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MODELLING OF THE MOVEMENT OF GAS STREAMS WITH COARSE PARTICLES

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It is impossible to construct models for gas with particles in the sense of difference and similarity theory considered for example in [1]. Partial modelling methods are used in [2] for studying "flows of suspensions when the particles are so small that their movement for the majority of time is governed by Stoke's law."

In this work an attempt to use these methods in the case of coarse particles. Conditions are obtained with whose fulfillment there is similarity of particle movement. In order to check these conditions a series of experiments is performed in transparent geometrically similar arrangements. The results are presented as cine-particles and curves.

The problem is considered of modelling movement of two-phase media (gas, solid particles) in channels. The medium studied is distinguished from the gas with particles studied normally by the fact that the volume concentration of particles may exceed the gas concentration and the characteristic size of particles is comparable with the channel cross section. Strictly speaking these particles cannot be considered as a pseudogas (for example, particles of dust in a gas stream), and they exhibit enormous inertia since their mass concentration may exceed by two orders of magnitude the gas mass concentration. In the future in order to emphasize this distinction the word "particle" is substituted by "lumps." The most marked example of this process is movement of lumps in pulsed pneumatic transport (PPT) equipment.

This equipment consists of a receiver filled with compressed air, a supply line with a quick-acting valve, a collector and a transport line separated by a nozzle grid, and also an intake device. The simplest installations are considered whose transport line is a straight channel of constant cross section placed vertically.

Here and subsequently the indices r, c, and n are used for denoting characteristics of the receiver, collector, and nozzle grid respectively, the same values in the channel are used without indices, and lump parameters are marked with an asterisk.

There is gas in the receiver at pressure P_r. After opening the valve gas from the receiver is fed through the supply line to the collector and through the nozzle grid it percolates into the channel. In the collector pressure P_c is established depending on P_r and on the resistance of the supply line and nozzle grid to the gas flow.

Lumps lie on the grid in the channel. After passing through the nozzle grid, gas filters through the layer of lumps as a result of which they start to move through the channel.

When the pressure in the receiver falls to a certain established cut-off pressure the valve closes, pressure in the collector falls to atmospheric, and gas flow in the channel ceases. If lumps still remain in the channel then they are transported by the next gas pulse.

We show that for modelling these processes the requirements of the classical theory of difference and similarity [1] are not fulfilled.

We assume that there are two geometrically similar equipments for transporting lumps (the smaller we shall call the model, and the larger we shall call the full-scale) in which there are similar (in the sense of difference and similarity theory) processes. Then in view of geometric similarity and unchangeability of the force of gravity the following relationships are fulfilled

$$d' = md, \quad g' = g, \tag{1}$$

where values with a prime relate to the model, without a prime to the full-scale equipment, and m is modelling scale.

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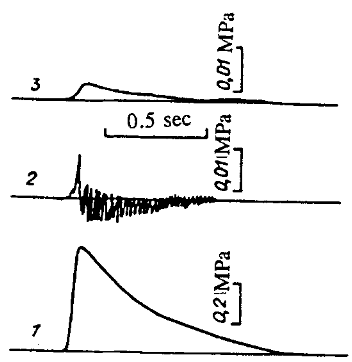

Fig. 1

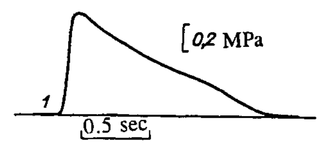

Fig. 2

Since external pressure remains atmospheric, then the density and viscosity of the transporting gas retained:

$$\rho' = \rho, \quad \mu' = \mu. \tag{2}$$

It is apparent that in view of the similarity of the processes the Reynolds Re and Froude Fr numbers for the model and full-scale equipment should coincide:

$$\frac{\rho du}{\mu} = \mathrm{Re} = \mathrm{Re}' = \frac{\rho' d' u'}{\mu'}, \qquad \frac{u^2}{dg} = \mathrm{Fr} = \mathrm{Fr}' = \frac{(u')^2}{d'g'}. \tag{3}$$

Conditions are derived from relationships (1)-(3) which should satisfy velocity for the model and full-scale equipment: $u'/u = m^{-1}$ for conformity of Re values, and $u'/u = m^{1/2}$ for conformity of Fr values.

Whence it can be seen that it is possible to obtain similarity by changing relationships (1) and (2). The ratio for dimensions is definite and it involves the idea of modelling. A change in the force of gravity or external pressure is quite an expensive action. For the majority of gases viscosity varies very little. Thus, it is impossible to realize conditions which provide similarity of transportation processes in the model and full-scale equipment.

Since it is not possible to obtain complete similarity of the transportation processes then it is necessary to attempt to realize them partially. What is this?

Partial similarity involves the fact that we fail to achieve similarity of gas flows and we only try to obtain similarity of movement of the transported material possibly using for this dissimilar gas flows.

We formulate the main assumptions about outflow of the gas stream and its interaction with particles:

a) gas expansion in the receiver occurs adiabatically;

b) gas temperature in the receiver, collector, and channel is the same at all instants of time: $T_r(t) = T_c(t) = T(t)$;

c) outflow of gas through the nozzle grid is critical;

d) pressure (and consequently also density) of gas in the collector and pressure in the receiver is connected linearly: $P_c(t) = bP_r(t)$, $b < 1$;

e) gas pressure in the channel almost equals atmospheric;

f) in order to describe interaction of phases we use an equation applied to gas flow around a single sphere since this flow has been studied for a larger range of Re values than gas filtration through densely packed particles.

Force F operating on a particle from the direction of the gas stream has the form

TABLE 1

Test number	Equipment	V_r, liter	$P_p(0)$, MPa	P_c (maximum), MPa	b	Error in satisfying similarity condition, %		Error in determining the leading front, %	Deviation of lump movement from similarity, %
						first	second		
1	Full-scale	60	1,6	0,68	0,42	8	17	5	24
2	Model	15	1,0	0,53	0,53			13	
3	Full-scale	80	2,1	0,86	0, 41	18	1	1	12
4	Model	15	1,15	0,61	0,53			10	

$$F = C(\mathrm{Re})S_*\rho(u - w)^2, \quad \mathrm{Re} = \rho d(u - w)/\mu. \tag{4}$$

Here u, w are gas and lump velocities; d, S_* are lump characteristic size and cross sectional area.

The dependence C(Re) is given for example in [3, Fig. 7, p. 50]. We note for us the most important feature of the curve, i.e., in the range from 10^3 to $2 \cdot 10^5$ the resistance factor C is almost independent of Re;

g) gas temperature in the model and full-scale equipment is the same.

Let the gas flow out from the receiver of volume V_r and at some instant of time (we shall calculate it as zero) it has the pressure $P_r(0)$ and temperature $T_r(0)$. Here and subsequently entries in brackets indicate dependence on time (t).

Density and velocity in the critical section (i.e., at the nozzle grid) are connected with characteristics of gas in the collector by the following equations [4, p. 69] (γ is the adiabatic exponent for air):

$$\rho_n = 0{,}636\,\rho_c, \quad u_n = \left[\frac{qP_c}{\rho_c}\right]^{1/2}, \quad q = \frac{2\gamma}{\gamma + 1}. \tag{5}$$

In view of (5) and assumption d we write

$$\rho_n(t) = 0{,}636\, b\rho_r(t) = b_1\rho_r(t).$$

In view of (5) and assumptions *a* and b we find that

$$u_n(t) = \left[\frac{qP_r(t)}{\rho_r(t)}\right]^{1/2} = \left[\frac{qP_r(0)}{\rho_r^{\gamma}(0)}\right]^{1/2}\rho_r(t)^{(\gamma-1)/2}.$$

Whence for flow rate we have the expression ($n = (\gamma + 1)/2$)

$$Q(t) = b_1 S_n\left[\frac{qP_r(0)}{\rho_r^{\gamma}(0)}\right]^{1/2}\rho_r(t)^n = b_2\rho_r(t)^n. \tag{6}$$

The weight of gas in the receiver is obviously expressed in terms of density:

$$M_r(t) = \rho_r(t)V_r. \tag{7}$$

From (6) and (7) for $\rho_r(t)$ a differential equation is derived

$$\frac{d}{dt}\rho_r(t) = -\frac{b_2}{V_r}\rho_r(t)^n. \tag{8}$$

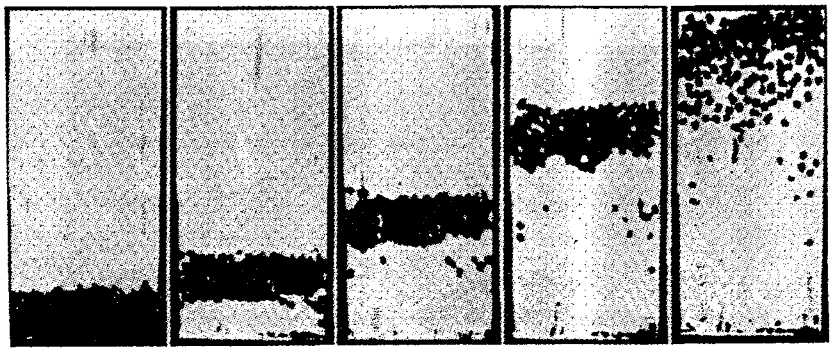

Fig. 3

For air it is possible to assume that $\gamma = 1.4$, then the solution of Eq. (8) is given by the equation

$$\rho_r(t) = \rho_r(0)\left(1 + \frac{t}{\tau}\right)^{-5}, \tag{9}$$

where $\tau = 5V_r/[b_1S_nu_n(0)]$; $u_n(0) = [(7/6)RT_r(0)]^{1/2}$; R is the gas constant for air (it equals the ratio of universal gas constant to the molar mass for air).

Gas velocity in the channel is determined from the equalities of gas flow rate in the critical section and in the chemical close to the nozzle grid:

$$u(0) = b_1\left(\frac{S_n}{S}\right)\left[\frac{\rho_r(0)}{\rho(0)}\right]u_n(0). \tag{10}$$

Conditions are derived below which should satisfy parameters of the equipment so that the gas flows obtained provide similarity of movement for the transported particles. Subsequently these conditions will be called similarity conditions.

From similarity of particle movement and equalities (1) and (2) we derive conditions which should satisfy the ratio of velocity and particle acceleration, and also characteristic times for the model and full-scale equipment:

$$\frac{w'}{w} = \left(\frac{d'g'}{dg}\right)^{1/2} = m^{1/2}, \quad \frac{a'}{a} = \frac{g'}{g} = 1, \quad \frac{\tau'}{\tau} = \left(\frac{d'g}{g'd}\right)^{1/2} = m^{1/2}. \tag{11}$$

When values depending on time for the model full-scale equipment are equal, then equality is understood not at identical instants of time, but on the corresponding time scale, i.e., instead of $a(t) = a'(t)$ we take $a(t/\tau) = a'(t/\tau')$.

From the third equality of (11), (9), and assumption g we derive the first similarity condition:

$$m^{1/2} = \frac{\tau'}{\tau} = \frac{V_r'bS_n}{V_rb'S_n'}. \tag{12}$$

From the second law of Newton for particles of the model and full-scale equipment and the second equality of (11) it follows that $F'/(\rho_*'V_*') = g' + a' = g + a = F/(\rho_*V_*)$.

By using (1), (2), (4), and the fact that S_* and V_* are proportional to d^2 and d^3 respectively, this equality leads to the form

Let gas velocity for the model and full-scale equipment satisfy similarity conditions (11):

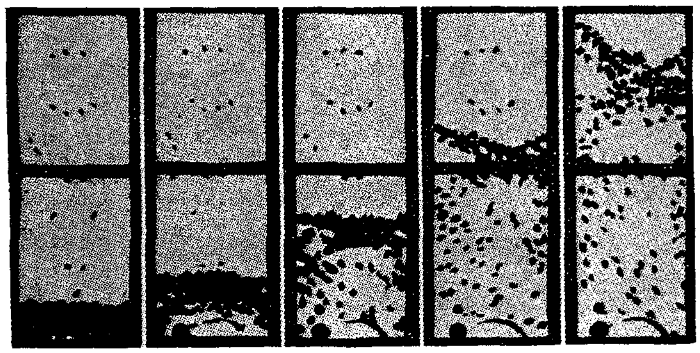

Fig. 4

$$C(\mathrm{Re})(u - w)^2\rho'_* m = C(\mathrm{Re}')(u' - w')^2\rho_*. \tag{13}$$

$$\frac{u'}{u} = m^{1/2}. \tag{14}$$

Then taking account of assumption f for satisfaction of equality (13) in a certain range of Re values it is sufficient to take for the model and full-scale equipment particles of the same density.

From (1), (2), (10), (14) and assumption g we have the second similarity condition:

$$m^{5/2} = \frac{S'_r b' P'_n(0)}{S_r b P_n(0)}. \tag{15}$$

In order to check these modelling conditions two transparent geometrically similar equipments were prepared. The dimensions of the full-scale equipment were 8 × 76 × 200 cm. The nozzle grid is uniformly placed nozzles with diameter 0.18 cm and with an overall area of 8.26 cm^2. The dimensions of the model are half as much, nozzle dimensions are retained, and their number is reduced by a factor of four.

Oak cylinders with height equal to the diameter (4 cm for the full-scale equipment and 2 cm for the model) were used as lumps. In each experiment 230 lumps were loaded into the channel.

Gas from the receiver started to enter the collector after switching on the electromagnetic valve.

In the experiments a record was made of initial pressure in the receiver by a manometer and also there was a record of static pressure in the collector (Figs. 1 and 2, transducer 1), and for the model also in the channel (Fig. 1, transducers 2 and 3 placed in the lower and upper parts of the channel).

Signals from strain-gage transducers entered an amplifier and then galvanometers of an oscillograph.

In the measurements each transducer used the same cable, amplification channel, oscillograph and galvanometer channel as during calibration. The process of lump movement in the channel was recorded on film with a high-speed cine-camera.

Synchronization of the time for gas supply from the receiver with processes on the cine-film was carried out by simultaneous switching of the electromagnetic valve and the mark generator recorded on film.

A series of experiments was performed in these models with different parameters (the receiver volume and the initial gas pressure in it was varied).

Given below is the substantiation of the assumptions a-f:

a) the characteristic flow time for the process is 1 sec and therefore heat exchange between the gas and walls may be ignored;

b) according to [5, p. 107] with adiabatic outflow gas velocity in the channel is connected with its temperature at rest by the equation

As experiments show, gas velocity nowhere exceeds 50 m/sec. Then according to Eq. (16) the change in temperature is not more than 1.25°C (about 0.4% of its value);

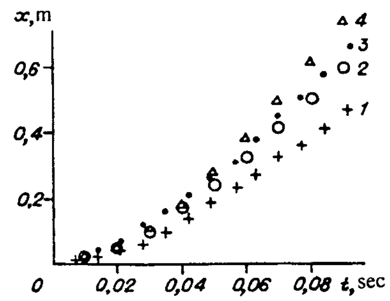

Fig. 5

$$T_p - T = 5 \cdot 10^{-4} u^2. \quad (16)$$

c) as can be seen from pressure oscillograms (Figs. 1 and 2), particles manage to travel the channel with a pressure difference in the collector and the channel providing critical outflow from the nozzle grid;

d) coefficient b remains constant with a constant receiver volume and a change in initial pressure in it. With an increase in receiver volume coefficient b increases, and this dependence is stronger if the volume of the supply line equals the receiver volume;

e) this assumption is confirmed by pressure oscillograms recorded from transducers 2 and 3;

f) values of Re realized in the test are within the limits from $4 \cdot 10^3$ to $7 \cdot 10^4$, and within these limits the resistance factor in (4) remains constant.

Thus, all of the assumptions concerning outflow of gas from the receiver into the channel are fulfilled; consequently it is possible to expect similarity of particle movement.

It is necessary to indicate one more implicit assumption with respect to lump movement, i.e., about the unidimensional nature of movement. With the same initial conditions movement of lumps may occur differently since the distribution of lumps on the grid is a random value and it cannot coincide in two different tests.

In Figs. 3 and 4 lump movement is demonstrated in the full-scale and model equipment respectively. The first photograph shows the position of lumps at the zero instant of time, and each of the following show it at instants of time greater by 0.025 sec than the preceding one (time is reckoned in the model scale, and the zero instant relates to the start of lump movement).

Given in Table 1 are the results of those tests in which similarity conditions were precisely satisfied.

Shown in Fig. 5 is movement of the particle leading front. Acceleration time t and the path x travelled by lumps are given in the scale of the model, and numbers 1-4 correspond to the test number in Table 1.

Since possible values of volumes are discrete and coefficient b depends on receiver volume, then similarity conditions were satisfied with a certain error. In view of the fact that lump movement is not unidimensional, particularly in the model, a significant error was permitted in determining the position of the leading front. A rough guide may be the greatest pressure in the collector, i.e., the greater the pressure, the more rapidly lumps should accelerate (here all of the values should be taken on one scale). A similar picture was observed in all tests apart from when $V_r = 10$ liters. On the whole it is possible to conclude that deviation from similarity in lump movement does not exceed deviation from similarity in the initial test conditions and measurement errors, which can be seen from Table 1.

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