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CFD Simulation Methodology for Gas-solid Flow in Bypass

Pneumatic Conveying - A Review

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Abstract

This paper presents a review of numerical models for simulation of gas-solid flow in bypass pneumatic conveying. The kinetic theory, conventional frictional-kinetic model and a new modified frictional-kinetic model are described in some detail. The experimental results for pressure drops based on a number of test cases are presented and compared with numerical results obtained with different numerical models. The convergences of the modified frictional-kinetic model with different values of constants are also illustrated. Moreover, the fluidisation charts of different materials with flow mode boundaries are presented to provide guidance on what frictional approach to use for Computational Fluid Dynamics (CFD) analysis of gas-solid flow in a bypass pneumatic conveying system. Furthermore, a flow chart for the CFD simulation methodology of bypass pneumatic conveying is demonstrated. These outcomes and the associated design guidelines could assist in choosing the most appropriate models for simulation of pneumatic conveying.

Keywords: pneumatic conveying; frictional-kinetic model; CFD simulation; review

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0. Introduction

Many kinds of loose bulk solid materials in various industries need to be stored and conveyed from one location to another. Pneumatic conveying is a common technology to transport bulk materials through an enclosed channel by employing air as carrier. It has been widely used in chemical, food processing or mining industries. There are several reasons for pneumatic conveying to be the most common method to transport powdered and granular materials for industry. Firstly, by applying horizontal and vertical pipelines and bends with any combination of orientations, the arrangement of pneumatic conveying system is quite flexible in both plant layout and operation. Secondly, the enclosed conveying condition allows the system to transport various kinds of granular materials including hazardous bulk materials without generating environmental problems. Thirdly, this system can operate automatically and the labour costs can be reduced without constant need for controlling and monitoring the conveying process ^[1-3].

There are two types of pneumatic conveying: Dilute phase offers the greatest flexibility in design, but the relatively high conveying velocities can cause serious operational problems including attrition and erosive wear of pipelines; Dense phase can reduce the required energy consumption through achieving reliable low flow velocity and decrease the associated conveying problems including particle attrition and erosive wear of pipelines. However, dense phase conveying is critically depending on the physical properties of the materials to be conveyed: Dense phase plug flow is only possible with non-cohesive particles with high bulk permeability; and dense phase bed flow is only possible in a conventional pipeline for materials with proper air retention characteristics. Since many materials do not exhibit the necessary physical properties to be conveyed in dense phase flow regime with low velocity, the bypass system is an alternative and satisfactory option to solve this problem in industry due to its adaptability to those limited and less flexible materials [1, 4-6].

The bypass pneumatic conveying system employs a secondary pipe with fixed slots at regular intervals inside the standard conveying pipeline. Orifices are welded into each slot and the air can enter the regular opening freely without any external source of air. When the pipeline blocks and the materials are impermeable, the system will provide an alternative route for the air. Through decreasing the conveying velocity of the flow mixture to a minimum value and increasing the solid loading ratio (SLR), this form of conveying leads to a reduction in energy consumption [5-9].

Pressure drop is one of the most important parameters for dense phase pneumatic conveying design and analysis. Many efforts have been carried out to measure pressure drop experimentally and numerically. Commercial CFD (Computational Fluid Dynamics) software programs were applied to simulate the gas-solid flow in recent years in order to better assess pneumatic conveying flow and reduce or eliminate the need for more expensive pilot plant conveying test work [6, 10-12]. CFD is seen as a powerful simulation tool as it can capture three-dimensional flow behaviour

without time consuming experiment. The Eulerian approach is a common method to investigate industrial flows^[13].

The pressure drop prediction strongly depends on the numerical models that are chosen to describe the interactions between particles within the pneumatic conveying. In the past years, the kinetic theory was applied to investigate gas-solid flow behaviours for pneumatic conveying^[14-17]. In order to consider frictional stress between particles, the frictional-kinetic model was also applied on dense phase pneumatic conveying simulation^[6, 18]. However, this model was used directly without any physical justification. The equation for frictional-kinetic model was generated from soil mechanical principles and the constants used in the semi-empirical model were originally summarized from measurements of inclined chutes with glass beads only. Therefore, an appropriate frictional-kinetic model for pressure drop prediction of different materials in pneumatic conveying is vital to be proposed.

1. Mode of flow prediction

For simulation of gas-solid flow in bypass pneumatic conveying, factors of permeability and de-aeration are difficult to define due to the need of using various measuring techniques^[4]. Thus, fluidisation diagrams using ‘loose-poured’ bulk density are commonly utilised to predict the particulate mode of flow for different materials in pneumatic conveying. Different fluidisation diagrams plotting mean particle diameter against loose-poured bulk density are adopted, as shown in Fig. 1 to Fig. 4. Boundaries between different modes of flow are drawn to classify various materials into different regions to predict their flow modes^[4, 19].

Flyash, alumina and sand are chosen as material samples and the corresponding parameters are showed in table 1. The regions to which flyash, alumina and sand fall into are presented in the modified Geldart’s fluidisation diagram, modified Molerus’s fluidisation diagram, modified Dixon’s fluidisation diagram^[4] and Pan’s fluidisation diagram^[19], as shown in Fig. 1, Fig. 2, Fig. 3 and Fig. 4, respectively. It can be found

that flyash is located in the region corresponding to fluidised dense phase in all four of the diagrams. Flyash has very fine powders and a relative low loose-poured bulk density. As described by Konrad ^[20] and Jaworski & Dyakowski ^[21], dilute phase systems typically exhibit low mass flow ratios (less than 15) or low solid concentrations (less than 10%). Sand belongs to the region of dilute phase in all four diagrams. Sand has a very large particle diameter and a high loose-poured bulk density, so sand powders can easily settle out while conveying due to the influence of gravity. The sand powders which do not settle out are conveyed in dilute phase. Interestingly, alumina powders are located in the intermediate area between the fluidised dense phase, dilute phase and unknown regions. This means that alumina powders can be regulated to transport in either fluidised dense phase or dilute phase, depending on different conveying conditions, by varying the air mass flow rate and solid mass flow rate.

Table 1 Parameters for flyash, alumina and sand

Description	Symbol	Unit	Value		
			flyash	alumina	sand
Average Particle Diameter	d_p	μm	14.7	76.7	378
Particle Density	ρ_p	kg/m^3	2093	4088	2600
Loose Poured Bulk Density	ρ_{lb}	kg/m^3	820	1046	1616
Tapped Bulk Density	ρ_{tb}	kg/m^3	992	1115	1636
Fluidised Bulk Density	ρ_{fb}	kg/m^3	505	863	1247

Fig. 1 Modified Geldart fluidisation chart with flow modes boundaries ^[4]

Fig. 2 Modified Molerus fluidisation chart with flow modes boundaries ^[4]

Fig. 3 Modified Dixon fluidisation chart with flow modes boundaries ^[4]

Fig. 4 Pan's Fluidisation chart with flow modes boundaries ^[19]

2. Magnified appearance of three regimes in pneumatic conveying

Gas-solid flows can be divided into three regimes: dilute regime, intermediate regime and dense regime. At the dilute regime, the particles are treated as an ideal gas and the kinetic contributions dominate the transport conditions. At the intermediate

regime, the particle-particle contact is very brief which means that the kinetic-collisional contributions are dominant during the particulate transport. In the dense regime, as the solids volume is close to the packing state and particle-particle contact is sustained over significantly longer time periods, the stress between all the particles can be calculated as the sum of frictional stress and kinetic-collisional stress. The three regimes and associated stress states are showed graphically in Fig. 5

Fig. 5 Three mechanisms of particle regimes during transport

In dense phase flow (e.g. fluidised bed, riser, hopper flow and pneumatic conveying) where the solids volume fraction is high, individual particles are in sustained contact. Thus, the kinetic theory of granular flow is applied to model kinetic stress, while the frictional stress model is used to calculate friction stress when sustained inter particle contact occurs. In bypass pneumatic conveying, the flow can also be divided into three regimes including dilute regime, intermediate regime and dense regime.

2.1 Experiment set up and mesh generation

A schematic diagram of the bypass pneumatic conveying test rig is showed in Fig. 6. The main pipe was 6.5m in length with an 80mm inner diameter. The inner diameter for inner bypass pipe was 27mm with 16 bypass flutes placed at regular intervals of 400mm^[5-6].

Fig. 6 Schematic diagram for bypass pneumatic conveying test rig ^[5-6]

The structures of bypass pipe and flute geometry are showed in Fig. 7. Two pitches being 45° to upstream and downstream were set for each flute. The diameter of circular opening in the centre of the orifice plate is 7mm.

Fig. 7 Structure of bypass pipe and flute geometry (unit: mm) ^[5-6]

The pipe used for conducting simulation was 6.5m in length with 16 flutes, as shown in Fig. 8, and two random flutes from the longitudinal plane are selected as mesh examples, as shown in Fig. 9 (a).

Furthermore, Fig. 9 (b) and Fig. 9 (c) show mesh results of the longitudinal plane and cross-sectional area, respectively. 2,577,358 elements were adopted for conducting numerical simulation.

Fig. 8 Sketch of computational domain

(a) longitudinal plane (partially shown)

(b) longitudinal plane (one flute)

(c) cross-sectional area A-A

Fig. 9 Mesh system for bypass pipeline

2.2 Experiment observation

With Test-flyash as an example of flyash cases, the three different regimes are showed in Fig. 10 (a) which was captured by high speed camera. The dilute regime is located at the upper part of the bypass pipeline, the main part of the intermediate regime is located at the centre of the bypass pipeline while the dense regime is located at the bottom part of the bypass pipeline. Magnifications of three regimes are also showed in Fig. 10 (b) to (d). In the dilute regime, the material has low solid concentration as shown in Fig. 10 (b), while the dense regime in Fig. 10 (d) has high solid concentration.

The concentration of material in intermediate regime observed in Fig. 10 (c) is between the dilute regime and dense regime.

(a) Three regimes in bypass pneumatic conveying

(b) Dilute regime

(c) Intermediate regime

(d) Dense regime

Fig. 10 Magnified appearance of three regimes in bypass pneumatic conveying for flyash

(Test-flyash: $m_a=0.0157\text{kg/s}$, $m_s=1.4951\text{kg/s}$)

Similarly, as an example for alumina cases, using high speed photography images, different regimes of Test-alumina are presented in Fig. 11 (a). Three different regimes including dilute regime at the upper half part, dense regime at the bottom part and intermediate regime in between. The magnifications of three regimes are also showed in Fig. 11 (b) to (d). Compared with Test-flyash, the boundaries between different regimes for Test-alumina are less distinct, and it is more continuous for the dilute/dense layer transfer of particles.

(a) Three regimes in bypass pneumatic conveying

(b) Dilute regime

(c) Intermediate regime

(d) Dense regime

Fig. 11 Magnified appearance of three regimes in bypass pneumatic conveying for alumina

(Test-alumina: $m_a=0.0207\text{kg/s}$, $m_s=2.6747\text{ kg/s}$)

For sand, again the high speed images show different flow regions of Test-sand. Sand is the type of material to be conveyed only in dilute phase within conventional pipelines. Thus, Fig. 12 (a) only shows distribution for two regimes. It is obvious to distinguish between the dilute regime and dense regime as shown in Fig. 12 (b) and (c). However, within bypass pneumatic conveying, sand has a dense phase capability, which means if there is material full bore dune or plug appearing during conveying, air can be forced into the bypass pipeline through the last nozzle and then be forced back to the main pipeline through the next nozzle. In this way, the material of sand dune or plug can move forward intermittently and not cause a blockage within the system.

(a) Two regimes in bypass pneumatic conveying

(b) Dilute regime

(c) Dense regime

Fig. 12 Magnified appearances of two regimes in bypass pneumatic conveying for sand

(Test-sand: $m_a=0.0317\text{kg/s}$, $m_s=0.3649\text{kg/s}$)

For all the dense flows of flyash, alumina and sand, the concentration of particles is

very low in the upper part of the bypass pneumatic conveying, and particle-particle collisions dominate the flow of particles. From kinetic theory of granular flow, the constitutive models for the stresses of particles in the bypass pneumatic conveying can be used in this area relating to a state where the solids volume fraction is low. However, the particle concentration will increase in intermediate regime and is even higher in dense regime, and the particles interact with multiple neighbors 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 of collision and friction stresses will influence the flow behaviour. Thus, it is practical to develop a new stress model which combines kinetic-collisional and frictional-kinetic stresses simultaneously to investigate the gas-solids flow behaviour in bypass pneumatic conveying.

3. Conventional numerical models for flow prediction

3.1 Euler-Euler model and Lagrange model

There are two methods used to simulate multiphase flow in CFD modelling, the Euler-Lagrange method and the Euler-Euler method. The Euler-Lagrange method treats fluid as a continuum by solving the Navier-Stokes equations. By applying Newton's Law of Motion to a fluid element, this vector equation can be obtained for viscous, heat conducting fluid. The Navier-Stoke equation is also called the momentum equation and can be expressed as the instantaneous continuity equation (1), momentum equation (2) and energy equation (3).

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} [\rho u_j] = 0 \quad (1)$$

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} [\rho u_i u_j + p \delta_{ij} - \tau_{ji}] = 0, i = 1, 2, 3 \quad (2)$$

$$\frac{\partial}{\partial t} (\rho e_0) + \frac{\partial}{\partial x_j} [\rho u_j e_0 + u_j p + q_j - u_i \tau_{ji}] = 0 \quad (3)$$

By tracking a large number of particles, bubbles, or droplets, the dispersed phase is solved through the calculated flow field. It is undesirable when dispersed second phase occupies a high volume fraction, such as liquid-liquid mixtures^[22] or fluidized beds^[23].

The Euler-Euler model approach treats both continuous phases and dispersed phases as interpenetrating continua. In this approach, the sum of phasic volume fractions is always equal to one and these volume fractions are assumed to be continuous functions of space and time. This model provides the basic idea of the mathematical approach to simulate the mechanism of the flow along a bypass pneumatic conveying pipeline.

The Euler-Euler model has no limitations on particle numbers being simulated and it can be applied to model dense phase gas solid flow, such as bypass pneumatic conveying. There are three types of Euler-Euler models: the Volume of Fluid (VOF) model, the mixture model and the Eulerian model, as summarized in table 2.

Table 2 Properties and suitable application condition of three types of Euler-Euler models

Model Name	Properties	Suitable Simulation Conditions
VOF model	Simulation for the free surface between immiscible fluids where the solid phase and gas phase are not mixing together. A single set of momentum equations is shared by the fluids and the volume fraction of each of the fluids in each computational cell is tracked throughout the domain.	a) wave-structure interactions ^[24] b) rise of single and multiple bubbles in sheared liquids ^[25] c) gas liquid reactor internals ^[26] d) stratified flows ^[27] e) steady or transient tracking of any gas-solid interface ^[28]
Mixture model	Appropriate for calculating more than two phases of flow. The mixture model solves the mixture momentum equation and prescribes relative velocities to describe the dispersed phases.	a) low loading particle-laden flows ^[29] a) flows with bubbles ^[30] b) sedimentation ^[31] c) cyclone separators ^[32]
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.	a) bubble columns ^[33] b) risers ^[34] c) particle suspension ^[35] and fluidized beds ^[36]

3.2 Eulerian approach

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. Furthermore, where the volume fraction of one phase exceeds the limitation of 10%, the Eulerian approach can be applied. This approach tracks particles or droplets continuously and is applicable for the simulation of fluidized beds and risers^[37].

Investigations about flow patterns and fluidization processes with the Eulerian approach were conducted where the particle phase had similar differential equations to the gas phase^[38-43]. The most recent numerical research using the Eulerian model was conducted by Ma *et al*^[12] and flow characteristics of gas-solid flow in a pneumatic conveying system were studied to predict the pressure drop in a pipeline.

Qi^[44] utilized the Eulerian approach combined with the energy minimization multi-scale (EMMS) theory to develop a new theoretical model to model drag in dense fluidized systems. Compared with empirical model, this model was without empirical factors. Therefore, this model can be applied for simulating various flow conditions in circulating fluidized beds (CFBs). Non-uniform particle distribution was also considered in the simulation. It was found that the drag values from simulation results agreed well with experimental data. The new model described the interactions between the gas and particle phases reasonably well.

In order to evaluate the heat transfer coefficient between the hot wall and the gas-solid dense phase flow, Zheng *et al*^[45] conducted experiments and simulations with the Eulerian model for dense gas-solid flow as a means to measure mass flow rate. The simulated results showed reasonable agreement with the experimental results.

By using the Eulerian approach based on the kinetic theory of granular flow, Wang

et al ^[46] modeled flow behaviour of gas and particles in a riser with the gas-solid two-fluid model. In addition, a cluster structure-dependent (CSD) drag coefficient model was incorporated into the two-fluid model. Solid velocity and concentration of particle profiles from simulation were in reasonable agreement with experimental results.

3.3 Turbulence models

Turbulent flow appears in most engineering problems. A turbulence model is a computational procedure to describe turbulent interaction under different conditions. With turbulence models, it is not necessary to firstly calculate the full time-dependent flow field and resolve all the details of turbulent fluctuations to obtain a mean flow. How turbulence affects the mean flow is the only thing needed to be specified. The turbulence models need to be simple, accurate and economic with wide applicability.

For the gas phase, turbulent flow can be calculated using several approaches. By solving the Reynolds-Averaged Navier-Stokes (RANS) equations with suitable models for turbulent quantities or by computing turbulence directly, the turbulent flows can be computed.

The two equation models are the most common turbulence models where the K-epsilon ($k - \varepsilon$) models are the most popular of the two equation models used to compute turbulence. There are mainly three different turbulence models including the k -standard model, RNG model k and Realizable model. Three different methods are provided for models to simulate turbulence in multiphase flows. These methods are a mixture of the turbulence model, dispersed turbulence model and each phase turbulence model. McGlinchey ^[9] predicted the pressure drop based on the Eulerian-Eularian model in horizontal and vertical pipes and different multiphase turbulence models were adopted for the research. However, no reliable laws could be drawn from the study.

For the solid phase, the turbulence model depends on how the effective viscosity of the particle phase is defined. There are three kinds of numerical models. The first model is the particle phase constant viscosity model which assumes that the particle phase viscosity is constant ^[43, 47]. The second model extends the gas phase turbulence model to gas-solid flow ($k - \varepsilon - k_p$ model), however, this model is restricted to dilute gas-solid flow since it does not consider the mechanism of particle-particle collision ^[48, 49].

The third model is the particle kinetic theory model which is based on the kinetic theories of non-uniform dense gases as described by Chapman and Cowling ^[50]. This model appears to be the most promising mathematical approach to describe the behaviour of particle phase flow in gas-solid flow systems ^[51]. Many investigations have been developed based on the particle phase kinetic theory ^[52-55].

3.3.1 Three main types of turbulence models

There are three types of turbulence models: the standard, RNG and realizable $k - \varepsilon$ models. Although all these models have similar forms of transport equations for k and ε , the methods to calculate turbulent viscosity are different.

The standard $k - \varepsilon$ model is the most practically and widely used in engineering calculations and this model was proposed by Launder and Spalding ^[56]. Although it is a semi-empirical model, it has been considered as the most popular turbulence model to give robust, economic and accurate simulation results for a variety of turbulent flows. This model assumes that the flow is fully turbulent and the molecular viscosity can be omitted. The standard $k - \varepsilon$ model is applicable for fully turbulent flows.

The RNG model improves the accuracy for simulation of rapid strained flows, swirling flows. Compared with standard model, the RNG model is more accurate and reliable for a wider type of flows. The RNG model has similar form of standard model. While standard model is good for high Reynolds numbers, the RNG model accounts

for low Reynolds number effects based on the analytically derived differential formula for effective viscosity. Furthermore, this model has an additional term in the ε equation that predicts more accurately for rapidly strained flows. And the effect of swirl on turbulence is also included.

The realizable model has been proven to have superior performance for flows with strong streamline curvature, vortices and rotation. Compared with standard $k-\varepsilon$ model, the realizable model has a modified transport equation for the dissipation rate, (ε). Moreover, the realizable $k-\varepsilon$ model contains an alternative formulation for the turbulent viscosity. Both the standard $k-\varepsilon$ model and the RNG $k-\varepsilon$ model are not realizable. This is because the term “realizable” means that the model satisfies certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows.

Comparing with the standard model, both the RNG and realizable models provide large improvements for those flows with strong streamline curvatures, vortices and rotations. However, for fine powder dense phase conveying, the flow is dominated by the slower moving dense layer which has very little swirl, vortices occurrence and excessive flow rotation. In addition, the work of Ma *et al* ^[57] has showed that the RNG and standard provided the same pressure drop prediction results, and realizable under-predict fine powder dense phase conveying in a conventional single bore pipeline. It is also important to note that the standard $k-\varepsilon$ model is the most computationally economic turbulence model and has been widely used in engineering calculation. Thus, the standard $k-\varepsilon$ model has been chosen to conduct the simulation of pressure drop prediction in this study.

3.3.2 Options for $k-\varepsilon$ model

The modelling of turbulence in multiphase flows is even more complex when compared with single phase flows. There are three types of methods for different turbulence models within the simulation: mixture turbulence model, dispersed

turbulence model and the each phase turbulence model.

(1) Mixture turbulence model

The mixture turbulence model is the extension of single-phase $k-\varepsilon$ model. It is widely used in the separation of phases, stratified multiphase flows as well as when the density ratio between phases is close to 1. The dispersed turbulence is applicable when the concentrations of the secondary phases are dilute, i.e. when the inter-particle collisions are negligible and the primary-phase turbulence is dominant in the random motion of the secondary phases. This model is employed when there is clearly one primary continuous phase and the rest are dispersed dilute secondary phases.

(2) Per phase turbulence model

The per phase turbulence model solves a set of k and ε transport equations for each phase. This model is useful when the turbulence transfer among the phases plays a dominant role. Per phase model is the most general multiphase turbulence model which considers turbulence in both phases separately without any limitation. However, it is questionable to use per phase turbulence models for solid phase directly as the models were originally developed for simulating fluids.

(3) Dispersed turbulence model

The dispersed model is based on the Tchen theory of dispersion of discrete particles through homogeneous turbulence. When the concentration of the secondary phase is dilute and there is clearly one primary continuous phase, this model is applicable. The dispersed turbulence model neglects the inter-particle collisions as it is assumed that the primary-phase turbulence plays the dominant role in the random motion of the secondary phases. In the case of particulate flows, the secondary particle phase resistance is dominated by particle-particle and particle-wall interactions, like collision and friction and the dispersed turbulence model better describes the primary air turbulence effect on the solids phase. As such, the simulation in this study adopts the

dispersed turbulence as it has been used by researchers^[12, 58] to conduct pressure drop prediction for dense phase flow, and reasonable results were found.

3.4 Basic mathematical models

The basic mathematical models used in pressure drop prediction are described in this section. First of all, the volume fraction equation and conservation equations are detailed. Then, the equations for interphase exchange coefficient, solid pressure, radial distribution function, solids shear stress, granular temperature are expressed.

3.4.1 Volume fraction equation

The phasic volume fractions are incorporated into the multiphase flow as interpenetrating continua. Phasic volume fractions represent the individual space for each phase. The phasic volume of phase q is,

$$V_q = \int_V \alpha_q dV \quad (4)$$

and

$$\sum_{q=1}^n \alpha_q = 1 \quad (5)$$

where the subscript q stands for gas phase g or solid phase s , α_q is the volume fraction of phase q .

3.4.2 Conservation equations

Each phase must satisfy the laws of mass conservation and momentum conservation. The continuity equation for phase q :

$$\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = 0 \quad (6)$$

where ρ_q is the density of phase q , $\vec{v}_q$ is the velocity of phase q .

The momentum equation for gas phase g is given by

$$\frac{\partial}{\partial t}(\alpha_g \rho_g \vec{v}_g) + \nabla \cdot (\alpha_g \rho_g \vec{v}_g \vec{v}_g) = -\alpha_g \nabla p + \nabla \cdot \tau_g + \alpha_g \rho_g \vec{g} + K_{sg} (\vec{v}_s - \vec{v}_g) \quad (7)$$

where K_{sg} is the interphase exchange coefficient.

The momentum equation for solid phase s is expressed by

$$\frac{\partial}{\partial t}(\alpha_s \rho_s \vec{v}_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s \vec{v}_s) = -\alpha_s \nabla p - \nabla p_s + \nabla \cdot \tau_s + \alpha_s \rho_s \vec{g} + K_{sg} (\vec{v}_g - \vec{v}_s) \quad (8)$$

where τ_i is stress-strain tensor of phase i , p is the pressure shared by all phases,

p_s is the s^{th} solid pressure.

$$\tau_i = \alpha_i \mu_i \left(\nabla \vec{v}_i + \nabla \vec{v}_i^T \right) + \alpha_i \left(\lambda_i - \frac{2}{3} \mu_i \right) \nabla \cdot \vec{v}_i I \quad (9)$$

where μ_i is the shear viscosity of phase i , λ_i is the bulk viscosity of phase i .

3.4.3 Interphase exchange coefficient

Each secondary phase for fluid-fluid flows is assumed to form droplets or bubbles. For example, if there are two fluids with unequal amounts, because the droplets or bubbles can be easily formed by the sparser fluid, the modelling of primary fluid should be the predominant fluid. The general form for the exchange coefficient for these types of bubbly, liquid-liquid or gas-liquid mixtures is showed:

$$\tau_{pq} = \frac{\rho_p f}{6\tau_p} d_p A_i \quad (10)$$

where A_i is the interfacial area, f is the drag function which is defined differently for the different exchange-coefficient models, and τ_p is the “particulate relaxation time” which is defined as

$$\tau_p = \frac{\rho_p d_p^2}{18\mu_q} \quad (11)$$

where d_p is the diameter of the bubbles or droplets of phase p .

Based on the relative Reynolds number (Re), a drag coefficient (C_D) is included in nearly all definitions of f . With different drag coefficients, there shows various drag function^[59-61]. The available and suitable drag functions can be selected to describe the interphase exchange coefficient for each pair of phases in fluid-fluid flows. Many researchers have successfully simulated the pneumatic conveying of fine particles using the classical drag models^[5-6, 12, 16, 62].

For granular flows, according to equation (7) and (8), the momentum exchange between gas and solid phases depends on the value of the gas-solid and solid-solid exchange coefficient K_{sg} ($= K_{gs}$). Gidaspow *et al*^[62] combined Wen and Yu model^[59] and Ergun equation^[64] to calculate the interphase momentum transfer coefficient between the gas phase and solid phase. The gas-solid exchange coefficient K_{sg} is expressed in the following forms:

When $\alpha_l > 0.8$, the fluid-solid exchange coefficient K_{sl} is of the following form:

$$K_{sl} = \frac{3}{4} C_D \frac{\alpha_s \alpha_l \rho_l |\vec{v}_s - \vec{v}_l|}{d_s} \alpha_l^{-2.65} \quad (12)$$

where

$$C_D = \frac{24}{\alpha_l Re_s} \left[1 + 0.15 (\alpha_l Re_s)^{0.687} \right] \quad (13)$$

When $\alpha_l \leq 0.8$,

$$K_{sl} = 150 \frac{\alpha_s (1 - \alpha_l) \mu_l}{\alpha_l d_s^2} + 1.75 \frac{\rho_l \alpha_s |\vec{v}_s - \vec{v}_l|}{d_s} \quad (14)$$

where d_s is the diameter of the particles of solid g .

3.4.4 Solid pressure

When the solids volume fraction is less than the maximum value allowed and the granular flows are in a compressible regime, a solid pressure is employed for the pressure gradient term and its value is calculated individually ^[65]. The granular temperature is introduced into this model for the expression of solids pressure. The solids pressure p_s is composed of a kinetic term and a second term due to particle collisions:

$$p_s = \alpha_s \rho_s \Theta + 2 \rho_s (1 + e_{ss}) \alpha_s^2 g_{0,ss} \Theta_s \quad (15)$$

where e_{ss} is the coefficient of restitution for particle collisions, $g_{0,ss}$ is the radial distribution function, Θ_s is the granular temperature.

3.4.5 Radial distribution function

The radial distribution function $g_{0,ss}$ is a correction factor that modifies the probability of collisions between particles when the solid granular phase becomes dense. One of the most popular models is proposed by Ogawa *et al* ^[66] and used for the analysis in this study:

$$g_{0,ss} = \left[1 - \left(\frac{\alpha_s}{\alpha_{s,max}} \right)^{\frac{1}{3}} \right]^{-1} \quad (16)$$

3.4.6 Solids shear stress

In the momentum equation, μ_s and λ_s is the shear viscosity and bulk viscosity of solid phase, and μ_s can be expressed as:

$$\mu_s = \mu_{s,col} + \mu_{s,kin} + \mu_{s,fr} \quad (17)$$

The collisional part of the shear viscosity $\mu_{s,col}$ is modelled as:

$$\mu_{s,col} = \frac{4}{5} \alpha_s^2 \rho_s d_s g_{0,ss} (1 + e_{ss}) \left(\frac{\Theta_s}{\pi} \right)^{1/2} \quad (18)$$

The kinetic viscosity $\mu_{s,kin}$, as presented from Gidaspow *et al* ^[13] is:

$$\mu_{s,kin} = \frac{10 \rho_s d_s \sqrt{\Theta_s \pi}}{96 \alpha_s (1 + e_{ss}) g_{0,ss}} \left[1 + \frac{4}{5} g_{0,ss} \alpha_s (1 + e_{ss}) \right]^2 \alpha_s \quad (19)$$

The details of frictional viscosity $\mu_{s,fr}$ will be discussed in section 3.7.

The bulk viscosity λ_s can be expressed as:

$$\lambda_s = \frac{4}{3} \alpha_s \rho_s d_s g_{0,ss} (1 + e_{ss}) \left(\frac{\Theta_s}{\pi} \right)^{1/2} \quad (20)$$

3.4.7 Granular temperature

For the solids phase, the granular temperature is closely related to the kinetic energy of the random motion of the particles. The granular temperature Θ_s equation (neglecting convection and diffusion in the transport equation) is ^[52]:

$$\begin{aligned} \frac{3}{2} \left[\frac{\partial}{\partial t} (\rho_s \alpha_s \Theta_s) + \nabla \cdot (\rho_s \alpha_s \vec{v}_s \Theta_s) \right] = \\ (-p_s I + \tau_s) : \nabla \vec{v}_s + \nabla \cdot (k_{\Theta_s} \nabla \Theta_s) - \gamma_{\Theta_s} + \phi_{gs} \end{aligned} \quad (21)$$

The diffusion coefficient for granular energy k_{Θ_s} is

$$k_{\Theta_s} = \frac{150 \rho_s d_s \sqrt{\Theta_s \pi}}{384 (1 + e_{ss}) g_{0,ss}} \left[1 + \frac{6}{5} \alpha_s g_{0,ss} (1 + e_{ss}) \right]^2 + 2 \rho_s \alpha_s^2 d_s (1 + e_{ss}) g_{0,ss} \left(\frac{\Theta_s}{\pi} \right)^{1/2} \quad (22)$$

The collisional dissipation of energy γ_{Θ_s} , represents the rate of energy ^[65],

$$\gamma_{\Theta_s} = \frac{12 (1 - e_{ss}^2) g_{0,ss}}{d_s \sqrt{\pi}} \rho_s \alpha_s^2 \Theta_s^{3/2} \quad (23)$$

And the transfer of the kinetic energy of random fluctuations in the particle velocity from the solid phase s^{th} to the gas phase g^{th} or solid phase is expressed by ϕ_{gs}

$$\phi_{gs} = -3K_g \Theta_s \quad (24)$$

3.5 CFD-DEM model

CFD-DEM is a combined approach of CFD which solves the flow of continuum fluid by the local averaged Navier-Stokes equations and Discrete Element Method (DEM) which applies Newton's laws of motion to every particle [68]. CFD-DEM model is widely applied for the modelling or simulation of pneumatic conveying and other fluid-solids or fluid-particles systems. Tsuji et al [69-70] firstly proposed this model and then many researchers have adopted this model in the studies of pneumatic conveying with millimetre-scale particle diameter, as shown in Table 3.

Table 3 Different investigations of CFD-DEM model

Author	Material	Research objective	d_p	ρ (kg/m ³)	Particle numbers
Mohammadr eza <i>et al</i> [71]	Spherical glass beads	Horizontal pneumatic conveying	1.5mm 2mm	2540 kg/m ³	[-]
Ebrahimi et al [72]	Spherical glass beads	Horizontal pneumatic conveying	0.8 mm-1mm 1.5mm 2 mm	2540 kg/m ³	5000
	Non-spherical glass beads		1 mm×1.5 mm	1140 kg/m ³	
Oschmann et al [73]	Non-spherical particles	Fluidized beds	spheres ($d=7$ mm), cylinders ($d=6$ mm, $l=6$ mm), cuboids ($l=6$ mm, $w=6$ mm, $h=5$ mm) and plates ($l=2$ mm, $w=9$ mm, $h=10$ mm)	1380 kg/m ³	4500
		Pneumatic conveying	spheres ($d=2.8$ mm), cylinders ($d=2$ mm, $l=3.76$ mm), plates with a quadratic base ($l=3.39$ mm, $w=3.39$ mm, $h=1$	1123 kg/m ³	

			mm) and cubes ($l=w=h=2.26$ mm)		
Li <i>et al</i> ^[74]	Spherical particles	Horizontal pneumatic conveying	3 mm	1000 kg/m ³	[-]
Krugger -Emden and Oschmann ^[75]	Non-spherical particles	Pneumatic conveying in a pipe bend	Sphere ($d=2.8$ mm), cubes($a=2.26$ mm,), pyramids($a=3.26$ mm, $b=3.26$ mm, $h=3.26$ mm), plates($a=3.39$ mm, $b=3.39$ mm, $c=1$ mm), icosahedrons($a=1.74$)	1123 kg/m ³	[-]
Kuang <i>et al</i> ^[76]	Spherical particle	Pneumatic conveying	5.0 2.17 3.73	880 1130 1350 kg/m ³	[-]
Tan <i>et al</i> ^[77]	Spherical particles	Pneumatic conveying	2 mm	2000 kg/m ³	[-]
		Concrete pumping	2mm 15mm	2960 kg/m ³	
Stratton and Wensrich ^[78]	Polyethylene pellets (Spherical)	Horizontal slug flow pneumatic conveying	4 mm	922 kg/m ³	[-]
Tsuji ^[79]	Polystyrene (Spherical)	Spouted bed	10 mm	1000 kg/m ³	500 1000
	[-]	Fast circulating fluidized bed	3 mm	2500 kg/m ³	200000
Fraige and Langston ^[80]	Polystyrene particles 2006	Horizontal pneumatic conveying	1.96-2.3mm	1080 kg/m ³	450-8000
Lim <i>et al</i> ^[81]	Polypropylene (Spherical)	Pneumatic conveying	2.8mm	1123 kg/m ³	500 1000
Xiang <i>et al</i> ^[82]	Nylon	Dense phase pneumatic conveying	3mm	1135 kg/m ³	40000
Li <i>et al</i> ^[83]	Spherical polyethylene pellets	Low-velocity slug flow pneumatic conveying	5 mm	880 kg/m ³	[-]
			3 mm		

Recently, studies about fine particle simulations have been increased. By applying CFD-DEM approach, Chen *et al* ^[84] numerically investigated the particle transport and deposition in pulmonary airway, and the simulation results were compared with experiment results. In the experiment, the particle diameter was 3~7 μ m. However, as

DEM simulation requires intensive computational resources, a cluster of 10 μm diameter spherical element with the closely spaced particles was adopted. The predictions agreed well with experimental results. It was validated that the CFD-DEM approach is suitable for the prediction of multiphase flow in human airway. Tong *et al* [85] numerical investigated the powder dispersion in an inhaler by using a coupled CFD-DEM technique. All formed agglomerates with a diameter of 51 μm were applied in the simulation instead of the primary particles with an average diameter of 3.27 μm . The capability of CFD-DEM modelling to study various dispersion mechanisms and their relative importance has been demonstrated. Zhou *et al* [86] studied the pneumatic conveying of fine particles with particle diameter of 100 μm through a small-scale horizontal slit by applying CFD-DEM method. The mass flow ratios for all simulating cases were less than 18 which are close to dilute phase. For the bulk movement of fine particles, the simulation results were in good agreement with the video-imaging experimental outcomes. Moreover, the pressure drop versus gas velocity profile obtained from simulation showed a good agreement with experimental results. Watano *et al* [87] used a simplified model to analyse the particle movement in a pneumatic conveying process with particle diameter of 300 μm . Numerical simulation of electrostatic charge in powder pneumatic conveying process is conducted and verified by experimental results of electrification of particles during pneumatic conveying process. However, few literatures have been demonstrated to apply CFD-DEM model specifically for simulation of pneumatic conveying with fine particle. This might be because limited number of particles or clusters can be applied in the simulation with CFD-DEM model which is more suitable for dilute phase pneumatic conveying.

3.6 Particle phase kinetic theory

Based on the theory for non-uniform dense gases described in Chapman and Cowling^[50], the kinetic theory has been taken and developed to study gas-solid two-phase flow behaviour. The kinetic theory approach uses the one equation model to determine the turbulent kinetic energy of the particles. It also assumes either a Maxwellian distribution for the particles, or a non-Maxwellian distribution for both dilute and dense cases.

The kinetic theory based description of gas-solid flows has been an active area of research for the past years^[88-92]. Rao and Nott^[93] derived a kinetic theory for rough inelastic particles. Zhao *et al.*^[94] developed a kinetic theory model for rough spheres. Both particle friction and rotation were considered for energy fluxes. Yang^[95] modified the kinetic theory of granular flow for frictional spheres in dense system including rotation, sliding and sticking collisions. Based on this modified the kinetic theory, the hydrodynamics of a dense solid-gas fluidized bed is studied for rotating rough particles.

Lun *et al.*^[65] initially developed two kinetic theories to calculate rapid flows of cohesionless granular materials, and examined in detail the problem of simple shear flow. The first analysis was developed for particles of arbitrary inelasticity and the second analysis was developed for almost completely elastic particles. It was found that the results from the first theory at higher concentrations were surprisingly close to those of the second theory. The second theory was found to be more appropriate for low concentrations as it can distinguish some of the finer details of the overall flow behaviour. Dehghan *et al.*^[96] used the kinetic theory of granular flow to simulate particle motion near a flat wall in a dilute turbulent gas-solid flow. Effects of flow density, material density, particle diameter, free stream velocity, granular temperature and particulate viscosity on gas-solid flow were investigated. Compared with experiment results, it was found that the kinetic theory can be useful in the dilute region

to predict particle flow behaviour. Zhong *et al* ^[97] used the kinetic theory of granular flow with a three-dimensional Eulerian multiphase model to numerically investigate gas-solid flow behaviour in spout-fluid beds. The simulation results were influenced by the coefficient of restitution due to non-ideal particle collisions. Under different operating conditions, the internal jet and gas-solid flow patterns with an appropriate coefficient of restitution of 0.93 were obtained. It was also found that the movement of particles was dominated by the gas drag force and particle collisions.

By using the Eulerian two-fluid model (TFM), Wang *et al* ^[98] studied the flow behaviour of a gas-solid injector. The gas phase was modelled by the $k-\varepsilon$ turbulent model and the particle phase was modelled by the kinetic theory of granular flow. It was found that the simulation results were in good agreement with experimental results. Based on the simulation results, the gas-solid flow pattern, gas velocity, particle velocity and the static pressure under different driving jet velocities, backpressures and convergent section angles were analysed. The conventional particle kinetic theory model generally does not take into account time-averaged turbulence behaviour. In order to fill this gap, Chan *et al* ^[99] proposed a comprehensive kinetic theory with turbulence modulation to predict the gas-solid flow in a vertical pipe. A transport equation of the particle phase turbulent kinetic energy was proposed and used for

particle phase turbulence (k_p model). The effective viscosity of the particle phase includes the laminar viscosity caused by particle-particle collisions described by the kinetic theory and the turbulent viscosity caused by the collection of particles. The applicability of this model to pneumatic conveying in a horizontal pipe and bend hasn't been demonstrated yet.

Liu *et al* ^[100] applied the kinetic theory of granular flow to perform the transport properties of the solid phase. The Eulerian continuum two-fluid model for both of gas phase and solid phase was used to study the influence of various physical parameters on the hydrodynamics of gas-solid two-phase flow in a precalciner. From the

computational simulations, the unsteady gas-solid flow behaviour and particle-particle coefficient of restitution on the hydrodynamics of solid flow were described. Based on the kinetic theory of granular flow, Lu *et al* ^[40] used a transient two-dimensional hydrodynamic model to predict the dynamic behaviour of gas-solid flow in a riser. Time-averaged particle concentrations, velocities, computed total granular temperature distributions and instantaneous solids concentration frequencies from simulated results were in good agreement with experimental measurements. According to the simulation results, the effects of initial conditions, inlet geometry, riser diameter and vertical inclination were also analysed.

A flow chart for a proposed model structure is summarized as shown in Fig. 13. The optimal way to simulate dense phase gas-solid flow in pneumatic conveying is the Euler-Euler method with Eulerian model, combined with standard $k-\varepsilon$ model and dispersed turbulence model. The models for solid pressure ^[65], radial distribution function ^[66], and granular temperature ^[52] are determined. For solid shear stresses, the collisional viscosity ^[63, 67], kinetic viscosity ^[67] and bulk viscosity ^[65] are detailed. The frictional viscosity is not taken into account in this numerical model.

Fig. 13 Flow chart of proposed model structure for dense phase pneumatic conveying

3.7 Conventional frictional-kinetic model

The continuity, momentum equations used in this study for gas phase and particle phase are as the same as in Ma *et al* ^[12] and Pu *et al*'s research ^[16]. For non-mass transfer flow, the continuity equation for any phase is showed in equation (6). The momentum equations for gas phase and solid phase are showed in equation (7) and (8).

In the momentum equation, μ_s is the shear viscosity of solid phase, and μ_s can be expressed as equation (17). The collisional part of the shear viscosity and the kinetic viscosity are the same as adopted in Ma *et al* ^[12]'s research.

Savage ^[101] assumed that stress tensor $\vec{\tau}$ is the sum of the kinetic stress tensor $\vec{\tau}_k$ and the frictional stress tensor $\vec{\tau}_f$, which encapsulates the yield and flow behaviour of granular materials, as showed in equation (25).

$$\vec{\tau} = \vec{\tau}_k + \vec{\tau}_f \quad (25)$$

The solids pressure p_s is showed as equation (15) and the radial distribution function $g_{0,ss}$ is showed in equation (16). As illustrated by Fluent ^[102], when the solid pressure model proposed by Lun *et al* ^[65] was adopted in equation (16), the radial function tends to infinity when the solid volume fraction tends to the packing limit. Then, the frictional pressure as described by equation (15) can be directly used in the calculation of frictional viscosity, and the based-KTGF (based-kinetic theory granular flow) model which describes the frictional pressure can be the chosen accordingly. In

this way, $\mu_{s,fr}$ in equation (17) which represents frictional viscosity corresponding to friction between particles, can be calculated by Schaefer' model ^[103] as following:

$$\mu_{s,fr} = \frac{p_s \sin \phi}{2\sqrt{I_{2D}}} \quad (26)$$

where p_s is the solid pressure, ϕ is the angle of internal friction, I_{2D} is the second invariant of the deviatoric stress tensor. The method described as above is named the conventional frictional-kinetic model in this study.

4. Modified frictional-kinetic model

4.1 Review of frictional-kinetic model

Based on analysing the fully developed flow of granular material (glass beads) down an inclined chute experimentally, Johnson and Jackson^[104, 105] derived constitutive expressions for frictional contribution to the total stress. The Coulomb relationship between frictional shear S_f and normal shear N_f is showed as equation (27). It was observed in experiment that frictional normal stress rose instantly with increase of bulk density. When bulk density is close to the packing limit, the frictional normal stress diverged. This behaviour can be presented as a simple algebraic equation (28).

$$S_f = N_f \sin \phi \quad (27)$$

$$N_f(\alpha) = \begin{cases} Fr \frac{(\alpha_s - \alpha_{\min})^p}{(\alpha_{\max} - \alpha_s)^n} & \text{if } \alpha_s > \alpha_{\min} \\ 0 & \text{if } \alpha_s \leq \alpha_{\min} \end{cases} \quad (28)$$

where $Fr=0.05$, $n=5$, $p=2$, $\alpha_{\min}=0.5$ and $\alpha_{\max}=0.65$ were constants chosen based on the research of Scarlett and Todd^[106], where N_f increased rapidly while α_s was close to $\alpha_{\max}$, and it was supposed that N_f would vanish for $\alpha_s \leq \alpha_{\min}$ where particles were not in sustained contact.

Savage^[101] assumed that stress tensor $\vec{\tau}$ is the sum of the kinetic stress tensor $\vec{\tau}_k$ and the frictional stress tensor $\vec{\tau}_f$, as shown in equation (25). The kinetic stress tensor $\vec{\tau}_k$ is modelled by kinetic theory of granular flows while frictional stress tensor $\vec{\tau}_f$ can be defined the same as equation (9). The stress assumption proposed by Savage^[36]

as shown in equation (25) has been employed by researchers to pursue improved simulation results for dense granular flows. The corresponding shear viscosity μ_s for solids phase can be described as the same as stated in equation (17), and the frictional viscosity $\mu_{s,f}$ can be also defined by equation (26).

The corresponding solid pressure p_s is different from the solids pressure defined in the conventional frictional-kinetic model. Compared with equation (15), a friction term has been added for p_s in equation (29). The new solids pressure equation includes both of the kinetic and friction contributions.

$$p_s = \left[1 + 2g_0\varepsilon_s(1+e) \right] \varepsilon_s \rho_s \theta + Fr \frac{(\alpha_s - \alpha_{\min})^n}{(\alpha_{\max} - \alpha_s)^p} \quad (29)$$

Syamlal *et al* ^[67] derived Multiphase Flow with Interphase eXchanges (MFIx) computer model to calculate dense or dilute gas-solid flow especially for chemical reactions and heat transfer. With MFIx calculation, the detailed information of pressure, temperature, composition and velocity distributions can be obtained. For solid stress, a switching between two entirely different constitutive relations was coded in MFIx showed as following:

$$\tau = \begin{cases} P_{s-kinetic} I + \tau_{s-kinetic} & \text{if } \varepsilon_s < \varepsilon_{s-critical} \\ P_{s-friction} I + \tau_{s-friction} & \text{if } \varepsilon_s \geq \varepsilon_{s-critical} \end{cases} \quad (30)$$

The frictional stress P_s is:

$$P_{s-friction} = \begin{cases} 0 & \text{if } \varepsilon_s < \varepsilon_{s-critical} \\ 10^{25} (\varepsilon_s - \varepsilon_{s-critical})^{10} & \text{if } \varepsilon_s \geq \varepsilon_{s-critical} \end{cases} \quad (31)$$

Srivastava and Sundaresan ^[107] also described a frictional-kinetic rheological model which treated kinetic and frictional stresses additively for dense assemblies of solids in a gas-particle mixture, which is the same as equation (25). Kinetic theory was used for expressing kinetic stress, while frictional stress and frictional viscosity described by

Schaeffer^[103] as shown in equation (32) and (26), respectively, were employed and modified to calculate strain rate fluctuations and slow relaxation of the assembly to the yield surface. By invoking the critical solids fraction state, a simplified version of the model was obtained, as shown in equation (33). From analysing the simulation results, it was found that frictional stress had significant effect on bubble shape in fluidised bed. By applying a frictional stress model, features of gravity discharge from a bin could be predicted. However, the formation of stagnant shoulders at the corners of the bin and the discharge rate were predicted inaccurately.

$$P_c(v) = \begin{cases} Fr \frac{(\alpha_s - \alpha_{s, min})^p}{(\alpha_{s, max} - \alpha_s)^n} & \text{if } \alpha_s > \alpha_{min} \\ 0 & \text{if } \alpha_s \leq \alpha_{min} \end{cases} \quad (32)$$

$$\frac{\tau_f}{p_c(v)} = I - \sqrt{2} \sin \phi \frac{S}{\sqrt{S : S + T/d^2}} \quad (33)$$

Tardos *et al*^[108] proposed a new expression for average solid shear stress as shown in equation (34) and (35). Makkawi and Ocone^[109] applied this new expression to simulate a smooth merge of rapid-intermediate flows in a horizontal duct. These equations reduced to Coulomb yield condition for slow frictional flow. The rapid granular flow solution was merged with intermediate regime where kinetic-collisional and frictional contributions were not negligible. Compared with experiment results with wide range of gas-solid flow conditions, the simulation results showed good agreement. The intermediate flow regime where both frictional and collisional stresses coexist was classified at approximately $100 < Re < 3000$.

$$\tau_{s-Tardos} = P_s \sin \phi \tanh \left(\frac{a\sqrt{\pi}}{2} \right) \quad (34)$$

$$a = \frac{(du_s/dy)}{2\sqrt{2}\sigma} \quad (35)$$

where σ is shear rate, $\sigma = \omega\sqrt{\theta}/d_p$, coefficient $\omega = 1/4$.

Yassir *et al*^[110] also incorporated interparticle cohesion and frictional shear stress terms by using the MFIX simulation code with a two-fluid kinetic theory model to analyse the hydrodynamic features in a fully developed vertical duct flow. By comparing with measurements from Electrical Capacitance Tomography (ECT), the simulations using the frictional shear stress term provided better results. In addition, an improvement of the gas-solid distribution and a lowering of the solid carryover were obtained.

Wu and Arun^[111] incorporated a frictional-kinetic constitutive model with Eulerian-Eulerian two-fluid modelling approach to predict gas-solid flow behaviour in 3D spout-fluid beds. The frictional stress was also assumed to be additive where the particle stress tensor is the sum of kinetic stress tensor and frictional stress tensor, as shown in equation (25). The simulation results from Wu and Arun^[111] were compared with experimental data from He *et al*^[112]. With the additive frictional-kinetic constitutive model, it was found that stable spout region, fountain region and annular downcomer region were predicted correctly, and the typical flow patterns of spouted beds were obtained.

Wang *et al*^[113] used kinetic theory for particle rotation and friction stress models with a two-fluid model to predict particle flow behaviour and cluster size in a circulating fluidised bed (CFB) riser. By introducing an effective coefficient of restitution based on the kinetic theory for granular flow, the particle rotation was calculated. The particle frictional stress model composed of normal friction stress model^[114] and a modified frictional shear viscosity model^[67], as shown in equation (36). The simulation results were compared with experimental results. It was found that frictional stress was not significant to influence cluster size, particle flows and distributions and flow behaviour, as particle phase in the CFB was not dense enough to take into account sustained contact between particles.

$$\mu_{friction} = Fr \frac{(\alpha_s - \alpha_{s,min})^n \sin \phi}{\alpha_s (\alpha_{s,max} - \alpha_s)^p \sqrt{I_{2D}}} \quad \text{if } \alpha_s > \alpha_{s,min} \quad (36)$$

Ng *et al*^[115] assessed the frictional-kinetic model by simulating dense phase granular flow, in particular, Couette type flow. By adding a constant to the frictional stress model as shown in equation (37), the influence of frictional stress to the dense granular flow behaviour was studied. It was found that with pure kinetic theory based CFD simulation, the tangential velocity and stiff drops of the tangential velocity at the wall region was over-predicted. By incorporating a frictional stress, as derived by Schaeffer^[103] with solids pressure provided by Lun *et al*^[65], the simulation results were improved to have better agreement with experimental results. Thus, the importance of frictional stress model improved dense phase granular flow prediction. Further improvement of frictional-kinetic model needed to be conducted.

$$\vec{T} = \vec{T}_{kin} + A^* \times \vec{T}_{fr} \quad (37)$$

where $\vec{T}$ is the stress tensor describing yield and flow behaviour of granular materials, $\vec{T}_{kin}$ is the kinetic stress tensor, A^* is a constant and $\vec{T}_{fr}$ is the frictional stress tensor.

Wang *et al*^[116] and Lu *et al*^[117] also incorporated a frictional-kinetic constitutive model to Eulerian-Eulerian two-fluid model to simulate gas solid flow behaviour in spouted beds. The combination of the normal frictional stress model from Johnson and Jackson's^[114] as shown in equation (28), and the frictional shear viscosity model from Schaeffer^[103] were used to calculate friction stress. With an inverse tangent function, a smooth transitioning from the plastic and viscous regimes was provided. Compared with experimental data from He *et al*^[112], the simulation results of particle velocities and concentrations in spouted beds showed good agreement. It was found that the concentration of the transition point had influence on particle flow behaviour in spouted beds. With the same friction stress model, Wang *et al*^[118, 119] also simulated behaviour of gas and particles in a chemical looping combustion with two interconnected fluidised beds. Flow behaviour of bubbles was predicted and

distributions of concentration and velocity of particles were simulated. Computed leakage rates in the fuel reactor and pot-seal had good agreement with measurements.

Passalacqua and Marmo ^[54] investigated the gas-solid flow behaviour in bubbling fluidised beds with minimum fluidization conditions where particles are highly concentrated and frictional stresses between particles are important. Models including Johnson and Jackson ^[114], Syamlal *et al* ^[67] and Srivastava and Sundaresan ^[107] were applied in the simulation to compare with the results from classical kinetic theory of granular flow. The frictional pressure for Srivastava and Sundaresan ^[107] model was the same as Johnson and Jackson ^[114]. The frictional viscosity was as equation (38). By incorporating frictional-kinetic model, the prediction of the bubble diameter in a bubbling fluidised bed with a central jet was improved and the bubbles diameter distribution in a uniformly fed bubbling fluidised bed was positively affected.

$$\mu = P_{friction} \frac{\sqrt{2} \sin \varphi_f}{2 \sqrt{S_s : S_s + \frac{\Theta_s}{d_p^2}}} \quad (38)$$

Pu *et al* ^[16] applied frictional-kinetic stress model to simulate 3D flow behaviour of dense phase pneumatic conveying with pulverized coal in horizontal pipe under high pressure. The normal frictional stress model of Johnson and Jackson ^[114] and a modified frictional shear viscosity model of Syamlal *et al* ^[67] were adopted for friction stress. The simulation result at cross section agreed well with experiment results from electrical capacitance tomography (ECT) image. The influence of superficial velocities on solid concentration distribution was analysed. The formation and motion process of slug flow were similar to the visualization photographs from a high speed video camera.

Although both kinetic and frictional stress models have influence on granular flow behaviour, it is still unclear how these two models combine together. The frictional interactions play a very important role in many dense phase gas-solid flows. However, the frictional stress model applied in fluidised beds, mixers or horizontal pipes was

originally developed from soil mechanics where the particles are in consolidated state [106].

In reality, the particles in fluidised beds, mixer or horizontal pipe are in aerated state. Moreover, the semi-empirical constants in frictional stress models were obtained from the results of experiments conducted with only two types of material: glass beads and polystyrene beads. Many researchers have adopted Johnson and Jackson's frictional stress model and applied the constants proposed from these two materials directly in their studies without verifying the influences of critical volume fraction, packing limit and semi-empirical constants on gas-solid flow prediction. The semi-empirical constants that used by researchers are summarized in Table 4.

Johnson and Jackson [114, 121] derived the model based on experiments carried out with plate shear and inclined-plane shear flow, as shown in Fig. 14 and Fig. 15, respectively. Materials were in consolidated state and frictional stress appeared between different layers inside the material. Johnson and Jackson's model [114, 121] has been widely used to simulate gas-solid flow behaviour of fluidised beds, spouted bed, plate shearing, bin charge, rising bubble, chute etc. Constants of Fr , n , p , α_{min} and α_{max} were applied directly without physical verification.

Fig. 14 Nomenclature for plane shear of a horizontal layer [114]

Fig. 15 Inclined-plane shear flow ^[114]

Table 4 Semi-empirical constants that have been used by different investigators

Author	Materials	d_p (μm)	ρ (kg/m^3)	$\alpha_{\max}$	$\alpha_{\min}$	n	p	Fr
Johnson and Jackson ^[114] ; Inclined chute	Glass beads	1800	2980	0.63	0.5	2	5	0.05
	Polystyrene beads	1000	1095					
Wang <i>et al</i> ^[113, 116, 122] ; Spouted beds	From He <i>et al</i> ^[112]	1410	2503	0.593	0.5	2	5	0.05
Lu <i>et al</i> ^[117] ; Spouted beds	From He <i>et al</i> ^[112]	1410	2503	0.593	0.5	2	5	0.05
Srivastava <i>et al</i> ^[107] ; Bin discharge and rising bubble	Geldart A particles	100	2900	0.63	0.5	2	5	0.05
	Geldart B particles	1000						
Darelius <i>et al</i> ^[123] ; Mixing process	—	59	740	0.65	0.5	2	5	0.05
Wang <i>et al</i> ^[119] ; Fluidised beds	Methane fuel	120	3589	0.63	0.5	2	5	0.05
Pu <i>et al</i> ^[16] ; Horizontal pipe	Pulverized coal	80	1350	0.63	0.1	2	5	0.1

Sun <i>et al</i> ^[124] : Fluidised beds	Glass beads	196. 5	2467	0.63	0.5	2	5	0.05
Sun <i>et al</i> ^[125] : Spouted bed	From He <i>et al</i> ^[112]	1410	2503	0.63	0.5	2	5	0.05
Ocone <i>et al</i> ^[126] : Duct of arbitrary inclination	Unknown	150	2500	0.63	0.5	2	3	0.05
Johnson <i>et al</i> ^[60] : Chutes	Glass beads	1000	2900	0.63	0.5	2	5	0.05
Johnson and Jackson ^[124] : Plane shearing	Glass beads	1800	2980	0.63	—	0	40	3.65×10^{-32}
Johnson and Jackson ^[114] : Plane shearing	Poly-styrene beads	1000	1095	0.63	—	0	40	4.0×10^{-32}

As shown in Fig. 16, in dense phase pneumatic conveying, the material at the bottom of the pipe is packing closer than the materials on the top. Materials are moving forward simultaneously. Material cloud cluster at the bottom are pushing the front cloud cluster forward. Although the material is aerated in dense phase pneumatic conveying and not packed very close, the friction τ_f between particles at the bottom is still continual. The constants in equation (28) were obtained from research of Scarlett^[106], where $\alpha_{\min}$ was defined as 0.5, friction stress was assumed to vanish when $\alpha < \alpha_{\min}$. However, when the material is conveyed and aerated, the frictional stress is still exist at the bottom of the pipeline where $\alpha_s < 0.5$. Thus, constants from equation (28) which were only derived from experiment of glass beads may not be ideal or optimised when applied directly for calculation of frictional stress in dense

phase fine powder pneumatic conveying. Further research is required into the effect of the constants Fr , n , p , $\alpha_{\min}$ and $\alpha_{\max}$ on dense phase pneumatic conveying prediction using the CFD approach for different materials.

Fig. 16 dense phase pneumatic conveying shear flow

4.2 Proposal of a new modified frictional-kinetic model

4.2.1 Definitions of $\alpha_{s,\min}$ and $\alpha_{s,\max}$

Johnson and Jackson frictional model^[114] has been widely used to describe frictional pressure for dense flow. However, the Johnson and Jackson model for frictional pressure as shown in equation (28) was originally derived from soil mechanics where material is in a stagnant and consolidated state. The application of this model on pneumatic conveying where material is flowing and aerated needs to be conducted.

In Equation (39), the minimum solid volume fraction, $\alpha_{s,\min}$ is the critical value of the solid volume fraction when frictional stress can be added to the stress predicted by kinetic theory, of which $\alpha_{s,\min}$ is set to 0.5 as default. In addition, the default value for maximum material packing limit, $\alpha_{s,\max}$ is about 0.63. However, in dense phase flow, the minimum solids concentration must be sufficient for sustained contact of the

particles in densely aerated condition to occur, which may be related to the fluidised condition for the material.

When the material is in the fluidised state, the fluidized bulk density and the corresponding solid volume fraction can be obtained. For the maximum solids concentration, the volume concentrations must allow the initial shear to be overcome and translational shear motion to occur.

It has been found in Electrical Capacitance Tomography (ECT) analysis of the flyash that the concentration is much higher compared to the loose poured conditions ^[57]. As such, the solid volume fraction for the material would not exceed the value obtained from the tapped bulk density approach. Therefore it is proposed that the constants of $\alpha_{s,min}$ and $\alpha_{s,max}$ are redefined to fit with the actual flow conditions in pneumatic conveying, where $\alpha_{s,min}$ can be calculated from material fluidized state and $\alpha_{s,max}$ can be calculated from material tapped state. For different materials, $\alpha_{s,min}$ and $\alpha_{s,max}$ can be written as equation (39) and (40).

$$\alpha_{s,min} = \frac{\rho_{fb}}{\rho_p} \quad (39)$$

$$\alpha_{s,max} = \frac{\rho_{tb}}{\rho_p} \quad (40)$$

Table 5 $\alpha_{s,min}$ and $\alpha_{s,max}$ for different materials

Materials	$\alpha_{s,min}$	$\alpha_{s,max}$
Flyash	0.24	0.47
Alumina	0.21	0.27
Sand	0.47	0.63

As shown in table 5, based on the modified packing limit, $\alpha_{s,\min}$ and frictional packing limit, $\alpha_{s,\max}$ for different types of materials to fit with the actual solid volume fraction distribution in pneumatic conveying, the Johnson and Jackson frictional model can be rewritten as equation (41) to (43).

$$\text{Flyash:} \quad P_{friction} = \begin{cases} Fr \frac{(\alpha_s - 0.24)^n}{(0.47 - \alpha_s)^p} & \text{if } \alpha_s > 0.24 \\ 0 & \text{if } \alpha_s \leq 0.24 \end{cases} \quad (41)$$

$$\text{Alumina:} \quad P_{friction} = \begin{cases} Fr \frac{(\alpha_s - 0.21)^n}{(0.27 - \alpha_s)^p} & \text{if } \alpha_s > 0.21 \\ 0 & \text{if } \alpha_s \leq 0.21 \end{cases} \quad (42)$$

$$\text{Sand:} \quad P_{friction} = \begin{cases} Fr \frac{(\alpha_s - 0.47)^n}{(0.63 - \alpha_s)^p} & \text{if } \alpha_s > 0.47 \\ 0 & \text{if } \alpha_s \leq 0.47 \end{cases} \quad (43)$$

4.2.2 Definition of $\alpha_{s,off}$

In the original Johnson and Jackson frictional model^[114], when the volume fraction tends to the packing limit, the frictional stress tends to infinity. However, the infinite value for frictional pressure only appears in a consolidated state where particles are closely packed up rather than pneumatic state where material is flowing in the pipeline.

By applying equation (41) to (43) directly into pressure drop prediction for flyash, alumina and sand, the simulation cases are un-converged. This is because when the solid volume fraction is close to $\alpha_{s,\max}$, the frictional pressure in equation (41) to (43) tends to infinity and the pressure drop along the conveying pipeline is obviously over-predicted and numerical convergence is problematic.

To help alleviate excessive over-prediction and/or non-numerical convergence of the flow, an offset volume fraction $\alpha_{s,off}$ is now introduced into equation (41) to (43) to

describe the frictional pressure. In essence, $\alpha_{s,off}$ represents how far the material solid volume fraction is away from the maximum packing limit obtained from tapped bulk density.

Compared with the curve obtained using the original parameters in the Johnson-Jackson model, the curve obtained from modified model still has similar behaviour in frictional pressure, as shown in Fig. 17. The frictional pressure is relatively lower in value when α_s is lower than $\alpha_{s,min}$. In this way, the modified model can be used to calculate the frictional pressure for dense phase flows where particles have sustained contact, and material is not in a consolidated state and close to blocking the pipeline. Thus, the values of $\alpha_{s,off}$ will depend on the packing limit and should be reflective of the consolidated state of the material at which insipient blockage will occur, which needs to be investigated for different kinds of material.

Fig. 17 Frictional pressure with and without $\alpha_{s,off}$ as function of solid fraction

4.2.3 Summary of sensitivity analysis of modified frictional-kinetic model

Based on the sensitivity analysis, the most suitable choices of $\alpha_{s,off}$, Fr , n and p in this modified frictional-kinetic model for pressure drop prediction of flyash, alumina and sand in bypass pneumatic conveying are summarized in Table 6.

Table 6 $\alpha_{s,off}$, Fr , n and p for different materials

Items	Flyash	Alumina	Sand
$\alpha_{s,off}$	0.0009	0.005	0.05
Fr	0.05	0.05	0.05
n	2	2	2
p	3	3.05	3

For flyash, there is no significant influence on pressure drop prediction for all the case studies as the solid volume fraction does not rise above the minimum required to initiate frictional resistance equation. As such, no further analysis is conducted for flyash using frictional resistance.

For alumina, the pressure drop decreases with the increase of $\alpha_{s,off}$, with the simulations converging only when $\alpha_{s,off} \geq 0.005$. With the increase of Fr , decrease of n and increase of p , the pressure drop between pipeline inlet and outlet rises up and the alumina powders layer at the bottom of pipeline is thicker. In particular, it was found that when $Fr=0.05$, $n=3$ and $p=2$, the pressure drop prediction result is the closest to the experimental result.

For sand, the simulation converges only when $\alpha_{s,off} \geq 0.05$. With the decrease of $\alpha_{s,off}$, increase of Fr , decrease of n and increase of p , the pressure drop across the pipeline climbs and the layer of sand powders at the bottom of the pipeline is much

thicker. However, the pressure drops across the pipeline are always under-predicted no matter how much $\alpha_{s,off}$, Fr , n and p vary.

Table 7 summarises all the convergence conditions for pressure drop prediction by applying the modified frictional-kinetic model with different values of $\alpha_{s,off}$, Fr , n and p . This provides guidance for choosing appropriate constants in the modified frictional-kinetic model to obtain simulation convergence.

Table 7 Convergence for modified frictional-kinetic model with different values of $\alpha_{s,off}$, Fr , n and p

	Flyash		Alumina		Sand	
$\alpha_{s,off}$	< 0.0009	Un-converge	0.005	Un-converge	< 0.05	Un-converge
	≥ 0.0009	Converge	≥ 0.005	Converge	≥ 0.05	Converge
Fr	0.01~0.5	Converge	> 0.05	Un-converge	> 0.05	Un-converge
			≤ 0.05	Converge	≤ 0.05	Converge
n	1.4~2.5	Converge	< 2	Un-converge	< 2	Un-converge
			≥ 2	Converge	≥ 2	Converge
p	2.8~3.2	Converge	> 3.05	Un-converge	> 3	Un-converge
			≤ 3.05	Converge	≤ 3	Converge

The pressure drop prediction for alumina and sand is conducted by applying the modified frictional-kinetic model with a modified critical value for the solid volume fraction $\alpha_{s,min}$ and maximum packing limit $\alpha_{s,max}$. The constants $\alpha_{s,off}$, Fr , n and p used in the modified frictional pressure equation are adopted from Table 6. Thus, the modified frictional pressure equation can be written as equation (44) to (46), and modified radial distribution functions can be written as equation (47) to (49).

$$\text{Flyash: } P_{friction} = \begin{cases} 0.05 \frac{(\alpha_s - 0.24)^2}{(0.47 + 0.0009 - \alpha_s)^3} & \text{if } \alpha_s > 0.24 \\ 0 & \text{if } \alpha_s \leq 0.24 \end{cases} \quad (44)$$

$$\text{Alumina: } P_{friction} = \begin{cases} 0.05 \frac{(\alpha_s - 0.21)^2}{(0.27 + 0.005 - \alpha_s)^{3.05}} & \text{if } \alpha_s > 0.21 \\ 0 & \text{if } \alpha_s \leq 0.21 \end{cases} \quad (45)$$

$$\text{Sand: } P_{friction} = \begin{cases} 0.05 \frac{(\alpha_s - 0.47)^2}{(0.63 + 0.05 - \alpha_s)^3} & \text{if } \alpha_s > 0.47 \\ 0 & \text{if } \alpha_s \leq 0.47 \end{cases} \quad (46)$$

$$\text{Flyash: } g_{0,ss} = \left[1 - \left(\frac{\alpha_s}{0.24 + 0.0009} \right)^{\frac{1}{3}} \right]^{-1} \quad (47)$$

$$\text{Alumina: } g_{0,ss} = \left[1 - \left(\frac{\alpha_s}{0.27 + 0.005} \right)^{\frac{1}{3}} \right]^{-1} \quad (48)$$

$$\text{Sand: } g_{0,ss} = \left[1 - \left(\frac{\alpha_s}{0.27 + 0.005} \right)^{\frac{1}{3}} \right]^{-1} \quad (49)$$

5. Application of the modified frictional-kinetic model

The simulation results obtained by applying equation (44) to (49) have been compared with results from kinetic theory and the conventional frictional-kinetic model. They are presented as following:

5.1 Pressure drop prediction for flyash

The simulation results from the modified frictional-kinetic model, conventional frictional-kinetic model and kinetic theory are summarized in Fig. 18 compared with

experimental results. All the data can be divided into two groups including cases with lower pressure drops for less dense flows and cases with higher pressure drops for denser flows. It is obvious that the pressure drop calculated from different models show the same result. The modified frictional-kinetic model produces no improvement in pressure drop prediction for both of dilute and dense phase bypass pneumatic conveying with flyash.

Fig. 18 Experimental pressure drop Vs simulation pressure drop with different simulation models for flyash

5.2 Pressure drop prediction using modified frictional-kinetic model for alumina

The pressure drop prediction with the modified frictional-kinetic model for alumina was determined through CFD simulations. The simulation results are summarized in Fig. 19 and compared with results calculated by kinetic theory and the conventional frictional-kinetic model [6].

It can be seen that pressure drop prediction results for most of the alumina cases are still under-predicted with the modified frictional-kinetic model, since the shear viscosity $\mu_{s,col}$, kinetic viscosity $\mu_{s,kin}$ and frictional viscosity $\mu_{s,fr}$ in equation (17)

and bulk viscosity λ_s are slightly reduced with $\alpha_{s,off}=0.005$ compared with $\alpha_{s,off}=0$. Nevertheless, it is still found that results from the modified frictional-kinetic theory are much closer to the experimental results, especially for denser flows with higher pressure drops. In summary, the modified frictional-kinetic model is more appropriate and should be utilised for pressure drop prediction for alumina transporting in bypass pneumatic conveying systems.

Fig. 19 Experimental pressure drop Vs simulation pressure drop with different simulation models for alumina ^[6]

Therefore, compared with results obtained from kinetic theory and conventional frictional-kinetic model, the simulation with the modified frictional-kinetic model shows a great improvement on the pressure drop prediction results.

5.3 Pressure drop prediction with modified frictional-kinetic model for sand

The pressure drop prediction with the modified frictional-kinetic model for sand has been analysed. The simulation results are summarized in Fig. 20 and compared with simulation results obtained from kinetic theory and the conventional frictional-kinetic model ^[5]. Although all simulation cases numerically converged with the modified

frictional-kinetic model, the pressure drops for all the simulation cases are still largely under-predicted, especially for denser flows with higher pressure drops.

Fig. 20 Experimental pressure drop Vs simulation pressure drop with different simulation models for sand ^[5]

The original idea for the frictional pressure model is that the frictional pressure increases quickly when the solid volume fraction reaches the packing limit. However, sand is a type of material that is only to be conveyed in the dilute phase, so most of the sand powders closely pack at the bottom of pipeline during conveying.

The material packing limit obtained from the tapped bulk density in equation (40) is 0.63 which equals to the original value of packing limit in Fluent. Nevertheless, simulation with the modified frictional-kinetic model only converges when

$\alpha_{s,off} \geq 0.05$, and the pressure drop is largely under-predicted. This is because the offset

solid volume fraction $\alpha_{s,off}=0.05$ is too large, and the frictional pressure in equation (46) where the solid volume fraction is close to the packing limit is largely under-predicted, and the correction factor in equation (49) for radial distribution

function is also under-predicted. As a result, the shear viscosity $\alpha_{s,col}$, kinetic viscosity $\alpha_{s,kin}$ and frictional viscosity $\mu_{s,fr}$ in equation (17) and bulk viscosity λ_s are largely reduced with $\alpha_{s,off}=0.05$. As a result, the pressure drop prediction results are largely under-predicted.

Therefore, the conventional frictional-kinetic model with a modified friction packing limit and material packing limit is more appropriate for pressure drop prediction of sand transporting in bypass pneumatic conveying system, especially for those denser flows cases with higher pressure drops.

6. Selection of simulation models for different flow modes

As shown in Fig. 1 to Fig. 4, flyash, alumina and sand are classified into areas with different modes of flow. Combined with simulation analysis, the following results can be obtained.

Flyash represents materials that can naturally be conveyed in a fluidised dense phase mode of flow. Flyash has the same pressure drop prediction results as all the theories. However, there are probably some other important factors that are not yet identified in the CFD simulation with conventional or modified frictional-kinetic models for flyash. Thus, it is proposed that the modified frictional-kinetic model can be applied to conduct pressure drop prediction for materials which are capable of a fluidised dense phase.

For sand, which represents materials to be conveyed in a dilute phase only, the frictional stress plays a dominant role for cases with high SLR during conveying, the conventional frictional-kinetic model can be applied to conduct pressure drop prediction.

For alumina which represents materials that have marginal dense phase capability in the fluidised dense phase flow mode, the modified frictional-kinetic model can be applied to predict pressure drops. As such, Fig. 1 to Fig. 4 can be used to show which frictional model can be used in the CFD simulations, as shown in Fig. 21 to Fig. 24.

This may now provide guidance on what frictional approach to use for CFD analysis of powders in a bypass pneumatic conveying system.

Fig. 21 Geldart fluidisation chart of sand with flow modes boundaries

Fig. 22 Molerus fluidisation chart of sand with flow modes boundaries

Fig. 23 Dixon fluidisation chart of sand with flow modes boundaries

Fig. 24 Pan's Fluidisation chart of sand with flow modes boundaries

7. Discussion of simulation with different numerical models

7.1 Simulation with kinetic theory

Kinetic theory was utilised to undertake CFD based simulations in the bypass pneumatic conveying system to predict pressure drops for the three material types to be transported.

For flyash, kinetic theory provided generally good results for pressure drop prediction, especially for cases with lower pressure drop. However, the pressure drop was under-predicted for cases with low air mass flow rate. For alumina, applying kinetic theory provided a good prediction of results in cases with a lower pressure drop. Nevertheless, for cases with a large pressure drop, the pressure drop was largely under-predicted. For sand, only a few cases obtained numerical convergence for the pressure drop prediction when applying kinetic theory.

7.2 Simulation with conventional frictional-kinetic model

The conventional frictional-kinetic model was utilised to conduct pressure drop prediction using a CFD simulation. The solid volume fraction and pressure contours for different types of material are also presented with selected case studies analysed specifically to show the mechanism of bypass pneumatic conveying.

- For flyash, the conventional frictional-kinetic model showed the same pressure drop prediction results as kinetic theory. Subsequently, the conventional frictional-kinetic model had no influence on pressure drop prediction for flyash. This prediction was in contrast to the high solids concentration observed from the experiments where a thick layered flow moves along the bottom of pipeline. Therefore, compared with alumina and sand (which have good results and are discussed below), there are probably are some other important factors that are not yet identified in the CFD simulation with conventional frictional-kinetic model for flyash. Additionally, the minimum frictional packing limit might require redefinition to even lower levels than has been proposed in this study. The detailed reasons for the poor correlation need to be further investigated.

- For alumina, the conventional frictional-kinetic model provided much improved pressure drop prediction results compared with kinetic theory. However, the pressure drop for alumina cases was still generally under-predicted, especially for denser flows with high pressure drop and low air mass flow rate. For sand, the conventional frictional-kinetic model dramatically improved the pressure drop prediction result compared with results from kinetic theory, and had a good agreement with experimental results, especially for denser flows with high pressure drops and low air mass flow rate. The sustained contact within alumina and sand powders was captured by conventional frictional-kinetic model and showed slug type structure for the alumina while a dune type structure was exhibited by the sand. In both the alumina and sand, the friction-kinetic model generally increased the pressure drop in bypass pneumatic conveying.

7.3 Simulation with modified frictional-kinetic model

The modified frictional-kinetic model was developed based on the nature of gas-solid flow in bypass pneumatic conveying. An offset solid volume fraction $\alpha_{s,off}$ was introduced into the modified model. Plus, the critical volume fraction and close packing limit were redefined as a function of the fluidised bulk density (lower limit) and tapped bulk density (upper limit).

Sensitivity analysis for modified frictional pressure model was carried out for flyash, alumina and sand, by varying the friction constants (n, p, Fr). By adopting the appropriate constants in the newly proposed modified frictional pressure model, as shown in equation (50), the pressure drop was predicted and compared with results from kinetic theory and the conventional frictional-kinetic model.

$$P_{friction} = \begin{cases} Fr \frac{(\alpha_s - \alpha_{s,min})^n}{(\alpha_{s,max} + \alpha_{s,off} - \alpha_s)^p} & \text{if } \alpha_s > \alpha_{s,min} \\ 0 & \text{if } \alpha_s \leq \alpha_{s,min} \end{cases} \quad (50)$$

In addition, the solid volume fraction and pressure contours for different types of material were presented. Based on the CFD simulation results, flyash, alumina and sand were classified into areas with different modes of flow.

- For flyash case study, in much the same way as the conventional frictional model, the pressure drop prediction results were not sensitive to $\alpha_{s,off}$ and constants and always remained the same. Again this was due to the maximum solid volume fraction from the simulation always being much lower than the critical minimum solid volume fraction to initiate frictional resistance values. In this way, the frictional stress between flyash particles did not occur in the simulation at all. On the other hand, for the alumina studies, the pressure drop results showed excellent agreement with experimental results by choosing appropriate $\alpha_{s,off}$ and constants. It is clear that frictional stress plays an important role in the CFD simulation of the dense phase bypass pneumatic conveying for alumina. While for the sand study, the pressure drop was always under-predicted for all simulations when $\alpha_{s,off}$, and the frictional constants, were varied. This might be because the offset solid volume fraction $\alpha_{s,off}$ was too large for sand, and both the frictional pressure and the correction factor for the radial distribution function were under-predicted accordingly. In this way, the shear viscosity, kinetic viscosity, frictional viscosity, and bulk viscosity were largely reduced. As a result, the pressure drop prediction results are largely under-predicted with the modified frictional-kinetic model for sand.
- Methods to choose appropriate simulation models for different types of material with diverse flow modes were proposed. It was proposed that the modified frictional-kinetic model be applied for pressure drop prediction for material having a well-defined fluidised dense phase conveying potential. It was also proposed that the modified frictional-kinetic model be applied for pressure drop prediction for material that has some marginal fluidised dense phase capability.

It was proposed that the conventional frictional-kinetic model be applied for pressure drop prediction for material that is classified as being capable of dilute phase only in a conventional pipeline.

7.4 Flow chart for simulation of bypass pneumatic conveying

Based on all the research described above, a flow chart for the CFD simulation methodology for bypass pneumatic conveying is proposed and showed in Fig. 20. In this figure, the most important outcomes and the associated design guide for choosing appropriate models for simulation of bypass pneumatic conveying are indicated with colour.

The first step is to obtain the material parameters, and then the modes of conveying can be determined. If it is dense phase flow, the Euler-Euler is then adopted. Otherwise, the Euler-Lagrange can be applied. Based on the numbers and status of phases, the types of Euler-Euler multiphase model can be decided. If the flow has dense phases, the Eulerian model is then chosen. Otherwise, the VOF model and mixture model can be chosen for immiscible fluids and dispersed phases, respectively.

Based on the turbulence simulation-capable investigation, the $k-\varepsilon$ turbulence model for simulation can be selected. Since the standard $k-\varepsilon$ turbulence is more suitable for the simulation of gas-solid flow, it was chosen to model the turbulence of the gas phase in this study. Moreover, the dispersed turbulence model was chosen to be used to simulate the turbulence of the solid phase.

Next, the solid pressure, solid shear stress, radial distribution function and granular temperature are considered accordingly. If only the collisional viscosity, kinetic viscosity and bulk viscosities are considered, the kinetic theory is then selected as the simulation model for bypass pneumatic conveying. If the conventional frictional viscosity is also included, then the conventional frictional-kinetic model is chosen. Or if the modified frictional viscosity is included, then the modified frictional-kinetic model is selected.

In addition, based on the experimental and numerical investigation of bypass pneumatic conveying flow modes with flyash, alumina and sand, the simulation models for pressure drops with other types of material can be generally determined in advance. In this way, the guidance about how to conduct pressure drop prediction with various types of material can be provided.

Fig. 25 Proposed flow chart for simulation of bypass pneumatic conveying

8. Conclusion

This study was focused on gaining a better understanding of gas solid flow behaviour in bypass pneumatic conveying systems through the use of CFD-based simulations. Specific aspects of the flow were investigated, including the solids concentration variation of the flow with some investigative work conducted on the bypass flute airflow and pressure behaviour.

A large portion of the work was dedicated to investigating the pressure drop prediction from the CFD simulations - as the pressure drop is an important design parameter for pneumatic conveying system selection. A flow chart for the CFD simulation methodology for bypass pneumatic conveying is proposed. A design guide for simulation of bypass pneumatic conveying with appropriate models is also suggested.

It is understood that there are still aspects in this study that have not been fully investigated and solved. Some areas need further investigation to gain a better understanding of gas-solid flow as well as to further prove the applicability and validation of pressure drop prediction models with various types of material in bypass pneumatic conveying:

- Although the frictional packing limit in the conventional frictional-kinetic model and critical solid volume fraction in the modified frictional-kinetic model were modified based on the fluidised bulk density, the pressure drop for three types of material were still generally under-predicted when compared to the experimental results. Especially for flyash, the maximum solid volume fraction from simulation with kinetic theory, conventional frictional-kinetic model and modified frictional-kinetic model were much lower than the frictional packing limit and critical solid volume fraction. This indicated that the frictional packing limit and critical solid volume fraction might be actually be even lower than the

results calculated from fluidised bulk density. Further investigation of the frictional packing limit and critical solid volume fraction needs to be conducted.

- The pressure drop prediction with different types of material in this study was only conducted in bypass pneumatic conveying with a fixed geometry. Therefore, the influence of flute diameter, bypass pipeline diameter, distance between flutes and angle of pitches on pressure drop prediction along the whole pipeline needs to be further studied. However, as shown in this study, there are now new well defined CFD methodologies available to use for bypass flute geometry analysis which can reflect dense phase flow structure and subsequent pressure prediction.
- The pressure drop predictions for the predictive chart were obtained by only adopting three types of material in this study. However, using more types of material corresponding to these modes of flow will help re-enforce the findings and solutions presented in this study. In this way, the applicability of the predictive chart can be further defined and improved, and the outcomes from this further investigation can provide more accurate guidance for bypass pneumatic conveying system design.
- In this study, the gas-solid flow was assumed as an incompressible flow and the uniform velocity inlet boundary conditions were applied accordingly. However, the velocity magnitude distribution can be non-uniform at the pipeline inlet, and there actually should be difference between air velocity and particle velocity. Therefore, the pressure drop prediction in bypass pneumatic conveying systems with non-uniform velocity inlet boundary conditions can be an aspect to be further investigated.
- The particle properties of permeability, de-aeration, particle size distribution and particle shape were generally neglected in the simulation for this study. These basic parameters for particle properties play an important role in gas-solid flow behaviour in bypass pneumatic conveying. Therefore, the influence of

these parameters should also be included to a greater extent in the modified frictional-kinetic model for pressure drop prediction in bypass pneumatic conveying.

- The applicability of the predictive chart was only discussed with bypass pneumatic conveying with limited types of material. However, bypass pneumatic conveying is just one form of the gas-solid flow. The applicability of the predictive chart in choosing appropriate models for simulation with gas-solid flow behaviour needs to be further developed.

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Table 1 Parameters for flyash, alumina and sand

Table 2 Properties and suitable application condition of three types of Euler-Euler models

Table 3 Different investigations of CFD-DEM model

Table 4 Semi-empirical constants that have been used by different investigators

Table 5 $\alpha_{s,\min}$ and $\alpha_{s,\max}$ for different materials

Table 6 $\alpha_{s,off}$, Fr , n and p for different materials

Table 7 Convergence for modified frictional-kinetic model with different values of $\alpha_{s,off}$, Fr , n and p

Fig. 1 Modified Geldart fluidisation chart with flow modes boundaries

Fig. 2 Modified Molerus fluidisation chart with flow modes boundaries

Fig. 3 Modified Dixon fluidisation chart with flow modes boundaries

Fig. 4 Pan's Fluidisation chart with flow modes boundaries

Fig. 5 Three mechanisms of particle regimes during transport

Fig. 6 Schematic diagram for bypass pneumatic conveying test rig

Fig. 7 Structure of bypass pipe and flute geometry (unit: mm)

Fig. 8 Sketch of computational domain

Fig. 9 Mesh system for bypass pipeline

Fig. 10 Magnified appearance of three regimes in bypass pneumatic conveying Test-flyash

$$(m_a=0.0157\text{kg/s}, m_s=1.4951\text{kg/s})$$

Fig. 11 Magnified appearance of three regimes in bypass pneumatic conveying for Test-alumina

$$(m_a=0.0207\text{kg/s}, m_s=2.6747\text{ kg/s})$$

Fig. 12 Magnified appearances of two regimes in bypass pneumatic conveying Test-sand

$$(m_a=0.0317\text{kg/s}, m_s=0.3649\text{kg/s})$$

Fig. 13 Flow chart of proposed model structure for dense phase pneumatic conveying

Fig. 14 Nomenclature for plane shear of a horizontal layer ^[114]

Fig. 15 Inclined-plane shear flow ^[114]

Fig. 16 dense phase pneumatic conveying shear flow

Fig. 17 Frictional pressure with and without $\alpha_{s,off}$ as function of solid fraction

Fig. 18 Experimental pressure drop Vs simulation pressure drop with different simulation models for flyash

Fig. 19 Experimental pressure drop Vs simulation pressure drop with different simulation models for alumina

Fig. 20 Experimental pressure drop Vs simulation pressure drop with different simulation models for sand

Fig. 21 Geldart fluidisation chart of sand with flow modes boundaries

Fig. 22 Molerus fluidisation chart of sand with flow modes boundaries

Fig. 23 Dixon fluidisation chart of sand with flow modes boundaries

Fig. 24 Pan's Fluidisation chart of sand with flow modes boundaries

Fig. 25 Proposed flow chart for simulation of bypass pneumatic conveying

Highlights

- (1) Different numerical model are described and compared for pneumatic conveying.
- (2) Fluidisation charts of different materials with flow modes boundaries are showed.
- (3) Guidance on what frictional approach to use for CFD analysis is provided.
- (4) A flow chart for the CFD simulation methodology is demonstrated.