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EFFECT OF ELEVATED CARRIER-GAS PRESSURE ON HYDRAULIC CHARACTERISTICS OF GAS–SOLID PARTICLE TWO-PHASE FLOW

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The effect of elevated gas pressure on the hydraulic resistance and critical velocity of a two-phase flow is studied on a pneumatic-transport bench. It is established that for each working-pressure level there exists a limiting solid-phase concentration, the exceeding of which causes an abrupt rise in hydraulic resistance.

Gas flows in pipes in the presence of a disperse phase in the form of solid particles take place in various technological processes: in power engineering mining, the chemical industry, and metallurgy. Such flows are typical in practice in the pneumatic transport of granular materials, which is gaining wider use in the indicated areas.

Pneumatic transport is being developed to increase the concentration of granular material in the pipe and the transport distance, which makes it necessary to increase the carrier-gas pressure.

Preliminary estimates show that granular loads can be carried distances of from 1-2 to several tens of kilometers through a pneumatic-transport line (for example, coal, ore, and other raw materials from the production site to the consumer). The working gas pressures at the beginning of the pipe will be within 0.5 to 3-4 MPa.

The accumulated experimental material on two-phase flows [1-11], which has been generalized in the form of dependences for hydraulic resistances, critical velocities, sliding velocities, acceleration parameters, and other quantities, was obtained at small working pressures (0.1-0.2 MPa). The use of these results in the design of systems with increased carrier-gas pressure requires proper substantiation.

We studied the effect of an increase in gas pressure (to 1.4 MPa) on such hydraulic characteristics of two-phase flow as hydraulic resistance, critical velocity, and sliding velocity.

1. The study was performed on a pneumatic-transport bench, a diagram of which is shown in Fig. 1.

The bench is mounted in a closed scheme with two circuits: one for the pure gas and one for the two-phase suspension. The bench includes two series-connected circulation units (CU), which consist of spur-gear compressors of type 2AF51É52Sh in sealed enclosures, which are filled with gas simultaneously with the pneumatic-transport pipes. The noncirculating part of the bench consists of transport pipes with horizontal measuring sections and loading and unloading devices. The noncirculating part is filled with gas to the working pressure from a gas-supply unit with a bank of high-pressure cylinders ($p_w = 15$ MPa) and a system for controlling and monitoring the output pressure.

The loading device (LD) is a cyclone unit mounted on a cylindrical hopper, in whose lower part is a variable-speed drum feeder. The unloading device (UD) consists of a cyclone and a receiving hopper.

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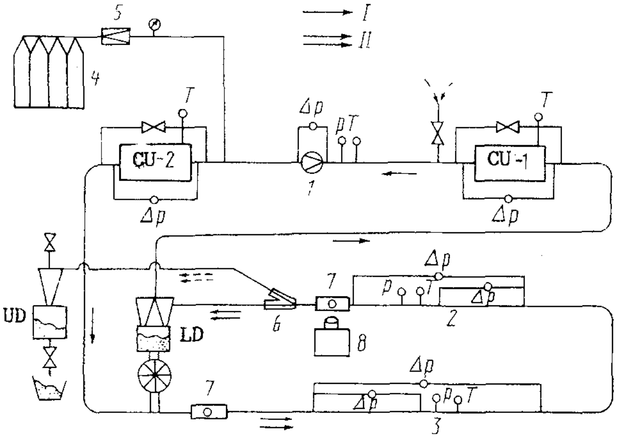

Fig. 1. Pneumatic-transport bench. 1) Benturi flowmeter; 2, 3) Du50 measuring sections; 4) gas-supply unit; 5) reducer; 6) flow switch; 7) transparent pipe inserts; 8) high-speed motion picture camera; p, T, Δp) pressure, temperature, and pressure-differential sensors; I) gas flow; II) two-phase flow.

Before the experiments, the studied granular material was loaded into the LD hopper. The noncirculating part of the bench is filled with gas to the required working pressure.

With the CU bypass cocks open, the drive motors of the compressors are started. A gas flow with a specified rate of from 0.03 to 0.7 kg/sec is established in the bench by means of the bypasses.

To switch to two-phase flow, the drive motor of the drum feeder is actuated, which feeds the granular material into the pipe. The solid particles are picked up by the gas flow and move along with it through the pipes, which have measuring sections, transparent inserts, and measuring devices, and at the end enter the cyclone unit.

The phases are separated in the cyclones: The gas from the cyclones enters the CU through discharge tubes, while the solid particles are collected in the cylindrical hopper and are reintroduced into the gas flow by means of the drum feeder.

The parameters of single- and two-phase flows were measured as follows. The flow rate of the gas was determined with the aid of a Venturi tube installed in the pure-gas circuit according to the readings of a "Sapfir-22DD" pressure-difference transducer, a DDI-20 excess-pressure gauge, and a TSM 0879 thermal converter.

The pressure losses in the measuring sections were also found using "Sapfir-22DD" sensors. The critical velocities were determined from the flow rate of the gas in conjunction with visual observation through the transparent inserts and photography of the particles by means of a "Pusk-16" high-speed motion picture camera.

The "Sapfir-22DD" sensors were powered by B5-49 supply units; the DDI-20 sensors operated in conjunction with an IVP-2. The TSM 0879 thermal converters were connected to a KSM-4 balancing bridge.

The sensors were interrogated and their readings were recorded automatically by means of a K 484/2M digital measuring and recording system. Sevenfold interrogation was performed under each set of experiment conditions. The interrogation time for one channel was 1 sec. Then the primary data were processed on a "Neiron I9.66" personal computer.

The working materials were air at an excess pressure of from 0 to 1.3 MPa and polyethylene granules (ρ_s = 930 kg/m^3 and d ≈ 3 mm).

The pressure gauges and drum feeder were calibrated before the experiments. The pressure gauges were calibrated with the aid of an MP-60M piston gauge.

The bench was switched to open-circuit operation for calibration of the drum feeder. The solid particles moved from the LD hopper through the drum feeder into the transport pipe, from which they passed by the LD cyclones and entered the unloading device. A dependence of the solid-phase delivery rate on the drum speed was established from the filling

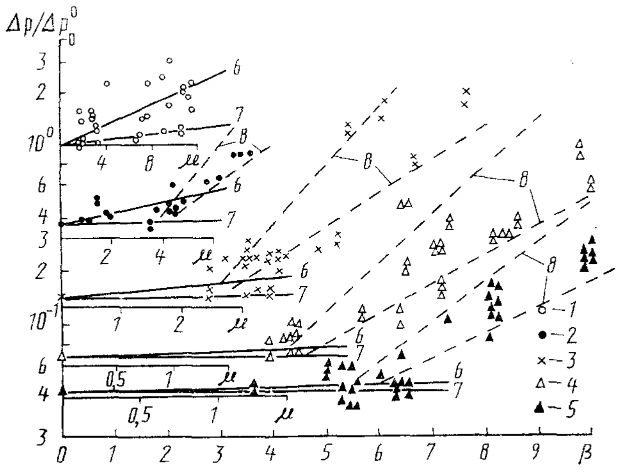

Fig. 2. Graph of $\Delta p/\Delta p_0{}^0$ versus volume and flow concentrations of solid particles in Du50 horizontal pipe: 1) $p_w = 0$; 2) 129 kPa; 3) 462 kPa; 4) 919 kPa; 5) 1315 kPa; 6) calculation [1] for $U = U_{min}$; calculation [1] for $U = U_{max}$; 8) calculation by formula (6) for $\beta > \beta_{th}$; β in %.

time of the UD hopper, the known mass of the granular material, and the rotation speed of the drum. In the experiments with polyethylene, it was from 0.145 to 1.50 kg/sec.

The experiments were performed in two steps: with pure air and with two-phase flow.

Pure-air tests at various working pressures made it possible to evaluate the reliability of the results by comparing the coefficients of hydraulic resistance of the measuring sections with the known data in the literature. The results of the pure-air experiments indicated that the flow in the measuring sections corresponded to that of hydraulically smooth pipes. In addition, the obtained resistances (Δp_0) provided a frame of reference for the hydraulic losses of the two-phase flow (Δp) at fixed carrier-gas flow rates.

Since exact coincidence of the gas flow rates in the pure-gas and two-phase experiments is complicated to achieve, the experimental points $\sqrt{\Delta p_0} \sim G_0$ were approximated by the method of least squares by a straight line $\sqrt{\Delta p_0} = a G_0$, and, therefore, $\Delta p_0 = a^2 G_0{}^2$.

2. For convenience of analysis of the effect of working pressure on the hydraulic resistance of two-phase flow, the experiment results were represented in the form

$$\frac{\Delta p}{\Delta p_0^0} = f_1(p_w, \beta) \quad \text{or} \quad \frac{\Delta p}{\Delta p_0^0} = f_2(p_w, \mu).$$

The volume concentration β is related to the solid-phase mass concentration as follows [2]:

$$\beta = \frac{1}{1 + \frac{1}{\mu} \frac{\rho_s}{\rho} \frac{U_s}{U}}. \tag{1}$$

In this expression, the ratio U_s/U is undetermined. High-speed photography was used to find it. The experiments, which under the operating conditions of the bench were performed at $p_w = 0$, showed that $U_s/U \approx 0.4$ in the range of gas velocities of 24 m/sec ≤ U ≤ 43 m/sec. With allowance for these U_s/U values, β was calculated by formula (1) for $p_w > 0$.

For motion of a pure gas in a pipe, the hydraulic resistance is determined by the Darcy–Weisbach law [12], from which it follows that for a constant mass flow rate, the resistance is inversely proportional to the gas density in accordance with the relation

$$\frac{\Delta p_0}{\Delta p_0^0} = \frac{\lambda}{\lambda^0} \frac{\rho_0^0}{\rho_0}, \tag{2}$$

i.e., an increase in pressure results in a decrease in resistance. For rough and hydraulically smooth pipes that obey the Blasius law, $\lambda = \lambda^0$.

A graph of $\Delta p/\Delta p_0{}^0$ versus β and μ obtained on the bench at various working pressures is provided in Fig. 2. These results show that the hydraulic resistance of the flow rises with an increase in β. At increased pressures, however, the hydraulic resistance of the two-phase flow remains lower than the resistance of the pure gas at zero excess pressure in the range of $\beta \leq \beta^0$. Starting with some $\beta = \beta_{th}$ and $\mu = \mu_{th}$, a sharp increase in resistance takes place, which, with increased β and μ, can exceed the losses of two-phase flow at $p_w = 0$. With an increase in working pressure, β_{th} is increased while μ_{th} is decreased.

The following formulas can be recommended for estimation of the hydraulic resistance of a two-phase flow at $p_w > 0$:

$$\frac{\Delta p}{\Delta p_0^0} = (1 + k\mu)\frac{\rho_0^0}{\rho_0}, \quad \mu < \mu_{th} \quad \beta < \beta_{th}; \tag{3}$$

$$\frac{\Delta p}{\Delta p_0^0} = (1 + k\mu_{th})\frac{\rho_0^0}{\rho_0} + K^*(\mu - \mu_{th}), \quad \mu \geqslant \mu_{th} \quad \beta \geqslant \beta_{th}. \tag{4}$$

Formula (3) and the first term of (4) are an extrapolation of Gasterstadt's formula to the region of elevated pressures. The Gasterstadt coefficient k is determined by well-known empirical relations [13] with allowance for the granular material used and the conditions of its motion in the pipe.

Calculations were performed by formula (3) using Smoldyrev's formula [1] for the coefficient k

$$k = c\,\frac{g(\rho_s/\rho - 1)}{U^2}\,D, \quad c = 0{,}075 - 0{,}1, \tag{5}$$

which was extrapolated to the working gas pressures and velocities realized in the bench experiments.

The results of these calculations are shown in Fig. 2 (curves 6 and 7). Comparison of the calculation and experiment data confirms the legitimacy of extrapolation of the formulas to the region of $p_w > 0$ for $\beta < \beta_{th}$ ($\mu < \mu_{th}$), but the agreement of the results is impaired with increasing β and p_w.

The coefficient K^* can be assumed to equal 0.2-0.5 on the basis of analysis of the obtained data. With an increase in working pressure, K^* has a tendency to decrease.

We shall discuss the possible mechanisms of variation of the hydraulic resistance of two-phase flow with an increase in carrier-gas pressure.

As follows from analysis of the empirical formulas for small β, (first flow regime) [13] and the experimental data at increased pressure for $\beta < \beta_{th}$ in Fig. 2, the pipe resistance is proportional to the mass fraction of particles or their volume concentration. These quantities are determined by the amount of particles that pass through the pipe cross section per unit time.

The increase in pipe resistance in the presence of particles in the flow can be explained by their lagging behind the gas and can be estimated [9]:

$$\Delta p_s = c_d\left(\frac{d}{D}\right)^2 \frac{\rho(U - U_s)^2}{2U} NL.$$

This lag is a consequence of loss of particle momentum. In a horizontal flow, two mechanisms of loss of particle momentum can be distinguished: a mechanism associated with particle interaction with the pipe walls and a mechanism governed by the collision of "fast" particles (i.e., particles that have been accelerated by the flow) and "slow" particles (that have lost a part of their momentum by reflection from the pipe walls).

With an increase in pressure, the density of the carrier gas is increased, the average particle velocity with respect to the gas velocity rises, and stable flow conditions without partial settling of the solid phase on the lower wall of the pipe are preserved, as is shown by experiments (see Sec. 3) at volume concentrations that exceed the values that correspond to low gas pressures. At $\beta < \beta_{th}$, therefore, the effect of the particles on the total resistance is reduced, which is confirmed by the reduction of the slope of $\Delta p/\Delta p_0{}^0 = f_1(\beta)$ with an increase in pressure.

With a relatively small quantity of particles (under experiment conditions with $\beta < \beta_{th}$), the determining mechanism is that of particle lag due to reflection from the pipe walls. With an increase in the amount of particles (second flow regime), the lag mechanism

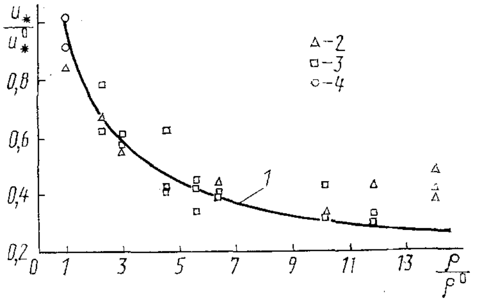

Fig. 3. Comparison of formula (7) with experimental data at elevated pressure: 1) calculation; 2) $\mu = 1.5\text{-}4.0$; 3) 5-9; 4) 11-15.

due to particle collisions begins to play a substantial role. In this regime, the increase in resistance, as earlier, is proportional to β and μ, or, what is the same, to the quantity of particles, but the proportionality factor can rise considerably.

The conditions for transition to the second flow regime and the hydraulic resistance at $\beta > \beta_{th}$ [the slope of $\Delta p/\Delta p_0{}^0 = f_1(\beta)$], in additon to being functions of the working gas pressure, are also dependent on the physical and geometrical characteristics of the particles and the pipe material, which determine the level of loss of particle momentum in each act of interaction with the pipe walls and between particles.

3. Analysis of the experimental data made it possible to determine over the entire range of working pressures the conditions of minimal (critical) carrier-gas velocity under which the granular material was transported stably without settling on the lower surface of the horizontal pipe.

As follows from the work of others [1, 14-16], for low-pressure pneumatic-transport systems, the critical velocity can be estimated by the formula

$$U_* = A\mu^{\omega}\sqrt{\frac{\rho_s}{\rho}}. \tag{6}$$

Here, $A = A(g, d, D)$ and $\omega = 0\text{-}0.5$. For evaluation, the validity of this formula under conditions of elevated carrier-gas pressure, Fig. 3 shows experimental data and the calculated dependence of the dimensionless critical velocity obtained by formula (6):

$$\frac{U_*}{U_*^0} = \sqrt{\frac{\rho^0}{\rho}}. \tag{7}$$

As is apparent from the data presented, with allowance for the possible effect of the flow concentration and exaggerated values of U_* due to the operating conditions of the bench (at $\rho/\rho^0 > 10$), formula (6) can also be used at elevated carrier-gas pressures.

Thus, the results of the studies show that with an increase in the pressure (density) of the carrier gas, the hydraulic resistance of a two-phase flow at concentrations that do not exceed μ_{th} is considerably lower than the resistance at zero excess pressure. A further increase in concentration causes a sharp rise in resistance, whose value can exceed the corresponding values at $p_w = 0$.

The results of the experiments at $\mu < \mu_{th}$ are in satisfactory agreement with the Smoldyrev's well-known empirical formula as extrapolated to elevated gas pressure. The extrapolated formulas for the critical velocities have the same agreement with the experimental data at elevated pressure. The reduction of critical velocity with a rise in pressure indicates an increase in the carrying capacity of the flow. Therefore, pneumatic-transport lines of increased pressure reduce erosion wear of both the pipes and the transported material (due to a reduction of critical velocity) as well as hydraulic resistance and, therefore, power expenditures for movement of two-phase flows. Experiments with granular materials with different combinations of geometrical and physical parameters are required for a more complete determination of the flow characteristics.

NOTATION

p_w is the working excess pressure of the carrier gas, in kPa; $\Delta p_0{}^0$ is the hydraulic resistance of a horizontal pipe for a pure gas with zero excess pressure, in N/m^2; Δp^0 is the hydraulic resistance at elevated pressure, in N/m^2; Δp is the hydraulic resistance for two-phase flow, in N/m^2; G is the mass flow rate of the gas, in kg/sec; G_s is the mass flow rate of the granular material, in kg/sec; $\mu = G_s/G$ is the mass concentration; β is the volume concentration of the solid phase; ρ is the gas density, in kg/m^3; ρ_s is the true density of the solid-phase material, in kg/m^3; U is the average cross-sectional velocity of the carrier gas, in m/sec; U_s is the average solid-particle velocity, in m/sec; D is the pipe diameter, in m; L is the pipe length, in m; and U_* is the critical velocity, in m/sec. The superscript "0" corresponds to $p_w = 0$ and the subscript "0" corresponds to the pure gas.

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UNSTEADY MASS TRANSFER TO DROPS IN LIQUID FLOW FOR APPRECIABLY DIFFERENT DIFFUSION COEFFICIENTS OF THE CONTINUOUS AND DISPERSE GAS PHASES

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UDC 532.72

Problems of unsteady convective heat and mass exchange between drops and a liquid flow are analyzed under a boundary condition of the "thermal capacitance" type. This condition is substantiated by the method of small perturbations.

Introduction. Problems of unsteady convective heat and mass exchange between drops (particles) and a liquid flow represent the least-studied and most-complicated area in the theory of processes of this class [1, 2]. It has been shown that the phenomenon has several characteristic stages [3, 4], and the necessary transfer equations have been provided [1, 5], which has made it possible to systematize the results achieved in this area for a number of situations of practical importance.

For analysis of the problem of heat- and mass-exchange interaction of drops with the surrounding medium, researchers are forced to resort to simplifications and to make certain

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