APPLICATION OF TWO-PHASE FLUIDIZATION THEORY TO DENSE-PHASE PNEUMATIC TRANSPORT

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Results are presented of an experimental investigation which confirms the possibility of applying two-phase fluidization theory to dense-phase pneumatic transport of pulverized and powdered materials.

Dense-phase pneumatic transport of pulverized and powdered materials differs considerably in its characteristics from ordinary pressure pneumatic transport.

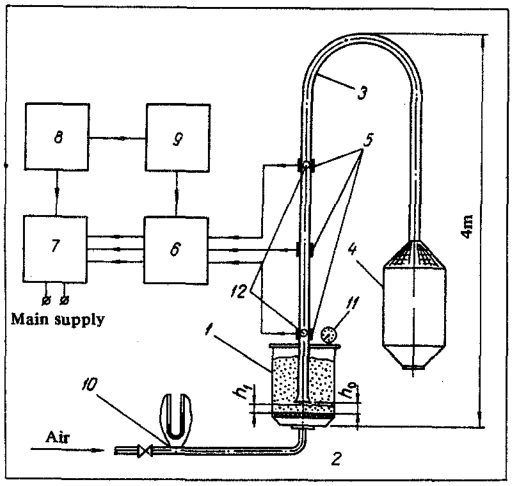

Fig. 1. Schematic of the experimental apparatus (9 is the power supply unit).

The "Superior Separator" company has published the following comparative data on the characteristics of dense-phase and ordinary pneumatic transport:

	For ordinary pneumatic transport	For dense-phase pneumatic transport
Mass concentration coefficient, μ, kg/kg	0.5–4	75–200
Air velocity, $\bar{\omega}_a$, m/sec	20–45	3–15
Diameter of the conveyor pipe, D_p, inch	3–30	3/4–4
Pressure, ΔP, kg/m^2	700–2800	2100–21000
Power consumption, 1000 hp/hr	2–7	0.8–2.5

We see then that dense-phase pneumatic transport is distinguished by high mixture concentration in the pipe, and comparatively small velocities of air and material, and requires higher air pressure at the pipe inlet.

Moreover, the computational relations of ordinary pneumatic transport prove to be unsuitable for dense-phase pneumatic transport, a fact which some authors have not taken into account [4].

We will apply the two-phase theory of the fluidized bed [1] to dense-phase pneumatic transport, i.e., we will consider, arbitrarily, that moving along the pipe there is a two-phase medium consisting of a pseudo-fluid (a fluidized material with porosity corresponding to minimum fluidization) and air bubbles.

We assume that the motive force in the pseudo-fluid—air bubble system is the excess pressure of the air at the pipe inlet.

This kind of model permits us to avoid examination of the motion of an individual particle in the air stream and to go over to mean velocities of the mass of fluidized material.

We note that Wen [5] has demonstrated experimentally the fruitfulness of this kind of transition for horizontal pneumatic transport in the dense phase.

To confirm the validity of the proposed model, and to obtain some characteristics of vertical pneumatic transport in the dense phase, we constructed a laboratory apparatus, a model of an intermittent (chamber feed) pneumatic elevator.

The apparatus (Fig. 1) consisted of a transparent cylinder 1 of diameter 200 mm and height 380 mm, a porous diaphragm 2, a pipe 3, and a receiving hopper with filter 4. The pressure in the cylinder was recorded on the oscillograph 7 with the aid of strain gauges 11. The air mass flowrate was measured in advance by the calibrated diaphragm 10. To determine the mean porosity of the mixture by the "cut-off" method, two cut-off valves 12 were located at a certain distance apart along the pipe.

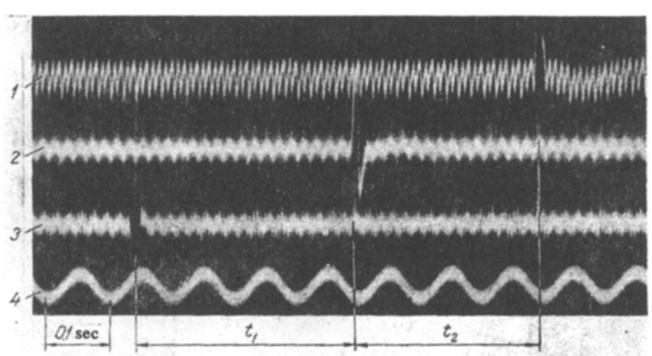

Fig. 2. Oscillogram for measurement of sphere velocity: 1, 2, 3) signals from the induction probes; 4) signal time generator.

To determine the velocity of the material, induction probes 5 were spaced along the pipe at intervals of 1 m.

Table 1

Determination of $\bar{\omega}_s$ with $D_p = 20$ mm, $\Delta P = 0.4$ kg/cm^2, $t = 18°$ C

d_s, mm	γ_s, g/cm^3	$\bar{\omega}_a$, m/sec at V, Nm^3/hr $V_1=5.3$	$V_2=8$	$V_3=10$	$\bar{\omega}_s$, m/sec at V, Nm^3/hr $V_1=5.3$	$V_2=8$	$V_3=10$	ω_{sr}, m/sec according to [2]
8	1.1	4.66	7.06	8.84	2.31	3.3	4.09	9.9
10	0.98				2.36	3.41	4.05	8.9
14	0.904				2.32	3.35	4.1	6.7

The cylinder was loaded with 15 kg of apatite concentrate, which is a powdered polydisperse material with mean particle diameter 60 μ. In addition to the apatite, the cylinder contained a certain number of hollow metal spheres of various diameters. During transportation the spheres, moving along the pipe with the material, were recorded successively by each induction probe; the signals were passed through the amplifier 6 and recorded on a N-102 type oscillograph 7. A simultaneous record was made of the signals from clock 8.

From the oscillogram (Fig. 2) we determined the time in which the spheres passed through the measuring sections, and calculated the mean velocities of the spheres over the measurement sections of the pipe.

Since the law of velocity variation along the pipe was not known, we took arithmetic mean values of the velocities of the spheres as a first approximation.

Results of the experiment carried out in a 20-mm pipe are given in Table 1.

In each regime 15 discharge cycles were carried out.

It may be seen from the table that the velocity of the spheres depends only on the transportation regime (mass flowrate of air) and is practically independent of the size of the spheres.

The calculated critical velocities of the spheres in the confined conditions are far greater than the filtration velocities obtained in the experiment at small air mass flowrates.

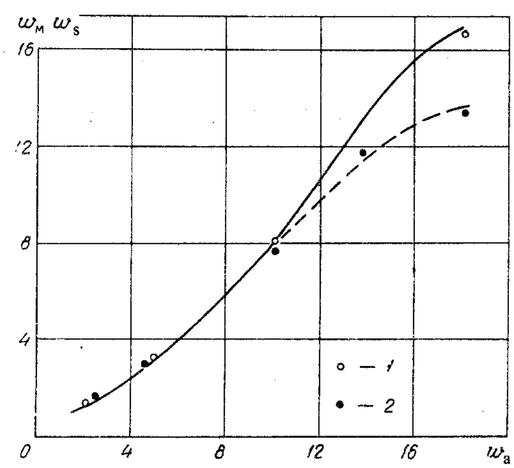

Fig. 3. Dependence of mean velocities (m/sec) of material $\bar{\omega}_m$(1) and sphere $\bar{\omega}_s$ (2) on the mean air velocity $\bar{\omega}_a$ with $\gamma_s = 1.0$ g/cm^3, $D_p = 12$ mm, $d_s = 8$ mm.

With the apatite missing, spheres located at the porous diaphragm directly below the pipe did not rise, even at the maximum air supply rate.

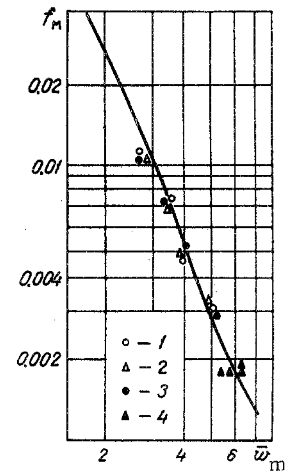

Fig. 4. Dependence of modified friction coefficient f_M on the mean velocity of the material $\bar{\omega}_m$ (m/sec) along pipes with $D_p = 14$ mm (1), 20 (2), 34 (3) and 70 (4).

It is not possible to explain the motion of the spheres of different sizes with identical velocities at the same air velocity on the basis of ideas that are valid for ordinary pneumatic transport. An explanation may be found if the spheres are regarded as aggregates of particles or particles of pseudo-fluid in the pseudo-fluid—air bubbles system. In this case the velocity of the spheres will be equal to the velocity of the pseudo-fluid, independently of the sphere size [3].

The volumetric weights of the hollow spheres were chosen to be about equal to the weight of unit volume of the fluidized material at concentrations corresponding to minimum fluidization ($m_{l.s} = 0.7$, $\gamma_s = 1.0$ g/cm^3).

To determine the slip velocity of the hollow spheres relative to the moving material, the following experiment was performed.

Spheres of diameter $d_s = 8$ mm and specific weight $\gamma_s = 1.0$ g/cm^3 were injected directly into the conveyor pipe through a special fitting, and their mean velocity was determined along the measuring section in various transportation regimes. Then, for the same transportation regimes, the mean porosity of the mixture in the pipe was determined by the "cut-off" method. From the known capacity of the system and the mean porosity of the mixture, the mean velocity of the mixture was calculated. The material velocities thus obtained were compared with those of the spheres (Fig. 3).

It may be seen from Fig. 3 that the velocities of the hollow spheres and of the material are practically the same at velocities of the material typical for pneumatic transport in the dense phase ($\bar{\omega}_M = 3 - 6$ m/sec).

Table 2

Determination of $\bar{\omega}_s$ with $D_p = 70$ mm, $H = 15$ m, $\Delta P = 2.1$ kg/cm^2, $t = 20°$ C, $d_s = 28$ mm, $\gamma_s = 10$ g/cm^3

$\bar{\omega}_a$, m/sec	$\bar{\omega}_a$, m/sec First section	Second section	Mean over transportation
10.34	4.87	5.33	5.1
13.2	5	6.12	5.56
15.03	6.66	6.94	6.8

The influence of the specific weight of the spheres on the slip velocity was verified in one of the transportation regimes, when spheres of different specific weight were injected into the pipe. The dependence of $\omega_{sl} = 3.5$ on γ_s at $D_p = 12$ mm, $d_s = 8$ mm, $\omega_a = 5.6$ m/sec and $\omega_m = 3.5$ m/sec was then as follows:

γ_s, g/cm^3	ω_s, m/sec	ω_{sl}, m/sec
0.9—1.0	3.58	0.08
1.4	3.56	0.06
2.9	3.23	0.27
3.8	2.96	0.54
7.8	1.82	1.68

It was thus established that the slip of a sphere relative to the material being transported was practically zero with $\gamma_s \le 1.4$ g/cm^3, and material velocity $\bar{\omega}_m < 10$ m/sec.

All this gives reason to believe that the sphere velocities obtained (Table 1) are the mean velocities of the fluidized material, and confirms the correctness of the two-phase model assumed.

The characteristic pulsations of the transportation process are explained by bursting of the air bubbles.

One important characteristic of pipe conveyors is the modified friction coefficient of the material

$$f_M = \Delta P D_p g / 2 H G_M \bar{\omega}_m.$$

The graphical correlation of the experimental data (Fig. 4) is in complete agreement with the section of the curve obtained by Wen for horizontal pneumatic transport in the dense phase in the same range of pipe and particle diameters. The equality of the modified friction coefficients for vertical and horizontal pneumatic transport in the dense phase is one more distinctive peculiarity of this type of transportation.

The experiment confirms the correctness of the relation obtained by Hariu and Molstad [6], Wen et al.:

$$\bar{\omega}_m \approx 0.5 \bar{\omega}_a.$$

At the same time as the velocities were measured, measurements were made of the height of the residual material h_0 at the end of transportation as a function of the distance between the porous diaphragm and the inlet nozzle of the pipe, h_1 (Fig. 1).

The residual height proved to be roughly equal to the distance between the porous diaphragm and the pipe inlet nozzle, independently of the pipe diameter and the transportation regime.

Further investigations were carried out on semi-industrial equipment with a pipe diameter $D_p = 70$ mm and a height $H = 15$ m. Measurement of the material velocities was made by the method described above, the measurement sections being at heights of 4 and 10 m. The results of the experiment for three transportation regimes are presented in Table 2.

It may be seen from Table 2 that the mean velocity of the fluidized material varies very little with height, which agrees with the observations of Wen [5]. The uniform nature of the motion of grain during transportation in the dense phase has also been remarked by Welshof [7].

It is possible that the increase of slip velocity of the air bubbles is a result of expansion of the gas with transportation height.

NOTATION

$m_{l,s}$) limiting stability porosity; ω_s and $\bar{\omega}_m$) mean velocities of the spheres and fluidized material; $\bar{\omega}_a$) mean velocity of air referred to total pipe cross section; ω_{sl}) slip velocity of a sphere relative to material being transported; d_s) sphere diameter; γ_s) specific weight of metal sphere; f_M) modified friction coefficient; D_p) pipe diameter; ΔP) pressure drop; H) elevation; t_1, t_2) times taken by a sphere to cross the first and second measuring sections, respectively; V) mass flowrate of air; G_M) capacity per second per-unit area of conveyor pipe; g) free-fall acceleration.

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