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ON THE QUESTION OF BULK MATERIALS PNEUMATIC CONVEYING THROUGH HORIZONTAL PIPES DESIGN METHODS

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The paper presents the scientifically based calculations for the dependences of the basic parameters for the pneumatic transportation of disperse solid materials in horizontal straight pipelines - a critical velocity of airflow and a specific pressure gradient. The physical models are described which represent the basis of the method for calculation of the above parameters of transportation. The results are presented on the comparison of computational and experimental data in a wide range of the pneumatic transport conditions

INTRODUCTION

Pneumatic pipeline conveying of bulk materials is widely used in different spheres of industry, particularly, in thermal engineering while coal dust delivery to fireboxes and ash removal; rail and ship transport while grains, cement, sand and other bulk materials reloading; metallurgy and chemical industry wastes management, in grain processing companies and others.

For pneumatic conveying systems engineering and assurance of their operation reliability and efficiency, science-based methods of the systems aerodynamic design, developed on the basis of special theoretical and experimental researches of gas suspension flows in pipes are required.

At present time gas suspension flows fundamental researches are conducted in three areas: turbulence researches [1-5]; research of physical mechanism of solids motion while pneumatic conveying [6-9]; study of integral parameters – pressure drop along the pipe length and pneumatic conveying critical velocity [10-20].

While pressure drops researching, special attention is paid to friction hydraulic resistance studying while stable pneumatic conveying through straight horizontal pipes as gas suspension flows dynamic and kinematic structures in pipes of this type are more complex than those in vertical ones. In addition it is considered that the pressure drop in the pipe working part ends is small versus the pressure in the initial section of the part. It enables to consider the working part of the pipe as relatively short and the gas (air) as an incompressible medium [21]. In case with long pipelines when the air compressibility cannot be neglected, the pipeline is conditionally divided into short parts and the pressure loss is measured in each single part without considering the compressibility; afterwards the results are summed up along the whole pipeline length.

Review of works on pressure drop ΔP_m study while pneumatic conveying through horizontal pipes allows concluding that most of the suggested designed dependences for ΔPm value determination come to one of the following two formulas:

$$\Delta P_m = \left(1 + B_1 \cdot \alpha_m\right)\lambda \frac{L}{D}\frac{\rho U^2}{2} \qquad (1)$$

or

$$\Delta P_m = \left(\lambda + B_2 \cdot \alpha_m\right)\frac{L}{D}\frac{\rho U^2}{2}, \tag{2}$$

where L – pipe design part length;

D – pipe inner diameter;

ρ – air density, U and λ – mean velocity and hydraulic friction coefficient while air motion;

α_m – mass concentration equal to the ratio of bulk material mass flow rate to the air mass flow rate;

B_1 and B_2 – empirical coefficients considering solids influence on ΔP_m value. Let us mention the experimental data on B_1 and B_2 coefficients given in the scientific literature is multivarious thus there are some difficulties in choosing these coefficients while ΔP_m pressure drop design for any given particular conditions of pneumatic conveying.

Depending on the air flow mean velocity pneumatic conveying modes are distinguished into stable (without the pipe lower wall siltation) and unstable (with the pipe lower wall siltation). The mode, dividing pneumatic conveying stable and unstable modes, is called critical and the air flow mean velocity U_{cr} corresponding with it – the critical velocity of pneumatic conveying. By now a range of empiric formulas for the critical velocity estimation has been suggested, the scope of which is limited as a rule by the experimental conditions while which the formulas were obtained. In addition the values of the empiric coefficients being part of the formula can change within quite a wide range. For example in [20] the following formula is recommended

$$U_{cr} = b\sqrt{\alpha_m a g D}, \tag{3}$$

$$a = \frac{\rho_s}{\rho} - 1, \tag{4}$$

where g – acceleration of gravity;

ρ_s – solids density;

b – empiric coefficient the value of which differs within the range of 0,15 – 0,3 and more and it's unknown what the coefficient depends on.

Thus limitation and in some cases unacceptably low accuracy degree of the suggested dependences for the determination of the pressure drop and critical velocity while pneumatic conveying and a great variety of pneumatic conveying conditions in practice do not always allow choosing the design formula corresponding with the conditions of the given engineering object. Hence the development of ΔP_m and U_{cr} integral parameters generalized scientifically proven design methods suitable for practical application within the wide range of pneumatic conveying conditions change is quite important. Such design methods are developed by the article authors and published particularly in [22, 23]. They are obtained on the basis of the defined physical models of gas suspensions motion through pipes with the use of experimental material. However after having published the design methods, the authors collected more experimental material on pneumatic conveying and conducted their own experimental researches. That is why the prime object of the present article is ΔP_m and U_{cr} developed design methods approbation on the basis of wide experimental material for the purpose of the methods reliability degree determination.

Specific pressure drop $\Delta P_m/L$ (per unit of the pipe length) and critical velocity U_{cr} design theory is summarized below then the corresponding design dependences are written out, the characteristics of bulk materials and pipes used in the experiments are described, the results of the comparison of the designed values of $\Delta P_m/L$ and U_{cr} with the corresponding experimental values are given.

1. SPECIFIC PRESSURE DROP

For specific pressure drop determination the Bernoulli's equation for settled incompressible two phase medium flow [24] is used. In case of isothermal gas suspension motion as an incompressible medium the Bernoulli's equation presented in the form of pressures is as following:

$$\rho_e \frac{U_m^2}{2} + P + \mathrm{Z} + E = \mathrm{const}, \tag{5}$$

$$\rho_e = \rho\beta \frac{\left(1-C_p\right)^3}{\left(1-C\right)^2} + \rho_s\beta_s \frac{C_p^3}{C^2}, \tag{6}$$

$$C_p = \frac{Q_s}{Q+Q_s}, \tag{7}$$

where ρ_e and U_m – effective density and gas suspension mean velocity about the flow cross section;

P_m – pressure;

Z – flow cross section mass centers mark against the plane of reference;

C and C_p – solids mean volume and expendable concentrations about the flow cross section;

$Q,\ Q_s$ – air and solids volume flow rate;

β and β_s – Coriolis coefficients for the gas and solid phase flows.

From the physical standpoint the Bernoulli's equation parts are specific mechanical energy within the specified flow cross section i. e. the energy related to the gas suspension volume unit, the value E in (5) is waste specific energy consumed for hydraulic resistance force overcoming.

In case with the settled steady gas suspension motion through a horizontal pipe specific kinetic and potential energies of position are permanent in all the cross sections of the pipe. In this case writing the Bernoulli's equation (5) for any two cross sections 1–1 and 2–2 and taking into account the basic hydraulic equation of the settled steady motion of the incompressible medium through a round pipe we obtain:

$$(P_m)_1 - \left(P_m\right)_2 = E = \frac{4_{\tau 0}}{D} L, \tag{8}$$

where $(P_m)_1$ and $\left(P_m\right)_2$ – pressure in the sections 1–1 and 2–2 respectively;

τ_0 – mean shear stress along the pipe cross section perimeter;

L – the distance between the sections 1–1 and 2–2 or the same as – the length of the design pipe part.

The value $\tau 0$ is assumed as a rule as proportional to the flow specific kinetic energy. In case with a gas suspension the flow kinetic energy is presented by the first component of the Bernoulli's equation (5) that is why the expression for τ_0 can be written down the following way:

$$\tau_0 = \frac{\lambda_m}{4} \cdot \rho_e \cdot \frac{U_m^2}{2}, \tag{9}$$

where λ_m – hydraulic friction coefficient while pneumatic conveying.

Having replaced the Coriolis coefficients β and β_s included in (6) by their mean value $\beta_m = \frac{1}{2}\left(\beta + \beta_s\right)$, substituted (6) to (9) then replaced the value τ0 in (8) by its expression (9) and denoted the pressure drop $(P_m)_1 - (P_m)_2$ with the symbol ΔP_m we will obtain:

$$\Delta P_m = \left[\rho \frac{\left(1-C_p\right)^3}{\left(1-C\right)^2} + \rho_s \frac{C_p^3}{C^2}\right] \beta_m \lambda_m \cdot \frac{L}{D} \frac{U_m^2}{2} \tag{10}$$

or having divided both parts of the equation (10) by L,

$$\frac{\Delta P_m}{L} = \left[\rho \frac{\left(1-C_p\right)^3}{\left(1-C\right)^2} + \rho_s \frac{C_p^3}{C^2}\right] \beta_m \lambda_m \cdot \frac{1}{D} \frac{U_m^2}{2}. \tag{11}$$

The equation (11) is transformed to the form

$$\frac{\Delta P_m}{L} = \left[\frac{\left(1-C_p\right)^3}{\left(1-C\right)^2} + \bar{\rho}_s \frac{C_p^3}{C^2}\right] \frac{\bar{\lambda}_m}{\left(1-C_p\right)^2} \cdot \frac{\Delta P}{L}; \tag{12}$$

$$\bar{\rho}_s = \frac{\rho_s}{\rho}, \tag{13}$$

$$\bar{\lambda}_m = \frac{\beta_m \lambda_m}{\lambda}, \tag{14}$$

$$\frac{\Delta P}{L} = \lambda \rho \frac{U^2}{2D}, \tag{15}$$

where $\lambda -$ hydraulic friction coefficient for the air moving through the pipe with the diameter D at the mean velocity $U = Q/F$;

F – pipe cross section area;

$\Delta P / L$ – specific pressure drop while the air motion.

Thus a scientifically proven common expression for specific pressure drops while pneumatic conveying through horizontal pipes (12) is obtained on the basis of the Bernoulli's equation for the two phase flow. The value $\bar{\lambda}_m$ included into (12) is determined as a result of the experimental data on $\Delta P_m / L$ measurement processing.

While $\bar{\lambda}_m$ determining it is found out that bulk materials pumped through pipes by air flow should be divided into two categories: fine and coarse disperse. Milled powdered solids the mean size d_s of which does not exceed as a rule 100 micron and the Reynolds number $\mathrm{Re}_s = d_s W_s / \nu \le 6$, where $W_s -$ terminal velocity; $\nu -$ air kinematic viscosity belong to fine disperse materials. Particularly cement, ash, coal dust, ferrous and nonferrous metal ores concentrates refer to these materials. Mixture flows of air and milled bulk materials are called dust-laden as a rule. The characteristic feature of them is that while stable pneumatic conveying the solids averaged volume concentration is almost evenly distributed about the pipe cross section and mean concentrations of C and C_p are so close to each other that can be taken equal.

It is found out for dust-laden flows the value $\overline{\lambda}_m < 1$ at $\mathrm{Re}_s < 6$ and mean velocities of the air flow close or equal to the critical velocity and within the limits $\mathrm{Re}_s \to 6$ or $U \to \infty$ the value $\overline{\lambda}_m \to 1$. At that, the inequality $\overline{\lambda}_m < 1$ can result from turbulence suppression provided milled suspension presence in the air flow.

Then the parameter α (the suspension and gas volume flow rate concentrations ratio) is used

$$\alpha = \frac{C_p}{1 - C_p}. \tag{16}$$

The parameter can be expressed in terms of regularly set values G_s, Q and ρ_s, where G_s – solids mass flow rate. In this case we have

$$\alpha = \frac{G_s}{\rho_s Q}. \tag{17}$$

From the equation (16) we obtain

$$C_p = \frac{\alpha}{1 + \alpha}. \tag{18}$$

The equation (12) is transformed, taking into account the expression (17) and the approximate equality of $C = C_p$, to the form

$$\frac{\Delta P_m}{L} = \overline{\lambda}_m \left[1 + \left(\overline{\rho}_s - 1 \right) \frac{\alpha}{1 + \alpha} \right] \left(1 + \alpha \right)^2 \cdot \frac{\Delta P}{L}. \tag{19}$$

In case with dust-laden flows the empiric dependence for $\overline{\lambda}_m$ takes the form:

$$\overline{\lambda}_m = \overline{\lambda}_{cr} \left[1 + \left(0,43 + 0,19\,\mathrm{Re}_s \right) \left(1 - \frac{U_{cr}}{U} \right)^2 \right], \tag{20}$$

$$\overline{\lambda}_{cr} = \left[1 - \left(1 - \varphi \right) th \left(47,16\sqrt{\alpha_{cr}} \right) \right] + \left(1 + \alpha_{cr} \right)^{-2}, \tag{21}$$

$$\varphi = 0,127 + \left(1 + 1,016\,\mathrm{Re}_s \right) 0,022\,\mathrm{Re}_s, \tag{22}$$

where α_{cr} – the value of α at $Q = Q_{cr}$.

The dependences (20) – (21) scope is limited by the values $0,0002 \le \alpha \le 0,1$; $U \ge U_{cr}$, $\mathrm{Re}_s \le 6$, $d_s \le 100$ micron.

Coarse disperse materials are bulk materials with the particles mean size $d_s \le 100$ micron and $\mathrm{Re}_s > 6$. While coarse disperse materials pneumatic conveying through horizontal pipes, solids averaged local volume concentration is unevenly distributed about the pipe vertical diameter as a result of which the field of gas suspension motion averaged velocities is characterized by axial asymmetry. In this case as opposed to dust-laden air flows, C and C_p concentrations are not equal, i. e. $C \ne C_p$, gas suspension hydraulic friction coefficient $\lambda_m > \lambda$, and thus the value $\overline{\lambda}_m > 1$ at $\mathrm{Re}_s > 6$, and air flows mean velocities close or equal to the critical velocity and $\overline{\lambda}_m \to 1$ at $\mathrm{Re}_s \to 6$ or $U \to \infty$.

For the determination of mean volume concentration C it is recommended to use the semiempirical algebraic equation, obtained in the sphere of bulk materials hydraulic conveying researches [24]:

$$C\left[1-f_p\left(1-\frac{C}{C_{\max}}\right)^{2,16}\left(\frac{U_{cr}}{U}\right)^{1,66}\right]=C_p, \tag{23}$$

$$f_p=0,45\left[1+signx_p\cdot th\left(0,967\left|x_p\right|^{0,6}\right)\right], \tag{24}$$

$$x_p=\lg \mathrm{Re}_s-0,88, \tag{25}$$

where $C_{\max}$ – limit possible volume concentration. The value C_p in (23) is determined by formula (18) and considered known while pneumatic conveying design.

In case of coarse disperse materials pneumatic conveying the specific pressure drop is estimated by formula (12), the concentration C is determined by solving the equation (23) and the parameter $\overline{\lambda}_m$ is determined by the empiric dependence:

$$\overline{\lambda}_m=\overline{\lambda}_{cr}\left(1-A\cdot th\left[1,276\left[1-\frac{U_{cr}}{U}\right]\cdot\lg \mathrm{Re}_s\right]\right), \tag{26}$$

$$\overline{\lambda}_{cr}=1+0,667\left(\lg\frac{\mathrm{Re}_s}{6}\right)^{1,94}\cdot th\left(93\alpha_{cr}^{0,8}\right), \tag{27}$$

$$A=th\left[a\left(\overline{\lambda}_{cr}-1\right)^{0,707}\right], \tag{28}$$

$$a=1,875-0,44\lg \mathrm{Re}_s. \tag{29}$$

The dependence (26) is determined within $6<\mathrm{Re}\le 3200$, $U\ge U_{cr}$, $d_s>100$ micron.

2. FLOW CRITICAL VELOCITY

As stated in [24] the only condition determining the critical mode of solid disperse materials hydraulic conveying through horizontal pipes is the equality of averaged shear stress on the pipe lower wall while solids and fluid mixture stable motion and averaged sliding friction force of solids with the pipe lower wall. The analogous condition also determines the critical mode of bulk materials pneumatic conveying as it physically expresses limit dynamic balance between the gas suspension flow and solids continuous flow, moving near the pipe lower wall. Taking into account the condition, the algebraic equation for determination of the critical velocity of the air motion while pneumatic conveying, is obtained.

$$\overline{\lambda}_{cr}\left[1+\left(\overline{\rho}_s-1\right)\frac{\alpha_{cr}}{1+\alpha_{cr}}\right]\left(1+\alpha_{cr}\right)^2\lambda_{cr}\frac{U_{cr}^2}{2gD}=\left(\overline{\rho}_s-1\right)\cdot K_1, \tag{30}$$

$$K_1=\beta_1\alpha_{cr} \tag{31}$$

at $0<\alpha_{cr}<0,04$;

$$K_1=\beta_1\cdot 0,04+\beta_2\left(\alpha_{cr}-0,04\right) \tag{32}$$

at $0,04<\alpha_{cr}<0,1$; for fine disperse solids

$$\overline{\lambda}_{cr}\left[\frac{\left(1-C_{p,cr}\right)^3}{\left(1-C_{cr}\right)^2}+\overline{\rho}_s\frac{C_{p,cr}^3}{C_{cr}^2}\right]\frac{\lambda_{cr}}{\left(1-C_{p,cr}\right)^2}\frac{U_{cr}^2}{2gD}=\left(\overline{\rho}_s-1\right)\cdot K_2, \tag{33}$$

$$K_2=0,313\alpha_{cr}^{0,6}\cdot th\left(17,27\beta_3\right) \tag{34}$$

for coarse disperse solids

The coefficients β_1 and β_2 in (31) and (32) and β_3 in (34) depend upon the diameter ratio d_s / D.

The equations (29) and (32) are solved by numerical or graphical method and G_s, $\overline{\rho}_s$, Re_s, d_s, v, D are considered given at that. In case of graphical solution of the equation (30), for example, several approximate values of the critical velocity $U_{cr,i}(i=1,2,3...)$ are given. Then the corresponding air consumption is determined $Q_{cr,i}=U_{cr,i}\cdot\pi D^2/4$ following which the corresponding values $\alpha_{cr,i}, C_{p,i}$ and $\overline{\lambda}_{cr,i}$ are estimated by the formulas (17), (18), (21) and $\lambda_{cr,i}$ is determined. At that $\lambda_{cr,i}$ coefficients are estimated by ordinary hydraulic formulas depending on the variation range of the Reynolds number $Re_i = DU_{cr,i}/\nu$ for the air flow: hydraulically smooth pipes area, transition area, hydraulically rough pipes area. Having denoted the left part of the equation (30) by F_1 and the right one by F_2, the graphs of F_1 and F_2 functions dependence of $U_{cr,i}$ are plotted. The absciss of the graphs intersection point corresponds with the target value of the critical velocity U_{cr} for the pneumatic conveying specified conditions.

Thus scientifically proven pressure drop and flow critical pneumatic conveying velocity design methods are summarized above. Let us proceed to considering the question of the design methods reliability.

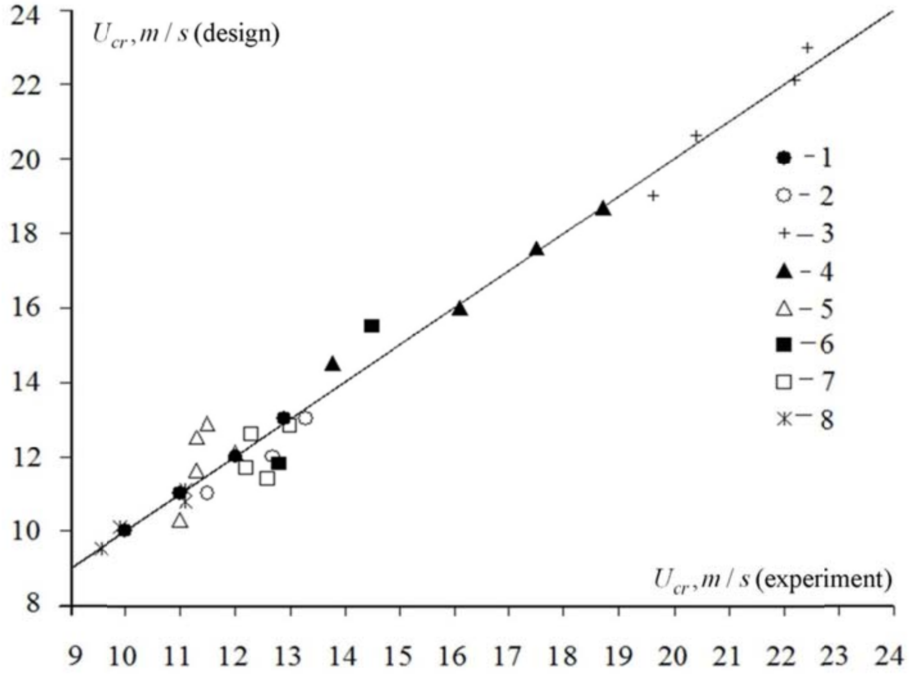

Figure 1 – Comparison of pneumatic conveying critical velocities designed and experimental values: 1 – cement; 2 – ash; 3 – coal; 4 – iron ore concentrate; 5 – styropor; 6 – polystyrene; 7 – soybean; 8 – bran

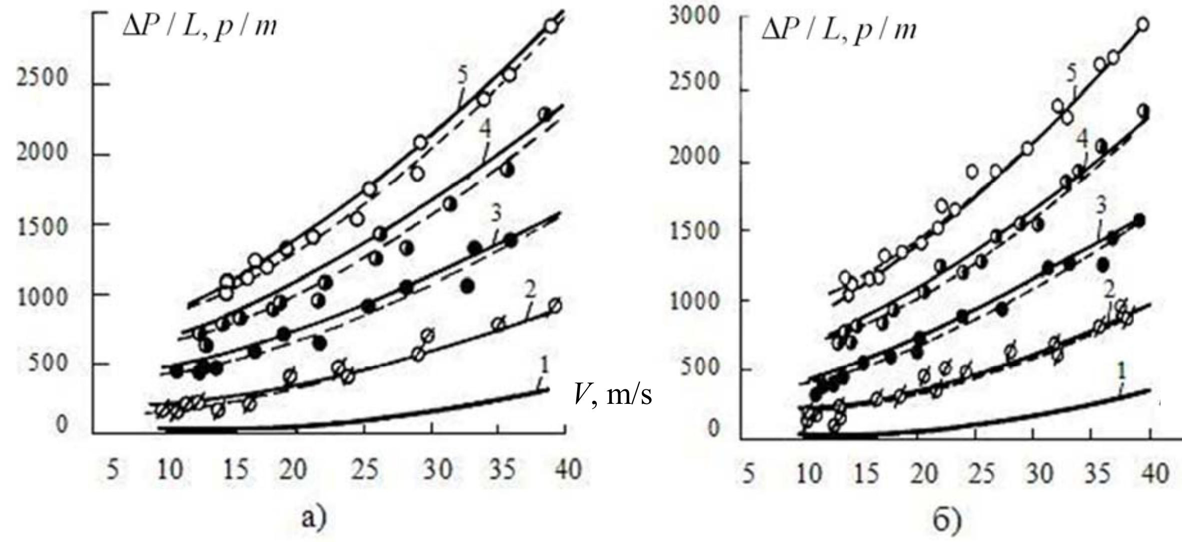

Figure 2 – The V dependence of $\Delta P_m / L$: *a* – cement; *b* – ash (dots experimental values; dashed line – averaged experimental curves; continuous line – design):
1 – G_s = 0 kg/hour; 2 – G_s = 5000 kg/hour; 3 – G_s = 10000 kg/hour; 4 – G_s = 15000 kg/hour;
5 – G_s = 20000 kg/hour

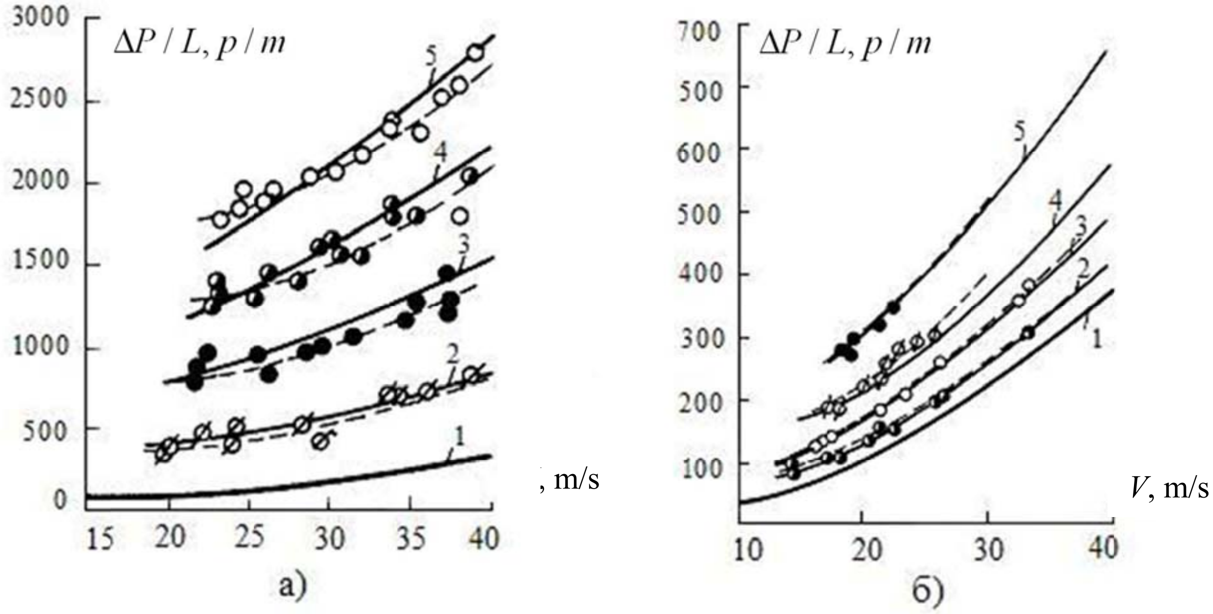

Figure 3 – The V dependence of $\Delta P_m / L$: *a* – coal dust; *b* – iron ore concentrate
(dots – experimental values; dashed line – averaged experimental curves; continuous line – design):
a: 1 – G_s = 0 kg/hour; 2 – G_s = 5000 kg/hour; 3 – G_s = 10000 kg/hour; 4 – G_s = 15000 kg/hour;
5 – G_s = 20000 kg/hour;
b: 1 – G_s = 0 kg/hour; 2 – G_s = 250 kg/hour; 3 – G_s = 500 kg/hour; 4 – G_s = 750 kg/hour;
5 – G_s = 1350 kg/hour

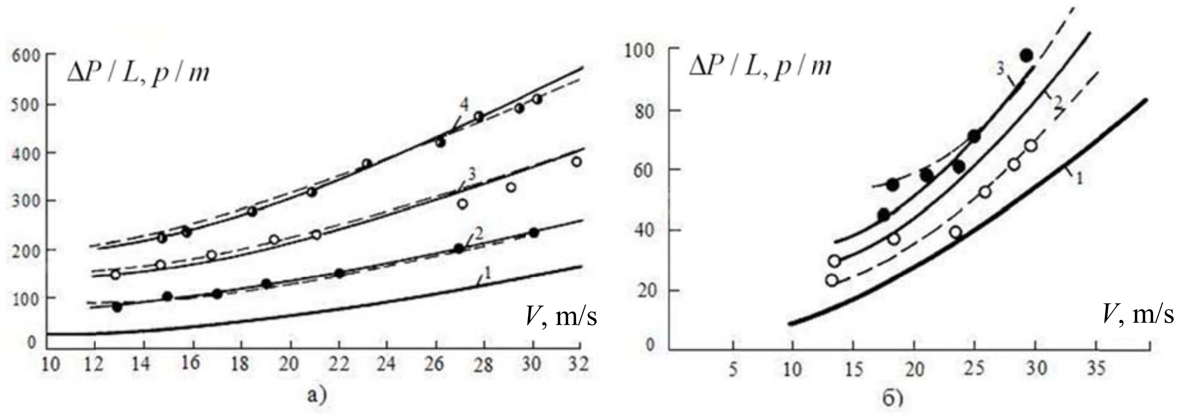

Figure 4 – The V dependence of $\Delta P_m / L$:
a – styropor; *b* – polystyrene (dots – experimental values; dashed line – averaged experimental curves; continuous line – design):
a: 1 – $G_s = 0$ kg/hour; 2 – $G_s = 251$ kg/hour; 3 – $G_s = 743$ kg/hour; 4 – $G_s = 1244$ kg/hour
b: 1 – $G_s = 0$ kg/hour; 2 – $G_s = 228$ kg/hour; 3 – $G_s = 380$ kg/hour

3. RELIABILITY of $\Delta P_m / L$ and U_{cr} DESIGN METHODS

For the reliability determination of the methods under consideration the experimental material of $\Delta P_m / L$ and U_{cr} parameters measurement, corresponding with the wide range of pneumatic conveying conditions change is used. Experimental data is generally taken from literary sources. In addition own experimental researches of U dependence of $\Delta P_m / L$ while sand and gravel pneumatic conveying were conducted.

At the same time we will describe the laboratory facility used for conducting researches of sand and gravel pneumatic conveying. It comprised a steel horizontal pipe with the length of 8 m and the inner diameter of 25,4 mm, an exhauster working for suction, arranged at the end of the pipe and a measuring hopper for supplying bulk material into the pipe. The pipe work part length where the pressure drop was measured was 2 m. At the ends of this pipe part, there were pressure samplers connected with the differential manometer by means of flexible hoses. The pressure fluid was water. The Venturi pipe, equipped with a differential manometer, the tubes of which were filled with water, was used for the air consumption and mean velocity measuring. The air consumption was regulated by the ball valve, arranged at the end of the pipe in front of the exhauster. Both differential manometers used for pressure drop and air mean velocity measurement were arranged below the pipe.

The air flow mean velocity was determined by formula

$$U = \mu \frac{\left(\frac{d_0}{D}\right)^2}{\sqrt{1-\left(\frac{d_0}{D}\right)^2}} \sqrt{2g\Delta h_u \cdot \frac{\rho_w}{\rho}}, \tag{35}$$

where μ – calibration coefficient;

d_0 – the Venturi pipe throat diameter;

Δh_u – differential manometer heights drop;

ρ_w – water density; for the given Venturi pipe the parameter $\left(\frac{d_0}{D}\right)^2 = 0,62$.

Specific pressure drop in the pipe work part is estimated by formula

$$\frac{\Delta P_m}{L} = \frac{\Delta h_p}{L} \cdot g \cdot \rho_w \tag{36}$$

where Δh_p – differential manometer heights difference.

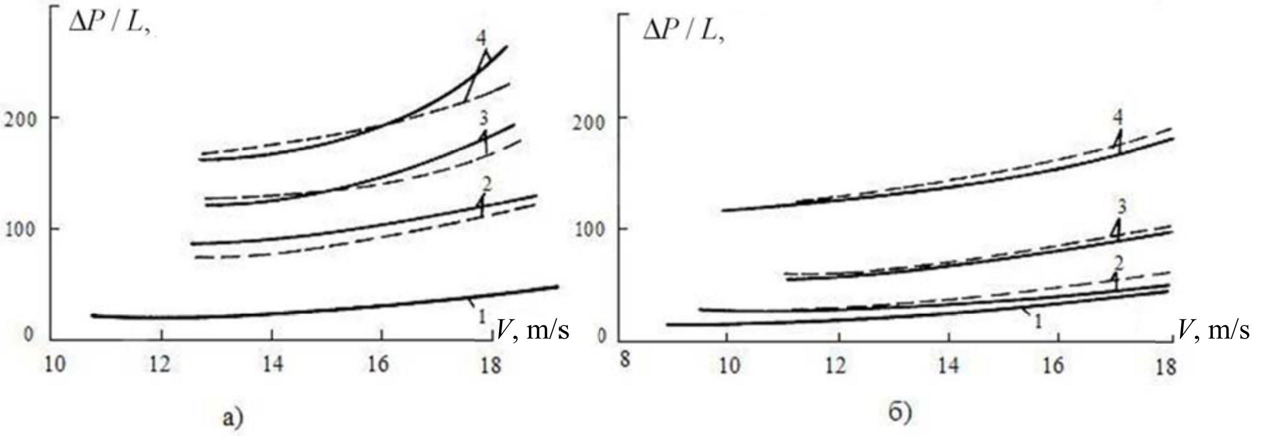

Figure 5 – The *V* dependence of $\Delta P_m / L$; a — soybean; *b* – bran (dashed line — experimental curves; continuous lines – design);
a: 1 – G_s = 0 kg/hour; 2 – G_s = 540 kg/hour; 3 – G_s = 1080 kg/hour; 4 – G_s = 1800 kg/hour
b: 1 – G_s = 0 kg/hour; 2 – G_s = 360 kg/hour; 3 – G_s = 1440 kg/hour; 4 – G_s = 3600 kg/hour

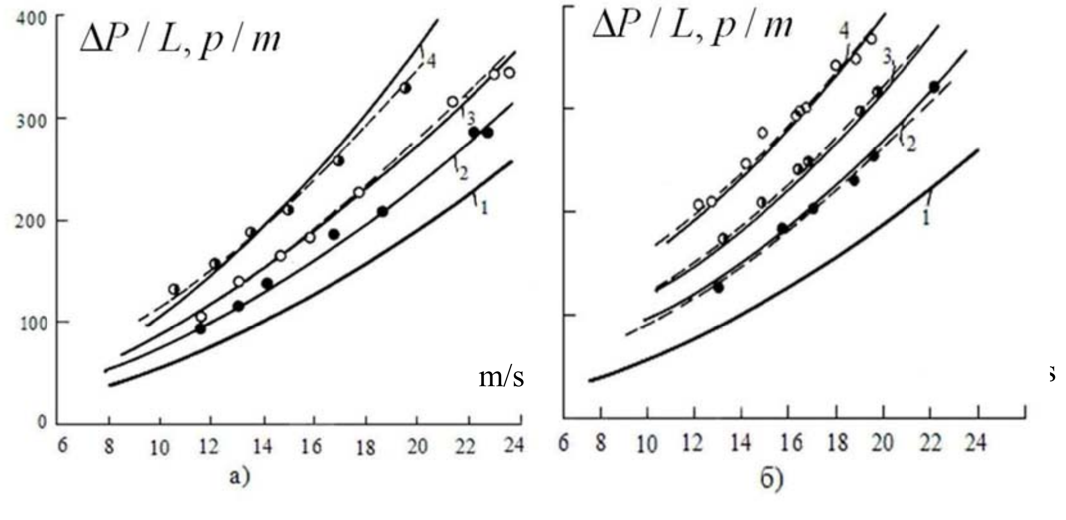

Figure 6 – The *V* dependence of $\Delta P_m / L$; a — sand; b – gravel (dots – experimental values; dashed line – averaged experimental curves; continuous line – design);
a: 1 – G_s = 0 kg/hour; 2 – G_s = 25,2 kg/hour; 3 – G_s = 43,56 kg/hour; 4 – G_s = 95 kg/hour
b: 1 – G_s = 0 kg/hour; 2 – G_s = 31,9 kg/hour; 3 – G_s = 54,97 kg/hour; 4 – G_s = 97,6 kg/hour

Three sets of experiments were conducted. A hydraulic test for the hydraulic friction coefficient determination, while air motion in the pipe, was conducted during the first set. For this purpose the exhauster was turned on and operating in the suction mode. While operating, the height drops Δh_u and Δh_p, corresponding with the different degrees of the flow cross section overlapping by the ball valve, were measured simultaneously, then the values U and $\Delta P / L$ were determined by the corresponding formulas (35) and (36). The hydraulic friction coefficient λ values were estimated according to the above mentioned measured values. As a result it was determined that under the conditions of this experiment the hydraulic friction coefficient follows the law

$$\lambda = \frac{0,2122}{\mathrm{Re}^{0,2267}}, \tag{37}$$

where the Reynolds number $\mathrm{Re} = UD / \nu$; while its determination the air kinematic viscosity was taken equal: $\nu = 1,5 \cdot 10^{-6}\,\mathrm{m}^2/\mathrm{s}$.

Table 1. Bulk materials characteristics and pipe parameters

No.	material name	d_s, mm	ρ_s, kg/m^3	W_s, cm/s	Re_s	G_s, kg/hour	D, mm	literary source
fine disperse solids								
1	cement	0,021	3060	4,08	0,057	5000–20000	50	[19]
2	ash	0,023	2400	3,84	0,059	5000–20000	50	[19]
3	coal dust	0,05	1600	12,1	0,40	5000–20000	50	[19]
4	iron ore concentrate	0,08	4500	49,3	2,63	250–1350	51	[18]
coarse disperse solids								
5	sand	0,37	2650	223	55	25,2–95,1	25,4	–
6	bran	1	1000	286	190	365–2700	80	[17]
7	gravel	1,23	2700	561	460	31,9–97,6	25,4	–
8	styropor	2,385	1050	499	793	251–1244	52,6	[13]
9	polystyrene	5	595	498	1660	228–380	100	[13]
10	soybean	7	1100	677	3162	540–3600	80	[17]

During the second set of experiments, the air motion mean velocities and the specific pressure drops corresponding with them while sand pneumatic conveying with the specified mass flow rate were measured at different degrees of flow cross-section overlapping by the ball valve. The third set of researches is analogues to the second one and deals with gravel pneumatic conveying. In the second and the third sets of experiments the critical velocity was not studied.

The names, characteristics, mass flow rates of the several most typical bulk materials, pipe diameters used in experimental researches of pneumatic conveying and literary sources containing measurement results used for the $\Delta P_m / L$ and U parameters design methods reliability check are given in the table.

For the possible comparison of $\Delta P_m / L$ and U_{cr} parameters designed and experimental values, for every individual case, the hydraulic friction law while air motion in the pipe used in the experiment was determined first of all. At that the air density was taken equal $\rho = {}^{1}\!/_{2}\,\mathrm{kg/m}^3$ that corresponds with the standard conditions, i. e. the pressure P = 101,3 kPa and T = 293 K or $t = 20^\circ$ C. The air dynamic viscosity was taken equal $1{,}8 \cdot 10^{-6}$ Pa·s.

While the critical velocity design method reliability determination this velocity was determined, on one side, experimentally as corresponding with the minimum curve of U dependence of $\Delta P_m / L$ and on the other side – estimated on the basis of the design method for the specified experimental conditions.

The comparison results of U_{cr} experimental and designed values are given in fig. 1. One can see that all the dots are grouped in proximity to the coordinate angle bisector. The arithmetic mean relative deviation of U_{cr} design values from the experimental ones is 3,4 % being within the flow mean velocity measurements accuracy, proving the reliability of the developed methods of pneumatic conveying critical velocity design.

For the specific pressure drop design method reliability determination the values $\Delta P_m / L$ were estimated in the critical and supercritical pneumatic conveying modes within the range of mean velocities $U \geq U_{cr}$ change, corresponding with this experiment. The estimation results are shown in fig. 2*, a, b* as continuous curves.

In the figures dots stand for specific pressure drops experimental values and dashed lines – averaged experimental values, obtained by least square method. As it comes from the figures the design curves of U dependence of $\Delta P_m / L$ adequately agree with the corresponding experimental curves within the $\Delta P_m / L$ value measurement errors. This proves the reliability of the developed specific pressure drops design method within the wide range of pneumatic conveying conditions change.

CONCLUSION

The reliability study results of the air flow critical velocities and specific pressure drops design methods developed by the article authors are given above. It is determined that within the wide range of pneumatic conveying conditions (0,021 mm $\leq d_s \leq$ 7 mm, 1000 kg/m^3 $\leq \rho_s \leq$ 4500 kg/m^3, 25 kg/hour $\leq G_s \leq$ 20000 kg/hour, 25,4 mm $\leq D \leq$ 100 mm) change mean relative deviations of the $\Delta P_m / L$ and U_{cr} parameters design values from the corresponding experimental ones are within the parameters accuracy, proving a high enough reliability degree of the developed design method.

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