Journal
of Achievements in Materials and Manufacturing Engineering

VOLUME 55
ISSUE 2
December
2012

Influence of bed particle size on gas-powder two phase flow conditions in descending packed bed. Model investigation (3D physical model)

B. Panic*
Department of Metallurgy, Silesian University of Technology,
ul. Krasińskiego 8, 40-019 Katowice, Poland
* Corresponding e-mail address: bogdan.panic@polsl.pl

Received 12.10.2012; published in revised form 01.12.2012

Analysis and modelling

ABSTRACT

Purpose: The aim of the research is to create basis for introduction of mathematical model for two phase flow in descending packed bed.

Design/methodology/approach: Iron obtaining from ore in shaft furnace is connected with accumulation of small particles inside the furnace, which can cause increased gas flow resistance. It is important that no flow disturbances occur. Hence researches were conducted to model (construction of 3D physical model) the flow of gas with powder through two bed types.

Findings: Intense accumulation of both powder fractions at the bottom of the bed was noted. Between analysed bed types, a large radial diversification of static pressure has been revealed occurring on the nozzles level. Two reasons of such diversification were identified.

Research limitations/implications: Radial changes of static pressure and gas flow resistance along bed height were registered (physical model 3D). Radial distribution of analysed bed was investigated. Amount of powder accumulated in bed was measured with division on "dynamic" and "static" powder. 2D models provide excellent visualization of the occurring phenomena. In full 3D visualization is much more difficult but they mirror real conditions in a better way. Next stage of the research will be conducted with real materials.

Practical implications: The developed calculation procedure could be used in flow and its disturbances evaluation in real shaft metallurgical units.

Originality/value: In 3D model "static" powder (with its radial distribution) at the tuyere level and in the higher part of bed was measured.

Keywords: Gas - solid flow; Radial distribution of flow; Moving bed; Physical modeling; Powder hold up

Reference to this paper should be given in the following way:
B. Panic, Influence of bed particle size on gas-powder two phase flow conditions in descending packed bed. Model investigation (3D physical model), Journal of Achievements in Materials and Manufacturing Engineering 55/2 (2012) 567-572.

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1. Introduction

Processes of obtaining iron from ore in shaft furnaces are conducted with multiple phases (gas, packed and powder particles, liquids). Constant modernization 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 process”, most of all to Corex and Midrex processes and their varieties Finex and Hyl III. In the recent years efforts had been undertaken to increase the amount of coal dust insufflated into the blast furnace through nozzles as fuel partially replacing blast furnace coke [1-4]. Large amounts of unburned coal and high level of ash can be a consequence[5]. Feedstock can also be a source of powder or it can be introduced to the unit within the scope of process procedure. (e.g. Corex process) [6, 7].

Small particles accumulation inside the furnace decreases bed permeability which can cause increase gas flow resistance. On account of reactor large size and process technology, research of multiphase flow is difficult to conduct on a working furnace. Thus physical simulation is a useful toll suited for studying the occurring phenomenon [8-13].

The described research are a part of KBN research project. The aim of the research is to create basis for introduction of mathematical model of two phase (gas + powder) flow through descending packed bed, with simultaneous analysis of changes along reactor height and radius, bed velocity, static gas pressure and void coefficient.

2. Model investigations

2.1. Experimental installation

Figure 1 presents physical model of the two –phase gas – powder flow through the moving (descending) packed bed. Descending bed (Fig. 2) was placed in the PCV column of an inside diameter of 196 mm and height of 1 m. Air was used as a gas that is fed to the system with constant volume flow rate, determined by the rotameter. The amount of fed powder is dispensed by worm feeder. The powder in the gas stream is injected into the bed through four nozzles located along the column’s perimeter.

As the powder carried by gas partially settles on the pieces of the bed ("static" powder) and partially moves in inter-pieces spaces ("dynamic" powder), so at the bottom of the column, between the feeder and collector, there is a valve that allows measurement of amount of both of those powder’s fractions.

Gas with the powder leaving the bed by four exhaust stubs is directed to the cyclone dust collector. During the investigations the motion of the packed bed is generated by the continuous removal of the part of bed through the feeder located in the bottom.

When constructing a physical model there were taken into account the Reynolds’ and Froude’s criteria indicating the similarity of the conditions of the conducted study to the conditions prevailing in the blast furnace shaft and in the reduction shaft of the Corex installation.

Fig.1. Experimental apparatus

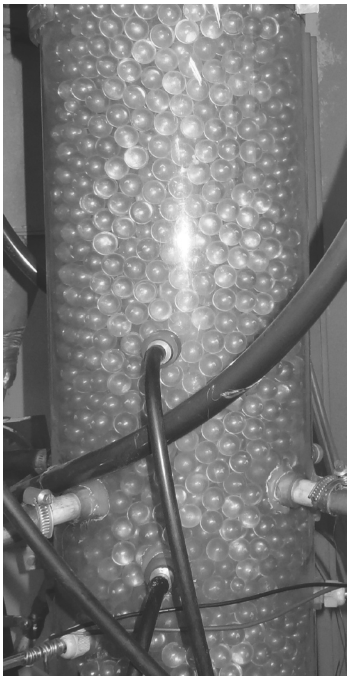

Fig. 2. Descending bed

2.2. Experimental procedure

Pressure differences along bed height (ΔP1 on section 0-100 mm, ΔP2 on section 100-200 mm, ΔP3 on section 200-400 mm) was measured using electronic manometer set. Amount of "static powder"(powder held up on bed packing – coefficient ε_{ps}). After reaching steady state together with bed and powder administration held up, measurement of "dynamic" (passing through packed space – coefficient ε_{pd}). Total amount of "static" powder was obtained after the bed was cleared of the accumulated powder on the end of the experiment. Total amount of powder accumulated in the bed is expressed by the equation:

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

Research was conducted in scope of superficial gas velocity (velocity with respect to research column free section) from maximum to minimum value. As its minimum velocity, the velocity at which powder transport to research column was observed has been assumed, whereas maximum velocity was determined by the tending to zero amount of powder held up in the bed. Study have been realized with use of two types of beds consisting of glass spheres: 10mm and 16mm spheres. In the first case the beginning volumes of free spaces in the bed coefficient ε_0 was equal 0.39, whereas in the latter 0.41. Therefore the influence of the beginning volumes of free spaces in the bed coefficient influence was also investigated.

The radial distribution of static pressure was measured at 4 levels of model column.

For measuring the radial distribution of charge the experiments with the use of multi colours particles were conducted. At the top part of the column the coloured particles (markers) were placed – in addition to which each colour corresponded to a different horizontal position (in the axis of the column, 1/3th of a radius, 2/3rds of a radius and by the wall).

Experiments were started after the start of the bed. Every four minutes the position of coloured bed particles were measured on the segment from the top of the column to 0.8 m in depth, gaining the distribution of the bed particles velocity on that segment of height. In order to obtain the distribution in a bottom segment of the bed, the experiments were repeated by continuous placement on the coloured particles circles, the subsequent non-marked layers. The timelines in the lower segment were obtained by measuring the time in which the marked particles reached the bottom of a device.

Table 1 shows research results.

3. Research results

As a result of conducted investigation it has been noted that together with increase in bed particle diameter (increase of coefficient ε_0) the amount of accumulated "static" powder increases whereas "dynamic" powder amount held up in bed decreases (Fig. 3 and Fig. 4). Increase of ε_0 also shifts the maximum velocity into higher value range (from 0.8 m/s to 1.0 m/s). Together with increase of gas velocity the amount of "static" powder decreases and "dynamic" powder amount increases. In general, the gas flow resistance in case of a bed with lower ε_0 is bigger.

This upswing concerns both bed types.

Lower bed segment (0-100 mm) is an area of intensified held up of both powder fractions which influences the gas flow resistance observed in this region (Fig. 5). Research of radial distribution of static pressure was accomplished on 4 bed height levels (Fig. 6 and Fig. 7). While comparing both analysed bed types a large variation of pressure distribution on nozzle level can be noticed. In case of smaller bed (10 mm) the pressure is highest near the gas entry (by the wall), whereas when the bed consist of 16 mm spheres the pressure by the wall is lower than inside the bed.

Table 1.
Research conditions

			Measuring system	Blast furnace (shaft)	COREX (reduction shaft)
Diameter of bed pieces	d_z	m	0.010-0.016	0.01-0.03	0.015-0.025
Diameter of powder particles	d_p	mm	0.100-0.140	0.075-3.000	0.010-0.040
Diameter of column (shaft)		m	0.196	12	5
Rate of beginning volumes of free spaces in the bed	ε_0	-	0.39-0.41	0.42	0.42
Gas density	ρ_g	kg/m^3	1.205	0.67-0.85	0.96
Gas viscosity	μ_g	Pa·s	$1.86 \cdot 10^{-5}$	$(3.98\text{-}4.25) \cdot 10^{-5}$	$4.49 \cdot 10^{-5}$
Superficial gas velocity	U_g	m/s	0.4 - 1.0	1-2	1
Bed velocity	U_z	m/s	$0.45 \cdot 10^{-3}$	$(0.6\text{-}1.0) \cdot 10^{-3}$	$0.6 \cdot 10^{-3}$
Mass apparent velocity of the powder stream		kg/m^{2}s	0.45	0.025-0.10	0.02-0.154
Reynolds' Number	$Re = \rho_g U_g d_z / \mu_g$	-	267-1071	157-1281	320-535
Froude's Number	$Fr = U_z / (d_z \cdot g)^{1/2}$	-	$(1.01\text{-}1.27) \cdot 10^{-3}$	$(1.1\text{-}3.2) \cdot 10^{-3}$	$(1.1\text{-}1.6) \cdot 10^{-3}$

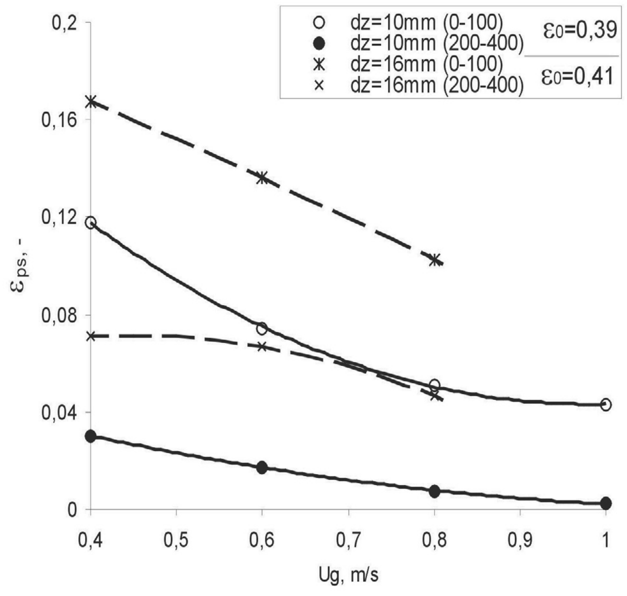

Fig. 3. ε_{ps} coefficient change

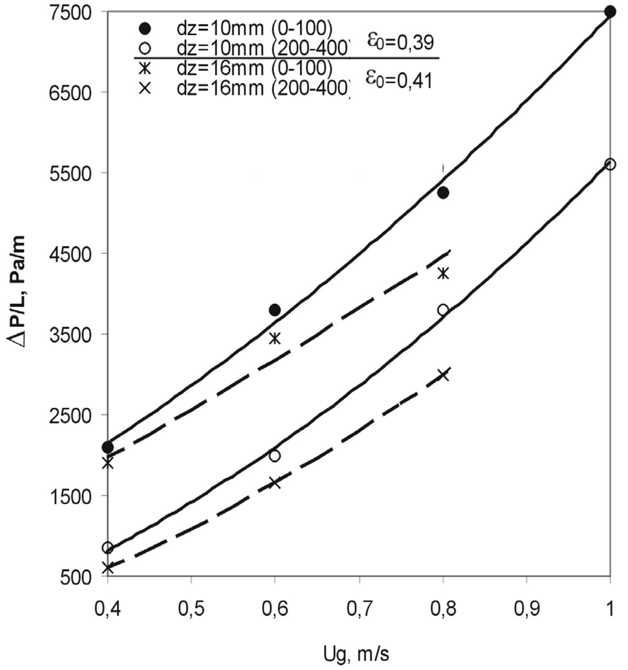

Fig. 5. Effect of size packed particles on gas flow resistance

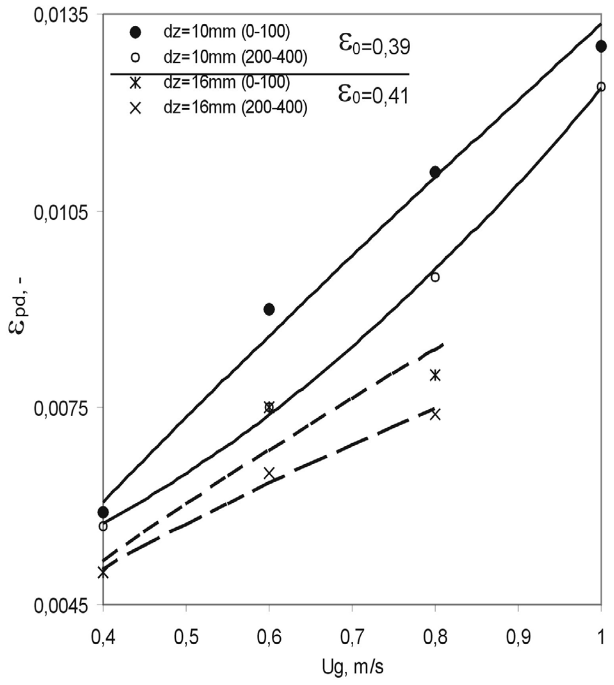

Fig. 4. ε_{pd} coefficient change

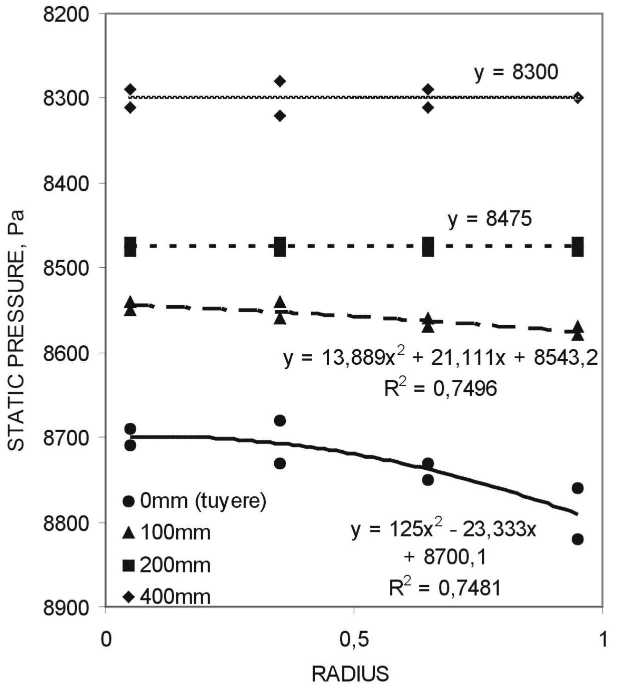

Fig. 6. Experimental values of static pressure radial distribution (dz=10 mm, Ug=0.4 m/s)

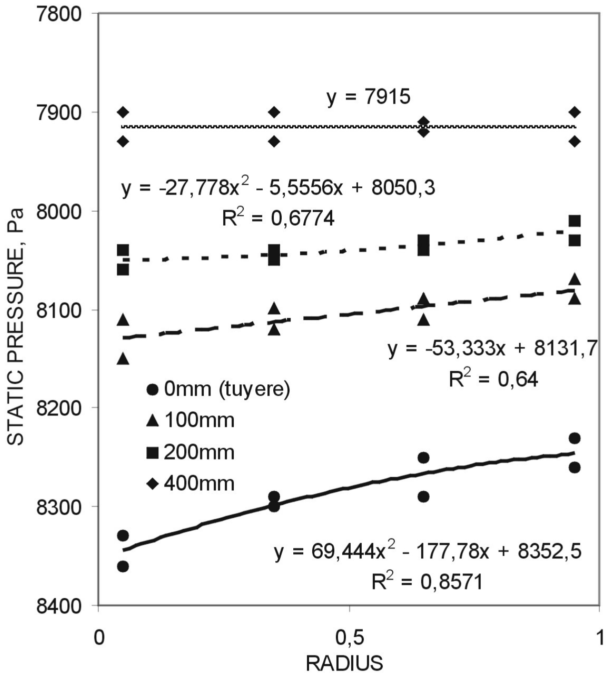

Fig. 7. Experimental values of static pressure radial distribution (dz=16 mm, Ug=0.4 m/s)

4. Data analysis and summary

Investigation of multiphase gas-powder-descending packed bed(glass spheres 10 mm and 16 mm) flow was conducted with use of full model (3D), together with 3D change of static pressure analysis. The amount of "dynamic" and "static" retained at the lower and at whole section of the bed height was measured. Intense accumulation of "dynamic" and "static" powder at the lower bed section has been noted.

Large radial variation of static pressure was noted between analysed bed types on nozzle level. In order to explain this variance radial distribution of analysed beds was investigated (Fig. 8 and Fig. 9).

It has been noted that the lover region is characterized by high bed particles velocity variation between the wall and the axis of the reactor. At the reactor bottom, around the axis of the column, a stagnant zone is arises (deadman). Particles in this zone remain still. After changing the bed particles to 16mm spheres, the stagnant zone slightly widens without changing height. Velocity of the particles located closer to the column walls increases, around the stagnant zone. As previously noted, the particle convergence is causing partial powder removal from the bed [14], and faster convergence intensifies this process [15]. Hence the pressure drop in this region in case of a bed consisting of 16mm spheres. The second cause of the radial variation of the static pressure occurring on nozzle level is the change in the void size. Larger voids creates smaller resistance to the insufflated powder stream and allows deeper insertion.

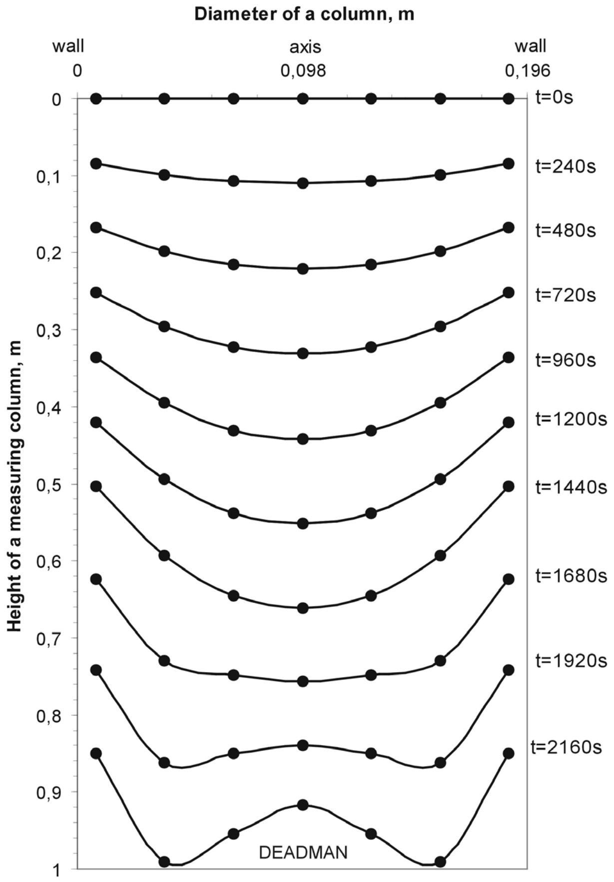

Fig. 8. Velocity distribution of bed particles (glass) along reactor's diameter, dz=10 mm, U_g=0.4 m/s

The research is in progress. Using experimentally obtained changes along bed height (measurement column), static pressure value and coefficients: ε_p, ε_{pd} and ε_{ps}, a mathematical model of two phase gas-powder flow in descending packed bed will be developed, that will take into account the amount of retained powder and gas flow resistance in bed.

The following assumption have been made to develop a model:

1. Full testing volume of the column V_k consists of:
   a) Testing volume of the lower column segment 0.1 m high (where intense powder accumulation occurs) $V_{k(0\text{-}100)}$,
   b) Testing volume of the upper column segment 0.3 m high (where less intense powder accumulation occurs) $V_{k(100\text{-}400)}$.
2. Volume $V_{k(0\text{-}100)}$ equals to sum of gas volume $V_{g(0\text{-}100)}$, "dynamic" powder volume $V_{pd(0\text{-}100)}$, "static" powder volume $V_{ps(0\text{-}100)}$ and the volume occupied by packed bed V_z,
3. Volume $V_{k(100\text{-}400)}$ equals to sum of gas volume $V_{g(100\text{-}400)}$, "dynamic" powder volume $V_{pd(100\text{-}400)}$, "static" powder volume $V_{ps(100\text{-}400)}$ and the volume occupied by packed bed V_z,
4. Packed layer consist of bed particles bounded by "static" powder and occupies volume corresponding to each segment height:

$$V_{s(0-100)} = \varepsilon_z + \varepsilon_{ps(0-100)} V_{k(0-100)}, \tag{2}$$

$$V_{s(100-400)} = \varepsilon_z + \varepsilon_{ps(100-400)} V_{k(100-400)}, \tag{3}$$

but

$$\varepsilon_{g(0-100)} + \varepsilon_{pd(0-100)} + \varepsilon_z + \varepsilon_{ps(0-400)} = 1, \tag{4}$$

$$\varepsilon_{g(100-400)} + \varepsilon_{pd(100-400)} + \varepsilon_z + \varepsilon_{ps(100-400)} = 1. \tag{5}$$

where:
ε_g – gas volume fraction,
ε_z – fraction of volume occupied by packed bed,
(0-100), (100-400) – indexes indicting corresponding column height segment.

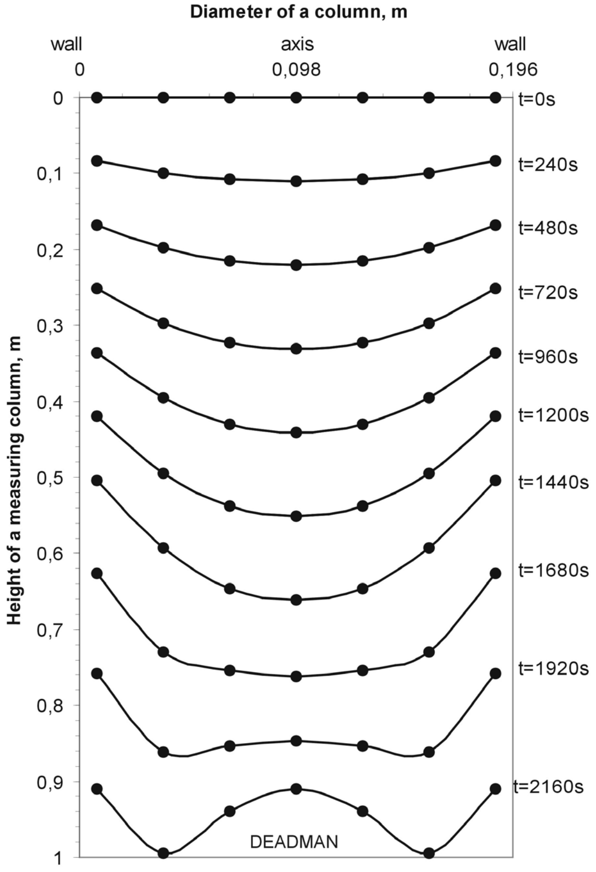

Fig. 9. Velocity distribution of bed particles (glass) along reactor's diameter, dz=16 mm, U_g=0.4 m/s

The developed procedure (based on physical 3D model) will be able to be utilized in assessment of flow and its disturbances in real shaft metallurgical units.

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