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## MODELING OF THE GRAVITATIONAL FLOW OF A GRANULAR MEDIUM: THE ROLE OF BOUNDARY CONDITIONS AND THEIR PARAMETERS

### ANNOTATION

The flow of granular materials is critical to a wide variety of industrial processes. However, the influence of boundary conditions on the parameters of the gravitational flow of granular materials underlying granular flows is poorly understood.

The aim of this work is to study the influence of boundary conditions on the slope (substrate material and its roughness) on the parameters of the gravitational flow of the material, determined by the equation of state of the granular medium. In the course of the study, the equations of state of the granular medium were determined and the primary influence on the relationship between the dilatancy and the "temperature" of the granular medium was established, which affects the degree of its roughness.

**Keywords:** granular medium; shear deformation; quasi diffusion mixing.

## ДОНАДОР МУХИТНИНГ ГРАВИТАЦИОН ОВИМИНИ МОДЕЛЛАШТИРИШ: ЧЕГАРАВИЙ ШАРТЛАРИНИНГ РОЛИ ВА УЛАРНИНГ ПАРАМЕТРЛАРИ

### ANNOTATSIYA

Donador materiallar oqimi turli xil sanoat jarayonlari uchun juda muhimdir. Biroq, chegara sharoitlarining donador oqimlar ostidagi donador materiallarning tortishish oqimi parametrlariga ta'siri yomon tushunilgan.

Ishning maqsadi nishabdagi chegara sharoitlarining (substrat materiali va uning qo'polligi) granüler muhit holati tenglamasi bilan aniqlangan materialning tortishish oqimining parametrlariga ta'sirini o'rganishdir. Tadqiqot jarayonida donador muhitning holati tenglamasi aniqlandi va kengayish va uning pürüzlülük darajasiga ega bo'lgan donador muhitning "harorati" o'rtasidagi bog'liqlikka asosiy ta'sir o'rnatildi.

**Kalit so'zlar:** donador muhit, siljish deformatsiyasi, kvaziffuziya aralashtirish.

## МОДЕЛИРОВАНИЕ ГРАВИТАЦИОННОГО ТЕЧЕНИЯ ЗЕРНИСТОЙ СРЕДЫ: РОЛЬ ГРАНИЧНЫХ УСЛОВИЙ И ИХ ПАРАМЕТРЫ

### АННОТАЦИЯ

Поток зернистых материалов имеет решающее значение для широкого спектра промышленных процессов. Однако, влияние граничных условий на параметры гравитационного течения зернистых материалов, лежащий в основе гранулированных потоков, плохо изучена.

Целью работы является исследование влияния граничных условий на скате (материала подложки и его шероховатости) на параметры гравитационного течения материала, определяемые уравнением состояния зернистой среды. В ходе исследования определена уравнения состояния зернистой среды и установлено первостепенное влияние на взаимосвязь между дилатансией и «температурой» зернистой среды оказывающий на степень ее шероховатости.

**Ключевые слова:** зернистая среда, деформация сдвига, газодиффузионное перемешивание.

### **Introduction**

The production and processing of granular materials is associated with the implementation of various technological processes: grinding, mixing, granulation, transportation, sorting, drying, and others. For the rational organization of processes, it is necessary to take into account the features of the interaction of particles, depending on the nature of their movement, both on the working bodies of the corresponding equipment, and in devices for carrying out auxiliary operations: transportation, loading. Insufficient consideration of the features of the movement of granular media can lead to a violation of the technological regime and, as a result, to a deterioration in the quality of the product. It is known that fast gravitational flow of granular materials is one of the most common types of flows.

Significant in terms of the number of processes, such as hydro mechanical and heat and mass transfer processes for processing granular materials, as well as auxiliary technological operations, proceed in the mode of fast gravitational flow. A significant feature of this kind of flows is the presence of a condition for the rapid shear of material particles, as a result of which the particles acquire a significant speed of chaotic movement. Such a roll of a flow is often called initial, since their regularities are determined by the inertia of the particles and the transfer of momentum during their mutual collision in the flow [1–5]. In this regard, the study of the influence of boundary conditions on the parameters of the gravitational flow of the material is relevant today.

### **Research Methods**

The study of the influence of boundary conditions on the parameters of the gravitational flow of the material was carried out in the scientific laboratory of the Tashkent Institute of Chemical Technology. To determine the physical and mechanical properties of granular materials and the recovery factor at low collision speeds, respectively, standard methods and a method based on the analysis of sound vibrations were used.

To calculate the specific dissipation energy in the collision of particles, the oblique impact hypothesis (Rouse) was used. Also, to process the results of the data obtained and check the adequacy to the real process, physicochemical methods of research and planning of a multifactorial experiment using the MATLAB application package were used.

### **Result and discussion**

An analysis of fast gravitational flows of granular materials shows that they are accompanied by mutual displacement of particles, which is of a very complex nature [1,6-10]. On the one hand, due to the difference in the rates of translational movement of particles in the direction of the slope, the particles have a relative shear velocity, and on the other hand, due to mutual collisions of particles, the latter acquire an additional component of the rate of chaotic movements. The result of the chaotic movement of particles is a transverse mass transfer in a shear flow. Transverse mass transfer in a shear flow is accompanied by momentum transfer, which is carried by particles moving at different speeds depending on the coordinate. Obviously, the transverse mass transfer under such conditions leads to an increase in the intensity of the mutual movement of particles. In this case, the intensity of the mutual movement of particles will increase in proportion to the coefficient of transverse quasi-diffusion of particles  $D_{dif}$  and the gradient of the speed of translational motion of particles in the shear direction - the shear rate  $du/dy$ .

If this intensity is estimated through the kinetic energy of the corresponding masses, and the quasi-diffusion coefficient is determined as the product of the fluctuation velocity of particles and the average distance between particles [11–14], then we obtain the corresponding calculated dependence:

$$E_{nm} = \frac{1}{4} \rho s V' \frac{du}{dy} \quad (1)$$

The fluctuation velocity  $V'$  of particles is determined from the energy balance equation in the form

$$V' = \left[ \frac{(1+k)(0,05+0,08\mu)(1+s/d)}{[3sC/2d]\rho_s/\rho_g + e_c} \right]^{1/2} bd \frac{du}{dy}, \quad (2)$$

where  $e_c$  - is the fraction of the kinetic energy dissipated during the collision of particles.

Taking into account the results of the study carried out in [15-18], the fraction of energy dissipated during the collision of particles is determined as a function of the physical and mechanical properties of the material using the following relationship:

$$e_c \approx (1-k^2) + \frac{2}{\pi}(1+k) + 0,5\lambda - 0,125\mu^2(1+k)^2 - \frac{2}{3}\lambda\mu(k+1) - 0,125\lambda^2 \quad (3)$$

The kinetic energy of mutual displacements of particles due to their fluctuation velocity can be determined as follows:

$$E_f = \frac{1}{2} \rho (V')^2$$

The average value of the relative velocity of particles as a result of their different translational velocity in the shear flow is calculated as the product of the average shear velocity and the difference in the coordinates of the centers of particles of different layers  $\Delta y = bd$ , i.e.

$$V_{OTI} = bd \frac{du}{dy}$$

Then the kinetic energy of the particles in their relative translational movement in the shear direction can be calculated using the following expression:

$$E = \frac{1}{2} \rho (bd)^2 \left( \frac{du}{dy} \right)^2 \quad (4)$$

In accordance with the complex nature of the motion of particles in a gravitational flow, the kinetic energy of their mutual displacements is defined as the sum of the kinetic energies of particles in their relative translational displacement during shear  $E_{sh}$ , during their chaotic motion  $E_m$  and transverse mass transfer  $E_{mt}$ :

$$E_{OTI} = E_{SH} + E_M + E_{MT} \quad (5)$$

After substituting into relation (5) the values of the energy components in accordance with expressions (1), (3) and (4) and replacing the velocity fluctuation  $V'$  with expression (2), we obtain

$$E_{OTI} = \frac{1}{2} \rho \left[ (bd)^2 + \frac{1}{2} s \phi bd + \phi^2 (bd)^2 \right] \left( \frac{du}{dy} \right)^2, \quad (6)$$

where  $\phi$  is a complex that determines the dissipative component of energy and depends on the flow conditions of particles ( $\varepsilon$ ,  $du/dy$ ), their size and physical and mechanical properties

$$\phi = \left[ \frac{(1+k)(0,005+0,08\mu)(1+s/d)}{[3sC/2d]\rho_s/\rho_g + (1-k^2) + \frac{2}{\pi}(1+k) + 0,5\lambda - 0,125\mu^2(1+k)^2 - \frac{2}{3}\lambda\mu(k+1) - 0,1265\lambda^2} \right]^{1/2}$$

The forms of mutual movement of particles taken into account in a fast gravitational flow are accompanied by their collisions, as a result of which the mechanical energy of the particles is dissipated. Moreover, in a steady flow, the relative velocity of colliding particles and the frequency of their collisions are so high that they provide complete dissipation of the energy generated by the shear.

Using the obtained expression for the "temperature" of the granular medium (6), we write the corresponding equation of state of the granular medium in the following form [19-22]:

$$\rho \bar{\varepsilon} = \chi \frac{1}{2} \rho \left[ (bd)^2 + \frac{1}{2} s \phi bd + \phi^2 (bd)^2 \right] \left( \frac{du}{dy} \right)^2 \quad (7)$$

To assess the adequacy of the equation of state of a granular medium (7), a comparison was made [10,15] of the velocity and porosity profiles for the flow of ceramic granules ( $d=6,6 \cdot 10^{-3} \text{m}$ ), obtained using X-ray study and by using an experimental-analytical method based on the equation of state (7).

Further study of the prognostic properties of the equation of state of a granular medium (7) was carried out [25] by determining the coefficient  $\chi$  as a function of the conditions for the flow of a granular material and the physical and mechanical properties of its particles. At this stage of the study, not only model granular materials (Table 1) with a wide range of physical and mechanical properties and particle geometry were used, but also rough slopes with different roughness geometries made of various materials. At the same time, only beads and ceramic granules can be attributed to the class of incoherent inelastic granular materials with particles close in shape to spherical ones. Polyethylene granules did not fully correspond to the specified class of materials, due to the more complex shape of the particles, which are cylinders with a ratio of length to diameter equal to 0.6 ... 0.7 with smooth edges.

Ammophos granules, however, not only did not correspond to spheres due to the presence of a significant number of sharp and smoothed edges on their surface, but also were distinguished by a clear manifestation of a tendency to abrasion. Due to abrasion, ammophos particles were replaced by new ones after each series of parallel experiments. The particle shape factor given in the table is calculated as the ratio of the particle surface to the surface of a sphere of equivalent volume. The value of the surface of the particles is determined experimentally by an indirect method, as a value proportional to the mass of the liquid film that wets the surface of the particle.

The study of the coefficient of the equation of state of a granular medium (7) was carried out for various materials under the conditions of a steady-state developed gravitational flow [15].

Figure 1 shows the results of studying the coefficient  $\chi$  of the equation of state for a granular medium (7) as a function of the relative layer height  $h/d$  on a rough slope for granular materials (Table 1).

Physical and mechanical properties of granular materials were determined using standard methods [26].

The recovery coefficient at low collision velocities was determined using a method based on the analysis of sound vibrations generated in a monolith on a substrate by a spherical particle during its multiple jumps [27].

The reduction factor  $\lambda$  was determined using the method proposed in [27].

Table 1. Properties of model materials

Material	Glass beads	Ceramic granules	High density polyethylene granules	Ammophos granules
Equivalent particle diameter, $d=10^{-3} \text{m}$	3,385	6,6	4,1	2,2
Shape factor	1	1	1,27	1,54
Material density, $\text{kg/m}^3$	2500	2086	920	1670

Friction coefficient, $\mu$	0,1	0,44	0,4	0,7
Reduction factor, $\lambda$	0,28	0,57	0,67	0,9
Recovery factor, $k$	0,92	0,67	0,65	0,25
Angle of repose, $\alpha_0$ , degrees	26	36	41	36
Transparency of the fixed layer $\varepsilon_0$ , $M^3 \cdot M^{-3}$	0,37	0,4	0,42	0,4

The above results indicate that for non-cohesive inelastic granular materials consisting of particles close to spherical in shape (beads and ceramic granules), the correlation coefficient  $\chi$  between the work on dilatancy of the granular medium under fast shear ( $\rho\bar{\varepsilon}$ ) and the "temperature" of the granular medium is close to unity and practically does not depend on the flux value in the studied range of its change. For this kind of granular materials, the equation of state for fast shear can be represented as

$$\rho\bar{\varepsilon} = E_{OTI} \quad (8)$$

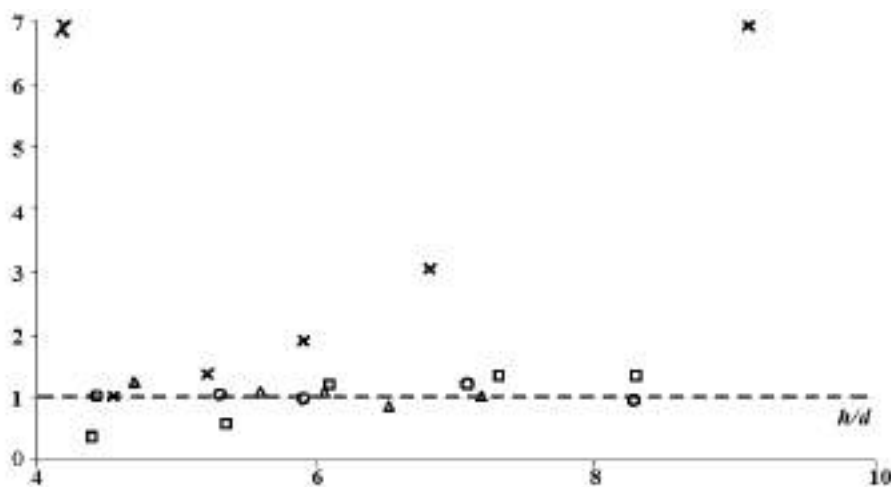


Figure 1. Dependence of the coefficient  $\chi$  of equation (7) of the state of a granular medium on the relative layer height  $h/d$  on a rough slope at a relative angle of 1.1 for granular materials.  $\circ$ -beads,  $\Delta$ -ceramic granules,  $\square$ -polyethylene granules;  $\times$ -ammophos x-granules

To a certain extent, this result can be considered as confirmation of the adequacy of the phenomenology underlying the equation of state for a granular medium (7). At the same time, there is a significant dependence of the relationship coefficient on the flow rate of non-spherical polyethylene granules, especially in the region of small thicknesses of the material layer on the slope, which, apparently, indicates the complex nature of the influence of the particle shape factor on the relationship between porosity, pressure, and shear rate in fast gravitational flow of granular material.

Analysis of the profiles reveals that with an increase in the thickness of the ammophos layer, a paradoxical increase in porosity in the central part of the flow is observed, accompanied by a decrease in the shear rate. When explaining the reasons for such a change in the flow parameters, a hypothesis was proposed for an increase in the "connectivity" of ammophos particles with increasing pressure, due to their complex shape and tendency to attrition.

In order to confirm this hypothesis, a study was made of the dynamic coefficient of friction as a function of normal pressure. The dynamic coefficient of friction is defined as the ratio of shear and normal stresses [29].

The study was carried out using a simple shear cell according to the standard technique [25] in the range of stress changes corresponding to the conditions of amorphous flow at different layer thicknesses.

The results of the study, shown in Figure 2, indicate a significant increase in the dynamic coefficient of friction with an increase in normal pressure (layer thickness). The result obtained can be considered as a consequence of an increase in the connectivity of amorphous particles with an increase in the normal stress. This is obviously due to the fact that an increase in the pressing force against each other of rough particles of irregular shape, prone to abrasion, leads to an increase in the number of contact points and bridges between them. As a result, some effective connectivity of particles appears, which, when the medium is shifted, causes the formation of agglomerates and additional voids between them, which contribute to an increase in porosity in the flow.

As a result of this increase in connectivity and the secondary effect of porosity, a paradoxical increase in the dilatancy of the medium is observed, accompanied by a decrease in temperature, which causes the anomalous coefficient  $\chi$  of the equation of state of the medium with an increase in the thickness of the amorphous layer on the slope.

Literary sources [11,15,26] indicate that the flow parameters are significantly affected by the interaction of the gravitational flow of a granular medium with a rough slope.

The study of the influence of the material of the substrate installed on the slope and the conditions of interaction of flow particles with it on the relationship coefficient  $\chi$  of the equation of state of a granular medium (7) indicates that different adhesion conditions on the substrates were provided due to the different geometry of the substrate roughness.

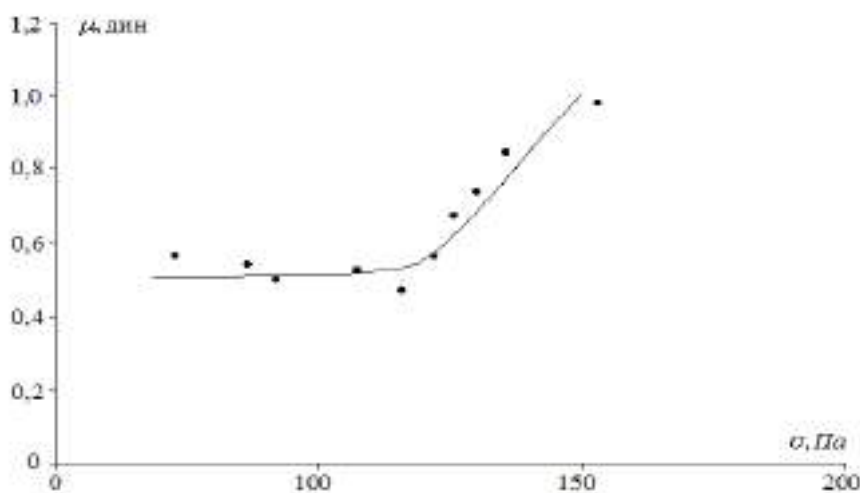


Figure 2. Dynamic coefficient of friction as a function of normal stresses for granular amorphous

Obviously, the named component of the energy of mutual displacements of particles should be determined by the boundary conditions of the flow at the bottom of the layer as a factor affecting the dilatancy of the granular medium. Since the proposed method for determining the velocity and porosity profiles in a gravitational flow assumes the presence of a no-slip condition on a rough slope, the sliding of particles on substrates becomes an unaccounted factor that reduces the dilatancy of a granular medium in a shear flow.

It is likely that the result of partial slippage of the granular material on the substrate is an underestimated value of the flow dilatancy, and, as a consequence, the appearance of fractional values of the coefficients.

An additional indirect confirmation of the conclusions drawn can be the results of a study by foreign and domestic researchers [29, 30], who observed a decrease in the dilatancy of granular media in gravitational flows when particles slip on the substrate without a decrease in shear rate during the transition from a developed gravitational flow to a splashing one.

### **Conclusion**

The conducted studies on the influence of the boundary conditions on the slope (substrate material and its roughness) on the parameters of the gravitational flow of the material, determined by the equation of state of the granular medium, make it possible to rationally organize the processes: grinding, mixing, granulation, transportation, sorting, drying, etc. the relationship between dilatancy and the "temperature" of a granular medium is influenced not by the substrate material, but by the degree of its roughness.

When particles slip on the substrate, a zone of additional absorption of the energy of chaotic movements of particles is formed, which leads to a decrease in the "temperature" in the flow of granular material.

## REFERENCES. ИҚТИБОСЛАР. СНОСКИ.

1. Sarbolayev F, Dzhurayev KH., Khamidov B. Kinetika i modelirovaniye protsessa smeshivaniya chastits pri sdvigovoy deformatsii zernistoy sredy [Kinetics and modeling of the process of mixing particles during shear deformation of a granular medium]. *Khimicheskaya tekhnologiya. Kontrol' i upravleniye*, 2016, vol. 2 no. 68, pp. 62-67.
2. Kevin F. Measurements of Gravity Driven Granular Channel Flows. PhD.diss. University of Massachusetts Amherst Follow, 2011, 101 p.
3. Huan C. NMR Experiments on Vibro uidized and Gas Fluidized Granular Systems. Ph.D. University of Massachusetts-Amherst, 2008, 101 p.
4. Reyes F., Garzó V, Khalil N. Hydrodynamic granular segregation induced by boundary heating and shear. *Phys Rev E Stat Nonlin Soft Matter Phys.* 2014. vol.89.no 5, pp. 1-5.
5. Hutton S., Forsyth A., Rhodes M., Osborne CF. Effect of interparticle force on mixing and segregation of dry granular materials. *Phys Rev E Stat Nonlin Soft Matter Phys.* 2004. vol. 70. no 3, pp. 31-35.
6. Christov IC, Stone HA. Resolving a paradox of anomalous scalings in the diffusion of granular materials. *Proc Natl Acad Sci.USA.* 2012. vol.109. no 40, pp.16013-16017.
7. Khakhar D., Mccarthy J., Ottino J. Mixing and segregation of granular materials in chute flows *Physical review. E, Statistical, nonlinear, and soft matter physics.* 1999 vol. 9. no 3, pp. 594-610.
8. Bal A., Dhagat N. Upflow anaerobic sludge blanket reactor--a review. *Indian J Environ Health.* 2001. vol. 43. no 2, pp.1-82.
9. Pohlman N., Severson B., Ottino J., Lueptow R. Surface roughness effects in granular matter: influence on angle of repose and the absence of segregation. *Phys Rev E Stat Nonlin Soft Matter Phys.* 2006. vol. 73 no 3, pp. 031304-1-9.
10. Forsyth A., Hutton S., Osborne C., Rhodes M. Effects of interparticle force on the packing of spherical granular material. *Phys Rev Lett.* 2001. vol. 87 no 24, pp. 244301-1-3.
11. Dolgunin, V., Ukolov A. Segregation modeling of particle rapid gravity flow. *Powder Technology*, 1995, vol. 83, pp. 95-103.
12. Zhou Y., Xu B., Yu A., Zulli P. Numerical investigation of the angle of repose of monosized spheres. *Phys Rev E Stat Nonlin Soft Matter Phys.* 2001 vol. 64 no 2, pp. 021301-1-8.
13. Brewster R, Grest G., Levine A. Effects of cohesion on the surface angle and velocity profiles of granular material in a rotating drum. *Phys Rev E Stat Nonlin Soft Matter Phys.* 2009 vol. 79 no1, pp. 011305-1-7.
14. Liao C., Hsiao S., Nien H. Density-driven spontaneous streak segregation patterns in a thin rotating drum. *Phys Rev E Stat Nonlin Soft Matter Phys.* 2014 vol. 89 no 6, pp. 062204-1-5.
15. Sarbolayev F., Khamidov B., Dzhurayev KH. [Investigation of the prognostic properties of the equation of state of a granular medium at fast shear and the development of a method for determining its parameters]. *Sbornik statey Respublikanskoy nauchno-tekhnicheskoy konferentsii «Aktual'nyye voprosy innovatsionnykh tekhnologiy v khimicheskoy, neftegazopererabatyvayushchey i pishchevoy promyshlennosti» [Collection of articles of the Republican scientific and technical conference "Topical issues of innovative technologies in the chemical, oil and gas processing and food industries"]*. Tashkent, 2015, pp. 231-232.
16. Li H, Mccarthy J. Phase diagrams for cohesive particle mixing and segregation. *Phys Rev E Stat Nonlin Soft Matter Phys.* 2005. vol. 71 no 2, pp. 0213051-8.
17. Granular-front formation in free-surface flow of concentrated suspensions. Leonardi A, Cabrera M, Wittel FK, Kaitna R, Mendoza M, Wu W, Herrmann HJ. *Phys Rev E Stat Nonlin Soft Matter Phys.* 2015. Vol. 92 no 5, pp. 0522041-1-13.
18. Richard M., Zhekai D., Hongyi X., Paul B. Modeling Segregation in Modulated Granular Flow. *EPJ Web of Conferences. Powders & Grains.* 2017.140. 03018. 10.1051/epjconf/201714003018.

19. Borshchev V.Ya., Shubin P.A., Ukolov. A.A. [Investigation of the behavior of single particles under shear deformations in a granular medium]. *Sbornik trudov nauchno-prakticheskoy konfrentsii "Progressivnyye tekhnologii razvitiya"* [Collection of works of the scientific-practical conference "Progressive technologies of development"] Tambov, 2004, pp. 171-173.
20. Stephens D.J. and Bridgwater J. The Mixing and Segregation of Cohesionless Particulate Materials: Part II. Microscopic Mechanisms for Particles Differing in Size. *Powder Technology*, 1978, 21, p. 29.
21. Bridgwater J., Cooke M. N., Scott A.M.. Interparticle Percolation: Equipment Development and mean Percolation Velocities. *Trans. I Chem. E.*, 1978, vol. 56, p. 157.
22. Savage S., Sayed M. Stresses developed by dry cohesionless granular materials sheared in an annular shear cell. *Journal of Fluid Mechanics*. 1984. vol. 142, pp. 391-430.
23. Borshchov V.Ya., Dolgunin V.N., Shubin R.A. The conveyor shear cell for determination of particle tendency to segregation and mixing during shear flow of particulate solids. *Bulletin of the Tambov State Technical University*, 2006, vol. 12, no. 3-1, pp. 695-699.
24. Z.Li, Y.Zhou, T.H.North. Counteraction of particulate segregation during transient liquid-phase bonding of aluminium-based IVIMC material. *Journal of materials science*. 1995, vol. 30, pp.1075-1082.
25. Sarbolayev F., Ergashev G., Khamidov B., Dzhurayev Kh. [Investigation of the prognostic properties of a granular medium]. *Mezhdunarodnaya nauchno-tekhnicheskaya konferentsiya "Aktual'nyye problemy innovatsionnykh tekhnologiy v razvitii khimicheskoy, nefte-gazovoy i pishchevoy promyshlennosti"*. Tashkent, 2016, pp. 72-73.
26. Andrianov E.I. Methods of structural-mechanical characterization of prosthetic materials. [*Metody opredeleniya strukturno-mekhanicheskikh kharakteristik poroshkoobraznykh materialov*]. Moscow, Khimiya Publ., 1982. 256 p.
27. Dolgunin V.N. Kineticheskiye zakonomernosti segregatsii pri bystrom gravitatsionnom techenii zernistykh materialov. [Kinetic Regularities of Segregation in the Rapid Gravitational Flow of Granular Materials]. *Teoreticheskiye osnovy khimicheskoy tekhnologii*, 2006, vol.40, no 4. pp. 393-416.
28. Ivanov O.O., Ukolov A.A. [Determination of the kinetic characteristics of segregation in a fast shear flow of granular material]. *Trudy TGTU. [Proc. of the Tambov State Technical University]*. Tambov, 1999, pp. 12-18. (in Russian).
29. Savage S.B., Nedderman R.M., Tuzun U., Houlsby G.T. Flow of granular Materials. *Chem. Eng. Sei.*, 1982, vol. 37, pp. 782-791.
30. Dolgunin V.N., Ukolov A.A., Allenov., D.N., Ivanov O.O. Surface and resilience effects of particles undergoing rapid shear flow. *4 World Congress of Particle Technologies*: Sydney, Australia, full texts of papers in CD. 2002.