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PHYSICAL AND MATHEMATICAL MODELING OF PHENOMENA PROCEEDING WITH GAS – POWDER TWO PHASE FLOW THROUGH MOVING PACKED BED IN METALLURGICAL SHAFT FURNACES

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Preliminary Note – Prethodno priopćenje

Physical and chemical processes in shaft furnaces proceeds in counter – current system. Reacting gas carrying powders flows up in packed bed of descending metallurgical materials. In this system the problem of bed particles hanging up appears. That is why the author undertook the investigations of gas – powder flow in descending bed. Physical model with glass bed and glass powders was constructed. The experiments were carried out and the influences of gas velocity, type and size of powders, type and size of bed particles and powder concentration in gas were established. The conditions, in which bed hanging up appears were defined. Mathematical model of two phase (gas + powder) flow in moving bed was developed.

Key words: modeling, blast furnace, gas – powder flow, powder hold up

Fizikalno i matematičko modeliranje fenomena procedure s dvofaznim tokom plin-prašak kroz pokretni "packed bed" u metalurškim pećima. Fizikalni i kemijski procesi u metalurškim pećima odvijaju se po protustrujnom sustavu. Reakcijski plin koji prenosi prašak utječe u "packed bed" opadajućeg metalurškog materijala. Kod ovog sustava javlja se problem zaostajanja čestica u sloju. Zbog toga je autor proveo istraživanje protoka plin-prašak u opadajućem sloju. Izrađen je fizički model sa staklemim slojem i staklenim praškom. Provedeni su eksperimenti i određeni su utjecaj brzine plina, tipa i veličine praška, tipa i veličine čestica sloja (bed particles) i koncentracije praška u plinu. Definirani su uvjeti u kojima se javlja zaostajanje u sloju. Razvijen je matematički model toka dvije faze (plin+prašak) u "moving bed".

Ključne riječi: modeliranje, metalurška peć, tok plin-prašak, zadržavanje praška

INTRODUCTION

A lot of metallurgical processes take places in shaft furnaces, where reacting gas carrying powders flows up in packed bed of descending metallurgical materials. Gas + powder two phase flow in fixed packed bed has been investigated by author for many years [1]. At present author undertakes the investigations with moving bed. Physical model with glass bed and glass powders was constructed. The experiments were carried out and the influences of gas velocity, type and size of powders, type and size of bed particles and powder concentration in gas were established. The conditions, in which bed hanging up appears were defined.

EXPERIMENTAL INSTALLATION AND PROCEDURE

Physical model has been constructed to find principal dependences for gas + powder flow in moving bed as a basis for mathematical model. Experimental column made of plexi has inner diameter of 114 mm and height of 400 mm. Moving down of the bed particles is generated by the extraction of particles at the bottom, using screw feeder. The gas–air feeds an installation with constant volume rate of flow, checked by rotameter. Pressure drops along the column are measured by using of differential manometer system. The powder transported by gas is injected into the lower part of packed bed. The feed rate of powder is controlled by screw feeder, dosing the powder to gas. Gas with powder leaves the column at the top, flowing to the cyclone.

The hold up of powder in bed and gas pressure drop were measured as a results of experiments. Powder hold up in bed was defined stopping powder feed and bed moving. Powder leaves the bed and it is measured in cyclone. Schematic diagram of model installation and the table containing gas flow conditions, bed rates and physical properties of materials used in model were presented earlier [2]. Similarity of author installation conditions with conditions in blast furnace shaft and reduction shaft of Corex were showed.

As materials for bed particles, glass spheres (8 and 10 mm), alumina spheres (7 mm), blast furnace pellets

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(10 mm) were used. Powders were of glass (110-130 μm, 90-110 μm), and iron sinters (90-130 μm).

RESULTS

The influences of powder concentration in gas, bed particle size, powder particle size on hold ups of powder and gas pressure drop in moving packed bed were defined and described earlier [2, 3]. In this paper the influence of bed type and powder hold ups in bed (Figure 1) and gas pressure drops in moving packed bed (Figure 2) are presented.

The results were the basis for mathematical model of two phase (gas +powder) flow in moving packed bed developed by author.

MATHEMATICAL MODEL

The results [2,3] were the basis for mathematical model of two phase (gas +powder) flow in moving packed bed developed by author. In the experiment it was observed that the total powder is the sum of static powder (powder particles settled on the packed particles) and the dynamic powder (powder particles moving in the packed bed void). Hence it appears that:

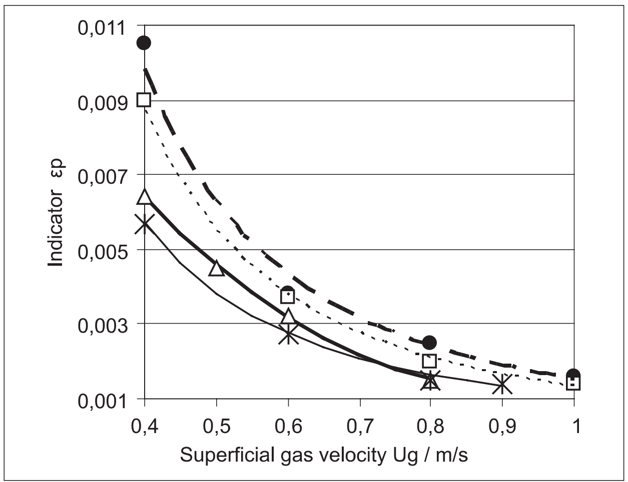

Figure 1 The influence of bed and powder type on powder hold ups in bed.

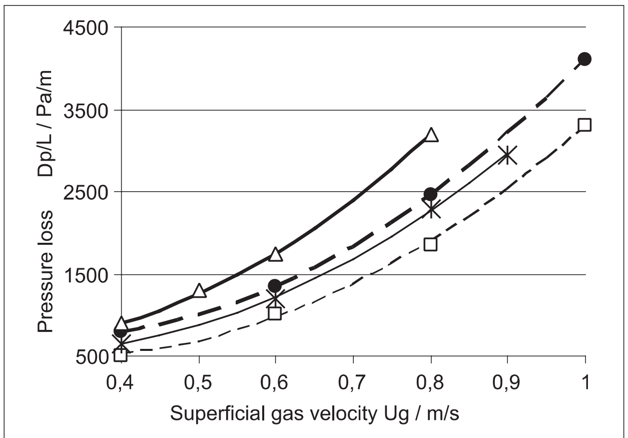

Figure 2 The influence of bed and powder type on gas pressure drops in moving packed bed.

$$\varepsilon_g+\varepsilon_{pd}+\varepsilon_z+\varepsilon_{ps}=1, \quad (1),$$

$$V_s=(\varepsilon_z+\varepsilon_{ps})V_k, \quad (2).$$

The fundamental equations of continuity and momentum for gas, powder and bed are presented below.

Gas phase

Continuity equation:

$$d(\varepsilon_g \rho_g \vec{U}_g^{'}) / dx = 0, \quad (3).$$

Momentum equation:

$$d(\varepsilon_g \rho_g \vec{U}_g^{'} |\vec{U}_g^{'}|) / dx = -d(p\varepsilon_g) / dx - (\vec{F}_{g-z} + \vec{F}_{g-p}) \quad (4).$$

Powder phase

Continuity equation:

$$d(\varepsilon_{pd} \rho_p \vec{U}_p^{'}) / dx = Rs - Rd, \quad (5).$$

Momentum equation:

$$d(\varepsilon_{pd} \rho_p |\vec{U}_p^{'}| \vec{U}_p^{'}) / dx = \vec{F}_{g-p} + \vec{F}_{p-z}, \quad (6).$$

Packed bed phase

Continuity equation:

$$d((\varepsilon_z + \varepsilon_{ps}) \rho_{zps} \vec{U}_z^{'}) / dx = Rd - Rs, \quad (7).$$

Momentum equation:

$$d((\varepsilon_z + \varepsilon_{ps}) \rho_{zps} |\vec{U}_z^{'}| \vec{U}_z^{'}) / dx = \vec{F}_{g-z} + \vec{F}_{p-z} + \vec{F}_{z-z}, \quad (8).$$

where $\varepsilon_z=1-\varepsilon_0$ (9);

$$\varepsilon_p=\varepsilon_{ps}+\varepsilon_{pd} \quad (10).$$

The drag caused by the forces interacting between gas and pieces of the bed surrounded by the static powder is described, similar to the papers [1,4,5], by the modified Ergun equation:

$$\vec{F}_{(g-z)} = 150\mu \left(\frac{\varepsilon_z + \varepsilon_{ps}}{(\varepsilon_{pd} + \varepsilon_g)\varphi_e d_e} \right)^2 \left(\frac{\vec{U}_g}{\varepsilon_g} - \vec{U}_z \right) + \\ + 1{,}75 \rho_g \left(\frac{\varepsilon_z + \varepsilon_{ps}}{(\varepsilon_{pd} + \varepsilon_g)\varphi_e d_e} \right) \left(\frac{\vec{U}_g}{\varepsilon_g} - \vec{U}_z \right) \left| \frac{\vec{U}_g}{\varepsilon_g} - \vec{U}_z \right| \quad (11),$$

where

$$d_e = d_z \sqrt[3]{\frac{\varepsilon_z + \varepsilon_{ps}}{\varepsilon_z}} \quad (12).$$

The drag caused by the forces interacting between gas and dynamic powder particles was formulated basing on the Darcy-Weisbach's equations, where the overall drag force is the sum of drag forces of single particles (conception similar to [1, 4-8])

$$\vec{F}_{(g-p)} = \frac{3}{4} C_m \frac{\rho_g \varepsilon_{pd}}{\varphi_p d_p} \left| \frac{\vec{U}_g}{\varepsilon_g} - \vec{U}_{pd} \right| \left(\frac{\vec{U}_g}{\varepsilon_g} - \vec{U}_{pd} \right) \quad (13)$$

where C_m is the modified drag coefficient of powder caused by the gas-powder interaction. It is usually assumed [1, 4, 8, 9] that C_m can be expressed in terms of drag coefficient for a single particle C_d

$$C_m = F_0(\varepsilon_g) C_d \quad (14);$$

$$F_0(\varepsilon_g) = (\varepsilon_g)^{-4,65} \quad (15),$$

where $F_0(\varepsilon_g)$ is Richardson – Zaki's voidage function [10].

The drag coefficient C_d is function of Reynold's number and it is formulated by. Stokes, Allen and Newton [11]:

$$C_d = \frac{24,0}{\mathrm{Re}_p} \quad \text{when} \quad \mathrm{Re}_p \le 0,4 \qquad (16),$$

$$C_d = 24,0(1,0 + 1,15\mathrm{Re}_p^{(0,69)}) / \mathrm{Re}_p$$

when $\qquad 0,4 < \mathrm{Re}_p \le 10^3 \qquad (17),$

$$C_d = 0,44 \quad \text{when} \quad \mathrm{Re}_p > 10^3 \qquad (18),$$

where Re_p is expressed with consideration of „slip":

$$\mathrm{Re}_p = \frac{\varphi_p d_p \rho_g \varepsilon_g}{\mu_g}\left(\frac{\vec{U}_g}{\varepsilon_g} - \vec{U}_{pd}\right) \qquad (19).$$

The drag $F_{p\text{-}z}$, caused by the interaction forces between dynamic powder particles and bed particles surrounded by static powder can be formulated on basis of the gravity force of spherical particles in fluid and the Fanning's equation

$$\vec{F}_{(p-z)} = \varepsilon_{pd}\rho_p F_k \frac{(\vec{U}_{pd} - \vec{U}_z)\left|\vec{U}_{pd} - \vec{U}_z\right|}{2d_h} \qquad (20),$$

where

$$F_k = \left(2\frac{\left(1 - \dfrac{\rho_g}{\rho_p}\right)}{F_r^2} + f_{kk}\right) \qquad (21).$$

The coefficient F_k includes the Froude's number:

$$F_r = \frac{(\vec{U}_{pd} - \vec{U}_z)}{\sqrt{d_h g}} \qquad (22).$$

The drag caused by the interaction forces between moving bed particles surrounded by static powder was described by equation

$$\vec{F}_{z-z} = (\varepsilon_z + \varepsilon_{ps})\mu_{zz}\nabla^2\vec{U}_z \qquad (23).$$

The expression $\mu_{zz}\nabla^2 U_z$ considers friction forces between bed particles as for fluid particles.

Developed model assumes that the powder and gas velocity is constant in the longitudinal direction, equations (3) to (4) can be transformed as follows:

$$\vec{F}_{g-p} = -d(p(\varepsilon_g)) / dx - \vec{F}_{g-z} \qquad (24).$$

The procedure of calculating values of the ε_{ps} and ε_{pd} indicators, coefficient F_k and Froude's number was begun by introducing of experimentally obtained values of the $_p$ indicator into equation (10) and pressure loss into equation (24). Relations between indicators $_{ps}$ and $_{pd}$, and coefficient F_k for different model system are expressed by equations (25)(26)(27)(28). For model system – bed of glass spheres or high alumina spheres + glass powders:

$$\varepsilon_{ps} = 25\,808\varepsilon_{pd}^2 + 40,689\varepsilon_{pd} + 0,0011 \qquad (25),$$

$$F_k = -2,4565 ln(Fr) + 14,009 \qquad (26);$$

For model system – bed of high alumina spheres or blast furnace pellets + iron sinter powders:

$$\varepsilon_{ps} = -25\,006\varepsilon_{pd}^2 + 56,558\varepsilon_{pd} + 0,002 \qquad (27).$$

$$Fk = 15,12(Fr^{-0,13})exp(-0,01Fr) \qquad (28).$$

Figures 3 and 4 show relations ε_{ps}=f(ε_{pd}) and F_k=f(Fr). For explanation of the most frequently used symbols, see List of symbols.

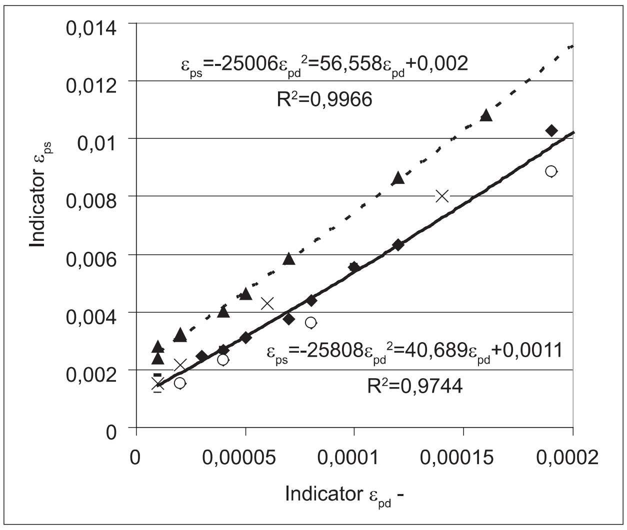

Figure 3 Relations between indicators ε_{ps} and ε_{pd}

Table 1 **List of frequently used marks**

	d_z / m	ε_0 -	d_p / μm	Φ_p -	G / kg/m²s
◆	0,01	0,38	110-130	0,88	0,45
■	0,01	0,38	110-130	0,88	0,35
○	0,01	0,38	90-110	0,82	0,45
•	0,008	0,36	110-130	0,88	0,45
×	0,007	0,36	110-130	0,88	0,45
▲	0,007	0,36	90-130	0,76	0,45
□	0,01	0,39	90-130	0,76	0,45
◆ ■ ○ •	bed: glass spheres, powder: glass				
×	bed: high alumina spheres, powder: glass				
▲	bed: high alumina spheres, powder: iron sinter dust				
□	bed: blast furnace pellets, powder: iron sinter dust				

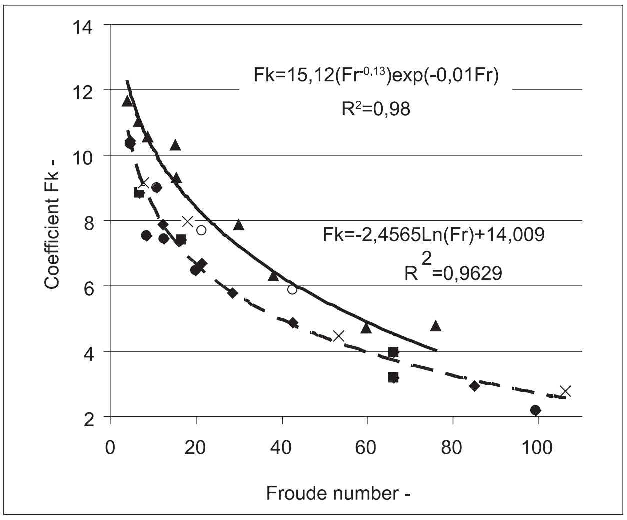

Figure 4 Relations between Froude number and additional pressure loss coefficient

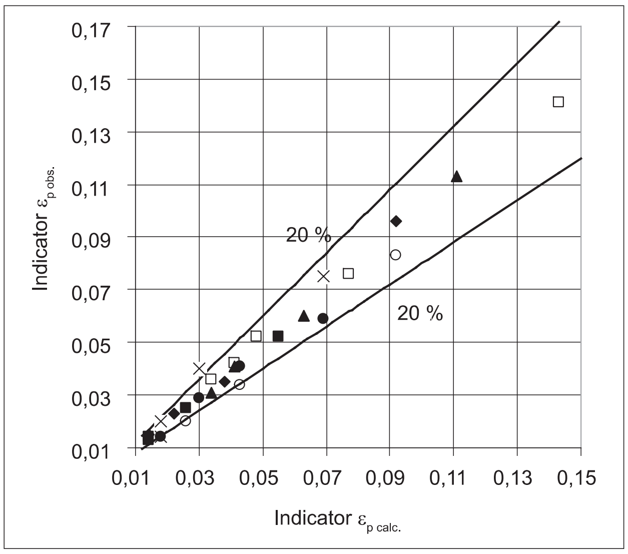

Figure 5 Comparison of experimental data with calculated values for powder hold up.

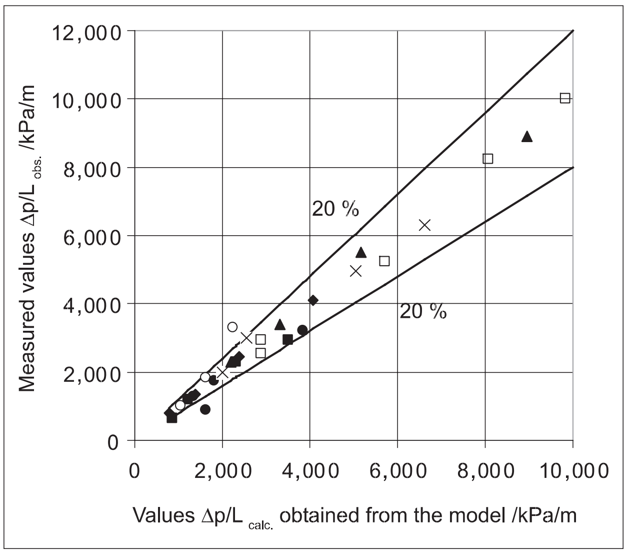

Figure 6 Comparison of experimental data with calculated values for pressure loss.

DISCUSSION OF EXPERIMENTAL AND MODEL RESULTS

Exchanging the bed of glass spheres for the bed of alumina spheres, considerable increase of powder hold up and gas pressure drop in moving packed bed were noticed. Surface properties of bed particles changed and better conditions for powder hold up occurred. True gas velocity in bed increased because of void friction decrease. The exchange glass powder for sinter powder caused change of powder particle shapes. Increase of powder hold up and gas pressure drop in moving bed were observed. Comparing the system "alumina particle bed – sinter powder" and "blast furnace pellet bed – sinter powder", it was noted that surface properties of bed particles as well as void friction of bed changed. The void friction was 0,36 for alumina bed and 0,39 for blast furnace pellet bed. That is why in blast furnace pellet bed in which void friction is higher, powder hold up increases but gas pressure drop decreases. For investigated system- packed bed of coke + blast furnace powder, at maximal applied gas velocities and feed rate of powder 0,45 kg/m^{2}s bed hanging up appeared.

The mathematical model was developed. For each experimental point, using the mathematical model, the pressure loss and powder hold up were calculated. Calculated values are not different than measured ones more than 20 % (Figure 5 and Figure 6).

CONCLUSION

1. Developed model allows satisfactory evaluate pressure loss of gas with powder flow and powder hold up in descending bed. The steady flow perturbation of gas + powder two phase flow in moving bed is possible to predict.

2. It was stated, that the hanging hazard of descending appears when the powder concentration in gas and gas velocity increase. The conditions of hanging can be defined with the ratio of bed material column pressure on experimental column cross-section to gas phase pressure at the level of gas with powder injection. When this ratio is more than 1, the bed hanging appears.

3. In further investigations the influence of gas velocity, type and concentration of powder in gas, size and shape of powder particles on hold ups of powder and gas pressure drop in packed bed as a function of experimental radius and with participation of liquid phase will be defined.

LIST OF SYMBOLS

C_d	drag coefficient of a single particle	-
C_m	modified drag coefficient of powders due to gas in packed bed	-
d_e	equivalent diameter for packed bed particles and static powder	m
d_h	hydraulic diameter	m
d_p	powder diameter	m
d_z	diameter of a packed particle	m
f_{kk}	interaction coefficient between powders and packed particles	-
$F_{0(\varepsilon g}$	Richardson- Zaki's function	-
$F_{g\text{-}p}$	interaction force between gas and pieces of dynamic powder	N/m^3
$F_{g\text{-}z}$	interaction force between gas and pieces of bed surrounded by static	N/m^3
$F_{p\text{-}z}$	powder interaction force between dynamic powder particles and bed particles surrounded by static powder	N/m^3
$F_{z\text{-}z}$	interaction force between bed particles	N/m^3
F_k	additional pressure loss coefficient	-
F_r	Froude number	-
G	powder feed rate	kg/m^{2}s
L	length of packed column under consideration	m
p	pressure	Pa
Re_p	Reynolds number	-
Rd	detaching rate of powder from particle surface	kg/m^{3}s

Rs	sticking rate of powder to particle surface	kg/m^3s
U_g	superficial gas velocity	m/s
U_p	powder velocity	m/s
U_{pd}	dynamic powder velocity	m/s
U_z	bed particles velocity	m/s
Δp	pressure difference	Pa
ε_0	void fraction in packed bed	-
ε_p	volume fraction of total (dynamic and static) hold up of powders	-
ε_g	volume fraction of gas	-
ε_{pd}	volume fraction of the dynamic hold up of powders	-
ε_z	volume fraction of bed	-
ε_{ps}	volume fraction of the static hold up of powders	-
φ_e	shape factor of equivalent bed pieces	-
φ_p	shape factor of a powder	-
μ_g	viscosity of gas	Pa s
μ_{zz}	coefficient of friction between bed particles	Pa s
ρ_g	density of gas	kg/m^3
ρ_p	density of a powder	kg/m^3
ρ_z	density of packed bed	kg/m^3

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Note: The responsible translator for English language is the lecturer from Silesian University of Technology Katowice, Poland.