УДК 532.545

THE CONVEYOR SHEAR CELL FOR DETERMINATION OF PARTICLE TENDENCY TO SEGREGATION AND MIXING DURING SHEAR FLOW OF PARTICULATE SOLIDS

V.Ya. Borshchov[2], V.N. Dolgunin[1], R.A. Shubin[1]

Departaments: «Tehnological Equipmet and Food Tecnologies» (1) «Machines and Devices of Chemical Manufactures», TSTU (2)

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

Key words and phrases: granular medium; shear deformation; quasi-diffusion mixing.

Abstract: An original experimental unit for investigation of segregation and mixing effects during two-dimensional shear flow of particulate solids for a wide range of shear rates is developed. An analytical approach is suggested in order to calculate the coefficient of quasidiffusional mixing during shear flow of particulate solids.

Nomenclature

b, b_0 – geometrical parameters;
c – concentration of test component of granular mixture;
d – diameter of test particle;
D_{dif} – coefficient of quasi-diffusion;
l – common length of a zone having stable flow conditions in the channel;
s – mean distance between particles;
u – the mean velocity of layer particles;
V' is the fluctuation velocity of particles;
($x, y, \overline{\Delta x_i}$) – Cartesian coordinate;
α – corner of an inclination of the channel;
τ – deformation time;
ρ_b – bulk density of particulate solids.

1 Introduction

The basic effects of particle interactions caused by shear deformation of particulate solids are mixing and segregation. Traditionally in order to estimate these effects the simple and annular shear cells are used [1, 2]. Thereby there are obvious impediments to obtain the experimental data to be suitable for analysis. First of all these impediments are caused by cyclic character of the shear in the simple shear cell and the complex spatial distribution of velocity of particles in the annular shear cell.

In this paper we propose an original experimental unit for investigation of segregation and mixing effects during two-dimensional shear flow of particulate solids.

In our former investigation [3] we have suggested a method to forecast the mixing effects of particles during their rapid shear flow, when momentum is carried by the inertia of particles and exchanged in the course interparticle collisions.

According to this method the coefficient of quasidiffusional mixing is calculated as follows

$$D_{\text{dif}} = \frac{1}{2}\left(V's\right), \qquad (1)$$

where V' is the fluctuation velocity of particles; s is the mean distance between particles.

In the present paper this method is developed in terms of "slow" shear flow of particulate solids when prolonged interparticle contacts take place.

2 Experimental unit and method

The suggested unit (Fig. 1) is a conveyor belt cell providing an uninterrupted shear flow of particulate solids. The conveyor belt 6 has a fabric frame covered by the rubber. The outward surface of the belt was rough. The roughness value is equal to a half of the particle diameter. The conveyor belt embraces driving *5* and tighting *8* drums. The drums have been mounted on a metallic frame, which was installed at an angle α to the horizontal. The angle could be adjusted.

The lower branch of the conveyor belt was located in a channel *1* of square cross section. The bottom of the channel *2* was rough and it was installed parallel to the belt. The distance between the channel bottom and the conveyor belt could be adjusted due to the channel motion. There are a row of tube elements *7* mounted on the frame over the lower branch of the conveyor to provide a constant depth channel. The unit have been supplied by a dosage devise *4* to give up granular materials to the channel under lower conveyor belt. In order to change the movement velocity of the belt the driving drum has a drive consisting of an electric motor of direct current, reducer and a chain drive. The shear flow of particles is provided in the channel due to its bottom roughness and the conveyor belt roughness. The shear strain intensity is changed by means of the variation of the belt velocity and the flow depth in the channel.

The research on the interaction effects of particles in the unit is carried out in the following way. First of all in the course of large experiments the area of stable kinematical and structural conditions of the flow is determined. There are two restricting slide-valves 3 in the channel in order to control the test particle distribution in this area.

An indicator method is used to investigate shear rate and mixing effects in the flow. The indicator particles were adequate to the uniform particles of the flow excepting their colour only. The spherical nonelastic ceramic balls of diameters $6{,}6 \cdot 10^{-3}$ m were used to determine the velocity profile and investigate particle interactions during shear flow of particulate solids. The channel is installed up to a certain angle to the horizontal and then the channel depth and conveyor velocity are adjusted. Therewith the dosage devise gives up granular materials to the channel under lower conveyor branch. In order to define the experimental velocity profile of particles the belt electric drive is switched off when the steady state of the shear flow is achieved.

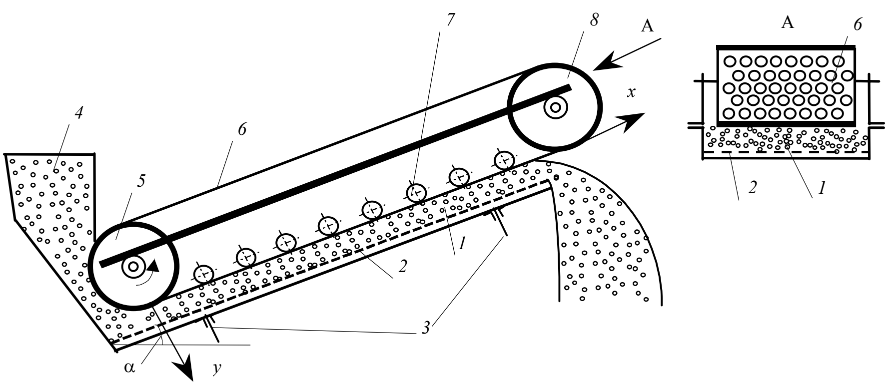


Fig. 1 Schematic of test unit:
1 – channel, *2* – bottom of the channel; *3* – slide-valves; *4*– dosage devise;
5 – driving drum; *6*– conveyor belt; *7* – tube elements; *8* – tighting drum

Then the flow particles in the channel beginning are replaced with the indicator particles. These particles are led into the channel through its side wall. The indicator must fill the whole cross section of the channel that is adequate to its impulse putting into. Further the electric drive is switched on until the lower conveyor branch has a displasment equal to the area length having stable flow conditions. Then this area is restricted by the slide-valves and the channel moves away from the unit. By means of the vertical plates the material in the channel is divided into n zones. The material of every zone is divided into m horizontal layers by the use of a vacuum device which is analogous to the one used in [1]. The material of every layer is analysed to define the test particle concentration c.

Fig. 2 shows the experimental concentration distribution of the test particles towards the length (x-coordinate) and depth (y-coordinate) of the channel.

This distribution is used to calculate the mean statistical coordinates of the particle displacement for m horizontal layers in the following way

$$\Delta \bar{x}_i = \frac{1}{\bar{c}_i l} \int_0^l c_i x dx , \qquad (2)$$

where $\Delta \bar{x}_i$ is the mean statistical coordinate of the test particle displacement in the layer of i-number; $\bar{c}_i$ is the mean concentration of test particles in the layer i-number; l is the common length of a zone having stable flow conditions in the channel.

The mean velocity u_i of i-layer particles is calculated as follows

$$u_i = \Delta x_i / \tau ,$$

where τ is the deformation time.

Fig. 3 shows the velocity profile during shear flow of ceramic balls in the shear cell. Further the shear rate (du/dy) profile has been obtained by differentiation of this profile.

By means of this method it was found out that the suggested shear cell allows to obtain a rather wide zone of a two dimensional shear flow of particulate solids. This factor is favourable for observation of particle tendency to segregation and mixing

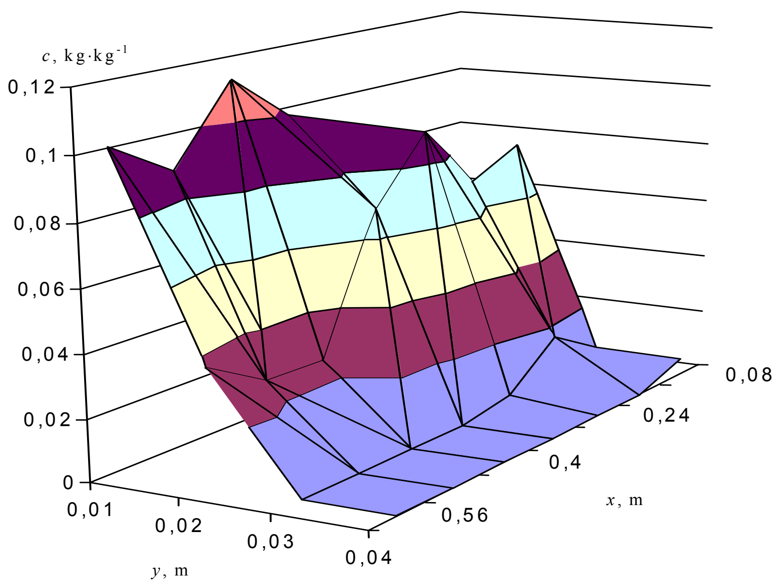
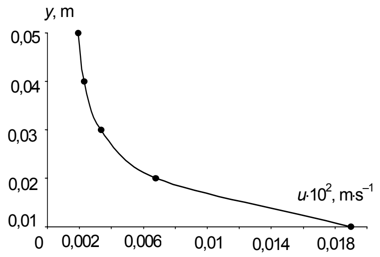
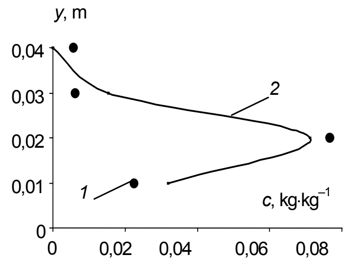


Fig. 2 Spatial distribution of coloured uniform particles in the channel



a)



b)

Fig. 3 Velosity (*a*) and concentration (*b*) profiles of coloured test particles:
1 – exsperimental; *2* – calculated

during shear flow of particulate solids. Besides the indicator method allows to obtain the reliable experimental data to check the adequacy of an analytical method for simulation of mixing dynamics of particles in the course of their shear deformation.

3 Mathematical simulation of mixing

The analysis of the experimental data allowed to suggest a mathematical description of mixing effects during shear flow of particulate solids. This description is based on the mass transfer equation taking into account convection and quasidiffusion

$$\partial c\rho_b / \partial \tau = -\partial uc\rho_b / \partial x + \partial / \partial y \left(D_{\text{dif}} \rho_b \, \partial c / \partial y \right), \qquad (3)$$

where D_{dif} is the coefficient of quasidiffusional mixing, u is the mean velocity of particles towards shear direction x, c is the concentration of test particles, ρ_b is the bulk density of particulate solids.

The coefficient of quasidiffusional mixing is calculated analytically taking into account structural and kinematic properties of the flow namely the fraction of void volume ε and the shear rate du/dy. This method was developed earlier in [3] for the mixing prediction of particles during their rapid shear flow.

As a result of a kinematical analysis the coefficient of quasidiffusional mixing was expressed as follows

$$D_{\text{dif}} = 1/2 \, du/dy \, bds \sin\left(\pi(d+s) / 4d \right), \qquad (4)$$

where $(du/dy)bd$ is the mean relative velocity between particles of neighbouring flow layers, d is the mean particles diameter, $b = \left(\pi/\left(6(1-\varepsilon)\right)\right)^{0,33}$ 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 $\varepsilon = \varepsilon_0 = 0,2595$.

It should be pointed out that eq. (4) does not include particle properties excepting *d*. However, it is obvious that the fraction of the void volume is a function of these properties.

The initial conditions for eq. (3) are set as follows

$$c(0,x,y) = \begin{cases} 1, & 0 \le x \le 0,04; \\ 0, & x < 0, \ x > 0,04. \end{cases} \qquad (5)$$

Boundary conditions are formulated assuming the absence of particle fluxes through the upper and lower bed boundaries.

Eq. (3) was integrated numerically to get concentration profiles $c(\tau, x, y)$ of test particles differing from the uniform medium particles on the colour only.

Figure 3 shows the comparison of the experimental and calculated concentration profiles of test particles in the shear flows of ceramic balls. The comparison allows to observe that the adequacy of experimental and analytical results is quite satisfactoäry.

References

1 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, 21, p. 29, 1978.

2 Bridgwater J., Cooke M. N., and Scott A.M.. Interparticle Percolation: Equipment Development and mean Percolation Velocities. Trans. I Chem. E., 56. p. 157, 1978.

3 Dolgunin V.N. and Ukolov A.A.. Segregation modeling of particle rapid gravity flow. Powder Technology, 83, p. 95, 1995.

Конвейерная сдвиговая установка для определения склонности частиц к сегрегации и перемешиванию при сдвиговом течении зернистых материалов

В.Я. Борщев[2], В.Н. Долгунин[1], Р.А. Шубин[1]

Кафедры: «Технологическое оборудование и пищевые технологии» (1), «Машины и аппараты химических производств», ТГТУ (2)

Ключевые слова и фразы: зернистая среда; квазидифузионное перемешивание; сдвиговые деформации.

Аннотация: Представлена оригинальная экспериментальная установка для исследования эффектов сегрегации и перемешивания в двухмерном сдвиговом потоке зернистого материала при умеренных скоростях сдвига. Развит аналитический метод для вычисления коэффициента квазидиффузионного перемешивания в сдвиговом потоке зернистого материала.

Fliessschiebeanlage für die Bestimmung der Neigung der Teilchen zur Segregation und zur Vermischung bei der Schiebeströmung der körnigen Stoffe

Zusammenfassung: Es ist die originelle experimentale Anlage für die Forschung der Effekte der Segregation und der Vermischung im zweidimensionalen Schiebestrom des körnigen Stoffes bei den gemässigten Geschwindigkeiten der Verschiebung vorgestellt. Es ist die analytische Methode für die Berechnung des Koeffizienten der quasidiffusionischen Vermischung im Schiebestrom des körnigen Stoffes entwickelt.

Installation de convoyeur de décalage pour la définition de l'aptitude des particules pour la ségrégation et le mélange lors de l'écoulement de décalage des matériaux granulés

Résumé: Est proposée une installation originale pour l'étude de la ségrégation et du mélange dans un courant de décalage du matériel granulé à deux dimensions avec la vitesse de décalage modérée. Est développée la méthode analytique pour le calcul du coefficient du mélange quasidiffusionnel dans un courant de décalage du matériel granulé.