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Friction forces of particulate plugs moving in vertical and horizontal pipes

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ABSTRACT

This paper presents a comprehensive theoretical and experimental analysis of the friction forces of particulate plugs. Friction forces of particulate plugs play a key role in the estimation of the pressure gradient over a pneumatic conveying pipeline. Therefore, a theoretical model to calculate those forces for variable orientations of the pipe inclination ($0 \leq \alpha \leq 90$) was developed. In particular, were analyzed the behavior of various parameters such as plug length, plug diameter, internal friction of the material, wall friction, the pressure gradient due to airflow through the plug, and the stress transmission coefficient. The agreement of the new correlations was found to be in the range of ±15% for the stress ratio values. Moreover, by substituting these correlations into the newly developed theoretical model and comparing its values to experimental results, an agreement of ±30% for the plug friction force calculation was achieved. The present study enables a better understanding of the characteristics of the two-phase (gas–solids) plug flow regime.

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1. Introduction

For the last fifty years, industry tends to use pneumatic conveying systems as a performable transport for particulate solids from one unit to another. Such systems can operate in two major flow phases — dilute and dense. From the energy consumption point of view, the transport of particulate solids in the dense phase is preferable. The most widely used form of the dense phase flow is the plug flow.

In the plug flow regime, the particles are either moving together as solid pistons separated from each other by gas voids (although some internal circulations may occur) or the plugs are separated by a stationary layer of particles. A plug flow regime may exist in pneumatic conveying systems operating in high-pressure gradients and low gas velocities. The most common advantages of transporting particulate materials in the plug flow regime are the low energy consumption, the low particle attrition and the low pipe erosion. However, due to inaccurate approximation of the required pressure gradient of the plug regime, this kind of conveying processes can lead to pipeline blockage. As a consequence, the prediction of the plug flow regime requires full-scale industry tests.

Some recent works have helped to lend more information on the behavior of dense phase plug flows in horizontal and vertical conveying pipes [1–9]. However, for its design, several parameters must be considered. One of the more important ones is the wall friction force between the particles in the plug and the pipe wall. Li et al. [9] have found that slug flow regime cannot be obtained at low friction coefficient. Different piping materials and their roughness state as well as the different materials to be transport experience are contributing to considerable range of wall friction values.

The literature presents a number of basic models that predict the energy loss for plug flow conveying systems [6,10–14]. These models incorporate the wall friction as well as other parameters. The classic model of Muschelknautz and Krambrock [10] suggests that the main energy loss in horizontal dense phase conveying is due to the friction force between a bulk material and a pipe wall. Accordingly, the major cause to energy loss is due to the friction force caused by the bulk material weight. Although they developed their model with a wide variance of particles, it does not take into consideration a variance of pipe diameters. Based on Janssen static model for bins [15] on the one hand and the hydrostatic force of gravity on the other, Konrad et al. [11] applied a force balance on a single plug, and presented a model that predicts the pressure drop in a horizontal pipe due to plug flow. Further investigations for the horizontal plug flow [6,13,14] based on the same techniques as Konrad used resulted in semi-empirical expressions for the pressure gradient due to plug flow.

It should be emphasized that the previous models assumed that the stress distribution due to the gravity in the horizontal plug flow is hydrostatic and calculated it by the method of Wilson [16] which results the hydrostatic pressure distribution on the pipe wall. However, using the Wilson method does not provide the mechanical behavior for bulk materials, and as a result, the estimation of energy losses due to the plug flow might be inaccurate. Therefore, a new concept is required in order to calculate the true value of energy loss.

It is obvious that friction forces of particulate plugs play a key role in the estimation of the pressure gradient of particulate plugs. Hence, the achievement for design, performance prediction, and control of

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pneumatic conveying systems operating in the plug flow regime strongly depends on the models that predict friction forces of particulate plugs.

Roberts [17] presented the pioneering way for investigating of the forces required to convey particulate plugs. By using his techniques, Roberts and Jones [18] conducted a number of experiments in vertical Perspex pipes of 46 mm ID in order to investigate the effect of air permeation on reducing conveying forces. According to their work, the stress fields in the initial states of plug movement can be described very well by an active state of stress. However, once the flow is established the upper-bound stress condition appears to consist of a short passive zone above the force actuator, while the remainder of the plug is in the active state. By using the similar method as those of Roberts, Rabinovich et al. [4] investigated the friction forces on plugs of coarse particles moving upwards in a vertical pipe without airflow and developed a theoretical model to describe these friction forces. By analyzing the data from experimental results, they applied a reverse engineering method in order to predict the true stress transmission coefficient, which is a major component in the prediction of friction forces of plugs. They found that the stress ratio of coarse materials can be presented by a power law relationship ratio between the plug length and the pipe diameter.

Since past studies were based only on a few materials under limited experimental conditions, an investigation that includes more particulate properties is required. Therefore, the present study aims to fill this gap and to suggest a new theoretical model.

2. Theoretical model

In this section the physical relationship equations and their simplified models, which are based on a true consideration of stress distribution of bulk materials are presented. As the basis of this theory, it supposed that friction forces of the particulate plug's movement inside pipes can be analyzed by applying an equilibrium force balance on a slice of a plug. Firstly, the forces applied to a plug slice moving vertically were defined and then, the forces applied to a plug slice moving horizontally. Finally, for the general case of predicting friction forces of particulate plugs, the forces acting on a plug slice moving in an inclined pipe were defined.

2.1. Vertical plug

It is well-accepted in the literature [1,11–14,19,20], that in the force balance models based on analysis of the forces acting on differential slice of media length, the contribute of pressure drop component is presented by the total pressure drop force, $\Delta P\frac{\pi D^2}{4}$. The pressure force, however, is a combination of the drag force due to the airflow through the permeable particulate plug, $\varepsilon\Delta P\frac{\pi D^2}{4}$ and the pressure force acts directly on the particles, $(1-\varepsilon)\Delta P\frac{\pi D^2}{4}$. In the present work, the force balance equation was corrected since the drag force should be a part of the force balance (see Eq. (1)) and the pressure force is applied only as a boundary condition for the internal stress force.

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

where, P is the pressure through the plug.

In this way, a number of related cases can be defined by the single differential equation. For the well-known Janssen static model for bins [15], there is no pressure drop over the particulate bed and the shear stress on the wall is defined by $\tau_w=\mu_w k\sigma_a$, Eq. (1) becomes: $-\frac{d\sigma_a}{dx}-\frac{4\mu_w k\sigma_a}{D}+\rho_b g=0$. By applying the boundary condition for axial stress, $\sigma_a|_{x=0}=\sigma_c$,where σ_c is an external stress applied on the top of the bulk surface, the solution for Janssen model of non-cohesive bulk materials leads to the classical solution $\sigma_a=\frac{\rho_b gD}{4\mu_w k}\left(1-e^{\frac{-4\mu_w k}{D}x}\right)+\sigma_c e^{\frac{-4\mu_w k}{D}x}$. In the case of capsule or non-permeable plug conveying, $\varepsilon=0$ and Eq. (1) is presented by: $-\frac{d\sigma_a}{dx}+\frac{4\tau_w}{D}+\rho_b g=0$. Applying the boundary condition for the axial stress,$\sigma_a|_{x=0}=0$ the solution for this problem leads to $\sigma_a=\left(\rho_b g+\frac{4\tau_w}{D}\right)x$. For pneumatic capsule conveying the capsule moves due to the pressure force, $\sigma_a|_{x=L}=\Delta P$ and therefore, the pressure drop required to convey this capsule is $\Delta P=\left(\rho_b g+\frac{4\tau_w}{D}\right)L$. The particulate plug movement inside a vertical pipe can be analyzed similarly to the Janssen static model for bins. However, considering that the friction force acts in an opposite direction to the plug movement and the drag force is due to the gas flow through the plug, both contributes differ from Janssen model. Therefore the presented analysis of this kind of the plug movement was based on a force equilibrium acting on a slice of the plug (see Fig. 1).

For the particulate plug movement Eq. (1) presented as:

$$\varepsilon\frac{dP}{dx}+\frac{d\sigma_a}{dx}-\frac{4\tau_w}{D}-\rho_b g=0 \tag{2}$$

where σ_a is the stress in the axial direction, τ_w is the shear stress acting on the pipe wall ($\tau_w=c_w+\mu_w\sigma_{rt}$), D is the pipe diameter, ρ_b is the bulk density of the plug, g is the gravitational acceleration, ε is the void fraction and dP is the pressure drop through the plug. Assuming that in the vertical pipe orientation the total stress in the radial direction emerges only from the axial stress ($\sigma_{rt}=\sigma_r$), we can define the stress transmission coefficient as $k=\sigma_r/\sigma_a$. Hence, Eq. (2) becomes:

$$\frac{d\sigma_a}{dx}-\frac{4\mu_w k}{D}\sigma_a=\rho_b g+\frac{4c_w}{D}-\varepsilon\frac{dP}{dx}. \tag{3}$$

Assuming that the bulk density of the bulk material is not a function of the particulate bed length ($\rho_b\neq\rho_b(x)$) and P is linear and therefore

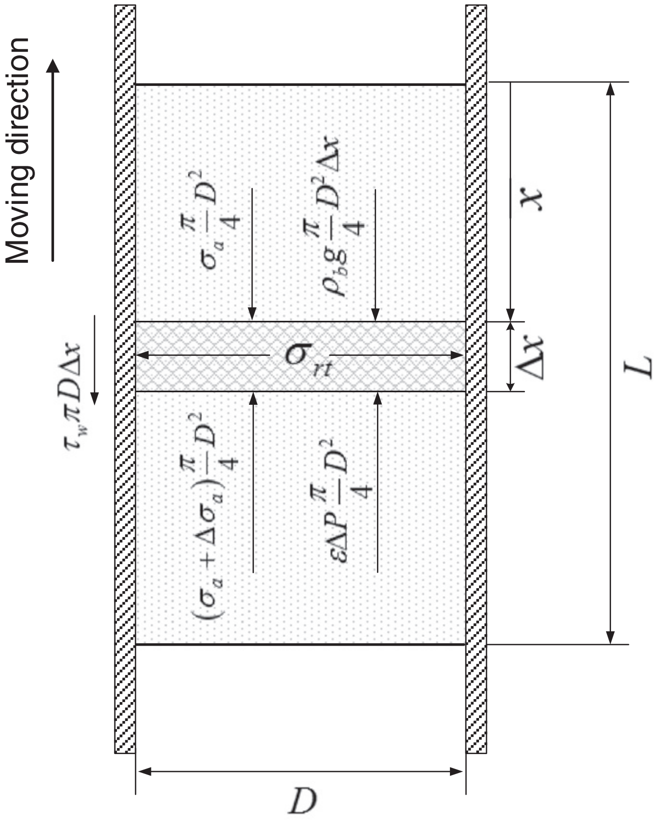

Fig. 1. Forces acting on a slice of a particulate plug moving vertically.

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