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PNEUMATIC CONVEYING OF FLY ASH WITH VARIOUS DIAMETER OF THE PIPELINE

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ABSTRACT
In this paper is described calculation of the pressure drop for pneumatic conveying of fly ash with various diameter of the pipeline. Maximal and minimal intensity of air velocity must be in defined borders. Intensity of air velocity is increased along the pipeline, so when the diameter of the pipeline increases, intensity of air velocity must drop. In this way it is avoided clogging and damage of the pipeline. In this case, the best way to calculate pressure drop in the pipeline is using λ_m – Fr method, which can also be used to determine air velocity, particle velocity, friction coefficient of solid, and other important parameters. This paper will show comparison between obtained data using λ_m – Fr method and obtained data using other methods.
Keywords: pneumatic conveying, pressure drop, various diameter, air velocity

1. INTRODUCTION
Pneumatic conveying with various diameter of the pipeline is pneumatic conveying with a pipeline in which the diameter changes from smaller to larger diameter as shown in Figure 2. Intensity of air velocity is increased along the pipeline to maximum value, so with the change in diameter, air velocity falls to a minimum value as shown in Figure 1. In this way it is avoided clogging and damage of the pipeline, because of too small or too high air velocity.

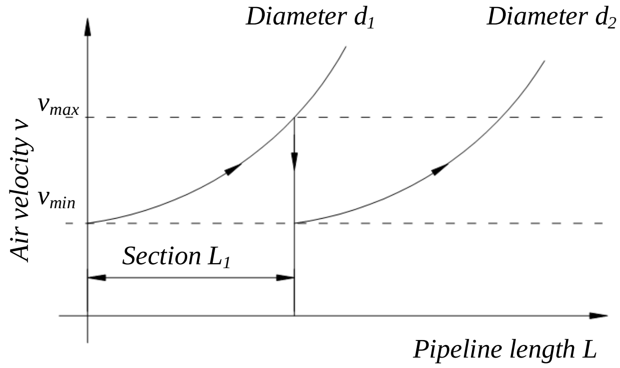


Figure 1. Air velocity profile and diameter change in the pneumatic conveying with various diameter of the pipeline

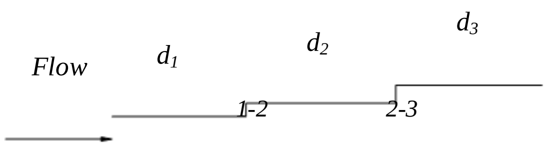


Figure 2. Change of the pipeline diameter

New section begins at the point where the diameter changes from d_1 to d_2 and ends at the point where diameter changes from d_2 to d_3 as shown in Figure 2. Pressure drops between sections are ignored.

2. DESCRIPTION OF THE METHOD
The best way to calculate pressure drop for pneumatic conveying of fly ash with various diameter is using λ_m – Fr method. There are two ways to calculate pressure drop using this method. First way is

using the assumption of incompressible air flow. This method is called "step by step" method. Pressure drop Δp can be calculated as [1]:

$$\Delta p = (\lambda + \mu_m \lambda_m)\rho v^2 \frac{\Delta l}{2D} + \mu_m \rho v \Delta u \,, \qquad ...(1)$$

where are: λ - coefficient of air friction, μ_m – solid-air mixing ratio, λ_m - coefficient of friction, ρ – air density, v – air velocity, Δl – length of the pipeline section, D – internal pipeline diameter, Δu – difference between solid velocity at the beginning and end of the pipeline.

Second way is using the assumption of isothermal air flow. This is called method of "long sections". Pressure drop can be calculated as [1]:

$$\frac{p_1^2 - p_2^2}{2p_2} = (\lambda + \mu_m \lambda_m)\frac{\rho_2 v_2{}^2}{2}\frac{l}{D} + (1 + \mu_m \frac{u_2}{v_2})\rho_2 v_2^2 \ln \frac{p_1}{p_2} \,, \qquad \ldots(2)$$

where p is the absolute pressure in the pipeline. Numbers 1 and 2 refer to the beginning and end of the section. Air velocity and air density in the pipeline can be calculated as:

$$\Delta p = p_i - p_{i+1}, \quad \rho_i = \frac{p_i}{RT}, \quad v_i = \frac{p_{i+1} v_{i+1}}{p_i} \,, \qquad \ldots(3)$$

where are: R – gas constant for air, T – air temperature in the pipeline.

Solid velocity can be calculated as [1]:

$$u = v \frac{1 - \sqrt{1 - \left(1 - \mathrm{Fr}^{*2} \frac{\lambda_m^*}{2}\right)\left[1 - \left(\frac{u_p}{v}\right)^2 \sin\delta - \left(\frac{u_p}{v}\right)^3 \cos^2\delta\right]}}{1 - \mathrm{Fr}^{*2}\frac{\lambda_m^*}{2}} \,. \qquad ...(4)$$

Fr^* is Froude number related to settling velocity u_p. $\lambda_m{}^*$ is friction coefficient of solid. Friction coefficient can be calculated as:

$$\lambda_m = \frac{u}{v}\lambda_m{}^* + 2\frac{\left(\cos^2\delta \frac{u_p}{v} + \sin\delta\right)}{\mathrm{Fr}^2 \frac{u}{v}} \,. \qquad ...(5)$$

Fr is Froude number related to air velocity. Fr and Fr^* can be calculated as:

$$\mathrm{Fr} = \frac{v}{\sqrt{gD}}, \quad \mathrm{Fr}^* = \frac{u_p}{\sqrt{gD}} \,. \qquad ...(6)$$

Settling velocity for air flow, where is $A \leq 4{,}8$, can be calculated as:

$$u_p = \frac{(\rho_m - \rho) g d^2}{18\eta}, A = \frac{4}{3}\frac{(\rho_m - \rho) g d^3 \rho}{\eta^2} \,, \qquad ...(7)$$

where are: ρ_m – solid density, d – average diameter of solid-particle assumed as sphere, η - dynamic viscosity of air. Internal pipeline diameter can be calculated as:

$$D = \sqrt{\frac{4q}{\pi v}} \,. \qquad ...(8)$$

q is volumetric flow of air, and can be calculated from volumetric flow of air at outlet of the compressor q_c and air density at outlet of the compressor ρ_c:

$$q = q_c \frac{\rho_c}{\rho} \,. \qquad ...(9)$$

The pressure drop calculation is from the end to the beginning of the pipeline, changing the pipeline diameter. Pressure at the end of the pipeline is equal to atmospheric pressure, and in this paper it is equal to 101000 Pa. At the end of the pipeline air velocity that can be used is 20-25 m/s, and that is the maximum air velocity which can be achieved. Minimal air velocity which can be achieved cannot be smaller than 10 m/s. Additional coefficient λ_s is needed to calculate friction coefficient of solid. After calculation of the diameter it is necessary to find nominal diameter and air velocity for nominal diameter. For horizontal pneumatic conveying λ_s is equal to 0,75 [2]. Now friction coefficient can be calculated as λ_m= (0,75- λ)/μ_m. From equations (4) and (5) it is possible to calculate friction coefficient of solid. Coefficient of air friction can be calculated as [3]:

$$\sqrt{\lambda} = 1 / \left(-1{,}8 \log \left[\frac{6{,}9}{\mathrm{Re}} + \left(\frac{k / D}{3{,}7} \right)^{1{,}11} \right] \right), \qquad \ldots(10)$$

where are: Re= $v D \rho / \eta$ – Reynolds number, k - internal harshness of the pipeline. Dynamic viscosity at temperature T_2 can be calculated as [4]:

$$\eta = 17{,}6 \cdot 10^{-6} \frac{273 + 124}{T_2 + 124} \left(\frac{T_2}{273} \right)^{3/2}. \qquad \ldots(11)$$

For booth method, "step by step" and "long sections", air temperature is constant for one section. For another section air temperature is different. Air temperature at end of the pipeline can be assumed. For "step by step" method air velocity and air density are constant for each subsection (one section is made from many smaller subsection). Froude number Fr is constant for each subsection. Solid velocity is not constant. After each subsection air velocity and air density can be calculated from equation (3). For "long sections" method, Froude number Fr is constant for each section, and can be calculated from average air velocity.

3. RESULTS

Conveyed solid material is fly ash. Mass flow of solid is m_s= 25 kg/s. Solid density is ρ_s= 2200 kg/m^3. Solid-air mixing ratio is μ_m= 20 kg$_{solid}$/kg$_{air}$. Air temperature at the end of the pipeline is T= 323 K. Average particle size is d= 25·10^{-6} m. Volumetric flow of air at outlet of the compressor is q_c= 1,25 m^3/s, and air density at outlet of the compressor is ρ_c= 1,20 kg/m^3. Air velocity at the end of the pipeline is assumed. Air velocity is v= 20 m/s. Internal harshness of the pipeline is k= 0,0001 m.

Table 1. Obtained results for pneumatic conveying of fly ash with various diameter

λ_m	0,0368
λ_m^*	0,03698
u_p, m/s	0,0405
A	1,073

Table 2. Conveying conditions for the comparison of the obtained data using the experiment, simulation and λ_m – Fr method

Point	Solid mass flow, kg/kg	Mass flow of air , kg/s	Gauge pressure p_1, kPa
C2	1,3179	0,0248	37,2
C4	1,1694	0,0492	58,2
D3	0,9838	0,0324	36,9
Other parameters: conveyed solid material is fly ash, T= 300 K, D= 0,053 m, p_0= 10^5 Pa, R= 287 kJ/kgK, l= 4 m.			

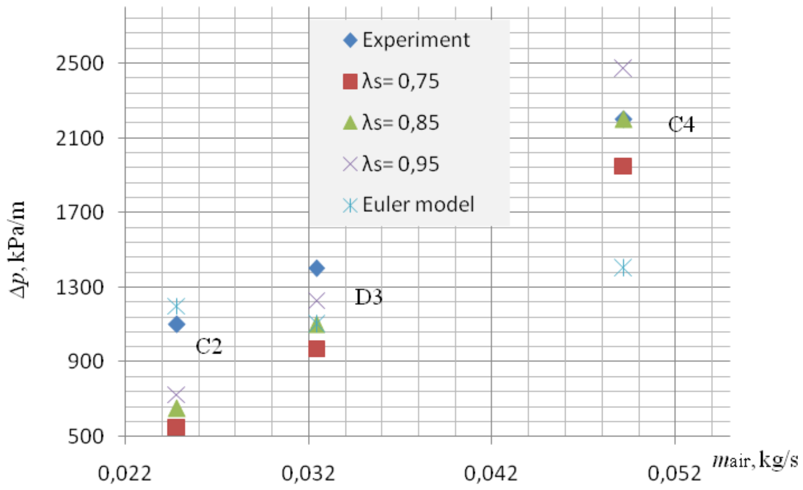
Table 3. Obtained results for horizontal pneumatic conveying of fly ash with various diameter

		Length L, m	Diameter D, m	Air velocity v, m/s	Solid velocity u, m/s	Absolute pressure p, bar	Temper-ature T, K
"long sections" method	***Section 1***	260	0,3127	10–17,87	9,96–17,51	1,81–1,01	323
	Section 2	40	0,263	13,6–15,2	13,5–15,1	2,04–1,81	343
"step by step" method	***Section 1***	260	0,3127	9,95–17,97	9,9–17,88	1,81–1,01	323
	Section 2	40	0,263	13,09–14,93	13,03–14,86	2,09–1,81	343

Table 4. Obtained results for vertical pneumatic conveying of fly ash with various diameter

		Length *L*, m	Diameter *D*, m	Air velocity *v*, m/s	Solid velocity *u*, m/s	Absolute pressure *p*, bar	Temper-ature *T*, K
"step by step" method	***Section 1***	130	0,3127	9,90–17,95	9,86–17,91	1,83–1,01	323
	Section 2	70	0,263	10,65–14,85	10,62–14,81	2,54–1,81	343

Figure 3. shows comparison between experimental and predicted data [5] and obtained data using λ_m – Fr "long section" method. As shown, additional coefficient λ_s has value 0,75-0,95. Air velocity is constant and its value is:



- C2; u=v= 8,84 m/s,
- C4; u=v= 12 m/s,
- D3; u= v= 9,15 m/s.

For point C4, best match between experiment and method is for λ_s= 0,85. For point D3 is for λ_s= 0,95. For point C2 is for λ_s= 0,95. Also, for λ_s = 0,75, λ_m – Fr method gives good results, better than Euler model.

Figure 3. Comparison of the pressure drop between experimental and predicted (Euler model) data and obtained data using λ_m – Fr "long sections" method

For the vertical pipeline pressure drop has a higher value than the horizontal one. One of the reasons for that is the changing of the coefficient of friction for solid along the vertical pipeline. For horizontal pipeline, coefficient of friction for solid is constant along the pipeline (λ^*= 0,0368).

5. CONCLUSION

To avoid clogging and damage of the pipeline during pneumatic conveying, it is the best to use various diameter of the pipeline. In this way intensity of air velocity is always in allowed values. Pressure drop can be calculated using λ_m – Fr method. Comparison between obtained data using λ_m – Fr method and obtained data using other methods shows that λ_m – Fr method is very reliable method.

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