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RESIDENCE TIME BEHAVIOUR OF SOLID MATERIAL IN GRATE SYSTEMS

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ABSTRACT

Grate systems are frequently applied in the field of thermal waste treatment. The description of the incineration process by a mathematical model is a very interesting task for research and development up to now. Therefore, the description of the solid material transport and of the mixing behaviour along the grate is an important precondition. The transport and the mixing behaviour both depend primarily on constructive parameter of the grate (e.g. forward or reverse acting system). Furthermore material properties (density, diameter etc.) and operation parameter (mass flux, grate velocity etc.) must be taken into account.

The degree of refining of an approach used for waste treatment should be related to the availability of data and the accuracy of the data. Calculations are only as accurate as the physical and chemical data used into the model.

In front of this background investigations at a cold grate model to study the main influencing parameters on the residence time behaviour were carried out. The results were evaluated by the "population balance method". This method seems to be well suited to describe the transport and mixing behaviour of solid material on grate systems depending on material properties as well as for different constructive and operation conditions.

KEYWORDS

Waste, combustion, grate systems, research plant, residence time behaviour, mathematical model, experimental investigations.

1 INTRODUCTION

Grate systems are frequently applied in the field of thermal waste treatment. The description of the incineration process with a mathematical model is a very interesting task for research and development up to now. The mathematical models primarily focused on the conversion of solid material in the packed and moved bed [e.g. 1-4]. These models showed that through the use of simplified approaches (spheres, summarised kinetic data etc.) good agreement of theoretical and experimental results can be obtained. At present models also include the post-combustion process with the mixing and residence time behaviour in the combustion chamber using CFD [e.g. 5-7]. The results of the solid bed conversion at the grate are required as an input condition for the CFD-modelling of the combustion chamber.

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1 INTRODUCTION

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All mathematical models incorporate approaches for description of the solid material transport along the grate, heat and mass transfer, kinetics etc. to different extents. The degree of refining of these approaches should be related to the availability and accuracy of the data. It is well known that calculations are only as accurate as the physical and chemical data used into the model.

This paper will focus on the description of the solid material transport on the grate. Referring to the above-mentioned models one can roughly differentiate between approaches using unmixed packed beds [e.g. 8] (cross/counter-current-flow) and approaches with mixed packed beds [e.g. 3,9]. With the exception of travelling grate systems, mixed packed beds are found in practice.

Investigations on a cold grate model concerning the mixing behaviour of the grate system will be introduced here. The results were evaluated using the "population balance method". This method was already used for a mathematical model for grate systems using summarised kinetic data. In this model the residence time behaviour is described by a serial cascade of continuous stirred reactors [3] dependent on the type of grate system. Meanwhile further investigations were carried out using a "cold" Plexiglas grate model to study the main parameters which influence the residence time behaviour. This paper presents the results of the variation of operating parameter and of material properties.

2 RESIDENCE TIME BEHAVIOUR OF SOLID MATERIAL ON THE GRATE

In general, it can be distinguished between three different model approaches and their combinations for the description of the mixed packed beds:

- Transport phenomena models,
- Population balance models,
- Empirical models.

For a detailed description of the transport and mixing behaviour of the solid particles, a solution for the transport equations over the total reaction volume would be necessary. Thereby the so-called effective transport coefficients vary. Such a procedure is not feasible in practice. No process can be examined so precisely in detail.

Based on this background, the "population balance method" was developed for the mathematical description of the mixing and residence time behaviour in reactor systems. Residence time functions give information regarding special fractions of material and the residence time of the fraction in the reactor. With the aid of this method the macro-mixing of a reactor can be described. This is already sufficient to describe the important interactions of the main influencing parameters in many cases, particularly in the field of thermal waste treatment.

The population balance models are characterised by fundamentally less expenditure for the inquiry of data and also for calculation in contrast to the transport phenomena models. This paper will explain how the population balance method can be applied to describe the transport of solid material along the grate.

3 EXPERIMENTAL SETTINGS

Unlike other systems such as rotary kilns [12-14] or fluidised bed reactors [15-19] little is known about the residence time behaviour of solid material at grate systems [e.g. 9-11]. Therefore the task of a fundamental investigation of the main parameters which influence grate systems still exists.

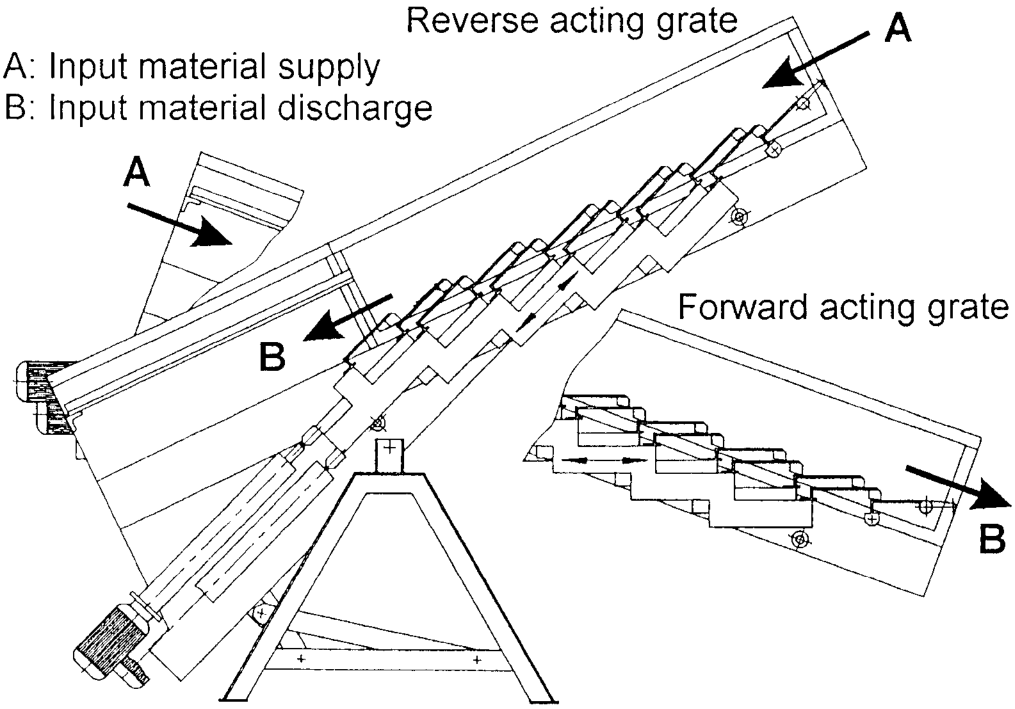

Fig. 1. Scheme of the cold model grate with testpositions for forward and reverse acting grate.

The investigations introduced here were carried out with a "cold" Plexiglass grate (Fig. 1). At such a experimental plant the residence time behaviour can be studied independent of the solid conversion. As can be recognised in Fig.1, reverse acting as well as forward acting grate systems can be investigated. The model fuel supply, via a manually operated feeding hopper, is nearly constant. The grate bars are driven by electric motors. The velocity of the grate bars is continuously adjustable. The solid material leaves the end of the grate via a chute.

Coloured pieces of model fuel were used as tracer material to investigate the residence time behaviour. For steady state conditions of the grate the tracer was introduced as a dirac pulse. The mass of the solid material m_i and the mass of the tracer $m_{T,i}$ which was discharged within the equal time periods Δt_i was determined. Furthermore, the number of tracer pieces $n_{T,i}$ was counted. Due o the fact, that particularly in the case of the reverse acting grate the tracer material is discharged only incompletely in a reasonable time, a special approximation of the end of the RTD-curve is necessary.

The mass related mean residence time is given by [e.g. 20]:

$$t_{m,M} = \frac{\sum_{i=1}^{n} t_i \cdot m_{T,i} \cdot \Delta t_i}{\sum_{i=1}^{n} m_{T,i} \cdot \Delta t_i} \quad (1).$$

Model material	Particle diameter [mm]	Particle mass [g]	Bulk density [kg/m³]	Material density [kg/m³]
Swelling clay	ca. 8 - 25	0,22 - 1,13	400	–
Wooden spheres	15	0,9 - 1	350	550
Ceramic spheres	10	1,38	1400	2200
Ceramic spheres	15	2,25 - 2,44	1300	2200
Ceramic spheres	20	9,4	1200	2200

Fig. 2. Special material data of the input materials.

The mean residence time related to the number of tracer pieces can be determined in the same way. With the mean residence time t_m, the mass flux $\dot{m}$, the bulk density ρ_b, the length l and the width b of the grate one can estimate the theoretical height h_{theo} of the packed bed:

$$h_{theo} = \frac{t_m \cdot \dot{m}}{l \cdot b \cdot \rho_b} \quad (2).$$

The evaluation of the residence time investigations is based on standardised values [21]. There the mass fluxes $\dot{m}_i$ and the calculated bed heights $h_{theo,i}$ of different test series referred to the maximum values $\dot{m}_{max}$ and $h_{theo,max}$. For the test series, "model fuels" were used. A summary of the characteristic data is given in Fig. 2.

4 RESULTS

Special emphasis lays primarily on the comparison of the residence time behaviour of reverse and forward acting grate systems. For both test series the mass fluxes and the model fuels were kept equal. With the results of this investigations the previously discussed assumptions regarding the mixing conditions and the residence time behaviour could be confirmed. In contrast to reverse acting systems, forward acting grate systems show a distinctly narrower residence time distribution (RTD). For small extents of dispersion ($Bo > 100$; nearly plug flow conditions) the RTD curve resembles a gaussian curve. There are a number of ways to determine the Bodenstein-Number from the curve. The width at the point of inflection ($2 \cdot \sigma$) is one of them. The variance σ^2 can be evaluated in general from:

$$\sigma^2 = \frac{\sum_{i=1}^{n} \left(t_i^2 \cdot M_i \cdot \Delta t_i \right)}{\sum_{i=1}^{n} \left(M_i \cdot \Delta t_i \right)} - t_m^2 \quad (3).$$

With

$$\sigma_\Theta^2 = \frac{\sigma^2}{t_m^2} \quad (4)$$

one obtains for small deviation from plug flow conditions

$$\sigma_{\Theta}^{2} = 2 \cdot \frac{D}{u \cdot L} = \frac{2}{Bo} \qquad (5).$$

For high extent of dispersion (Bo<100; large deviation from plug flow) the Bodenstein-Number can be determined from the parameters of the tracer curve. Due to the arrangement of the tests, the evaluation must be based on closed boundary conditions. For this an analytical expression is not available, however, the variance can be estimated by:

$$\sigma_{\Theta}^{2} = 2 \cdot \frac{D}{u \cdot L} - 2 \cdot \left[\frac{D}{u \cdot L}\right]^{2} \cdot \left[1 - e^{-\frac{u \cdot L}{D}}\right] \qquad (6).$$

The narrower the RTD-curve is, the larger the Bodenstein-Number. Corresponding to the results in Fig. 3 forward acting grate shows a narrower RTD with higher Bodenstein-Number than reverse acting grate. Furthermore a smaller mean residence time results for forward acting grate in comparison to the reverse acting system. The same dependence will be obtained for the theoretical height of the bed according to expression eq.(2).

Parameter	Model material	u_G [mm/s]	$t_m(m_{T,i})$ [min]	$\sigma^2(m_{T,i})$ [min²]	Bo [-]	$h_{m,theo}$ [mm]	$h_{m,gem}$ [mm]
Reverse acting grate	Swelling clay	3,5	28,23	278,34	4,46	28,4	35,3
Forward acting grate	Swelling clay	3,5	15,89	8,26	60,07	14,9	23,3

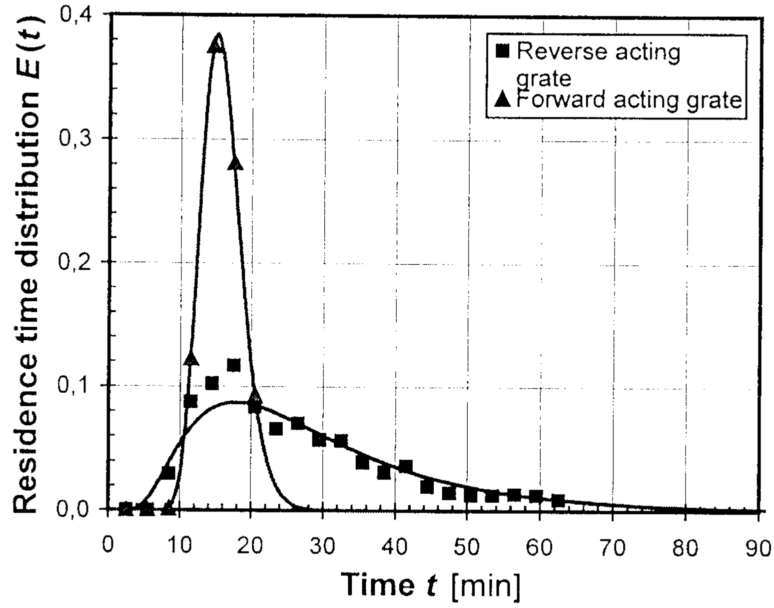

Fig. 3. Comparison of the residence time distribution for forward and reverse acting grate systems.

For the test series in Fig. 3 the mean residence time of the forward acting system is roughly the half of the residence time of the reverse acting system. The Bodenstein-Numbers differ around a factor 0.1. For the axial dispersion coefficient D one obtains around a factor 5 smaller value for the forward acting grate in comparison to the reverse acting grate.

If the residence time behaviour is approximated by a series of connected continuously stirred reactor (CSR) elements for the number of elements n_{CSR} a first estimation is obtained as follows:

$$n_{CSR} = 1 + \frac{Bo}{2} \text{ for } Bo > 2 \qquad (7),$$

$$n_{CSR} = 1 + \sqrt{\frac{Bo^{2}}{4} + 1} \text{ for } Bo > 8 \text{ resp.} \qquad (8),$$

$$n_{CSR} = \frac{Bo}{2} \text{ for } Bo > 50 \quad (9).$$

Therefore with the data for the example in Fig.3 a number of elements for the forward acting grate n_{CSR}=30 and for the reverse acting grate n_{CSR}=4 result. For the forward acting grate, plug flow conditions can be estimated roughly. Based on the assumption that the reverse acting grate model has 4 air zones in reality, every air zone can be described as a *CSR*-element [3,10,11].

Besides the grate construction, the mass flux and the grate bar velocity have a great influence on the residence time behaviour. Both parameters were investigated for reverse acting conditions.

The increase of the mass flux in principle leads to a decrease of the residence time (Fig. 4), with the exception of the limiting state where the bulk material slides depending on the inclination of the grate.

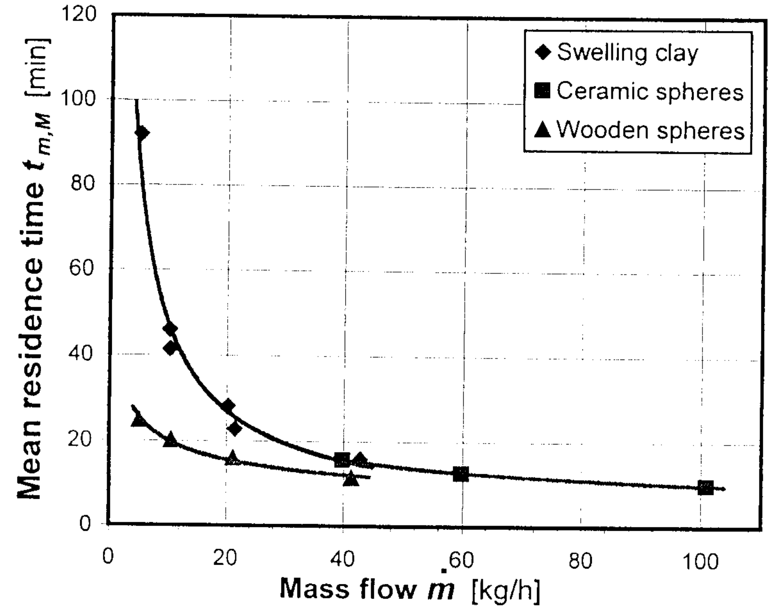

Fig. 4. Influence of the mass flow on the mean residence time for different model materials.

Parameter	Model material	u_R [mm/s]	$t_m(m_{T,i})$ [min]	$\sigma^2(m_{T,i})$ [min]	Bo [-]	h_{theo} [mm]	h_{gem} [mm]
Reverse acting grate	Swelling clay	3,5	46,13	817,5	3,4	23,2	29,7
Reverse acting grate	Swelling clay	1,75	53,06	791,6	5,91	26,5	36,9
Reverse acting grate	Swelling clay	0,875	68,85	1246,6	6,42	33,4	40,9

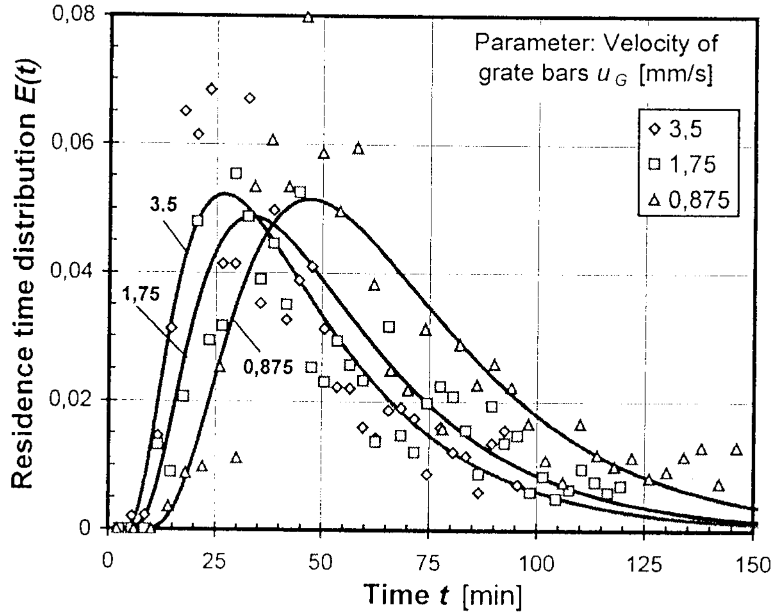

Fig. 5. Influence of the grate bar velocity on the residence time distribution (example: swelling clay).

The influence of the grate bar velocity can be summarised as follows: The increase in velocity causes a decrease in mean residence time and a narrower RTD-curve, i.e. the variation around the mean residence time becomes smaller. Simultaneously, the axial dispersion coefficient which characterises the degree of back mixing increases (Fig 5). It should be mentioned, that there is no contradict between a narrower RTD-curve and an increment in dispersion coefficient because dimension afflicted parameters (σ, t_m, D) are considered here.

For constant mass flux, bed height increases with decreasing grate bar velocity (Fig. 6). The bed height also increases with raising of mass flux.

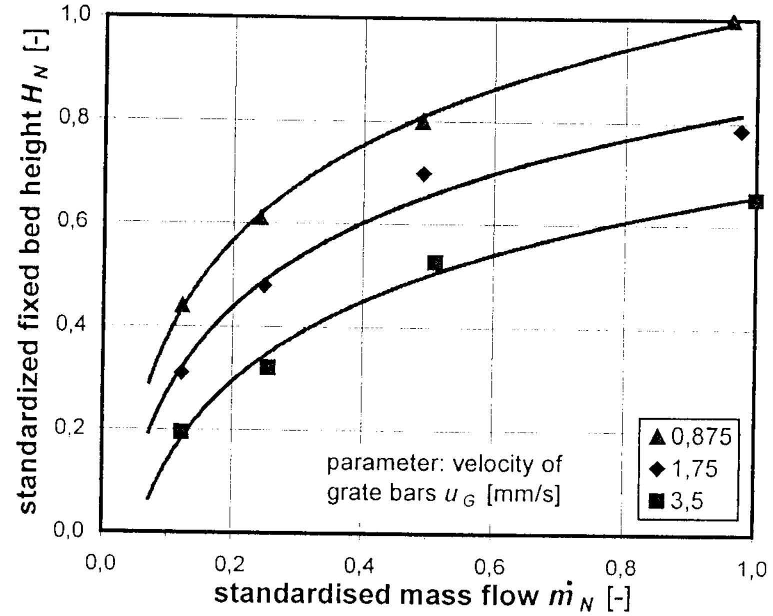

Fig. 6. Height of the flue bed in dependence on the mass flow and the grate bar velocity (example: wooden spheres).

The results of the before mentioned investigations show that the population balance method is well suited to characterise the residence time behaviour of grate systems. There constructive features of the grate systems as well as operational parameters are considered. The approach on basis of population balance models is capable of describing the transport behaviour of a grate within an overall simulation model [10]. Therewith, in contrary to the transport phenomena models less expenditure for the inquiry of data and also for calculation is generally necessary.

The next step for the further development of this approach is the implementation of the conversion of solid material, e.g. the reduction of the particle size and the enlargement of the particle number etc. during the overall combustion process. A count of coloured tracer material in industrial grate systems seems to be unfeasible. The adaptation of the results from the cold-grate system to real conditions can be supported by radio tracer measurements. First measurements with indium were carried out on the forward acting pilot grate [10] in connection with the investigation of the behaviour of heavy metals depending on operational conditions [22]. Thereby model waste was used. The waste mass flow and grate movement were held constant.

Fig. 7 shows an example of measured residence time distribution for the detectors along the grate. Due to the insufficient shielding of the detectors the shape of the curves is widened. Therefore an evaluation of the axial back mixing and a calculation of the Boden-

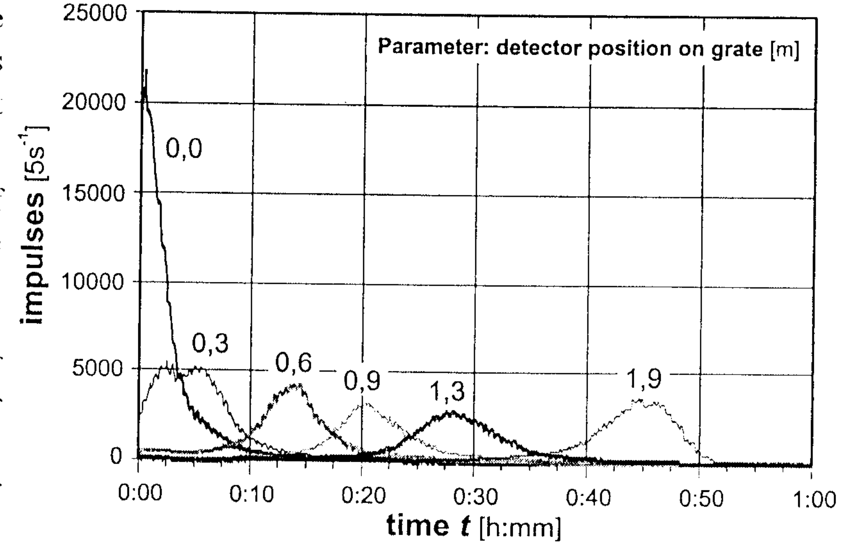

Fig. 7. Residence time distribution (RTD) measurement of waste material on the grate.

stein-Number is difficult. Here the mean residence time is defined as the time of maximum impulses. The linear correlation between detector position and mean residence time leads to the conclusion that axial back mixing is negligible so that nearly plug flow conditions prevail. The measured mean overall residence time is in the range of one hour. Next step is the correlation of the results obtained from the cold grate with the radio tracer measurements at the pilot grate. There the scale-up of the geometric parameters should be involved.

5 ACKNOWLEDGMENTS

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6 NOTATION

Symbols

Latin Letter

b	width [m]
Bo	Bodenstein-Number [–]
D	dispersion coefficient [m^2/s]
E	residence time distribution RTD
h	height [m]
H	height, standardised [-]
l	length [m]
L	characteristic length
m	mass [kg]
n	number [–]
t	time [s]
u	velocity [m/s]

Greek Letter

α	angle [°]
ρ	density [kg/m^3]
σ^2	variance [min^2]

Indices

Superscripts

$\bullet$	derivation of time [/h] (mass flux etc.)

Subscripts

b	bulk (density)
CSR	continuous stirred reactor element
G	grate
i	control variable
m	mean
max	maximum
N	referred to number
n	refers to standard state
T	tracer
$theo$	theoretical
Θ	standardised time

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