A PHENOMENOLOGICAL DESCRIPTION OF MIXING-SEGREGATION EFFECTS DURING SHEAR DEFORMATION OF PARTICULATE SOLIDS

V. Dolgunin,[a] V. Borschev[b], A. Klimov[a], R. Shubin[b]

[a]*Department of Technological Eqipment and Food Technology, State Technical University, 106 Sovetskaya str., 392000, Tambov, Russia*
[b] *Department of Mashines and Apparatus of Chemical Technology , State Technical University, 106 Sovetskaya str., 392000, Tambov, Russia*

Abstract

The mixing–segregation kinetics in the course of shear flow of particulate solids at low shear rates is studied analytically and experimentally. The experimental research was carried out by the use of the conveyor shear cell developed previously [1]. The phenomenological description of the segregation–mixing dynamics during shear flow of nonelastic cohesionless rough spherical particles is suggested. Only one experimental constant (segregation coefficient) is used to forecast the segregation–mixing dynamics. The method of the segregation coefficient determination is developed.
Keywords: particulate solids, shear deformation, mixing, segregation

1. Introduction

In our previous paper [1] we have suggested the experimental unit and method of segregation and mixing exploration during shear deformation of particulate solids.
Then a mathematical description of the mixing effect during shear flow of particulate solids was carried out. The kinetic parameters of the mixing flux were determined on the basis of the analysis of chaotic transversal movements of spherical nonelastic cohesionless particles (transversal mass transfer) in a restricted environment. These chaotic movements are formally analogical to the quasidiffusional mixing of particles. That is why the mixing flux of particles is expressed as follows [1]

$$j_m = -D_{dif}\rho_b(\partial c/\partial y) = -0{,}5s\rho_b \cdot u_t(\partial c/\partial y) = -0{,}5s\rho_b \cdot b \cdot d \cdot \sin(\pi/4 \cdot (d+s)/d)(\partial u/\partial y)(\partial c/\partial y) \qquad (1)$$

where D_{dif} is the coefficient of quasidiffusional mixing, c is the concentration of test particles, ρ_b is the bulk density of particulate solids, $u_t = (du/dy)bd$ is the mean relative velocity between particles of neighbouring flow layers, d is the mean particle diameter, $b = (\pi/(6(1-\varepsilon)))^{0.33}$ is the geometrical parameter, $s = (b/b_0 - 1)d$ is the mean distance between particles, b_0 is the geometrical parameter b, calculated at $\varepsilon = \varepsilon_0 = 0{,}2595$.

However, the real particulate solids is not uniform in complex of physical and mechanical properties and then the chaotic movements are accompanied by systematic displacements of particles because of segregation effects.

Although segregation has long been known and has been used over centuries in human activities, e.g., in grain and cereal cleaning, gold dust mining, etc., the scientific cognition of this physical phenomenon is still in its infancy [3]. This is because the segregation phenomenon, albeit simple in appearance, has extremely complex and diverse physical mechanisms. For example, only for the formation of heaps, Enstad [4] revealed 12 possible mechanisms of segregation.

For this reason, to describe segregation, the tools of mathematical statistics and probability theory are widely used, [5]. The corresponding statistical simulation models do not represent the physical essence of the process and have limited predictive power, but can be useful in some specific cases of describing the segregation in systems under complex hydrodynamic conditions.

A higher predictive power is characteristic of models constructed by deterministic analysis [2, 6–8]. However, many of these models were developed for different specific cases and are often contradict one another. For example, models proposed by Bagnold [6] and Stephens and Bridgwater [7] predicted opposite directions of the displacement of large particles, depending on the shear velocity gradient direction. Practice showed [2, 8] that both of the two approaches to modeling the segregation kinetics are mutually exclusive even within the bulk of a single shear flow.

In the context of the above, it is very important to perform investigations to reveal mechanisms and kinetic laws of segregation for the most general and practically important cases of flow of granular media, e.g., shear deformation flows.

2. Segregation kinetics during shear deformation of particulate solids

The segregation flux j_s is determined on the basis of the mechanism of hydromechanical segregation [2]. Thereby the approaches are used which were developed earlier in [2] for the mixing-segregation prediction of particles during their rapid shear flow, when momentum is carried by the inertia of particles and exchanged in the course of interparticle collisions. In the present paper these approaches are developed in terms of "slow" shear flow of particulate solids when prolonged interparticle contacts take place.

This mechanism presupposes that segregation takes place due to generation of the excess moment of forces acting on the nonuniform particles. This mechanism is adapted here for the conditions of the low shear rates, when the collision forces between particles are negligible.

In accordance with the mechanism of hydromechanical segregation and taking into account the fact that the segregation kinetics at low shear rates doesn't depend practically on the shear stress [9] we formulated the segregation driving force as the relative excess moment of forces acting on a test particle in a nonuniform medium:

$$\Delta M_r = (M - M_0)/M_0 \qquad (2)$$

where $M = M_G + M_F$ is the sum moment of gravity M_G friction M_F forces acting on a test particle of the mixture, M_0 is analogous moment acting on an average particle of the mixture.

The gravity force moment is calculated as earlier in [2, 10]. Assuming that the frictional forces value is proportional to the shear stress value we determined M_F as follows

$$M_F = \sigma_\tau \pi (d^2/4) \cos\gamma (1-\sin\gamma)((bd/2) tg\alpha + (d/2)\sin\gamma) \qquad (3)$$

where σ_τ is the shear stress, α is the inclination angle of the flow to the horizontal, γ is the mean value of the angle between the shear surface and radius of a test particle in the contact point of interacting particles.

Taking into account that the segregation intensity is proportional to the shear rate [9] we expressed the segregation flux in the following way

$$j_S = K_s c \rho_b u_r \Delta M_r = K_s c \rho_b b (du/dy) \Delta M_r \qquad (4)$$

where K_s is the segregation coefficient, u_r is the mean relative shear velocity between interacting particles.

Thereby the segregation coefficient acquires the physical sense of the relation between transversal and tangent velocities of test particles and ΔM_r parameter is adequate to the separation factor which determines the inclination of mixture particles to segregation.

Taking into consideration these circumstances we suggested a method for the segregation coefficient determination as the relative transversal velocity of the test particle in the conveyor shear cell [1]. The coefficient is determined as follows

$$K = u_t / (\Delta M_r b d (du/dy)) \qquad (5)$$

where u_t is the mean transversal velocity of a test particle determined experimentally in the conveyor shear cell [1] using uniform bulk particles.

The experimental results shown on Figs. 1 and 2 allows to conclude that the segregation coefficient is the experimental constant, which doesn't depend on shear rate and size of large and small spherical cohesionless nonelastic test particles for the investigated range of the particulate ratio and shear rates.

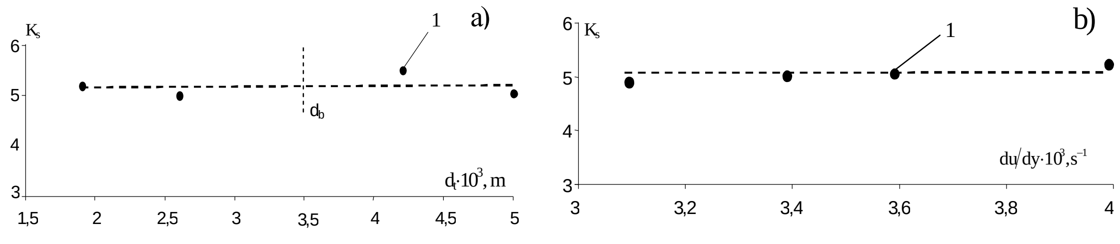
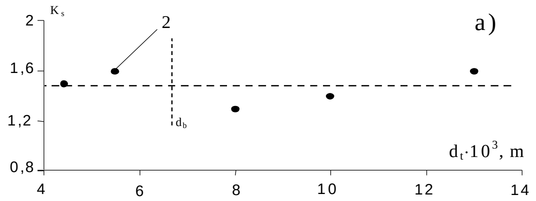


Fig. 1 Segregation coefficient dependence on the test particle diameter (a) and the shear rate (b) for glass beads ($d_b = 3.5 \cdot 10^{-3}$ *m*)



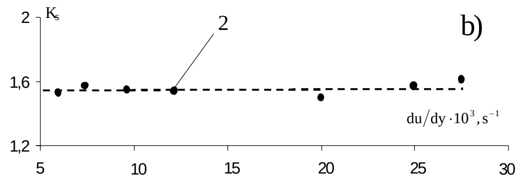


Fig. 2 Segregation coefficient dependence on the test particle diameter (a) and the shear rate (b) for ceramic granules ($d_b = 6.6{\cdot}10^{-3}\ m$)

3. Mathematical simulations of segregation–mixing effects

The mathematical description of the joint segregation–mixing effect in the course of shear deformation of particulate solids is based on the general mass transfer equation taking into account the fluxes of convection, segregation and mixing of particles, differing in size and density. Neglecting the mixing flux towards shear direction we formulated this equation adapted to the steady two-dimensional shear flow as follows

$$\partial c\rho_b / \partial \tau = -\partial(uc\rho_b)/\partial x + \partial(j_m - j_s)/\partial y \qquad (6)$$

where u is the mean particle velocity towards shear direction *x*, (x, y) Cartesian coordinates, τ is the time.

The boundary conditions for Eq. (6) are formulated in the absence of transverse material flows at the upper and lower boundaries of the moving layer of particles. The initial condition has the form

$$\begin{cases} c(0 < x \le 0.04, y, 0) = 1 \\ c(x > 0.04, y, 0) = 0 \end{cases}$$

The kinetic parameters D_{dif}, and ΔM_r of this equation are calculated, depending on the flow characteristics, using corresponding physicomechanical characteristics of a granular material, and the kinetic constant K_s is found by the proposed experimental and analytical method (Figs 1 and 2).

The flow characteristics, such as $u(y)$ and $\varepsilon(y)$, were gotten experimentally by means of the method using the conveyor shear cell [1].

The comparison of the calculated and experimental results shown on Figs. 3 and 4 reveals their adequacy.

The standard deviation between the named results of segregation–mixing dynamics modeling is 5…6 percentage. Thus the Eqs. (1, 4, 6) has rather high predictive power, which is confirmed by the results of studying the segregation kinetics and dynamics. Furthermore, the study showed that not only can the mathematical model of the shear flow separation mechanism be used to describe the separation of a mixture of particles, but also this model can be applied to predict the velocities of both small and large single spherical cohesionless particles during shear deformation using a single kinetic coefficient.

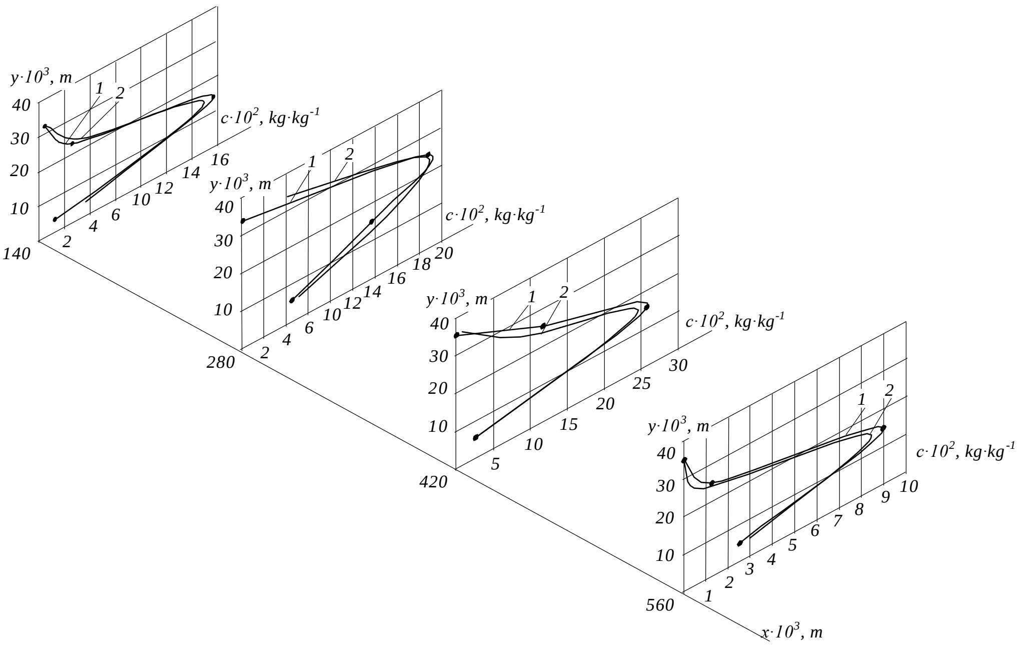


Fig. 3 Segregation dynamics during shear deformation of ceramic granules ($d_t = 4.4\cdot10^{-3}$ *m*, $d_b = 6.6\cdot10^{-3}$ *m*) in the conveyor shear cell at the mean shear rate 0.475 s^{-1} 1 – experimental; 2 – calculated

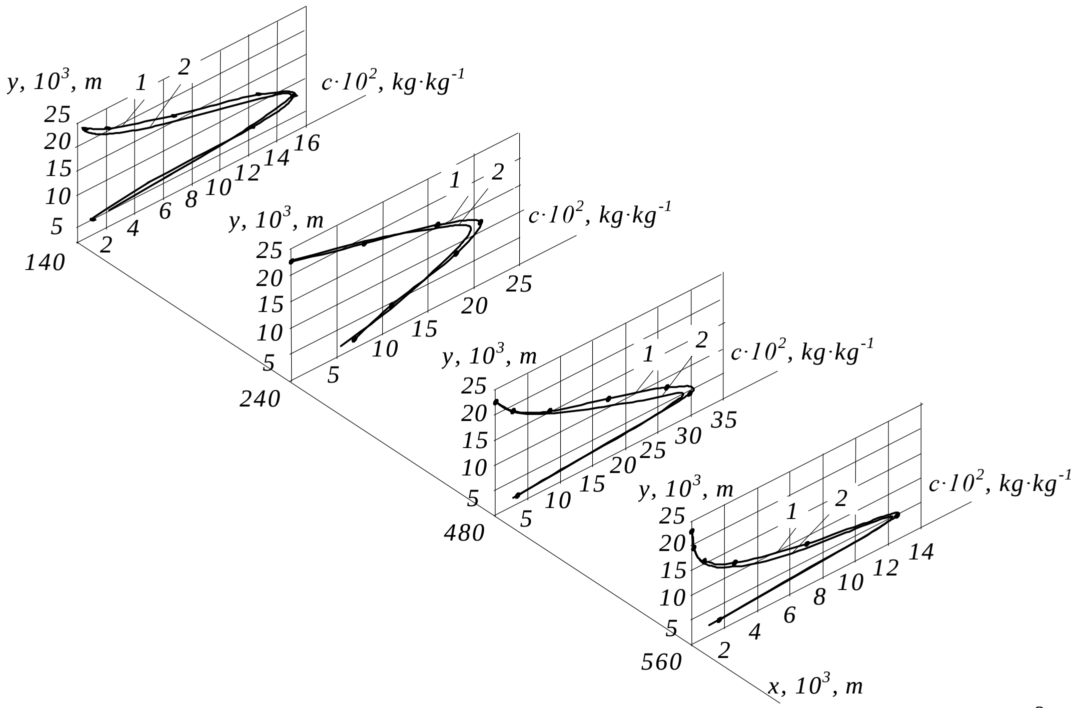


Fig. 4 Segregation dynamics during shear deformation of glass beads ($d_t = 3.1\cdot10^{-3}$ *m*, $d_b = 3.5\cdot10^{-3}$ *m*) in the conveyor shear cell at the mean shear rate 0.76 s^{-1} 1 – experimental; 2 – calculated

References

1. Dolgunin V., Borschev V. and Klimov A. The conveyor shear cell for determination of particle tendency to segregation and mixing. 4th European congress of chemical engineering, full text of papers in CD-ROM; Granada, Spain, 2003.

2. Dolgunin V., Ukolov A. Segregation modeling of particle rapid gravity flow // Powder Technology. – 1995. – N 83. – P.95 – 103.

3. Savage, S.B., Interparticle Percolation and Segregation in Granular Materials: A Review, in Developments in Engineering Mechanics, Selvadurai, A.P.S., Ed., Amsterdam: Elsevier Science, 1987, p. 347.

4. Enstad, G.G., Segregation of Powders and Its Minimization, in Proc. of the 2nd Israel Conf. for Conveying and Handling of Particulate Solids, Kalman, H., Ed., Jerusalem, Israel, May 26--28, 1997, p. 11.52.

5. Pershin, V.F., Modeling of Mixing of a Granular Material in a Cross Section of a Rotating Drum, Teor. Osn. Khim. Tekhnol., 1986, vol. 20, no. 4, p. 508.

6. Bagnold, R.A., Experiments on a Gravity-Free Dispersion of Large Solid Spheres in a Newtonian Fluid under Shear, Proc. Roy. Soc. London, Ser. A, 1954, vol. 225, p. 49.

7. Stephens, D.J. and Bridgwater, J., The Mixing and Segregation of Cohesion less Particulate Materials: Part I. Failure Zone Formation; Part II. Microscopic Mechanisms for Particles Differing in Size, Powder Technol., 1978, vol. 21, p. 17.

8. Dolgunin, V.N., Kudy, A.N., and Ukolov, A.A., Development of the Model of Segregation of Particles Undergoing Granular Flow Down on Inclined Chute, Powder Technol., 1998, vol. 56, p. 211.

9 Bridgwater, J., Cooke, M.H., and Scoott, A.M., Interparticle Percolation: Equipment Development and Mean Percolation Velocities, Trans. I Chem. E, 1978, vol. 56, p. 157.

10. Dolgunin, V.N., Ukolov, A.A., and Klassen, P.V., Model of the Segregation Mechanism in a Rapid Gravity Flow of Particles, Teor. Osn. Khim. Tekhnol., 1992, vol. 26, no. 5, p. 100.