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MODEL OF WASTE COMBUSTION ON THE GRATE

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Abstract
The algorithm describing mass transport on the reciprocal moving and drum grates have been presented. Three main processes are taken into account: combustion of a single fuel particle, porous structure of the fuel layer and fuel transport on the grate and their mutual relations were analyzed. Each process is described by its own model: reactor, fuel particle, heat tranfer and chemical reaction. The model describing the grate is designed as similar to the chemical reactor and the cascade of batch reactors simulates the tranport on the grate.

Streszczenie
W pracy przedstawiono algorytm opisujący transport masy na rusztach posuwistych, posuwisto – zwrotnych i walcowych. Struktura modelu oparta jest na trzech głównych blokach zagadnień do których należą: spalanie pojedynczego ziarna paliwa, przestrzeń porowata w warstwie oraz analiza ruchu ziaren na ruszcie. Określono system powiązań parametrycznych w/w zagadnień. Każde z zagadnień wymaga opisu za pomocą podmodeli, są nimi: podmodel reaktora, paliwa (odpad/cząstka), transportu ciepła oraz reakcji. Zastosowano podobieństwo modelu rusztu do modelu reaktora chemicznego. Użyto kaskadę reaktorów zbiornikowych w dyskretyzacji warstwy.

Keywords: **Waste combustion of the fuel layer on the grate; Model of combustion process of a single particle; Forward and reverse acting grate; Residence time distribution (RTD); Mixing rate; Dispersion intensity.**

1. INTRODUCTION

The high-temperature processes undergoing in the ovens and combustion chambers of various types of fuels deal with changes of gas, liquid and solid substances in these circumstances. As an example the combustion and gasification of fuel on the grate systems can be discuused. The grate system is designed to transport raw fuel and waste as well as products of combustion: carbonization, slag and provide proper primary air distribution along the grate.

There are several constructions of moving grates dedicated to the waste incineration. There

are forward movinmg grates, reciprocal moving grates, and systems of moving and nonmoving grate bars. The special type is drum grate built of the system of inclined drums [1]. All above mentioned types of grates are discussed in the paper and were investigated in laboratory conditions on the Silesian University of Technology in Gliwice, Poland.

Several basic issues are important in mathematical description of the processes on the grate: heat and mass transfer in homogenic and heterogenic environment, mechanical transport of material. Thus the main model should have following submodels: reactor, fuel, heat transport and chemical reactions. All detailes of submodels should correspond with the detailed composition of main model of the grate and combustion chamber.

2. WASTE TRANSPORT MODEL

2.1. Structure of the model

The structure of the transport model of waste material incinerated on moving grates: forward moving grates, reciprocal moving grates and drum grates is based on the relations between three main issues:

- Combustion, pyrolysis and gasification of fuel particle,
- Porosity of the fuel layer,
- Movement of the particles on the grate.

Mutual relations between these processes is presented in Fig. 1. Each of the processes should be described by separare submodels: e.g. Particle combustion can be analysed as composition of mass transfer model, heat transfer model and fuel model. The main assumptions of the model are presented below [2].

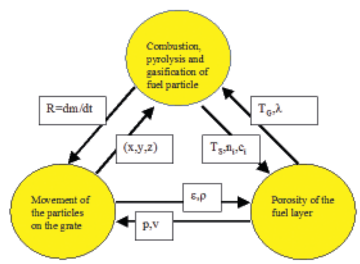

Figure 1.
Interdiscipline relations in the model of waste combustion on the grate.
R – mass decrement [kg/s], (x,y,z) – coordinates of the particle [m], p, v – pressure and volume of the porous medium, ε – layer porosity [-],ρ – bulk density of the waste [kg/m^3], n_i – mole rate of the gas substance i [mole/s], c_i – concentration of gas substance i in the porous volume [mole/mole], T_Z – temperature of solid phase [K], T_G – temperature of gas phase [K], λ – air excess coefficient

3. MODEL OF COMBUSTION PROCESS OF A SINGLE PARTICLE

Presented analysis was carried out for two kinds of particle material – beech wood and coke particles [3]. Two cases were analysed :

– heating of a single fuel particle without chemical reaction,
– heating of a single fuel particle with a endothermic and exothermic reactions.

Degassing process was omitted this analysis. The first version of calculations was dedicated to the heating process of 2R diameter sphere with no inner heat sources and with uniform initial temperature t_p placed in the surrounding volume of a temperature $t_{oś}$. The assumption was that the convection heat transfer coefficient α was known and constant. The calculation procedure was based on the paper [4]. Following parameters of solid waste particle were taken into account : density, heat conduction coefficient, heat capacity and their influence on the heating time. For heating process of the coke particle without chemical reaction the convective heat transfer from the surrounding gas to the surface of the particle and heat conduction to the inside volume of the particle were taken into account. The combustion process introduces additional elements to this equation – chemical reactions enthalpies on the outer surface and inside the porous surface of the particle. Mass change of the coke particle was determined from the equation for the reaction rate. The radiation heat and chemical reaction heat create heat rate causing the increase of the surface temperature and a new Biot number calculation.

Presented model shows shrinking of the reacting surface of the coke particle with constant amount of ash, so this model can be described as model of gradual conversion. The heat transfer calculations were performed according to [4] whereas in the paper [3] detailed algorithm of mass decrement was presented as well as time history inside the particles for two typical chemical reactions:

- Exothermic: $C + O2 \rightarrow CO2$
- Endothermic: $C + H2O \rightarrow CO + H2$.

3.1 Results and discussion

As it was easy to predict, the exothermic reaction increased heating rate of particle in comparison with process without the reaction. Endothermic reaction increases the time of particle heating. As to the influence of material of the particle the heating time of coke particle is about 14 s and for beech wood this time is much longer (about 100s) – Fig. 2. The influence of physical and chemical parameters of the fuel was simulated: density, heat conduction coefficient, heat capacity of material. Values of these parameters were chosen in the range of solid waste material. Increase of heat capacity as well as increase of density of material increases heating time and, in contrast, increase of heat conduction coefficient decreases the heating time of the particle.

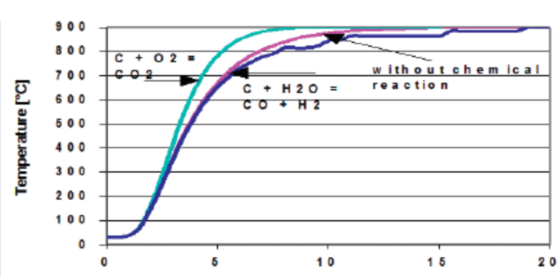

Figure 2.
The time function of temperature of coke particle d=0.01 [m] for heating process without chemical reaction and with exothermic and endothermic reactions [3]

4. MOVEMENT OF THE PARTICLES IN THE FUEL LAYER

Grate is very important element in the waste incineration system. A grate should fulfil its function as transport, mixing and air distribution element to ensure complete combustion of waste. Three types of grates widely applied in incineration plants were specially analyzed: forward moving grate, reciprocal moving grate and drum grate. Other types of grates can be similarly analyzed by presented algorithm.

The paper [2] defines theoretical formulas for determining parameters important for mass transport process and methods of their investigations are proposed. The investigated parameters are: residence time distribution, dispersion coefficients and mixing rate of material. The mechanism of dispersive transport of material on the mixing grate was described by two dispersion coefficients: longitudinal and transversal. The dispersion coefficient D_L describes mass transport along the main grate axis while the transversal transport describes coefficient D_p.

Analogy between the combustion chamber with moving grate and chemical flow reactor was assumed [5] and mathematical formulas for real residence time of material in these types of reactors were applied.

4.1 Investigation of residence time of waste material on the grate

In real reactors, and on the grates, mass transfer model lies in between these two opposite cases. For practical reasons it is important to assess how close the real flow is to one of these ideal cases and to estimate validity of experimental results with theoretical data. One of possible criterion of such assessment is the residence time function (RTD) of fuel particles on the grate.

Real residence time of particle on the grate is a random variable and it can be described by statistical distribution function E(τ), which is known as residence time spectrum. Product E(τ)dτ defines fraction of particles of the residence time between τ and τ+dτ in the output flow from the grate.

The residence time functions are the only and objective description of flow dynamics in real system. For practical interpretations the shape of functions can be related to the dimensionless Peclet number defined as:

$$Pe_L = \frac{u \cdot L}{D_L} \qquad (1)$$

Where L – length of reactor, u – linear velocity, D_L – dispersion coefficient.

The value of Peclet number characterizes the dynamics of the flow and defines mixing intensity along the grate. The shape of residence time distribution depend on the value of Pe number [6].

Experimental study

The aim of this study was to determine real time of residence of waste material on forward moving grate and reciprocal moving grate by means of experimental methods using marked material elements. The tests were carried out in "cold state", without heat and mass transfer effects. As a result only physical parameters of investigated material were simulated in the tests [7].

Test stand for investigation of residence time of material on the grate.

Specially built test stand can be adapted for modeling of forward moving grate (Fig. 3), reciprocal moving grate and drum grate in "cold state". Computerized system allows continuous velocity and leap control of grate bars. The grate consists of seven moving and six non-moving bars.

Tests were performed with the use of following materials:

Keramsite – (swelled clay) - artificial porous material produced by burning of clay granules, being used as insulating material, wood – waste wood chips, biomass – shredded air-dry green biomass, (tree branches, grass), mixture of keramsite + wood + biomass.

Markers of investigated materials were dyed and introduced to the main stream of material as Dirac impulse.

Tests combinations:

Following alternative combinations of test parameters were investigated:

- forward moving grate: inclination angle 9^0 to 16^0, grate bars velocity 1.5 to 7 mm/s.
- reciprocal moving grate: inclination angle 20^0 to 30^0, grate bars velocity 1.5 to 7 mm/s.

Mathematical algorithm.

E(t), the time distribution of solid material, the RTD – Residence Time Distribution [6]:

$$E(t) = \frac{u}{\sqrt{4\pi tD}} \exp\left[-\frac{(L-ut)^2}{4tD}\right] \qquad (2)$$

the variance is defined as:

$$\sigma_t^2 = \frac{\Sigma t_i^2 E(t_i)\Delta t_i}{\Sigma E(t_i)\Delta t_i} + t_m^2 \tag{3}$$

for open vessel

$$\frac{\sigma_t^2}{t_m^2} = \frac{2}{Pe_L^2}\left(Pe_L + 4\right) \tag{4}$$

from this we find value of Pe.

$$t_m = \frac{\Sigma t_i c_i \Delta t_i}{\Sigma c_i \Delta t_i} \tag{5}$$

4.2. Investigation of longitudinal and transversal dispersion of mass on the grates

Coefficients were determined by applying theoretical analysis and dimensional analysis. Theoretically obtained values of coefficients for various parameters of material (density, particle diameter) and various parameters of grate movement (grate bars velocity, inclination angle) were verified using two methods. First method is based on analysis of Peclet number calculated from the residence time distribution. The second method based on comparison of experimentally determined concentration field with values obtained by means of mathematical method. Both methods give satisfactory results [8].

4.3. Investigation of mixing intensity of material on the grate [9]

Beside the investigation of residence time of material on the grate the rate of material mixing was determined. Materials were introduced separately one after another in the following sequence: keramsite, biomass, wood chips. Mass of each component was strictly measured:

- keramsite m_k = 2kg (1.6 kg fraction 10-17 mm, 0.4 kg fraction 17-20 mm)
- biomass m_b = 1 kg
- wood chips $m_{śd}$ = 2 kg.

After the time corresponding to the average time of residence of material the grate was stopped and the samples of materials were taken for analysis.

Method of drawing of samples

The rate of material mixing was determined by separation of material laying on every grate bar by the two plastic sheets – forming so called "cascades". Material of every "cascade" was divided into five equal parts and mass composition of each part was determined. Average composition of all five parts of the "cascade" was calculated.

Method of determining of mixing rate

The analyzed material is multicomponent and non uniform. Mixing rate was determined having in mind one basic component which decides of the quality of the whole mixture. All other components are taken as "second" component. The ideal mixture expected in every "cascade" should have the same composition as original material introduced at the inlet of the grate.

Tests for determining rate of mixing were carried out for three versions of concentration of main components:

1. main component – wood chips – expected value of concentration p = 0.4
2. main component – keramsite – expected value of concentration p = 0.4
3. main component – biomass – expected value of concentration p = 0.2

The value of mixing rate of components on all grate bars was calculated according to Rose formula (6) [10]:

$$M = 1 - \frac{\sigma}{\sigma_0} \tag{6}$$

Standard deviation for the initial segregation can be defined as (7);

$$\sigma_0 = [p_0(1-p_0)]^2 \tag{7}$$

Standard deviation of test results was determined according relation (8):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - p)^2}{n}} \tag{8}$$

where: x_i – mass concentration of main component in analyzed sample,

p – expected value of concentration of main component,

n – number of samples taken for analysis (n=5 for each of "cascade").

Calculated values of mixing rate M for some tests are presented in Fig. 4a, 4b.

Figure 3.
Test stand (forward moving grate)

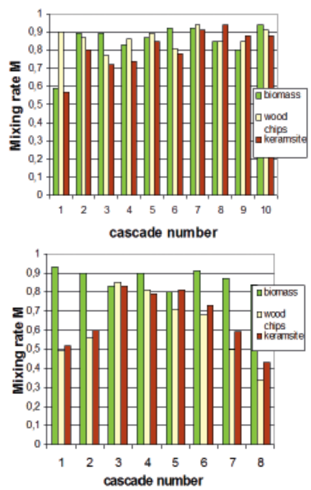

Figure 4.
Values of mixing rate of components for: a) forward moving grate, b) reciprocal (reverse)moving grate [9]; where: M_b- mixing rate of biomass, $M_{śd}$- mixing rate of wood chips, M_k – mixing rate of keramsite

4.4. Results and discussion

Forward moving grate

In this case concentration of marker material was a U-shaped (looking from above the grate). It can be noticed, that the influence of the grate inclination angle is not substantial for average residence material time, and that main influencing parameter is velocity of grate bars movement.

For forward moving grates one can observe:
– small backward mixing,
– short average residence times,
– low thickness of the material layer on the grate.

Particles of the biggest size, despite of the same density as other particles, show tendency to move faster and to leave the grate in shorter time than the other particles (Fig. 5a) (lower times of residence and greater values of E(Θ)). The same tendency is observed for increased velocity of grate bars (Fig. 5b).

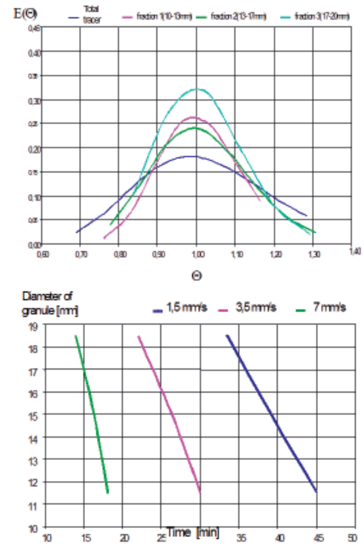

Figure 5.
a) Residence time for various fraction of keramsite on the forward moving grate (inclination angle 13^0, bars velocity 3,5 mm/s). b) Residence time for various fractions of keramsite for various size of particles and various bars velocity for forward moving grate (inclination angle 13^0)

Reciprocal (Reverse)moving grate

Tests on the reciprocal moving grate show that the mixing rate of material was very high on the whole length of the grate. The biggest particles of material of various sizes but of similar bulk density have on this type of grate shorter times of residence but the distribution function E(ό) showing mass ratio of output material of the average residence time has much lower values than on forward moving grate. Longitudinal dispersion is medium and high with the Peclet number within the range 5 to 60. For all polydispersed materials separation has a specific form – the small size fraction was concentrated in the upper side of the grate and the great size fraction in the lower side of the grate. For inclination angle 30° the residence time was short. Transport in this case was controlled by natural angle of repose, which was close to the grate inclination angle.

For all combinations of inclination angle and bars velocities the biomass has a tendency to swell and forms waves with free spaces inside.

For angles lower than 20° transport of all materials was directed to the upper side of the grate for all bars velocities and from practical point of view this case has no practical use.

For all tested materials the residence time was long and no. distinctive maximum of function $E(\theta)$ was observed.

Mixing rate of material

For forward moving grate the values of mixing rates M in all "cascades" were similar and had high values (Fig. 4a).

For reciprocal moving grate the values of mixing rates change in a broad range (Fig. 4b). High values were observed in the middle part of the grate while in the inlet and outlet these values are low because of concurrent transport of material. Smaller particles are transported to the upper part of the grate while bigger particles are transported more quickly. The size of particles influences velocity of transport to the greater extent than the density of material.

5. CONCLUSIONS

Presented in the chapter 2.1. general model of mass trasport in chemical reactors, and, as a special example on the moving grates, is composed of three main submodels: Combustion, pyrolysis and gasification of fuel particle, porosity of the fuel layer and movement of the particles on the grate (Fig. 1). They are related to the real parameters of the fuel combustion process on moving grate. In literature these problems are not sufficiently described, especially the analysis of particle movement on the moving grates and combustion porcess of single particle of waste-originated fuel. Theses problems are to some extent expalined in this paper.

It should be noted, that full description of combustion on the grate needs combination of single particle combustion model with the model of combustion in the layer. Parameters interrelated in these processes are temperature of gas phase, heat transfer between fuel particles, combustion rate, gas composition and kinetics of H_2, CH_4, CO oxidation [9], [12]. Method of movement analysis using marker particles presented in the paper brings importanat information on the particles movement structure and gives the understanding of all main processes undergoing in the layer. In many cases it is the only practical method of analysis of movement on the grate.

The information obtained from the investigations helps in determining grate velocity and grate iclination needed for designing and operation of the incineration system. This information is also helpful in modelling combustion processes of waste material on moving grates for various sizes of fuel particles [9].

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