdot A \cdot \left(T_g - T_{sw}\right) - \frac{d\dot{M}_{CO_2(z)}}{dz} \cdot \Delta h_{CO_2}, \qquad T_s(0) = T_{s0}$$

The change of the thermal energy of the solid is equal to the heat transferred from the gas to the solid minus the decomposition enthalpy.

Numerical simulation

The MATLAB solver bvp4c requires an initial guess to be supplied for a solution. For a very crude initial guess this method fails in many cases. Now, the idea is to use one numerical solution as the new initial guess for slightly different parameters. This method is called **continuation**.

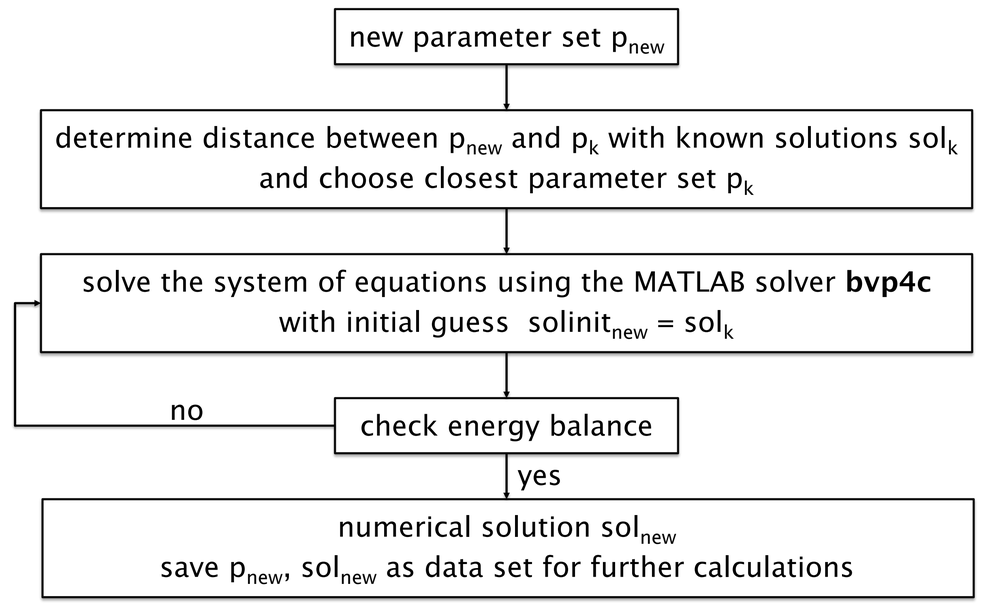
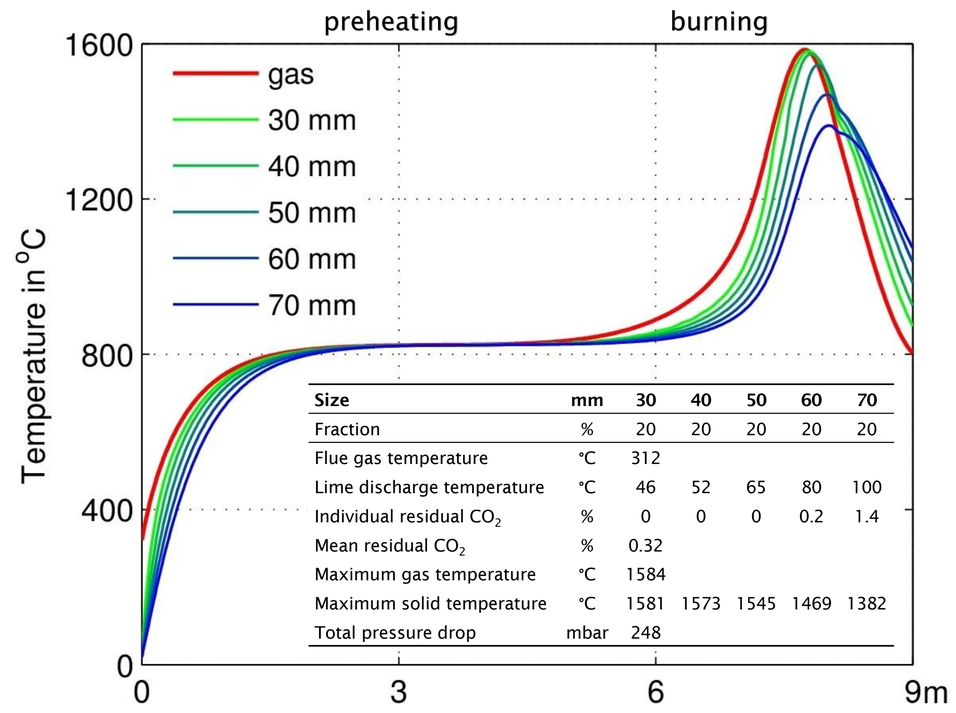


Figure 3. Scheme of the numerical solution strategy

Now we are able to simulate the temperature profiles inside the normal shaft kiln with a particle size distribution.



Size	mm	30	40	50	60	70
Fraction	%	20	20	20	20	20
Flue gas temperature	°C	312				
Lime discharge temperature	°C	46	52	65	80	100
Individual residual CO_2	%	0	0	0	0.2	1.4
Mean residual CO_2	%	0.32				
Maximum gas temperature	°C	1584				
Maximum solid temperature	°C	1581	1573	1545	1469	1382
Total pressure drop	mbar	248				

Figure 4. Temperature profiles for a particle size distribution

Results and Discussion

We applied several numerical methods for solving the system of differential equations. For this, we tested various solvers and compared them in view of our purposes. We found that the continuation method provides stable, fast and precise numerical results. The sensitivity of the boundary values, however, is a property of the nonlinear system and could not be circumvented.

The influence of the particle size distribution on the calcination process is investigated for the first time. This shows that a smaller particle size results in a higher lime temperature and a lower residual of CO_2. The simulation results are in good agreement with the real behavior. Furthermore, the influence on the energy consumption and the operating conditions can now be studied by performing many parameter variations.

Conclusions

- A stable numerical code was developed to simulate the lime calcination process in normal shaft kilns
- The influence of each parameter can be investigated and the results will be published soon
- A program was created which is very helpful for the lime industry for the improvement and understanding of the behavior inside the kiln

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