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DETERMINATION OF SOLID PARTICLE VELOCITY IN A PNEUMATIC CONVEYING SYSTEM

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Abstract

Pneumatic conveying systems are pipeline systems for transport of powdered, granular, fibrous and similar solid materials in a stream of gas flow, usually air flow. The method of mathematical calculation of velocity of the transported material in pneumatic conveying systems is described in the paper. The paper also deals with the problem of numerical simulation of two-phase fluid-solid flow in the pipeline of pneumatic conveying system. For numerical simulation Ansys CFX software is used, and results are compared with those obtained by mathematical calculation. The practical example of wheat transport is investigated in the paper, which is consists of horizontal and vertical pipelines, connected by appropriate elbows.

Key words: *pneumatic conveying, air, granular material, velocity,*

1 INTRODUCTION

Pneumatic conveying is called the transport of dry bulk particulate materials (powder, granular and fibrous materials) in the air stream. Pneumatic conveying systems are pipeline systems for transport of powdered (coal dust, ash, flower etc.), granular (corn, wheat, sunflower, soybeans, sugar, fodder etc.), fibrous (sawdust and different thready material) and similar solid materials in a stream of gas flow, usually air flow. According to the specific mass flow of the transported material, so called solids loading ratio ($\mu = \dot{m}_m / \dot{m}_a$, where $\dot{m}_m$ - mass flow of the transported material, $\dot{m}_a$ - mass flow of the air), the flying pneumatic transport can be of low (μ<1), medium (1<μ<10) and high (10<μ<40) mass concentrations [1], [3].

Since the density of the transported material is higher than the density of the transport air even more than 1000 times, the volume concentration of the transported material in the pipeline does not exceed 5% even for pneumatic conveying of high mass concentration. For low mass concentration pneumatic conveying, the volume concentration of the transported material does not exceed 1% [2], [3].

If the material is conveyed in suspension in the air through the pipeline it is referred to as dilute phase conveying. If the material is conveyed at low velocity in a non-suspension mode, through all or part of the pipeline, it is referred to as dense phase conveying [4].

Pneumatic conveying system can be open and closed. Closed systems are used for the special purpose, where there is a danger of gas and/or material leakage from the system. According to the gas pressure values in the system, these systems are positive pressure, negative pressure and combined pneumatic conveying systems [4], [5], presented in Fig.1. Positions shown in Fig.1 are: 1 – blower, 2, 6 – mixer, 3, 7 – pipeline, 4, 8 - separator; 5 – dispenser.

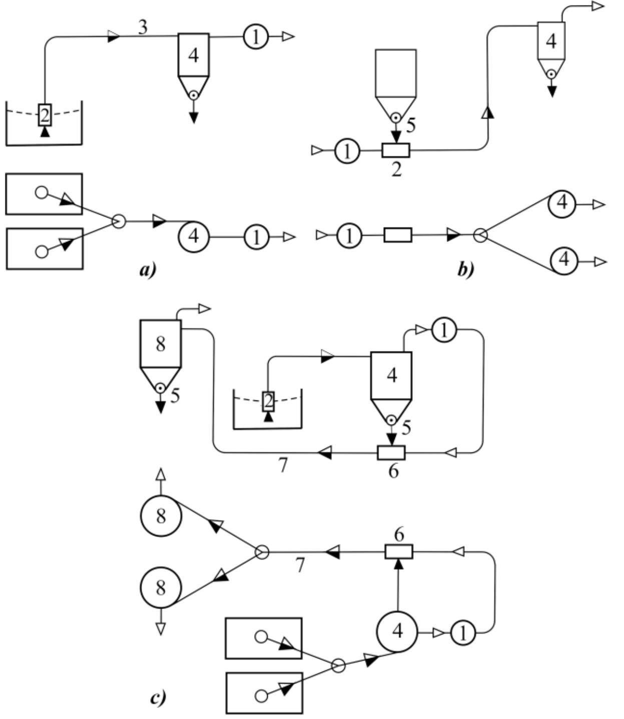

Fig. 1 *Pneumatic conveying systems a) negative pressure (vacuum) system, b) positive pressure system, c) negative and positive pressure (combined) system.*

According to the pressure drop of the transported air (Δp), the flying pneumatic transport can be low pressure (Δp<0,1 bar), medium pressure (Δp=0,1÷1 bar) and high pressure (Δp>1 bar).

In many studies, the effect of particle size on pressure drop and system operation has been studied [6], [7].

The calculation of the transport air pressure drop is usually performed according to the isothermal flow model (T=const.), and in the case of low-pressure pneumatic conveying according to the incompressible fluid model (ρ_a=const.).

Some researchers have studied the pressure drop in horizontal pneumatic conveying [8] and vertical pneumatic conveying [9], to mathematically model the system as accurately as possible.

Experimental investigations have been conducted in both vertical and horizontal pipes, giving conclusions of particle velocity and acceleration [10] and trying to contribute to better energy efficiency of the system [11].

Numerical simulations have evolved from the application of one-dimensional theories [12] to complex simulations using modern cfd software [13], [15].

2 MOVEMENT OF SOLID PARTICLES OF TRANSPORTED MATERIAL

In the general case of the inclined pipeline, the movement of solid particles of transported material in the fluid flow and the forces acting on the particles are shown in Fig.2. In the elementary volume of the pipeline, in the direction of pipeline, the following forces act in the direction of the pipeline: dF_o - drag force, dT_m – friction force of a particle and gravity component $dG_m \sin\alpha$, where: α - the angle of inclination of the pipeline towards the horizontal. It is assumed that the normal components of the gravity force of the particles, in the direction of the pipeline, are balanced by the buoyancy forces acting on the particles of the solid material.

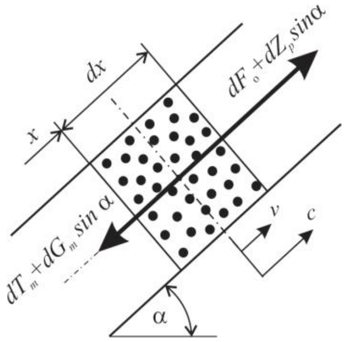

Fig. 2 *Forces acting in a pipe segment*

Differential equation of particle motion can be written:

$$dm_m \frac{dv}{dt} = dF_o + dZ_p \sin\alpha - dG_m \sin\alpha - dT_{m,}. \qquad (1)$$

By substituting the expression for forces, it is obtained:

$$\frac{dv}{dt} = g\left(1-\frac{\rho_a}{\rho_m}\right)\left[\frac{(c-v)^2}{c_o^2} - \sin\alpha\right] - \frac{\lambda_{m.\alpha}}{2D}\cdot v^2 \ , \qquad (2)$$

where: v–particle velocity, c–air velocity, ρ_a–air density, ρ_m–material density, $\lambda_{m.\alpha}$-friction coefficient of material in a straight pipeline inclined at an angle α to the horizontal.

Data on the values of the coefficients $\lambda_{m.x}$ and $\lambda_{m.y}$, for different transported materials, can be found in the professional literature, and the coefficient $\lambda_{m.\alpha}$ (for $0<\alpha<90^o$) can be calculated using the formula:

$$\lambda_{m.\alpha} = \lambda_{m.x} \cos\alpha + \lambda_{m.y}(1-\cos\alpha) \qquad (5)$$

where $\lambda_{m.\alpha} = \lambda_{m.x}$, for $\alpha=0^o$ and $\lambda_{m.\alpha} = \lambda_{m.y}$, for $\alpha=90^o$.

According to equation (2), it can be concluded that the acceleration of solid particles of material has the maximal value at the beginning of motion (v=0) and that with increasing particle velocity, their acceleration decreases. From the moment when the particles of the material reach the limit velocity $v=v_{k\cdot\alpha}$ (for dv/dt=0) their movement continues with uniform velocity, and if the condition is v<c:

$$\frac{v_{k.\alpha}}{c} = \frac{1-\sqrt{1-\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)\left[1-\frac{\lambda_{m.\alpha}}{2}\frac{Fr_o^2}{\left[1-(\rho_v/\rho_m)\right]}\right]}}{1-\frac{\lambda_{m.\alpha}}{2}\frac{Fr_o^2}{\left[1-(\rho_v/\rho_m)\right]}} \qquad (3)$$

Where Froude number $Fr_o = c_o \big/ \sqrt{gD}$, and c_o is called the floating velocity, which brings to a floating state a solid particle of material (v = 0) in the vertical flow of fluid.

If $dv/dt = v\cdot dv/dx$ and $v=\beta\cdot c$ ($\beta=v/c$), the differential equation (2) becomes:

$$dx = k \frac{\beta\, d\beta}{\frac{2\beta_{k\alpha} - \left(1-\frac{c_o^2}{c^2}\sin\alpha\right)}{\beta_{k\alpha}^2}\beta^2 - 2\beta + \left(1-\frac{c_o^2}{c^2}\sin\alpha\right)} \ ,(4)$$

where: $k = \frac{c_o^2}{g\left(1-\frac{\rho_v}{\rho_m}\right)}$, $\beta_{k.\alpha} = v_{k.\alpha}/c$, and the variable

$\beta=v/c$ changes within the boundaries $0 \le \beta \le \beta_{k.\alpha}$.

With the initial condition $\beta=0$ (v=0) for x=0 the integral of the differential equation (4) becomes:

$$x = k\left[A_\alpha \ln\frac{\beta_{k.\alpha}}{\beta_{k.\alpha}-\beta} - B_\alpha \ln(1+a_\alpha\beta)\right]$$

$$for\ \ \beta_{k.\alpha} \neq \frac{1}{2}\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)$$

$$x = k\left[\frac{1}{2}\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)\ln\frac{1-\frac{c_o^2}{c^2}\sin\alpha}{\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)-\beta} - \beta\right] \qquad (5)$$

$$for\ \ \beta_{k.\alpha} = \frac{1}{2}\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)$$

where:

$$A_\alpha = \frac{\beta_{k.\alpha}^2}{\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)-\beta_{k.\alpha}} \ , \quad a_\alpha = \frac{\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)-2\beta_{k.\alpha}}{\beta_{k.\alpha}\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)}$$

$$B_\alpha = \frac{\beta_{k.\alpha}^2\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)}{\left[\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)-2\beta_{k.\alpha}\right]\left[\left(1-\frac{c_o^2}{c^2}\sin\alpha\right)-\beta_{k.\alpha}\right]} \ .$$

In the elbows of the transport pipeline, a centrifugal force acts on the particles of the transported material, which can be several times greater than the weight of the particles:

$$dF_c = \frac{v^2}{R_s} dm_m \ , \qquad (6)$$

where F_c - centrifugal force, R_s – radius of the external elbow curvature.

Gravitational force and friction force also act on solid particles. For different elbow position, different differential equations of particle motion are obtained [2].

Here are going to present the solution of two cases (Fig.3), which are later use in the practical example of pneumatic conveying of wheat.

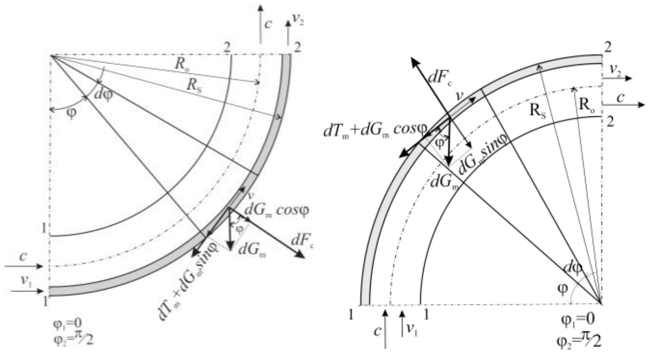

Fig. 3 *Illustration of elbows for eq. (7) and eq. (8)*

For the case given in Fig. 3a, velocity on the outlet cross-section of the elbow can be calculated by a formula [2]:

$$v_2=\frac{1}{e^{\frac{\pi}{2}\cdot f}}\sqrt{v_1^2-\frac{2gR_s}{4f^2+1}\left[\left(1+3fe^{\pi\cdot f}\right)-2f^2\right]}\,, \qquad (7)$$

and for the case given in Fig. 3b:

$$v_2=\frac{1}{e^{\frac{\pi}{2}f}}\sqrt{v_1^2+\frac{2gR_s}{4f^2+1}\left[3f+e^{\pi\cdot f}\left(2f^2-1\right)\right]}\,, \qquad (8)$$

3 NUMERICAL SIMULATION OF PNEUMATIC CONVEYING

An example of pneumatic conveying system is consists of one horizontal and one vertical pipeline, connected by elbows, as shown in Fig.4. Pipe diameter is 125 mm, with a wall roughness of 2 μm. This system is used for pneumatic transport of wheat, which has a density ρ_m=1350 kg/m^3 and its floating velocity c_o=9,5 m/s. Mass flow rate of the transported wheat is $\dot{m}_m$ =2 kg/s. Three values of transport air velocity are considered in the paper: 20, 24 and 30 m/s.

The pneumatic conveying system was calculated and numerically simulated, using the ANSYS CFX software. The task was to determinate the velocity of the transported material and the pressure drop in the system.

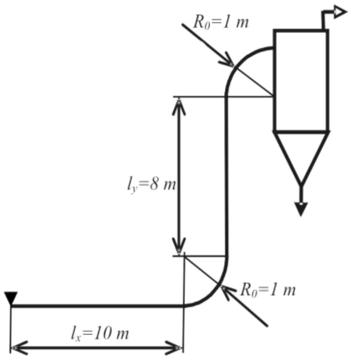

Fig. 4 *Scheme of pneumatic conveying*

Geometric model and the discretization mesh were developed in ANSYS ICEM CFD. The mesh is consist of 342023 nodes and almost million elements, which are mostly tetrahedral, with prismatic elements along the pipe walls (Fig.5). The meshing is refined in the vicinity of the walls and the average value of y+ is around 35. Grid independent test showed that the mesh is adequate regarding the number and quality of elements.

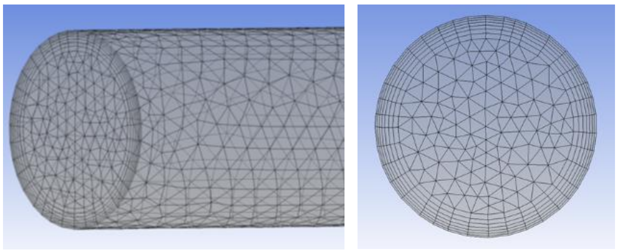

Fig. 5 *Discretization mesh of the pipeline*

The standard k-ε turbulence model is used. Interpolation of values is done using the high-resolution scheme and the convergence criteria were that the rms values of the residuals are smaller than 10^{-4}.

The multiphase model used in Ansys CFX is Eulerian-Eulerian multiphase flow model. Fluid (air) and particle (wheat) was defined in a basic setting, as an interface transfer is chosen Particle model. The Particle model for interfacial transfer between two phases assumes that one of the phases is continuous (phase A) and the other is dispersed (phase B) [16]. The surface area per unit volume is calculated by assuming that phase B is present as spherical particles of mean diameter d_B. Using this model, the interphase contact area is [16]:

$$A_{AB}=(6\cdot r_B)/d_B\,, \qquad (9)$$

Where r_B is a minimum volume fraction to ensure the area density does not go exactly to zero.

Numerical simulations are conducted for three different values of air velocity (c=20 m/s, 24 m/s and 30 m/s), according to recommendation given in literature.

Velocities of transported solid particles are obtained by numerical simulations and these values are compared with results obtained by calculations. There are differences in velocity values in the control sections along the pipeline, as it can be seen in Fig. 6, 7 and 8.

Control sections are: 1. and of the horizontal pipeline (entrance to the elbow), 2. entrance to the vertical pipeline (exit from the elbow), 3. exit from the vertical pipeline (entrance to the elbow) and 4. exit to the elbow.

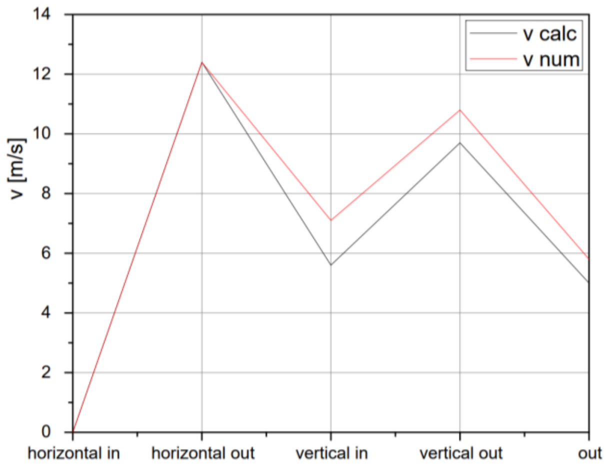

Fig. 6 *Particle velocity distribution along the pipeline for air velocity c=20 m/s*

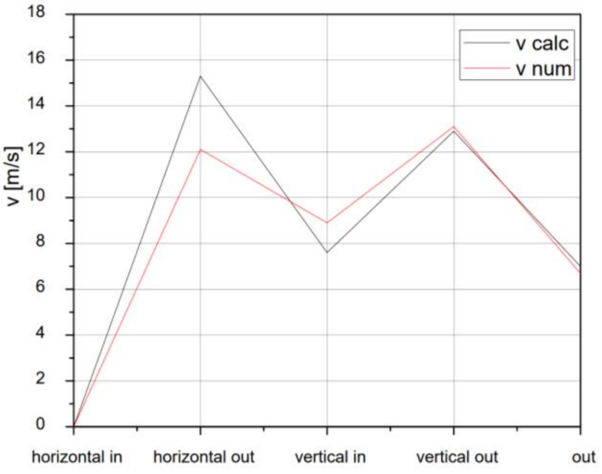

Fig. 7 *Particle velocity distribution along the pipeline for air velocity c=24 m/s*

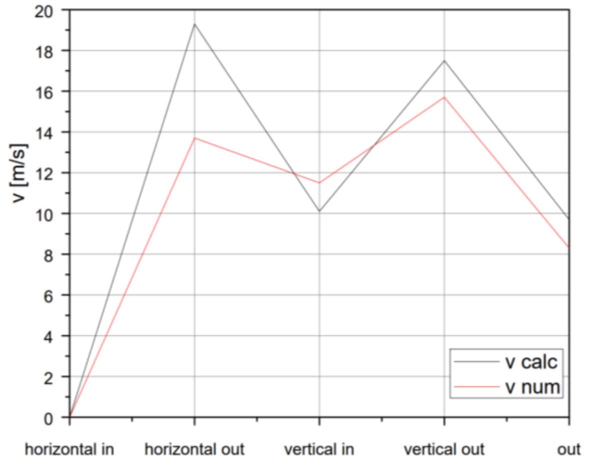

Fig. 8 *Particle velocity distribution along the pipeline for air velocity c=30 m/s*

As the velocity of the transported air increases, so does the difference in the value of the transported material velocities. The differences in velocity values are a consequence of a very complex mathematical modelling of two-phase fluid-solid flow.

4 CONCLUSION

Pneumatic transport is a very useful way of transporting bulk material by pipeline. An example of pneumatic conveying system was calculated using the equations presented in the paper. Also, numerical simulations of multiphase flow (fluid-solid) were performed, for 3 different values of transport air velocity. Analytically and numerically obtained results match satisfactorily, showing good agreement of solid phase velocity values along the pipeline. The differences of the obtained results in control cross-sections along the pipeline are the result of very complex two-phase flow.

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