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Gas–solid flow behaviour prediction for sand in bypass pneumatic conveying with conventional frictional-kinetic model

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ABSTRACT

Bypass pneumatic conveying is an alternative way to convey material which does not have dense phase transport capability. The computational fluid dynamics based commercial software Fluent 6.3 is used to investigate the pressure drop as well as the gas–solid flow behaviour in a bypass pneumatic conveying system. The conveyed material was sand with a mean particle size of 378 µm and the solid loading ratio was in the range of 10–123. The conventional frictional-kinetic model combining frictional and kinetic stresses simultaneously was applied for pressure drop prediction. The simulation results were then compared with experimental results from bypass pneumatic conveying tests. Selected image results from the computational fluid dynamics simulations were utilised and compared with images captured from high speed camera. In addition, a test case with low air mass flow rate and high solid loading ratio 82.49 was chosen as an example to show detailed gas–solid flow behaviour in the simulation of highly dense flows. It was found that conventional frictional-kinetic model with modified packing limit and friction packing limit has greatly improved the pressure drop prediction result compared with kinetic theory without friction. The detailed analysis for the selected test case showed how the full bore dune formation and deformation of sand and bypass flutes interact. High amplitude fluctuations and variation in pressure and gas velocity were observed. The gas velocity vectors indicate a high degree of air penetration from the flute into the bypass pipe. This behaviour provides an aeration mechanism which is what makes the bypass system work and allows non-dense phase material to be conveyed in a dense mode of flow.

1. Introduction

Dense phase pneumatic conveying is widely used in conveying projects for various dry powder materials due to its low energy consumption. Particles of sand range in size from 50 µm to 2000 µm in diameter [1]. The diameter of sand particles considered in this paper is about 378 µm and the loose poured bulk density is about 1616 kg/m^3. This type of sand has been classified as a type of material to be only transported in a dilute phase as described in the Geldart fluidisation chart [2].

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In order to convey in dense phase material such as sand without natural dense phase conveying capability, bypass pneumatic conveying systems have been developed as an alternative. Such systems are studied in this paper using a numerical approach. Pressure drop, which is the most important parameter for pneumatic conveying system design, is the main focus of this paper.

The numerical approach potentially eliminates experimental test work thus saving on space, time, money and labour, and it gives both quantitative and qualitative data throughout the whole modelled section of pipeline. Computational fluid dynamic (CFD) has been used by many researchers [3-12] to study gas–solid flow behaviour for fine powder material. This computational tool can potentially provide a practical way to reduce risks of design flaws and to optimise engineering design, as well as providing researchers with a tool for scientific investigation. The commercial software package Fluent is a popular CFD simulation tool for computing fluid flow, heat transfer and reactions for industrial applications.

By conducting simulations with the CFD approach using the Euler–Euler two phase flow model, investigations of flow patterns and fluidisation processes with the Eulerian approach were conducted where the particle phase had similar differential equations to the gas phase [13-18]. Examples of Euler–Euler two phase flow simulation of gas-particle fluidisation and pipeline transport are as following: By using the Eulerian model, Ma et al. [9] numerically studied flow characteristics of gas–solid flow in a pneumatic conveying system to predict the pressure drop in a pipeline. Based on the theory for non-uniform dense gases described in Chapman and Cowling [19], the kinetic theory has been taken and developed to study gas–solid two-phase flow behaviour by Gidaspow [20]. Taghipour et al. [21] studied the hydrodynamics of a two-dimensional gas–solid fluidised bed reactor experimentally and numerically. A multifluid Eulerian model, which considers the conservation of mass and momentum for the gas and fluid phases, was applied. The kinetic theory of granular flow, which considers the conservation of solid fluctuation energy, was used for closure of the solids stress terms. Generally, the Euler–Euler model approach for gas-particle flow treats both continuous phases and dispersed phases as interpenetrating continua [22]. The Eulerian model solves a set of momentum and continuity equations for each phase. The coupling of phases is based on pressure and inter-phase exchange coefficients. The Eulerian approach is a common method for calculating gas–solid flow when the volume fractions of phases are comparable, or the interaction within and between the phases plays a significant role while determining the hydrodynamics of the system [19]. However, the capability of the Eulerian model to predict pressure drop in bypass pneumatic conveying needs to be further developed.

For all the dense flows of granular material in bypass pneumatic conveying, the concentration of particles is very low in the upper part of the bypass pneumatic conveying where gas drag dominates flow of particles in the upper part and non-frictional collisional stress is more important than frictional stress. Kinetic theory can be used in this area where the solids volume fraction is low. However, the particle concentration will be higher in the intermediate regime compared with the upper lean part and is even higher in the dense regime, and the particles interact with multiple neighbours through sustained contact. Part of the solids stresses in the intermediate and dense zones is due to frictional interactions between particles at points of sustained contact. In the intermediate regime and dense regime, both collision and friction stress will influence the flow behaviour. Thus, it is practical to use a stress model which combines kinetic-collisional and frictional-kinetic stresses simultaneously to investigate the gas–solid flow behaviour in bypass pneumatic conveying. Pu et al. [23] applied the frictional-kinetic stress model to simulate 3D flow behaviour of dense phase pneumatic conveying with pulverised coal in horizontal pipe under high pressure. The normal frictional stress model of Johnson and Jackson [24] and a modified frictional shear viscosity model of Syamlal et al. [25] were adopted for friction stress. The simulated solid volume fraction distribution on a cross section of the pipe agreed well with experimental electrical capacitance tomography image. The influences of superficial velocity on solid concentration distribution were analysed. The predicted processes of slug formation and transport (motion) were similar to those seen in the visualisation photographs obtained using high speed video camera. However, the pressure drop along the normal pipeline without bypass pipe was not studied in Pu's research. Moreover, research applying the frictional-kinetic model for pressure drop prediction in bypass pneumatic conveying with sand type material has not been carried out yet.

This paper reports pressure drop prediction for sand utilising the conventional frictional-kinetic model. The conventional frictional-kinetic model is applied for calculation of kinetic and frictional regimes, where the kinetic theory is used and the frictional viscosity is described by Schaefer's expression [26] with modified packing limit and friction pack limit. Initially, the simulation results are compared with experimental results. Two simulation cases are selected to represent two regimes: firstly gas–solid flow behaviour of less dense flows with high air mass flow rate, and secondly denser flows with low air mass flow rate. Plots of solid volume fraction distribution and pressure profiles are presented to show the influence of the conventional frictional-kinetic model on simulation results. One particular test case has been chosen to show gas–solid flow behaviour in the simulation of highly dense flows. In addition, this case will show the mechanisms by which bypass systems can provide a dense phase capability to non-dense phase capable material. By applying the conventional frictional-kinetic model in simulations, dune formation and deformation for a typical dense phase test case with analysis of solid volume fraction and velocity distribution in bypass pneumatic conveying is showed.

2. Experiment

A schematic diagram of the experimental bypass setup is showed in Fig. 1. The main pipe was a mild steel pipe approximately 6.5 m in length with an 80 mm inner diameter. The inner bypass pipe consists of a 27 mm inner diameter bypass pipe with 16 bypass flutes spaced 400 mm apart. The structure of the bypass pipe and flute arrangement at the sight glass