

Estimation of gas flow dustiness in the main pipelines of booster compressor stations

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Abstract. The article provides groundings for cleaning the gas flows of major pipelines from soild particles in order to improve the compressor operation reliability. One obtained formulas for determination of the dust level in the vertical and horizontal sections of the pipelines supplying gas to the booster compressor stations. Ways of structural modernization of vertical pipeline sections using the inbuilt separation devices for more efficient removal of dust particles from the gas flow are described.

1. Introduction

Gases and their mixtures are treated in the chemical and gas processing industries. Compressor machines transfer gas flows. Gases conveyed by process and main pipelines often contain various solid impurities like sand particles, dust, welded slag, corrosion scale. In pneumatic transport installations gas recirculation flows, feeding to the suction line of the booster compressors, contain a small fraction of transported materials.

Solid particles in a gas flow, entering piston compressors, cause increased wear of piston rings, valves and cylinders. They also impair impellers and inner walls of centrifugal blowers. Therefore, they decrease performance of gas compressor stations and units, namely, reducing reliability and economical operation.

At the principal facilities of the main gas pipelines and technological pneumatic transport units there are used devices for cleaning gas from mechanical impurities: oil and dry dust collectors, filters, scrubbers, adsorbers, separators of various designs. At the same time, an important issue is a stable conveyance of solid particles and impurities by a gas flow through pipelines in order to prevent them from lying on the walls of pipeline horizontal sections and dropping them out of the flow in vertical sections.

It is rational to install separating devices for preliminary separation of a gas flow from solid impurities on the vertical sections of the pipeline. It enables to maintain pipeline performance at the target level and purify gases in the main separators more efficiently.

2. Analysis and statement of a problem. Purpose and objectives of the research

For stable conveyance of gas together with solid impurities through the pipeline, it is necessary to maintain a certain value of critical velocity of the gas flow. A number of formulas have been proposed for determining the conveyance velocity of the gas flow [1].



Empirical formulas are proposed for calculating critical velocity of the gas flow, wherein solid particles do not sediment at the bottom of a horizontal pipeline [1]:

$$W = 5,6 \cdot D^{0,34} \cdot d^{0,36} \cdot \left(\frac{\rho_T}{\rho} \right) \cdot m^{0,25} \quad (1)$$

$$W = A \cdot \sqrt{\rho_T} + B \cdot L^2 \quad (2)$$

where

D – pipeline diameter, m; d – average particle diameter, m; ρ_T – particle density, kg / m³ (in the formula (2) – t / m³); ρ – is the gas flow density, kg / m³; m – mass coefficient of the suspension, kg / kg; L – length of the pipeline, m; A, B – empirical coefficients.

As it follows from the presented equations, the speed of horizontal conveyance is mainly influenced by the pipeline diameter and suspension coefficient, and pipeline length affect is insignificant.

Pipeline length affects the flow state and the conveyance nature of the dusty gas flow if the flow properties vary along the length of the pipe. It is possible if temperature of the flow conveyance varies along the length of the pipeline. Then it is necessary to determine the velocity, based on the physical properties of the flow in the middle part of the pipe, or to calculate it separately for individual pipeline sections.

In case of vertical conveyance of the dusty gas flow, a blockage phenomenon can occur. If a gas flow velocity is below the critical value, the distance between particles decreases, their concentration in the flow increases and particles get into the hydrodynamic trajectory of the particles moving ahead, their front resistance falls and therefore their terminal velocity rises causing particle dropping out i.e. a phenomenon of blockage takes place.

To determine the ascending gas flow velocity at which the phenomenon of suspended material blockage arises, there are proposed [2] the following formulas:

$$W = 10,5 + 0,57 \cdot U_B \quad (3)$$

$$W = 1,4 \cdot m^{0,28} \cdot U_B \quad (4)$$

where

U_B – velocity of particles of a given size, m / s.

For steady conveyance of a dusty gas flow in a vertical pipeline, it is proposed [2] to determine gas flow velocity using the following formula:

$$W = k \cdot U_B \quad (5)$$

where

k – is an experimental coefficient, the choice of which depends on the size of the conveyed particles.

Formulas (3) – (5) have significant disadvantages. There is no specific way of choosing the experimental coefficient "k" and "m" parameter, as well as there is no record of conveyed particles concentration influence on the operating velocity of the gas flow. Pipeline diameter and some other parameters, complicating particle motion in the conveyed gas flow are also not considered.

Purpose of the paper is to study the influence of solid phase concentration in the flow, the effect of solid particles sizes and pipeline diameter on the velocity of sustainable conveyance of the dusty gas flow along the vertical and horizontal sections of pipelines. Objective of the paper is to ground a general analytical expression for calculating gas flow velocity and deriving equations wherein gas flow velocity would be a function of such parameters like concentration of particles in the flow, particle terminal velocity and pipeline diameter.

3. Regularities of weighing and conveyance of solid particles by a gas flow

3.1 Theoretical grounding

In stationary conditions behind the accelerating section or at the outlet of the gas pipeline, concentration of particles of a given size (dy), weighted by the gas flow over the elementary time ($d\tau$), is proportional to the limiting concentration of particles of this size (y_{PR}), that can arise in a gas flow at its complete saturation with suspended particles, that is, presented in the form of a dependence:

$$\frac{dy}{d\tau} = -k \cdot y_{PR} \quad (6)$$

In this case, the value of limiting concentration of particles is considered as a parameter that takes into account the influence of deterministic factors (particle mass, averaged velocity of the gas flow) and parameters complicating the particle motion – turbulence and flow pulsation, rotation and joint impacts of particles, their impacts against the pipeline walls.

Having divided the variables and integrating equation (6) replacing the logarithm according to the initial and boundary conditions, we obtain

$$y = y_{PR} \cdot 10^{-k_1 \cdot \tau} \quad (7)$$

Particle residence time in the pipeline τ increases with growing the conveyance height and decreases with growth of gas flow velocity. We take the first approximation of:

$$\tau = k_2 \cdot \frac{h}{u_T} = k_2 \cdot \frac{h}{W} \quad (8)$$

For a stationary section of a gas-conveying pipeline, the particle velocity (u_T) is close to the flow velocity (w), therefore in equation one takes (8) $u_T = W$. Having substituted equation (8) in (7), we obtain:

$$y = y_{PR} \cdot 10^{-\frac{k_1 \cdot k_2 \cdot h}{W}} = y_{PR} \cdot 10^{-k_0 \cdot \frac{h}{W}} \quad (9)$$

For gas transmission pipelines with a stationary regime of particle motion $k_0 \cdot h = b$ – then

$$y = y_{PR} \cdot 10^{-\frac{b}{W}} \quad (10)$$

or

$$\lg y = \lg y_{PR} - \frac{b}{W} \quad (11)$$

We replace $a = \lg y_{PR}$ in equation (11). Further from the formula (11), one obtains an equation to determine the working velocity of the gas flow for sustainable conveyance of solid particles of the type:

$$W = \frac{b}{a - \lg y} \quad (12)$$

where

y – current concentration of solid particles in the gas flow, g / m³; a, b – experimental constants.

The constant " a " is a logarithm of the limiting concentration of particles in the gas flow to which this value asymptotically approaches with increasing of gas flow velocity.

The constant " b " characterizes particles' ability to pass into suspended state in a pipeline of a given diameter. It represents the energy, expended by the flow on the distribution of particles along the channel section. For fine particles smaller than 100 μ m, this constant has lower value. In this case, the

particles are distributed more evenly over the cross section of the pipeline, and their concentration approaches the limiting value. As the constant value increases, the gradient of particles concentration in the gas flow grows and the current value of the particle concentration differs more and more from the limiting value.

3.2 Experimental research

The experimental setup consists of vertical and horizontal pipelines of various diameters (0.02 – 0.2 m) and a length up to 3 m, that are connected to a cyclone and a bag filter. Model materials, quartz, aluminum and copper powders, were fed uniformly by a belt feeder into the initial section of the pipeline. The air flow, upon which the averaged gas flow velocities were calculated, were measured at the inlet of the initial section of the pipeline by a calibrated collector. Pressure drops were measured by a manometer with an inclined moving scale connected to several (up to ten) piezometric rings behind the accelerating section. A turbogas blower acted like agitator. With the reduction of flow velocity, its value (W) was fixed at a constant flow rate of material (G) to the section of the pipeline (F). When specific pressure drops reached the minimum value the formula $y = G / FW$ was used for each material to determine the particle concentration y . Up to reaching the maximum concentration of particles, pressure pulsations in the stationary section of the pipeline were relatively small and were not detected, if distances between piezometric rings for measuring the pressure exceeded 0.5 m. Pressure fluctuations in the accelerating section of the pipeline were somewhat larger, but in all cases they were in range of 5 to 10% of the measured value.

They increased sharply after concentration of particles in the gas flow exceeded its limiting value, at which elements of a dense phase in the form of aggregates of particles began to separate from the flow. In accordance with the work objectives, only the data obtained at the stationary section of the pipeline with the concentration of particles not exceeding the limiting values were recorded.

The graphs (Figure 1 (a), (b)) in the coordinates $\lg y = f(1/W)$ show the dependence of the concentration of mono-fraction particles on the gas velocity for the vertical and horizontal pipelines of various diameters, respectively.

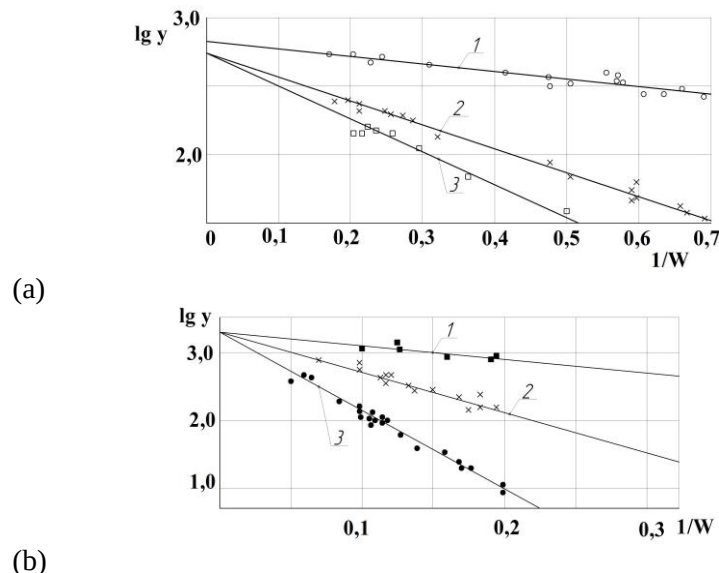


Figure 1. Dependence of the particle concentration in the vertical (a) and horizontal (b) pipelines on the gas flow velocity: 1 – 3 – diameter of the pipeline, 0.03; 0.04 and 0.08 m. respectively.

As it can be seen from Figure 1 (a), (b) the experimental data for stationary sections are expressed by straight lines, which correspond to equation (11). The ordinate of intersection point of each straight

line with the ordinate axis provides a value of the constant "a", which is a logarithm of that value of the particle concentration in the gas flow to which it tends with increasing flow velocity.

Constant "a" value increases with growing of the conveyed particle size and is practically independent on the diameter of the pipeline, since straight lines within the monofraction for pipelines of different diameters intersect on the ordinate axis at one point. Constant "b" is a tangent of lines inclination to the abscissa axis (Figure 1 a, b). Values of these constants, obtained experimentally, are given in Table 1.

Table 1. The main properties of particles and values of constants "a" and "b".

Monofraction, mm	Average particle size, mm	Density, kg / m ³	Terminal velocity U_B , m / s	Pipe-line diameter D , m	Constants			
					vertical		horizontal	
					a	b	a	b
-0,105 +0,075	0,09	2600	0,67	0,02	3,33	0,71	4,25	6,0
				0,03	3,26	1,81	4,20	11,5
				0,04	3,26	3,1	4,18	16,1
-0,105 +0,075	0,09	2700	0,45	0,03	2,82	0,68	3,31	2,58
				0,04	2,80	1,76	3,30	6,02
				0,08	2,78	2,48	3,30	11,4
-0,105 +0,075	0,09	8800	0,92	0,02	3,68	3,0	—	—
				0,04	—	—	4,31	16,7
				0,08	3,68	4,78	—	—

3.3 Analysis and summarizing of the research results

Analysis of the experimental data showed that the constants "a" and "b" are single-valued non-linear functions of easily determined characteristics, such as a particle velocity (U_B) and a diameter of the pipeline (D). i.e

$$a = f(U_B) \quad (13)$$

$$b = f(U_B \cdot D) \quad (14)$$

which can not be expressed by a single equation for particles with different terminal velocities. It is due to a complex nature of the phenomena occurring under the interaction of particles of different diameters with the turbulent flow in the pipeline. When a particle size and a pipeline diameter change, flow regime of the particles, flow turbulence, boundary layer on the particle surface, and other parameters also change.

Therefore, non-linear connections of the form (13) and (14) will be presented in a wide range of terminal velocity changes for solid particles by several equations of the form:

$$a = m_1 \cdot 10^{\frac{-n_1}{U_B}} \quad (15)$$

$$b = m_2 \cdot (U_B \cdot D)^{n_2} \quad (16)$$

Formulas for determining the constants "a" and "b" under the conditions for conveying of particles in a vertical pipeline are described in Table 2.

Table 2. Formulas for determining the experimental constants "*a*" and "*b*".

Terminal velocity of the conveying particles U_B , m / s	Constant	
	<i>a</i>	<i>b</i>
0,1 – 0,4	$2,9 \cdot 10^{-0,024/U_B}$	0,25
0,4 – 1,0	$4,3 \cdot 10^{-0,08/U_B}$	$10^{5,2} \cdot (U_B \cdot D)^{2,9}$
1,0 – 10	$5,8 \cdot 10^{-0,21/U_B}$	$180 \cdot (U_B \cdot D)^{1,26}$
10 – 20	$7,0 \cdot 10^{-1,3/U_B}$	$47 \cdot (U_B \cdot D)^{0,33}$

Formulas for determining the constants "*a*" and "*b*" under conditions of conveying the particles ($U_B = 0.4 - 12$ m / s) in the horizontal pipeline are:

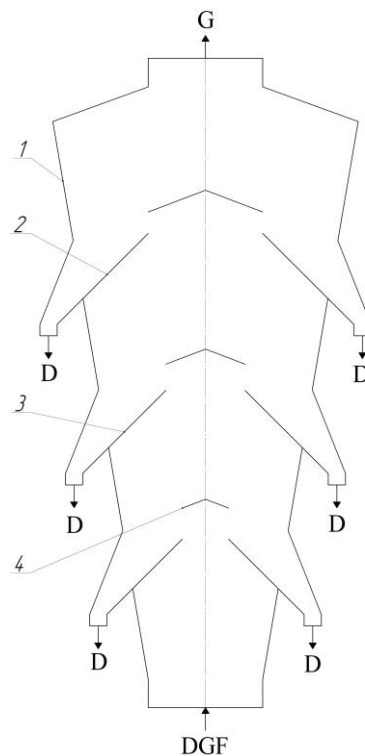
$$a = 2,9 \cdot 10^{-0,024/U_B} \quad (17)$$

$$b = 10^{4,5/(0,2/U_B) - 0,3/D} \quad (18)$$

The discrepancy between calculated and experimental data is in the range of 10 – 25%.

4. Hardware design of the separator on the vertical section of the pipeline

It is advisable to install a conical-shaped separator with the rectangular cross-section (Figure 2) on vertical pipeline sections for conveying a dusty gas flow. The opening angle of the conical-shaped housing is in the range $5 - 7^\circ$.

**Figure 2.** Separator scheme:

1 – housing; 2 – inclined shelf; 3 – discharge sleeve; 4 – reflector;
DGF – dusty gas flow; D – dust; G – purified gas.

On the height of the housing 1, there are installed inclined shelves 2, forming channels for the formation of an ascending jet. Under each shelf there are discharge sleeves 3 for removing separate fractions of captured dust particles. The gaseous flow is introduced into the separator and moves in its housing from the bottom up. A suspended layer with a relatively small concentration of particles takes place on the lower shelves. Gas velocity in this section is approximately equal to the velocity of the largest particles. That is, the principle of equilibrium classification takes place. Particles with a velocity greater than the velocity of the gas flow fall onto the surface of the shelves and are directed to the discharge sleeve. Particles with a terminal velocity less than the gas flow rate are carried to the middle shelves, where they are removed from the gas flow. On the upper shelves, the smallest fractions are removed from the gas flow. The results of particle separation from a dusty gas flow, using coal powder as an admixture (particle density 1500 kg / m^3), are shown in Table 3.

Table 3. Sieve analysis of the initial mixture and fractions captured in the separator.

Fraction type	Fraction content, %					
	+3 mm	−3+2 mm	−2+1 mm	−1+0,5 mm	−0,5+0,1 mm	−0,1 mm
Initial	28,2	21,2	16,4	5,2	23,0	6,0
Undersize	56,6	26,8	12,9	1,1	2,3	0,3
Middle-size	29,7	25,0	28,5	8,9	7,5	0,4
Extra-size	–	–	7,0	8,7	76,6	7,7

5. Conclusion

Results of the sieve analysis of separation products obtained in the apparatus show that two lower shelves provide effective removal of particles larger than 1 mm, and the upper shelf withdraw mainly fine particles smaller than 0.5 mm.

The proposed separator design operates effectively to clean dusty gas flows with particle sizes greater than $50 - 70 \text{ }\mu\text{m}$. Gravitational forces do not provide so efficient separation of particles of the smaller size. In addition, dusty gas flows containing highly disperse dust must be cleaned in centrifugal separators [4 – 9]. In this case the proposed separator serves as the first stage of purification to separate fractions higher than $70 - 75 \text{ }\mu\text{m}$ from the dusty gas flow. Therefore, the efficiency of separation and productivity of the centrifugal separator of the second stage of purification will be much higher. The advantage of the separator built up in the vertical section of the pipeline is a sufficient depuration efficiency (about 70 – 75%) at a relatively small hydraulic resistance (500 – 700 Pa).

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