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## INFLUENCE OF THE BED TYPE ON THE FLOW RESISTANCE CHANGE DURING THE TWO-PHASE (GAS + POWDER) FLOW THROUGH THE DESCENDING PACKED BED

### WPŁYW RODZAJU ZŁOŻA NA ZMIANĘ OPORÓW PRZEPIYU PODCZAS DWUFAZOWEGO (GAZ+PYŁ) PRZEPIYU PRZEZ SCHODZĄCE ZŁOŻE KAWAŁKOWE

The flow of gases with powder in the countercurrent to the charge materials occurs in many chemical processes. In the shaft metallurgical devices, the physical and chemical processes take place also in the countercurrent system. An important issue is that there are no disruptions of the flow in this multiphase system. Under real operating conditions of the device, the powder is generated within the process and its source is the charge or it is inserted to the device within the process procedure.

In this system, a problem of bed particle suspension appears. That is why the author undertook investigations on the gas – powder flow in the descending bed. A physical model of this system was constructed. The experiments were performed and the influence of gas velocity, a type and size of the bed and powder particles as well as the powder concentration in the gas was established. Conditions when the descending bed suspension occurs were defined. In the case of physical model with glass materials, the suspension of bed did not occur. Therefore, investigations using beds of high alumina materials, blast furnace pellets and iron powder were performed. The results are presented below. When the bed of glass spheres was replaced with the bed of alumina spheres, a considerable increase in the volume of powder held up in the bed the gas flow resistance were observed. The surface properties of bed particles changed and better conditions for powder holdup were created. The actual gas velocity in the bed increased due to void fraction reduction.

Replacement of the glass powder with the iron powder caused a change in the powder density, its surface properties and the shape factor. Greater amounts of the iron powder were held up in the bed and the gas flow resistance increased.

Comparing the alumina particle bed – iron powder system to the blast furnace pellet bed – iron powder system, changes in the surface properties of bed particles and the void fraction of bed changed. The study results were the basis for defining conditions of the descending bed suspension.

*Keywords:* descending packed bed, gas – powder flow, powder holdup, bed suspension

Przepływ gazów z pyłem w przeciwnym kierunku do materiałów wsadowych występuje w wielu procesach chemicznych. W szybowych agregatach metalurgicznych procesy fizykochemiczne zachodzą także w układzie przeciwnym. Istotnym jest by w tym wielofazowym układzie nie dochodziło do zakłóceń przepływu. W warunkach rzeczywistych pracy agregatów pył jest generowany podczas przebiegu procesu a jego źródłem są materiały wsadowe lub jest wprowadzany do agregatu w ramach procedury procesowej. W układzie takim pojawia się problem zawieszania cząstek złoża. Stąd autor podjął badania przepływu gaz + pył w złożu schodzącym. Skonstruowano model fizyczny układu. Przeprowadzono badania z analizą wpływu prędkości gazu, rodzaju i wielkości kawałków złoża, cząstek pyłu, ilości pyłu w gazie. Określono warunki, w których dochodzi do zawieszania schodzącego złoża.

W przypadku modelu z materiałów szklanych do zawieszania złoża nie doszło. W związku z tym podjęto badania na złożach z tworzyw wysokoglinowych na bazie  $Al_2O_3$  i grudek wielkopieczowych oraz pyłu żelaza. Otrzymane wyniki przedstawiono w niniejszej publikacji. Zamieniając złożo z kul szklanych na złożo z kul wysokoglinowych stwierdza się wyraźny wzrost ilości zatrzymanego w złożu pyłu i oporów przepływu gazu. Zmianie uległy własności powierzchniowe cząstek złoża, powstały korzystne warunki do odkładania pyłu, wzrosła prędkość rzeczywista gazu w wyniku zmniejszenia wolnych przestrzeni.

Zastąpienie pyłu szklanego pyłem żelaza spowodowało że zmianie uległa gęstość pyłu, jego własności powierzchniowe, współczynnik kształtu. Pył żelaza został zatrzymany w złożu w większej ilości, wzrosły też opory przepływu gazu.

Przy porównaniu układów złożo z kul wysokoglinowych – pył żelaza i złożo z grudek wielkopieczowych – pył żelaza, stwierdzono zmianę nie tylko własności powierzchniowych złoża ale również średnicy cząstek złoża a co za tym idzie wskaźnika początkowych wolnych przestrzeni. Uzyskane wyniki badań były podstawą do określenia warunków, w których dochodzi do zawieszania schodzącego złoża.

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## 1. Introduction

In shaft furnaces, especially in the blast furnace, three functions have dominant influence on the course of the process: heat exchange between the gas and the charge, chemical reactions together with corresponding physical phenomena and the flow of the gas and the charge. The heat exchange and material reduction functions are well known and basing on them, it is possible to determine the process state vector, especially while modeling phenomena. Research in this field was conducted, among others, by A. Łędzki et al. [1-2]. On the other hand, the flow aerodynamics requires much more study, as up till now empirical dependencies have been used to determine it. It concerns not only the gas medium but, above all, the gas flowing with powder through the descending charge.

All the abovementioned factors prompted the author to undertake the research of flow resistance and the amount of powder suspended in the bed during the two-phase (gas + powder) flow in order to establish their real impact on bed suspension conditions.

The researches were conducted:

- to evaluate the influence of gas velocity, type of powder particles in gas and type of bed particles on the gas flow resistance through the packed bed;
- to evaluate the influence of gas velocity, type of powder particles in gas and type of bed particles on the volume of “static” and “dynamic” powder accumulated in the bed, as well as the total volume of powder accumulated in the bed;
- to identify the conditions in which the descending bed is suspended.

Since the real operating conditions of metallurgical devices, including high temperatures, preclude proper measurements to be taken for studies of metallurgical processes, physical and mathematical modeling is most frequently used [3-6]. For the purpose of this research, a physical model of two-phase gas-powder flow through descending (moving) packed bed was designed and constructed. During the first stage, the research was conducted using a model of glass bed - glass powder system. Under the applied conditions, even those extremely unfavorable for gas flow, no bed suspension occurred. Therefore, the research was continued for the bed of high alumina spheres – iron powder system and metallurgical systems (blast furnace pellets – iron powder). The performed investigations showed that under certain conditions at given bed descending speed and gas velocity, bed suspension occurs as the gas phase pressure at the gas and powder blow level increases above the pressure imposed by the bed material spurt and the “static” powder embedded in it on the apparatus cross-section.

## 2. Experimental installation and procedure

Figure 1 presents an outline of the research system. The descending bed was placed in the PCV column of the inner diameter of 196mm and height of 1m. Air was used as gas that is fed to the system with the constant volume flow rate, determined by the rotameter. The amount of fed powder is dispensed by a screw feeder. The powder in the gas stream is injected into the bed through four nozzles located along

the column's perimeter. The powder carried by gas partially settles on the pieces of the bed (“static” powder) and partially moves in inter-pieces spaces (“dynamic” powder). 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 at the bottom.

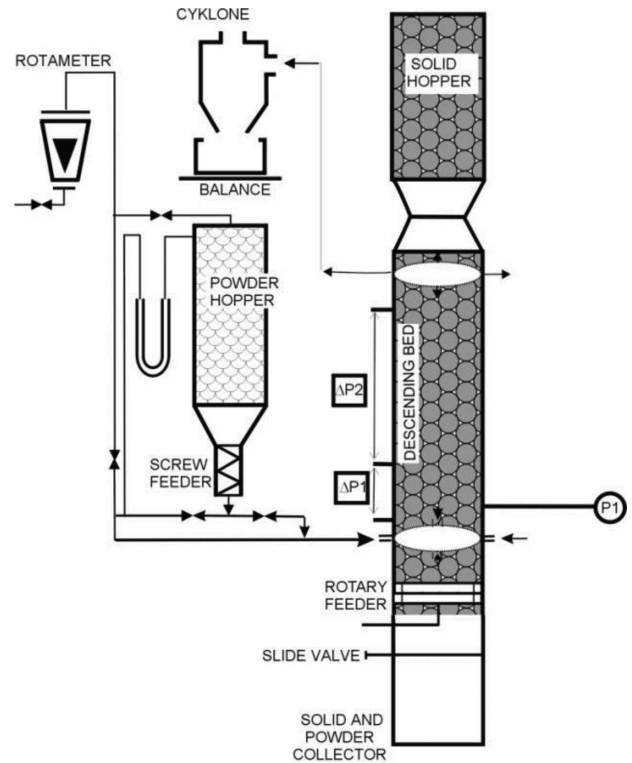


Fig. 1. Experimental apparatus

Pressure differences ( $\Delta P$ ) along the bed height (on section 0-100mm and on section 100-400mm) were measured using an electronic manometers' set. The amount of accumulated “static powder”(powder settled on the bed particles) and the amount of “dynamic” powder (powder passing through the inter – pieces spaces) were measured. The total amount of powder accumulated in the bed is expressed by the equation:

$$\varepsilon_p = \varepsilon_{ps} + \varepsilon_{pd} \quad (1)$$

where:

$\varepsilon_p$  – volume fraction of total (dynamic and static) hold up of powders;

$\varepsilon_{ps}$  – volume fractions of the static hold up of powders;

$\varepsilon_{pd}$  – volume fraction of the dynamic hold up of powders.

The research conditions were referred to conditions inside a blast furnace shaft and the reduction shaft of Corex installation and presented in Table 1. 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.

TABLE 1

Research conditions

			Measuring system	Blast furnace (shaft)	COREX (reduction shaft)
Diameter of bed pieces	$d_z$	m	0.013-0.016	0.01-0.03	0.015-0.025
Diameter of powder particles	$d_p$	m	$(0.090-0.130) \cdot 10^{-3}$	$(0.075-3.000) \cdot 10^{-3}$	$(0.010-0.040) \cdot 10^{-3}$
Diameter of column (shaft)	D	m	0.196	12	5
Rate of initial volumes of free spaces in the bed	$\varepsilon_0$	-	0.41-0.48	0.42	0.42
Gas density	$\rho_g$	kg/m <sup>3</sup>	1.205	0.67-0.85	0.96
Gas viscosity	$\mu_g$	Pa·s	$1.86 \cdot 10^{-5}$	$(3.98-4.25) \cdot 10^{-5}$	$4.49 \cdot 10^{-5}$
Gas apparent velocity	$U_g$	m/s	0.4 - 1.2	1-2	1
Bed velocity	$U_z$	m/s	$0.45 \cdot 10^{-3}$	$(0.6-1.0) \cdot 10^{-3}$	$0.6 \cdot 10^{-3}$
Apparent mass flow rate of the powder	G	kg/m <sup>2</sup> ·s	0.45	0.025-0.10	0.02-0.154
Reynolds' Number $Re = \rho_g U_g d_z / \mu_g$	-	-	348-1285	157-1281	320-535
Froude's Number $Fr = U_z / (d_z \cdot g)^{1/2}$	-	-	$(1.1-1.3) \cdot 10^{-3}$	$(1.1-3.2) \cdot 10^{-3}$	$(1.1-1.6) \cdot 10^{-3}$

where: g – gravitational acceleration = 9,81 m/s<sup>2</sup>

Materials used in studies are glass spheres (0.016 m), high alumina spheres (0.013 m), blast furnace pellets (0.016 m) as well as powder in the form of glass spheres  $((0.110-0.130) \cdot 10^{-3} \text{m})$  and iron powder  $((0.090-0.130) \cdot 10^{-3} \text{m})$ . They are supposed to simulate iron-rich materials and not combusted coal particles. Dimensionless numbers indicate a similarity of conditions of the research conducted using the experimental installation to conditions in the Corex installation reduction shaft and blast furnace shaft.

### 3. Discussion of experimental results

The investigations were conducted at the maximum and minimum superficial gas velocity. The minimum superficial velocity of gas was the velocity value at the point where powder transfer into the test column was observed. The maximum superficial velocity of gas, on the other hand, was the velocity determined by the volume of powder held up in the bed which tended to zero. Under the applied conditions in the glass bed – glass powder system, no suspension of the descending bed occurred. Therefore, the research was continued for the bed of high alumina spheres – iron powder system and the metallurgical system: the bed of blast furnace pellets – iron powder. The high alumina bed - Fe powder system was collated with the bed of glass spheres – glass powder system. Figures 2-9 show graphical representations of the test results of powder mass held up in the bed and gas flow resistance (where:  $\varepsilon_{ps}$  – volume fractions of the static hold up of powders,  $\varepsilon_{pd}$  – volume fraction of the dynamic hold up of powders,  $\varepsilon_p$  – vol-

ume fraction of total (dynamic and static) hold up of powders  $\Delta P/L$  – gas flow resistance). Frequently used marks and their meanings are listed in Table 2.

When the bed of glass spheres + glass powder system was replaced with the high alumina + iron powder system (Figures 2-5), the iron powder (all fractions) was held up in the bed in a greater mass.

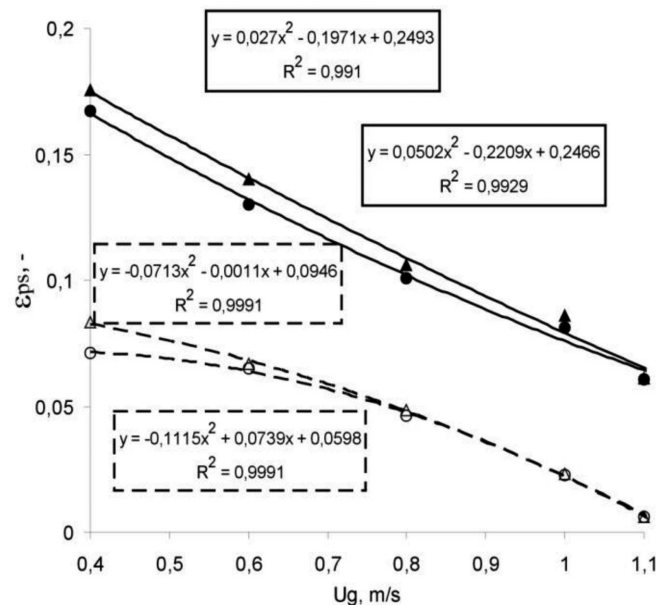


Fig. 2. Influence of the replacement of the bed of glass spheres + glass powder system with the bed of high alumina spheres + iron powder system on the mass of "static" powder held up in the bed

List of frequently used marks

$L_{(0-100)}, \text{ mm}$	$L_{(100-400)}, \text{ mm}$	$d_z, \text{ m}$	$\varepsilon_0, -$	$d_p, \text{ m}$	$\Phi_p, -$	$G, \text{ kg/m}^2\text{s}$	Notes
▲	△	0.013	0.45	$(90-130) \cdot 10^{-3}$	0.76	0.45	bed: $\text{Al}_2\text{O}_3$ spheres; powder: Fe powder
●	○	0.016	0.41	$(110-130) \cdot 10^{-3}$	0.88	0.45	bed: glass spheres; powder: glass beads
■	□	0.016	0.48	$(90-130) \cdot 10^{-3}$	0.76	0.45	bed: blast furnace pellets; powder: Fe powder

where: L - length of packed column under consideration; (0-100), (100-400), - indexes indicating corresponding column height segment,  $\phi_p$  - shape factor of the powder

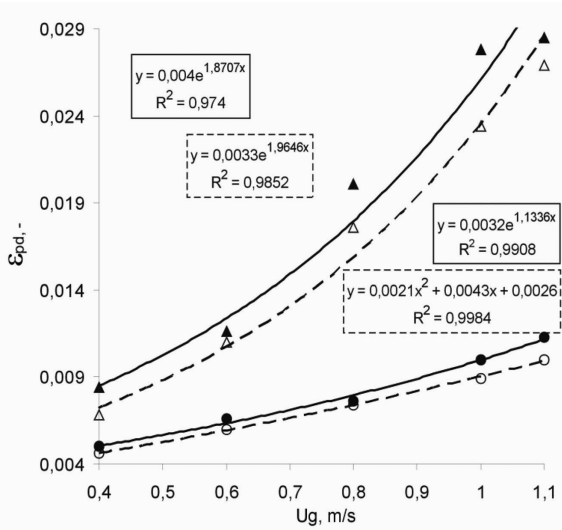


Fig. 3. Influence of the replacement of the bed of glass spheres + glass powder system with the bed of high alumina spheres + iron powder system on the mass of “dynamic” powder held up in the bed

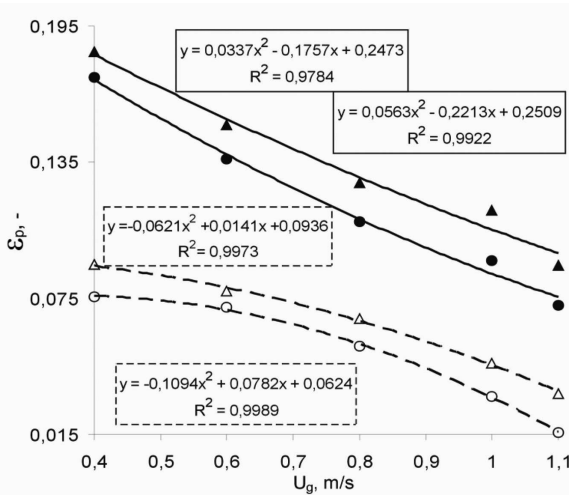


Fig. 4. Influence of the replacement of the bed of glass spheres + glass powder system with the bed of high alumina spheres + iron powder system on the total mass of powder held up in the bed

Despite the higher  $\varepsilon_0$  value, the gas flow resistance also increased. For the bed of high alumina spheres + iron powder system, the maximum velocity was determined by the bed movement distortions. During the next stage, the bed of high alumina spheres, based on  $\text{Al}_2\text{O}_3$  ( $\varepsilon_0 = 0.45$ ), was compared to the bed of blast furnace pellets of 0.016 m in diameter

( $\varepsilon_0 = 0.48$ ). In the case of metallurgical system, i.e. the bed of blast furnace pellets and Fe powder system, greater masses of powder fractions held up in the bed were observed and the maximum velocity shifted from 1.1 m/s to 1.2 m/s, which is shown in Figures 6 to 9.

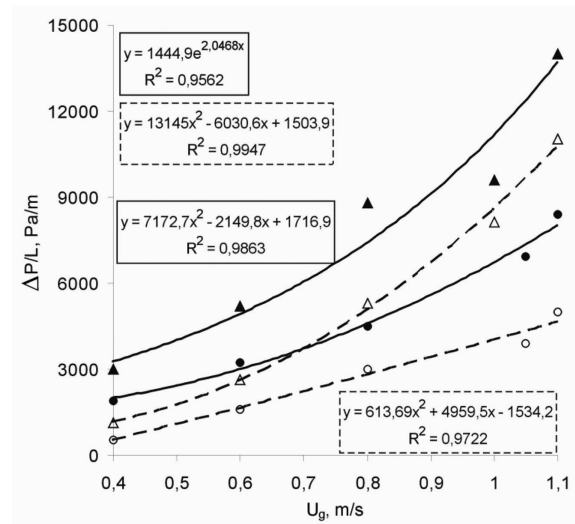


Fig. 5. Influence of the replacement of the bed of glass spheres + glass powder system with the bed of high alumina spheres + iron powder system on the resistances of gas-carrying powder flow through the moving packed bed

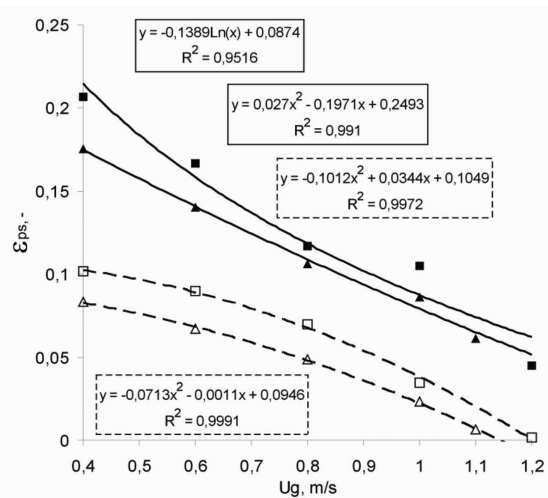


Fig. 6. Influence of the replacement of the bed of high alumina spheres + iron powder system with the bed of blast furnace pellets + iron powder system on the mass of “static” powder held up in the bed

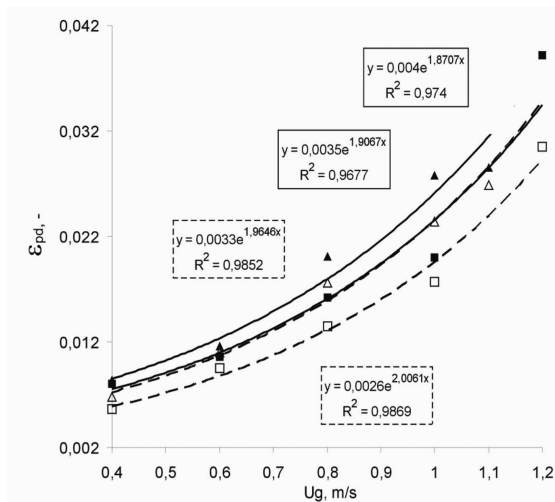


Fig. 7. Influence of the replacement of the bed of high alumina spheres + iron powder system with the bed of blast furnace pellets + iron powder system on the mass of "dynamic" powder held up in the bed

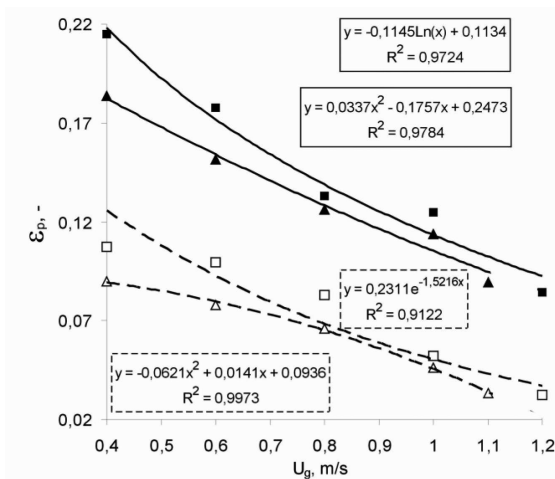


Fig. 8. Influence of the replacement of the bed of high alumina spheres + iron powder system with the bed of blast furnace pellets + iron powder system on the total mass of powder held up in the bed

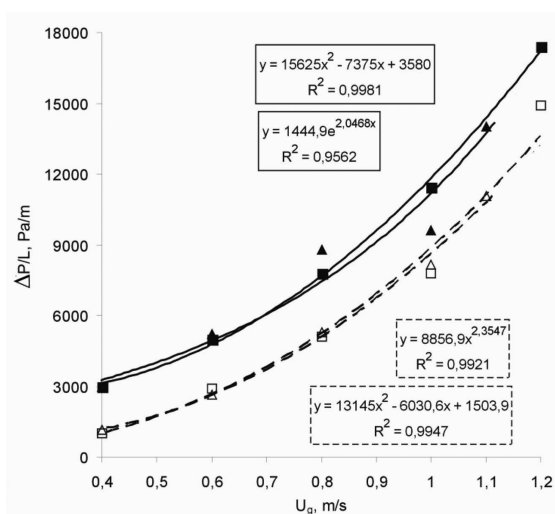


Fig. 9. Influence of the replacement of the bed of high alumina spheres + iron powder system with the bed of blast furnace pellets + iron powder system on the resistances of gas-carrying powder flow through the moving packed bed

For both bed types, maximum velocities were determined by the bed movement distortions.

The replacement of the bed of high alumina spheres with the bed of blast furnace pellets caused slightly elevated gas flow resistance values, particularly seen at high gas velocities (Fig. 9).

#### 4. Suspension parameter - PZ

For the bed of high alumina – Fe powder and the bed of blast furnace pellets – Fe powder systems, bed suspension occurred at the maximum velocities used in this research. For those conditions, the pressure  $P_z$  was calculated as the pressure imposed by the bed material spurt and the "static" powder embedded in it on the apparatus cross-section  $A_k$  (the measurement column) at the point of gas and powder blow, using the following equation:

$$P_z = \frac{(m_z + m_{ps})g}{A_k} \quad (2)$$

where:  $m_z$  – mass of the bed material, kg;  $m_{ps}$  – mass of the "static" powder, kg,  $A_k$  – cross-section at the measuring column,  $m^2$ ;  $P_z$  – pressure imposed by the bed material spurt and the "static" powder embedded in it on the apparatus cross-section, Pa.

The calculated pressure  $P_z$  was referred to the gas phase pressure  $P_g$  at the point of gas and powder blow. The value of pressure  $P_g$  is a result of flow resistance measurements made in the research  $\frac{\Delta P}{L}$ . For the calculated relation  $\frac{P_z}{P_g}$ , the values larger than one were obtained, which resulted from inhibition of undisturbed gravitational movement of the bed particles by inter-particle effects in the bed and the friction between the bed and the apparatus walls.

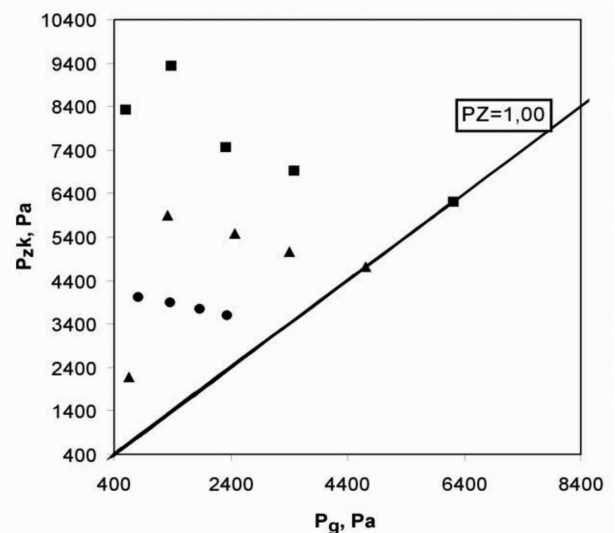


Fig. 10. Parameter determining bed suspension moment during the two-phase (gas + powder) flow through the moving packed bed

Therefore, due to free movement suppressing effects, a coefficient adjusting the undisturbed gravitational movement of bed particles was applied, and the relation  $\frac{P_z k}{P_g}$  was defined as the PZ suspension parameter. The assumed value  $k=0.61$



ensured that under the bed suspension conditions, the value of PZ parameter is less than or equal to one (Fig. 10), where:  $P_z k$  – adjusted pressure imposed by the bed material spurt and the “static” powder embedded in it on the apparatus cross-section, Pa;  $P_g$  – gas phase pressure at the point of gas and powder blow, Pa.

## 5. Summary and conclusions

Replacement of the bed of glass spheres + glass powder system with the bed of high alumina spheres + iron powder system caused changes in the bed particles surface properties and advantageous conditions for the powder build up were created. The changes also involved powder density, its surface properties, the shape factor and initial volumes of free spaces. This caused the iron powder holdup in the bed in a larger mass, the increase in the gas flow resistance and the bed suspension at the maximum gas velocity. While comparing the bed of high alumina spheres – iron powder system with the bed of blast furnace pellets – iron powder system, which is a typical metallurgical system, it can be seen that the change in the bed surface properties is accompanied by the change in the bed particle diameter and, thus, the initial volumes of free spaces coefficient (0.45 for the high alumina spheres and 0.48 for the blast furnace pellets). In the bed of blast furnace pellets with a higher initial free space coefficient, the mass

of held up powder is greater but the resistances of gas flow through the bed are slightly higher but at a greater gas velocity. In the bed of high alumina spheres, the free spaces become smaller, the actual gas velocity and the amount of “dynamic” powder increase. In this case, the bed suspension also occurs at the maximum velocity. A comprehensive evaluation of the influence of the bed material, i.e. the surface properties of compared beds, is hampered by different values of their free space coefficients,  $\epsilon_0$ , which significantly affect the amount of powder held up in the bed and the gas flow resistance.

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