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Residence Time Behavior of Wastes in Rotary Kiln Systems – Experimental Investigations and Mathematical Modelling

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The behavior of the solid, also called residence time behavior or reactor behavior in connection with the apparatus, has an important influence on the course of the conversion over the reactor length. Therefore, the residence time behavior and the main influencing parameters for the control of the residence time behavior are of particular importance for the optimization of the total process. In addition, the description of the residence time behavior forms an important basis for the mathematical modeling of the solid conversion.

In this paper, the residence time behavior of special wastes, Plexiglass granules and substitute fuels or model substances, e.g. sand, were investigated in a pilot rotary kiln through cold and hot experiments and with the help of mathematical models.

1 Introduction

For rotary kiln systems, structural influencing variables, such as rotary kiln radius R, rotary kiln length L, and operational influencing variables, such as mass flow m_F, angle of inclination β, rotary kiln rotational speed n, are important parameters when considering the residence time behavior (**Fig. 1**).

The residence time behavior is also influenced by the characteristics of the starting material, such as

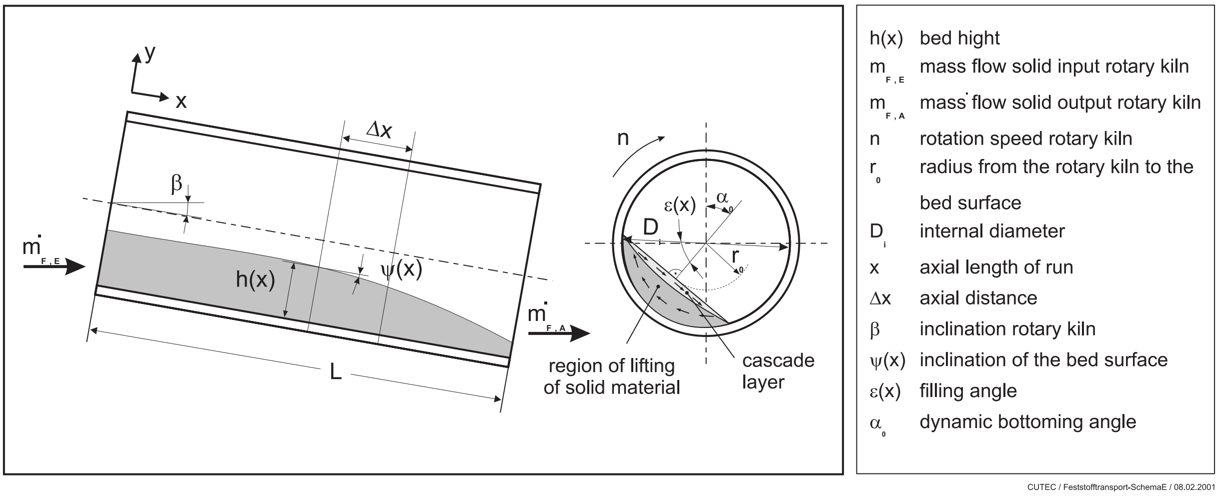

Fig. 1: Important main influencing parameters for the solid transport

composition, bulk density ρ_F, angle of repose α_o, particle-size distribution, etc. In rotary kilns in particular, the residence time behavior can be described through path-dependent values, such as filling height h (x), angle of bed inclination ψ (x) and filling angle ε(x).

The Input-Step-Response-Method /1/ with various tracers /2, 3, 4/ has proven suitable to a great extent for the experimental investigation of the residence time behavior in hot and cold tests.

In the cold tests, variations of the mass flow and inclination were carried out. In the hot tests, the residence time behavior is investigated indirectly through a comparison of the calculated and measured temperature profiles for the solid along the length of the rotary kiln. For the calculation of the temperature profile with the help of a mathematical model, a residence time model, among other things, is applied.

2 Experimental Procedure

The investigations were carried out in a pilot rotary kiln with an internal diameter of 0.3 m and a length of 5.1 m. The starting material is fed into the rotary kiln using a conveyor worm /5/. In order to investigate the residence time behavior, a Dirac impulse, in the form of a certain amount of solid labeled with color (tracer), was given to the stationary solid mass flow over a screw conveyor /1, 9/. The following parameters (**Tab. 1**) were varied in the experiments.

Tab. 1: Parameters and degree of variation

Parameter	**Degree of variation**					
Wall temperature [°C]	20				300	500
Material	Plexiglass	substitute fuel	-	-	sand	
Angle of kiln inclination β [°]	0	0,65	1,3	1,95	0,65	
Kiln rotation speed [u/min]	3				11	
Mass flow m_F [kg/h]	30	50	-	-	25	50

3 Model formulations

When considering solid transport models, one can roughly differentiate between balance models /e.g. 6/ and maximum gradient models or models divided into segments. Balance models are generally based on the basic element „stirred reactor“ (abbreviated as SR in the following text). Maximum gradient models are obtained through the connection of several SR elements or zones (segments) in series.

3.1 Balance models

Models according to the basic element stirred reactor (global models or black box models) do not regard the solid transport in the reactor in detail, but specify the characteristic values, such as the average residence time of axial dispersion, through geometric and structural considerations and/or from relationships gained from experimental results. The basic equation for the determination of a global average residence time for rotary kiln systems based on appropriate formulations in the literature /7/ can be defined as follows: $\tau = \frac{k_1 \cdot L \cdot f_1(a_0)}{n \cdot D_i \cdot f_2(\beta)}$ (1). The equation is valid for small degrees of filling ϕ, e.g. smaller than 15 to 20 %.

3.2 Maximum Gradient Models

The characterization of the solid transport was refined through the geometrical description of the conditions in the filling, e.g. by Saeman through the introduction of an angle of bed inclination ψ (x) (Fig. 1) which represents the angle between the rotary kiln axis and the surface of the bed: $\tan\psi = \frac{dh}{dx} = -R \cdot \sin\varepsilon \cdot \frac{d\varepsilon}{dx}$ (2).

With the help of work by Hogg, Shoji and Austin /8/, Equation (2) can be transformed into a dimensionless form dependent upon the important geometric, material and operating parameters. Similar to the equation from Saemon, this equation is only valid for small degrees of filling.

The possibility to connect stirred reactor elements in series will not be discussed here, but referred to in the literature /1, 9/.

4 Results

The representation of the results can be subdivided into experimental results from the cold tests with granules and substitute fuels, into the presentation of the results from the calculations of the average residence time for selected experiments and the results from the hot tests.

As expected, a reduction of the residence time was determined with increasing inclination for all experiments.

For average degrees of filling greater than ca. 20 %, a distinct dependence of residence time upon mass flow results at a constant inclination and rotational speed. At a nearly constant degree of filling, the residence time increases correspondingly with decreasing mass flow. The degree to which the residence time increases lessens with increasing inclination.

For average degrees of filling less than 20 %, the residence time shows no significant dependence upon the mass flow. As the results show, Plexiglass and substitute fuels basically result in similar dependencies. Due to the low filling density ρ_F of substitute fuels, 460 kg/m^3, in comparison with Plexiglass, 700 kg/m^3, but with comparable constant mass flows, the degree of filling ϕ for substitute fuels increases correspondingly (e.g. V1 Plexiglass, ϕ = 29% and V9 substitute fuels, ϕ = 36%).

A comparison with the calculated residence times from the balance models (here: model formulation Saeman Equation (1)) shows a deviation from the measured values of up to 28 % for Plexiglass granules and up to 56 % for substitute fuels for degrees of filling < 20%. According to Equation (1), the mass flow is not included in the calculation of the residence time, therefore the same residence time is calculated for both mass flows. This formula cannot be applied for inclinations of 0°. With the help of this simple equation (1), a first approximation for the average residence time can be determined for the range of validity specified by Saeman („small degrees of filling).

The formulation according to Austin *et al* from the maximum gradient model, displays the principle dependence of the average residence time on the operating parameters, however, it does not consider that the influence of the mass flow on the residence time decreases for degrees of filling less than 20 %. The deviations from the measured values for granules and substitute fuels lie between 0 and 1 % from the measured values and are therefore relatively small.

For the hot tests with sand and without mass transfer, a mathematical model which considers the heat transfer mechanisms, including the changing processes such as enthalpy flow, and which will not be discussed in detail here, is used for the calculation of the temperature profile. The formulation according to Austin is chosen here for the residence time model. Conclusions concerning the suitability of the total residence time model for the practice can be obtained through a comparison of the calculated temperature profiles and the experimental examination of the temperatures (**Fig. 2**)

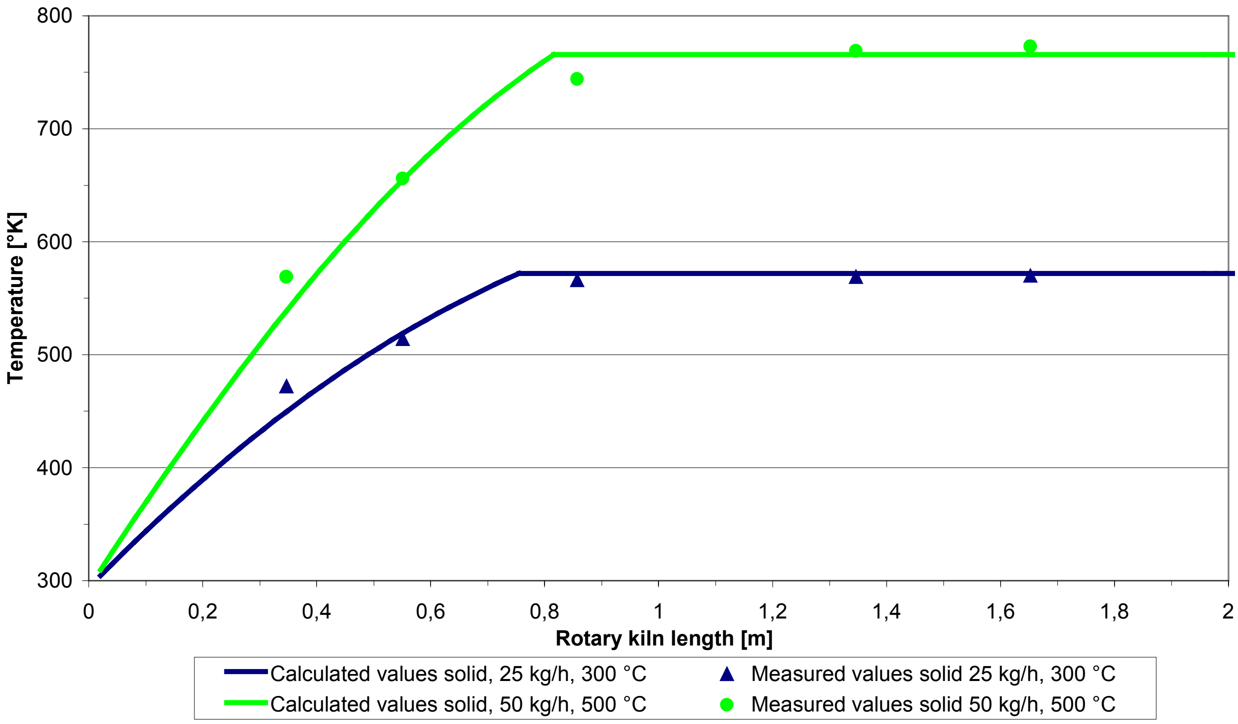

Fig. 2: Calculated and experimentally determined temperatures

Fig. 2 shows the calculated and measured temperatures for the solid at 300 °C and 500 °C wall temperature for 25 and 50 kg/h.

The measured values can be approximated with sufficient accuracy using the model.

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