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HYDRAULIC DESIGN SPECIFYING OF AERODISPERSE FLOWS OF POWDERED MATERIALS

Hydrodynamic characteristic features of powdered materials aerodisperse flows and questions of their design methods specification compared with the granular materials flows are considered.

PROBLEM STATEMENT IN GENERAL

In response to increasing pneumatic conveying use in different fields of industry, there is the necessity of additional aerodisperse flow researches. Problems, occurring while pneumatic conveying systems design and use are solved mostly by means of carrying out of labour intensive and expensive experiments. The obtained afterwards empiric dependences are applicable as a rule only for the limited range of those systems that meet the experiment requirements. The generalization of results of experimental researches carried out under different conditions, causes significant design errors. For this reason designs are carried out with unreasonably wide range of limits causing the increase of power consumption by assemblies and conveying pipeline fallings.

The hydraulic design primary task is the correct estimation of pressure losses along the line providing the least power consumption while the stable conveying process with the specified performance.

ANALYSIS OF THE LATEST ACHIEVEMENTS AND PUBLICATIONS

The known hydraulic resistance design methods used in hydromechanics for single-phase mediums are based on the use of Bernoulli's equation, expressing the flow energy balance. For two-phase aerodisperse flows conditions it was modified in 2004. [1]. The generalized method of hydraulic resistances design in a gas suspension [2] flow, ensuring high accuracy of designs for granular materials was developed on the basis of Bernoulli's equation. However it turned out that the design results for powdered material gas suspension with the particles size of no less than 100μm deviate considerably from the experimental data. Carrying out of additional theoretical and experimental researches was required for establishing the reasons of the fact.

AIM OF WORK

The aim of the work is specifying of hydraulic design methods of powdered material flows pneumatic conveying.

BASIC RESEARCH MATERIAL PRESENTATION

The category of powdered solids includes milled solid materials with the mean size of particles not exceeding 100 μm. Cement, ash, powdered coal, ferrous and nonferrous metal ores and others belong to it.

Gas suspension flows in pipes are turbulent as a rule. However their turbulent structure and related with it integral parameters haven’t been sufficiently studied so far. As a rule, dust-laden gas flow is considered as a single phase fluid flow the density and viscosity of which are the same as those of the gas suspension. According to practice, for a model fluid like this, designed values of specific pressure drops, obtained by a formula analogous to pipeline hydraulics of homogeneous fluid, are too high in comparison with the experimental ones, i.e. actual specific pressure drops are less than the designed ones due to the fine suspension influence on the statistical mode of pulsating motion of the carrier medium and therefore on mean specific dissipation of the flow kinetic energy. Thus while using the hydraulic method, the designed dependence should be corrected for $\Delta P/L$ determination, considering suspension influence on specific pressure drop.

General expression for specific pressure drop, while gas suspension motion in pipe, can be derived on the basis of Bernoulli's equation set up for the suspension flow. While setting up this equation, the gas suspension is considered as heterogeneous continuous medium comprising two interacting continuums one of which refers to the gas phase and the other one – to the solid phase.

The characteristic feature of the pipeline part under consideration, where the gas suspension motion is considered as low-pressure is relatively small pressure drops between the initial and the final flow sections. In this case the gas can be considered as non-compressed medium and its density as a constant value. The heat exchange mode is isothermal. Under the conditions, the Bernulli's equation takes the following form [1]:

$$P_1 - P_2 = \Delta P_f + \rho_p g (Z_2 - Z_1), \tag{1}$$

where P_1 и P_2 – pressure in the initial and final flow sections;

ΔP_f – friction pressure losses;

ρ_p – flow rate density of the gas suspension;

g – acceleration of gravity;

Z_1 and Z_2 – the height of the flow effective cross-section mass centers location against the plane of reference.

Having divided both parts of the equation (1) by L and denoted $(P_1 - P_2)/L$ and $\left(z_2 - z_1\right)/L$ respectively by $\Delta P/L$ and $\sin\alpha$, where α – the pipe inclination angle against the horizontal plane will be:

$$\frac{\Delta P}{L} = \frac{\Delta P_f}{L} + \rho_p g \sin\alpha. \tag{2}$$

Using the hydraulic method, the gas suspension is considered as a single-phase homogeneous fluid with the density ρ_m and the effective viscosity γ_m, thus by analogy with the expression of specific pressure losses in pipeline hydraulics for horizontal pipeline we have:

$$\frac{\Delta P_f}{L} = \lambda'_m \rho_m \frac{u_m^2}{2D}, \tag{3}$$

where λ'_m – designed coefficient of hydraulic friction for the model fluid under consideration;

D – pipe inner diameter. In the flow of fine dispersed particles when the material and air mean velocities can be equated to each other, the value u_m can be expressed in terms of the air velocity u:

$$u_m = u(1 + \mu_v), \tag{4}$$

where μ_v – volume flow rate concentration of the mixture.

From the expressions (3) and (4) we obtain:

$$\frac{\Delta P_f}{L} = \lambda'_m \rho_m \left(1 + \mu_v\right)^2 \frac{u^2}{2D}. \tag{5}$$

Designed coefficient of hydraulic friction λ'_m included into (3) depends upon Reynolds number $\mathrm{Re}_m = uD/\upsilon_m$, where $v_m = \gamma_m/\rho_m$ – gas suspension kinematic viscosity and upon inner pipe wall relative equivalent roughness K_{ex}/D.

For λ'_m value determination a formula analogous to the Altschul formula, obtained for homogeneous fluid flow [3] is used:

$$\lambda'_m = 0{,}11\left(\frac{68}{\mathrm{Re}_m} + \frac{K_{ex}}{D}\right)^{0{,}25}. \tag{6}$$

Thus formula (5), considering (6) allows to determine specific pressure drop while homogeneous fluid motion, modeling dust-laden gas in pipes.

Concerning the gas suspension dynamic viscosity γ_m, the value γ_m for small values of volume concentration μ_v is determined by the formula analogous to suspensions [4]:

$$\gamma_m = \gamma(1 + 3{,}5\mu_v), \tag{7}$$

where γ – gas dynamic viscosity.

Practically the actual hydraulic friction coefficient, denoted by γ_m in the powdered materials flow is considerably lower than the designed hydraulic friction coefficient λ'_m. As an example proving the above mentioned, in the figure 1 there is the ratio dependence of λ_m/λ'_m to μ_v obtained after processing of the experimental data, taken from [5], for measuring $\Delta P_f/L$ while pneumatic conveying of cement with $d_s = 0{,}021$ mm fineness and $\rho_s = 3060$ kg/m^{3}density through a horizontal pipe with $D = 0{,}05$ m diameter. For determination of λ_m/λ'_m for the set mean velocities of the gas, the value λ_m was evaluated by the formula:

$$\lambda_m = \left(\frac{\Delta P_f}{L}\right)_{ex} \Bigg/ \rho_m (1+\mu_v)^2 \frac{u^2}{2D}, \tag{8}$$

where $\left(\Delta P_f/L\right)_{ex}$ – experimental value of the specific pressure drop in the gas suspension flow. λ'_m coefficient is evaluated by formula (6).

As seen in figure 1, value λ_m/λ'_m is about 0,2. Such a considerable hydraulic friction coefficient λ_m decrease in comparison with the designed coefficient λ'_m can be physically explained by means of the turbulence suppression with powdered suspension. It should be noted the abovementioned specific pressure decrease is peculiar for gas suspensions containing powdered particles only. While hydraulic pipeline conveying of the particles the effect is not observed and in this case $\lambda'_m = \lambda_m$. Thus the solids relatively high density ρ_S/ρ and the particles inertness related to it in the process of their conveying by gas pulsating motion apparently play the crucial role in the turbulence suppression.

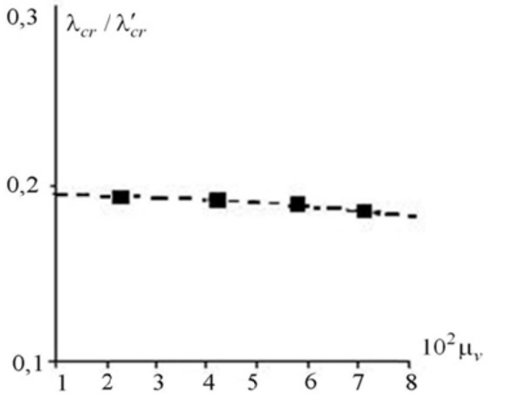

Figure 1 – μ_v dependence of $\frac{\lambda_m}{\lambda'_m}$ value for the critical mode of cement pneumatic conveying

The physical mechanism of fine suspension influence on gas turbulence can be explained the following way. According to [6], in any turbulent two-phase flow, mechanical energy overall transition from mean motion to pulsating happens in two «ways» simultaneously due to the carrier medium stability loss, vortex decay and by means of large- or small-scale disturbances or vortex sheddings caused by gas or fluid flow around solids. As solids density as a rule is three orders higher than gas (air) density, powdered particles are more inert than gas and therefore they don't fully take gas pulsating motion, i. e. do not constantly follow pulsating gas volumes surrounding them. In this case large vortexes in the flow get split causing the pulsation energy weakening. That is why the turbulence energy generated by continuous cascade formation and decaying processes of vortexes of different orders decreases all over the pulsations frequency spectrum in comparison with the turbulence energy of the corresponding homogeneous model fluid flow. On the other side, small-scale disturbances occurring due to the gas flow around powdered suspension slightly increase the turbulence energy within the high frequency spectrum range. Thus in the gas suspension flows under consideration the process of the turbulence weakening by means of vortexes splitting prevails over the process of the flow additional turbulization, conditioned by flowing around the suspension and eventually causing the turbulence suppression.

For suspension coarse particles flowed around within the resistance quadratic realm, additional turbulence energy generation, related to this flowing around can prevail over the turbulence energy suppression, conditioned by vortexes splitting and causing gas turbulization intensity increase.

For taking into account powdered suspension influence on specific pressure drop, determined by the formula analogous to (5), the hydraulic friction coefficient λ'_m in formula (3) should be substituted for λ_m. As a result of the substitution and subsequent elementary transformations we obtain:

$$\frac{\Delta P_f}{L} = \bar{\lambda}\bar{\rho}\left(1+\mu_v\right)^2 \lambda \frac{\rho u^2}{2D} = \bar{\lambda}\bar{\rho}\left(1+\mu_v\right)^2 \left(\frac{\Delta P_f}{L}\right)_h; \tag{9}$$

$$\left(\frac{\Delta P_f}{L}\right)_h = \lambda \frac{\rho u^2}{2D}; \tag{10}$$

$$\bar{\rho} = 1 + \left(\Delta_T - 1\right)\frac{\mu_v}{1+\mu_v}, \tag{11}$$

where λ and $\left(\Delta P_f / L\right)_h$ – hydraulic friction coefficient and specific pressure drop in the corresponding gas flow; $\bar{\lambda} = \lambda_m / \lambda$ – the parameter considering powdered suspension influence on $\Delta P_f / L$. (11) comprises $\Delta_T = \frac{\rho_S}{\rho}$ value.

For evaluating λ coefficient Altschul formula can be recommended by analogy with (6)

$$\lambda = 0{,}11\left(\frac{68}{\mathrm{Re}} + \frac{K_{ex}}{D}\right)^{0{,}25}. \tag{12}$$

Here Reynolds number $\mathrm{Re} = \frac{uD}{\nu}$, where ν – the gas kinematic viscosity; $\nu = \mu / \rho$.

$\overline{\lambda}$ parameter is determined on the base of experimental data of $\Delta P_S / L$ measurement as the dependence for λ_m design for the flows under consideration is unknown. For $\overline{\lambda}$ parameter determination experimental data of specific pressure drops while cement, ash, milled coal [5] and iron ore concentrate [7] pneumatic conveying at mean speeds of $u \geq u_{cr}$ gas motion is used. In this case hydraulic friction parameters included into λ_m and λ are determined by respective formulas (8) and (12). On the basis of the abovementioned experimental data it is determined that $\overline{\lambda}$ value depends generally upon α_S, Re_S, and u / u_{cr}. The empirical dependence of $\overline{\lambda}$ value upon the determining parameters is as follows:

$$\overline{\lambda} = \left[\overline{\lambda}_{cr} + 0{,}0082\left(\frac{u}{u_{cr}}\right)\right]; \tag{13}$$

$$\overline{\lambda}_{cr} = 1 - (1 - \varphi)\,th\left(47{,}16\sqrt{\mu_v}\right); \tag{14}$$

$$\varphi = 0{,}127 + \left(1 + 1{,}016\,\mathrm{Re}_S\right)0{,}022\,\mathrm{Re}_S. \tag{15}$$

The formula (15) comprises the Reynolds number:

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

where w_S – the particle terminal velocity.

Results of experimental data processing referred to the pneumatic conveying critical mode are given in figure 2. Here experimental values are denoted with dots $\overline{\lambda}_{cr}$ and designed values derived from formulas (14) and (15) – with full line.

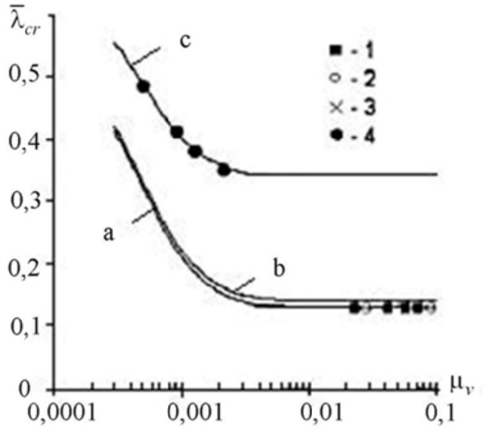

Figure 2 – μ_v dependence of $\overline{\lambda}_{cr}$ with $u = u_{cr}$:
1 – cement, Re_S=0,05; 2 – ash, Re_S=0,059; 3 – coal, Re_S=0,4;
4 – iron ore concentrate, Re_S=2,63

As we can see formulas (14) and (15) satisfactory approximate experimental data:

a – Re_S=0,058; b – Re_S=0,4; c – Re_S=2,63.

Particularly it follows from formulas (13) and (14) that in limit case with $\varphi = 1$ and $u/u_{cr} = 1$ the value $\bar{\lambda} = 1/(1+\mu_v)^2 \approx 1$ and in this case powdered suspension does not promote the turbulence suppression. Thus the algebraic equation positive root

$$0,022352\,\mathrm{Re}_S^2 + 0,022\,\mathrm{Re}_S - 0,873 = 0, \tag{16}$$

derived from formula (15) with $\varphi = 1$ corresponds with the limit value $(\mathrm{Re}_S)_{cr}$ at which the turbulence suppression will not be observed any more. Having solved the equation (16) we will have $(\mathrm{Re}_T)_{cr} \approx 5,78$. The empiric formulas (13) and (14) scope is

$$\left.\begin{array}{l} \mu_v < 0,1 \\ u \geq u_{cr} \\ \mathrm{Re}_T < 5,78 \\ dT \leq 100\text{micron} \end{array}\right\}.$$

CONCLUSION

Summing it up formulas (9) – (11), considering (13) – (15), allow determining specific pressure drop $\Delta P_f / L$ at powdered solids pneumatic conveying velocities $u \geq u_{cr}$. Check designs show that the method error is no more than 15-20 %.

FURTHER DEVELOPMENT POSSIBILITIES

For the conformation of the research results within pneumatic conveying wider parameters range additional experimental researches are planned.

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