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SOME WAYS TO CONTROL SEGREGATION AND MIXING IN GRAVITY FLOWS OF PARTICULATE SOLIDS

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Represented by a Member of the Editorial Board Professor V.I. Konovalov

Key words and phrases: aeration; hydromechanical segregation; migration; segregation; vibration.

Abstract: Experimental and analytical investigation of segregation in particulate media at various conditions of a gravity flow are carried out in this paper. Basic segregation effects for the particles differing on size and density and parameters of rapid shear flows flow to control the segregation are explored. The most effective methods to control the segregation in gravity flows of particulate solids are suggested.

Symbols

c – the test component concentration, kg·kg^{-1};
D_{dif} – coefficient of quasidiffusional mixing, m^2·s^{-1};
D_m – coefficient of migration, m^2·s^{-1};
d – diameter of particle, m;
F – the collision frequency, s^{-1};
j – the particles flux, kg·(m^2·s)$^{-1}$;
K_s – coefficient of segregation, m·s^{-1};
k – coefficient of relative velocity of segregation, N^{-1}·s^{-1};
m – the particle mass, kg;
ΔM – nonuniformity parameter, N·m;
S – mean distance between particles, m;
t – time, s;
v – the mean velocity, m·s^{-1};
v' – the mean fluctuation velocity, m·s^{-1};
x, y – cartesian coordinates;
α – the indination angle, grad;
Δ – driving forces of segregation processes;
$\bar{\varepsilon}$ – flow dilatation;
ρ – particles density, kg·m^{-3};
P – analog gidrostatic pressure in a particulate medium, N·m^{-2}.

1 Introduction

The segregation phenomenon takes place in many circumstances within solids process and handling plants and gives rise to a wide range of unwanted effects in many industries handling and processing solids. The influence of the practical effects of segregation on the product quality and process kinetics may be both negative and positive. Thus it is necessary to control segregation intensity and as a result to decrease separation of nonuniform particles if the ideal mixture is needed or to increase separation if the nonuniform particulate medium is being optimum for technological process.

Segregation tends to occur whenever bulk materials flows are accompanied by the movement of particles relatively to each other.

2 Theoretical aspects of particle segregation in a shear flow

The recently developed [1] general model of segregation dynamics in a shear flow of particulate solids takes into account convection, quasidiffusional mixing and two fluxes of segregation. For a steady two-dimensional shear flow such model is formulated as follows:

$$\frac{\partial c\rho_b}{\partial \tau} = -\frac{\partial uc\rho_b}{\partial x} + \frac{\partial}{\partial y}\left(\rho_b\left(D_{dif}\frac{\partial c}{\partial y} - D_m c\frac{\partial \ln s}{\partial y} - K\Delta Mc\right)\right), \quad (1)$$

where $c = c(\tau, x, y)$ is the test component concentration, τ – time, u – velocity towards shear direction x, s – mean distance between particles, ΔM is the local nonuniformity parameter; D_{dif}, D_m, K are the coefficients of quasidiffusional mixing, migration and hydromechanical segregation respectively, ρ_b – bulk density.

The flux of hydromechanical segregation is proportional to the degree of local nonuniformity of a medium. The nonuniformity parameter is a total excess moment of friction forces ΔM_f, gravity forces ΔM_g, and impact momenta ΔM_c, acting on a test particle in a conventionally homogeneous medium relative to a certain instantaneous axis of rotation as follows

$$J_s = k\Delta Mc\rho_b, \quad (2)$$

where k – is the kinetic constant of segregation, defined by the experimental method [2]; c – is the concentration of test particles; $\Delta M = \Delta M_f + \Delta M_g + \Delta M_c$ – is the total excess sum of moments of frictional, gravity forces and impact momenta [3].

When the ΔM value is positive the particle is more likely moved towards overlying layers of the bed, and on the other hand, if the value of the ΔM is negative – the particle is more likely to descent to the underlying bed.

The flux value of migration, caused by spatial nonuniformity of particulate medium, is defined as a relative velocity of the quasidiffusional displacement of nonuniform particles. The migration flux is proportional to the degree of spatial nonuniformity of particulate medium. Such nonuniformity degree is defined as a rate of change of the mean distance between particles in the direction of migration Flux as follows

$$J_m = D_m \frac{\partial \ln S}{\partial y} c\rho, \quad (3)$$

where D_m is the migration coefficient, calculated by analytical method [4] using the traditional physical and mechanical constants of particles and shear flow parameters.

The migration coefficient for spherical cohesionless particles, having diameters d_1 and d_2, and densities ρ_1 and ρ_2 respectively, is defined as

$$D_m = \frac{\overline{m}(c)(\overline{V}')^2}{4\overline{F}}\left(\frac{d_1^2}{m_1\overline{d}^2} - \frac{d_2^2}{m_2\overline{d}^2}\right), \quad (4)$$

where $\overline{m}(c)$ is the mean particle mass; $\overline{F}$, $\overline{V}$’ are the mean collision frequency and the mean fluctuation velocity respectively.

In the course of migration the heavier particles move towards the gradient of fraction volume of solid phase, whereas the light particles are forced into the area with a greater fraction of void volume.

The analysis of the model of segregation dynamics (1) shows, that the segregation intensity may be controlled by the influence of kinematic and structural characteristics of shear flow of particulate solids.

Therewith the important factors influencing hydromechanical segregation and migration are shear rate $\frac{\partial u}{\partial y}$ and the gradient of the fraction of void volume respectively.

3 Experimental and analytical investigations of segregation on size and density

In our experimental investigation we used a test unit that consists of an inclined open channel with a rough perforated bottom [3].

The experimental procedure is as follows. When the steady flow is achieved the particles go into receiving tray. To determine the particle distribution along the bed depth the tray contains cells.

To analyze the segregation dynamics we determined the profiles of particle velocity and fraction of void volume. We defined such profiles on the basis of the experimental data including bed depth, channel inclination angle and particle distribution along the tray. Besides we took into account the function of the interrelation

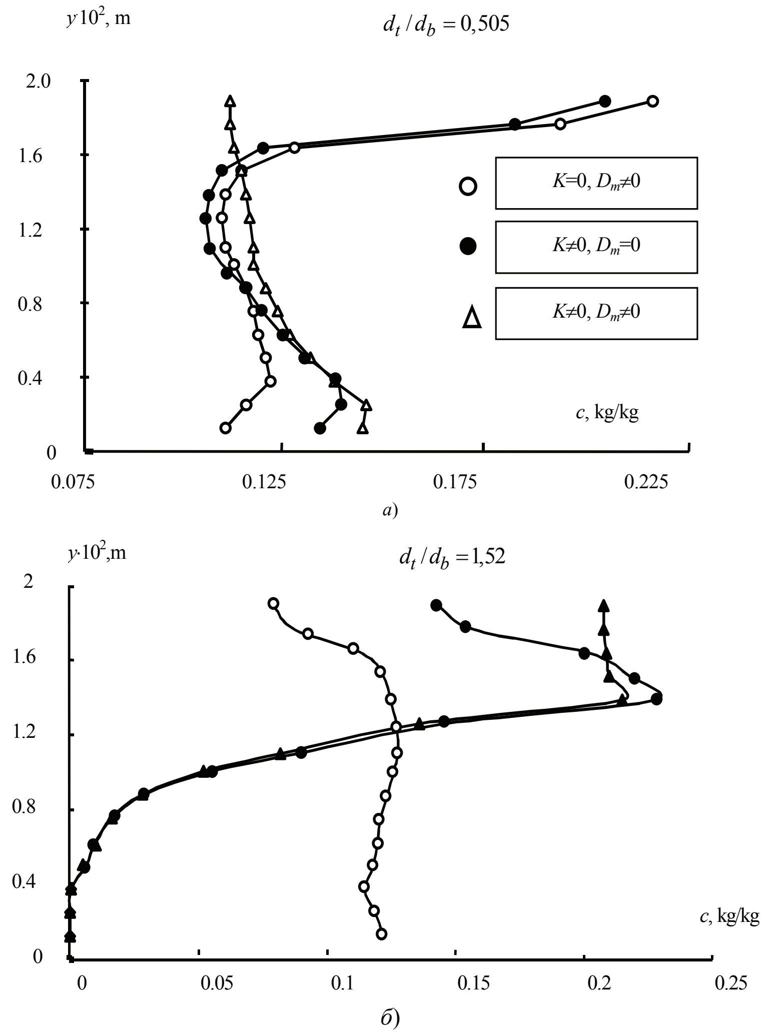
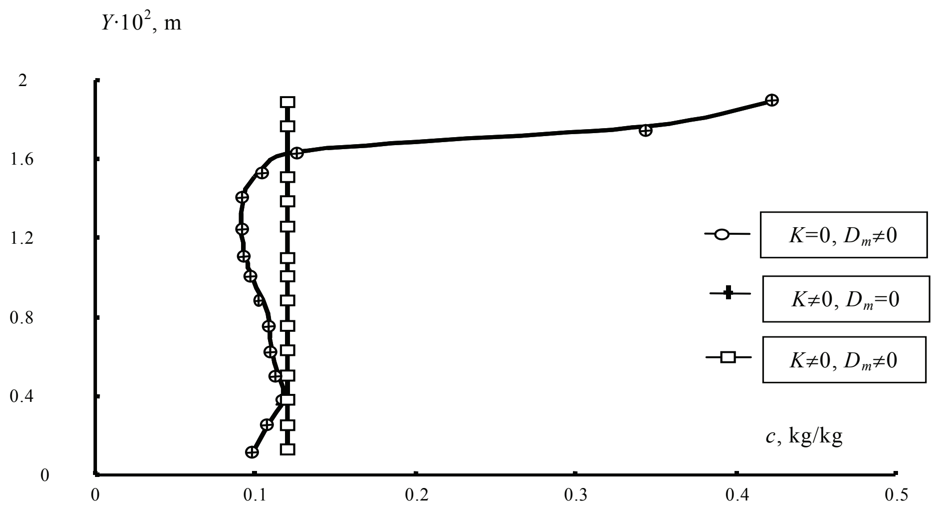


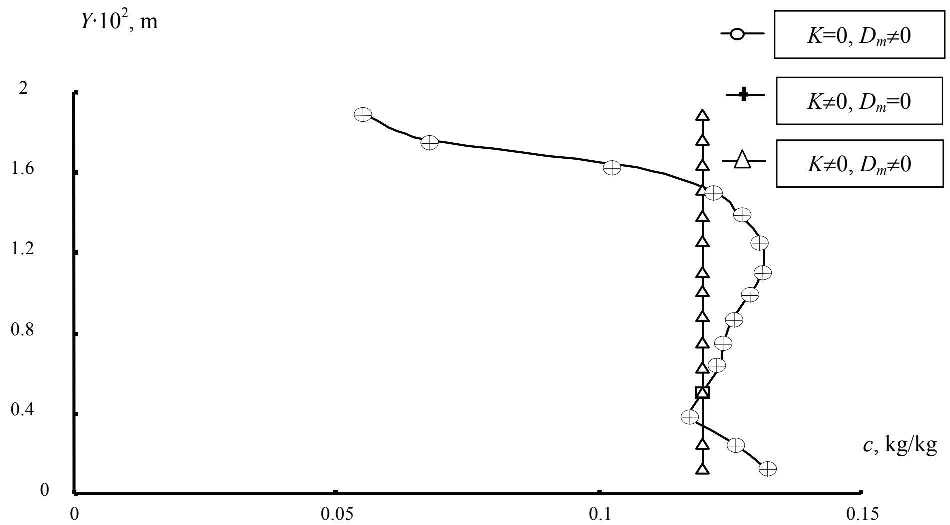
Fig. 1 Concentration profiles in the gravity flow of glass beads mixture consisting of the bulk material (d_b = 3,4 mm, ρ_b = 2500 kg/m^3, c_b = 88 %) and the test component:

a – d_t = 1,7 mm, ρ_t = 2500 kg/m^3, c_t = 12 %;

b – d_t = 5,1 mm, ρ_t = 2500 kg/m^3, c_t = 12 %



a)



б)

Fig. 2 Concentration profiles in the gravity flow of glass beads mixture consisting of the bulk material (d_b = 3,4 mm, ρ_b = 2500 kg/m^3, c_b = 88 %) and the test component:

a – d_t = 3,4 mm, ρ_t = 1000 kg/m^3, c_t = 12 %;

b – d_t = 3,4 mm, ρ_t = 10000 kg/m^3, c_t = 12 %

ship between the bed dilatation, total pressure and shear rate, which is formal analogy between a particulate medium at a rapid shear flow and a dense gas, as follows

$$p\bar{\varepsilon} = \psi v , \quad (5)$$

where p is the total pressure in a particulate medium, $\bar{\varepsilon}$ is the shear flow dilatation [3], v is the granular material "temperature", expressed as a function of the shear rate [3], ψ is the coefficient of the physical and mechanical properties of the particles.

The analytical investigations of segregation on size and density for varies d_t and ρ_t of test component of particulate mixture using Eqv. (1) and the profiles of velocity and fraction of void volume are shown on Figs. 1, 2.

The analysis of this results testify to the fact that the main mechanism for segregation on density is migration and for segregation on size it is hydromechanical segregation. So, in order to control segregation on size we must change the shear rate and in case of segregation on density we must influence the gradient of the fraction of void volume.

4 The methods to control segregation in particulate media

The most wide-spread type of particulate solids movement taking place at the various manufacturing processes is the gravity flow. Segregation control in the gravity flow of particulate solids may be realized in the way to change the geometrical flow parameters such as the chute angle and the bed depth. The experimental investigation show that the segregation efficiency is being maximum at the chute angle close to the angle of repose of the material (Fig. 3) and the bed depth equal 4 – 6*d* (Fig. 4). The segregation efficiency is evaluated as the variation coefficient, which is calculated as a percentage ratio of the standard of concentration distribution of the test component c_i to its mean concentration $\bar{c}$

$$E_s = \frac{100}{\bar{c}} \sqrt{\sum_{i=1}^{n} \frac{m_i}{\sum m_i} \left(c_i - \bar{c}\right)^2} , \qquad (6)$$

where m_i is the material mass in *i* – cell, *n* is the total number of cells.

On the other way the aeration and vibration of the bed are used as a methods to control the segregation in particulate media. The above mentioned technique and apparatus were adapted taking into account the specific character of the particulate material flow on an inclined chute during the transverse aeration and vibration.

The aeration influence on segregation in aerated gravity flows of particulate solids was analyzed by means of determination of a test component distribution in the moving bed of particulate mixtures (table 1) on a rough chute.

Fig. 5 describes experimental results of the investigation on the efficiency of segregation in gravity flows of mixtures of particulate solids during their aeration in the direction from the bed bottom to its free surface during this experiment. Bed depth was equal to 6-8 particle diameters.

The results testify to the fact that the aeration process in the direction of the free surface reduces the efficiency of segregation on size (mixtures 1, 2, 3) and increases its efficiency for particles differing in density (mixture 4). It should be pointed out that the

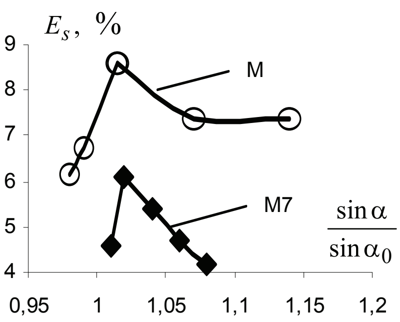


Fig. 3 The segregation efficiency as a dependence of the chute angle for varies mixtures (tabl. 1)

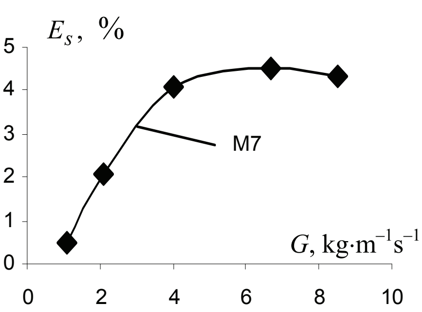


Fig. 4 The segregation efficiency as a dependence of bed depths for mixture M7 (tabl. 1)

Table 1

Characteristics of particulate material mixtures

	mixture materials	$d \cdot 10^3$, m	ρ_b, kg/m^3	α_0, deg	w_m, m/s
1	Silicagel (high porosity)	+3.5-3.75-50% +4.25-4.5-50%	610	30	0.94
2	Superphosphate	+2.2-2.5-50% +2.8-3.0-50%	1080	35	0.959
3	Porcelain	5.5-50% 7.0-50%	1100	30.5	1.71
4	Superphosphate Silicagel (low porosity)	+3.75-4.0-85% +3.75-4.0-15%	1000	35	1.18
5	Superphosphate	+2.0-2.2-50% +2.6-2.8-50%	1080	35	0.88
6	Superphosphate	+3.5-3.75-50% +4.0-4.25-50%	1080	35	1.27
7	Silicagel (high porosity)	+3.5-3.75-50% +4.0-4.25-50%	610	30	0.919
8	Silicagel (low porosity) Silicagel (high porosity)	+4.0-4.25-10% +4.0-4.25-90%	470	30	0.94

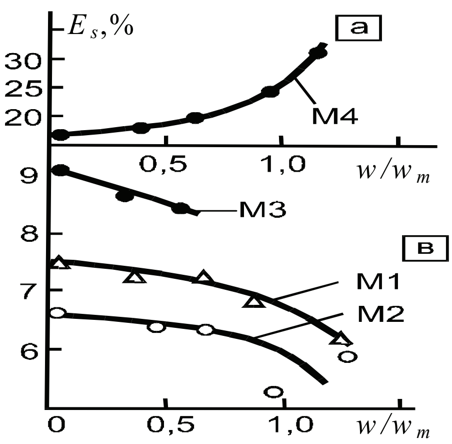


Fig. 5 Influence of aerating air velocity w/w_m towards the free bed surface on segregation efficiency E_s of various particulate mixtures (table 1)

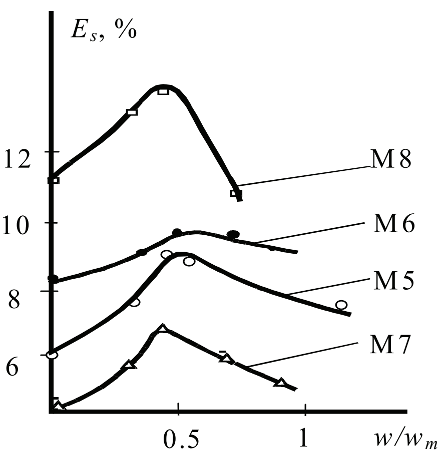


Fig. 6 Influence of aerating air velocity w/w_m towards the bed bottom on segregation efficiency E_s of various particulate mixtures (table 1)

influence of the aeration intensity on segregation is relatively small unless the minimum fluidization rate is achieved. Obviously it is connected with the prevailing influence of air separation at high air velocities.

Fig. 6 describes experimental results of the influence of the aeration intensity in the direction from the free bed surface to its bottom on particle segregation on size (mixtures 5, 6, 7) and density (mixture 8). The results testify to the fact that the efficiency of segregation increases with the increase of the aeration intensity (up to relative rate values $w/w_m \approx 0{,}45$). The relative velocity being further increased, the efficiency of segregation decreases, but it is still high enough as compared to the efficiency in the non-aerated flow even at $w/w_m = -1$. These results demonstrate the prevailing influence of the segregation effects in the granular medium as compared to the air separation within a wide range of aeration rate variations.

The experimental investigation of the vibration influence on particle segregation was performed on an inclined vibrated chute under various vibration parameters (frequency and acceleration) and inclination angles. The experiment consisted in determination of the distribution of large particles along the depth of the bed of glass beads mixture of fractions (3,25…3,5 mm – 88 % and 3,6…3,75 mm – 12 %) by analyzing experimental information obtained during the particle free-fall phase using experimental unit. [3]

As a result of the experimental investigation the influence of the slope angle of vibrated chute on segregation during gravity flow of beads differing in size were explored. It was found out that the segregation efficiency E_s had a maximum value at the inclination angle $\approx 28^{\circ}$ approximating the angle of repose of the material (Fig. 7) at the various vibration accelerations.

Besides the investigation results, presented in Figs. 8–13, show that the features of functions characterising the influence of vibration acceleration (Figs. 8, 10, 12) and vibration frequency (Figs. 9, 11, 13) on segregation efficiency essentially depended on the angle the of chute slope.

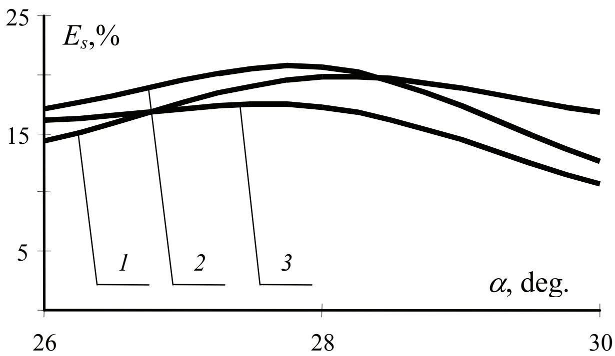


Fig. 7 The s egregation efficiency E_s as a dependence of the chute angle at different vibration accelerations:
1 – 2 g; *2* – 4 g; *3* – 7 g (for the frequency 50 Hz)

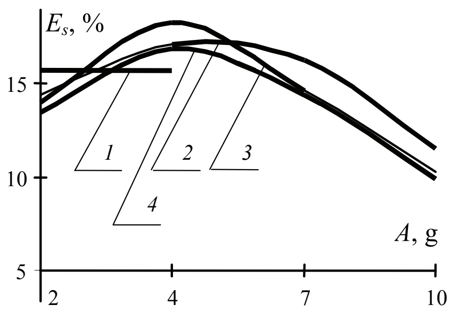


Fig. 8 The segregation efficiency E_s as a dependence of the vibration acceleration *A* at different frequencies:
1 – 35 Hz; *2* – 50 Hz; *3* – 100 Hz;
4 – 150 Hz (for the chute angle 26°)

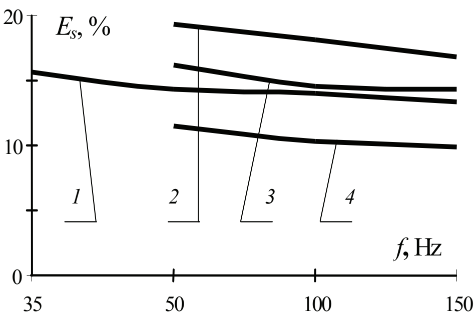


Fig. 9 The segregation efficiency E_s as a dependence of frequency *f* at different vibration accelerations *A* :
1 – 2 g; *2* – 4 g; *3* – 7 g; *4* – 10 g
(for the chute angle 26°)

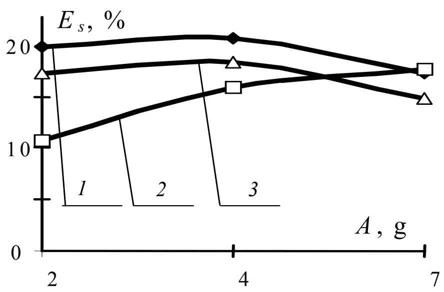


Fig. 10 The segregation efficiency E_s as a dependence of the vibration acceleration *A* at different frequencies (for the chute angle 28°)

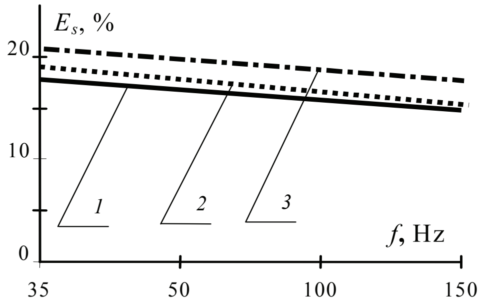


Fig. 11 The segregation efficiency E_s as a dependence of the vibration frequency *f* at different vibration accelerations:
1 – 2 g; *2* – 3 g; *3* – 7 g
(for the chute angle 28°)

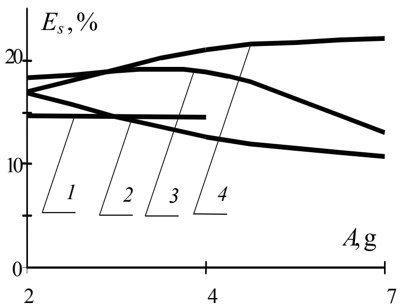


Fig. 12 The segregation efficiency E_s as a dependence of the vibration acceleration *A* at different frequencies:
1 – 35 Hz; *2* – 50 Hz;
3 – 100 Hz; *4* – 150 Hz
(for the chute angle 30°)

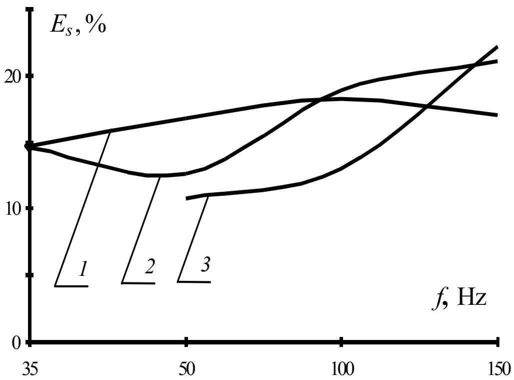


Fig. 13 The segregation efficiency E_s as a dependence of the vibration frequency *f* at different vibration accelerations:
1 – 2 g; *2* – 4 g; *3* – 7 g
(for the chute angle 30°)

Also it was found out that at inclination angles 26° and 28° the segregation efficiency decreases, when the frequency of vibration increases. Figs. 8, 10 present experimental results, characterizing the influence of the vibration acceleration on segregation of the glass beads in their gravity flow. The results testify to the fact that the segregation efficiency has a maximum at the acceleration of vibration equal approximately to 4-5 g. When the inclination angle is equal to 30° the influence of vibration conditions on segregation in gravity flow was variegated. At the constant frequencies 50, 100 Hz, as Fig. 12 shows, segregation decreases and at the frequency 150 Hz increases with increase in acceleration. Fig. 13 shows the tendency of segregation efficiency to increase with the increase in the frequency of vibration.

The experimental results allow to draw the following conclusions. The vibration parameters exert the essential influence on the granular material segregation in gravity flows.

As the results of investigation of the above mentioned methods, the optimum conditions for segregation and mixing in gravity flows of mixtures, consisting of particles differing in size and density are determined.

References

1. Dolgunin V.N., Ukolov A.A, Ivanov O.O. Research on particle segregation during rapid gravity flow // The 3-rd Israel conference for conveging and bulk solids handling. Proceeding. Jerusalem. 2000: Pp. 8.67 – 8.73.
2. Dolgunin V.N., Kudy A.N., Ukolov A.A., Tyalin A.G. Segregation kinetics in moving granular media // The forum for Bulk Solids Handing, Proceedings, Jerusalem, 1997, p. 11.75 – 11.81.
3. Dolgunin V.N., Ukolov A.A. // Powder Technology. V.83 (1995). Pp. 95-103.
4. Dolgunin V.N., Kudy A.N., Ukolov A.A. // Powder Technology. V.96 (1998). Pp. 211-218.

Способы управления сегрегацией и перемешиванием в гравитационных потоках зернистой среды

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Ключевые слова и фразы: вибрация; гидромеханическое разделение; миграция; продувка; сегрегация.

Аннотация: Проведено экспериментальное и аналитическое исследование сегрегации в зернистых средах при различных состояниях зернистой среды. Для управления сегрегацией исследованы основные эффекты сегрегации для частиц, различающихся по размеру и плотности и параметрам быстрого сдвигового течения. Предложены наиболее эффективные методы для контроля сегрегации в быстрых потоках твердых частиц.

Verfahren der Steuerung von Segregation und Mischung in den Gravitationsströmen des Körnigmediums

Zusammenfassung: In diesem Artikel wurde die experimentelle und analytische Untersuchung der Segregation in den Körnigmedien bei den verschiedenen Zuständen des Körnigmediums durchgeführt. Für die Steuerung von Segregation wurden die Haupteffekte der Segregation für die durch Gröβe, Dichte und Parameter der schnellen Verschiebungsströmung unterschiedlichen Teilchen untersucht. Es sind die effektivere Methoden für die Segregationskontrolle in den schnellen Strömen der Hartteilchen vorgeschlagen.

Moyens de la gestion de la ségrégation et du mélange dans les courants de gravitation du milieu granulé

Résumé: Dans cet article est réalisée l’étude expérimentale et analytique de la ségrégation dans les milieux granulés avec les états différents du milieu granulé. Pour la gestion de la ségrégation sont étudiés les effets essentiels de la ségrégation pour les particules qui se distinguent par les dimensions, par la densité et par les paramètres du courant rapide du décalage. Sont proposées les méthodes les plus efficaces pour le contrôle de la ségrégation dans les courants rapides des particules solides.