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Investigating the conveying mechanism of particulate plugs with stationary layers

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ABSTRACT

This paper presents an investigation into pneumatic conveying mechanism of particulate plugs with stationary layers. A plug flow regime may exist in pneumatic conveying systems operating with high-pressure gradients and low gas velocities. The most significant advantages of transporting particulate materials in a plug form is low energy consumption, low particle attrition and low pipe erosion. However, due to inaccurate approximations of the required pressure gradient of the plug, this kind of conveying processes can lead to pipeline blockage. This study presents a model for predicting pressure loss of particulate plugs that include a pick-up mechanism of a stationary layer of particles to be introduced between the plugs. The mechanism takes into account various parameters including the fraction of stationary layer (α), pipe and particulate characteristics, plug velocity and slope of pick-up layer. It was shown that the plug repose angle, θ, plays a very important role in determining the characteristics of plug flow conveying regime. Moreover, it was showed that the bulk density ratio (between the bulk density of the plug and the stationary layer) in some cases may make a significant contribution to pressure loss prediction. The model developed in this study was validated by the experimental measurements of other research teams and good agreement was found. The results of the present work provide information for updating major characteristic variables for pneumatic conveying systems operating as a plug flow. This can be useful both for designers and for future research studies.

1. Introduction

The use of dense phase flows in pneumatic conveying systems has recently become a preferable mode of transporting particulate solids from one process to another. However, due to inaccurate approximation of the required pressure gradient of the plugs, this kind of conveying processes can lead to pipeline blockage. As a consequence, nowadays, the predicting the plug flow regime usually requires full-scale industrial tests. Therefore, there is a need to develop more accurate models in order to analyze conveying properties and to predict energy loss.

More than forty years have passed since the pioneering research of Muschelknautz and Krambrock [1] on pneumatic conveying in dense phase flow. Based on an analysis of results for a various range of material proprieties ($\rho_p = 150 \div 1400\ \mathrm{kg/m^3}$ and $d_p = 10 \div 700\ \mu\mathrm{m}$), they developed a semi-empirical model to predict the pressure loss in a dense phase pneumatic conveying system. The model suggested that the main resistance force in dense phase conveying is the friction of the particulate bulk media with the pipe wall. Also, the model assumed that the pressure loss increases in an exponential manner as a function of the plug length. Although Muschelknautz and Krambrock [1] used a various range of pipe diameters in their investigation ($D = 20 \div 200\ \mathrm{mm}$), the model does not account that parameter to contribute to the pressure loss calculation.

A significant contribution in this research field was made by Konrad et al. [2]. Based on Janssen's static model for bins [3] and the hydrostatic force of gravity, they applied a force balance on a single slug, and presented a model that predicts the pressure drop in a horizontal pipe due to slug flow. The model considered the slug as a packed bed of the material (therefore treated as a plug) that moves inside a horizontal pipe due to the slip velocity between the gas and the solids. Therefore, to estimate the slip velocity, Konrad suggested to use the Ergun [4] equation for packed bed flows, while the slip velocity was defined as the difference between the superficial gas velocity and the mean particle velocity. Konrad also defined the velocity of the moving slug as the particle velocity in the front of the slug. To calculate the difference between the mean particle and slug velocities, it was assumed that the slug velocity is equal to the particle velocity ahead of the slug in addition of the propagation velocity. Furthermore, to estimate the propagation velocity, Konrad made an analogy to gas–liquid flows based on Zukoski's [5] work ($U_{pv} \sim C\sqrt{gD}$), while the coefficient was defined as $C = 0.542$. It should be pointed that using the gas–liquid analogy to estimate propagation velocity of a slug may be incorrect for gas–particle

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flows, and therefore, applying this correlation for pneumatic conveying as plug flow regime may seriously affect the prediction of the slip velocity.

Further investigation in low velocity pneumatic conveying systems was made by Mi and Wypych [6]. The work was conducted by developing a theoretical model which was validated by experimental results for coarse particles. The theoretical model was based on a similar analysis of the force balance on particulate media that is moving in a horizontal pipe, which was previously proposed by Konrad. However, contrary to Konrad, Mi and Wypych redefined the slug velocity and the total radial stress acting on the pipe wall. Consequently, the slug velocity is defined to be equal to the mean particle velocity of the moving plug. In addition, the radial stress components of the particulate media were divided into two major components. The first component of the radial stress arises from the material self-weight, and the second one from the axial stress via a stress transmission coefficient. To estimate the self-weight radial stress component, the authors, similar to Konrad, suggested to use the hydrostatic technique of Wilson et al. [7]. However, it should be pointed that Wilson's hydrostatic stress distribution results from hydrostatic pressure distribution on the pipe wall. Therefore, using his method does not account for the mechanical behavior of bulk materials, and as a result, the estimation of energy losses due to the plug flow might be inaccurate. In addition, the authors provided an expression for the stress transmission coefficient. Accordingly, the coefficient can be defined as a function of the static internal friction angle that is applied in the equations based on Mohr circles, both for active and passive cases. However, the difference between the cases is too large and, therefore, based on their experimental results the authors suggested to use an active case to calculate the stress transmission coefficient.

Pan and Wypych [8] contributed additional point of view in the investigation of low velocity pneumatic conveying systems. The work was conducted by redefining the theoretical model proposed by Mi and Wypych and further its validation by adding three materials to their investigation. Contrary to Mi and Wypych, Pan and Wypych defined the slip velocity as the difference between the gas and the slug velocities. This simplifies the calculation of the slip velocity and therefore, the determination of the mean particle velocity of the plug is not required. Similar to Mi and Wypych, they also divided the radial stress into two major components with one difference. Contrary to Mi and Wypych, the radial stress due to material self-weight was applied directly to the force balance, and as a result, its contribution to the total pressure drop was reduced.

Yi [9] had made another effort in developing a model for pressure loss in horizontal pipes due to a low velocity slug flow regime. This model differed from previous models in that the author considered the frontal stress caused by resistance of the stationary layer of particles between consequent plugs by experimentally observing single plug movement and evoking the principles of powder mechanics. These results indicated that pressure loss predictions have higher values that are closer to experimental results. However, to present this effect as a part of the frontal stress of the slug, Yi treated the resistance effect as a lifting force of raising up the particles from the surface of the stationary layer to the top of the pipe. It should be pointed out that using this technique to describe the resistant trend contributed by a stationary layer is questionable. In addition, similar to Konrad, Yi defined the slug velocity as the velocity of the particles in the front of the moving slug. However, contrary to Konrad, the slip velocity was treated as the velocity difference between the gas and the slug. To calculate the total pressure loss due to slug movement, Yi used a linear combination of the contributed forces. However, the compressibility principle of bulk material requires that the differential equation be defined and further its solution by applying contributions as boundary conditions at the front of the plug.

Some recent experimental works have provided further information on the slug flow regime [10,11]. Krull [10] performed experiments in full scale pneumatic conveying systems by generating both single and consequent slugs using two different feeding systems — a blow tank and a rotary valve, respectively. According to his experimental results for a single slug system, there is a wide variance of slug lengths gained for given mass flow rates of both solids and gas. The work of Tan et al. [12] used the experimental results of Krull to validate a model of the air mass conservation law in order to predict pressure loss in the movement of a horizontal slug. According to this work, slug velocity is a function of the bulk permeability factor. The investigation work of Lecreps [11] focused both on the analysis and generalization of previous models using kinetic theory techniques for characterizing particulate slug movement. The work showed that the particle velocity within the slug differs, and pointed out that the prediction of particle velocity within the slug is a key requirement to calculate the pressure loss when only knowledge of the material and conveying characteristics are available. However, the author indicated that the velocity of the particles within a moving slug is not only a direct function of the gas supply velocity, which varies along the length of the pipe, but also of many other different parameters, and therefore, the prediction of this velocity is difficult. As a solution, the author suggested to use mean particle velocity as the slug velocity.

It is obvious that friction forces of particulate plugs play a key role in estimating the pressure gradient of particulate plugs. Therefore, Shaul and Kalman [13] analyzed the friction forces of particulate plugs moving in vertical and horizontal pipes. Accordingly, a new theoretical model to calculate the friction forces for variable orientations of the pipe inclination ($0 \leq \alpha \leq 90$) was developed. For predicting the friction forces a value of the stress transmission coefficient, which is the ratio between the radial and axial stresses within the plug core, was required. Therefore, the experimental technics were defined and a reverse engineering method was applied in order to define this coefficient. As a consequence, an empirical expression for the stress transmission coefficient was formulated and the effect of various parameters, such as plug length, pipe diameter, internal friction of the material, wall friction and the air flow through the plug, was determined. It should be mentioned that the study does not account for a possible ability of the plug to move inside a horizontal pipe which contains a stationary layer of the particles.

The motivation for this work is to develop an accurate and reliable model which will account for a true mechanism of particulate plug movement in a horizontal pipe containing a stationary layer of particles between consequent plugs. The model must take into account the contribution of key parameters such as: the slope of the plug front and the friction of particles picked-up from the stationary layer to the moving plug, acceleration of the particles and the friction resistance of the stationary layer.

2. Theoretical model

This section presents the physical relationship equations and their simplified models. These models consider the stress distribution of bulk materials. As the basis of further presented theory, it is assumed that the friction forces between the particulate plug and the pipe wall can be defined by using the method of Shaul and Kalman [13]. Then, the contribution of additional resistances related to the pick-up mechanism can be applied.

2.1. Mechanics of the plug movement inside horizontal pipes without a stationary layer

By analyzing the force balance on a differential slice of a conveying bulk element in a vertical plug, a general differential equation of the force balance was defined by Shaul and Kalman [13]:

$$\varepsilon \frac{dP}{dx} + \frac{d\sigma_a}{dx} + \frac{4\tau_w}{D} + \rho_b g = 0, \tag{1}$$

where P is the pressure through the bulk media, and therefore, Eq. (1) contains components acting in axial direction, which are: $\varepsilon(dP/dx)$ is