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PARAMETRIC ANALYSIS OF VERTICAL PNEUMATIC CONVEYING SYSTEM PERFORMANCE

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Abstract: One of the most common types of material transport in different branches of industry is pneumatic transport. There are different calculation methods of this kind of transport. In one sort of this calculation the difference arises from the fact that the air by which the material is being transported can be treated as compressible or incompressible. This type of calculations is the subject of this work, as well as the influences that the physical properties of the transported material and the properties of the vertical air-lift itself have on the pressure drop that arises in the transport process. The pressure drop calculations, as well as the required velocity values with combination of the friction coefficients are being analyzed.
Keywords: air-lift, compressible flow, incompressible flow, calculation method

1. INTRODUCTION

Since the end of the nineteenth century when air first started to be used for transport of granular materials, until today, pneumatic transport as assumed a prominent place in the metallurgy, agriculture, food and chemical industry etc. Simply, when it is compared with mechanical transport, one can find whole range of benefits. Pneumatic conveying can be carried out in all directions, adapting to the available space and other conditions. Since he material is transported through the pipe, the pollution of the environment is reduced. Furthermore, pneumatic conveying requires low maintenance and low manpower costs, has multiple use – one pipeline can be used for a variety of products, and it is easily automatically controlled. Some disadvantages of this type of conveying are that there is a need for high power consumption, parts of the equipment are subjected to wear and abrasion, and incorrect design can result in degradation (damage) of transported material [7, 11].

The most secure way to design the pneumatic conveying system is for the supplier of needed equipment to build a pilot-plant system, if it is possible, in order to simulate the conditions in which the real conveying system will work. This is rarely the case, and one needs to have high level skills to design the system in a proper way. Since there are numerous calculation methods, one must be careful in selecting the right one. The literature is scars on the influence of the calculation method choice on the behavior of the conveying system. An equation for pressure drop at steady state conditions along straight sections of pipe at any inclination angle was developed in [3]. Wolfe el al. developed an equation for pressure drop in horizontal conveying system [15]. Levy et al. developed an analytical model for gas-solid suspension flow through pipe at different inclination angles [9]. Differences in pressure drop for materials with similar physical characteristics are investigated in [13]. The effects of particle size and density on the fluid dynamic behavior of vertical gas-solid transport are the subject of [12]. The influence of conveyed material particles non-sphericity was the topic of [8]. Güner studied the conveying characteristics of some agricultural seeds [5]. Liang et al. studied the influence of coal characteristics on pneumatic conveying at high pressure [10]. Chladek et al. investigated the influence of operating conditions and conveyed particle properties on vertical air-lift performance [2]. The influence of pneumatic conveying direction on the pressure drop is discussed in [1, 6].

The aim of this paper is to analyze the influence of calculation choice on the performance of the vertical air-lift conveying system. To be more exact, the authors wish to investigate the influence of air compressibility on pressure drop and other characteristics of the vertical air-lift system. The subject of this paper is also the influence of the geometrical parameters of the vertical air-lift as well as the type of conveyed material on the air-lift performance.

2. VERTICAL PNEUMATIC CONVEYING

It has already been pointed out that pneumatic conveying can take place in various directions. One of the special aspects of pneumatic transport is pneumatic conveying in vertical direction, which is often referred to as air-lift or air-lift. In fact, it is a conveying of material in vertical direction with the help of airflow at a certain velocity.

The material being transported comes from the silo and by the use of a dozer it is pumped into the fluidization chamber. In the lower part of this chamber a perforated bottom is located through which the air is forced in. The air flows through the space between material particles and fluidizes them. Fluidized material moves vertically upwards through the pipe at which end a damper is located. The role of the damper is to create a required counter pressure due to which the conveyed material "falls out" from the air flow and goes for further processing. The smallest particles of conveyed material remain in the air, hence it passes through the filter which retains this particles and cleaned air goes to the atmosphere [14].

The pressure drop during the flow of a mixture of solid particles and air is certainly greater than the pressure drop during the flow of a clean fluid. Usually it is assumed that the pressure drop of a mixture is equal to the sum of pure fluid pressure drop Δp_f and additional pressure drop due to the presence of solid particles in a fluid stream Δp_s, i.e.:

$$\Delta p = \Delta p_s + \Delta p_f . \tag{1}$$

Due to the high concentration of particles in the mixture the pressure drop of pure fluid can be neglected compared to the additional pressure drop. On the other hand, Darcy equation, i.e. Karman Kozeniev form of this equation, can be formally used for calculation of the additional pressure drop Δp_s [14, 4]:

$$\Delta p_s = \lambda_s \frac{\Phi(1-\varepsilon)}{\varepsilon^3} \frac{L}{d} \frac{\rho_f w^2}{2} . \tag{2}$$

Here λ_s is the friction coefficient between air and material particulate and depends on the Reynolds number, particulate's shape and roughness of its surface, ε is the porosity of the fluidized bed, ϕ is the shape factor, L is the lifting height, ρ_f is air density while w is the air velocity.

Flow can be considered as incompressible or compressible, and hence the differences in the calculation. Regardless of the type of calculation, the conveyed material particles are treated ass mooth equivalent spheres of certain diameter d. In this case the shape factor ϕ becomes equal to unity, and friction coefficient depends only on the Reynolds number Re. The friction between real material particles and air is not the same as friction between spheres and air. Hence a coefficient ψ_s is introduced, which indicates the difference in magnitude of real material fluidization pressure drop and the modeled one.

One of the steps of the calculation is determination of the Reynolds number for the equivalent spherical particle according to the following formula:

$$\mathrm{Re} = \frac{1}{1-\varepsilon} \frac{wd}{\nu_v} , \tag{3}$$

where υ_v is the air kinematic viscosity.

Experiments show that, regardless of the size of the spheres and their physical properties, the dependence of λ_s from Re can be displayed by the use of experimental curves:

$$\lambda_s = \frac{340}{\text{Re}}, \ \text{Re} < 1 \ \text{and} \tag{4}$$

$$\lambda_s = \frac{325}{\text{Re}} + \frac{9}{\text{Re}^{0,12}}, \ 1 < \text{Re} < 10^4. \tag{5}$$

Analysis of the influence of the counter pressure Δp_e on pressure distribution in the air-lift leads to the following expression for the case of incompressible flow of air [14, 4]:

$$\Delta p_s = g\rho_\varepsilon L + \frac{4\lambda_r \mu_r \Delta p_e L}{D}, \tag{6}$$

where: g - acceleration due to Earth's gravity, ρ_ε - bulk density, λ_r - coefficient of proportionality between radial and axial pressure, μ_r - friction coefficient between material particles and tube's wall, D - air-lift's tube diameter.

Without going into the process of equations derivation, which is available in the literature, the equation for pressure drop calculation of compressible air flow between fluidized material particles is as follows:

$$\frac{p_1^2 - p_2^2}{2p_2} = g\rho_\varepsilon L + \frac{4\lambda_r \mu_r \Delta p_e L}{D}. \tag{7}$$

Here p_1 is the pressure that has to be provided at the entrance of the air-lift's tube and p_2 is the ambient pressure.

The similarity between equations (6) and (7) is evident. Practically, the right hand side of these equations is the same and the only difference between them is on the left. In equation (6) on the left hand side is the pressure drop to be determined, while by the use of equation (7) one can directly determine the pressure p_1 that is necessary to be provide dat air-lift tube entrance.

The pressure drop is determined din the first step of the calculation, and based on that value the following calculation is conducted by iterations. Coefficient λ_s is assumed based on which Reynolds number is calculated(3). Then by using equation (4) or (5) the assumed value of friction coefficient is checked until a predetermined accuracy is achieved.

3. INFLUENCE OF PHYSICAL PROPERTIES OF MATERIALS ON THEIR FLUIDIZATION

In this paper, for three characteristic materials whose physical properties are given in Table 1, the differences in calculated pressure drop occurring independence on whether the calculation uses the expression (6) or (7) are shown. In calculations, the following values of environmental and air-lift parameters were adopted: air temperature: 20°C, ambient pressure p_2 = 1 bar; counter pressure due to the widening of pipe at the end of air-lift: Δp_e = 500 Pa.

Table 1.Conveyed material characteristics [4]

material	d, mm	ε	μ_r	λ_r	ψ_s
cement	0,07	0,663	0,5	0,3	1,12
wheat	4	0,416	0,5	0,3	1,05
soya	7	0,339	0,27	0,28	1,22

In order to provide the same air flow required for conveyed material fluidization, for all three considered materials, it was adopted: air-lift capacity: 100 t/h, mass concentration: 100 kg/kg.

Figure 1 shows the differences in pressure drop Δp^* which is obtained using equations (6) and (7). Higher pressure drop is calculated when the air flow between the fluidized material particles is considered as incompressible. It is seen immediately that the influence of the calculation method is more expressed industry materials, such as cement. The dependence of the difference in calculated pressure drops from lifting height is nearly linear, with the slope coefficient of the curve higher for dusty materials. This suggests that with the increase of lifting height, with the same air-lift's pipe diameter and the same other conditions, the influence of the calculation method is more rapidly increasing with dusty material in relation to the grain ones.

The influence of the calculation type on the friction coefficient values of equivalent spheres λ_s and air velocity w_1 for all three materials is shown in Figure 2. It is easily visible the characteristic of incompressible flow-the values of the friction coefficient as well as the velocity are constant regardless of the type of material to be transported and its lifting height.

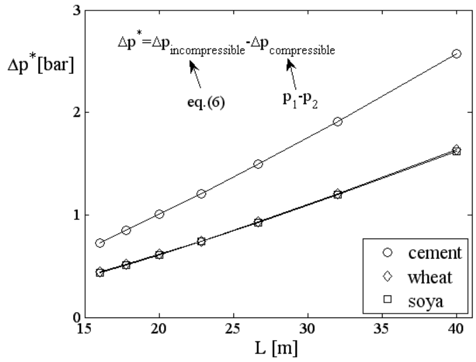

Figure 1. The difference in calculated pressure drop depending on the calculation method

Furthermore, it is visible the connection between the values of velocity and friction coefficient. Regardless of the calculation method, one can see the simultaneous increase in velocity and decrease in friction coefficient values. Here it is evident the "exchange" between the shape and the friction drag coefficients in the total drag coefficient of the materials particulate.

The differences are noticeable in terms of these values, depending on the size of the conveyed material. Thus, for example, the friction coefficient λ_s is slightly greater for wheat compared to soya, butt he same coefficient for cement is greater over a hundred times. The reason can be found in the fact that cement is one of the dusty materials with a much smaller equivalent spheres diameter compared to the other two materials (Table 1). When the calculation of the air-lift pressure drop is based on compressible air flow, this difference is even more expressed. The friction coefficient for cement is greater more than a thousand times than that for the considered granular materials.

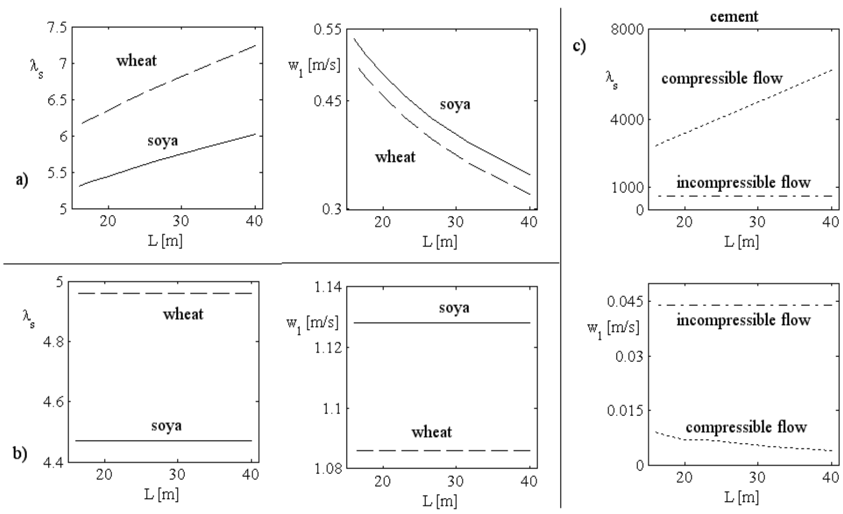

Figure 2.The effect of the calculation method on the air velocity and friction coefficient: a) compressible flow, b) incompressible flow, c) cement

Of course, given the fact that cement has such a great value of this coefficient, it is clear that the air flow velocity required for its fluidization is very small, so small that the Reynolds number is less than unity. This is not the case for granular materials. Air velocity required for soya fluidization is slightly greater compared to wheat, which is logical given the small difference in the equivalent spheres diameter by which the transported material is modeled.

It is interesting to note that although this is a calculation that is based on the compressible air flow between the particles being transported, this kind of calculation gives a smaller velocity values compared to the use of equation which treats the air flow as incompressible. This is a consequence of the way that the pressure drop is determined in these calculation methods. The pressure drop is obtained in the first step of the calculation, from equations (6) and (7). At that point any further difference regarding the calculation vanishes. In further steps of the calculation Darcy equation is used to determine the product $\lambda_s w_1^2$, regardless on the compressibility of the air flow. In order to achieve fluidization of conveyed material, the values of λ_s and of Reynolds number which is determined based on the velocity w_1 should be located on the curve that is defined by equations (4) or (5).

4. INFLUENCE OF AIR-LIFT PARAMETERS ON MATERIAL FLUIDIZATION

It often happens that the calculated values of the pressure drop are "ignored" when it is necessary to provide a higher material lifting, leaving the same system for air blowing i.e., for fluidization provision. Further analyzes gives the answer on the influence of the changes in pipe's diameter as well as the lifting height on the pressure drop. In that sense, for a constant lifting height of *L*= 20m, the influence of changes in air-lift's pipe diameter is analyzed, while the variation of conveyed material lifting height is performed for the constant air-lift's pipe diameter of *D* = 200 mm.

Regardless of whether the air flow is treated as incompressible or compressible, the change of height has a much greater impact on the pressure at the air-lift's entrance, both for grain and for dusty materials (Figure3). And not only that; At the same ratio *L*/*D*, which is obtained by changing the lifting height for constant value of air-lift's pipe diameter, for all three considered materials a greater value of pressure drop is calculated (Figure 4).

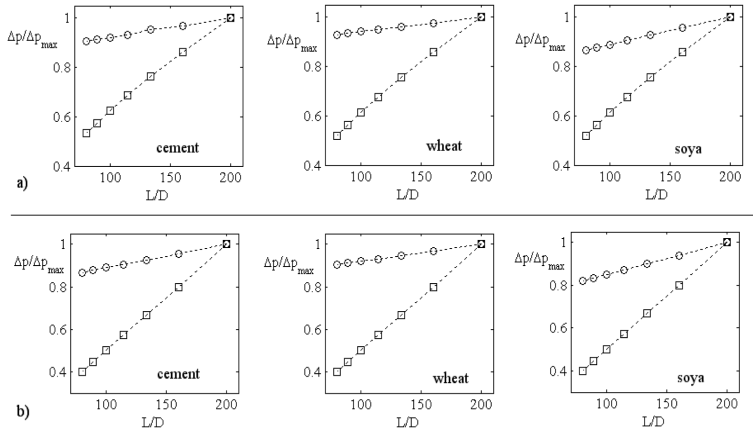

Figure 3. Sensitivity of pressure drop on the change of air-lift's pipe diameter and lifting height of the material: a) calculation based on the compressible air flow, b) calculation based on the incompressible air flow; circle- change in diameter, square-change of height

Figure 4 clearly shows that the order of magnitude of pressure drop is the same both for dusty and granular materials, regardless of the significant differences that exist in the values of other quantities important for the calculation of pneumatic conveying. However, although the pressure that has to be provided at the air-lift's entrance has almost the same value both for cement and soya, the air velocity required for fluidization is not nearly the same. While for cement fluidization the airflow velocity of 0.05 m/s is enough, for the fluidization of soya it is necessary to provide a velocity of1 m/s, as seen earlier in the text.

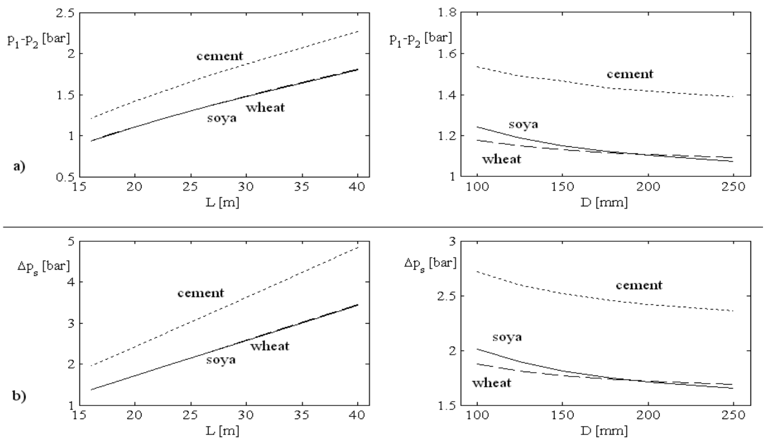

Figure 4. The influence of air-lift's diameter and lifting height on the values of pressure drop: a) compressible flow of air, b) incompressible air flow

It is noticeable the similarity in curves regardless of the calculation method. The only difference is the pressure drop value. Now, one can conclude that air-lift with one specific pipe's diameter can be used for conveying of different granular materials with the increase in pressure drop by increasing the lifting height. But, if one has an air-lift of certain height, with the change of pipe's diameter, there are some deviations in the pressure drop even for materials of the same type – in this case granular materials. Only at specific lifting height and pipe's diameter, the same air-lift can be used for pneumatic conveying of soya and wheat being materials of the same type. Obviously, pressure drop for pneumatic conveying of cement is greater, due to higher concentration of materials particles in the conveying tube.

5. CONCLUSIONS

Pneumatic conveying is a common method of transporting goods in different branches of industry but also in everyday life. The physics of this kind of material transport is rather difficult to understand, due to the fact that there are many factors influencing this two-phase flow system. Designing of such system represents a challenge for there are a variety of calculation methods for doing that.

The aim of this paper is to analyze a particular type of pneumatic conveying calculations in which the air, as transporting fluid, can be treated as compressible or incompressible. These calculations are performed for three different materials, which allowed the analysis of the influence of different parameters of conveyed material on the pressure drop. At the end a change in tube's diameter and in air-lifting height is analyzed in respect to the calculation method and calculated pressure drop.

It was shown that the greater pressure drop is obtained by the use of relations which are based on the incompressible air flow, regardless of whether it is a vertical pneumatic transport of dusty or granular materials. Not only that the influence of the applied calculation method is more evident in dusty materials, but it is more rapidly increasing also. The analysis of the velocity and friction factor between the air and transported material showed that once again dusty material has a different behavior compared to the grain ones. The value of the friction factor is several hundred times greater for cement than for wheat or soya. Because of that the fluidization velocity is comparatively smaller, but the values of the pressure drop are of the same order of magnitude for all three considered materials.

When the parameters of air-lift itself are at stake, one can conclude that the change in the lifting height has a greater influence on the calculated pressure drop, both for dusty and grain materials. There is no difference in pressure drop value for different grain materials, when for the same tube's diameter one changes the lifting height. But, that is not the case with the change in diameter for constant lifting height. Then, for only one pair of diameter – lifting height values, both soya and wheat have the same pressure drop.

It can be concluded that the designing of air-lift system is highly complex due to a great number of influencing factors, related both to conveyed material and air-lift itself. Calculations that are presented in this paper are on the engineering level of use, but they give a great insight into very complex two-phase flow field which is present in the pneumatic conveying systems.

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