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DESIGN TECHNIQUE OF THE PNEUMOTRANSPORT CRITICAL REGIME AT MINOR DIFFERENTIAL PRESSURE

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Abstract

The design technique parameters of the pneumotransport critical regime at minor differential pressure is worked out. The design technique is illustrated.

Keywords: pneumotransport, aerodynamic calculation, pneumotransporting critical regime

Solid dispersed materials pumping through pipelines by means of air flow is widely used in all fields of industry. But the reliability and the effectiveness of the pneumotransport installation work depends generally on the design data of the main pneumotransporting parameters chosen at the installation design stage. One of the main pneumotransport parameters is the critical velocity of the air flow. At this velocity solid particles fall out on the bottom of the horizontal pipe wall, and the pipeline blockage begins. It is evident that the reliable design technique of the pneumotransport installation critical regime is necessary for the insurance of the stable work.

Many design functions for defining the pneumotransporting critical velocity have been known by present time [1, 2]. But they are of empirical character and the fields of their application are limited by the experiment conditions. Limitation and in some cases prohibitive low accuracy degree of these functions do not always meet modern requirements of the industrial pneumotransport system creation.

In this article the attempt to work out a theoretically well-grounded and more reliable design technique of the pneumotransportation critical velocity is made. The task is to define the mass flow rate $G_{W,K}$ and the medium velocity $U_{W,K}$ of the air flow corresponding to the pneumotransporting critical regime for the designed mass flow rate G_S, density ρ_S and medium grain size d_S of the solid material particles, diameter section D and the relative equivalent roughness δ / D of the pipeline. Moreover the question is about pneumotransport at minor differential pressure when air compressibility may be neglected and its density may be considered unchangeable along the pipeline.

In case of the stable and continuous pneumotransporting regime the conditions of mass flow rate of solid material and air are carried out:

$$\rho_S S V_S F = G_S, \qquad (1)$$

$$\rho_W (1-S) V_W F = G_W, \qquad (2)$$

where S is a medium by pipe cross section volumetrical concentration of solid particles; ρ_W is air density; V_S and V_W are medium real velocities of solid particles and air movement; F is the area of the pipe cross section. By definition the real velocities of V_S and V_W are:

$$V_S = \frac{Q_S}{SF}, \qquad (3)$$

$$V_W = \frac{Q_W}{(1-S)F}, \qquad (4)$$

where Q_S and Q_W are volumetrical flow rate of the solid material and air. If this flow rate refers to the whole area F then the medium velocities U_S and U_W of the solid particles and gas are:

$$U_S = \frac{Q_S}{F}, \qquad (5)$$

$$U_W = \frac{Q_W}{F}, \qquad (6)$$

comparing (3) and (4) with the corresponding expressions (5) and (6) we get

$$U_S = SV_S, \qquad (7)$$

$$U_W = (1-S)V_W. \qquad (8)$$

As $Q_S + Q_W = Q$, where Q is a volumetrical flow rate of air and particles, the expressions (5) and (6) may be written as follows:

$$U_S = S_\rho U, \qquad (9)$$

$$U_W = (1-S_\rho)U, \qquad (10)$$

where $S_\rho = \frac{Q_S}{Q}$ is a flow rate volumetrical concentration of solid particles; $U = \frac{Q}{F}$ is a medium velocity of air and solid particles mixture movement. Having excluded from (9) and (10) the velocity U we get:

$$U_S = \frac{S_\rho}{1-S_\rho} U_W. \qquad (11)$$

In view of equalities (7) and (11) the formula takes the form:

$$\rho_S \frac{S_\rho}{1-S_\rho} U_W F = G_S.$$

Hence we get:

$$U_W = \frac{G_S}{\rho_S F} \cdot \frac{1-S_\rho}{\mathrm{S}_\rho}. \qquad (12)$$

Formula (12) is competent for the medium air velocities $U_W \geq U_{W,K}$, that's why in case of the critical pneumotransporting regime it takes the form:

$$U_{W,K} = \frac{G_S}{\rho_S F} \cdot \frac{1-S_{\rho,K}}{\mathrm{S}_{\rho,K}}, \qquad (13)$$

where $S_{\rho,K}$ is a flow rate volumetrical concentration of solid particles in critical pneumotransport regime.

Thus to define the values of the critical velocity $U_{W,K}$ by formula (13) it is necessary to know the quantity $S_{\rho,K}$ that depends on the concentration S_K and characteristics of the solid material. In case of minor differential pressure when the air may be considered as incompressible medium airdynamic processes at pneumotransport should be qualitatively similar to the hydrodynamic processes at hydrotransport. That's why to define the quantity $S_{\rho,K}$ we use the formula obtained as a part of the pipeline hydrotransport study [3]. It takes the form:

$$S_{\rho,K} = S_K \left[1 - \varphi(Re_S) \left(1 - \frac{S_K}{S_m} \right)^{2,16} \right], \tag{14}$$

$$\varphi(Re_S) = 0,45 \left[1 + signf \cdot th\left(0,967 |f|^{0,6} \right) \right], \tag{15}$$

$$f = \lg Re_S - 0,88 . \tag{16}$$

Here S_K is a medium volumetrical concentration corresponding to the critical regime; S_m is the maximum possible concentration of the solid particles; $signf$ is a sign of quantity f; $Re_S = \dfrac{W_S d_S}{\nu_n}$ is Reynold's number for solid particles, where W_S is a falling free velocity of an isolated solid particle with the d_S diameter in the stationary air; ν_S is the kinematic viscosity of air.

It should be noted that the formulas (14) - (16) are not empirical as they represent results approximation of the numerical design of the flow rate concentration based on the theoretical research of the fields with averaged concentrations and velocities in turbulent suspended flows. This formula is tested on various experimental materials as for the measurement of the flow rate concentration and is characterized by a rather high degree of reliability.

As (14) consists of concentration S_K, the quantity of which is unknown, the set of simultaneous equations (13) and (14) makes it impossible to determine the velocity $U_{W,K}$ as there are two equations and three unknown quantities $U_{W,K}$, $S_{\rho,K}$ and S_K. Thus, for closure of a set of equations (13) and (14) it is necessary to form one more equation connecting the velocity $U_{W,K}$ with the parameters defining it. For this we proceed from the following considerations.

Let's add the quotations (9) and (10) together and we shall have:

$$U_S + U_W = U ,$$

or

$$U_W = U - U_S . \tag{17}$$

Being substituted in (17) instead of U_S the quantity $\dfrac{G_S}{\rho_S F}$ takes the form:

$$U_W = U - \frac{G_S}{\rho_S F} . \tag{18}$$

As the formula (18) is competent for the velocities $U_W \geq U_{W,K}$ and $U \geq U_K$ the following equation is fulfilled in the critical regime of pneumotransportation:

$$U_{W,K} = U - \frac{G_S}{\rho_S F} , \tag{19}$$

where U_K is a critical air and solid particles mixture velocity of motion. To define the quantity U_K we use the technique worked out for hydrotransport having adapted it to pneumotransport conditions. The above mentioned design technique U_K is grounded enough and connects the quantity U_K with the flow characteristics, solid particles and the pipeline. It takes into account, in particular, uneven character of solid particles distribution in depth of flow and the main asymmetry of high velocity field typical for the critical regime of transporting. The equation of the critical regime of hydrotransporting [3] thus obtained takes the form:

$$\frac{\rho_{0,K}}{\rho_W} \cdot \frac{\lambda_K}{(1-\alpha_K)\omega_K^2} \cdot \frac{U_K^2}{2gD} = \frac{K_0(\Delta_S - 1)\beta S_m h_K}{1+\alpha_K}, \quad (20)$$

where $\rho_{0,K}$ is the mixture density at the upper horizontal pipe wall; α_K is a parameter of the axial asymmetry of the velocity field defined as the quantity ratio Δ_r, that is the distance from the kinematic axle of the flow to geometric axle of the pipe, to diameter D of this pipe; λ_K is a coefficient of the hydraulic friction at the motion of the medium carrier in the pipe having the diameter $D(1-\varepsilon_K)$; ω_K is a parameter representing a maximum average velocity ratio in the medium carrier to the maximum average velocity in the medium carrier and solid particles mixture flow at the equal average velocities of the flows; K_0 is a coefficient of the solid material friction sliding; $\Delta_S = \rho_S / \rho_W$ is the solid particles density and medium carrier ratio; β is a coefficient of dilatation; h_K is the ratio of highly concentrated ground layer of solid particles thickness to the pipe diameter D.

As pneumotransport is usually characterized by minor volumelric concentrations and great Reynold's numbers at which coefficient of hydraulic friction refers to the field of quadric resistance, let's assume that $\frac{\rho_{0,K}}{\rho_W} = 1$, $\omega_K = 1$ and λ_K depends only on the relative roughness of the inner pipe wall with:

$$\lambda_K = \frac{\lambda_W}{(1-\alpha_K)^{0,25}}, \quad (21)$$

where λ_W is a coefficient of the hydraulic friction at the air motion in the pipe of D diameter set either experimentally or by Shifrinson's formula:

$$\lambda_K = 0{,}11\left(\frac{\delta}{D}\right)^{0,25}.$$

It is assumed then that quantity h_K for minor volumerical concentrations may be expressed as:

$$h_K = \frac{S_K}{\beta S_m}.$$

In view of above mentioned assumptions equation (20) takes a simplified form:

$$\frac{\lambda_K}{1-\alpha_K} \cdot \frac{U_K^2}{2gD} = \frac{K_0(\Delta_S - 1)S_K}{1+\alpha_K}.$$

Hence it appears:

$$U_K = \sqrt{gD} \cdot \sqrt{\frac{2K_0(\Delta_S - 1)S_K}{\lambda_K} \cdot \frac{1-\alpha_K}{1+\alpha_K}} \, . \tag{22}$$

Substituting in (19) instead of U_K its expression (22) the formula of critical velocity $U_{W,K}$ is found:

$$U_{W,K} = \sqrt{gD} \cdot \sqrt{\frac{2K_0(\Delta_S - 1)S_K}{\lambda_K} \cdot \frac{1-\alpha_K}{1+\alpha_K}} - \frac{G_S}{\rho_S F} . \tag{23}$$

Parameter α_K incoming in (23) is defined according to the expression [3]:

$$\alpha_K = 2{,}44\sqrt{\frac{Fr_S}{\Delta_S - 1}}\left(0{,}25 + 0{,}244\sqrt{\frac{Fr_S}{\Delta_S - 1}}\right) th\left(0{,}714\sqrt{\frac{S_K}{S_m}}\right), \tag{24}$$

where $Fr_S = \frac{W_S^2}{gd_S}$ is the Frud number for the solid material particles.

Thus the equation closing the set of equations (13) and (14) is obtained. That's why the solution of the closed system of three equations (13), (14), and (23) makes it possible to define three parameters $U_{W,K}$, $S_{\rho,K}$ and S_K that characterize the critical regime of the pneumotransport. This is what critical regime design technique of the pneumotransport means.

The solution of the above mentioned equation system is realized graphically. For this purpose the values of concentration are presented $(S_K)_1$, $(S_K)_2$ … and the corresponding values of the flow rate concentration $(S_{\rho K})_1$, $(S_{\rho K})_2$ … are defined by the formula (14), then the velocities $(U_{W,K})_1$, $(U_{W,K})_2$ … are determined in line with the formula (13). According to the obtained values $(U_{W,K})_1$, $(U_{W,K})_2$ … the graph function $U_{W,K} = \varphi_1(S_K)$ is formed.

Then for presenting the values concentrations $(S_K)_1$, $(S_K)_2$ the values $(U_{W,K})_1$, $(U_{W,K})_2$ are found by formula (23), then the graph of the function $U_{W,K} = \varphi_1(S_K)$. The abscissa of the intersection of curves $\varphi_1(S_K)$ and $\varphi_2(S_K)$ gives the unknown value of concentration S_K and the ordinate – the critical velocity value $U_{W,K}$. According to the velocity value $U_{W,K}$ the mass air flow rate $G_{W,K} = \rho_W U_{W,K} F$ is defined. It is necessary for the pumping over of the solid material with the given mass flow rate G_S along the pipeline with D diameter in the critical pneumotransporting regime.

As an example experimental curves of specific differential pressure dependence $\Delta P / L$ from the average velocity air motion U_W borrowed from [2] are shown. In these experiments the pipe diameter $D = 0{,}1$ m, the average grain size of solid particles is $d_S = 5$, the density $\rho_S = 595$ kg/m^3.

The curves 1, 2 and 3 correspond to mass flow rate G_S, equal to 0,228 and 380 kg/h. The straight line crossing the curves 2 and 3 corresponds to the critical regimes of pneumotransporting. According to these data $U_{W,K} = 11{,}7$ m/sec for $G_S = 228$ kg/h and $U_{W,K} = 15$ m/sec for $G_S = 380$ kg/h.

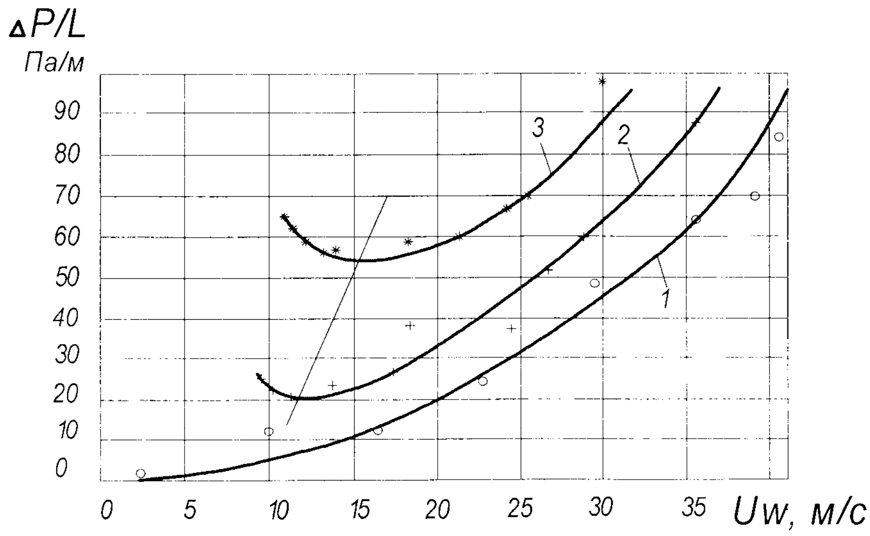

Figure 1 – Experimental curve dependence of the quantity $\Delta\rho / L$ from the velocity U_W borrowed from [2]: 1- $G_S = 0$, 2 - $G_S = 228$ kg/h, 3 - $G_S = 380$ kg/h

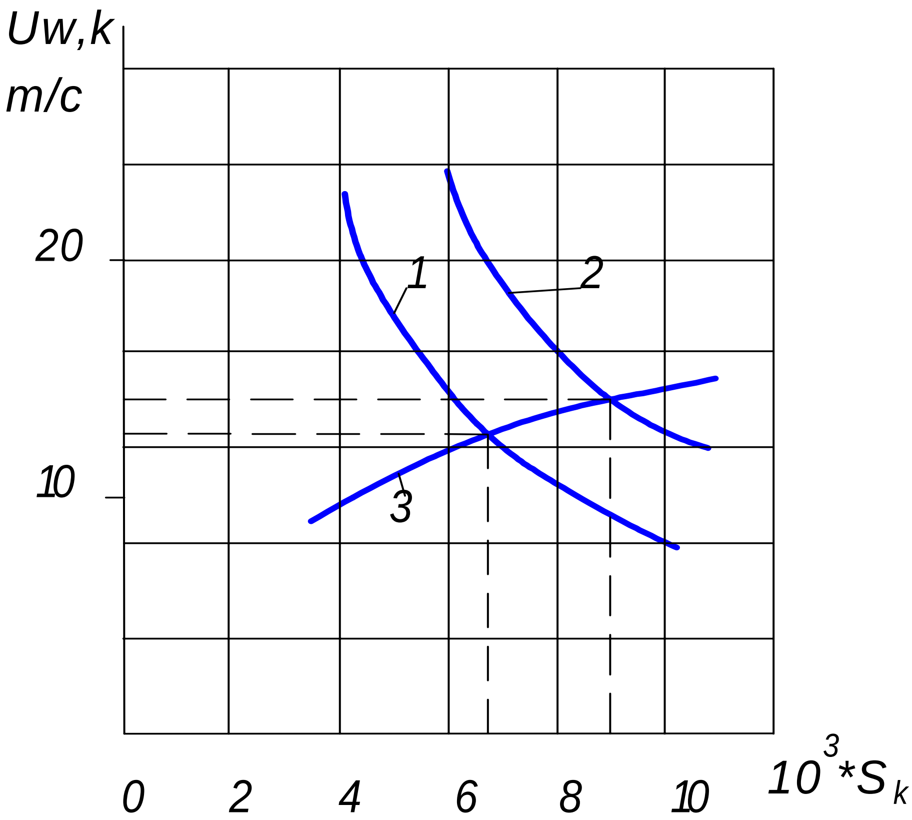

Figure 2 – To the critical regime design: 1 - $\varphi_1(S_K)$ at $G_S = 228$ kg/h
2 - $\varphi_1(S_K)$ at $G_S = 3800$ kg/h
3 - $\varphi_2(S_K)$.

The critical regime design technique is done for each of mass flow rate $G_S = 228$ kg/h and $G_S = 380$ kg/h. And here $W_S = 5{,}1$ m/sec, $K_0 = 0{,}3$, $\lambda_W = 0{,}01$, $\rho_W = 1{,}2$ kg/m^3, $U_W = 0{,}15 \cdot 10^4$ m^3/sec is taken into account. Calculation of function $\varphi_1(S_K)$ and $\varphi_2(S_K)$ is carried out for the values S_K, equal to 0,004; 0,006; 0,008; 0,01. The graphs of these functions are given in Fig. 1. The curves 1 and 2 refer to the function $\varphi_1(S_K)$ at $G_S = 228$ kg/h and $G_S = 380$ kg/h respectively and the curve 3 to the function $\varphi_2(S_K)$. The calculated values S_K and $U_{W,K}$ are determined by the curves intersections φ_1 and φ_2. As a result $S_K = 0{,}007$, $U_{W,K} = 12{,}2$ m/sec, for $G_S = 228$ kg/h and $S_K = 0{,}0093$, $U_{W,K} = 14$ m/sec., for $G_S = 380$ kg/h are obtained. As we see, the calculated values of the critical velocities practically coincide with the experimental ones. It may testify to the reliability of the developed critical regime design technique of the pneumotransporting. Now the solution is to approve this technique on the extensive experimental material.

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