Powder Technology 283 (2015) 579–592

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Three plugs model

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ARTICLE INFO

Article history:
Received 11 March 2015
Received in revised form 4 May 2015
Accepted 9 May 2015
Available online 9 June 2015

Keywords:
Pneumatic conveying
Plug regime
Plug mechanics
Pressure loss on the plug
Stress transmission coefficient

ABSTRACT

This paper presents an investigation into pneumatic conveying mechanism of particulate plugs moving in horizontal pipes. 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 particles attrition and low pipe erosion. However, due to inaccurate approximations of the required pressure gradient of the plug, these kind of conveying processes can lead to pipeline blockage. It is obvious that mechanical modeling of particulate plugs movement play a key role to assess pressure loss occurs in pneumatic conveying systems. The present study presents a fundamental physical model and targeted to provide complete information on the mechanics of plugs movement, while combines characteristics of three different types of plugs as they move inside vertical or horizontal pipes. By using the model, it is possible to compare the energy loses of different plug types at specific conveying conditions, and hence, to characterize the existence of possible type of plug shape. The present work provides a several examples for such kind of analysis. The results of the present work provide information to update major characteristic variables for pneumatic conveying systems operating in a plug flow mode. This will be useful for both the designers and for further research works.

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. Those systems can operate in two major flow phases - dilute and dense. If the material is transported with high gas velocity in the form of a suspension, it is referred to as dilute phase flow. If the material is conveyed at low velocity in a non-suspension mode, it is referred to as dense phase flow. From the energy consumption point of view, the transport of particulate solids in the dense phase mode is preferable. The most widely used form of the dense phase flow is the plug flow.

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 particles 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. Consequently, the prediction of the plug flow regime requires full-scale industrial tests.

One of the most important parts enabling to predict the pressure loss due to the plug flow is the mechanism of plug movement. Thus, to describe powder mechanics of plug movement in vertical and horizontal pipes, the literature provides some models which are mainly based on force balance on a single plug [1–6]. A brief summary of these models and the assumptions they use is given below.

1.1. Previous mechanical models of plug movement

More than thirty years have passed since the pioneering research of Konrad et al. [1] which presented the principal theoretical model of plug movement in a horizontal pipe. According to this work, the mechanics of a plug movement inside a horizontal pipe containing stationary layer of the particles between plugs, is described. The plug movement in the pipe was treated as movement of a packed bed of the material that moves due to the slip velocity between the gas and the solids. As the plug moving in the pipe it picks up the particles from the stationary layer, by particles acceleration to the plug velocity in the front of the plug, and leaves behind a same amount of the particles. Thus, by performing a force balance on a single plug, which was based on a similar analysis of Janssen for bins [7], and also by estimating the hydrostatic force of gravity of bulk media by using the hydrostatic technics of Wilson [8], a theoretical equation to predict the pressure loss that required to move a single plug was firstly derived. This model accounts for the axial stress contribution due to particles acceleration in the front of the moving plug. In addition, the authors provided theoretical expression for the stress transmission coefficient, k (ratio between the radial and axial stresses). Accordingly, the transmission coefficient can be defined as a function of the static internal friction angle based on Mohr circles, both for *active* and *passive* cases. However, the difference

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http://dx.doi.org/10.1016/j.powtec.2015.05.047
0032-5910/

between the cases is too large and, therefore, based on their experimental results the authors suggested to use a *passive* case to calculate the stress transmission coefficient.

Further theoretical model has been developed by Mi and Wypych [2]. This model was based on a similar analysis of the force balance on particulate media that is moving in a horizontal pipe containing stationary layer of the particles, which was previously proposed by Konrad. However, contrary to Konrad, Mi and Wypych pointed out that the calculation of the total radial stress acting on the pipe wall must be 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 the stress transmission coefficient. To calculate this stress transmission coefficient the authors defined a function of the static internal friction angle that is applied in the equations based on Mohr circles, both for *active* and *passive* cases. Contrary to the results of Konrad and based on experimental measurements of radial stress and calculations of axial stress, the authors proposed to use only *active* stress state to calculate this coefficient. In addition, to estimate the self-weight radial stress component, the authors, similar to Konrad, suggested to use the hydrostatic technics of Wilson [8].

Pan and Wypych [3] contributed additional point of view in developing a mechanical model for single plug conveying in horizontal pipes containing stationary layer of the particles. This model was conducted by redefining the theoretical model proposed by Mi and Wypych. Similar to Mi and Wypych, they also divided the radial stress into two major components with one difference. In this work 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 twice reduced. Additionally, based on their experimental results the authors, contrary to Konrad, suggested to use only *active* stress case for the stress transmission coefficient.

The work of Yi [4] presented an additional effort in developing a mechanical model for particulate plug movement in horizontal pipes containing stationary layer of the particles. This model differs from previous proposed models in that the author considered the frontal stress caused by the resistance of the stationary layer of particles between consequent plugs by experimentally observing single plugs movement and evoking the principles of particulate plug mechanics. Therefore, the resistance of stationary layer to plug movement was firstly presented and added to the calculation of overall plug energy loss. Such added contribution, resulted in higher values of pressure loss predictions, which are closer to experimental results. However, to present this effect as a part of the frontal stress of the slug, Yi treated the resistance 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 contribution of the stationary layer on the pressure drop is questionable. To calculate the total pressure loss due to a single plug movement, Yi used a linear combination of the contributed forces. However, the compressibility principle of bulk material requires that the stress differential equations must be solved and the stationary layer resistance is applied as a boundary condition at the front of the plug.

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 [5] 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 result, 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 this study does not accounted for a case that the plug moves while a stationary layer of particles exist between consequent plugs.

Further research into plug regime conveying was made by Shaul and Kalman [6]. They presented a model predicting the pressure loss due to plugs movement and pick-up mechanism of stationary layers of particles between the plugs. This 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 pointed out 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 might make a significant contribution to pressure loss prediction. The model developed in this study was validated by experimental measurements of other research teams [9,10] and good agreement was found.

1.2. The limitations of the previous mechanical models

Unfortunately, the models presented by Konrad et al., Mi and Wypych, Pan and Wypych, and Yi, did not accounting the possible appearance of particulate slope in the front of the plug, and therefore, this component was neglected in pressure loss calculations. In addition, to estimate the self-weight radial stress component, the works of Mi and Wypych, Pan and Wypych and Yi, similar to Konrad, suggested to use the hydrostatic technics of Wilson [8]. However, it should be pointed that Wilson's hydrostatic stress distribution results from hydrostatic pressure distribution on the pipe wall. Therefore, using this method does account for the mechanical behavior of bulk materials, and as a result, the estimation of energy losses due to the plug flow may be inaccurate. Moreover, the authors disagreed in estimating the stress transmission coefficient. The literature presents numerous works related to the stress transmission coefficient for plugs for either the *active* [3,11,12] or the *passive* [1,13–15] condition. Accordingly, to those works, this 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, it should be pointed out that the difference between the cases is too large and, therefore, the pressure loss prediction will vary significantly. Fortunately, a significant contribution to analysis of the stress transmission coefficient was previously presented in the work of Shaul and Kalman [5]. Accordantly, this coefficient is strongly depends on powders and conveying characteristics and its value was formulated to be between the *active* and *passive* failure cases.

Although in previous works of Shaul and Kalman [5,6] were presented mechanical models of plug movement in horizontal and vertical pipes, the models, however, does not provided a possible case of plug movement mechanics which is able to move along a stationary bed of particles. Moreover, the literature is either does not presents a comprehensive mechanical model for this case of the plug movement.

1.3. Present research objectives

Even though the plug flow regime is one of the most efficient flow regimes, there is not sufficient theoretical knowledge in order to use this flow regime in the design process. The present work introduces a fundamental theoretical investigation on the plug flow regime and targeted to provide an understanding of the structure of dynamic plugs as they move through a conveying system. The motivation for this work is to develop an accurate and reliable generalized model that will account for a true mechanism of particulate plug movement in horizontal pipes. 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.

The results of the present work provide information to update major characteristics variables for pneumatic conveying systems operating as