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Pressue losses design while bulk solids pneumatic conveying

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Summary. A new theoretically justified technique of the hydraulic design of aerodispersed flows in horizontal pipes is developed. The existing techniques are of empiric nature and are correct only for a limited range of conditions that are close to the experiment conditions. The new technique is developed on the basis of the solution of the Bernulli's equation for two phase flows considering the latest researches in the sphere of hydraulic conveying.

The revised designs by the new technique show their conformity to the results of the experimental researches within the wide range of characteristics of pneumatic conveying systems and conveyed materials.

Key words: pneumatic conveying, aerodispersed flow, hydraulic design, bulk solids

INTRODUCTION

Under the conditions of the increasing use of pneumatic conveying systems in the different fields of industry there arises the necessity of further researches of aerodispersed flows. Problems of engineering and using of pneumatic conveying systems are solved mostly by conducting labor-intensive and expensive experiments. At that, the obtained dependences as a rule are applicable for the limited range of systems, meeting the experiment conditions. The generalization of results of other experimental researches conducted under different conditions leads to considerable design errors. The designs are conducted with unreasonably high margins. The compressed air overconsumption and its pressure lead to the increase of power intensity of units, primary equipment wear. It makes the air cleaning process complicated and leads to the conveying pipeline falling.

RESEARCH AND PUBLICATIONS ANALYSIS

The most important task of the bulk solids pneumatic conveying hydraulic design is the correct evaluation of pressure losses along the pipeline that enable the least power consumption at steady conveying process with the specified efficiency.

The well known techniques of the pressure losses hydraulic design can be divided into two types, differing in the main formulas structure. The Gastershtadt formula can be referred to the first type. The formula takes the form [12]:

$$\frac{\Delta P}{L} = (1 + K\,\mu)\frac{\Delta P_a}{L}, \qquad (1)$$

where: ΔP and ΔP_a – pressure losses at the pipeline segment of the L length,

μ – mixture mass concentration,

K – Gastershtadt empirical coefficient.

As different researchers say the dependence (1) can be considered as general and the numerical values of the coefficient K should be experimentally determined for every individual case.

Upon carefully conducted experiments formula (1) provides the results that are sufficient for engineering practice. It is simple and convenient for engineering designs yet all practical attempts for K coefficient justification have been unsuccessful.

The techniques of hydraulic design, having the Darcy – Weisbach formula for homogeneous liquids as their base (second type) are widely used in the practice of pneumatic conveying systems engineering. One of the variants of this formula suggested by G. Zegler [Zegler 1937] is as follows:

$$\frac{\Delta P}{L} = \lambda_m \frac{\rho_a U_a}{2D}, \tag{2}$$

where: λ_m – coefficient of hydraulic resistance to the motion of the air and conveyed material mixture,

ρ_a and U_a – density and air motion velocity, D – pipeline diameter.

The coefficient λ_m in formula (2) is determined experimentally. The modified variant of formula (2) suggested by V. Bart [Bart 1960]:

$$\frac{\Delta P}{L} = (\lambda_a + \mu \lambda_s) \frac{\rho_a U_a^2}{2D}, \tag{3}$$

where: λ_s – additional coefficient of resistance, reflecting the presence of solids in the mixture, determined experimentally.

There are known attempts of creating analytical techniques of design [6, 7, 15, 24] but they are true for flows of low concentration (up to 5 kg/kg) only therefore are of not wide spread. The biggest part of industrial pneumatic conveying systems operate at the concentrations of 15–25 kg/kg and above.

In most commonly known works the semi-empirical design methods based on the use of the experimental data have been suggested [2-4, 8, 9]. This fact does not provide the required accuracy of design. [10, 11, 13, 14, 16, 17, 19-22].

Thus by now a generalized technique of pneumatic conveying settled flows hydraulic design suitable for a wide range of pneumatic conveying conditions has not been developed yet.

WORK PURPOSE

The work purpose is the creation of scientifically based engineering techniques of hydraulic design of settled flows in horizontal pipes for industrial pneumatic conveying systems engineering with the purpose of their reliability and operation efficiency control.

MATHEMATIC MODEL

Hydraulic equations of continuity, energy balance (analogue of the Bernoulli's equation), hydraulic resistances and gas equations serve as basic equations for solving tasks of gas suspension flow in the pipe at hydraulic design of pneumatic conveying systems. While writing them down we assume that the gas expansion process is isothermal and the flow is one dimensional, i. e. the mixture temperature during the conveying process is permanent and its density and concentration change while going from one pipe section to another one.

We assume the carrying medium as incompressible while considering the problem of specific pressure losses in the pipeline, i. e. at its short parts. under these conditions hydraulic equations of continuity and gas suspension motion are as following:

$$\rho_S S U_S = G_S, \tag{4}$$

$$\rho_a (1 - S) U_a \omega = G_a, \tag{5}$$

$$\rho_m \frac{U_m^2}{2} + P + \Delta P = const, \tag{6}$$

where: ρ_S, ρ_a, ρ_m – solids density, air density, air and solids mixture density respectively,

G_S, G_a – mass consumption of material and air,

P – pressure,

ΔP – pressure losses at the pipeline part of L length.

The expression (6) is the Bernulli's equation for the gas suspension. The equation (6) is transformed, taking into account the respective dependencies, given in the works [21] and [8]:

$$\left[\frac{1-S}{(1-C)^2}\cdot\beta_a+\frac{\rho_S}{\rho_a}\cdot\frac{S^3}{C^2\cdot(1-S)^2}\cdot\beta_S\right]\cdot\beta_a\cdot\frac{U_a^2}{2}+ \\ +P+\Delta P=const \qquad (7)$$

where: β_a and β_S – non-dimensional coefficients, being analogues of Coriolis coefficient for the carrying agent flow. If however β_a takes the values 1.04÷1.1 for carrying agent, β_S may differ considerably from 1.

The equation (7) includes volume flow concentration S equal to the ratio of solids volume flow rate Q_S to the gas suspension $Q = Q_S + Q_a$ volume flow rate, i. e. $S=\frac{Q_S}{Q_S+Q_a}$ and the mean volume concentration C, taking into account the velocity fields asymmetry and concentrations in the pipe cross section. The concentration S and C functional connection obtained from the results of pipeline conveying [18] hydraulic research:

$$S=C\left[1-f\left(\mathrm{Re}_S\right)\left(1-\frac{C}{C_{\mathrm{mas}}}\right)^{2,16}\left(\frac{u_{cr}}{u}\right)1,66\right], \qquad (8)$$

$$f(\mathrm{Re}_S)=0,45\left[1+SignX\cdot th\left(0,967|X|^{0,6}\right)\right], \qquad (9)$$

$$X=\lg\mathrm{Re}_S-0,88, \qquad (10)$$

where: C_{mas} – limit volume concentration of solid material,

u_{cr} – critical velocity of pneumatic through horizontal pipeline, corresponding to the beginning of solids falling on the pipe low wall,

Re_S – Reynolds number expressed through the free falling velocity w_S and solids mean diameter, i. e.

$$\mathrm{Re}_S=\frac{w_S d_S}{v_g},$$

where: v_g – gas kinematic viscosity.

Taking into account the fact that gas suspension volume concentrations are not big as a rule we assume that the Coriolis coefficient for the gas phase is 1, i.e. $\beta_a \approx 1$. Furthermore the values $S \ll 1$ and $C \ll 1$ of the first summand in the square brackets can be neglected as the value of the summand is much less than the second summand in these brackets. Taking into account the above mentioned and after some transformations the equation (7) can be reduced to the following form:

$$\left[1+\frac{\mu^3\left(\frac{\rho_a}{\rho_S}\right)^2}{C^2\left(1-\mu\frac{\rho_a}{\rho_S}\right)^2}\beta_S\right]\rho_a\frac{U_a^2}{2}+P+\Delta P=const, \qquad (11)$$

where: $\mu=\frac{G_S}{G_a}$ – mixture mass concentration.

As it is known in hydraulics specific pressure loss in the pipeline $\frac{\Delta P}{L}$ determined by the friction of the incompressible liquid is proportional to the specific (per the volume unit) kinematic energy of the flow $\rho\frac{U^2}{2}$ which is expressed with the first summand of the left side of the Bernulli's equation (6) and determined by the Darcy – Weisbach formula:

$$\frac{\Delta P}{L}=\lambda\frac{1}{d}\rho\frac{U^2}{2}, \qquad (12)$$

where: λ – hydraulic friction coefficient,

d – pipe drift diameter.

Passing from the fluid flow to the gas suspension flow and taking into account the expression in the round brackets of the left side of the Bernulli's equation (11) we write by analogy with (12):

$$\frac{\Delta P}{L}=\left[1+\frac{\mu^{3}\left(\frac{\rho_a}{\rho_S}\right)^{2}}{C^{2}\left(1-\mu\frac{\rho_a}{\rho_S}\right)^{2}}\beta_S\right]\lambda_m\frac{\rho_a}{d}\frac{U_a^{2}}{2}. \quad (13)$$

The expression (10) can be introduced the following way:

$$\frac{\Delta P}{L}=\varphi\frac{\Delta P_a}{L}, \quad (14)$$

where: $\frac{\Delta P_a}{L}$ – specific pressure losses while clean air movement:

$$\frac{\Delta P_a}{L}=\lambda_a\frac{\rho_a}{d}\frac{U_a^{2}}{2}, \quad (15)$$

φ coefficient –

$$\varphi=\left[1+\frac{\mu^{3}\left(\frac{\rho_a}{\rho_S}\right)}{C^{2}\left(1-\mu\frac{\rho_a}{\rho_S}\right)^{2}}\beta_S\right]\frac{\lambda_m}{\lambda_a}. \quad (16)$$

For the practical application of formula (11) we determine the parameters λ_a, λ_m and β_S. As for the coefficients of hydraulic resistance λ_a and λ_m their values are equal in the quadratic realm of resistance as they do not depend upon Re_a number. In case of pre quadratic realm of the hydraulic resistance the value λ_a is determined by Altschul formula:

$$\lambda_a=0{,}11\cdot\left[\frac{68}{\mathrm{Re}_a}+\frac{K_e}{d}\right]^{0{,}25}, \quad (17)$$

where: $\mathrm{Re}_a=\frac{U_a d}{\nu_a}$ – the Reynolds number,

ν_a – air kinematic viscosity,

K_e – relative roughness of the pipe inner walls.

The value λ_m is determined by the same formula (10) but taking into account the Reynolds number $\mathrm{Re}_a=\frac{U_a d}{\nu_m}$, where the mixture viscosity can be determined by the formula:

$$\nu_m=\nu_a\frac{1+3{,}5C}{1+\left(\frac{\rho_S}{\rho_a}-1\right)C}. \quad (18)$$

The functional dependency of the Coriolis coefficient β_S for a solid body from the determining parameters is deduced by processing the experimental data of measuring the specific pressure losses due the friction in the horizontal pipe.

If we assign $\frac{\lambda_m}{\lambda_a}\approx 1$ that is correct for the flows of low concentration and introduce the notation:

$$K=\left[\frac{\mu\frac{\rho_g}{\rho_S}}{C(1-\mu\frac{\rho_g}{\rho_S})}\right]^{2}\cdot\beta_S, \quad (19)$$

$\varphi=1+K_\mu$ in this case formula (16) is transformed to the Gastershtadt empiric formula (1).

The crucial significance of formula (16) is in its theoretical justification of the coefficient K dependence from its determining parameters.

The checking evaluation by formula (11) has shown their almost full coincidence with the experimental data. The design error is no more than 10 %.

CONCLUSIONS

1. The scientifically-based technique of the pneumatic conveying parameters design, based on the aerodynamic equations of continuity is suggested for the steady air disperse flow as a compressible medium.

2. The scientifically-based technique for determining and analyzing the coefficient included into the Geisterstadt formula is suggested.

3. The suggested formula (14) can be recommended for the hydraulic design of steady air disperse flows in the horizontal pneumatic conveying line.

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РАСЧЕТ ПОТЕРЬ ДАВЛЕНИЯ ПРИ ПНЕВМОТРАНСПОРТИРОВАНИИ СЫПУЧИХ МАТЕРИАЛОВ

Михаил Чальцев

Аннотация. Разработана новая, теоретически обоснованная методика гидравлического расчета аэродисперсных потоков в горизонтальном пневмотранспортном трубопроводе. Существующие методики носят эмпирический характер и справедливы лишь для ограниченного круга условий, близких к условиям эксперимента. Новая методика разработана на основе решения уравнения Бернулли для двухфазных потоков, с учетом новейших исследований в области гидротранспорта.

Проверочные расчеты по новой методике показывают соответствие результатам экспериментальных исследований в широком диапазоне характеристик пневмотранспортных систем и транспортируемых материалов.

Ключевые слова: пневматическое транспортирование, аэродисперсный поток, гидравлический расчет, сыпучий материал