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MODEL INVESTIGATIONS 3D OF GAS-POWDER TWO PHASE FLOW IN DESCENDING PACKED BED IN METALLURGICAL SHAFT FURNACES

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This paper presents the second phase of model investigations of static pressure radial distribution conducted on 4 levels of bed height. During the phase the diameter of glass bed particles was increased, blast-furnace pellets were introduced as bed and iron powder was used as powder. Experiments were carried out with regard to gas velocity, bed and powder type and size of bed particles. The radial distribution of 3 fractions of powder accumulated in the bed – static powder, dynamic powder and total powder was calculated from experimentally obtained values of radial distribution of static powder. The influence analysis of the change of investigated bed and powder parameters on values of interaction forces between flow phases as well as on phenomena occurring in the system was conducted.

Key words: metallurgy, shaft furnaces, system: descending packed bed-gas-powder, radial distribution of flow

INTRODUCTION

Processes of obtaining iron from ore in shaft furnaces are conducted in multiple phases (gas, packed and powder particles, liquids). Constant modernisation of the blast furnace, improvement of process efficiency and intensity entail the domination of the blast furnace in production of iron from ore. The remaining part falls on so called "iron ore direct reduction processes", most of all to Corex and Midrex processes. On account of large sizes of metallurgical reactors and process technologies, researches of multiphase flows are difficult to do on a working furnace [1-2]. Thus physical and mathematical simulation based on the theory of liquid dynamics is a useful tool to study occurring phenomena and is frequently used in Department of Metallurgy The Silesian University of Technology [3-6]. In the first phase 3D research into radial flow distribution for the system "gas transporting powder – moving packed bed" was conducted only in the model system "glass bed – glass powder". Its results together with the way of making measurements and the experimental apparatus applied are described in [6].

In the second research phase the diameter of glass bed particles was increased (increase ε_0), blast-furnace pellets were introduced and iron powder was used as powder. The researches were carried out with use of the procedure described earlier and the physical model [6]. The aim of this paper is to demonstrate findings of these investigations. When conducting them there were taken into account the Reynolds' and Froude's criteria indicating the similarity of the study conditions to the conditions prevailing in the blast furnace shaft and in the reduction shaft of the Corex installation (Table 1). Volume rate of total amount of powder accumulated in the packed bed is expressed by the equation (1):

Table 1 **Research conditions**

		Measuring system	Blast (furnace shaft)	COREX (reduction shaft)
d_z	/ m	0,016	0,01 - 0,03	0,015 -0,025
d_p	/ mm	0,090 - 0,130	0,075 -3,000	0,010 -0,040
D_k	/ m	0,196	12	5
ε_0	/ -	0,41 - 0,48	0,42	0,42
ρ_g	/ kg/m^3	1,205	0,67 - 0,85	0,96
μ_g	/ Pa·s	$1,86\cdot10^{-5}$	$(3,98 - 4,25)\cdot10^{-5}$	$4,49\cdot10^{-5}$
U_g	/ m/s	0,4 - 1,2	1 - 2	1
U_z	/ m/s	$0,45\cdot10^{-3}$	$(0,6 -1,0)\cdot10^{-3}$	$0,6\cdot10^{-3}$
G	/ kg/m^{2}s	0,45	0,025 -0,10	0,02 -0,154
Re = $\rho_g U_g d_z/\mu_g$	/ -	414 – 1 243	157 - 1 281	320 - 535
Fr = $U_z/(d_z\cdot g)^{1/2}$	/ -	$1,1\cdot10^{-3}$	$(1,1 - 3,2)\cdot10^{-3}$	$(1,1 -1,6)\cdot10^{-3}$

$$\varepsilon_p = \varepsilon_{ps(0 - 100)} + \varepsilon_{ps(100 - 400)} + \varepsilon_{pd(0 - 100)} + \varepsilon_{pd(100 - 400)}. \quad (1)$$

RESULTS OF THE RESEARCH OF STATIC PRESSURE RADIAL DISTRIBUTION

Investigations into distribution of static pressure have been performed at 4 levels of bed height. Research results are illustrated in Figures 1 to 4. Diversification of pressure distribution on the nozzle level has been noticed in all analyzed beds. When a bed consists of 0,016 m spheres or pellets, the pressure is lower by the wall

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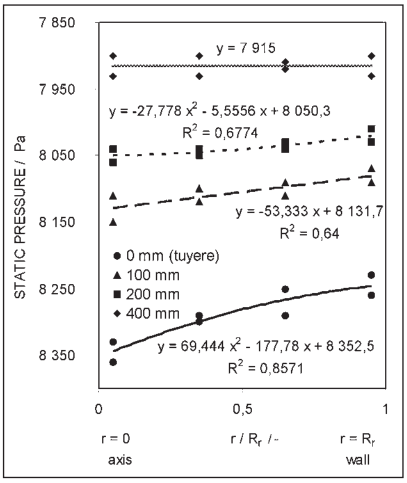

Figure 1 Values of static pressure radial distribution (bed: glass beads $\varepsilon_0 = 0{,}41$; $d_p = 0{,}110 - 0{,}130$ mm; $\varphi_p = 0{,}88$; $U_g = 0{,}4$ m/s)

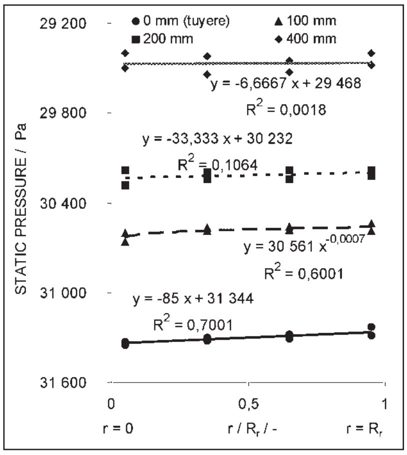

Figure 2 Values of static pressure radial distribution (bed: glass beads $\varepsilon_0 = 0{,}41$; $d_p = 0{,}110 - 0{,}130$ mm; $\varphi_p = 0{,}88$; $U_g = 1{,}1$ m/s)

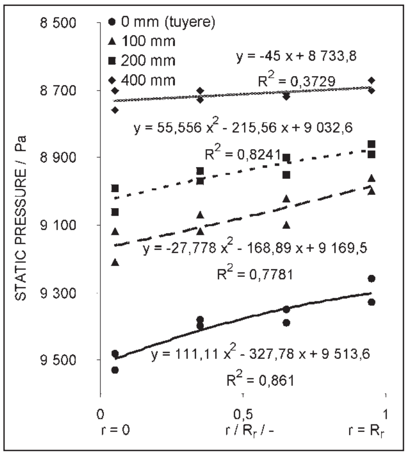

Figure 3 Values of static pressure radial distribution (bed: pellets $\varepsilon_0 = 0{,}48$; $d_p = 0{,}090 - 0{,}130$ mm; $\varphi_p = 0{,}76$; $U_g = 0{,}4$ m/s)

than inside the bed. In each case pressure diversification towards the radius decreases as the level of bed height increases. At the minimum gas velocity (superficial gas velocity 0,4 m/s) the pressure in upper sections of a bed takes a constant, or close to constant value.

RESULTS OF THE RADIAL DISTRIBUTION OF "STATIC", "DYNAMIC" AND "TOTAL" POWDER

A mathematical model described in [5] has been used to calculate the radial distribution of all analysed powder fractions. The model was adapted by use of following assumptions:

1 Full testing volume of the column V_k consists of:

a) testing volume of the lower column segment 0,1 m high – $V_{k(0-100)} = V_{g(0-100)} + V_{pd(0-100)} + V_{ps(0-100)} + V_{z(0-100)}$, (2)

b) testing volume of the upper column segment 0,3 m high – $V_{k(100-400)} = V_{g(100-400)} + V_{pd(100-400)} + V_{ps(100-400)} + V_{z(100-400)}$. (3)

2 Packed layer consists of bed particles bounded by "static" powder and occupies volume corresponding to each segment height:

$$V_{s(0-100)} = (\varepsilon_z + \varepsilon_{ps(0-100)}) V_{k(0-100)}, \tag{4}$$

$$V_{s(100-400)} = (\varepsilon_z + \varepsilon_{ps(100-400)}) V_{k(100-400)} \tag{5}$$

but

$$\varepsilon_{g(0-100)} + \varepsilon_{pd(0-100)} + \varepsilon_z + \varepsilon_{ps(0-100)} = 1 \tag{6}$$

$$\varepsilon_{g(100-400)} + \varepsilon_{pd(100-400)} + \varepsilon_z + \varepsilon_{ps(100-400)} = 1. \tag{7}$$

The correlation of additional resistance coefficient induced by gravitation, collisions and powder particle friction F_k with the Froude's number has been established.

For a model system blast-furnace pellet bed + Fe powder , in case of testing volume of the lower column segment 0,1 m high, the value of coefficient F_k is expressed by the equation:

$$F_k = 2{,}807 Fr^{-1{,}8336}, \tag{8}$$

and in case of testing volume of the upper column segment 0,3 m high by:

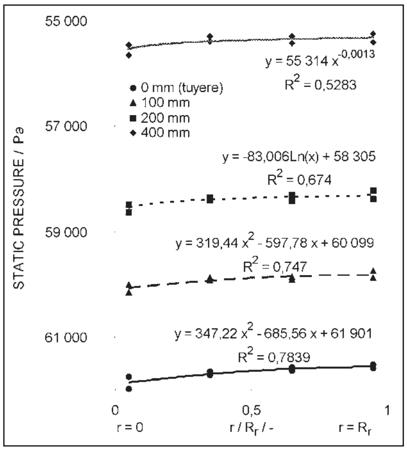

Figure 4 Values of static pressure radial distribution (bed: pellets $\varepsilon_0 = 0{,}48$; $d_p = 0{,}090 - 0{,}130$ mm; $\varphi_p = 0{,}76$; $U_g = 1{,}2$ m/s)

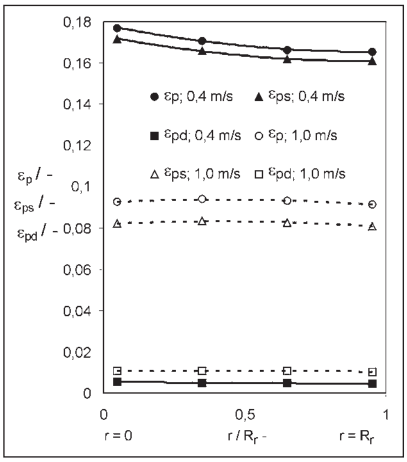

Figure 5 Distribution of volume friction ε_p, ε_{ps}, ε_{pd}, (bed: glass globules $\varepsilon_0 = 0{,}41$; $d_p = 0{,}110 - 0{,}130$ mm; $\varphi_p = 0{,}88$; level: 0 - 100 mm)

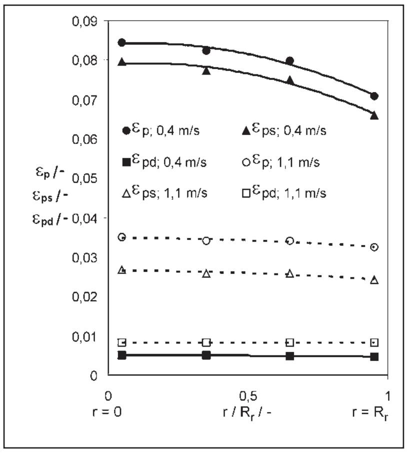

Figure 6 Distribution of volume friction ε_p, ε_{ps}, ε_{pd}, (bed: glass globules $\varepsilon_0 = 0{,}41$; $d_p = 0{,}110 - 0{,}130$ mm; $\varphi_p = 0{,}88$; level: 100 - 400 mm)

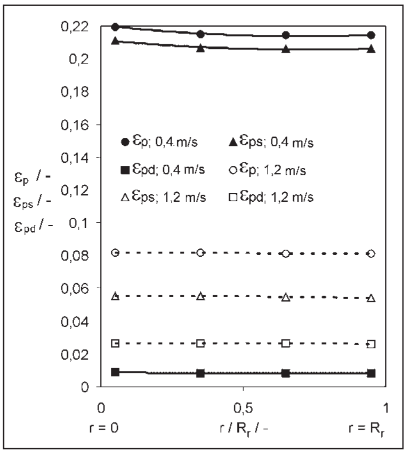

Figure 7 Distribution of volume friction ε_p, ε_{ps}, ε_{pd}, (bed: pellets $\varepsilon_0 = 0,48$; $d_p = 0,090 - 0,130$ mm; $\varphi_p = 0,76$; level: 0 - 100 mm)

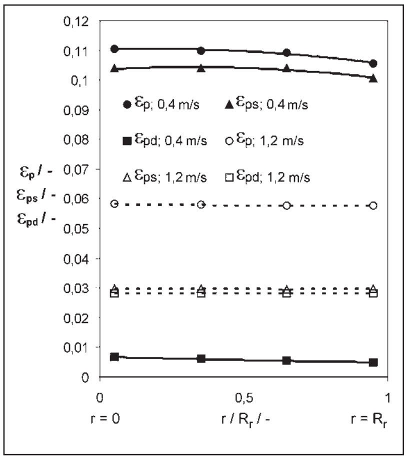

Figure 8 Distribution of volume friction ε_p, ε_{ps}, ε_{pd}, (bed: pellets $\varepsilon_0 = 0,48$; $d_p = 0,090 - 0,130$ mm; $\varphi_p = 0,76$; level: 100 - 400 mm)

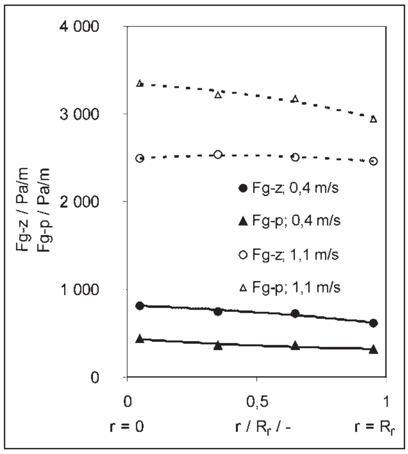

Figure 9 Calculated values of Fg - z and Fg - p (bed: glass globules $\varepsilon_0 = 0,41$; $d_p = 0,110 - 0,130$ mm; $\varphi_p = 0,88$; level: 0 - 100 mm)

$$F_k = 1,74\ Fr^{-1,9016}. \tag{9}$$

Next the radial distribution of values for ε_{ps}, ε_{pd} and ε_p coefficients was calculated.

It was observed that the concentration of "static" powder is lower by the wall than in the inner part of the bed (Figures 5 and 6).

For the system "blast furnace particles + Fe powder", the distribution of "static" powder in the lower segment of the bed height is almost uniform (Figure 7). At the minimum gas velocity a coefficient grows from the walls towards the axis of the bed as it is presented in Figure 6 and Figure 8.

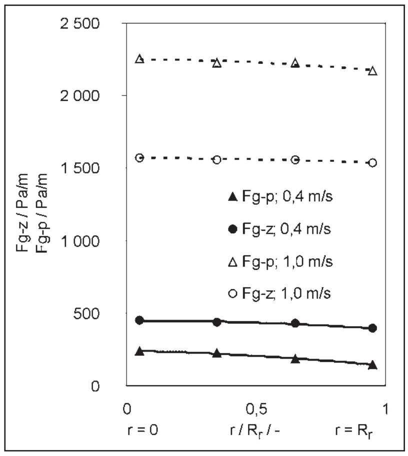

Figure 10 Calculated values of Fg - z and Fg - p (bed: glass globules $\varepsilon_0 = 0,41$; $d_p = 0,110 - 0,130$ mm; $\varphi_p = 0,88$; level: 100 - 400 mm)

SUMMARY

Between the analysed bed types of 1,6 mm diameter (coefficients ε_0 equal 0,41 and 0,48) there has been revealed just a small radial diversification of "static" pressure. Whereas big differences occur when comparing these beds to smaller beds of 0,01 m diameter and a coefficient ε_0 of 0,39 (researches described in [6]). In case of smaller bed the pressure is highest near the gas entry (by the wall), and drags of gas flow increase from the axis to the column walls. When the bed consists of 0,016 m spheres or blast-furnace particles, the pressure by the wall is lower than in the inner part of the bed.

The change of the size of bed particles also results in the diversified character of radial distribution of powder held up in the bed. With smaller beds the maximum powder volume accumulates by the walls and with 0,016 m sphere or particle beds the accumulation of "static" powder is smaller by the wall than inside the bed. Therefore the mathematical model was used to calculate the radial distribution of drag interaction gas-bed Fg-z and gas-powder Fg-p for the system 0,016 m glass sphere bed + 110 - 130 um glass powder. The investigation explained the reasons of the differences and its results are shown in Figures 9 and 10. When the bed consists of 0,016 spheres, drags Fg-z and Fg-p grow from walls towards the axis, so contrary to 0,01m spheres [6].

Thus, the reason of radial diversification of "static" pressure occurring at the tuyere level is the change of bed particle size corresponding to the change of bed void size. Larger bed voids offer smaller resistance to the stream of injected powder and allow its deeper insertion. That leads to the change of radial distribution of powder fractions retained in the bed. The results obtained in the investigation allow better understanding of the causes of radial diversification of amounts of powder accumulated in the bed as well as the value of static pressure that can occur in shaft furnaces with the change of bed and powder type – change of particle size.

List of symbols

d_k	diameter of column (shaft)	/ m
d_p	powder diameter	/ m
d_z	diameter of a packed particle	/ m

Fg-p	interaction force between gas	
	and pieces of dynamic powder	/ N/m^3
Fg-z	interaction force between gas	
	and pieces of bed surrounded by	/ N/m^3
F_k	static	-
F_r	additional pressure loss	-
G	coefficient	/ kg/m^2s
p	Froude number	/ Pa
Re	powder feed rate	-
U_g	pressure	/ m/s
U_z	Reynolds number	/ m/s
ε_0	superficial gas velocity	-
ε_p	bed particles velocity	
	void fraction in packed bed	-
ε_g	volume fraction of total	-
ε_{pd}	(dynamic and static) hold up of	
	powders	-
ε_z	volume fraction of gas	-
ε_{ps}	volume fraction of the dynamic	
	hold up of powders	-
φ_p	volume fraction of bed	-
μ_g	volume fraction of the static hold	/ Pa s
ρ_g	up of powders	/ kg/m^3
	shape factor of a powder	
	viscosity of gas	
	density of gas	

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Note: The responsible person for English language is B. Kozłowska, Katowice, Poland