A new model for mass flow measurement in pneumatic conveying

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ABSTRACT

Mass flow rate measurement is a key element in pneumatic conveying systems irrespective of the industry in which these systems are used. Extensive research has been conducted in this area in the past few decades and many techniques have been developed. Nevertheless, most of the research conducted so far has been tested in laboratory scale plants and only a few attempts have been performed in real industrial settings. The techniques available, mostly calculate mass flow rate indirectly, by obtaining separate measurements of solids velocity and concentration. These measurements have high demands on instrumentation considering the inherent characteristics of the pneumatic conveying process. In this paper a new model for determination of mass flow rate is introduced. For the application of the technique only on-line pressure measurements from a section of the pipeline are necessary, implying that the technique does not pose high demands on instrumentation. Further, the model is experimentally validated for a powder Type A (according to Geldart classification). It is shown that the average error is 0.1 %.

1 INTRODUCTION

Pneumatic conveying of particulate materials is widely used in several kinds of industries, including the food processing industry, chemical, power generation, mining and many others. In these systems, measuring the mass flow rate is an important aspect due to the fact that it is related to the control of product quality and process efficiency. However, measuring mass flow rate represents a challenge because of the fluctuations in solids velocity and concentration in time and space.

Since the stream transported by pneumatic conveying comprises more than one phase, problems arise when it comes to instrumentation to perform the measurements. There are many methods that have been developed for this purpose. Some of them are inferential; meaning that the mass flow rate is obtained from separate measurements of solids velocity and solids concentration. These measurements are then combined to obtain the mass flow rate in the system. Other methods such as the thermal ones measure mass flow rate directly. The measurement techniques already developed use sensors based on several principles as well such as microwave, gamma radiation, ultrasonics, electrostatic and capacitance for example. Process tomography has also been used to get a better understanding of the flow. These methods have been reviewed elsewhere [1], [2]. Each one has its own advantages and disadvantages. Among others, important desirable characteristics in these techniques are non intrusiveness of the sensors, accuracy and robustness.

In the present paper, a new model for mass flow rate calculation of a powder Type A (according to the Geldart classification) [3], is suggested. The main novelty of the work presented here lies in the simplicity of the measurement system used to calculate an accurate mass flow rate in the pneumatic conveying experimental rig.

2 PROPOSED MODEL

For the application of this model only one section of the pipeline in a pneumatic conveying system is used for the calculation of mass flow rate. The model proposed is empirical and it is as follows:

$$\boxed{\frac{dm}{dt} = \rho_S V_{pipe} \frac{P(Q)}{(\overline{P})^2} \frac{d\overline{P}}{dt}}$$

where *dm/dt* is the mass variation in time contained in the volume of the pipe section evaluated, whereas *P(Q)* is the absolute pressure value at which m =0 and it is a function of *Q* (air flow rate), $\overline{P}$ is the average absolute pressure in the pipe section evaluated, ρ_s is the density of the solids transported and V_{pipe} is the volume of the section of the pipe under study.

The most important advantage of the model is that it only requires the measurements of pressure between two points in a conveying pipe to calculate the mass flow rate of a Geldart Type A powder.

3 EXPERIMENTAL WORK

3.1 Experimental setup

The pneumatic conveying rig available at POSTEC (Department of Powder Science and Technology) of Tel-Tek (Telemark Technological Research and Development Centre) was used for the experimental tests. See Figure 1.

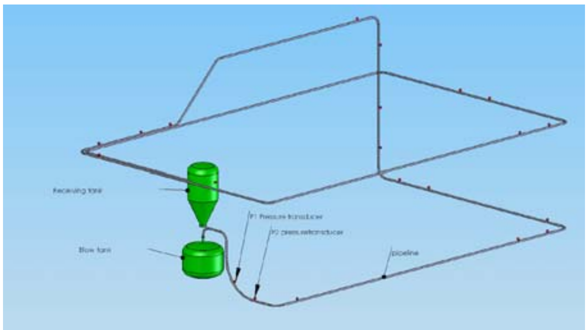

Figure 1: Schematic diagram of the experimental setup.

The rig comprises a blow tank of 3.5 m^3, a receiving tank of 2.6 m^3 mounted on load cells to measure the mass at the end of the line, and a set of pipes which are horizontal, vertical as well as bends. The total pipeline length is 140 m. Several pressure transducers are located at different sections of the pipeline. Two air flow meters are also available in the system, one at the beginning of the line and one at the end.

3.2 Experimental procedure

Several tests were performed with a powder Type A of density 3120 kg/m^3 at pressure values ranging from 3 to 4 bar. During the tests pressure signals were recorded as well as the load collected at the receiving tank. See figure 2.

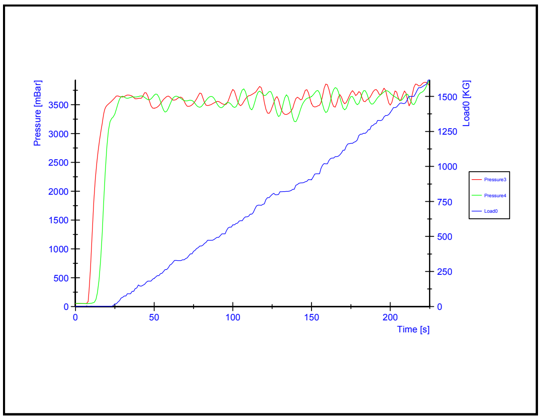

Figure 2: Example of pressure signals and load measurement recorded during a test.

The experimental tests were programmed as follows:

a) Calibration step

In order to determine *P(Q)*, which is an unknown parameter from the model, the criteria of having constant air volume flow rate was followed. Linear regression was applied in order to choose a value of *P(Q)*, such that the error between the mass flow rate calculated to the mass flow rate measured by the load cells would be 0.1% (corresponding to instrument error).

b) Cross-validation step

Tests were used in order to cross-validate the mass flow rate model.

4 RESULTS AND DISCUSSION

Figure 3 and 5 show two tests results with the curves of mass accumulated in the receiving tank (in red) which are obtained from the load cells located at the end of the line; while the curves in yellow show the mass accumulated in the tank which is calculated using the model. Figure 3 shows the curves obtained for the calibration step and figure 5 shows the curves obtained for the cross-validation step.

It is clear from observing the calculated and measured curves that the measured curve shows fluctuations while the calculated curves are totally smooth. This is due to the fluctuations of air flow rate which were not taken into account in the mass flow rate calculation in any of these tests. For the particular cases presented here the air flow rate showed low variation (see values of σ_q from Tables 1 and 2).

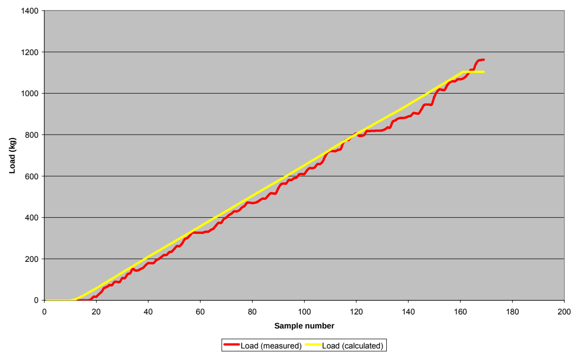

Figure 3: Calibration curve (test A). Blow tank pressure=4 bar.

It is important to point out that there is a time delay present since the mass collected is measured at the end of the pipeline but in order to calculate the mass flow with the model, pressure data from the initial section of the pipeline was used. Moreover, the start and end of each test is not clearly determined in some cases since there can be still some powder left in the pipeline when the tests are stopped.

In Table 1 the parameters obtained from the calibration test are shown. Linear regression was applied to the results of this test and *P(Q)* was found to be 1.93. To obtain *P(Q)* the mass flow rate calculated curve was compared against the mass flow rate measured curve to get an error close to the instrument error (0.11%). This resulted in an error of 29.3±16.7 kg of the calculated mass when compared with the mass measured with the load cells.

Table 1: Parameters calculated from test A.

$\overline{Q}$ (m^3/h)	σ_Q (m^3/h)	$P(Q)$ (bar)	% error in mass flow rate	Error (kg)
295.4	80.7	1.93	0.11	29.3±16.7

The error between the mass flow rates calculated and the mass flow rates measured was analyzed. From this analysis it was very clear that the mass flow rates calculated have a trend of being lower than the mass flow rates measured. This is shown for test A in Figure 4.

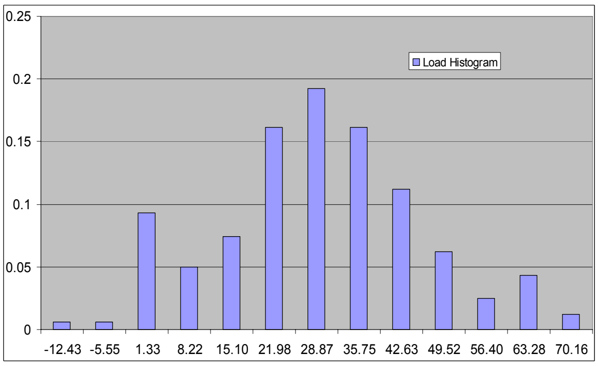

Figure 4: Frequency distribution of the error between the mass flow rate calculated and the mass flow rate measured in the calibration test.

The value of 1.93 for *P(Q)* obtained from the calibration test was tested with another data set in order to achieve a cross-validation of the mass flow rate calculation. Some important parameters obtained from this test are shown in Table 2.

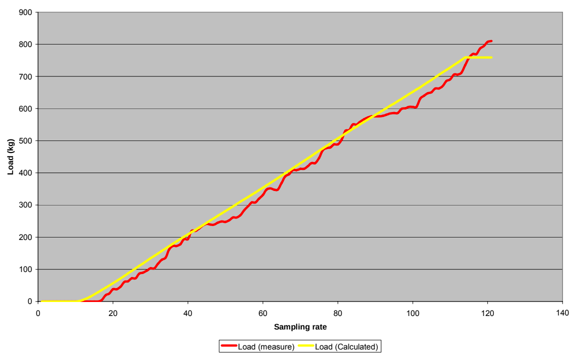

Figure 5: Cross-validation curve (test B). Blow tank pressure=4 bar.

It is clear from both tests that the mean air volume flow rate ($\overline{Q}$) is similar and since both tests were performed also under the same tank pressure, it is expected to have similar conveying characteristics for the same powder. In addition, the standard deviation values of the air volume flow rate are very close to each other and they are low indicating that there was a low variation of air volume flow rate around the mean value. Therefore, it was not necessary to take into account air flow variation into the model and the calculation showed very good results.

From the cross-validation test an error of 0.1% in the mass flow rate was found, which is lower than the error from the calibration test implying that the value chosen for *P(Q)* was accurate. In addition, the error between the mass measured and mass calculated is low (24.9±16.1 kg) and similar in both tests. The fact that the value of *P*, namely the absolute pressure value where there is no mass transport (m =0) is related to the air volume flow rate, can be inferred from the results obtained.

Table 2: Parameters calculated from test B.

$\overline{Q}$ (m^3/h)	σ_Q (m^3/h)	% error in mass flow rate	Error (kg)
295.3	82.4	0.1	24.9±16.1

5 CONCLUSIONS

The proposed model is able to calculate the mass flow quite accurately showing a small deviation with a trend of calculating values lower than measured in the pneumatic conveying rig used. The model has been tested and proved to be successful whenever the air flow rate does not show high variation since the value of *P* from the model is a function of *Q*.

The model was validated for a powder Type A and density of 3120 kg/m^3. Further work needs to be done with the purpose of testing different ranges of air volume flow rate in order to find their corresponding function *P(Q)*.

ACKNOWLEDGEMENT

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