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Application of the principles of gas permeability and stochastic particle agitation to predict the pressure loss in slug flow pneumatic conveying systems

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ABSTRACT

This paper focuses on the development and applicability of a single slug or total slug model that combines the concepts of gas permeability through bulk material (Ergun's model), particle agitation (kinetic theory) and gas expansion along a conveying pipeline (ideal gas law). Due to the independent development of those three models, a system of three equations with three unknowns can be solved to obtain the pressure loss, particle velocity and gas density along a slug. Calculations were carried out and compared with the experimental data obtained during horizontal slug flow pneumatic conveying of plastic pellets. The effects of the most relevant physical parameters to be input in the prediction model such as slug porosity, stresses, supply air velocity and total slug length are discussed on the basis of experimental and numerical results.

1. Introduction

Where product quality, energy expenditure or dust reduction is of particular concern, slug flow pneumatic conveying appears as the ideal and sometimes only way to transport a particulate material. In slug flow pneumatic conveying, particles are conveyed in the form of slugs that fill the entire cross section. The slugs, separated by gas pockets, move gently along the pipeline. This type of flow has the advantage that it only needs a small amount of gas to transport high capacities. Moreover, pipe wear, dust generation and product attrition generated by dilute phase conveying can be significantly reduced. In the early days of dense phase pneumatic conveying, slug flow was undesirable, and additional technologies such as by-pass systems were integrated in the conveying system to avoid the formation of slugs [1]. Later, as the many advantages of slug flow were recognised, additional techniques necessary to realise a smooth slug transport were developed like the injection of secondary air at different locations over the conveying line or the intermittent supply of material or air to the conveying line. Advantage is usually taken from the fact that slug flow naturally occurs for some materials such as plastic pellets for a more or less wide range of supply gas velocities. For this reason, diverse classifications were developed to assess on the basis of simple physical properties such as particle size and solids density the capability of a bulk material to be conveyed in the form of slugs [2,3].

Even though there has been increased interest in dense phase conveying since the seventies and the development of special dense phase pneumatic conveying systems, the lack of existing and reliable design procedures restricts its application. Beside the optimisation of the pipe layout, the designer must focus on the determination of the pressure loss required to transport in a given pipe diameter the desired solids mass flow rate with the optimal gas velocity. Until now, a significant part of the research has been focusing on the development of prediction models for those key design parameters based on bulk solids mechanics and the assumption that slugs are moving packed beds but the success of such theories is very limited. A new incentive has been provided by experimental work recently published by Lecreps [4,5], which showed that instead of being compact entities as assumed in most theoretical models, slugs are aerated structures presenting a significant free volume that limits the contacts between slug particles. This discovery fundamentally changes the approach that should be adopted for the prediction and design of low-velocity slug flow pneumatic conveying systems.

This paper addresses the development and applicability of a new pressure loss prediction model that in contrast to existing theories is no longer based on the principles of bulk solids mechanics but relies on the condition that particles within a slug are slightly fluidised.

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2. Development of pressure loss prediction model

2.1. Model fundaments

One approach to handling a gas–solid flow system is to make an analogy with a single-fluid system. In this approach, slugs are considered as permeable structures through which the leakage of gas during the transport process is permitted. In that regard, the semi-empirical equation Ergun developed to describe the pressure loss through a bed of bulk material of given porosity permeated by a gas was found to be suitable for application in slug flow pneumatic conveying [5–8]. The model of Ergun is a fluid based model that describes the pressure loss through a slug by considering the material permeability.

Another approach was used by Lecreps [5] who successfully managed to predict the pressure loss along a moving slug by applying a modified form of the kinetic theory to describe the wall shear stress induced by moving slugs. The model of Lecreps is a particle model that predicts the pressure loss in a system based on the stochastic agitation of the particles composing the slug and their characteristics such as velocity.

Those two models were developed independently of each other but are both built on the postulate that slugs are permeable structures. Together, they form a system of two equations that can be solved to obtain both the pressure loss and particle velocity along a slug. However, during slug flow pneumatic conveying, the significant pressure loss occurring along the pipeline leads to the decrease of the air density and consequent gas expansion. In turn, the significant increase of gas volume down the pipe results in the increase of the air velocity, which affects the pressure loss gradient. To consider the air expansion in the prediction model, the ideal gas law is applied to calculate the gas density as a function of the pressure. As a result, a 3-equation-system can be solved iteratively to predict the pressure loss, slug/particle velocity and gas density simultaneously.

The prediction model considers the gas permeation within slugs and the wall shear stress at the boundary between the slugs and the pipe wall. Therefore, the pressure loss in the gas pockets where the particles are motionless and most of the air is flowing above the layer of particles is negligible. As a result, the pressure loss can be assumed to be equal to the sum of the pressure losses along each individual slug only. The model then considers a total slug length corresponding to the combination of all individual slugs.

2.2. Mathematical modelling

2.2.1. Ideal gas law

The ideal gas law is applied to take into account the effects of gas expansion along the pipeline and calculate the corresponding superficial gas velocity at any location along the pipe. For this purpose, a total slug length L_{slug} is subdivided into n equal parts of length L_s as shown in Fig. 1.

$$L_s = \frac{L_{slug}}{n}$$

Introducing a counting variable i and considering that slugs are entities moving with a velocity less than the superficial gas velocity v_f, the average particle velocity v_p in each part becomes:

$$v_{p_i} = v_{f_i} - v_{slip_i}$$

where $i = 1, 2, 3 .. n$ and v_{slip} is the relative velocity between gas and slug particles.

For a given gas mass flow rate $\dot{m}_{f_{in}}$, the general expression of gas velocity for any part length is:

$$v_{f_i} = \frac{\dot{m}_{f_{in}}}{\rho_{f_i} \cdot A}$$

where A is the pipe cross-section area, and ρ_f the average air density in each part i expressed as:

$$\rho_{f_i} = \frac{P_{i-1} + P_i}{2 \cdot R \cdot T} \tag{1}$$

where P is the pressure in Pa, R the gas constant in J/kg K and T the temperature in K.

The form of the ideal gas law given by Eq. (1) will be used to include the gas expansion effect into the Ergun equation (Eq. (2)).

2.2.2. Ergun

Based on theoretical and experimental investigations, Ergun developed a general equation for pressure drop through fixed beds of particles as a function of the superficial velocity of the gas permeating through it [9]. The Ergun equation considers that the total energy losses in fixed beds are caused by simultaneous kinetic and viscous energy losses. The viscous energy losses are proportional to $(1-\varepsilon)^2/\varepsilon^3$ and the kinetic energy losses to $(1-\varepsilon)/\varepsilon^3$. As slugs are not fixed entities, for slug flow, the original Ergun equation requires modification to include the superficial slip velocity between the moving slug particles and the fluid. In addition, the Ergun equation is modified to take into consideration the changes of gas density along the pipe as per Eq. (1). The resulting modified Ergun equation given in Eq. (2) permits calculation of the pressure profile over a bed of particles permeated by a gas

$$\frac{\Delta P_i}{\Delta L} = 150 \cdot \frac{(1-\varepsilon)^2 \cdot \eta_i}{\varepsilon^3 \cdot {d_p}^2} \cdot v_{slip_i} + 1.75 \cdot \frac{(1-\varepsilon) \cdot \rho_{f_i}}{\varepsilon^3 \cdot d_p} \cdot v_{slip_i}^2 \tag{2}$$

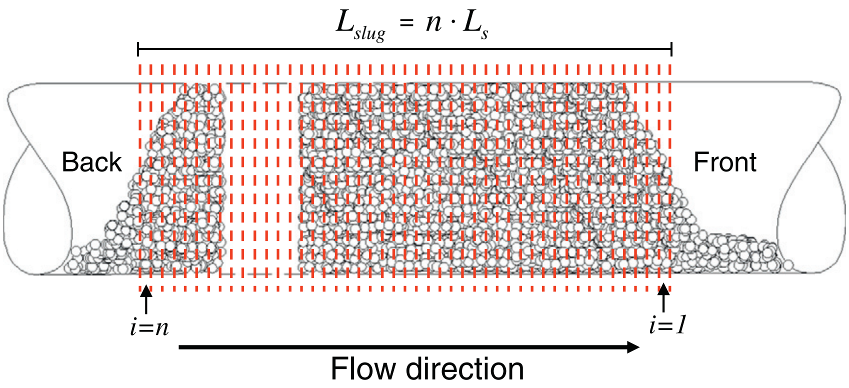

Fig. 1. Definition of the total slug length as used in the prediction model.