A HYDRODYNAMIC STUDY OF THE INITIAL STAGE OF A VERTICAL CONDUIT FOR CONVEYING MATERIAL

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Results are shown of a study concerning the pneumatic transport process in the initial stage of a vertical conveyor conduit. A relation is derived for calculating the local drag coefficient.

A vertical initial stage of a conduit for conveying material is widely used in modern pneumatic transport systems and most often with reciprocating pumps. A hydrodynamic analysis of various routing systems has shown that a vertical initial stage is most effective in every case, inasmuch as it ensures a high stability of the pneumatic transport process and is economical in terms of lower transport velocities, less conduit wear, and lower air flow rates. The hydrodynamic relations in a vertical pneumatic transport system have been studied in [2-5], but very little is known about the initial stage [1].

The initial stage of a pneumatic transport system includes a receiver device followed by a straight pipe segment. The drag in the initial stage is, during pneumatic transport, reflected in the energy loss on mixing the phases in the receiver and on accelerating the solid particles up to the maximum velocity at which the transport then proceeds along the stabilized stage of the conduit. A concentration and velocity field typical of a stabilized two-phase flow is gradually developing in the initial stage as the particles are accelerated.

With the additivity principle applied to the drags of both phases, the carrier medium and the conveyed material, the total drag coefficient in the initial stage during pneumatic transport can be expressed as follows:

$$\zeta = \zeta_{\mathrm{M}} + \lambda \frac{l}{D} + \zeta_{\mathrm{M.o}}. \tag{1}$$

The local drag coefficient ζ_{M} is an analog of the local drag coefficient in a one-phase flow and comprises the sum of two components:

$$\zeta_{\mathrm{M}} = \zeta_{\mathrm{M}_1} + \zeta_{\mathrm{M}_2}. \tag{2}$$

Only the first term ζ_{M_1} representing the energy loss on acceleration of the solid component has a theoretical basis and is defined by the relation [2, 3, et al.]

$$\zeta_{\mathrm{M}_1} = 2\mu \frac{v_0 - v_{\mathrm{m}}}{v_0}. \tag{3}$$

Some linearization of the pneumatic process along the initial stage of the conduit is involved in the derivation of formula (3), and the resulting degree of approximation has been evaluated in [1]. One usually disregards the interaction between solid particles and the conduit wall as well as the compressibility of the carrier medium within the initial stage, one then begins with a zero initial velocity of particles, and one determines the resultant final velocity of particles as the difference between the carrier velocity and the descent velocity of particles.

The second term in (2) represents the energy loss on mixing the phases in the reciever and the energy loss, not accounted for by the first term, on accelerating the conveyed particles to their stabilized velocity. A relation for calculating the second term can be found from experiments based on the theory of similarity.

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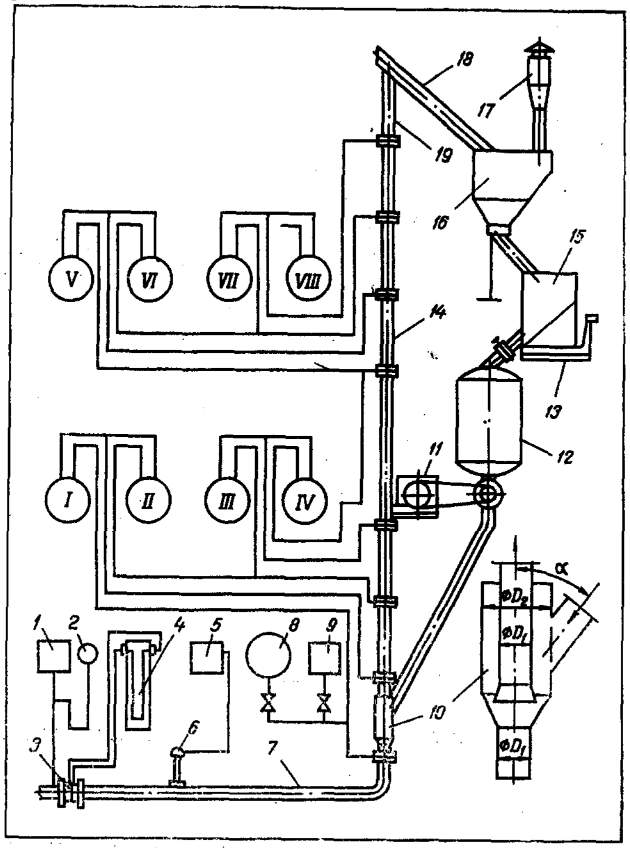

Fig. 1. Schematic diagram of the test apparatus: 1), 8), and 9) recording manometers, 2) manometer, 3) diaphragm, 4) differential manometer, 5) electronic bridge circuit, 6) resistance thermometer, 7) air conduit, 10) T-chamber receiver, 11) drive box, 12) feeder, 13) weighing balance, 14) conveyor conduit, 15) and 16) bins, 17) separator, 18) trough, 19) measuring chamber, I to VIII recording differential manometers.

Measurements necessary for determining ζ_M were made on the pneumatic transport apparatus available at the BIZhT (Belorussian Institute of Railroad Engineers) laboratory [6]. This apparatus is shown schematically in Fig. 1. Its essential features are: a long vertical conduit, a wide range of values over which the two-phase flow parameters can be varied, and provisions for automatic data recording. For our tests the apparatus included two parallel steel conduits with different parameters: 125 mm and 69 mm. The height of the straight riser was 27 m.

Each conduit was equipped with an interchangeable receiver comprising a T-joint, a T-chamber, or a reciprocating pump. In the first two variants the disperse material was fed into the receiver from the bin by means of a metering screw which, driven by an electric motor through a speed-reducer gear box, ensured that the solid phase could be fed at a steady but adjustable rate into the air stream. In the third variant the same feed system was used only for precharging the pump with material. The essential parameters of all equipment are listed in Table 1.

In an analysis of the initial stage, the accuracy of the results will largely depend on satisfying the condition that pressure drops ΔP be measured over a conduit length L greater than the length of the initial stage l_i, i. e., that the acceleration of conveyed particles be already completed within a conduit segment of such a length L. This condition was satisfied in all tests by calibration against the $\Delta P(L)$ curve.

In order to have this $\Delta P(L)$ curve, we had seven measuring segments installed in the conduit: 3 m long each, except the fourth one 6 m long. The number of segments and their length had been selected so as to pinpoint the conduit segment where the solid component ceased to be accelerated, also to satisfy the requirement that $L > l_i$.

TABLE 1. Basic Dimensions, Coefficients $\zeta_{M.O}$ and β of Various Types of Receivers

Type of receiver	Receiver dimensions			Local drag coefficient $\zeta_{M.O}$	Coefficient β in formulas (7) and (8)
	D_1, mm	$\frac{D_2}{D_1}$	α,deg		
T-joint	125	—	45	0,10	1,54
T-chamber	69 125	2,5 2,5	45 45	0,85 0,59	1,0
Reciprocating pump from the Krasnogorsk Works	150	9,3	—	2,2	1,31
Reciprocating pump from the Slavinsk Works	69	14,5	—	2,2—2,5	1,20

Notes: 1) $\zeta_{M.O}$ is referred to the effective conduit section; 2) $\zeta_{M.O}$ for the reciprocating pumps is calculated without the drag in the sprayer and in the aerators taken into account.

The initial stage was not longer than 18 m for all the kinds of particles conveyed through the conduit over the entire test range of velocities and concentrations. The acceleration stage became longer, as the concentration and the velocity of the solid component in the two-phase stream increased. In all tests the pressure drop ΔP was the same across at least two or three segments behind the acceleration stage. For this reason, the drag coefficient λ determined on the basis of the pressure drops across these segments corresponded to that in a stabilized two-phase stream.

Not less important in an analysis of two-phase flow, especially with a fine dispersion of solid material, is the design of the pressure sampling system along the conduit. The device for pressure sampling has been described in [6] but, in addition, each measuring chamber was equipped with a nozzle for passing compressed air during as well as before each test. In order to prevent conveyed material from straying into the measuring system, special filters with very low drag and easily removable for periodic cleaning had been installed in the surge tubes.

Because the pressure in the conduit was pulsating in most transport tests, all pressure drops were recorded automatically through differential manometers for better accuracy, and the mean pressure was determined from the diagram.

The method of analysis and test data evaluation was based on two equations:

$$\Delta P = 0.5 \zeta v_0^2 \rho_0, \tag{4}$$

$$\zeta_{M_2} = \zeta - \zeta_{M.O} - \lambda \frac{l}{D} - 2\mu \frac{v_0 - v_s}{v_0} . \tag{5}$$

TABLE 2. Test Conditions

Test series No.	Conveyed material	d, mm	V_m, m/sec	ρ_s, kg/m³	D,mm	Transport modes			Number of tests
						μ	v_0, m/sec	ρ_0, kg/m³	
	Ground limestone	0,049	0,37	2730	69	2—46	8—31	1,3—1,9	14
	Mineral powder	0,048	0,41	2530	69	10—45	7—21	1,3—1,8	17
	Apatite concentrate	0,088	0,82	3220	69	7—80	6—29	1,5—2,5	12
	Quartz sand	0,250	1,92	2650	69	5—35	11—27	1,3—1,8	8
	Firebrick crumbs	2,830	8,58	—	69	2—19	14—31	1,3—1,5	6
	Wheat	3,800	7,80	1260	69	4—20	12—28	1,3—1,5	10
	Cereal	1,700	6,00	1330	69	4—24	5—28	1,3—1,9	7
	Dolomite powder	0,140	1,15	2700	69	5—65	8—30	1,4—2,3	14
	Apatite concentrate	0,088	0,82	3220	125	8—30	11—32	1,4—1,6	8
	Dolomite flour	0,140	1,15	2700	125	3—17	13—43	1,3—1,5	6
	Quartz sand	0,250	1,92	2650	125	2—21	9—45	1,3—1,9	12
	Quartz sand	"	"	"	125	6—7	12—13	1,5—3,7	10
	Cereal	1,700	6,00	1330	125	3—11	9—36	1,3—1,5	12
	Quartz sand	0,250	1,92	2650	125	6—21	9—27	1,3—1,5	7
	Apatite concentrate	0,088	0,82	3220	150	12—25	8—12	3,7—4,7	14
	Mineral powder	0,048	0,41	2530	69	33—70	8—19	1,6—2,3	30

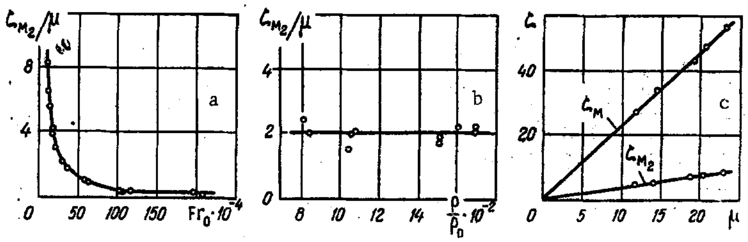

Fig. 2. Drag test data pertaining to the initial stage of a pneumatic transport conduit conveying: a) ground limestone, b) quartz sand, c) mineral powder.

The local drag coefficient $\zeta_{M.O}$ in the initial stage was determined in preliminary tests with pure air blown through the conduit. Its values are listed in Table 1. The drag coefficient λ under pneumatic transport conditions was determined from test data pertaining to the stabilized stage of a two-phase flow immediately following the initial stage in the conduit [7]. The end purpose of the test data evaluation was to determine the ζ_{M2} component of the local drag coefficient during pneumatic transport.

The transport modes and the characteristics of disperse materials used in the study on this apparatus* are listed in Table 2. The tests covered a wide range of concentrations and velocities. The use of a stepwise inclined end conduit before the unloading stage [8] instead of the conventional bent with a transition from vertical to horizontal flow, for instance, made it necessary to test at high concentrations of the solid phase (μ = 30 to 80) and low carrier velocities (v_0 = 6 to 15 m/sec). The transport of powders in these modes proceeded continuously and stably, although at the upper limit of concentrations and the lower limit of velocities there occurred appreciable pulsations. The highest mass concentration of powder was $\mu = 20$ and the corresponding lowest velocity was $v_0 = 12$ m/sec. Higher concentrations could not be attained, owing to the limited supply of granular material. At low and high concentrations the velocity at the entrance to the initial stage was determined with the change in the carrier density ρ_0 taken into account.

According to Table 2, the sizes as well as the velocities and densities of particles typified the characteristics of most industrial materials conveyed pneumatically. Besides determining ζ_M and its components, several series of tests were performed to evaluate the dependence of ζ_{M_2} on the basic hydrodynamic similarity groups.

A major effect on coefficient ζ_{M_2} has the Froude number Fr_0, which refers the relative velocity at the exit from the initial stage to the average weighted size of conveyed particles. In Fig. 2a is shown the relation $\zeta_{M_2}/\mu = f(Fr_0)$ plotted for test series No. 1 with ground limestone. The power-law character of this relation has been confirmed also by an evaluation of data pertaining to other test series.

On the basis of test series No. 12 (Table 2), the effect of the density ratio ρ/ρ_0, density of solid to density of air, in the conveyed mixture on the magnitude of ζ_{M_2} has been established for quartz sand. A wide variation in the ratio ρ/ρ_0 was achieved by adjusting the backpressure in the separator of the test apparatus. The transport modes in this test series were characterized by $Fr_0 \cong$ idem and $\mu \cong$ idem (air velocity $v_0 = 12.5 \pm 0.5$ m/sec and weight concentration $\mu = 6.5 \pm 0.5$). An evaluation of the test results is shown in Fig. 2b. The drag coefficient in the initial stage remained constant under the given pneumatic transport conditions, although the ratio ρ/ρ_0 was varied over a wide range.

The tests in series No. 2 included pneumatic transport of mineral powder in the 69 mm (diameter) conduit, with Fr_0 = idem and μ = var. These conditions were satisfied by holding the stabilization velocity of the carrier within 20 ± 1 m/sec, i. e., with negligible fluctuations, while changing the load, i. e., the amount of conveyed solid phase in each test. According to Fig. 2c, the local drag coefficient during pneumatic transport ζ_M and its component ζ_{M_2} were proportional to the weight concentration at discharge.

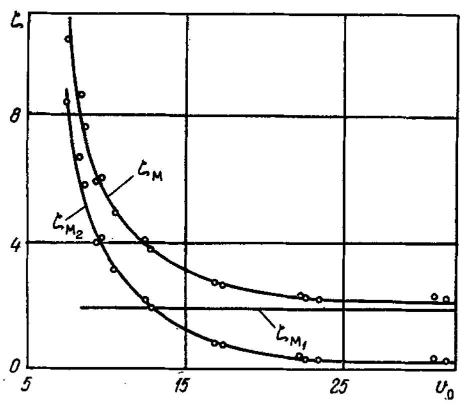

Fig. 3. Local drag coefficient in the initial stage, as a function of the transport velocity.

*M. P. Kuchma assisted in performing these experiments.

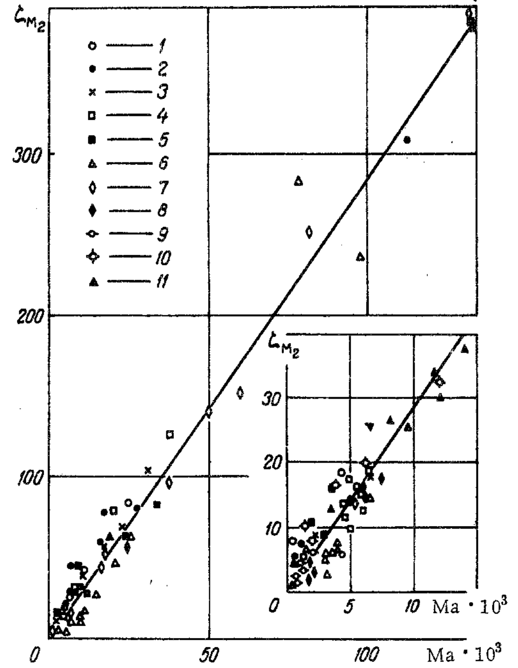

Fig. 4. Local drag coefficient ζ_{M_2} as a function of the Mach number Ma, in the initial stage of the pneumatic system with a T-chamber receiver and either the D = 69.4 mm conduit conveying: 2) apatite concentrate, 3) quartz sand, 6) mineral powder, 7) ground limestone, 9) cereal, 10) firebrick crumbs, and 11) wheat, or the D = 125 mm conduit conveying: 1) apatite concentrate, 4) quartz sand, 5) dolomite flour, and 8) cereal.

No effect of the diameter ratio D/d, conduit diameter to particle diameter, on the magnitude of coefficient ζ_{M_2} was detected.

The effect of the governing similarity groups on the drag coefficient in the initial stage was evaluated in terms of the following universal relation to cover all tests:

$$\zeta_{M_2} = C\mu\, \mathrm{Fr}_0^{-m}\, \mathrm{Fr}_s^{n}. \tag{6}$$

The values of coefficient C and of exponents m, n were found by processing the test data on a Minsk-22 computer by the method of least squares. The velocity of particles in the phase mixing stage v_m was tentatively taken as 1 m/sec for all materials. An evaluation of tests the T-chamber receiver yielded C = 2863, m = 1.36, and n = 1.31.

In order to find whether the universal relation (6) would also apply to other types of receiver, we performed the test series No. 14 on this apparatus with the T-joint receiver and test series Nos. 15, 16 with the reciprocating pump. These tests have confirmed the universality of relation (6) with the earlier established values of exponents m and n, but the coefficient C was found to increase with the higher drag in those other two types of receiver.

Taking into account the type of receiver (the initial conditions and the geometry of the mixing process), one may write the universal relation (6) more reasonably in the following form:

$$\zeta_{M_2} = 2863\beta\mu\, \mathrm{Fr}_0^{-1.36}\, \mathrm{Fr}_s^{1.31}. \tag{7}$$

For the receiver types in this study the coefficient β varies between 1.0 and 1.5, its specific values are listed in Table 1. It is to be noted that the values obtained here for β correspond to those for industrial models of reciprocating pumps and a fixed geometry of T-joint and T-chamber receivers.

In most published references the authors recommend that the design of a vertical initial stage be based on a drag value comprising the ζ_{M_1}-term alone. The inaccuracy of such a design is made evident by the graphs in Fig. 3 representing the local drag coefficients ζ_{M_1} and ζ_{M_2} as functions of the carrier velocity during pneumatic transport of ground limestone, referred to $\mu = 1$. At practical transport velocities in a vertical initial stage $v_0 < 15$ m/sec, ζ_{M_1} is 1.5 to 4.4 times lower than the true local drag coefficient ζ_M. The lower the initial transport velocity is, the larger becomes the error in calculating the drag in the initial stage on the basis of ζ_{M_1} alone.

An evaluation of test data in terms of the criterial relation (7) is shown in Fig. 4. Here the abscissa axis represents $M = \mu \mathrm{Fr}_0^{-1.36}\, \mathrm{Fr}_s^{1.31}$ and the ordinate axis represents ζ_{M_2}. The generalizing straight line corresponds here to the computer-evaluated test results. According to Fig. 4, all tests are closely enough generalized by the criterial relation derived here. The computed standard deviation is 15.2%. Large deviations are typical mainly of the transport tests at high concentrations and low velocities. In such transport modes the recorded parameters were fluctuating widely and the measuring chambers clogged up rather fast.

Based on the total set of experiments, the design equation for the local drag coefficient in the initial stage of vertical conduit is

$$\zeta_M = 2\mu \frac{v_0 - v_m}{v_0} + 2863\beta\mu\, \mathrm{Fr}_0^{-1.36}\, \mathrm{Fr}_s^{1.31}. \tag{8}$$

The validity of relation (8) has been established over a wide variation range of the similarity groups and simplexes: $5 < \mu < 80$, $15 \cdot 10^3 < \mathrm{Fr}_0 < 20 \cdot 10^6$, $26 < \mathrm{Fr}_s < 21 \cdot 10^2$. Coefficient β is found in Table 1, depending on the type of receiver.

Besides the criterial relation (7) there is also a formula for ζ_{M_2}:

$$\zeta_{M_2} = 3200\beta\mu \frac{d^{0.05}}{v_0^{2.72}}. \tag{9}$$

In this case the reliability of calculations for powder materials has been verified for velocities of the carrier medium within the $v_0 = 6$ to 45 m/sec range, ensuring a weight concentration of conveyed material μ from 80 to 5. For granular materials these ranges of v_0 and μ are narrower. As the transport velocity was varied from 6 to 36 m/sec, the maximum concentration corresponding to a stable transport mode was $\mu = 20$. In all cases tested here, the transport mode was characterized by a velocity $v_0 > v_S$.

A comparison between the pressure drop ΔP calculated according to the relations derived here and its value determined in tests indicates that for 90% of all tests the error did not exceed 17%.

NOTATION

ζ_M	is the local drag coefficient for the initial stage during pneumatic transport;
λ	is the drag coefficient for the stabilized stage with a two-phase flow;
$\zeta_{M.O}$	is the local drag coefficient for the initial stage during flow of pure air;
μ	is the weight concentration at discharge;
v_0	is the carrier velocity at the entrance to the initial stage;
ΔP	is the pressure drop across the measurement segment;
ρ_0	is the air density at the entrance to the initial stage;
$Fr_0 = v_0^2/gd$	is the Froude number referred to the relative velocity v_0;
$Fr_S = v_S^2/gd$	is the Froude number referred to the velocity of particles v_S in the phase mixing stage;
β	is the form factor of the receiver;
d	is the average weighted diameter of particles;
v_m	is the descent velocity of particles;
ρ_S	is the density of particles;
D_2	is the diameter of the receiver chamber.

LITERATURE CITED

1. Z. R. Gorbis, Heat Transfer and Hydrodynamics in Dispersion Streams through Vents [in Russian], Izd. Énergiya, Moscow (1970).
2. V. A. Uspenskii, Pneumatic Transport [in Russian], Metallurgizdat, Sverdlovsk (1959).
3. A. M. Dzyadzio and A. S. Kemmer, Pneumatic Transport in Grain Processing Plants [in Russian], Izd. Kolos, Moscow (1967).
4. V. A. Shvab, V. A. Smolovik, A. M. Kapustin, and G. G. Gainutdinov, Izd. Sibir. Otdel. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 3 (1963).
5. I. M. Razumov, Fluidized and Pneumatic Transport of Disperse Materials [in Russian], Izd. Khimiya, Moscow (1964).
6. M. E. Dogin, Test Apparatus for the Study of Linear and Local Drag in Pneumatic Transport Mains [in Russian], Izd. GOSINTI, Moscow (1965).
7. M. E. Dogin, Inzh. Fiz. Zh., 19, No. 5 (1970).
8. M. E. Dogin, A. V. Starovoitov, M. P. Kuchma, and Yu. V. Savel'ev, Authors' Disclos., No. 283017, Byull. Izobret. i Otkryt., No. 30 (1970).