EXPERIMENTAL STUDY OF THE DRAG OF A GRAPHITE SUSPENSION IN AIR FLOWING THROUGH PIPES

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UDC 532.529.3:622.648

Results are given of tests on the drag of graphite particles, sizes 100 and 200 μ, pneumatically transported through horizontal and vertical pipes 5.33, 8.16, and 18.8 mm in diameter.

Many studies have been made concerning the drag in pneumatic transport (e.g., [1-10]). Owing to the complicated mechanism of interaction between mixture components and interaction with the channel wall, however, the calculation formulas derived by various authors are incomplete. Several problems require further study and refinement. Thus, for example, there are almost no data available on the losses of pressure head in a descending flow of a solid-in-air suspension. The assumptions made by some authors for calculating the drag in this case are based on wrong concepts. The drag of a suspension in air flowing through small-diameter pipes has not been studied thoroughly enough. It must be noted, furthermore, that only a limited number of different solid substances was used in earlier experiments. Data available on the loss of head in a pneumatic transport of graphite are altogether few and they apply only to very fine particles [6-8].

In this study we have analyzed the drag in an air stream carrying particles of synthetic graphite through pipes 5.33, 8.16, and 18.8 mm in diameter. The tests were performed with two narrow-tolerance fractions of particles: 100 and 230 μ nominal size. The test pipes were positioned horizontally and vertically.

The test apparatus consisted of an open gas and solids circulation system operating on the same principle as in [11]. Air was pumped in with a reciprocating compressor. The pressure pulsations were smoothed out by means of an equalizing chamber and filters were used for cleaning the air of oil and moisture. The solid particles were injected into the air stream from a special-purpose bin far away from the test segment. The resulting air–graphite mixture was passed through a test segment for pressure-drop measurements and then into a separator where the solid particles were again extracted; the clean air was exhausted into the atmosphere. The duration of each test was at least 10 min. The rate of air flow was measured with a double diaphragm, the rate of graphite injection was measured by weighing the particles recovered in the separator. The pressure drop across the test segment was measured with a differential manometer; a micromanometer with a slanted scale was used for small pressure drops.

The test pipes were of stainless steel. The pressure was picked off at two pipe sections, at three holes spaced around the circumference and 0.3 or 0.5 mm in diameter, under a 120° angle. The pressure pickoffs at each section were combined into a common receptacle. The pressure drop was measured across pipe segments of relative length $l/d = 194$ ($d = 5.33$ mm), 86 ($d = 8.16$ mm), and 100 ($d = 18.8$ mm). The test segment was preceded by a hydrodynamic stabilizer segment longer than 100 d for each pipe. In the case of the 5.33 mm pipe, two separate measurements were made with different lengths of the prestabilizer segment: 103 d and 160 d; the absence of any discrepancy between the results of both measurements here indicates that all tests have been performed with particles already past the acceleration stage.

Preliminary measurements of the hydraulic drag coefficient for pure air with the Reynolds number within the 6000–50,000 range agreed closely (within ±3%) with the Blasius formula.

Moscow Power Institute, Moscow. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 22, No. 4, pp. 597-602, April, 1972. Original article submitted July 9, 1971.

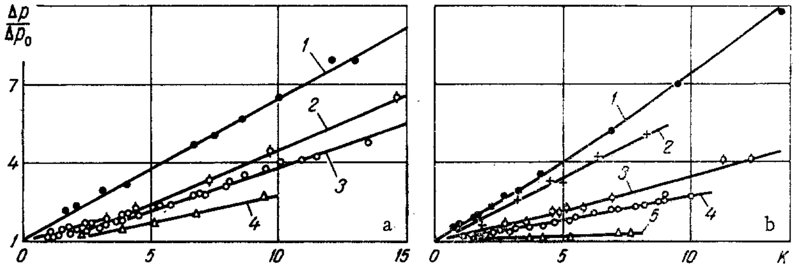

Fig. 1. Effects of concentration and of the Reynolds number on the drag in an ascending stream of air with particles (a) $d_s = 100\ \mu$ and (b) $d_s = 230\ \mu$ through a pipe 18.8 mm in diameter; for (a): 1) Re = 6300; 2) 12,000; 3) 19,000; 4) 32,000; for (b): 1) Re = 6400; 2) 7600; 3) 11,500; 4) 19,000; 5) 32,000.

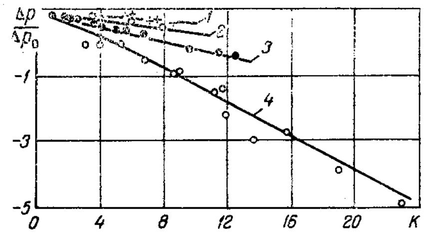

Fig. 2. Test data on a descending stream of air with particles $d_s = 230\ \mu$ through the d = 18.8 mm pipe: 1) Re = 33,500; 2) 20,000; 3) 11,500; 4) 6300.

Nineteen series of tests were performed subsequently with a solid suspension in air. Each series was characterized by a specific particle size or Reynolds number of the carrier medium. In tests with the d = 18.8 mm pipe the Reynolds number was varied from 6300 to 33,500, in tests with the d = 5.33 mm and the d = 8.16 mm pipe the Reynolds number was maintained almost constant (Re ≈ 15,000). All tests with the 5.33 mm pipe and the 8.16 mm pipe were performed under almost isothermal conditions. Measurements in the 18.8 mm pipe were made under isothermal conditions as well as under conditions of heat transfer, i.e., while the stream was heating up. The pressure drop across the test pipes was measured within an accuracy of 1.5%. The rate of air flow and of graphite injection were measured within an accuracy of 2% and 1%, respectively.

The evaluation of test data was reduced to finding the following relation:

$$\frac{\Delta p}{\Delta p_0} = f(K). \tag{1}$$

The values of Δp_0 were calculated according to the Darcy formula.

The results of tests with the 18.8 mm pipe in a vertical position and with an ascending air–graphite stream are shown in Fig. 1a, b. For an analysis of these data, relation (1) can be rewritten as

$$\frac{\Delta p}{\Delta p_0} = \frac{\Delta p_0'}{\Delta p_0} + \frac{\Delta p_s}{\Delta p_0} + \frac{\Delta p_{s,l}}{\Delta p_0}. \tag{2}$$

The ratio $\Delta p_0'/\Delta p_0$ in Eq. (2) is generally not equal to unity, since the presence of solid particles may change the velocity profile of an air stream, its turbulence level, etc.

The pressure head lost on maintaining a column of suspended particles is found from the formula:

$$\Delta p_{s,l} = \rho g l K \frac{w_a}{w_s}. \tag{3}$$

Expressing Δp_0 in terms of the Darcy equation, we have

$$\frac{\Delta p_{s,l}}{\Delta p_0} = \frac{2}{\xi} \cdot \frac{gd}{w_a^2} K \frac{w_a}{w_s}. \tag{4}$$

If w_s/w_a is independent of the Reynolds number, then formula (4) yields $\Delta p_{s,l}/\Delta p_0 \sim \mathrm{Re}^{-1.75}$. The most likely explanation for the strong dependence on the Reynolds number in Fig. 1a, b would then be that, as the Reynolds number for an ascending stream decreases with all the other conditions remaining the same, the relative fraction of the pressure head lost on maintaining the column of suspended particles increases.

We will estimate the magnitude of $\Delta p_s/\Delta p_0$. For this we need data from which $\Delta p_0'/\Delta p_0$ and $\Delta p_{s,l}/\Delta p_0$ can be determined. The second of these two ratios can be calculated by formula (4) with w_s/w_a known. For a quantitative evaluation of w_s/w_a, we measured the velocities of the $d_s = 230\ \mu$ particles

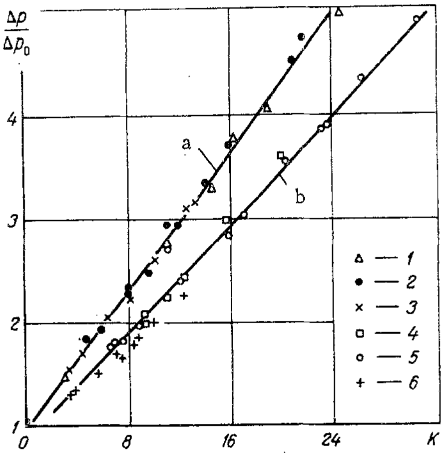

Fig. 3. Experimental data on resistance in tubes 8.16 mm (a) and 5.33 mm in diameter (b): 1, 4) d_s = 100 μ (horizontal flow); 2, 5) d_s = 230 μ (horizontal flow); 3, 6) d_s = 230 μ (upward flow).

during the flow of air with a graphite suspension through the d = 17.1 mm pipe in [12]. On the basis of these tests, we let w_s/w_a = 0.6; we also assume $\Delta p_0' = \Delta p_0$. For all data in Fig. 1b, then, formula (2) yields $\Delta p_s/\Delta p_0 \approx 0$. With the same value of w_s/w_a an analogous calculation for the data in Fig. 1a (d_s = 100 μ) yields $\Delta p_s/\Delta p_0 > 0$; for example, $\Delta p_s/\Delta p_0 \approx 1.5$ for K = 10. As d_s becomes smaller, the ratio w_s/w_a should obviously increase and result in a higher ratio $\Delta p_s/\Delta p_0$ for d_s = 100 μ. An analysis of the data for the 18.8 mm pipe reveals, indeed, a higher ratio $\Delta p_s/\Delta p_0$ for smaller particles.

In Fig. 2 are shown the results of drag measurements with d_s = 230 μ particles suspended in a descending air stream through the 18.8 mm pipe. Evidently, $\Delta p/\Delta p_0$ decreases as the concentration increases and, in fact, $\Delta p/\Delta p_0 < 0$ in our tests when K > 5 with Re = 6300 or K > 8 with Re = 11,500. These results can be explained by a negative $\Delta p_{s,l}/\Delta p_0$ in (2) for a descending stream. By the way, this has not been recognized in the literature and in [2], for example, $\Delta p_{s,l} = 0$. Considering the sign of $\Delta p_{s,l}/\Delta p_0$ and that under the conditions prevailing in our case one may expect $w_s/w_a \geq 1$, formula (2) with $w_s/w_a = 1$ and $\Delta p_0' = \Delta p_0$ for Re = 33,500 and Re = 20,000 will yield $\Delta p_s/\Delta p_0 \approx 0$ for d_s = 230 μ, as in the case of an ascending stream; For Re = 11,500 and Re = 6300, $\Delta p_s/\Delta p_0' > 0$. When K = 10, for example, $\Delta p_s/\Delta p_0 \approx 1$ for Re = 11,500 and $\Delta p_s/\Delta p_0 \approx 2$ for Re = 6300. The last result differs appreciably from those obtained for an ascending stream. It can be explained, apparently, by the appreciably higher loss of head on pumping the carrier air under conditions of negative pressure gradients, i.e., $\Delta p_0' > \Delta p_0$. Furthermore, the data in Fig. 2 refer to conditions where the stream was heating up, which resulted in additional pressure losses on the acceleration of both the air and the solid particles. Since the temperature drop in the air during the heat transfer tests did not exceed 20°C, hence the pressure head lost on accelerating the air remained approximately 3-4% of Δp_0. An exact calculation of the pressure head lost on accelerating the particles is difficult, because it is not known to what extent the particles respond to the acceleration of the carrier air. If it is assumed that the velocity of solid particles increases by the same amount as the velocity of the air, when the latter is heating up, then the pressure head lost on accelerating solid particles will have been estimated as the maximum possible. For our test conditions such an estimate will yield a pressure drop due to acceleration of the solid particles of the order of (0.04-0.05) $\cdot \Delta p_0 K$. Calculations show that the correction accounting for this acceleration is appreciable at large values of the Reynolds number but has almost no effect on the test results corresponding to Re = 6300 and Re = 11,500.

In Fig. 3 are shown the results of drag tests with the air carrying a graphite suspension through the 5.33 mm and the 8.16 mm pipe in a horizontal and in a vertical position. A characteristic feature of these tests was that the size of particles had no effect on relation (1). The loss of pressure head was almost the same in an ascending and in a horizontal flow of the graphite–air mixture through the 8.16 mm pipe and, in the case of the 5.33 mm pipe, the drag was even somewhat smaller in an ascending than in a horizontal flow. Taking $\Delta p_{s,l}/\Delta p_0$ according to formula (4) into account for both these pipes, however, will result in different values for ascending and for horizontal flow respectively in the 8.16 mm as well as in the 5.33 mm pipe. Inasmuch as $\Delta p_{s,l}/\Delta p_0 \approx 0$ for d = 5.33 mm and $\Delta p_{s,l}/\Delta p_0$ = 0.06-0.10 for d = 8.16 mm, our results indicate that the increased drag in these pipes is due to a higher Δp_s. The divergence between drag test points for horizontal and for ascending flow in the 5.33 mm and in the 8.16 mm pipe (taking $\Delta p_{s,l}/\Delta p_0$ into account) can be explained by the different frequency of collisions between particles and the pipe wall, this frequency being evidently higher during a horizontal than during a vertical transport on account of the effect of gravity forces. We note that an evaluation in terms of relation (1) in Fig. 3 does not reveal the effect of the pipe diameter on the absolute loss of pressure head due to collisions between particles and the pipe wall. The value of $\Delta p_s/l$ is much higher for the 5.33 mm pipe than for the 8.16 mm pipe. For K = 10, then, $\Delta p_s/l = 6 \cdot 10^3$ N/m³ for the first pipe and $1.8 \cdot 10^3$ N/m³ for the second pipe. Considering that the concentration of particles was the same and $\Delta p_s/l = 7 \cdot 10^2$ N/m³ in all tests with the 18.8 mm pipe, one may conclude that $\Delta p_s/l$ increased as the pipe diameter decreased. This had, evidently, to do with the higher number of collisions between particles and the wall. It apparently also explains the appreciable discrepancy (by a multiple) between our test data for small-diameter pipes and the values calculated by the formulas in [1], which is evidence of the unique character of the drag mechanism in the transport of solid particles through small-diameter pipes – a mechanism requiring further studies.

NOTATION

Δp	is the pressure drop in a pipe during the flow of an air–graphite mixture, N/m^2;
Δp_0	is the pressure drop for pure air, N/m^2;
$\Delta p_0'$	is the pressure head lost on pumping the air alone of an air–graphite mixture;
Δp_s	is the pressure drop due to the frictional drag of solid particles;
$\Delta p_{s,l}$	is the pressure head lost on lifting the solid particles;
d	is the pipe diameter;
d_s	is the diameter of the solid particles;
G	is the mass flow rate of the air;
G_s	is the mass rate of particle injection;
$K = G_s/G$	is the mass concentration of particles in the air;
$Re = 4G/\pi d\mu$	is the Reynolds number;
g	is the acceleration of free fall;
l	is the pipe length;
w_a	is the air velocity;
w_s	is the particle velocity;
μ	is the air viscosity;
ρ	is the air density;
ξ	is the frictional-drag coefficient for pure air.

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