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Air mass balance for mass flow rate calculation in pneumatic conveying

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ABSTRACT

Mass flow rate of solids is probably the most important parameter in pneumatic conveying systems. It is a challenging task to measure this parameter in gas–solid flows.

A new and simple model is presented and described to calculate the mass flow rate of solids in pneumatic conveying systems, based on air flow and pressure measurements. The principle of the model is conservation of mass, and it is applied in a horizontal straight pipe section. Two tests need to be performed on the actual conveying rig to be used for calibration of the model. Due to the kind of sensors used to carry out the necessary measurements, application of the model is rather inexpensive and non-intrusive.

The model has been validated successfully with data from two different single blow tank conveying systems and in dense and dilute phase conveying. Four test materials were used for validation of the model: alumina, baryte, cement and dextrose.

Provided that the requirements to apply the air mass balance model are fulfilled, its effective widespread application on real industrial systems seems plausible.

1. Introduction

Pneumatic conveying systems are used widely in a variety of industrial settings since several different types of materials can be conveyed [1].

Mass flow rate of solids is probably the most important parameter to measure in this kind of systems since it is vital for effective operation and control of the process. However, the nature of gas–solids flow makes measuring mass flow rate of solids much more complicated in relation to liquid or gas (single-phase) flows. The properties of the conveyed solids vary greatly from material to material and have a major influence in the process. In addition, as mentioned by Kost et al. [2], the varying properties of solids also cause variations from measurement system to measurement system.

Throughout the years, several techniques, models and simulations have been made in order to understand the flow in conveying pipelines. They have estimated the mass flow rate directly or by two separate measurements of concentration and velocity; each one of them showing strengths and weaknesses. Several mass flow meters have been developed based on different principles such as ultrasound, capacitance, electrostatics, pressure, microwave, tomography and so on [3–5] though none of them has become a standard for mass flow rate measurement in industry.

An ideal gas–solid flow meter should be non-intrusive, rugged, require little or no calibration, have a broad temperature range for operation, be independent of solids and gas types, be independent of particle size and inexpensive [3]. In addition, the flow meter should show accuracy and reproducibility. It is very challenging to achieve all these characteristics in a gas–solids flow meter, therefore, research is ongoing.

Research on mass flow measurement with the use of pressure sensors has been done in the past. In 1992, a differential pressure based gas–solid flow meter was developed by Cabrejos and Klinzing [6], later on, a flow meter based on pressure drop over a standard section of piping was developed for dilute phase conveying [7]. A system including a differential pressure transducer, a capacitance sensor, a pressure transducer and a temperature transducer was developed for measuring powder flow rate by Huang et al. [8]. A model based on pressure drop was defined and used for mass flow rate measurement in vertical conveying [9].

In the present paper, a model based on pressure and air flow measurements was developed to calculate mass flow rate of solids in dilute and dense phase pneumatic conveying.

2. Model

2.1. Known parameters

— Particle density
— Gas properties

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- Pipe diameter
- Pipe section length
- Air volume flow in the system
- Pressure in a horizontal pipe section

2.2. Assumptions

- Isothermal conditions are considered during the conveying cycle and along the system.
- There is no accumulation of mass in the pipe section and no reflux of solids.
- Steady state, one-dimensional flow
- The velocity of the mixture (gas and solids) is the same as the velocity of air only.
- Uniform gas and solids velocity over the cross section of the pipe
- Compressible flow

2.3. Model description

A horizontal pipe section is considered for the model (control volume). See Fig. 1. The model is basically an air mass balance model.

Since it is assumed that there is no accumulation of mass in the pipe section,

$$\dot{m}_{ai} = \dot{m}_{ao} \tag{1}$$

The volume of the pipe section is partly filled by solids and the rest of it is filled by air,

$$V_p = V_s + V_a \tag{2}$$

The mass of air in the pipe section is given by Eq. (3) after multiplying Eq. (2) by ρ_a.

If the pipe section was filled with air only, the mass of air would be given by Eq. (2),

$$\rho_a V_p = V_s \rho_a + \rho_a V_a \tag{3}$$

To find mass of solids Eq. (3) is multiplied by ρ_s/ρ_a,

$$\rho_s V_p = V_s \rho_s + \frac{C\rho_s}{\rho_a} \tag{4}$$

where

$$C = \rho_a V_a \tag{5}$$

C can be calculated and it represents mass of air (kg) contained in the pipe section.

Therefore, the mass of solids contained in the pipe section under study at a time t is:

$$m_s = \rho_s V_p - \frac{C\rho_s}{\rho_a} \tag{6}$$

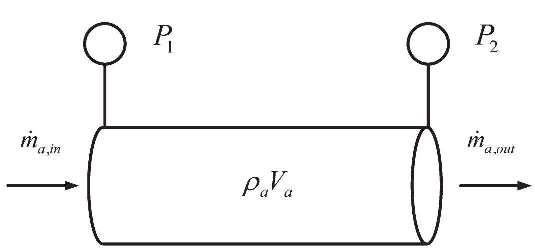

Fig. 1. Scheme of the pipe section.

In order to calculate ρ_a under isothermal conditions, and taking into account the compressibility effect:

$$\rho_a = \rho_g \frac{\bar{P} + 1.013}{1.013} \tag{7}$$

With the purpose of calculating the mass flow rate of solids, it is necessary to calculate their velocity. The velocity of the mixture is approximated by calculating the velocity of air. Taking into account the compressibility effect, the volume flow rate of air at the position where the pressure transducer is located (P_1 in Fig. 1) is,

$$\dot{V}_1 = \frac{1.013 \cdot Q}{(P_1 + 1.013) \cdot 3600} \tag{8}$$

Velocity at the position of P_1 is,

$$v_1 = \frac{\dot{V}_1}{A} \tag{9}$$

Likewise the velocity at the position of P_2 (see Fig. 1), v_2 is calculated. Then, the average velocity of the pipe section is,

$$\bar{v} = \frac{v_1 + v_2}{2} \tag{10}$$

The time it takes for the solids to move from the position of the first transmitter to the position of the second transmitter is,

$$t = L/\bar{v} \tag{11}$$

Finally, the mass flow rate of solids is calculated by:

$$\dot{m}_s = \frac{m_s}{t} \tag{12}$$

$$\dot{m}_s = \frac{\rho_s \bar{v}}{L}\left(V_p - \frac{1.013C}{\rho_g\left(\bar{P} + 1.013\right)}\right) \tag{13}$$

3. Experimental work

3.1. Particulate materials

Four different materials were used for the experimental tests (see Table 1):

- Alumina of the quality used as raw material in aluminium industry.
- Baryte used as a weighting material for drilling operation.
- Cement of oil well quality used for the casing operation in oil drilling.
- Dextrose monohydrate used in both food and pharmaceutical applications.

3.2. Experimental rigs

Two different pneumatic conveying experimental rigs that are available at the Department of Powder Science and Technology

Table 1
Characteristics of the materials.

Material	Mean particle size (microns)	Particle density (kg/m^3)
Alumina	97.5	2000
Baryte	17.5	4500
Cement	12.8	3120
Dextrose	138.2	1522