NONUNIFORMITY OF MOTION OF PARTICLES OF A DENSE BED IN VERTICAL RECTANGULAR CHANNELS

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The nonuniformity of motion of a disperse medium in rectangular channels without blowing has been investigated in relation to various factors. The basic results are given.

In a number of cases for a moving dense bed with transverse or multipass blowing, channels of rectangular cross section may be preferable to channels of cylindrical shape with a counterflow. The reasons for this are as follows: a) the thickness of the blown layer may be small owing to the development of the blowing front in the other two coordinate directions; b) the thickness of the blown layer is constant; c) it is easy to ensure conditions of uniform inflow and outflow of gas; d) control of operation is more favorable than for counterflow; e) heat losses can be reduced since the two most developed sides of the channel are occupied by ducts for supplying and removing the gas; f) the intensity of heat transfer (owing to the more uniform distribution of gas in the bed) may be higher and approach that in the fixed bed [1]. Therefore it is desirable to employ the principle of cross blow-through of a moving dense bed. However, the literature lacks data on the mechanics, aerodynamics and heat transfer in a bed with transverse blowing.

In this paper we present the basic results of an investigation of the effect of various factors on the longitudinal and transverse nonuniformity of motion of a disperse medium. This information is important in itself; it is also necessary for studying the distribution of the gas flow in the bed and the intensity of the processes taking place in such systems. Data on the aerodynamics and heat transfer in a moving bed with transverse blowing were obtained in an independent study which will be reported in a subsequent paper.

EXPERIMENTAL METHOD AND TEST RIGS

Basically, the experiments consisted in studying the variation with time and over the height of the apparatus of a colored intermediate layer of granular material moving with the bed in a half-channel with a glazed wall, through which it was possible to make visual observations and measurements of the transit time and trajectory of the marked particles and thus to obtain velocity diagrams in the central longitudinal section of the channel. The unimportance of the so-called "corner effect" and the absence of significant distortions of the solids flow pattern connected with the presence of a glazed wall have been noted by a number of authors and confirmed by radioactive [2, 3] and X-ray [4] methods.

The velocity field was studied by this method on cold models of vertical rectangular channels without blowing by varying the flow rate (mean velocity), material and particle size, wall roughness, channel dimensions, etc. All the data were obtained for continuous motion of the bed and the measurements were repeated not less than three times. Measurements (Fig. 1) over the height of the channels were made every 100 mm and at five points in each section (in the wall layer and in the core). At the end of each experiment the flow rate was determined by weighing, the specific bulk weight of the moving bed (mean for the entire channel and at typical sections) by the cut-off method.

In order to study the mechanics of motion we constructed two test rigs. The first was a cold model of a heat transfer chamber and was therefore made of chrome-magnesite brick. The rig was equipped with a bucket elevator for returning the packing. The second rig had a channel with movable and interchangeable walls and was equipped with different discharge devices. The side walls of the second rig were of glass or wood and artificially roughened by gluing emery paper of different degrees of roughness to the side walls. The dimensions of these rigs, the characteristics of the disperse material employed and the experimental conditions are given in Table 1. Here, to characterize the degree of constraint imposed on the motion of the bed, together with the ratio D_{eq}/d_T adopted in [1], we have used for each particle size the

Table 1

Characteristics of Investigated Channels and Moving Bed

Rig	Channel dimensions, M			Packing material	Particle size d_T, mm	Bed velocity,[2] m/sec	Constraint factors	
	thickness Δ	width l	height H				D_{eq}/d_T	Δ/l
First	0.35	0.175	2.8	chrome	1.4	0.0009–0.0033	175	0.5
Second	0.15	0.10	1.0	concrete	1.4	0.0009–0.0033	85.7	1.5
"	vary	vary	1.0	periclase	5.0	0.0025–0.035	20–50	0.6–2.5
"	vary	vary	1.0	small ceramic cylinders	7.5/16.5[1]	0.013–0.05	9–23	0.1–2.0
					5.5/11.5[1]	0.0033–0.04	12.5–31.0	

Remarks. 1) Numerator—outside diam., denominator—length of cylinder. 2) Limits of variation of mean bed velocity in the tests.

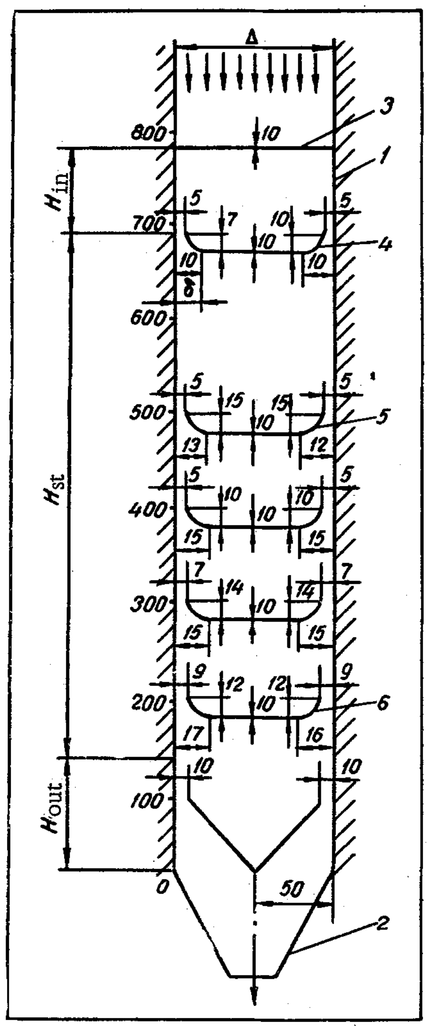

Fig. 1. Diagram showing geometry of colored layers (walls, wood; material, periclase; V_b = 0.00975 m/sec; shaft section $\Delta \times l$ = 0.1 × 0.1 m^2): 1) channel walls, 2) hopper, 3, 4, 5, and 6) colored layer at commencement of motion, at beginning and middle of stabilized zone, and at beginning of outlet zone.

geometrical ratio Δ/l, which takes into account the "slitlikeness" of the channel (Δ is the thickness of the blown layer, l the width of the channel). Then the equivalent channel diameter and the mean particle velocity are as follows:

$$D_{eq} = 4F/\Pi = 2\Delta l/(\Delta + l), \ \bar{V}_b = G_b/\Delta l \gamma_{sp}.$$

For particles of chrome-concrete and periclase (magnesium oxide) of irregular shape the particle diameter d_T was determined as a weighted mean value. The local velocity of the observed colored particle was determined from the measured trajectory and time of motion. Since, apart from the geometrical ratios, the relative roughness of the walls, and the particles, the most important similarity criterion is the Froude number Fr [1], this number was determined for each case from the expression

$$\mathrm{Fr} = gD_{eq}/\bar{V}_b^2.$$

Obviously, the longitudinal and transverse nonuniformity of particle motion is determined by the coefficients of internal and external friction of the moving bed, which, in their turn, are determined by the relation [1] (in the absence of blowing, i.e., when Re = 0)

$$f_{in}/f_{ex} = \varphi_1 (\rho_T/\rho, \ f'_{in}/f'_{ex}, \mathrm{Fr}, \ D_{eq}/d_T),$$

where f'_{in}, f'_{ex}, f_{in}, f_{ex} are the coefficients of internal and external friction of the fixed (prime) and moving beds, and ρ_T, ρ are the densities of the solid and gaseous components.

Determination of the coefficients f_{in}, f_{ex} involves considerable technical difficulties [1, 5, 7, 8]. Therefore it is convenient to characterize the nonuniformity of particle motion directly in terms of the change in the velocity field. We adopted the following method of reducing the experimental data. To judge the stabilization of the velocity field, i.e., the longitudinal nonuniformity of particle motion over the channel height, we used data on the variation of the thickness of the wall layer and the configuration and height of the colored layer in the flow core. The uniformity of particle motion in transverse sections of the channel was estimated from the dependence of the ratio of mean to maximum particle velocity on the ratio Δ/l at different Froude numbers. In this case the maximum particle velocity was observed on the axis of the channel, the minimum particle velocity in the wall layer.

BASIC RESULTS OF INVESTIGATION

Our observations showed that in general the motion is similar to that in cylindrical channels. A wall layer is formed. This layer is characterized by an appreciable transverse velocity gradient, rotation, mixing, and slippage of the particles, and a decrease in packing density. In the flow core, owing to their roughness, the motion of the particles is almost of the "piston" type. From data on the change in thickness of the wall layer δ, obtained under different conditions, we can, by analogy with the motion of a liquid, distinguish three zones of motion over the height of the channel (Fig. 1): an initial stabilization zone in which the velocity field is formed and δ increases from zero at the inlet to some constant value; a zone of stabilized motion in which the thickness of the wall layer and the configuration of the velocity profile in the core of the flow do not change, and an outlet zone affected by the discharge conditions, in which the thickness of the wall layer increases and the motion of the particles in the flow core becomes significantly less "pistonlike" (a funneling effect is observed). This is illustrated in Fig. 2, which is typical of other granular materials (altogether 176 diagrams were plotted).

Clearly, the stabilization zone is small and does not exceed the equivalent diameter of the channel ($H_{st}/D_{eq} \leq \leq 1$). The extent of the zone of stabilized motion is basically determined by the influence of the discharge conditions. In accordance with Fig. 2, the greatest nonuniformity occurs in the inlet and outlet parts of the channel, whereas in the stabilized zone there is no longitudinal nonuniformity.

Table 2 gives data on the relative height of the outlet zone of influence H_{out}/D_{eq} obtained on the second rig with an ordinary hopper discharge. According to these data the extent of the discharge influence zone depends on the width and thickness of the bed, which determine the value of D_{eq}, and on the shape and roughness of the particles. The data presented are in agreement with the data obtained by Zenz [6]. Thus the ratio H_{out}/D_{eq} for periclase (rough particles) is close to 2. For smooth particles (ceramic cylinders), where the angle of internal friction is much smaller, this ratio also decreases, which corresponds to the conclusions of [6] concerning the nature of the effect of the angle of internal friction on H_{out}/D_{eq}. In any case with decrease in D_{eq} the values of H_{out} and H_{out}/D_{eq} fall. The above data are practically independent of the roughness of the walls and the velocity of the dense-phase bed. In the experiments the velocity was varied from 0.0009 to 0.0033 m/sec for chrome-concrete particles, from 0.0025 to 0.035 m/sec for periclase, and from 0.0013 to 0.05 m/sec for ceramic cylinders.

As a rule, $H_{out}/D_{eq} > 1$ and, consequently, the extent of the outlet zone is greater than that of the initial stabilization zone. Obviously, for a blown bed, from the standpoint of the uniform distribution of gas in the bed, it is most rational to use the stabilized zone, and measures should be taken to reduce the size of the parts of the channel characterized by significant nonuniformity of motion. Basically this means the discharge influence zone.

Placing various baffles in the hopper in order to retard the motion of the particles in the flow core produced virtually no reduction in the longitudinal nonuniformity in the discharge influence zone (diagram 1, Fig. 3). The use of a perforated baffle in the presence of a lower hopper (dense-bed discharge) also failed to produce the desired effect. The best result ($H_{out} = 0$) is obtained with free discharge of the bed from the channel (beyond a perforated baffle-free-falling low-density bed-diagram 3). H_{out} can be

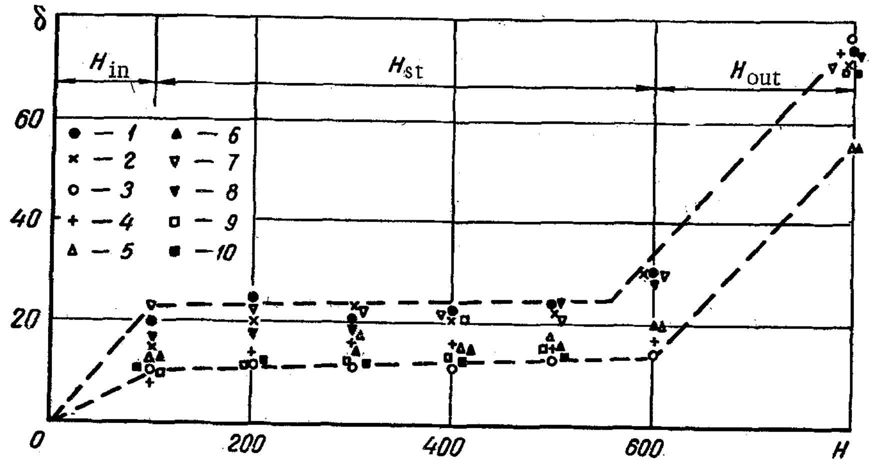

Fig. 2. Variation of thickness δ, mm, of wall layer of moving particles of periclase over height of channel H, mm, (wood walls) at V_b = 0.0027 m/sec (1–5) and 0.009 m/sec (6–10): 1) at Δ = 150 mm and l = 250 mm; 2) 150 mm and 200 mm; 3) 150 and 150; 4) 150 and 5) 100 and 100; 6) 100 and 200; 7) 150 and 250; 8) 150 and 200; 9) 150 and 150; 10) 150 and 100.

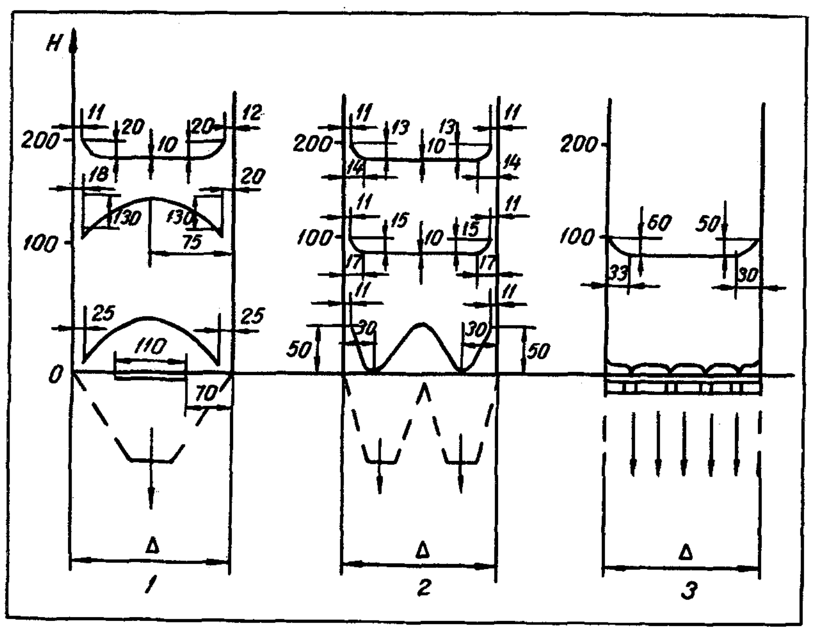

Fig. 3. Variation of geometry of colored layer configuration over height of channel in relation to various measures aimed at reducing the dimensions of the discharge influence zone.

Table 2

Relative Influence of Discharge Conditions for Various Channels

Particle material	Channel dimensions, m,			H_{out}, m	H_{out}/D_{eq}
	Δ	l	D_{eq}		
Periclase	0.25	0.25	0.25	0.45	1.8
Periclase	0.25	0.1	0.143	0.25	1.75
Periclase	0.1	0.1	0.1	0.15	1.5
Ceramic cylinders 5.5/11.5 mm	0.25	0.25	0.25	0.25	1.0
Ceramic cylinders 7.5/16.5 mm	0.20	0.20	0.20	0.20	1.0
The same	0.15	0.1	0.12	0.101	0.84

halved by using a hopper with two discharge orifices (diagram 2). The presence of the above three characteristic zones of motion of the dense bed was established on the basis of a study of the kinematic properties of the particles, manifested in their longitudinal nonuniformity of motion. In [2] Platonov considers the formation of similar zones from the standpoint of the dynamics of the moving bed. In this case it is shown that irrespective of the previous history of the bed, at the commencement of motion its density falls to a certain critical value, subsequently remains unchanged (in the zone of stabilized motion) and changes again in the outlet zone. According to our data, in the stabilized zone the packing density remains constant and increases somewhat in the discharge influence zone. Thus, for chrome-concrete γ_{st} = 1750 kg/m^3, and γ_{out} = 1850 kg/m^3.

The effect of roughness of the walls was expressed in an increase in the thickness of the wall zone. Thus, for chrome-concrete on the stabilized section on transition from glass and smooth wood walls to brick δ increased from 5 d_T to 35 d_T, and on transition from wood walls to walls with artificial roughness from 5 d_T to 10 d_T.

The study of transverse nonuniformity was based on data obtained in the stabilized zone. In accordance with Fig. 4, the Froude number was varied within wide limits (from 10^3 to $3 \cdot 10^5$ for periclase and from 600 to $2 \cdot 10^5$ for ceramic cylinders). The critical value of Fr at which the dense-bed regime goes over into the low-density (free-falling) regime [1] was not attained. The ratio Δ/l was also varied within wide limits. In accordance with Fig. 4, the greatest nonuniformity occurred in narrow slitlike channels with $\Delta/l < 1$. In this case V_b/V_{max} may reach 0.5–0.7. With broadening of the channel the nonuniformity decreases and at Δ/l = 1.5 for periclase particles and Δ/l = 1 for ceramic cylinders reaches a certain value ($V_b/V_{max} \approx$ ≈ 9) which remains practically constant with further increase in the geometrical dimensions of the channel and the ratio Δ/l. If we trace the change in transverse nonuniformity over the entire height of the channel for fixed Δ/l (Fig. 4), we observe that it remains constant in the stabilized zone and increases sharply in the discharge influence zone. Here it should be noted that in the outlet zone the particle velocity in the wall layer sharply decreases, while the velocity in the flow core significantly increases, as compared with the values characteristic of the stabilized zone. This effect, due to the influence of the discharge orifice, is the more pronounced, the greater the flow rate and hence the mean particle velocity.

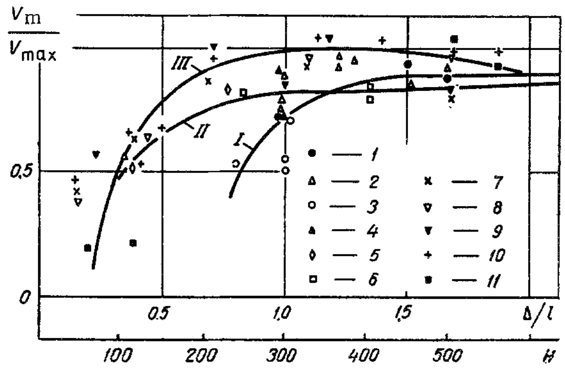

Fig. 4. Effect of constraint conditions on uniformity of particle motion for ceramic cylinders (1) Fr = 600–4600; 2) 4600–24 900; 3) 33 000–205 000)–I and periclase (4) Fr = = 10^3–$8 \cdot 10^3$; 5) $8 \cdot 10^3$–$6 \cdot 10^4$–$30 \cdot 10^4$)–II and variation of nonuniformity of particle motion over height of channel (material – chrome-concrete, shaft section $\Delta \times l$ = 0.15 × 0.1 m^2) with smooth walls (7) V_b = 0.0009 m/sec, 8) 0.0033) and with walls artifically roughened (9) V_b = 0.0009 m/sec, 10) 0.0015, 11) 0.0033)–III.

The above data are virtually independent of the Froude number (Fig. 4), which is attributable to the constancy of the conditions of motion of the bed in all the experiments.

NOTATION

D_{eq} is the equivalent diameter of channel, d_T is the particle diameter, Δ is the thickness of blown layer, l is the channel width, G_b is the mass flow rate of packing, V_b is the mean particle velocity, δ is the thickness of wall layer, H_{st} is the height of stabilized zone, H_{out} is the height of discharge influence zone.

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