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Methods for in-situ porosity determination of moving porous columns and application to horizontal slug flow pneumatic conveying

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ABSTRACT

Two methods were developed to investigate the porosity of moving slugs in situ during horizontal slug flow pneumatic conveying. The first method consists in applying a permeability model in combination with measurements of pressure loss and fluid velocity along the slugs. A review of existing models describing the resistance of porous structures to fluid flow revealed that the semi-empirical model of Ergun is particularly suitable to investigate the porosity profile along moving slugs. The second method consists in a direct determination method involving a slug-catcher able to catch a moving slug in a fraction of a second and simultaneously separate it into three horizontal layers. Those two methods were applied to analyse the porosity of naturally occurring slugs during pneumatic transport of polypropylene pellets. It was found that in contrast to common belief, slugs are slightly fluidised structures that do not display any porosity gradient over the pipe cross-section height. The slug porosity appeared independent of the gas conveying velocity, all slugs displaying an average porosity around 0.41, which is slightly higher than the bulk porosity of 0.38. Most of the slugs displayed a rear that is denser than the front. However, some slugs had a front that is denser than the rear while other slugs displayed a relatively constant porosity over the entire length. Those unique results refuting the commonly used hypothesis that slugs are compact structures give a new incentive to the area of slug flow pneumatic conveying. While bulk solids mechanics can no longer be applied to explain the stresses induced by moving slugs, the validity of other theories that imply that slugs are fluidised structures should be investigated.

1. Introduction

Even though pneumatic conveying of particulate solids is one of the innovations that characterise industry of the 19th century, this transport method represents a wide and on-going subject of research in both industry and academia. Most of the theoretical work deals with the systematisation or prediction of the relevant design parameters such as pressure, mass flow rate and velocity of both gas and solid phase to provide plant designers with diagrams, tables and equations easy to handle. While this has been satisfactorily achieved in the field of high velocity pneumatic conveying by integrating friction factors as in the transport of gas alone, the design of low velocity pneumatic conveying systems and particularly slug flow conveying systems still remains a problem. This is because the complex physical mechanisms involved in the transport of high particle concentrations in a gas phase have still not been fully understood, making the physical and mathematical description of slug flow conveying processes a real challenge. The complexity of the task is further enhanced by the fact that the particle and slug characteristics determining the pressure drop such as slug porosity and stress states are difficult to measure experimentally. In fact, because slug flow is a dynamic process, the measurements must be performed in-situ during conveying operations by using non-intrusive methods consisting either of measuring devices especially developed for this application or high-technology equipments such as PET (Positron emission tomography) and PEPT (Positron emission particle tracking) systems rarely available for this application. For those reasons, the existing models for slug flow pneumatic conveying rather rely on assumptions, which have never or rarely been verified experimentally. In particular, most models assume that slugs are particulate structures somewhat compressed by the pressure difference existing between rear and front. Therefore, the high pressure loss occurring during slug flow pneumatic conveying is assumed to result from the transfer of axial stresses into radial direction by interparticle contacts similarly to the Jenike silo theory [1]. Further, the Mohr circle is applied to describe the stresses acting on a moving slug under the premise that either passive or active stress case, i.e. pushing of pulling failure occurs. While those assumptions seem to have been widely accepted since the publication of a slug flow model by Konrad in 1980 [2], no experimental validation can be found. As a result, and because of the high complexity and lack of reliability of the existing models, those are rarely used and the designers are left with the dilemma of either investing into cost

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and time intensive trials usually performed in scale 1:1, or turning to high velocity pneumatic conveying.

Key parameter of slug flow pneumatic conveying is the slug porosity, which strongly determines the nature of the physical mechanisms involved in slug flow. If slugs are packed moving beds, bulk solids mechanics can be applied to describe the stresses induced by moving slugs. On the other hand, if slugs are fluidised structures, the porosity will determine the degree of permeability and resistance of the plug to fluid flow. In fact, Aziz and Klinzing [3] were concluding from experiments where they conveyed plugs of fine powder whose front and back section had been previously consolidated that the transport of material appears easier if a certain amount of permeation is possible. Attempts to measure the density of material in a pneumatic conveying pipe were made by Mason [4] and Williams [5] who used capacitance techniques to measure the average density at a pipe cross-section and the density profile across pipe cross-section, respectively. However, none of the tests were performed on slug flow pneumatic conveying. Kuang [6] used discrete particle simulation to investigate the porosity distribution within a slug of Polyethylene pellets and found that the average solid concentration of a slug across the pipe cross-section fluctuates around a constant that is lower than the bulk density, a new result that supports the need for experimental validation.

This paper focuses on the development and application of experimental methods to investigate the porosity of moving slugs. The most relevant existing models describing the resistance of porous structures to fluid flow are reviewed with respect to their applicability in the field of pneumatic conveying and especially slug flow. The goal is to find a model suitable to investigate the porosity of moving slugs based on simple measurements such as pressure and velocity. Besides, a slug-catcher was developed to provide a direct measurement of the slug porosity. Both methods were applied to slug flow pneumatic conveying of plastic pellets in an industrial scale pilot plant.

2. Gas permeation through bulk materials—A review of existing models

2.1. Existing models and their applicability in pneumatic conveying

The most relevant existing models describing fluid flow through porous structures can be classified into three categories depending on the approach the authors used for their development: voids modelling, dimensional analysis or particle force balance. Blake [7], Kozeny [8], Carman [9], Ergun [10] and Batel [11] used a similar approach to Hagen–Poiseuille's [12] to model the voids in a bulk material and obtain a relationship between pressure loss and fluid velocity. Later, Rumpf [13] criticised those porosity functions which are based on experimental investigations previously published in the literature and numerous assumptions, especially with regard to geometric modelling of the voids. He proposed instead to use the approach of dimensional analysis. Finally, other authors chose to approach the concept of fluid flow through packed columns by applying a force balance on single particles. This is the case of Burke and Plummer [14] and later Molerus [15].

A comprehensive review of those models was realised with the goal of establishing whether they can be used to investigate the permeability of moving slugs. The details of the review will be published in a separate paper but the main findings are summarized here. The models of Batel, Rumpf, and Burke and Plummer were found not to be suitable for this application for the following reasons. The relationship between porosity ε and relative velocity v_f defined by Batel as $v_f \sim \frac{\varepsilon^2}{(1-\varepsilon)^2}$ was proved to not be valid when Donat [16] showed the existence of the correlation $v_f \sim \frac{\varepsilon^3}{(1-\varepsilon)^2}$. Furthermore, even though the model of Burke and Plummer was developed for both viscous and turbulent flow conditions and expressions for each flow regime were obtained, it was found that only the kinetic flow case (turbulent flow) is applicable, which is supported by the findings of Kozeny [8], Ergun [10], Leva [17] and Carman [9]. Finally, the Rumpf model developed on the basis of dimensional analysis was limited in its development and offered a qualitative relationship between physical parameters including pressure loss ΔP, fluid velocity v_f and bed porosity ε rather than an expression to describe the permeability quantitatively.

On the other hand, the three models of Carman–Kozeny [8], Ergun [10] and Molerus [15] were found to be suitable for application in pneumatic conveying from a theoretical point of view. For this reason, their concepts are detailed below and critically reviewed.

2.2. Gas permeation models applicable in pneumatic conveying

2.2.1. Blake, Kozeny and Carman

Similar to Poiseuile [12], Kozeny [8] derived an equation for the fluid velocity by modelling the voids in a bulk material. He assumed the granular bed to be equivalent to a group of parallel, similar channels, so that the total internal surface and the total internal volume are equal to the particle surface and the pores volume, respectively, in the bed itself. He applied the assumption of Dupuit–Forchheimer [18] to take into account the higher velocities in the pores in comparison to the apparent velocity and obtained Eq. (1). Eq. (1) had also previously been reported by Blake [7] while establishing plots illustrating the relationship between the friction factor, defined by $\frac{\Delta P \cdot d_p}{\rho_f \cdot v_f^2 \cdot L_{bed}}$ and the particle Reynolds number $Re_p = \frac{\rho_f \cdot v_f \cdot d_p}{\eta_f}$ for both narrow and wide particle size distributions.

$$v_f = \frac{\varepsilon^3}{k \cdot \eta_f \cdot S_p^2} \cdot \frac{\Delta P}{L_{bed}} \tag{1}$$

where k is a dimensionless constant, η_f is the fluid dynamic viscosity, S_p is the area of particle surface per unit volume of packed space and L_{bed} is the bed length.

Kozeny also considered the fact that due to the sinuous flow of the fluid through the packed bed, the fluid rather travels through the length L_e than the bed length L_{bed}, thus leading to Eq. (2).

$$v_f = \frac{\varepsilon^3}{k_0 \cdot \eta_f \cdot S_p^2} \cdot \frac{\Delta P}{L_{bed}} \cdot \left(\frac{L_{bed}}{L_e}\right)^2 \tag{2}$$

Where the value for the expression $k_0 \cdot \left(\frac{L_e}{L_{bed}}\right)^2$ and hence k was determined from experimental investigations to be about 5.

Later, Carman [9] implemented the particle sphericity or shape factor ϕ to consider non-spherical particles and eliminate the surface area S_p. He obtained the following expression generally known as the Carman–Kozeny equation:

$$\frac{\Delta P}{L_{bed}} = K_C \cdot \frac{(1-\varepsilon)^2}{\varepsilon^3} \cdot \frac{\eta_f}{d_p^2 \cdot \phi^2} \cdot v_f \tag{3}$$

where K_C is a material constant determined by Carman to equal 180 and d_p is the particle diameter. It should be noted that the correlation $v_f \sim \frac{\varepsilon^3}{(1-\varepsilon)^2}$ given by Eq. (3) was also established by Donat [16].

The Carman–Kozeny equation (Eq. (3)) represents one of the most elaborate forms of the permeability equation based on the approach of Poiseuille. It was developed in an attempt to provide a general equation applicable in a wide range of application. Nevertheless, Ergun suggested that the Carman–Kozeny equation is only applicable in laminar flow conditions since the Blake plot leads exactly to the model of Carman when applied on laminar flow conditions [10]. Carman himself found a greater deviation of the model in turbulent flow and attributed this phenomenon to greater influence of the particle shape in this flow region.

Whether the constant K_C is a strength or weakness of the model was also subject to discussions: Strength because results of satisfactory accuracy can be achieved even without exact knowledge of certain