Identification and Development of Embedded Computational Fluid Dynamic Models for Densely Packed Passive Bypass Pneumatic Conveying Systems

A thesis submitted for the fulfilment of the requirements for the award of the degree of

Doctor of Philosophy

From

The University of Newcastle

By

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School of Engineering
Centre for Bulk Solids and Particulate Technologies
Aug, 2013
DECLARATION

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution

__________________________

Ying Wang
Firstly, I would like to thank both of my supervisors Dr. Ken Williams and Prof Mark Jones of the University of Newcastle for their guidance and assistance during the development of this thesis. Dr. Ken Williams provides essential guidance and clarifying important ideas, which gave me confidence to finish the research goals. Also for Professor Mark Jones for providing professional working environment at the Centre for Bulk Solids and Particulate Technologies at the University of Newcastle to solve world problems.

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# NOMENCLATURE

**Upper Case Letters**

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<thead>
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<th>Description</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>$A_{in}$</td>
<td>cross section area at the pipeline inlet</td>
<td>$[m^2]$</td>
</tr>
<tr>
<td>$A^*$</td>
<td>constant in Ng et al’s equation [1]</td>
<td>[–]</td>
</tr>
<tr>
<td>$D$</td>
<td>pipe diameter</td>
<td>[m]</td>
</tr>
<tr>
<td>$D_s$</td>
<td>diffusivity for solid phase</td>
<td>[–]</td>
</tr>
<tr>
<td>$D_{ij}$</td>
<td>component of stress tensor</td>
<td>[–]</td>
</tr>
<tr>
<td>$D_g$</td>
<td>diffusivity for gas phase</td>
<td>[–]</td>
</tr>
<tr>
<td>$Fr$</td>
<td>constant in Johnson and Jackson model [2, 3]</td>
<td>[–]</td>
</tr>
<tr>
<td>$Fr'$</td>
<td>Froude number</td>
<td>[–]</td>
</tr>
<tr>
<td>$Fr_s$</td>
<td>solids Froude number</td>
<td>[–]</td>
</tr>
<tr>
<td>$G_{k,m}$</td>
<td>turbulence kinetic energy</td>
<td>[–]</td>
</tr>
<tr>
<td>$I$</td>
<td>turbulence intensity</td>
<td>[–]</td>
</tr>
<tr>
<td>$I_{2D}$</td>
<td>the second invariant of the deviatoric stress tensor</td>
<td>[–]</td>
</tr>
<tr>
<td>$K_{sg}$</td>
<td>interphase exchange coefficient</td>
<td>[–]</td>
</tr>
<tr>
<td>$K_w$</td>
<td>stress transmission coefficient</td>
<td>[–]</td>
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<th>Symbol</th>
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<tr>
<td>$K_{gs}$</td>
<td>gas-solid exchange coefficient</td>
<td>[-]</td>
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<tr>
<td>$L_{t,g}$</td>
<td>the length scale</td>
<td>[m]</td>
</tr>
<tr>
<td>$L$</td>
<td>length of pipe</td>
<td>[m]</td>
</tr>
<tr>
<td>$\Delta P_{fg}$</td>
<td>frictional pipeline pressure drop caused by air</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$\Delta P_{fs}$</td>
<td>frictional pipeline pressure drop caused by solids</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$\Delta P$</td>
<td>pressure drop</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$P_c(v)$</td>
<td>frictional pressure in Srivastava and Sundaresan’s model [4]</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$P_{s-kinetic}$</td>
<td>kinetic part of solid pressure in Syamlal et al’s model [4]</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$P_{s-friction}$</td>
<td>fricitional part of solid pressure in Syamlal et al’s model [4]</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$\hat{T}$</td>
<td>stress tensor describing yield and flow behaviour of granular materials</td>
<td>[-]</td>
</tr>
<tr>
<td>$\hat{T}_{fr}$</td>
<td>frictional stress tensor</td>
<td>[-]</td>
</tr>
<tr>
<td>$\hat{T}_{kin}$</td>
<td>kinetic stress tensor</td>
<td>[-]</td>
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**Lower Case Letters**

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<tr>
<td>$c$</td>
<td>inter particle cohesion</td>
<td>[-]</td>
</tr>
<tr>
<td>$c_w$</td>
<td>particle wall cohesion</td>
<td>[-]</td>
</tr>
<tr>
<td>$d_p$</td>
<td>average particle diameter</td>
<td>[m]</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>$d_{p1}$</td>
<td>particle diameter $p1$</td>
<td>[m]</td>
</tr>
<tr>
<td>$d_{p2}$</td>
<td>particle diameter $p2$</td>
<td>[m]</td>
</tr>
<tr>
<td>$d_s$</td>
<td>diameter of the particles</td>
<td>[m]</td>
</tr>
<tr>
<td>$e_{ss}$</td>
<td>coefficient of restitution for particle collisions</td>
<td>[−]</td>
</tr>
<tr>
<td>$g_{0,ss}$</td>
<td>radial distribution function</td>
<td>[−]</td>
</tr>
<tr>
<td>$k_g$</td>
<td>covariance of the velocities of gas and dispersed phases</td>
<td>[−]</td>
</tr>
<tr>
<td>$l$</td>
<td>turbulence length scale</td>
<td>[m]</td>
</tr>
<tr>
<td>$m_a$</td>
<td>air mass flow rate</td>
<td>[kg/s]</td>
</tr>
<tr>
<td>$m_g$</td>
<td>gas mass flow rate</td>
<td>[kg/s]</td>
</tr>
<tr>
<td>$m_s$</td>
<td>solids mass flow rate</td>
<td>[kg/s]</td>
</tr>
<tr>
<td>$m_{SLR}$</td>
<td>solids loading ratio</td>
<td>[kg/s]</td>
</tr>
<tr>
<td>$n$</td>
<td>constant in Johnson and Jackson model [2, 3]</td>
<td>[−]</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure shared by all phases</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$p_s$</td>
<td>solid pressure</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$\dot{v}_{dr}$</td>
<td>drift velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>$v_g$</td>
<td>air velocity</td>
<td>[m/s]</td>
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</table>
\( \dot{v}_m \) mixture velocity \[ \text{kg/m}^3 \]

\( \dot{v}_q \) the velocity of phase \( q \) \[ \text{m/s} \]

**Greek Letters**

\( \alpha_{\text{max}} \) maximum packing limit \[ - \]

\( \alpha_{\text{min}} \) critical value of solids volume fraction \[ - \]

\( \alpha_{s, \text{max}} \) modified maximum material packing limit \[ - \]

\( \alpha_{s, \text{min}} \) modified critical value of solids volume fraction \[ - \]

\( \alpha_{s, \text{off}} \) offset volume fraction \[ - \]

\( \varnothing \) angle of internal friction \[ - \]

\( \varnothing_{gs} \) transfer of the kinetic energy of random fluctuations in the particle velocity \[ - \]

\( \varnothing_w \) angle of wall friction \[ - \]

\( \gamma_{\theta_s} \) collisional dissipation of energy \[ - \]

\( k_{\theta_s} \) diffusion coefficient for granular energy \[ - \]

\( \lambda_i \) bulk viscosity of phase i \[ - \]

\( \lambda_g \) air friction factor \[ - \]

\( \lambda_s \) bulk viscosity \[ - \]
<table>
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<th>Unit</th>
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<td>$\lambda_s'$</td>
<td>solids friction factor</td>
<td>[-]</td>
</tr>
<tr>
<td>$\mu_i$</td>
<td>shear viscosity of phase i</td>
<td>[-]</td>
</tr>
<tr>
<td>$\mu_s$</td>
<td>shear viscosity</td>
<td>[-]</td>
</tr>
<tr>
<td>$\mu_{s,\text{col}}$</td>
<td>collisional part of the shear viscosity</td>
<td>[-]</td>
</tr>
<tr>
<td>$\mu_{s,f}$</td>
<td>frictional viscosity</td>
<td>[-]</td>
</tr>
<tr>
<td>$\mu_{s,fr}$</td>
<td>frictional viscosity</td>
<td>[-]</td>
</tr>
<tr>
<td>$\mu_{s,\text{kin}}$</td>
<td>kinetic viscosity</td>
<td>[-]</td>
</tr>
<tr>
<td>$\Theta_s$</td>
<td>the granular temperature</td>
<td>[-]</td>
</tr>
<tr>
<td>$\theta$</td>
<td>angle between mean particle velocity and mean relative velocity</td>
<td>[-]</td>
</tr>
<tr>
<td>$\rho_g$</td>
<td>air density or gas density</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_p$</td>
<td>particle density</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_{fb}$</td>
<td>fluidized bulk density</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_{lb}$</td>
<td>loose poured bulk density</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>mixture density</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_q$</td>
<td>density of phase q</td>
<td>[kg/m$^3$]</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>solid density</td>
<td>[kg/m$^3$]</td>
</tr>
</tbody>
</table>
**NOMENCLATURE**

\[ \rho_{tb} \quad \text{tapped bulk density} \quad [\text{kg/m}^3] \]

\[ \sigma \quad \text{shear rate} \quad [-] \]

\[ \tilde{\tau} \quad \text{stress tensor} \quad [-] \]

\[ \tilde{\tau}_f \quad \text{the frictional stress tensor} \quad [-] \]

\[ \tau_{F,sg} \quad \text{characteristic particle relaxation time} \quad [-] \]

\[ \tau_i \quad \text{stress-strain tensor of phase i} \quad [-] \]

\[ \tilde{\tau}_k \quad \text{kinetic stress tensor} \quad [-] \]

\[ \tau_{s-Tardos} \quad \text{average solid shear stress in Tardos et al.'s model [5]} \quad [-] \]

\[ \tau_{t,sg} \quad \text{Lagrangian integral time scale} \quad [-] \]

\[ \tau_{t,g} \quad \text{characteristic time of turbulence eddies in gas phase} \quad [-] \]

**Subscripts**

\[ g \quad \text{gas phase} \]

\[ g^{th} \quad \text{gas phase} \]

\[ q \quad \text{phase q} \]

\[ s \quad \text{solid phase} \]

\[ s^{th} \quad \text{solid phase} \]
Note: Some symbols displayed above are the same symbols used in the cited articles by the relevant authors. Using the same symbols avoided confusion when discussing similar parameters derived by different researchers.
ABSTRACT

Bypass pneumatic conveying systems are a more reliable and efficient method for transporting fragile and erosive bulk solids which are not suitable to be transported by conventional dense phase pneumatic conveying systems. This thesis is mainly focused on developing novel particle resistance models to conduct Computational Fluid Dynamic (CFD) numerical simulations of a passive bypass pneumatic conveying system with three types of material: flyash, alumina and sand. CFD based simulations still pose significant challenges to ensure that the physical nature of gas-solid flow can be effectively presented by numerical simulation for bypass pneumatic conveying systems.

In this thesis, an experimental program was planned which defined the particle properties and conveying experiments were conducted within a bypass pneumatic conveying pipeline. Based on the parameters utilised in the experiment, the CFD based numerical investigation of pressure drop was initially conducted by applying kinetic theory and conventional frictional-kinetic model. By comparing simulation results with experimental results and analysing images captured by high speed camera for selected cases, resistance models which better represented sustained particle contact for dense flows were investigated.

Based on the review of previous research, this thesis proposed a modified frictional-kinetic model which better reflected the physical nature of gas-solid flow behaviour in bypass pneumatic conveying system for alumina and sand. Unfortunately, no improvement was found for the flyash flow prediction. The sensitivity analysis of empirical constants in the modified frictional-kinetic model was conducted and the most appropriate values were determined. The pressure drop was then predicted using the modified frictional-kinetic model, and the prediction results were compared with results from kinetic theory and conventional frictional-kinetic model. Combined with mode of flow charts, some guidance was provided which related the frictional resistance model type to the particle flow type in a bypass system.
CHAPTER 1 INTRODUCTION

1.1 General review of pneumatic conveying

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 uses. 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 conditions allow the system to transport various kinds of granular materials including hazardous bulk materials without generating environmental problems. Thirdly, this system can be operated automatically and the testing results can be used to optimise the system. Without the constant need for controlling and monitoring the conveying process, labour costs can be reduced.

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 velocity particle flow and reduction in associated conveying problems including particle attrition and erosive wear of pipelines. However, dense phase conveying is critically dependent 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 system 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.
The bypass pneumatic conveying system employs a secondary pipe with fixed slots at regular intervals inside the standard conveying line. 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 and increasing the solid loading ratio (SLR), this form of conveying leads to a reduction in energy consumption.

Pressure drop is of 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 to calculate pressure 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. CFD is seen as a powerful simulation tool as it can capture three-dimensional flow behaviour without time consuming experimental work. The Eulerian approach is a common method to investigate industrial flows.

1.2 Objectives of the thesis

This thesis aims to measure and simulate the pressure drop along the bypass pneumatic conveying pipeline. The pressure drop prediction strongly depends on the numerical models that are chosen to describe the interactions between particles within the pneumatic conveying flow. In the past years, the kinetic theory was applied to investigate gas-solid flow behaviours. In order to consider frictional stress between particles, the frictional-kinetic model was applied in gas-solid flow simulation. However, the model was applied directly without any physical justification. The form of the equation was generated from soil mechanical principles and the constants used in the semi-empirical model were originally summarised from measurements of inclined chutes with glass beads only. In this thesis, a modified frictional-kinetic model is proposed and applied to predict the pressure drop of bypass pneumatic conveying. Three different kinds of materials including flyash, alumina and sand were investigated both in experiment and simulation.
1.3 Overview of the thesis

This thesis will attempt to develop a modified frictional-kinetic model based on the existing research and new findings. Since the majority of researchers only apply frictional-kinetic model to simulate dense gas-solid flow by adopting Johnson and Jackson frictional model [2] directly, this research work is anticipated to modify the frictional-kinetic model based on different material properties including particle properties and bulk densities. The thesis will be developed in 7 chapters which are summarised as follows:

- Chapter 1 provides the general review of pneumatic conveying, types of pneumatic conveying as well as bypass pneumatic conveying system. The importance of pressure drop for pneumatic conveying system design is also briefly introduced. Thesis objective and overview are carried out as well.

- Chapter 2 introduces the pneumatic conveying system, modes of conveying as well as the predictive diagrams. Particularly, the innovatory system especially the passive bypass systems are described. Furthermore, the pressure drop prediction methods including experimental approach, mathematical approach and numerical approach are presented. The numerical approach used in pressure drop prediction are reviewed, discussed and determined.

- Chapter 3 presents the properties of different types of materials for different modes of flow. Then, the general arrangement of the conveying system, detailed configurations of conveying pipeline and instrumentation are described. A simple and representative CFD mesh geometry is derived to represent the characteristics of bypass pneumatic conveying for the CFD simulations. The experiment for different types of material is conducted and the results are summarised and analysed.

- Chapter 4 used CFD simulations to predict the pressure drop of the bypass pneumatic conveying using the kinetic theory for different types of material. The pressure drop prediction results are compared with experimental results. Specifically, the solid volume fraction distribution of representative cases are presented and compared with images captured by high speed camera. In addition, the pressure contours are also presented and analysed.
• Chapter 5 conducts the CFD based pressure drop prediction of bypass pneumatic conveying with conventional frictional-kinetic model for different types of material. Different frictional pressure models are reviewed and summarised. Some parameters used in conventional frictional-kinetic model are modified based on the nature of dense phase pneumatic conveying. Finally, by comparing with results from kinetic theory, improvement of pressure drop prediction with the conventional frictional-kinetic model is shown.

• Chapter 6 carries out the sensitivity analysis for a proposed modified frictional-kinetic model. After the empirical constants in the modified frictional-kinetic model are determined, the pressure drop prediction is conducted accordingly. Based on the pressure drop prediction results from this chapter as well as chapter 4 and 5, the guidance for choosing appropriate model to predict pressure drop with different types of material conveying in bypass pneumatic conveying system is also proposed.

• Chapter 7 presents the conclusions obtained from this research which is focussed on the pressure drop prediction for the bypass pneumatic conveying system. In addition, an outline of future work beyond this thesis is presented.
CHAPTER 2 BASICS OF PNEUMATIC CONVEYING

Pneumatic conveying is defined as a method to transport powder and granular material through an enclosed channel by using air as a transport medium. In order to design a dense phase pneumatic conveying system, the modes of flow for different types of materials should be initially determined and the system type should also be chosen. Materials are pneumatically conveyed in different modes, where dense phase pneumatic conveying is of particular interest in this thesis. Dense phase pneumatic conveying reduces the pipeline abrasion and energy consumption with low conveying velocity and high Solids Loading Ratios (SLR). Innovative pneumatic conveying systems are an alternative solution to transport fragile and erosive bulk solids which are not suitable to be transported by conventional dense phase pneumatic conveying systems. With even lower conveying velocity and high SLR, the design cost can be further reduced.

Once the tonnage rate for a system is known and the minimum transport velocity determined, the pressure drop along a pipeline is the main final parameter which provides guidance for industrial pneumatic conveying system design, and it is the main focus of this thesis. The mathematical approach, experimental approach and CFD approach are three main methods to provide information of pressure drop for pneumatic conveying designers. However, the mathematical approach, which the designer hopes will completely represent the conveying conditions, has a high degree of uncertainty for predicting pneumatic performance, in particular, the pressure drop. The experimental approach gives more related and detailed designing guide for designer; however, it is costly and time consuming. Ultimately, the numerical simulations can consider the influence of bypass pipeline characteristics and save time and cost compared to conducting full scale experiments, it has been a powerful tool in investigating gas-solid flow behaviour and predicting the pressure drop along a pneumatic conveying pipeline.

The results of multiphase flow CFD modelling provide detailed information of gas-solid flow in pneumatic conveying and can direct the design of pneumatic conveying system. To predict the pressure drop for bypass pneumatic conveying, the choice of simulation models is significant. Firstly, the way to model multiphase flow depends on how to treat continuous phases and dispersed phases within the simulation. Secondly, a computational procedure to describe turbulent interaction under different conditions has
caused the most problems in the turbulent flow. Thirdly, the turbulent kinetic energy of the particles needs to be determined.

The main aim of this chapter is to review and assess the methods that have been used to determine the pressure drop for pneumatic conveying system design. The types of pneumatic conveying system and modes of flow are also summarised. Besides, the main multiphase CFD modelling methods, Eulerian approaches, turbulence models and particle phase kinetic theory are reviewed and assessed.

2.1 System flexibility and types

Pneumatic conveying systems are widely employed to transport powdered and granular materials in industry. A system normally contains an air mover, a feeding device, conveying pipeline and a receiver to separate the conveying material and air, as shown in Fig 2.1. A compressor, fan or blower can be used as the air mover. A blow tank, rotary valve, vertical feeder or high pressure screw feeder can be applied as the feeder. The layout of conveying pipeline is flexible with horizontal and vertical straight sections and bends. Receivers are dominated by silos with a filter but can be other systems such as cyclones. High, low and negative pressure systems can be adopted for material transport. Since pneumatic conveying systems transport materials through a pipeline with an enclosed environment a wide range of materials, including hazardous materials, can be conveyed safely.

![Fig 2.1 Configuration example for a pneumatic conveying system](image)

With the appropriate choice and arrangement of equipment, materials can be conveyed for a long distance. Flexible plant layout and operation can be achieved by combining multiple point feeding into a single line, or separating a common line into a number of receiving hoppers. Conveying pipelines can run horizontally and vertically. Bends are
used to connect and combine different orientating pipelines into a single pipeline run. Pneumatic conveying systems not only take little space, but also can easily avoid existing equipment or structures through proper arrangement. Moreover, most of the pneumatic conveying systems can operate automatically.

Different types of pneumatic conveying systems are available for conveying a wide range of dry bulk granular materials. Most of the pneumatic conveying systems are conventional and they locate in a fixed position with constant operation. Alternatively, innovatory systems, batch operating systems, closed systems and mobile systems are more suitable to accommodate various types of materials. A conveying system can have either a positive or negative pressure, or a combination of the two. Most conveying systems transport materials continuously, however, sometimes conveying one batch at a time becomes more convenient for specific situations. Low and high operating pressures can be chosen for delivering materials to reception points maintained at atmospheric pressure. The illustration of combinations that are available for conventional systems with a single air source is shown in Fig 2.2.

![Fig 2.2 Illustration of combinations available for conventional system with a single air source](image)

### 2.2 Modes of conveying

Dilute phase and dense phase are two types of pneumatic conveying. For dilute phase, materials are conveyed in suspension in the conveying air with high velocities. While for dense phase, materials are conveyed in non-suspension in the conveying air, usually at lower velocities compared with dilute phase. Dilute phase is the most reliable and flexible conveying mode and almost all kinds of materials can be conveyed in the dilute phase when enough airflow is available. However, the relatively high conveying velocity in dilute phase causes particle degradation, pipeline abrasion and high power consumption.
For dense phase flow materials are conveyed with a low velocity and high solids loading ratio in which the particle breakage, pipeline abrasion and energy consumption are reduced. The general description for dense phase flow with fine powder is that it has two layers including a dilute phase layer flowing over a slower dense phase layer. There are two general modes of flow in dense phase. The first one is plug or slug flow and the second one is dune, fluidized dense phase or moving bed flow. The pneumatic conveying transition behaviour from dilute to plug conveying and from dilute to fluidized dense phase conveying are illustrated in Fig 2.3 and Fig 2.5, respectively. The general forms for plug flow and fluidized dense phase pneumatic conveying are shown in Fig 2.4 and Fig 2.6, respectively.

In moving bed flow, the material is conveyed at the bottom of the conveying pipeline with a format of dunes, as shown in Fig 2.3 (b) and Fig 2.5 (b). In addition, moving bed flow is only suitable in conventional pneumatic conveying systems when material has good air retention characteristics. While in slug or plug flow the material, which has good permeability, is conveyed in full bore plugs with air gaps [6].

For plug flow, the discrete plugs can vary in size and space in between. They can merge with other plugs or be destroyed. The plug behaviour is influenced by pneumatic conveying conditions through the pipeline including air pressure, solids mass flow rate and air mass flow rate. The general flow behaviour for plug flow in pneumatic conveying can be defined by pressure drop ($\Delta P$), air mass flow rate ($m_a$) and solids mass flow rate ($m_s$), as shown in Fig 2.4. It is complex and difficult to define the transition from dilute flow to plug flow. By decreasing $m_a$, the flow mode transfers from dilute phase to dense phase bed flow which has dense phase along the bottom pipeline and dilute phase on the top layer. As $m_a$ continues to decrease, a region with instabilities appears which is neither a slug nor a plug flow region. The characteristics for this region can vary according to material type. If $m_a$ is further reduced below a critical value, the dense phase steady state region of plug flow appears. At the front of each plug material picks up particles from a stationary layer, while at the back of the plug, material falls off.
For fluidized dense phase flow, there is a wave or dune like motion for the dense phase layer at the bottom of the pipe, as demonstrated in Fig 2.5 (c). This mode of flow is discontinuous and interspersed with a full bore pulse of material. It could appear to be a
concentrated dilute phase or dispersed dense phase flow or possibly both in combination. The pulse appears to re-aerate powder to fluidise the material. This mode of flow is suitable for conveying material with good air retention capabilities. It is hard to achieve this mode of flow with Materials that have large size distributions [7]. The general flow behaviour for fluidized dense phase flow can be defined by $\Delta P$, $m_a$ and $m_s$, as shown in Fig 2.6. Fluidized dense phase flow is similar to the behaviour of 'conveying in layers' observed from plug flow conveying. There is a smooth transition from dilute to dense phase conveying without the unstable zone for fluidized dense phase conveying. The majority of material is conveyed at the bottom of the pipeline while the higher velocity dilute flow dominates the upper layer.

Fig 2.5 Pneumatic conveying transition behaviour from dilute to fluidized dense phase conveying
Considering the mechanical properties of the product, some materials are not suitable to be conveyed in dense phase in conventional pipelines. These properties are mainly:

(1) Narrow particle size distribution and low dust percentage;
(2) Even particle shape;
(3) No cohesion or adhesion;
(4) Large particle size, greater than 0.3mm.

### 2.3 Predictive diagrams

By conveying the material in a pipeline experimentally or using some type of predictive technique, the potential for a material to be conveyed in dense phase can be determined. Since predictive technique leads to less cost compared with experimental method, a large number of charts have been developed to predict the material dense phase capability and have been reviewed by Jones and Williams [8].

Two subcategories of charts are summarized for predicting pneumatic conveying mode of flow capability. The ‘basic’ parameter based charts [9-11] use parameters of average particle size and particle density, while the ‘bulk-particle’ parameter based charts [12-14] use loose-poured bulk density to replace particle density.
2.3.1 Fluidised diagram with particle density

Geldart [10] initially developed diagrams based on investigation of bulk material fluidisation behaviour and classified the materials into 4 distinct groups labelled A, B, C and D. Geldart’s diagram has been also used to predict pneumatic conveying capabilities, as shown in Fig 2.7 as an example.

![Fig 2.7 Geldart fluidisation diagram with the ‘mode of flow’ data][8, 10]

Molerus [11] studied the fluidisation performance of a bulk material instead of pneumatic conveying performance, and applied particle adhesion equations to define the boundaries of different fluidisation classification groups based on Geldart’s chart. Despite different boundary criteria, very similar results were shown compared with Geldart [10].

Dixon [9] investigated the ability of a material to form slugs and developed a material slugging diagram. Dixon argued that a material forms either strong axisymmetric slugs, weak axisymmetric slugs or no slugs depending on particle density and average particle diameter. The areas of strong axisymmetric slugs and weak axisymmetric slugs have obvious combinations of mode of flow including fluidised dense phase, dilute only and plug type.

2.3.2 Fluidised diagram with loose-poured density

The behaviour of bulk material in dense phase pneumatic conveying is more important than individual particles. Thus, while predicting the particulate mode of flow for
pneumatic conveying systems, the ‘loose-poured’ bulk density might provide a more useful parameter than individual particle density. By replacing particle density with ‘loose-poured’ bulk density, Pan [12] developed a non-modified basic parameter diagram to predict the possible mode of flow capability of a material, as shown in Fig 2.8 as an example. Based on Pan’s work and by adopting similar technique that replacing particle with ‘loose-poured’ bulk density, Williams and Jones [13] modified the Geldart’s diagram [10], Molerus’s diagram [11] and Dixon’s diagram [9].

![Pan fluidisation diagram with the ‘mode of flow’ data](image)

**Fig 2.8 Pan fluidisation diagram with the ‘mode of flow’ data [8, 12]**

### 2.3.3 Diagram with air-particle bulk material

Researches about predicting the likely pneumatic conveying mode of flow for the air-particle behaviour of a bulk material were conducted. Parameters of fluidisation and de-aeration obtained from bench scale tests were considered. Mainwaring and Reed [15] developed a two-diagram predictive technique by using the steady state fluidisation pressure, permeability and de-aeration. Jones [16] proposed a single diagram by relating the permeability with de-aeration behaviour of a material. Chambers et al [17] proposed a dimensional parameter in a diagram by utilising parameters of particle density, permeability and de-aeration to predict mode of flow. Similarly, Fargette et al [18] proposed another dimensional parameter and replaced the particle density with bulk density. Moreover, Sanchez et al [19] proposed a two-parameter dimensionless diagram by considering permeability, de-aeration rate, gravitational forces, conveying gas properties and particle size. Since de-aeration rate is hard to determine, based on the
above work, Williams [14] developed a diagram with parameters of permeability and loose poured bulk density for modes of flow prediction. Compared with basic material diagrams, similar fluidised dense phase and plug flow regions are presented with a clear dilute phase region, as shown in Fig 2.9. Between these three different regions, there are unknown areas with mixing of two different regions, and the dense flow mode capability for these materials is generally not easily determined without some experimentation.

![Fig 2.9 Williams et al. fluidisation diagram with the ‘mode of flow’ data [8, 14]](image)

2.4 Innovatory systems

In order to convey materials without natural dense phase conveying capabilities at low velocities, innovatory systems have been developed to suit the conveying materials. Plug forming, air injection and passive bypass systems are the three main types of innovatory systems.

2.4.1 Plug forming systems

Plug forming systems have been developed to transport cohesive bulk materials which have a problem of conveying. A wide range of fine and cohesive bulk materials have shown conveying capability in the plug forming systems. In this type of conveying system, an air knife introduces air into the pipeline to separate the discharging material into discrete plugs. In this way, the bulk material conveying in the pipeline forms as intermittent short plugs. The plug forming system is shown in Fig 2.10.
2.4.2 Air injection (active bypass) systems

In an air injection system, a sub-pipe runs alongside the conveying pipeline with regular air injection points. With an independent air supply, materials exhibit good air retention properties while conveying. However, supply air which enters the main pipeline is insufficient to break up the plug or blockage. Also, with the additional air supply, energy consumption rises. Moreover, the conveying air velocity increases which causes erosive wear and particle degradation. Two types of air injection systems are shown in Fig 2.11.

![Diagram of air injection systems]

Fig 2.11 Different air injection systems

Barton [20] summarized the relevant air injection systems including the Gattys System [21], and the Swiss Aluminium Ltd. [22]. The Gattys System [21] is the original and
most basic system of bypass pneumatic conveying with air injection. Gattys system [21] has four types, as shown in Fig 2.12; it was developed with additional air to improve bulk material conveying. Air is introduced into the pressurised airline to fluidize the material being conveying. Type (A) and (B) have similar principles. The knee joint is used to connect the pressurised air line with the gas hose which has self-opening holes. The pressurised air line is placed outside the main pipeline in (A) and it is located inside the main pipeline in (B). In type (C), there is no plastic hose and the high pressure air is only introduced into pipeline through holes. Type (D) has three different configurations and the pressurised air line is located outside the conveying line.

For conveying bulk materials with the Swiss Aluminium Ltd system [22] as shown in Fig 2.13, compressed air is introduced to improve dense phase conveying conditions in the feed pipe system. The compressed air goes through the porous disc into the restriction areas where the cross sectional area reduces or where there is a blockage while conveying.

Since there are no boosters or injectors in this system, it is impossible to exceed the mass flow rate and maximum conveying velocity once they are established. There is no requirement for setting up costly accessory equipment and the porous disc can prevent materials entering into the compressed air line. However, the determination of the restriction areas is difficult without detailed direction from the patent text.
2.4.3 Passive bypass systems

The focus of this PhD is the analysis of a passive bypass system, as such, a more in depth discussion is conducted for this section of the basics of pneumatic conveying. Dense phase pneumatic conveying is critically dependent on the physical properties of a material. In order to reduce attrition and abrasion in the conveying process, as well as reduce the energy consumption, a passive bypass pneumatic conveying system can be an alternative solution to transport fragile and erosive bulk solids. The passive bypass system, can either allow an otherwise dilute phase only material to be conveyed in a denser state, or reduce even more the conveying velocity of a dense phase capable material, when compared to single bore conveying.

The general description of a passive bypass system is as follows. By inserting or connecting a small pipe, which has fixed flutes at regular intervals, into or onto a conventional conveying line, a passive bypass system can be constructed. Although there is no external source of air entering into the inner pipe, the conveying air can flow between the main and bypass pipe freely via the flute openings. It has a sub-pipe located outside the conveying pipeline which connects with the main pipeline at regular intervals along the length. A sketch of an internal and external bypass system is shown in Fig 2.14.
When the pipeline fills with material and insipient blockage commences, more conveying air will be forced into the bypass pipe which is designed to have a smaller diameter than the main pipeline. The air will then be forced back into the main pipeline through the flutes beyond the blockage due to the pressure difference between the main and bypass pipes. In this case, a blockage due to a material plug does not easily form, or if formed, can be broken. Generally, this technique is used to convey materials that may not have the air retention or permeability properties to convey in slug or plug type flow. Compared to a conventional system, the bypass system is able to convey materials with a high density ratio and a low air velocity. Therefore, lower power consumption, less particle degradation and pipeline wear will occur in this system. A bypass pneumatic conveying system with flowing material is shown in Fig 2.15.

The Möller Turboflow type system [23] is the most common passive bypass pneumatic conveying system. Möller et al [23] patented a pneumatic and hydraulic conveying installation for transporting granular bulk material, as shown in Fig 2.16. An internal pipe was inserted into a transport pipe with regular inlet and outlet openings. A perpendicular disc was positioned between an inlet and an outlet opening with a circular
hole in the middle of the disc. This disc was designed to generate turbulence within the transport pipe to provide aeration to the bulk materials and thereby inhibit clogging or blocking occurring during transportation.

Similar to the Swiss Aluminium Ltd. patent [22], without a booster or injectors, it is impossible to exceed the mass flow rate and the medium and maximum conveying velocity once they are determined. This type of system only needs an additional bypass pipeline to be inserted in, and it is not necessary to set up this type of conveying system with other additional accessory equipment. However, the number of intervals and spaces between flutes is difficult to determine without specific design guidelines. Moreover, the materials might get blocked inside the bypass pipeline when conveying very fine and sticky bulk materials.

![Diagram of conveying system by Moller](image)

**Fig 2.16 Conveying system by Moller [23]**

2.4.4 General hierarchy diagram of passive bypass pneumatic conveying systems

In order to represent where the passive bypass system is in relation to the pneumatic conveying systems, a hierarchal diagram is presented, as illustrated in Fig. 2.17. It is clear from this diagram that passive bypass system’s main purpose is to improve fine powder capability in the dense flow mode regime of fluidised dense phase conveying. The passive bypass pneumatic conveying system with internal bypass pipeline that is one of the most commercially available bypass pneumatic conveying systems is the research subject of this study where powdered materials of flyash, alumina and sand are conveyed.
2.5 Pressure drop investigation

In any pneumatic conveying system there are three operating parameters including the solids flow rate that the system must transport, the energy required to transport the tonnage, which is defined by the total pressure drop and the air flow rate. Pressure drop is the most important parameter for pneumatic conveying system design. This thesis is mainly concentrate on the investigation of pressure drop along the bypass pneumatic conveying pipeline. There are three main methods to predict the pressure drop for pneumatic conveying including experimental approach, mathematical approach and numerical approach.

2.5.1 Experimental approach

The experimental approach is normally used to investigate the pressure drop of a dense phase pneumatic conveying system with fine powders, because it usually gives a more related and detailed designing guide for industry. The pressure drop of a pneumatic conveying system has been investigated by the following researchers [24-29].

Geldart and Ling [24, 25] conveyed two sizes of fine coal \( d_{p1} = 22\mu m \), \( d_{p2} = 72\mu m \) with nitrogen, hydrogen, and carbon dioxide. Based on more than 600 data points, the evaluation and correlation of bends, acceleration and solids/wall friction on pressure drop and saltation velocities was conducted.

Aziz and Klinzing [26] transported fine coals to investigate operational characteristics, flow patterns and pressure loss behaviour for plug flow conveying. It was found that the pressure drop across the plug varied linearly with plug length. Moreover, as the gas velocity increased, the pressure drop also increased for the range of plug lengths studied.
Two pressure drop equations were proposed to predict pressure drop which had agreement within ±20% of the experimental results.

By using a Mohno pump, Morikawa et al [27] studied the phenomena in horizontal pneumatic conveying of powder experimentally. With a variation of a pipe diameter, speed of pump rotation and air velocity, the pressure gradient was investigated. The pressure gradient rose with an increasing solid loading ratio, but it shown no connection with pipe diameter.

Laouar and Molodtsof [28] characterized pressure drop in a dense phase pneumatic conveying system with different pipe diameters and pipe lengths at very low velocities. A general pressure drop law, which was independent of both flow regime and pipe diameter, was derived and applied to all the flows in his investigation where the gas superficial velocity remained lower than 0.2 m/s.

Based on particle properties and data from a simple vertical test chamber, Pan and Wypych [29] conducted a new test-design procedure and they accurately predicted the pressure drop and slug velocity in large-scale slug flow systems with low-velocities. The procedure in the presented study can be applied to materials with different shapes, densities, sizes and size distributions.

Since the scale-up technique from pilot plant conveying test work is costly and time consuming, it is more economic and timesaving to utilize numerical simulation to investigate bulk material flow behaviour and obtain information for designing various pneumatic conveying systems.

2.5.2 Friction based mathematical approach

Weber [30] proposed a two-phase fluid model which has been used to predict the pressure drop. Compared with one phase model which only relates to the losses due to air alone, Weber’s model includes the resistance and collisions of particles additively with equation (2-1) for the air and equation (2-2) for the solids.

\[ \Delta P_{fg} = \lambda_g \frac{\rho_g v_g^2 L}{2 \frac{D}{D}} \]  

\[ \Delta P_{fs} = m_{SLR} \lambda_s \frac{\rho_s v_s^2 L}{2 \frac{D}{D}} \]
where $\Delta P_{fg}$ is the frictional pipeline pressure drop caused by air, $\Delta P_{fs}$ is the frictional pipeline pressure drop caused by solids, $m_{SLR} = \frac{m_s}{m_b}$ is the solids loading ratio, $\lambda_a$ is the air friction factor, $\lambda_s'$ is the solids friction factor, $L$ is the length of pipe, $D$ is pipe diameter, $\rho_a$ is the air density, $v_b$ is the air velocity, $m_s$ is the solid mass flow rate, and $m_a$ is the air mass flow rate.

For dilute phase pneumatic conveying systems, the two-phase fluid model proposed by Weber [30] has been used to calculate the pressure drop. For horizontal dilute phase flow, Molerus [31] reviewed the physical meaning of the previous friction correlations. For vertical dilute phase flow, Rautiainen and Sarkomaa [32] proposed a friction correlation based on previous correlation. From the above research [30-32], Jones and Williams [7] found that the solids friction factor correlations are a function of solids loading ratio, Froude number ($Fr'$), solids Froude number ($Fr_s$) and some non-dimensional parameters, as shown in equation (2-3):

$$\lambda_s' = f(m_{SLR}, Fr', Fr_s, \frac{d_s}{D}, \frac{\rho_s}{\rho_b})$$  \hspace{1cm} (2-3)

where $Fr_s$ is based on Froude number based on particle settling velocity, $d_p$ is the average particle diameter, $\rho_s$ is the particle density, $\rho_g$ is the fluid density.

For fluidised dense phase pneumatic conveying, $\lambda_s$ in equation (2-2) illustrates the most important pressure component. Pan and Chambers [33] successfully evaluated the solids friction factors by conducting scale-up procedures by transporting material in a test rig and then back-calculating the solids friction factor, therefore essentially providing a lumped friction number which represents the solids friction in the pipe. This solids friction factor is then used to determine the total pipeline pressure drop in the scaled up pipeline. Weber [34] developed empirical correlations based on the work of Stegmaier [35] with fine powders. Based on experimental data with a variety of fine powders, Wypych [36] also compared the work of Stegmaier [35]. By adding gas density and pipeline length in the Stegmaier’s [35] correlation, an improvement was reported in the accuracy of the solids friction correlation. However, it was found that the convergence of the correlation was poor to predict the pressure drop. Based on the work of Seigel [37] and Szksay [38], Weber [30, 39] developed a mathematical technique while determining solids friction correlation to reduce the errors between experimental pressure drop and
predicting results for coarse powders. Jones and Williams [7] conducted a series of calculations to estimate solids friction factor with four material types conveyed in fluidised dense phase, and an empirical solids friction factor model was proposed. The empirical model, which was found to be independent of particle properties, has good capability to predict the pressure drop for fluidised dense phase pneumatic conveying with the material tested. However, for all these solids friction factor models and techniques, the accuracy of the models when applied to pipelines which are much larger in pipe bore and/or are longer in length, the models cannot accurately determine the pressure drop of the system suitable for reliable design.

When various data sets and the results of industrial scale tests were compared for dense phase pneumatic conveying with plugs, the Mi (Konrad)-based model [40], represented by equation (2-4) was found to be the best approach to predict the pressure drop.

\[
\frac{\Delta p}{L} = \frac{4 \tan \phi_w K_w F}{D} + \frac{4 \tan \phi_w (K_w + 1) c \cos \phi \cos (\omega - \phi_w)}{D} + 2 \rho_B g \tan \phi_w + \frac{4c_w}{D} \tag{2-4}
\]

Where \( \phi_w \) is the angle of wall friction, \( \phi \) is the angle of internal friction, \( c \) is the inter particle cohesion, \( c_w \) is the particle-wall cohesion, \( K_w \) is stress transmission coefficient. Equation (2-3) was initially developed to predict the pressure drop for a conventional pneumatic conveying system. Barton [20] directly employed this equation to predict the pressure drop of a bypass pneumatic conveying system. However, without considering the influences of a flute/orifice plate, internal or external bypass pipelines, the accuracy of the predicted results was uncertain.

2.5.3 Numerical approach

The numerical approach is the focus of this thesis. This is because the mathematical approaches calculate pressure drop without considering the influence of the bypass pipeline characteristics. Moreover, the accuracy of pressure gradient prediction using mathematical approaches is uncertain when the configurations are changed by adding a flute/orifice plate, internal or external bypass pipeline. Furthermore, numerical approach eliminates conducting all the tests thus saving on space, time, money and labour. The numerical approach gives both quantitative and qualitative data throughout the whole model by taking bypass pipeline characteristics into consideration.
CFD has been used by many researchers [41-49] to study gas-solid flow behaviour for fine powder material. While the combined approach of computational fluid dynamics (CFD) and discrete element method (DEM), which is referred as CFD-DEM method, is popular to simulate the gas-solid flow behaviour for larger particles with limited amount [50-52]. For DEM, by applying Newton's laws of motion to every particle, the motion of discrete solids or particles phase can be obtained. For CFD, by solving local averaged Navier–Stokes equations, the flow of continuum fluid can be described. By utilising Newton's third law, the interactions between the fluid phase and solids phase can be modelled. As the dense phase bypass pneumatic conveying has large amount of fine particles, CFD-DEM method would be time consuming and costly for the simulation. CFD approach should be the primary method to conduct simulation for bypass pneumatic conveying. The detailed numerical approach is presented in the following subchapter.

2.6 Computational Fluid Dynamic approach

The commercial Computational Fluid Dynamic (CFD) approach is one of the more powerful and flexible general-purpose computational fluid dynamics software packages to model flow, turbulence, heat transfer and reactions for industrial applications. It is based on fast and reliable computational methodology to provide accurate and practical solutions for reducing risks of potential design flaws, optimizing engineering design and provides researchers with a scientific tool.

2.6.1 Introduction of Fluent

Commercial software package Fluent is the most popular simulation tool of CFD to compute fluid flow, heat transfer and reactions for industrial applications. With special models, this software is able to model in-cylinder combustion, aero-acoustics and turbo-machinery with a broad reach.

FLUENT is written in the C computer language and makes full use of the flexibility and power offered by this language. It provides complete mesh flexibility, including the ability to solve flow problems using unstructured meshes that can be generated about complex geometries with relative ease. Based on the flow solution, the mesh methods can be modified accordingly [53].
2.6.2 Computational Fluid Dynamic application

Physical models provide accurate CFD analysis for a wide range of fluid problems. In the past few years CFD software has become more popular in solving and analysing flow behaviours when designing pneumatic conveying systems. Many researchers [41-49] have used the CFD approach to investigate pressure drop in pneumatic conveying systems.

By implementing a two fluid CFD model including the kinetic theory granular model in commercial CFX technology, Wachem et al [41] simulated bubbling fluidised beds with different superficial gas velocities and different column diameters. By comparing with existing correlations for bubble size and bubble velocity, it was found that the data obtained from simulations is useful when validating existing empirical correlations and provides information for improving existing correlations, determining new correlations and calculating specific physical properties of certain configurations.

By conducting simulations with the CFD approach using the Euler-Euler two phase flow model, Lee et al [42] studied dilute and dense phase pneumatic transport through a 90° bend. Two different granular materials including polypropylene beads and glass beads were investigated. By employing electrical capacitance tomography (ECT), particle image velocimetry and a phase doppler particle analyser, the solids concentration and velocity distribution in the pneumatic conveying system were measured. The core structures in the solid flow were observed experimentally and numerically in the post-bend region. The simulation results of the cross-section averages of the solid volume fraction in the clusters had the same order as the ECT results.

McGlinchey [43] predicted horizontal and vertical bend pressure drop by using the CFD software package Fluent with the Mixture and Eulerian model. By comparing with industrial-scale experiment results, the trends and flow patterns of pneumatic conveying were in good agreement, whereas the pressure drop with different conveying conditions and bend orientations had poor predicted results with a 10% to 90% error margin.

By applying the CFD approach with the granular kinetic model McGlinchey and Cowell [44] predicted the pressure drop of cement, with a particle size of 25um, conveying in bends and straight sections through a 53mm diameter pipeline bore. By comparing with
experiment results and changing the default parameters to increase the accuracy of the Fluent Eulerian model, it was found that only changing the inlet velocity of a material lead to significant changes in pressure drop prediction.

McGlinchey et al [45] used the 3D Fluent 6.3 Eulerian CFD model to investigate the flow behaviour of a single plug of material through three step geometries including an ‘abrupt’ step and two ‘gradual’ step-up geometries with a pipeline bore of 75-100 mm. From the plots of the solids volume fraction and solids velocity vector, the recirculation zones resulting from abrupt and gradual expansion were found to be potential sites for pipeline wear or particle degradation.

McGlinchey [46] studied the solids motion of a stationary plug in a passive bypass line with the CFD approach of the transient Eulerian model using the commercial software Fluent. All of the models adopted in the simulation were based on the horizontal and vertical bend pressure drop prediction investigation [43]. Further experimental verification needed to be conducted.

By using the commercial CFD software Fluent 6.3, Ma et al [47] numerically and experimentally studied the pressure drop across a horizontal bend for a flyash powder with a solids loading ratio in the range 20-70. The influencing factors including particle size, particle density, bend radius ratio, wall conditions and inlet velocity difference on pressure drop were analysed. The simulation results for the pressure drop prediction had good agreement with experimental results and the model employed in this study was promising for dense phase flow analysis.

Zhang et al [48] and Zhang et al [49] investigated an internal bypass pneumatic conveying system experimentally and numerically, which was referred to as double-tube socket (DTS) pipe. A CFD model was developed for dense phase flow and compared to the experimental results in the SLR range from 20.1~37.1. The predicted air volumetric flow rate and lowest energy power consumption were found to be in good agreement with experimental results. However, the variation of pressure drop with solids loading ratio and energy consumption in the fully developed part was found not as expected. The pressure drop prediction along the bypass pipeline needs to be further developed.
2.6.3 Computational Fluid Dynamic models

In order to conduct numerical investigation for pressure drop prediction, the review and assess of computational fluid dynamic multiphase modelling, Eulerian approach, turbulence models and particle phase kinetic theory are carried out.

2.6.3.1 Computational Fluid Dynamic multiphase modelling

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 (2-5), momentum equation (2-6) and energy equation (2-7).

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0 \tag{2-5}
\]

\[
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} [\rho u_i u_j + p \delta_{ij} - \tau_{ji}] = 0, \quad i = 1, 2, 3 \tag{2-6}
\]

\[
\frac{\partial}{\partial t} (\rho e_0) + \frac{\partial}{\partial x_j} [\rho u_j e_0 + u_j p + q_j - u_i \tau_{ji}] = 0 \tag{2-7}
\]

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 [54] or fluidized beds [55].

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 they are assumed to be continuous functions of space and time. This model provides the basic idea of the mathematical approach used within this thesis 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.
The VOF model is employed to simulate 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. It is applicable for the study of wave-structure interactions [56], rise of single and multiple bubbles in sheared liquids [57], gas liquid reactor internals [58], stratified flows [59] and the steady or transient tracking of any gas-solid interface [60].

The mixture model is 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. It is suitable to calculate low loading particle-laden flows [61], flows with bubbles [62], sedimentation [63] and cyclone separators [64].

The Eulerian model solves a set of momentum and continuity equations for each phase. The coupling of phases is based on pressure and inter-phase exchange coefficients. The Eulerian multiphase model is applied in simulating bubble columns [65], risers [66], particle suspension [67] and fluidized beds [68].

### 2.6.3.2 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 [69].

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 [55, 70-74]. The most recent numerical research using the Eulerian model was conducted by Ma et al [47] and flow characteristics of gas-solid flow in a pneumatic conveying system were studied to predict the pressure drop in a pipeline.

Qi [75] utilised 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 modelling, 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 describes 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 [76] 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 [77] modelled 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.

2.6.3.3 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 first 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 main approaches used to compute turbulent flow are summarised in Fig 2.18.

The two equation models are the most common turbulence models where the K-epsilon (k-ε) models are the most popular of the two equation models used to compute turbulence. Fluent offers three different k-ε turbulence models including the standard k-ε model, RNG k-ε model and Realizable k-ε model. Three different methods are provided for k-ε models to simulate turbulence in multiphase flows. These methods a mixture of the turbulence model, dispersed turbulence model and each phase turbulence model.
McGlinchey [46] 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 this paper.

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 [74, 78]. 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 [79, 80].

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 [81]. This model appears to be the most promising mathematical approach to describe the behaviour of particle phase flow in gas-solid flow systems [82]. Many investigations have been developed based on the particle phase kinetic theory [83-86]. The detailed choice of turbulence model will be presented in Chapter 4.
Fig 2.18 Main approaches used to compute turbulent flows
2.6.3.4 Particle phase kinetic theory

Based on the theory for non-uniform dense gases described in Chapman and Cowling [81], 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.

Lun et al [87] initially developed two kinetic theories to calculate rapid flows of cohesionless granular materials and examine 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 nearly completely elastic particles. The materials used for calculation were 1.0 mm diameter polystyrene spheres with a specific gravity of 1.095 and 1.8 mm diameter ballotini spherical glass beads with a specific gravity of 2.97. By comparing with other theories and experimental results, the results from the first theory at higher concentrations are 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 [88] 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 [89] 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.

Liu et al [90] applied the kinetic theory of granular flow to perform the transport properties of the solid phase. The Eulerian continuum two-fluid model for both 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.

By using the Eulerian two-fluid model (TFM), Wang et al [91] 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 velocity, backpressure and convergent section angle were analysed.

Based on the kinetic theory of granular flow, Lu et al [92] 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.

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 [93] 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.

2.7 Summary

System flexibility, types and modes of conveying are summarized for pneumatic conveying systems. Although the dense phase mode transports materials with low energy consumption and erosion, it is still not reliable to convey many types of
materials which have a narrow particle size distribution, low dust percentage, even particle shape, no cohesion or adhesion and large particle size, greater than 0.3mm. Compared with conventional dense phase pneumatic conveying systems, innovatory systems can transport materials without natural dense phase conveying capabilities at low velocities. Innovatory systems, in particular the Moller patent [23], is an alternative and commercially available solution to reduce pipeline erosion and lead to lower energy consumption. Pressure drop is the key parameter to provide accurate and practical solutions for optimizing industrial designs. Thus investigation of pressure drop in bypass pneumatic conveying is the main focus of this thesis.

The accuracy of pressure gradient prediction using mathematical approaches is uncertain when the configurations are changed by adding a flute/orifice plate, internal or external bypass pipeline, and experimental approach with full scale tests is costly and time consuming. This work has showed the potential for the use of numerical approach to give both quantitative and qualitative data throughout the whole model by taking bypass pipeline characteristics into consideration. Multiphase CFD simulation is the most powerful tool to investigate gas-solid flow behaviour for pneumatic conveying with fine powders. Eulerian approach with particle kinetic theory based on kinetic theories of non-uniform dense gases as described by Chapman and Cowling [81] is determined to predict the pressure drop for flyash, alumina and sand in dense bypass pneumatic conveying.
CHAPTER 3 EXPERIMENT PROGRAM AND DATA

This chapter firstly describes materials properties including particle size, particle density and bulk density for flyash, alumina and sand. Based on the basic parameter methods and air-particle characterisation method presented in this chapter, three types of bulk materials were transported in the bypass pneumatic conveying. The modes of flow for these materials used in this thesis are determined using basic materials properties.

The general arrangement of the conveying system, detailed configurations of conveying pipeline and instrumentation are then presented. Based on the physical conveying geometry model, a simple and representative CFD mesh geometry is derived to represent the characteristics of bypass pneumatic conveying for the CFD simulations.

Lastly, the experimental test procedure and test programme conducted for the bypass pneumatic conveying tests are listed. With different combination of the air mass flow rate and solids mass flow rate, the pressure drop of bypass pneumatic conveying was determined for the three material types. The pressure drop of the total pipeline was obtained via pressure gauge data collection system.

3.1 Material parameters

3.1.1 Particle size

The particle size is an essential parameter due to its influence on the natural force of attraction between particles. The particle size distribution was measured using a Mastersizer 2000, as shown in Fig 3.1. This equipment employs the technique of laser diffraction. Specifically, the intensity of the light scattered as a laser beam passing through a dispersed particulate sample is measured. Based on the amount of light scattering, the size of the particles that create the scattering pattern is analysed to calculate the size of the particles.
The detailed particle size distribution test results are presented in Fig 3.2 to 3.4. All three materials analysed exhibited a single mode structure and a wide range of size distribution. Compared to the flyash and alumina, the sand has the narrowest size distribution range, as shown in Fig 3.4.

**Fig 3.2 Particle size distribution analysis of flyash**
The average particle diameters for three types of materials are summarized in Table 3.1.

**Fig 3.3 Particle size distribution analysis of alumina**

**Fig 3.4 Particle size distribution analysis of sand**
Table 3.1 Particle diameter of materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Average Particle Diameter (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyash</td>
<td>378</td>
</tr>
<tr>
<td>Alumina</td>
<td>76.7</td>
</tr>
<tr>
<td>Sand</td>
<td>14.7</td>
</tr>
</tbody>
</table>

3.1.2 Particle density

Particle density is defined as the mass of an individual particle divided by the volume of the entire particle. The particle density was measured using an air displacement pycnometer and was determined by taking the average value of the density readings. The results are given in Table 3.2.

Table 3.2 Particle density of materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Average Particle Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyash</td>
<td>2093</td>
</tr>
<tr>
<td>Alumina</td>
<td>4088</td>
</tr>
<tr>
<td>Sand</td>
<td>2600</td>
</tr>
</tbody>
</table>

3.1.3 Bulk density

The bulk density is the mass of bulk material divided by the total volume occupied by the material. Test equipment used to determine the bulk density is shown in Fig 3.5.
The loose poured bulk density is obtained from the volume of material poured into a container where the material is in a loose, non-compacted or as poured condition, without any applied compacting force. This value is determined by the mass of the total material divided by the volume of the container. Three measurements were taken for each material and the average density was calculated, as shown in Table 3.3.

<table>
<thead>
<tr>
<th>Material</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyash</td>
<td>806</td>
<td>810</td>
<td>845</td>
<td>820</td>
</tr>
<tr>
<td>Alumina</td>
<td>1041</td>
<td>1047</td>
<td>1050</td>
<td>1046</td>
</tr>
<tr>
<td>Sand</td>
<td>1622</td>
<td>1601</td>
<td>1624</td>
<td>1616</td>
</tr>
</tbody>
</table>
(b) Tapped bulk density

The tapped bulk density is determined by measuring the weight per unit volume of a bulk material when the sample has been packed or compacted in the cylindrical container. By using a small metal stick, the material was ‘tapped’ gradually in the cylindrical container until no further compaction of material occurred. The change in height of the material in the container was measured by a linear displacement transducer and was recorded by computer. The value of the tapped bulk density is higher than that of the loose poured bulk density. Three measurements were conducted for each material to obtain the average value for the ‘tapped’ bulk density, as shown in Table 3.4.

<table>
<thead>
<tr>
<th>Material</th>
<th>Time 1</th>
<th>Time 2</th>
<th>Time 3</th>
<th>Tapped bulk density (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyash</td>
<td>0.0156</td>
<td>0.0155</td>
<td>0.0160</td>
<td>980</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>993</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1002</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>992</td>
</tr>
<tr>
<td>Alumina</td>
<td>0.0179</td>
<td>0.0178</td>
<td>0.0177</td>
<td>1102</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1119</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1125</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1115</td>
</tr>
<tr>
<td>Sand</td>
<td>0.0182</td>
<td>0.0179</td>
<td>0.0180</td>
<td>1697</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1693</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1518</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1636</td>
</tr>
</tbody>
</table>

(c) Fluidised bulk density

Fluidised bulk density is determined from the apparent bulk density when a material is in the fluidised state. The technique to measure this bulk density is derived from a typical fluidisation test. In a fluidisation test a vertical pipe is filled with the material. The air is then entrained into the pipe from the bottom, where the air velocity is increased until full fluidisation occurs. For these tests, the air was varied between 0 m/s and 225 mm/s. A differential pressure transducer was used to record the pressure change in the vertical pipe. The relationship between pressure in the vertical pipe and the superficial velocity of air is shown in Fig 3.6 to 3.8 for the three material types tested. The associated fluidised bulk density was calculated in Table 3.5 to 3.7. Compared with the loose poured bulk density and tapped bulk density, the fluidized bulk density is generally lower in value. The permeability of different types of material can be obtained from fluidisation tests as well and will be summarised in the part of material properties.
Flyash:

Initially the superficial velocity was increased steadily from 0mm/s to 250mm/s (i.e. increasing velocity), as can be seen in Fig 3.6. It was found that the pressure in the vertical pipe rose at a constant rate until the superficial velocity reached approximately 80mm/s. As the superficial velocity continued to be increased up to 225mm/s, the pressure remained at the same level. The superficial velocity was then decreased from 225mm/s to 0mm/s gradually (i.e. decreasing velocity), as shown again in Fig 3.6. It was observed that the pressure remained at the same value while the superficial velocity reduced to 40mm/s. After this point a fluctuation of pressure appeared as the superficial velocity dropped down to 0mm/s.

The variations in the fluidised bed depth of flyash were recorded simultaneously. In Fig 3.6, the fluidisation occurred when the superficial velocity reached 80mm/s. As the superficial velocity was increased from 80mm/s up to 225mm/s, the pressure and fluidised bed depth in the vertical pipe maintained the same value. The fluidised bulk density of flyash was determined by measuring the fluidised bed depth. The test and calculated result is shown in Table 3.5.

![Fig 3.6 Fluidisation chart of flyash](image)
As presented in Fig 3.7, firstly, the superficial velocity was increased from 0mm/s to 225mm/s continuously. It was found that the pressure in the vertical pipe rose dramatically with the increase of the superficial velocity up to 8.4mm/s. As the superficial velocity continued to go up to 225mm/s, the pressure in the vertical pipe remained almost at the same value. Secondly, the superficial velocity was reduced from 225mm/s to 0mm/s slowly. The pressure stayed around the same level until the superficial velocity decreased to 8.3mm/s. The pressure dropped down sharply while the superficial velocity climbed down to 0mm/s.

The variations in the fluidised bed depth of alumina were recorded simultaneously. In Fig 3.7, the fluidisation occurred when the superficial velocity reached 25mm/s. As the superficial velocity rose from 25mm/s up to 225mm/s, the pressure and fluidised bed depth in the vertical pipe stayed constant. The fluidised bulk density of alumina was determined by measuring the fluidised bed depth. The test results and calculated average are shown in Table 3.6.

### Table 3.5 Fluidised bulk density test results for flyash

<table>
<thead>
<tr>
<th>Initial bed depth (mm)</th>
<th>Fluidised bed depth (mm)</th>
<th>Fluidised Bulk Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>230</td>
<td>350</td>
<td>509</td>
</tr>
<tr>
<td>226</td>
<td>338</td>
<td>518</td>
</tr>
<tr>
<td>223</td>
<td>355</td>
<td>487</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>505</td>
</tr>
</tbody>
</table>
As shown in Fig 3.8, initially the superficial velocity was increased from 0mm/s to 225mm/s gradually. It was observed that the pressure in the vertical pipe increased quickly as the superficial velocity rose from 0mm/s to 110mm/s. As the superficial velocity continue to increase up to 225mm/s, the pressure in the vertical pipe didn’t change. The superficial velocity was then reduced from 225mm/s to 0mm/s steadily. The pressure was maintained at almost the same level until the superficial velocity decreased to 110mm/s. The pressure then dropped down at a steady rate as the superficial velocity decreased to 0mm/s.

**Fig 3.7 Fluidisation chart of alumina**

**Table 3.6 Fluidised bulk density test results for alumina**

<table>
<thead>
<tr>
<th>Initial bed depth (mm)</th>
<th>Fluidised bed depth (mm)</th>
<th>Fluidised Bulk Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>223</td>
<td>260</td>
<td>860</td>
</tr>
<tr>
<td>216</td>
<td>250</td>
<td>867</td>
</tr>
<tr>
<td>219</td>
<td>257</td>
<td>855</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>861</strong></td>
</tr>
</tbody>
</table>

**Sand:**

As shown in Fig 3.8, initially the superficial velocity was increased from 0mm/s to 225mm/s gradually. It was observed that the pressure in the vertical pipe increased quickly as the superficial velocity rose from 0mm/s to 110mm/s. As the superficial velocity continue to increase up to 225mm/s, the pressure in the vertical pipe didn’t change. The superficial velocity was then reduced from 225mm/s to 0mm/s steadily. The pressure was maintained at almost the same level until the superficial velocity decreased to 110mm/s. The pressure then dropped down at a steady rate as the superficial velocity decreased to 0mm/s.
The variations in the fluidised bed depth of alumina were recorded at the same time. In Fig 3.8, the fluidisation occurred when the superficial velocity reached 110mm/s. As the superficial velocity rose from 110mm/s up to 225mm/s, the pressure and fluidised bed depth in the vertical pipe stayed stable. The fluidised bulk density of sand was determined by measuring the fluidised bed depth. The test results and calculated average are shown in Table 3.7.

**Fig 3.8 Fluidisation chart of sand**

**Table 3.7 Fluidised bulk density test results for sand**

<table>
<thead>
<tr>
<th>Initial bed depth (mm)</th>
<th>Fluidised bed depth (mm)</th>
<th>Fluidised Bulk Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>221</td>
<td>270</td>
<td>1207</td>
</tr>
<tr>
<td>214</td>
<td>250</td>
<td>1263</td>
</tr>
<tr>
<td>207</td>
<td>240</td>
<td>1272</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>1247</td>
</tr>
</tbody>
</table>
The material properties are summarized as following:

The flyash parameters are:

- Average Particle Diameter: \( d_p = 14.7 \) \( \mu m \)
- Particle Density: \( \rho_p = 2093 \) kg/m\(^3\)
- Loose Poured Bulk Density: \( \rho_{lb} = 820 \) kg/m\(^3\)
- Tapped Bulk Density: \( \rho_{tb} = 992 \) kg/m\(^3\)
- Fluidised Bulk Density: \( \rho_{fb} = 505 \) kg/m\(^3\)

The alumina parameters are:

- Average Particle Diameter: \( d_p = 76.7 \) \( \mu m \)
- Particle Density: \( \rho_p = 4088 \) kg/m\(^3\)
- Loose Poured Bulk Density: \( \rho_{lb} = 1046 \) kg/m\(^3\)
- Tapped Bulk Density: \( \rho_{tb} = 1115 \) kg/m\(^3\)
- Fluidised Bulk Density: \( \rho_{fb} = 863 \) kg/m\(^3\)

The sand parameters are:

- Average Particle Diameter: \( d_p = 378 \) \( \mu m \)
- Particle Density: \( \rho_p = 2600 \) kg/m\(^3\)
- Loose Poured Bulk Density: \( \rho_{lb} = 1616 \) kg/m\(^3\)
- Tapped Bulk Density: \( \rho_{tb} = 1636 \) kg/m\(^3\)
- Fluidised Bulk Density: \( \rho_{fb} = 1247 \) kg/m\(^3\)

### 3.1.4 Mode of flow prediction

Permeability and de-aeration factors are difficult to define due to various measuring techniques. Thus, fluidisation diagrams using the‘loose-poured’ bulk density are
utilised to predict the particulate mode of flow for flyash, alumina and sand by pneumatic conveying. Different fluidisation diagrams with parameters of mean particle diameter and loose-poured bulk density are adopted. Boundaries between different modes of flow are drawn to classify the three materials tested into different regions to predict their flow modes. The regions to which flyash, alumina and sand fall into are presented in a modified Geldart’s fluidisation diagram, a modified Molerus’s fluidisation diagram, a modified Dixon’s fluidisation diagram [8] and a Pan’s fluidisation diagram [12], as shown in Fig 3.9, Fig 3.10, Fig 3.11 and Fig 3.12 respectively. It can be found that flyash is located in the region of fluidised dense phase in all four of the diagrams. Flyash has very fine powders and a relative low loose-poured bulk density. Sand belongs in the region of dilute phase in all four diagrams. Sand has a very large particle diameter and a high loose-poured bulk density, 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 locate around the joining area between the fluidised dense phase, dilute phase and unknown regions. This means that alumina powders can be regulated to be transported 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.

Fig 3.9 Modified Geldart fluidisation chart with flow modes boundaries [8]
Fig 3.10 Modified Molerus fluidisation chart with flow modes boundaries [8]

Fig 3.11 Modified Dixon fluidisation chart with flow modes boundaries [8]
3.2 Conveying pipeline configurations

3.2.1 General arrangement of the conveying system

The conveying air is supplied from a compressor in a positive pressure mode. The materials are discharged from the bottom of the feeding device into the conveying system which runs horizontally for 6.5 m. Through adjusting the proportion of total air flow to the blow tank and the feed pipe position, the discharge rate of material can be controlled. The mass flow rate is measured by load cells mounted on the receiving bin. The pipeline contains an inner bypass line with regular openings, called flutes, spaced 400 mm apart. The main pipe is a heavy black 80NB steel pipe with an 80 mm inner diameter. The bypass pipe is a medium black 25NB steel pipe with a 27 mm inner diameter. The pneumatic conveying test rig schematic diagram is shown in Fig 3.13.
3.2.2 Bypass pipe geometry

The structure of the bypass pipe and flute arrangement is shown in Fig 3.14. Each flute has two pitches, both being 45° to upstream and downstream. The air is able to enter the regularly spaced flutes without any additional external source of air. If the main pipeline blocks and the materials are impermeable, the internal bypass pipe provides an alternative route for the air. The main pipeline diameter is 80mm. The bypass pipeline internal diameter is 27mm and the external diameter is 32mm. The distance between the main pipeline and the bypass pipeline is approximately 1mm. The orifice plate has a 27mm diameter. The circular opening in the centre of the orifice plate and is 7mm in diameter. The distance between two orifice plates is 400mm.

3.2.3 Instrumentation

A series of pressure transmitters were set up along the pipeline to test the gauge pressure while conveying material. In order to measure the pressure difference between
the main and bypass pipe, differential pressure transmitters were used in the conveying system. The arrangement of the pressure transducer tap is shown in Fig 3.15. A piece of glass pipe was also fitted into the main pipeline as a watch glass. A High Speed Visual Camera (HSVC) Phantom 5 with 105 mm lens was used to observe the flow behaviour of materials inside the glass pipe. Labview software was used to monitor and record real-time data.

![Fig 3.15 Pressure transducer arrangement](image)

3.2.4 Geometry used for simulation

A sketch of the geometry for the computational domain of the conveying pipeline from pressure transducer P1 to P2 is shown in Fig 3.16. The total length of pipe used for computations was 6.5m, with 16 flutes in total. The geometry of bypass pipe was meshed using ANSYS 13.0. Since it is hard to detail the mesh results for the whole pipeline in this thesis, the mesh of two random flutes from the longitudinal plane are selected as examples, which are shown in Fig 3.17 (a). Moreover, Fig 3.17 (b) and Fig 3.18 (c) are mesh results of the longitudinal plane and cross-sectional area for one random flute, respectively, to express the mesh more clearly. There are 2,577,358 elements for the numerical simulation, with a maximum skewness value of 0.8358.

![Fig 3.16 Sketch of computational domain](image)
3.3 Conveying tests

The conveying tests were conducted separately for flyash, alumina and sand to investigate each material’s parameters and capabilities in dense phase bypass pneumatic conveying. Firstly, all the tests were conducted using the 6.5m bypass pneumatic conveying system.

3.3.1 Experimental test procedure

At the beginning of each test, the feeding blow tank is filled up with a certain quantity of material. The top valve and bottom valve are closed. The primary air is supplied to the conveying line. The top valve is then opened and the primary air starts to transport material through the conveying pipeline to the receiving bin. The variations of pressure during the conveying process are captured by the pressure transducers and are recorded by software Labview. After the material is discharge, the top valve is closed and all the material is now in the receiving bin.
The return line is used to move all the material back into the feeding blow tank. The secondary air supply is initialised. The bottom valve is opened and the secondary air supply is used to take the material back to the feeding blow tank until the weight of load cell doesn’t change anymore. The secondary air is then turned off and the bottom valve is closed. All above procedures are repeated to conduct tests for different materials.

3.3.2 Experimental test programme

The general conveying test programme is listed in Table 3.8 to Table 3.10. These tables show the air mass flow rate ($m_a$) and solids mass flow rate ($m_s$) for different materials.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$m_a$ / (kg/s)</th>
<th>$m_s$ / (kg/s)</th>
<th>Test No.</th>
<th>$m_a$ / (kg/s)</th>
<th>$m_s$ / (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyash-1</td>
<td>0.0681</td>
<td>1.4923</td>
<td>Flyash-13</td>
<td>0.0317</td>
<td>1.7578</td>
</tr>
<tr>
<td>Flyash-2</td>
<td>0.0681</td>
<td>1.0686</td>
<td>Flyash-14</td>
<td>0.0317</td>
<td>1.3761</td>
</tr>
<tr>
<td>Flyash-3</td>
<td>0.0681</td>
<td>0.7250</td>
<td>Flyash-15</td>
<td>0.0317</td>
<td>0.8869</td>
</tr>
<tr>
<td>Flyash-4</td>
<td>0.0524</td>
<td>2.3159</td>
<td>Flyash-16</td>
<td>0.0207</td>
<td>2.1308</td>
</tr>
<tr>
<td>Flyash-5</td>
<td>0.0524</td>
<td>1.6431</td>
<td>Flyash-17</td>
<td>0.0207</td>
<td>1.5919</td>
</tr>
<tr>
<td>Flyash-6</td>
<td>0.0524</td>
<td>1.2187</td>
<td>Flyash-18</td>
<td>0.0207</td>
<td>1.2923</td>
</tr>
<tr>
<td>Flyash-7</td>
<td>0.0524</td>
<td>0.8662</td>
<td>Flyash-19</td>
<td>0.0207</td>
<td>0.9211</td>
</tr>
<tr>
<td>Flyash-8</td>
<td>0.0417</td>
<td>2.4875</td>
<td>Flyash-20</td>
<td>0.0157</td>
<td>2.3358</td>
</tr>
<tr>
<td>Flyash-9</td>
<td>0.0417</td>
<td>2.0412</td>
<td>Flyash-21</td>
<td>0.0157</td>
<td>1.4951</td>
</tr>
<tr>
<td>Flyash-10</td>
<td>0.0417</td>
<td>1.2037</td>
<td>Flyash-22</td>
<td>0.0157</td>
<td>1.1722</td>
</tr>
<tr>
<td>Flyash-11</td>
<td>0.0417</td>
<td>0.7821</td>
<td>Flyash-23</td>
<td>0.0157</td>
<td>0.9271</td>
</tr>
<tr>
<td>Flyash-12</td>
<td>0.0317</td>
<td>2.5486</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 3.9 Test programme for Alumina

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$m_a$ / (kg/s)</th>
<th>$m_s$ / (kg/s)</th>
<th>Test No.</th>
<th>$m_a$ / (kg/s)</th>
<th>$m_s$ / (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina-1</td>
<td>0.0681</td>
<td>4.0078</td>
<td>Alumina-11</td>
<td>0.0317</td>
<td>2.9958</td>
</tr>
<tr>
<td>Alumina-2</td>
<td>0.0681</td>
<td>2.8231</td>
<td>Alumina-12</td>
<td>0.0317</td>
<td>2.8242</td>
</tr>
<tr>
<td>Alumina-3</td>
<td>0.0681</td>
<td>2.2780</td>
<td>Alumina-13</td>
<td>0.0317</td>
<td>2.2338</td>
</tr>
<tr>
<td>Alumina-4</td>
<td>0.0524</td>
<td>5.0964</td>
<td>Alumina-14</td>
<td>0.0207</td>
<td>3.1397</td>
</tr>
<tr>
<td>Alumina-5</td>
<td>0.0524</td>
<td>3.3127</td>
<td>Alumina-15</td>
<td>0.0207</td>
<td>2.6747</td>
</tr>
<tr>
<td>Alumina-6</td>
<td>0.0524</td>
<td>2.4462</td>
<td>Alumina-16</td>
<td>0.0157</td>
<td>3.0630</td>
</tr>
<tr>
<td>Alumina-7</td>
<td>0.0524</td>
<td>1.7832</td>
<td>Alumina-17</td>
<td>0.0157</td>
<td>2.8379</td>
</tr>
<tr>
<td>Alumina-8</td>
<td>0.0417</td>
<td>2.0078</td>
<td>Alumina-18</td>
<td>0.0157</td>
<td>2.3147</td>
</tr>
<tr>
<td>Alumina-9</td>
<td>0.0417</td>
<td>1.8823</td>
<td>Alumina-19</td>
<td>0.0157</td>
<td>1.6388</td>
</tr>
<tr>
<td>Alumina-10</td>
<td>0.0417</td>
<td>1.3544</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3.10 Test programme for Sand

<table>
<thead>
<tr>
<th>Test No.</th>
<th>$m_a$ / (kg/s)</th>
<th>$m_s$ / (kg/s)</th>
<th>Test No.</th>
<th>$m_a$ / (kg/s)</th>
<th>$m_s$ / (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand-1</td>
<td>0.0681</td>
<td>1.8008</td>
<td>Sand-8</td>
<td>0.0317</td>
<td>0.3649</td>
</tr>
<tr>
<td>Sand-2</td>
<td>0.0681</td>
<td>0.7415</td>
<td>Sand-9</td>
<td>0.0207</td>
<td>2.5415</td>
</tr>
<tr>
<td>Sand-3</td>
<td>0.0524</td>
<td>1.6824</td>
<td>Sand-10</td>
<td>0.0207</td>
<td>1.7156</td>
</tr>
<tr>
<td>Sand-4</td>
<td>0.0417</td>
<td>2.9303</td>
<td>Sand-11</td>
<td>0.0207</td>
<td>0.3002</td>
</tr>
<tr>
<td>Sand-5</td>
<td>0.0417</td>
<td>1.5074</td>
<td>Sand-12</td>
<td>0.0157</td>
<td>1.4493</td>
</tr>
<tr>
<td>Sand-6</td>
<td>0.0317</td>
<td>2.6149</td>
<td>Sand-13</td>
<td>0.0157</td>
<td>0.4939</td>
</tr>
<tr>
<td>Sand-7</td>
<td>0.0317</td>
<td>1.6203</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For each conveying test result, the analysis of each test is based on the region where the pressure at the pipe inlet and pressure at the bottom pot have only small fluctuations. It is important to select useful data from the test results. The data can be organised and used for subsequent analysis. In case the pressure tested by the pressure transducers had irregular fluctuations then the test was discarded.
Fig 3.18 shows the experimental measurements for the pressure at the feeding blow tank, pressure at the pipe inlet, pressure at the receiving bin and load cell weight. In the beginning, the pressure at the feeding blow tank, pipe inlet and receiving bin increases more dramatically than the rise in load cell weight. From the time of 35s, the pressure at the feeding blow tank, pipe inlet and receiving bin maintains a constant level without irregular fluctuations, while the load cell weight rises rapidly. At the end of this test, the pressure at the feeding blow tank, pipe inlet and receiving bin decreases while the load cell weight maintains approximately the same value. In other words, the system stops feeding material into the conveying pipeline. Furthermore, the solid mass flow rate can be calculated from the mass gain from the load cell weight of the receiving bin versus time.

In the period of steady state conditions, there are still obvious pressure fluctuations. A lower and upper bound of pressure fluctuations with a major amplitude value was observed. Although the gas pressure pulse analysis has a lot of error, the average of the pulse velocity fluctuation is close to the value of superficial gas velocity. Closer examination of the test data was conducted for each test result and the pressure drop with error bars are presented in the following subchapters.
3.4 Results and discussion

The test results, the relationship between air mass flow rate \( (m_a) \) and pressure drop \( (\Delta P) \) for a range of solids mass flow rates are as follows.

### 3.4.1 Flyash

Figure 3.19 shows the pressure drop during conveying flyash in the bypass pneumatic conveying pipeline with different solids mass flow rates. It was found for most cases that at the same air mass flow rate the pressure drop decreased with reducing solids mass flow rates. While the pressure drop increased with decreasing air mass flow rates.

![Fig 3.19 Experimental results of pressure drop for flyash](image_url)

### 3.4.2 Alumina

Figure 3.20 shows the pressure drop results using the bypass pneumatic conveying pipeline to convey alumina with different solids mass flow rates. It was found for most cases that with the same air mass flow rate, the pressure drop decreased with reducing solids mass flow rates. While the pressure drop increased with a decreasing air mass flow rate.
3.4.3 Sand

Figure 3.21 shows the pressure drop test results from conveying sand in the bypass pneumatic conveying line, with different solids mass flow rates. It was found in all cases that at the same air mass flow rate, the pressure drop decreased with reducing solids mass flow rate. While the pressure drop increased with a decreasing air mass flow rate.

Fig 3.20 Experimental results of pressure drop for alumina

Fig 3.21 Experimental results of pressure drop for sand
3.5 Conclusion

The anticipated outcome of this chapter was firstly to conduct basic test methods to gain important parameters which can be employed to predict modes of flow for different types of materials. Parameters include particle size, particle density and bulk density. Flyash had the widest particle size distribution, while sand had the narrowest particle size distribution. The loose poured bulk density and tapped bulk density were tested based on basic definition and test principles. The fluidised bulk density was obtained through a typical fluidisation test. Particle density was determined by average value of density readings. It shows that alumina has the highest particle density, and sand has a little lower particle density, while flyash has the lowest particle density.

The modes of flow for different types of materials were classified based on parameters of particle diameter and loose-poured bulk density. Flyash is in the fluidised dense phase region and sand is in the dilute only region, while alumina is in the undetermined region. The results indicate the flow capability of different types of materials in bypass pneumatic conveying.

The experimental test procedure was explained and the pressure drop data was obtained when the conveying is during the steady state conditions. The pressure drop along the bypass pneumatic conveying pipeline was measured for a range of conveying conditions by varying the air mass flow rate and solid mass flow rate. All the experimental test programmes were summarized in the tables. Based on the test results, the relationship between pressure drop, air mass flow rate and solid mass flow rate were presented and analysed. It was found that for all three types of materials, within different solid mass flow rate ranges, the pressure drop decreased with increasing of air mass flow rate. Moreover, with the same air mass flow rate, the pressure drop generally increased with increasing solid mass flow rate.

The sketch of the geometry of the computational domain is the conveying pipeline from pressure transducer \( P1 \) to \( P2 \) which is shown in Fig 3.16. The computation domain, which has total length of 6.5m with 16 flutes on the bypass pipeline, was determined to conduct the numerical investigation. The mesh was generated in Ansys 13.0 with details showing in longitudinal plane and cross-sectional area.
CHAPTER 4 PRESSURE DROP PREDICTION WITH KINETIC THEORY

Once the tonnage rate and minimum conveying velocity is known, the pressure drop is the final key parameter which will provide guidance for design and optimization of bypass pneumatic conveying system. In this chapter, Computational Fluid Dynamics based simulation is applied to investigate gas-solid flow behaviour and pressure drop and compared with the experimental results. The simulation models and equations used for pressure drop prediction for bypass pneumatic conveying with kinetic theory are detailed. The volume fraction equation is included into the multiphase flow and the conservation equations are described. The Eulerian model, which is the most complex multiphase models in CFD, is employed for each phase which solves a set of momentum and continuity equations for each phase. By employing pressure and interphase exchange coefficients, coupling between phases could be achieved. The equations of solid pressure, radial distribution function, solids shear stress and granular temperature, which are important components of kinetic theory, are also detailed. Compared with single phase flow, the modelling of turbulence in multiphase simulations is particularly difficult, because there are significantly more terms to be modelled in the momentum equations in multiphase flows. By comparing different types of turbulence models, the approaches to express turbulence in multiphase as well as momentum exchange between phases are determined.

The model structure used in this chapter will be presented based on the discussion and determination of numerical models. Boundary conditions are very important to the numerical simulation and are determined in this chapter. As there is interaction between phases in multiphase flow which is quite different from single phase flow, the numerical procedures to conduct simulation needs to be discussed and detailed.

The validation of simulation results is particularly important, as it determines whether the simulation model is accurately representing the objectives of investigation. Subsequently, experimental results from the bypass pneumatic conveying tests in Chapter 3 were used to compare with the simulation results obtained through applying kinetic theory. In addition, images captured from high speed camera were also utilised
and compared with selected image results from the CFD simulations. By comparing experimental results and simulation results, the accuracy of kinetic theory on pressure drop prediction for flyash, alumina and sand are discussed. This chapter generally evaluates the accuracy of kinetic theory on pressure drop prediction for three different fine powder materials.

4.1 Mathematical models

The mathematical models used in pressure drop prediction are described in this subchapter. 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. Lastly, the turbulence model and option for $k - \varepsilon$ model are discussed and determined, and the flow chart for proposed model structure is presented.

4.1.1 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,

$$V_q = \int_V \alpha_q dV$$  \hspace{1cm} (4-1)

and

$$\sum_{q=1}^{n} \alpha_q = 1$$  \hspace{1cm} (4-2)

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

4.1.2 Conservation equations

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

$$\frac{\partial}{\partial t} (\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = 0$$  \hspace{1cm} (4-3)

where $\rho_q$ 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

\[
\frac{\partial}{\partial t}(\alpha_g \rho_g \vec{v}_g) + \nabla \cdot (\alpha_g \rho_g \vec{v}_g \vec{v}_g) = -\alpha_g \nabla p + \nabla \cdot \tau_g + \alpha_g \rho_g \vec{g} + K_{sg}(\vec{v}_s - \vec{v}_g) \tag{4-4}
\]

where \( K_{sg} \) is the interphase exchange coefficient.

The momentum equation for solid phase \( s \) is expressed by

\[
\frac{\partial}{\partial t}(\alpha_s \rho_s \vec{v}_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_s \vec{v}_s) = -\alpha_s \nabla p - \nabla p_s + \nabla \cdot \tau_s + \alpha_s \rho_s \vec{g} + K_{gs}(\vec{v}_g - \vec{v}_s) \tag{4-5}
\]

where \( \tau_i \) is stress-strain tensor of phase \( i \), \( p \) is the pressure shared by all phases,

\[
\tau_i = \alpha_i \mu_i (\nabla \vec{v}_i + (\nabla \vec{v}_i)^T) + \alpha_i (\lambda_i - \frac{2}{3} \mu_i) \nabla \cdot \vec{v}_i I \tag{4-6}
\]

where \( \mu_i \) is the shear viscosity of phase \( i \), \( \lambda_i \) is the bulk viscosity of phase \( i \).

### 4.1.3 Interphase exchange coefficient

For granular flows, according to equation (4-5) and (4-6), 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 [94] combined Wen and Yu model [95] and Ergun equation [96] 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 \( \alpha_g > 0.8 \),

\[
K_{sg} = \frac{\alpha_s \rho_s \vec{v}_s}{\alpha_g \rho_g \vec{v}_g} \frac{d_s}{2.65} \tag{4-7}
\]

where

\[
C_D = \frac{24}{\alpha_g \rho_s \vec{v}_s} \left[ 1 + 0.15(\alpha_g \rho_s \vec{v}_s)^{0.687} \right] \tag{4-8}
\]

When \( \alpha_g \leq 0.8 \),

\[
K_{sg} = \frac{\alpha_s (1 - \alpha_g) \rho_s \vec{v}_s}{\alpha_g \rho_g \vec{v}_g} + \frac{1.75 \rho_s \alpha_s \vec{v}_s \vec{v}_g}{d_s} \tag{4-9}
\]

where \( d_s \) is the diameter of the particles of solid \( g \).
4.1.4 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 [87]. 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:

$$p_s = \alpha_s \rho_s \theta + 2 \rho_s (1 + e_{ss}) \alpha_s^2 g_{0,ss} \theta_s$$  \hspace{1cm} (4-10)

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

4.1.5 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 [97] and used for this analysis:

$$g_{0,ss} = \left[ 1 - \left( \frac{\alpha_s}{\alpha_{s,\text{max}}} \right)^2 \right]^{1/2}$$  \hspace{1cm} (4-11)

4.1.6 Solids shear stress

In the momentum equation, $\mu_s$ and $\lambda_s$ is the shear viscosity and bulk viscosity of solid phase, and $\mu_s$ can be expressed as:

$$\mu_s = \mu_{s,\text{col}} + \mu_{s,\text{kin}} + \mu_{s,fr}$$  \hspace{1cm} (4-12)

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

$$\mu_{s,\text{col}} = \frac{4}{5} \alpha_s^2 \rho_s d_s g_{0,ss} (1 + e_{ss}) \left( \frac{\alpha_s}{\pi} \right)^{1/2}$$  \hspace{1cm} (4-13)

The kinetic viscosity $\mu_{s,\text{kin}}$, as presented from Gidaspow et al [94] is:

$$\mu_{s,\text{kin}} = \frac{10 \rho_s d_s \sqrt{\theta_s \pi}}{96 \alpha_s (1 + e_{ss}) g_{0,ss}} \left[ 1 + \frac{4}{5} g_{0,ss} \alpha_s (1 + e_{ss}) \right]^2 \alpha_s$$  \hspace{1cm} (4-14)

The details of frictional viscosity $\mu_{s,fr}$ will be discussed in Chapter 5.
The bulk viscosity $\lambda_s$ can be expressed as:

$$\lambda_s = \frac{4}{3} \alpha_s \rho_s d_s g_{0,ss} (1 + e_{ss}) \left(\frac{\theta_s}{\pi}\right)^{1/2} \quad (4-15)$$

### 4.1.7 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 $\Theta_s$ equation (neglecting convection and diffusion in the transport equation) is [83]:

$$\frac{3}{2} \frac{\partial}{\partial t} \left( \rho_s \alpha_s \Theta_s \right) + \nabla \cdot \left( \rho_s \alpha_s \vec{v}_s \Theta_s \right) =$$

$$\left( -p_s I + \tau_s \right) : \nabla \vec{v}_s + \nabla \cdot \left( k_{\Theta_s} \nabla \Theta_s \right) - \gamma_{\Theta_s} + \Phi_{gs} \quad (4-16)$$

The diffusion coefficient for granular energy $k_{\Theta_s}$ is

$$k_{\Theta_s} = \frac{150 \rho_s d_s \sqrt{\theta_s \pi}}{384 \left(1 + e_{ss}\right) g_{0,ss}} \left[1 + \frac{6}{5} \alpha_s g_{0,ss} (1 + e_{ss})\right]^2 + 2 \rho_s \alpha_s^2 d_s (1 + e_{ss}) g_{0,ss} \left(\frac{\Theta_s}{\pi}\right)^{1/2} \quad (4-17)$$

The collisional dissipation of energy $\gamma_{\Theta_s}$, represents the rate of energy [87],

$$\gamma_{\Theta_s} = \frac{12 (1 - e_{ss}) g_{0,ss}}{d_s \sqrt{\pi}} \rho_s \alpha_s^2 \Theta_s^{3/2} \quad (4-18)$$

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 $\Phi_{gs}$

$$\Phi_{gs} = -3 K_{gs} \Theta_s \quad (4-19)$$

### 4.1.8 Turbulence model

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 $\varepsilon$, 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 [98]. 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 \( \varepsilon \) 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, \( \varepsilon \). 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 curvature, vortices and rotation. 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 [99] has shown 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 thesis.

The transport equations for the standard \( k-\varepsilon \) model are given as equation (4-20) and equation (4-21).

\[
\frac{\partial}{\partial t} (\rho_m k) + \nabla \cdot (\rho_m \vec{v}_m k) = \nabla \cdot \left( \frac{\mu_m}{\sigma_k} \nabla k \right) + G_{k,m} - \rho_m \varepsilon \tag{4-20}
\]
\[
\frac{\partial}{\partial t}(\rho_m \varepsilon) + \nabla \cdot (\rho_m \vec{v}_m \varepsilon) = \nabla \cdot \left( \frac{u_{tm}}{\sigma_{\varepsilon}} \nabla \varepsilon \right) + \varepsilon \left( C_{1\varepsilon} G_{k,m} - C_{2\varepsilon} \rho_m \varepsilon \right) \tag{4-21}
\]

where the mixture density \( \rho_m \) and velocity \( \vec{v}_m \) are calculated as:

\[
\rho_m = \sum_{i=1}^{N} \alpha_i \rho_i \tag{4-22}
\]

\[
\vec{v}_m = \frac{\sum_{i=1}^{N} \alpha_i \rho_i \vec{v}_i}{\sum_{i=1}^{N} \alpha_i \rho_i} \tag{4-23}
\]

The turbulent viscosity for the mixture is described as

\[
u_{t,m} = \rho_m C_u \frac{k^2}{\varepsilon} \tag{4-24}
\]

The production of turbulence kinetic energy \( G_{k,m} \) is calculated from

\[
G_{k,m} = u_{t,m} (\vec{v}_m + (\vec{v}_m)^T) : \nabla \vec{v}_m \tag{4-25}
\]

The model constants in these equations have the following values [98]:

\[
C_{1\varepsilon} = 1.44, \quad C_{2\varepsilon} = 1.92, \quad C_u = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\varepsilon = 1.3 \tag{4-26}
\]

### 4.1.9 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 $\varepsilon$ 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 thesis adopts the dispersed turbulence as it has been used by researchers [47, 100] to conduct pressure drop prediction for dense phase flow, and reasonable results were found. The transport equations for the dispersed model of standard $k$-$\varepsilon$ model are given as equation (4-27) and equation (4-28).

$$\frac{\partial}{\partial t} \left( \alpha_g \rho_g k_g \right) + \nabla \cdot \left( \alpha_g \rho_g \tilde{v}_g k_g \right) =$$

$$\nabla \cdot \left( \alpha_g \frac{u_{t,g}}{\sigma_k} \nabla k_g \right) + \alpha_g G_{k,g} - \alpha_g \rho_g \varepsilon_g + \alpha_g \rho_g \Pi_{k,g} \tag{4-27}$$

$$\frac{\partial}{\partial t} \left( \alpha_g \rho_g \varepsilon_g \right) + \nabla \cdot \left( \alpha_g \rho_g \tilde{v}_g \varepsilon_g \right) =$$

$$\nabla \cdot \left( \alpha_g \frac{u_{t,g}}{\sigma_\varepsilon} \nabla \varepsilon_g \right) + \alpha_g \frac{\varepsilon_g}{k_g} \left( C_{1\varepsilon} G_{k,g} - C_{2\varepsilon} \rho_g \varepsilon_g \right) + \alpha_g \rho_g \Pi_{\varepsilon g} \tag{4-28}$$

In equation (4-27) and equation (4-28), the term $G_{k,g}$ can be obtained from equation (4-25), the terms $\Pi_{k,g}$ and $\Pi_{\varepsilon g}$ can take the following form, and they represent the influence of dispersed particles on the gas phase.
\[ \Pi_{k \varepsilon} = \frac{\beta}{\alpha_{g \rho_g}} \left[ k_{sg} - 2k_g + (v_s - v_g) \cdot \tilde{v}_{dr} \right] \quad (4-29) \]

\[ \Pi_{\varepsilon \varepsilon} = C_{3 \varepsilon} \frac{\varepsilon_g}{k_g} \Pi_{k \varepsilon} \quad (4-30) \]

where \( k_g \) is the covariance of the velocities of gas and dispersed phases, \( \tilde{v}_{dr} \) is the drift velocity, \( D_s \) and \( D_g \) are diffusivities. Since the turbulence model for the solid phase is derived from the gas phase, the characteristic particle relaxation time \( \tau_{F,sg} \) and Lagrangian integral time scale \( \tau_{t,sg} \) become two important parameters for characterizing turbulence of the dispersed solid phase:

\[ \tau_{F,sg} = \frac{\alpha_{g \rho_g}}{\beta} \left( \frac{\rho_s}{\rho_g} + C_v \right) \quad (4-31) \]

\[ \tau_{t,sg} = \frac{\tau_{t,g}}{\sqrt{1 + C_g \rho^2}} \quad (4-32) \]

Where \( \xi = \frac{|\tilde{v}_{sg}| \tau_{t,g}}{L_{t,g}} \) and \( C_g = 1.8 - 1.35 \cos^2 \theta \). \( \tau_{t,g} \) is the characteristic time of turbulence eddies in gas phase, while \( L_{t,g} \) is the length scale, \( \theta \) is the angle between mean particle velocity and mean relative velocity.

### 4.1.10 Proposed model structure

Based on the simulation review and assessment for simulation models in Chapter 1 as well as comparison and discussion for models in this chapter, the flow chart for proposed model structure is summarised as shown in Fig 4.1. The optimal way to simulate dense phase gas-solid flow in pneumatic conveying is Euler-Euler method with Eulerian model, combined with standard \( k-\varepsilon \) model and dispersed turbulence model. The models for solid pressure [87], radial distribution function [97], and granular temperature [83] are determined. For solids shear stresses, the collisional viscosity [4, 94], kinetic viscosity [94] and bulk viscosity [87] are detailed. The frictional viscosity is not taken into account in this chapter. The capability of frictional model will be discussed and further developed in Chapter 5 and 6.
4.2 Boundary conditions

The velocity inlet boundary conditions were applied in the simulations. The uniform velocity boundary conditions as shown in (4-33) are used to define inlet flow velocity for the gas phase, where $v_g$ is the superficial velocity, $A_{in}$ is the cross section area at the inlet and $\rho_g$ is the air density at inlet. The turbulence intensity $I$ and turbulence length scale $l$ at inlet for gas phase are defined as (4-34) and (4-35), where $L$ is the relevant dimension of pipe. Equation (4-35) is based on the maximum value of mixing length in fully developed turbulent pipe flow and $L$ equals to diameter of the main pipe $D$.

$$v_g = \frac{m_a}{A_{in}\rho_g} \quad \text{(4-33)}$$

$$I = 0.16(Re)^{-1/8} \quad \text{(4-34)}$$

$$l = 0.07L \quad \text{(4-35)}$$

It was assumed that the initial particle velocity has the same velocity as the initial gas velocity, as shown in equation (4-36). The solid volume fraction is detailed in equation (4-37), where $m_s$ is the solids mass flow rate, $m_g$ is the air mass flow rate. Solid granular temperature $\Theta_s$ was calculated based on equation (4-38).

$$v_s = v_g \quad \text{(4-36)}$$

$$\alpha_s = \frac{m_s}{\rho_s} \left( \frac{m_g}{\rho_g} + \frac{m_s}{\rho_s} \right)^{-1} \quad \text{(4-37)}$$
At the outlet, the outflow boundary condition was applied. At the wall, a no slip boundary condition combined with the standard wall functions were specified for gas phase. The standard wall functions are based on work of Lun et al [87] have been extensively utilised in industrial flows. As described in FLUENT, these standard wall functions include the wall boundary conditions for the solution variables, including mean velocity, temperature, species concentration, \( k \) and \( \varepsilon \), are considered by the wall functions. As a result, it is not necessary to be over concerned about the boundary conditions at the walls because for a broad range of wall-bounded flows, especially when near-wall flows are not subjected to severe pressure gradients, and when the flows are not in strong non-equilibrium, the standard wall functions work reasonably well.

4.3 Numerical procedures

The Fluent calculation process for multiphase flow is highly coupled with the phasic volume fraction equations, the phasic momentum equations and shared pressure. These equations have been solved in a segregated fashion by using some variation of the SIMPLE algorithm to transform the total continuity into a shared pressure in order to couple the shared pressure with the momentum equations. Phase coupled SIMPLE, multiphase coupled and full multiphase coupled are three methods to solve the coupled system of equations arising in multiphase flows. The phase coupled SIMPLE algorithm which has been utilised for pressure-velocity coupling with a wide range of multiphase flows is considered in this thesis.

Second-order schemes which compute quantities at cell faces by using a multidimensional linear reconstruction approach are used for momentum, granular temperature, turbulent kinetic energy and turbulent dissipation rate solutions in the simulation. The QUICK scheme, which is based on a weighted average of second-order-upwind and central interpolations of the variable, is available for calculating a higher-order value of the convected variable at a face. It is accurate on structured meshes aligned with the flow direction and is used for volume fraction solution in this thesis. To obtain convergent solutions with the iterative scheme applied, under-relaxation factors chosen for simulation are shown in Table 4.1. The time step used was \( 1 \times 10^{-3} \)s.

\[
\theta_{s} = 0.004v_{s}^{2}
\]
Table 4.1 Under-relaxation factors for simulation

<table>
<thead>
<tr>
<th>Items</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>0.3</td>
</tr>
<tr>
<td>Density</td>
<td>0.5</td>
</tr>
<tr>
<td>Body Forces</td>
<td>0.5</td>
</tr>
<tr>
<td>Momentum</td>
<td>0.5</td>
</tr>
<tr>
<td>Volume Fraction</td>
<td>0.2</td>
</tr>
<tr>
<td>Granular Temperature</td>
<td>0.2</td>
</tr>
<tr>
<td>Turbulent Kinetic Energy</td>
<td>0.5</td>
</tr>
<tr>
<td>Turbulent Dissipation Rate</td>
<td>0.5</td>
</tr>
<tr>
<td>Turbulent Viscosity</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The steps to get convergent solutions used in this thesis are as following:

(a) With initial boundary conditions, compute the flow for gas phase without particles until a convergent result is obtained;

(b) Based on the calculation results from step (a), compute the flow for the solid phase until a converged solution occurs;

(c) Based on steps (a) and (b), conduct the calculation for gas and solid phase;

(d) Repeat step (a), (b) and (c) until convergent solutions occur for both of gas phase and solid phase.
4.4 Comparison of experiment data with prediction of pressure gradients

Based on simulation models and the solution strategies for dense phase pneumatic conveying modelling described above, the gas-solid flow in the bypass pneumatic conveying was simulated and the pressure drops along the bypass pneumatic conveying pipeline from P1 to P2 were obtained. The simulation results and experimental data for the pressure drop with flyash, alumina and sand are analysed in this subchapter.

4.4.1 Simulation results for flyash by applying kinetic theory

By applying kinetic theory, the pressure drop prediction results for flyash are compared with experimental results, and the relative errors are shown accordingly. Then, pictures captured by high speed camera are carried out as examples for dilute flows and dense flows for the gas-solid flow behaviour for flyash. Plus, the CFD flow description case studies for flyash are conducted. The solid volume fraction and absolute pressure distribution on the longitudinal plane are presented.

4.4.1.1 Pressure drop prediction comparing with experiment results for flyash

The comparison between experiment and simulation pressure drop for flyash is presented in Fig 4.2 with a straight line x=y defining the optimal correlation line. It was found that most of the data was distributed around straight line x=y. The simulation provides better results for cases with lower experimental pressure drop.
Fig 4.2 Comparison between experiment and simulation pressure drop for flyash by applying kinetic theory

Fig 4.3 shows the relative errors of simulation pressure drop variation with air mass flow rate. It was found that the relative errors increased with decreasing of air mass flow rate. Especially for cases with lowest air mass flow rate, the relative errors reach the largest. By applying kinetic theory, the simulation results for cases with $m_a \geq 0.0417\text{kg/s}$ have good agreement with experimental results, and the relative errors are lower than 50%. In the region of $m_a < 0.0417\text{kg/s}$, case Flyash-12 ($m_a=0.0317\text{kg/s}$ and $m_s=2.5486\text{kg/s}$) is the only test which provides good prediction results. The kinetic theory only takes particle momentum exchange due to translation and collision, as such for cases with $m_a$ lower than 0.0417kg/s, it the kinetic theory alone does not appear to fully explain the gas solid flow behaviour in bypass pneumatic conveying as the also cannot predict the pressure drop accurately.
4.4.1.2 High speed camera case studies for flyash

Flyash-1 and Flyash-21 are two cases representing dilute phase and dense phase flow respectively in the bypass pneumatic conveying. Flyash-1 ($m_a=0.0681$ kg/s, $m_s=1.4923$ kg/s) has low SLR=21.91 and the relative error is about 21%, while Flyash-21 ($m_a=0.0157$ kg/s, $m_s=1.4951$ kg/s) has high SLR=95.23 and the relative error is high at about 81%. For Flyash-1 and Flyash-21, pictures captured from high speed camera for are shown in Fig 4.4 and Fig 4.5, respectively.

For Flyash-1 in Fig 4.4, within the time range of 0.1s, the pneumatic conveying exhibited dispersed, fully developed flow. The flyash appears to be distributed uniformly across the pipe during conveying from $t=0$ s to $t=0.1$ s. In this case the interaction between particles is predominantly collisional, which can be described by kinetic theory.
For Flyash-21 with a much higher SLR when comparing the images in Fig 4.5, the interaction between particles at the upper part of pipe is still dominated by particle-particle collisions. However, the conveying particles easily concentrate at the lower part of the conveying pipeline due to influence of gravity with lower conveying flow rates and higher tonnage rates. Sustained contact between particles becomes longer since particles move forward as a parcel at the bottom of pipeline. With respect to the images shown in Fig 4.5, when time is $t=0s$, large material dune formation starts to occur. With the passage of time to $t=0.04s$, more material is building up to create the large dune formation. From $t=0.06s$ to $t=0.1s$, air is forced into the bypass pipeline through the last
flute and is then forced back to the main pipeline through the next flute to disturb the formation of the dune. At $t=0.1s$, the large dune formation mechanism is destroyed.

**Fig 4.5** Flyash-21 ($m_u=0.0157\text{kg/s}$, $m_s=1.4951\text{kg/s}$) showing the dense phase flow inside the pipeline

**4.4.1.3 CFD flow description case studies for flyash**

Fig 4.6 and Fig 4.7 present the CFD simulation results of solid volume fraction on the longitudinal plane for flyash using the kinetic theory based approach. In Fig 4.6, Flyash-1 has the uniform solid volume fraction distribution which is similar to what has been observed from high speed camera as shown in Fig 4.4.
Fig 4.6 Simulation results of solid volume fraction on the longitudinal plane for Flyash-1 with kinetic theory ($m_a=0.0681\text{kg/s}$, $m_s=1.4923\text{kg/s}$)

In Fig 4.7, Flyash-21 has higher solid volume fraction in the bottom part of pipeline compared to the upper part, which is in consistent with Fig 4.5. However, the relative error for pressure drop prediction of Flyash-21 is high at about 81% which underpredicted the pressure drop. Although flyash particle is very fine with an average particle diameter of 14.75um, the frictional stress may have to be considered where material is very concentrated. The investigation of pressure drop prediction for flyash with frictional stress will be conducted in Chapter 5 and 6.

Fig 4.7 Simulation results of solid volume fraction on the longitudinal plane for Flyash-21 with kinetic theory ($m_a=0.0157\text{kg/s}$, $m_s=1.4951\text{kg/s}$)

Fig 4.8 and Fig 4.9 show the pressure contour on the longitudinal plane within time range of 0.1s for Flyash-1 and Flyash-21, respectively. The decreasing tendency of
pressure can be observed, which is expected. The pressure contours for Flyash-1, which has uniform solid fraction distribution, show that the pressure in the main pipeline is larger than bypass pipeline. This is because Flyash-1 has low SLR and the conveying in bypass pneumatic conveying presents as dilute phase, where the bypass pipeline didn’t play any important role during the conveying. It can be observed that the pressure before the flute is larger than the pressure behind the flute in the bypass pipeline. This only presents the characteristics of orifice plates which inserted in the bypass pipeline. The relative error for pressure drop prediction is about 22% which is reasonable.

The pressure contours for Flyash-21 has the same tendency. However, Flyash-21 is dense phase bypass pneumatic conveying which has densified material at the bottom of the pipe. The simulation result only shows constant variation of pressure drop between inlet and outlet. It could not present the formation and deformation of material dunes which has been observed from high speed camera. Adding frictional stress into pressure drop prediction might have influence on pressure contours.

**Fig 4.8 Simulation results of absolute pressure on the longitudinal plane for Flyash-1 with kinetic theory ($m_a=0.0681\text{kg/s}, m_s=1.4923\text{kg/s}$)**

The pressure contours for Flyash-21 has the same tendency. However, Flyash-21 is dense phase bypass pneumatic conveying which has densified material at the bottom of the pipe. The simulation result only shows constant variation of pressure drop between inlet and outlet. It could not present the formation and deformation of material dunes which has been observed from high speed camera. Adding frictional stress into pressure drop prediction might have influence on pressure contours.
4.4.2 Simulation results for alumina by applying kinetic theory

By applying kinetic theory, the pressure drop prediction results for alumina are compared with experimental results, and the relative errors are shown accordingly. Then, images captured by high speed camera are carried out as examples for dilute flows and dense flows of the gas-solid flow behaviour for alumina. Moreover, the CFD flow description case studies for alumina are conducted. The solid volume fraction and absolute pressure distribution on the longitudinal plane are presented.

4.4.2.1 Pressure drop prediction comparing with experiment results for alumina

The comparison between experiment and simulation pressure drop for alumina is illustrated in Fig 4.10. It was found that some of the simulations were relatively in good agreement with the experimental pressure drop findings lower than 12kPa, however a poor correlation generally occurred. Cases with experimental pressure drops larger than 14kPa largely under-predict the pressure drop in the simulation. Generally, it was found that all the simulation results under predicted the pressure drop for the alumina.
Fig 4.10 Comparison between experiment and simulation pressure drop for alumina by applying kinetic theory

Fig 4.11 shows the relative errors of simulation pressure drop as a function of air mass flow rate. The relative errors increased as the air mass flow rate reduced, and became the biggest at the lowest air mass flow rate. The simulation results for cases with $m_a \geq 0.0681\text{kg/s}$ have the best agreement with experimental results as the relative errors are lower than 42%. In the region of $m_a < 0.0681\text{kg/s}$, Alumina-4 ($m_a=0.0524\text{kg/s}$ and $m_s=5.0964\text{kg/s}$) and Alumina-5 ($m_a=0.0524\text{kg/s}$ and $m_s=3.3127\text{kg/s}$) are the only two cases provides pressure prediction results with relative errors lower than 41%. For cases with $m_a$ lower than 0.0681kg/s, the kinetic theory cannot fully represent the gas solid flow behaviour in bypass pneumatic conveying for alumina. Generally, the pressure prediction for alumina is much worse in comparison to the flyash. The capability of kinetic theory to conduct pressure drop prediction for alumina is generally poor.
4.4.2.2 High speed camera case studies for alumina

Alumina-3 and Alumina-15 are selected as examples for dilute phase and dense phase, respectively. Fig 4.12 and Fig 4.13 show the material distribution during fully developed flow as recorded by high speed camera for Alumina-3 and Alumina-15 with time interval of 0.1s. For Alumina-3 in Fig 4.12, the material has a fairly uniform distribution. Compared with Flyash-1, the solid volume fraction is less uniform, and it has slightly larger solid volume fraction at the bottom part of pipe than the upper part. This is because alumina has much larger particle diameter (76.7um) and particle density (4088kg/m$^3$) compared with flyash. Due to the gravity, it is much easier for alumina particles to settle at the bottom of the pipeline while conveying.
Fig 4.12 Alumina-3 ($m_a=0.0681\text{kg/s}$, $m_s=2.2780\text{kg/s}$) showing the dilute phase flow inside the pipeline

For Alumina-15, as shown in the images displayed in Fig 4.13, with a higher SLR=33.45, it is obvious that alumina particles are close packed at the lower part of the conveying pipeline. Alumina has been classified as the material to be conveyed between dilute only and fluidised dense phase which has been explained in Chapter 3. However, due to the bypass pipeline capability, the lower conveying velocity and high particle concentration allows alumina particles have greater sustained contact compared with the flow exhibited in Alumina-3.
Fig 4.13 Alumina-15 \( (m_a=0.0207 \text{kg/s}, m_s=2.6747 \text{ kg/s}) \) showing the dense phase flow inside the pipeline

4.4.2.3 CFD flow description case studies for alumina

Fig 4.14 and Fig 4.15 illustrates the simulation results of solid volume fraction on the longitudinal plane for the two alumina cases. In Fig 4.14, it is obvious that there is a concentrated material layer at the bottom part of main pipe, especially from flute 6 to flute 16. The solid volume fraction distribution from simulation for alumina shows the same features compared with observation from the high speed camera. The relative error for pressure drop prediction for Alumina-3 is about 40%.
In Fig 4.15, the solid volume fraction in the bottom part is much higher than the upper part, which shows similar solids fraction distributions as shown in the images in Fig 4.13. However, the dense material is mainly distributed at the second half of the pipeline. This is in contrast to the experiments where the whole pipeline length is actually filled with material when the flow is fully developed. There is a material dune around flute 10 to flute 12 and a material slug at flute 15. The material slug at flute 15 is moving forward from $t=0s$ to $t=0.1s$. Air is forced into flute 14 and is then forced back into the main pipeline through flute 15 to disturb the slug, and the gas between the material dune and material slug is gradually becoming larger with the passage of time. For Alumina-15, the relative error for pressure drop prediction is about 73%, which is too large to present the real gas-solid flow. There is higher concentration of material at the bottom pipe at which the frictional stress cannot be neglected.
Fig 4.15 Simulation results of solid volume fraction on the longitudinal plane for Alumina-15 with kinetic theory ($m_a=0.0207\,\text{kg/s}, m_s=2.6747\,\text{kg/s}$)

Fig 4.16 and Fig 4.17 show the pressure contour on the longitudinal plane within the time range of 0.1s for alumina. Compared with Flyash-1, a similar decreasing tendency of pressure can be observed in Fig 4.16 for Alumina-3. In the case of Alumina-3, the solid volume fraction distribution is generally uniform and interaction between particles is mainly collision. By applying kinetic theory for pressure drop prediction, the simulation result had good agreement with experiment result. The relative error for pressure drop prediction is about 40% which is relatively much better.

Fig 4.16 Simulation results of absolute pressure on the longitudinal plane for Alumina-3 with kinetic theory ($m_a=0.0681\,\text{kg/s}, m_s=2.2780\,\text{kg/s}$)
For Alumina-15 at 0s, the pressure contours have a slight decrease from flute 1 to flute 13 and the pressure has large variation between flute 14 and flute 16 due to the material dune built up at flute 15 as showed in Fig 4.17. From 0s to 0.1s, the material dune gradually decreases, so the pressure difference between flute 14 and flute 16 decreases slowly.

![Fig 4.17 Simulation results of absolute pressure on the longitudinal plane for Alumina-15 with kinetic theory ($m_a=0.0207$kg/s, $m_s=2.6747$kg/s)](image)

4.4.3 Simulation results for sand by applying kinetic theory

By applying kinetic theory, the pressure drop prediction results for sand are compared with experimental results, and the relative errors are shown accordingly. Then, images captured by high speed camera are carried out as examples for dilute flows and dense flows of the gas-solid flow behaviour for sand. In addition, the CFD flow description case studies for sand are conducted. The solid volume fraction and absolute pressure distribution on the longitudinal plane are presented.

4.4.3.1 Pressure drop prediction comparing with experiment results for flyash

Pressure drop predictions for sand in bypass pneumatic conveying were conducted numerically. The comparison between experiment and simulation pressure drop for sand is shown in Fig 4.18. Surprisingly, unlike flyash and alumina, only a few cases of the sand bypass conveying obtained numerical convergence, generally with the higher experimental air mass flow rates. For these results, it can be seen from Fig 4.18 that the
pressure prediction was poor. For all the other cases, the convergence of the numerical solutions did not occur.

**Fig 4.18 Comparison between experiment and simulation pressure drop for sand by applying kinetic theory**

Fig 4.19 shows the relative errors of pressure drop prediction for different air mass flow rates. The relative errors are too large and show that the kinetic based model is insufficient to express the real flow behaviour for sand in bypass pneumatic conveying.

**Fig 4.19 Relative errors with different air mass flow rate for sand**
4.4.3.2 High speed camera case studies for sand

Sand-2 and Sand-8 are selected as examples for less dense flows with higher air mass flow rate and denser flow with lower air mass flow rate, respectively. Fig 4.20 and Fig 4.21 present the material distribution captured by high speed camera for Sand-2 (SLR=10.89) and Sand-8 (SLR=11.51) through sight glass. The flow is fully developed and the time interval is 0.1s. For Sand-2, the solid fraction distribution is dilute at the upper part of conveying pipeline with uniform distribution, while there is thick layer with higher solid volume fraction at the bottom of pipe 0s to 0.1s. Sand has been classified as the material to be conveyed in dilute phase which has been explained in Chapter 3. Moreover, sand has the largest particle diameter and (378um) and is easier to have constant interaction between particles. Thus, there is a thick layer at the bottom of conveying pipeline with high particle concentration. Moreover, in the thick layer, since sand particles have much longer sustained contact, the particles move forward with an extremely low velocity.
Fig 4.20 Sand-2 ($m_a=0.0681\text{kg/s}$, $m_s=0.7415\text{kg/s}$) showing the dilute phase flow inside the pipeline

For Sand-8, the sand concentrated at the bottom of the conveying pipeline with very low conveying velocity. Compared with flyash and alumina, sand has largest particle diameter (378um). With low conveying velocity and large particle diameter, sand conveying at the lower part of the pipeline has more chances to have sustained contact. Thus, frictional stress should play an important role for sand to be transported in bypass pneumatic conveying.
Fig 4.21 Sand-8 ($m_a = 0.0317\text{kg/s}$, $m_s = 0.3649\text{kg/s}$) showing the dense phase flow inside the pipeline

4.4.3.3 CFD flow description case studies for sand

Fig 4.22 and Fig 4.23 show the solid volume fraction distribution on the longitudinal plane from simulation. Fig 4.22 presents high solid concentration at the bottom of pipeline, which is similar to what has been observed from high speed camera. However, the relative error is about 76% which is still too large to predict pressure drop for Sand-2. The Frictional stress should be considered in the simulation even for Sand-2 which has low SLR and high air mass flow rate.
In Fig 4.23, the highest particle concentration appears in the mid-section of the front of pipe which is different from the distribution observed from high speed camera. For Sand-8, the relative error is about 86% which is very unreasonable. As sand has the largest particle diameter, sustained contact between particles in the dense phase conveying should be the longest compared with flyash and alumina. Moreover, in researches [101-103] where materials have similar particle diameter the frictional-kinetic model have been employed. Great improvement has been showed for the prediction of gas-solid flow. Thus, frictional stress between particles needs to be considered in pneumatic conveying for sand.
Fig 4.24 and Fig 4.25 show the pressure contour on the longitudinal plane within time range of 0.1s for sand. Sand-2 has similar decreasing tendency of pressure compared with Flyash-1 and Alumina-3, where the pressure decreases gradually from flute 1 to flute 16, as there is no material dune appears.

For Sand-8, the pressure has largest decrease tendency around flute 1 at 0s, since there is material full bore dune at that flute. The decrease tendency becomes smaller from 0s to 0.1s as the full bore dune is disturbed gradually.

**Fig 4.24 Simulation results of absolute pressure on the longitudinal plane for Sand-2 with kinetic theory ($m_a=0.0681\text{kg/s}, m_s=0.7415\text{kg/s}$)**

**Fig 4.25 Simulation results of absolute pressure on the longitudinal plane for Sand-8 with kinetic theory ($m_a=0.0317\text{kg/s}, m_s=0.3649\text{kg/s}$)**
4.5 Conclusion

This chapter firstly assesses and illustrates the numerical models used to predict pressure drop for fine powder materials transporting in bypass pneumatic conveying system. The Euler-Euler method with Eulerian model, combined with standard $k - \varepsilon$ model and dispersed turbulence model are chosen as the most advantageous way for conducting numerical simulations with flyash, alumina and sand. The models utilised for solid pressure [87], radial distribution function [97], and granular temperature [83] are also determined. The collisional viscosity [4, 94], kinetic viscosity [94] and bulk viscosity [87] are detailed for solids shear stresses in dense phase pneumatic conveying, but without considering the influence of frictional stress. The detailed frictional viscosity discussion, application and further development will get conducted in Chapter 5 and 6.

By applying the kinetic theory, the pressure drops along the conveying pipeline from pressure transducer P1 to P2 are predicted for different types of materials. The following conclusion can be obtained:

- For flyash, the experiment and simulation results generally agreed for cases with lower pressure drop by applying kinetic theory. The relative errors increased with decreasing of air mass flow rate. The relative errors reach the largest for case with lowest air mass flow rate. For cases with $m_a \geq 0.0417\text{kg/s}$, the relative errors are lower than 46%. However, except for Case-12, cases with $m_a < 0.0417\text{kg/s}$, the simulation results over under-predicted the pressure drop. From observation of pictures captured by high speed camera for Flyash-1 and Flyash-21, the flow behaviour for dilute phase and dense phase are presented. The simulation results are illustrated with solids volume fraction and pressure contours on the longitudinal plane for Flyash-1 and Flyash-21. The solids volume fraction was found uniform distribution at the longitudinal plane for Flyash-1, while there is a thick layer of material at the bottom of pipeline for Flyash-21. The simulation results for Flyash-1 and Flyash-21 showed the similar solids volume fraction distribution. However, the relative error for Flyash-21 is too large to describe the real gas-solid flow behaviour while there is area with high solids concentration. Although flyash has very fine particles and it has been classified as the material to be conveyed in fluidised dense phase, the sustained
contact between particles still might need to be considered for pressure drop prediction. Simulations with frictional stress which represents the long-term particles interactions will be further developed in Chapter 5 and 6.

- For alumina, cases with pressure drop lower than 8kPa provided better predicting results by applying kinetic theory. Particularly, cases with pressure drop larger than 14kPa, the pressure drop was largely under-predicted. Generally, the pressure drops from simulation were all under-predicted. The simulation results for cases with $m_a \geq 0.0681\text{kg/s}$ have good agreement with experimental results with relative errors lower than 40%. Alumina-4 and Alumina-5 are the only two cases with relative errors lower than 41% when $m_a < 0.0681\text{kg/s}$. Pictures captured form high speed camera are showed the gas-solid flow behaviour in bypass pneumatic conveying for Alumina-3 and Alumina-15 with time interval of 0.1s. The solids distribution is less uniform compared to Flyash-1 and there is obvious thick layer at the bottom of pipeline for Alumina-15. Larger particle diameter and particle density lead to alumina particles settle down at the bottom part of pipeline due to gravity easily. The simulation results for Alumina-3 showed better pressure drop prediction results compared with Alumina-15. However, the mechanism of bypass pneumatic conveying has been presented with Alumina-15 where there is appearing a material slug. Although the solids volume fraction on the longitudinal plane in simulation showed similar distribution as observed from high speed camera for those two cases, the pressure drop is still largely under-predicted. Although the flow mode for alumina powders are undetermined, the higher concentration of material at the bottom pipe where the frictional stress may not be neglected. Simulation with frictional stress for pressure drop prediction of alumina will be conducted in Chapter 5 and 6.

- For sand, by only applying kinetic theory only a few cases can get converged in the simulation of gas-solid flow behaviour in bypass pneumatic conveying. The relative errors are too large to express the real flow behaviour for sand in bypass pneumatic conveying. For Sand-2 (SLR=10.89) and Sand-8 (SLR=11.51), there is obvious thick layer of material at the bottom part of conveying pipeline from pictures captured from high speed camera, in despite of both of the cases have low SLR in which Sand-2 has larger air mass flow rate than Sand-8. Moreover, the conveying velocities of material at the bottom part of pipeline both are
extremely low. Compared with flyash and alumina that with fine powders, sand has the largest particle diameter, and it has been classified as the material to be conveyed in dilute phase. So there should be more chances for sand particles to have sustained contact. Thus, frictional stress should play an important role for sand transporting in bypass pneumatic conveying. Further application of frictional stress on pressure drop prediction in bypass pneumatic conveying with sand will be conducted in Chapter 5 and 6.

In conclusion, for all three kinds of material, due to influence of gravity, particle has high concentration at the bottom part of pipeline with low air mass flow rate and high SLR. An explanation for all above phenomena is that, sustained contact between particles should not be neglected, especially for sand. Therefore, the frictional stress which is part of solids shear stress will be assessed, applied and further developed in Chapter 5 and 6.
CHAPTER 5 PRESSURE DROP PREDICTION WITH CONVENTIONAL FRICTIONAL-KINETIC MODEL

In the previous chapter, it was proposed that the frictional stress should be added with the kinetic theory for conducting CFD analysis for flyash, alumina and sand, especially for those denser flows with low air mass flow rate and high solid mass flow rate which result in high pressure drops. The investigation of pressure drop prediction by applying conventional frictional-kinetic model for flyash, alumina and sand is carried out with the following aspects.

Firstly, three different regimes in bypass pneumatic conveying for different types of material are defined and classified. Since it is very important to choose the right model for describing the gas-solid flow behaviour particularly in dense regime, this chapter will present the basic idea of frictional-kinetic model and also review the application of this model used in previous research. Moreover, the packing limit and frictional packing limit used in the simulation are modified based on the actual solid volume fraction likely to be distributed within pneumatic conveying systems.

The CFD simulations with frictional-kinetic model for flyash, alumina and sand are conducted with the results summarised and compared with experimental results. The pressure drop results from kinetic theory from the previous chapter are also added and compared to frictional-kinetic model. The relative errors for applying different models with the three types of material are shown.

Finally, a detailed analysis of the solid volume fraction, gas velocity magnitude as well as pressure profiles on the longitudinal plane are carried out for a dense flow regime example for sand with high SLR with full bore dune formation and deformation are also described. The variation of gas velocity magnitude and pressure profiles around the flute where there are full bore dunes is illustrated. This illustration helps explain how velocity magnitudes vary with time and position at the flute while the full bore sand dunes gradually deforms, which helps explain the effectiveness of bypass pneumatic conveying systems.
5.1 Background

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 and kinetic-collisional stresses. The three regimes and associated stress state are shown graphically in Fig 5..

![Fig 5.1 Three mechanisms of particle regimes during transport](image)

In dense phase flow (e.g. fluidised bed, riser, hopper flow, 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. With Flyash-21 as an example for flyash cases, the three different regimes are shown in Fig 5.2 (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 shown in Fig 5.2 (b) to (d). In the dilute regime, the material has low solid concentration as shown in Fig 5.2 (b), while the dense regime in Fig 5.2 (d) has high solid concentration. The concentration of
material in intermediate regime is between the dilute regime and dense regime and it can be observed from Fig 5.2 (c).

![Diagram of three regimes](image)

(a) Three regimes in bypass pneumatic conveying

![Regime images](image)

(b) Dilute regime  (c) Intermediate regime  (d) Dense regime

**Fig 5.2 Magnified appearance of three regimes in bypass pneumatic conveying**

**Flyash-21**

Similarly, as an example for alumina cases, using high speed photography images, different regimes for Alumina-15 are presented in Fig 5.3 (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 shown in Fig 5.3 (b) to (d). Compared with Flyash-21, the boundaries between different regimes for Alumina-15 are less distinct, and it is more continuous for the dilute/dense layer transfer of particles.
CHAPTER 5 PRESSURE DROP PREDICTION WITH CONVENTIONAL FRICIONAL-KINETIC MODEL

(a) Three regimes in bypass pneumatic conveying

(b) Dilute regime                      (c) Intermediate regime                      (d) Dense regime

Fig 5.3 Magnified appearance of three regimes in bypass pneumatic conveying for Alumina-15

For Sand, again the high speed images show the different flow regions with an example for Sand-8 shown. As described in Chapter 3, sand is the type of material to convey only in dilute phase within conventional pipelines. Thus, Fig 5.4 (a) only shows distribution for two regimes. It is obvious to distinguish between the dilute regime and dense regime as shown in Fig 5.4 (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 is forced into the bypass pipeline through the last nozzle and then 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.
CHAPTER 5 PRESSURE DROP PREDICTION WITH CONVENTIONAL FRICIONAL-KINETIC MODEL

(a) Two regimes in bypass pneumatic conveying

(b) Dilute regime

(c) Dense regime

Fig 5.4 Magnified appearance of three regimes in bypass pneumatic conveying

San-8

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 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 and relate 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 neighbours through sustained contact. Part of the solids stresses in the intermediate and dense zones is due to frictional interactions between particles at points of sustained contact. In the intermediate regime and dense regime, both collision and friction stress will influence the flow behaviour. Thus, it is practical to 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.

5.2 The conventional frictional-kinetic model

As illustrated by the Fluent [53], when the solid pressure model proposed by Lun et al [87] was adopted as shown in equation (4-10), the radial function tends to infinity when the solid volume fraction tends to the packing limit. Then, the frictional pressure as described by equation (4-10) 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, \( \mu_{s,f} \) in
equation (4-12) which represents frictional viscosity corresponding to friction between
particles, can be calculated by Schaefer’ model [104] as following:

\[
\mu_{s,f} = \frac{p_s \sin \phi}{2 \sqrt{l_{2D}}}
\]

(5-1)

where \( p_s \) is the solid pressure, \( \phi \) is the angle of internal friction, \( l_{2D} \) is the second
invariant of the deviatoric stress tensor, as shown in equation (5-2).

\[
l_{2D} = \frac{1}{6} \left[ (D_{xx} - D_{yy})^2 + (D_{yy} - D_{zz})^2 + (D_{zz} - D_{xx})^2 \right]
+ D_{xy}^2 + D_{yx}^2 + D_{zx}^2
\]

(5-2)

where \( D_{ij} \) (\( i=x, y, z; j=x, y, z \)) is the component of stress tensor in Cartesian coordinates.
The method described as above is named the conventional frictional-kinetic model in
this thesis, and will be applied to conduct pressure drop prediction for different types of
material in this chapter.

5.3 Simulation with conventional frictional-kinetic model for flyash

The pressure drop for flyash is predicted using conventional frictional-kinetic model
with modified packing limits. The simulation results from kinetic theory and
conventional frictional-kinetic model are also co-presented in each graph for flyash,
alumina and sand, for comparison and compared to the experimental results. For each
type of material, two CFD simulation case studies are selected to present the gas-solid
flow behaviour, one representative of less dense flows while the other case study
representative of denser flows. In addition, the influence of the frictional-kinetic model
on solid volume fraction distribution and pressure profile for the CFD simulations is
presented and discussed.

5.3.1 Simulation results for flyash

The simulation results from conventional frictional-kinetic model and kinetic theory are
summarized in Fig 5.5 and compared with experimental results. All the data can be
divided into two groups: Group 1 is for cases with lower pressure drops for less dense
flows; Groups 2 is for cases with higher pressure drops for denser flows. Compared
with results from kinetic theory, conventional frictional-kinetic model has provided no improvement on pressure drop prediction in dense phase bypass pneumatic conveying for flyash.

Fig 5.6 shows the relative errors for pressure drop prediction from kinetic theory and the conventional frictional-kinetic model. All the data again is presented as two groups including group A with lower air mass flow rate for less dense flows and group B with higher air mass flow rate for denser flows. As stated in Chapter 4, the relative errors for pressure drop prediction increased with a decrease of air mass flow rate, i.e generally a poorer prediction for denser flows. However, as expected, the relative errors obtained from kinetic theory and conventional frictional-kinetic model are the same.

Ideally, for cases with lower air mass flow rate where the flows are denser, flyash powders more easily settle out and have longer periods of sustained contact and conventional frictional-kinetic model should have influenced pressure drop prediction. However, based on Fig 5.6, it is clear that the sustained contact effect between flyash particles cannot be captured and expressed by the conventional frictional-kinetic model even in the denser flows. The reason for this is not immediately clear but may relate to the solids concentration in the CFD simulation not effectively initiating the frictional
resistance component, hence no pressure increase is observed. Further research into is required.

![Graph showing relative errors vs air mass flow rate with kinetic theory and conventional frictional-kinetic model for flyash.]

**Fig 5.6 Relative errors Vs air mass flow rate with kinetic theory and conventional frictional-kinetic model for flyash**

### 5.3.2 Case study for flyash

In order to show the influence of conventional frictional-kinetic model based CFD simulation on pressure drop prediction for flyash, the solid volume fraction distributions as well as the pressure profiles on the longitudinal plane for Flyash-1 and Flyash-21 are shown. Flyash-1 represents the less dense flows while Flyash-21 represents denser flows.

#### 5.3.2.1 Simulation result for Flyash-1

The simulation results of solid volume fraction on the longitudinal plane with conventional frictional-kinetic model for Flyash-1 are shown in Fig 5.7. Comparing with the solid volume fraction distribution obtained from applying kinetic theory as shown in Fig 4.7, the solid volume fraction distribution remains homogeneous. That is because Flyash-1 has the dilute phase flow where there is only short contact between particles. Thus, the conventional frictional-kinetic model shows no significant change solid volume fraction behaviour compared with kinetic theory for dilute flows.
Fig 5.7 Simulation results of solid volume fraction on the longitudinal plane for Flyash-1 with conventional frictional-kinetic theory ($m_a=0.0681\text{kg/s}$, $m_s=1.4923\text{kg/s}$)

The pressure profiles on the longitudinal plane within time range of 0.1s for Flyash-1 are also presented in Fig 5.8, and it shows similar pressure decay behaviour to those shown in the kinetic model results (Fig 4.8.). In summary, even with the application of the conventional frictional-kinetic model, the pressure drop estimation for denser flows shows no change.

Fig 5.8 Simulation results of absolute pressure on the longitudinal plane for Flyash-1 with conventional frictional-kinetic theory ($m_a=0.0681\text{kg/s}$, $m_s=1.4923\text{kg/s}$)
5.3.2.2 Simulation result for Flyash-21

By applying conventional frictional-kinetic model, the simulation for Flyash-21 is conducted. The solid volume fraction on the longitudinal plane is shown in Fig 5.9. Flyash-21 is the example for dense flows where there is thick layer at the bottom of pipeline. However, compared with Fig 4.7 obtained from kinetic theory, the solid volume fraction distribution again remains relatively homogeneous and the solids volume fraction does not reflect the experimental conveying conditions.

The absolute pressure profiles on the longitudinal plane with conventional frictional-kinetic theory for Flyash-21 are shown in Fig 5.10. The pressure profiles demonstrate exactly the same results as shown in Fig 4.9. It appears that the conventional frictional-kinetic model has no influence on gas solid flow behaviour and the solid volume fraction distribution as the solids concentration and pressure profiles show no change.
5.3.3 Summary of case studies for Flyash-1 and Flyash-21

In summary, the conventional frictional-kinetic model has no influence on simulation results of solid volume fraction distribution and absolute pressure profiles compared with results from kinetic theory for both of the dilute flows and dense flows. The sustained contact between very fine flyash particles in denser flows cannot be captured by conventional frictional-kinetic model even in the dense flows. Further research of applying modified Johnson-Jackson frictional model combined with kinetic model on pressure drop prediction for flyash will be conducted in Chapter 6.

5.4 Simulation using conventional frictional-kinetic model for alumina

The CFD pressure drop simulations for alumina was carried out by incorporating the conventional frictional-kinetic model with modified packing limits, and the CFD simulation results were compared with experimental results. Again, two cases were taken as examples to show solid volume fraction and pressure profiles for less dense flows and denser flows by using the conventional frictional-kinetic model.

5.4.1 Simulation results for alumina

The pressure drop prediction with conventional frictional-kinetic model for alumina was conducted numerically. The simulation results are summarized in Fig 5.11 and compared with results calculated with kinetic theory and experiments. In Fig 5.11, the
CFD results using the frictional-kinetic theory are much closer to the experimental pressure results. Again, all the data can be divided into two groups. Group 1 are cases with lower pressure drops for less dense flows, and Group 2 are cases with higher pressure drops for denser flows. It can be observed from Fig 5.11 that when the results of conventional frictional-kinetic model are compared to those from the kinetic theory analysis that there is a general improvement in pressure prediction, especially for the denser flows in Group 2. In denser flows, from the experimental work, there is an obvious thicker layer at the bottom of conveying pipeline and particles have more sustained contact. For alumina, the conventional frictional-kinetic model adds to the frictional stress, especially in the dense areas of the flow. Previously, this frictional stress has been neglected by kinetic theory. As a result, the pressure drop goes up accordingly. Thus, frictional stress plays now correctly plays a more important role in the CFD simulation, especially for the denser flows.

**Fig 5.11 Experimental pressure drop against simulation pressure drop with kinetic theory and conventional frictional-kinetic model for alumina**

All the data can also be divided into two groups. In Fig 5.12, Group A includes cases with lower air mass flow rate for denser flows, while Group B includes cases with higher air mass flow rate for less dense flows. From the error analysis, although the relative errors for pressure drop prediction in both cases increased with decrease of air mass flow rate, the relative errors obtained from conventional frictional-kinetic model
are much lower than the error results from kinetic theory. In Fig 5.12, by applying conventional frictional-kinetic model, pressure prediction improvement for Group A is more apparent than Group B.

It is interesting to note that when $m_a=0.0681 \text{kg/s}$ the conventional frictional-kinetic model has no improvement on pressure drop prediction results, that is the case reflecting low solids concentration below the minimum limit required for frictional resistance to be calculated. When $m_a$ decreases to 0.0524 kg/s, the improved pressure prediction starts occurring as solids concentration areas increase above the minimum required to calculate frictional resistance. Subsequently, with the decrease of air mass flow rate, especially for those cases in Group A, the improvement becomes much larger, and the relative errors are generally 30% to 50% lower.

**Fig 5.12 Relative errors against air mass flow rate with kinetic theory and conventional frictional-kinetic model for alumina**

Thus, compared with kinetic theory, conventional frictional-kinetic model can reduce the relative errors for pressure drop prediction in dense phase bypass pneumatic conveying for alumina, especially for denser flows.
5.4.2 Case study for alumina

The solid volume fraction distributions and the absolute pressure profiles on the longitudinal plane for Alumina-3 and Alumina-15 are shown to illustrate how the conventional frictional-kinetic model has influence on pressure drop prediction for alumina. Alumina-3 represents the less dense flows, while Alumina-15 represents the denser flows.

5.4.2.1 Simulation result for Alumina-3

Fig 5.13 shows the simulation results of solid volume fraction on the longitudinal plane by applying conventional frictional-kinetic theory for Alumina-3. By comparing Fig 5.13 with Fig 4.14, it can be found that the solid volume fraction distribution appears to be relatively similar. This is because for Alumina-3, the flow is in dilute phase, and the contact between particles is not sustained sufficiently to cause solids volume fractions high enough to initiate frictional stress calculations. Thus, frictional stress does not play a significant role for dilute pneumatic conveying.

Fig 5.13 Simulation results of solid volume fraction on the longitudinal plane for Alumina-3 with conventional frictional-kinetic theory ($m_a=0.0681\text{kg/s}$, $m_s=2.2780\text{kg/s}$)

Fig 5.14 shows the absolute pressure profile on the longitudinal plane within time range of 0.1s for Alumina-3. Comparing Fig 5.14 with the kinetic friction only model of Fig 4.16, the pressure profile shows no difference. In both frictional cases, the flow shown for Alumina-3 exhibits a highly fluidised state and frictional stress has no influence on pressure profile in simulation.
5.4.2.2 Simulation result for Alumina-15

In contrast to the more dilute flow shown previously, Fig 5.15 shows the obvious change of solid volume fraction distribution for Alumina-15, when the conventional frictional-kinetic model is applied. In Fig 5.15, material shows continually solids volume change all along the pipeline and with short full bore dunes of alumina gradually moving along the pipeline with the conveying air. For example, the dune between flute 9 and 10 gradually moves forward to area between flute 10 and 11, and the length of sand dune become slowly shorter. Moreover, in the same period, as the air gaps between dunes move forward, the length of air gap changes as well. For instance, the gap between flute 4 and 7 slowly becomes larger as a result of the mechanism of bypass pneumatic conveying system. That is to say, air is forced into bypass pipeline through flute 3 due to the full bore dune between flute 3 and 4. Then air is forced back into the main pipeline through flute 4 to disturb the formation of dune. In this way, the material full bore dune can be disturbed and the gap between flute 4 and 7 becomes wider. For areas where material full bore dune appears in the main pipe, the pressure in the main pipeline is larger than the bypass pipeline, and the pressure at the last nozzle is larger than the next nozzle to force the air to flow in the bypass pipeline as well as through the flute to disturb the material build up.
CHAPTER 5 PRESSURE DROP PREDICTION WITH CONVENTIONAL FRICTIONAL-KINETIC MODEL

Fig 5.15 Simulation results of solid volume fraction on the longitudinal plane for Alumina-15 with conventional frictional-kinetic theory ($m_a=0.0207\,\text{kg/s}$, $m_s=2.6747\,\text{kg/s}$)

Fig 5.16 shows the pressure profiles variation due to the material motion in the simulation of the bypass pneumatic conveying for Alumina-15. The pressure drop between inlet and outlet becomes lower due to the material dune formation and deformation. The relative error for pressure drop prediction of Alumina-15 drops from 73% to 61% when the frictional resistance is initiated. The frictional-kinetic model plays important role in the dense phase bypass pneumatic conveying for alumina.

Fig 5.16 Simulation results of absolute pressure on the longitudinal plane for Alumina-15 with conventional frictional-kinetic theory ($m_a=0.0207\,\text{kg/s}$, $m_s=2.6747\,\text{kg/s}$)
5.4.3 Summary of simulation for alumina

For alumina transporting in bypass pneumatic conveying, the conventional frictional-kinetic model has great improvement on pressure drop prediction compared with results from kinetic theory especially for those denser flows, and all the data fit more with experimental results. The relative errors have been reduced dramatically, especially for those cases with lower air mass flow rate and higher pressure drops. However, all the pressure drops are still under-predicted.

For the case studies, when \( ma = 0.0681 \text{kg/s} \), the conventional frictional-kinetic model has no influence on solid volume fraction distribution and absolute pressure profiles. As air mass flow rate decreases, pressure drop prediction results with conventional frictional-kinetic model gradually improve compared to the results from kinetic theory. Although the relative errors are still too large, they drop down considerably. In summary, the conventional frictional-kinetic model has great improvement on pressure drop prediction for alumina, especially for those cases where there are denser flows with lower air mass flow rate. Application of modified Johnson-Jackson frictional model combined with kinetic model on pressure drop prediction for alumina is further studied in Chapter 6.

5.5 Simulation with conventional frictional-kinetic model for sand

The pressure drop prediction for sand utilising the conventional frictional-kinetic model with modified packing limit and modified friction pack limit is discussed in this section. Initially, the simulation results are compared with experimental results. Again, two simulation cases are selected to represent the gas-solid flow behaviour of less dense flows with high air mass flow rate as well as denser flows with low air mass flow rate. Figures of solid volume fraction distribution and pressure profiles are presented to show the influence of conventional frictional-kinetic model on simulation results.

5.5.1 Simulation results for sand

The pressure drop prediction with conventional frictional-kinetic model for sand is conducted. The simulation results are summarized in Fig 5.17 and compared with simulation results obtained from kinetic theory. In Fig 5.17, the results show a significant and quite dramatic improvement in pressure prediction using conventional
frictional-kinetic model. In all cases, the simulations converge, which did not occur for the kinetic friction only model. As before, all the data can be divided into two groups; cases with lower pressure drops for less dense flows and cases with higher pressure drops for dense flows. For less dense flows, the pressure drops for most of the cases are largely under-predicted. While for denser flows, the simulation results are close to experimental results.

![Graph showing experimental pressure drop against simulation pressure drop with kinetic theory and conventional frictional-kinetic model for sand.](image)

**Fig 5.17 Experimental pressure drop against simulation pressure drop with kinetic theory and conventional frictional-kinetic model for sand**

In Fig 5.18, the relative errors with conventional frictional-kinetic model decrease compared with results obtained from kinetic theory. Unlike flyash and alumina, not all the relative errors for pressure drop prediction increased with decreasing of air mass flow rate. Cases with low air mass flow rate and low SLR have large relative error. Compared with kinetic theory, conventional frictional-kinetic model has provided a capability for the CFD simulation for sand and also provided a dramatic improvement in pressure prediction capability (i.e. reduced errors) in dense phase bypass pneumatic conveying for sand.
5.5.2 Case study for sand

The solid volume fraction distributions and the absolute pressure profiles on the longitudinal plane for Sand-2 and Sand-8 are selected to show the typical behaviour of the flows for sand by applying conventional frictional-kinetic model. Sand-2 is an example for less dense flows with high air mass flow rate, while Sand-8 is an example for denser flows with low air mass flow rate.

5.5.2.1 Simulation result for Sand-2

Fig 5.19 shows the solid volume fraction distribution at the longitudinal plane for Sand-2. Compared with Fig 4.22 from the kinetic friction only simulation, there is thicker layer at the bottom of pipeline, and it is more similar to what has been observed from high speed camera (see Fig 4.20). However, the commencement location of dense material layer shown in Fig 5.19 does not change throughout the simulation, as was also observed in the kinetic only model simulation (Fig 4.20). Sand can only be conveyed in dilute phase in conventional pipelines and generally will deposit material at the bottom of the pipe when the flow is below the minimum conveying velocity. In the CFD simulation, the material is fully dispersed at the pipe entry, however, deposition is seen at some distance from pipe entry (i.e. it is a simulation peculiarity due to the initial
conditions). The variation in this dense layer will be mostly due to the flute airflow behaviour of the bypass pipe, which provides aeration capability to help promote the flow of the sand. The pressure drop across the pipeline rises because of the thicker layer as seen in Fig 5.19 and the included sustained contact between particles at the bottom of pipeline. The relative error by applying conventional frictional-kinetic model drops to 42% that is comparable to 72% using kinetic theory for Sand-2.

Fig 5.19 Simulation results of solid volume fraction on the longitudinal plane for Sand-2 with conventional frictional-kinetic theory ($m_s=0.0681\text{kg/s}, m_z=0.7415\text{kg/s}$)

Fig 5.20 shows the pressure profiles by applying frictional-kinetic theory within time period of 0.1s. Compared with the kinetic based model pressure profile from Fig 4.25, Fig 5.20 presents larger pressure decreasing tendency. This is because more material settles out at the bottom layer of pipeline and the frictional stress was included in the simulation and more energy was consumed during the process of conveying, so the pressure drop between inlet and outlet went up accordingly.
Fig 5.20 Simulation results of absolute pressure on the longitudinal plane for Sand-2 with conventional frictional-kinetic theory ($m_s=0.0681\text{kg/s}$, $m_s=0.7415\text{kg/s}$)

5.5.2.2 Simulation result for Sand-8

When compared with the results of kinetic model shown in Fig 4.23, the sand is seen to distribute all along the pipeline, with the highest solid volume fraction at the bottom of pipeline, as shown in Fig 5.21, which is more similar to what has been observed from the high speed camera (see Fig 4.21). Moreover, the solid volume fraction decreases with the increase of layer height within the pipe. From $t=0\text{s}$ to $t=0.1\text{s}$, the material layer in Fig 5.21 occurs at the same place without moving forward which is very similar to pictures shown high speed camera images. In the case of Sand-8, just a small part of sand particles convey in dilute phase, while most of the particles actually settle out without moving forward. There is very thick layer at the bottom of pipeline, and the increase of pressure drop is mainly due to the sustained contact between particles. By applying conventional frictional-kinetic model, the CFD simulation case for Sand-8 converged and the relative error for pressure drop prediction is about 63%. There was no CFD simulation convergence using the kinetic only friction. Thus conventional frictional-kinetic model offers better solutions for solid volume fraction distribution for Sand-8.
Fig 5.21 Simulation results of solid volume fraction on the longitudinal plane for Sand-8 with conventional frictional-kinetic theory ($m_a=0.0317\text{kg/s}$, $m_s=0.3649\text{kg/s}$)

Fig 5.22 shows the pressure profiles for Sand-8 by applying conventional frictional-kinetic model with the time period of 0.1s. The pressure gradually decreases from the inlet to outlet, as expected. In the kinetic only friction case shown in Fig 4.25, there is an area at the inlet that has a lower pressure than the main pipeline and bypass pipeline, and the absolute pressure profiles do not fit with the experimental observation. While Fig 5.22 shows that the pressure reduces quickly at the first three nozzles and then decreases gradually to the outlet due to the material building up right after nozzle 2. The absolute pressure profiles fit with the solid volume fraction distribution in Fig 5.21 and are more reasonable to express the real pressure distribution for simulation of bypass pneumatic conveying for Sand-8.

Fig 5.22 Simulation results of absolute pressure on the longitudinal plane for Sand-8 with conventional frictional-kinetic theory ($m_a=0.0317\text{kg/s}$, $m_s=0.3649\text{kg/s}$)
5.5.3 Summary of simulation for sand

Compared with results from kinetic theory, the conventional frictional-kinetic model has great improvement on pressure drop prediction for sand transportation in bypass pneumatic conveying, especially for denser flows. However, the simulation pressure drops are still under-predicted.

For the case studies, the conventional frictional-kinetic model improves the pressure drop prediction for Sand-2 and drops the relative error to 42%. It also helps simulation for Sand-8 getting converged with relative error of 63%. Observation from simulation results for Sand-2 and Sand-8 show that the solid volume fraction distribution and absolute pressure profiles are more reasonable by applying the conventional frictional-kinetic model.

Sand-2 represents the less dense flows with high air mass flow rate yet Sand-8 represents the flows with low air mass flow rate. The SLR values of Sand-2 and SLR of Sand-8 being 10.89 and 11.51 respectively are very low and the thick layer at the bottom of pipeline mainly remains at the same place without moving forward. Especially Sand-8 cannot represent the other cases with high SLR where particularly material dunes formation and deformation are observed. The formation and deformation of dunes can be observed while conducting experiment. Unfortunately, there are no images captured by high speed camera to compare the results of simulation cases with low air mass flow rate and high SLR. Further research of applying modified Johnson-Jackson frictional model combining with kinetic model on pressure drop prediction for sand will be conducted in Chapter 6.

5.6 Detailed illustration for sand case-6 with high SLR and low \( m_a \)

Cases selected above for analysis of solid volume fraction and pressure profiles only have low SLR values. In the above case studies for sand, the material settles down at the bottom of pipeline with a stable thick layer. However, for other denser flows with high SLR and low air mass flow rate, there are actually dune formations and deformations during the conveying process. As case Sand-6 has low air mass flow rate and high SLR=122.78, it is chosen as an example to show gas-solid flow behaviour in the simulation of highly dense flows. In addition, this case will show the mechanisms in which bypass systems can provide a dense phase capability to non-dense phase capable
material. By applying conventional frictional-kinetic model in simulation, the dune formation and deformation for Sand-6 with analysis of solid volume fraction and velocity distribution in bypass pneumatic conveying is shown in this subchapter.

5.6.1 General observation for simulation of Sand-6

Simulation of Sand-6 converged well on using frictional-kinetic model such that the pressure drop prediction results very close to the experimental results with a relative error of 22%. Fig 5.23 shows the predicted solid volume fraction profiles at the longitudinal plane. Fig 5.24 shows the simulation solid volume fraction for different cross-sections around flute 7 and 8.

It is obvious that around flute 7, as shown in Fig 5.23 and Fig 5.24, the sand layer deposit in the pipe and the top surface of the settled layer shows dense to dispersed solids concentration. Pu et al [105] used ECT equipment to study the dense phase pneumatic conveying of pulverized coal in a horizontal pipe. From his ECT images, it can be observed that the top surface of thick layer has similar shape. At this state, the gas-solid flow behaviour in the main pipe is similar to the flow in conventional pneumatic conveying pipe. At flute 8, as shown in Fig 5.23 and Fig 5.24, the material fully fills the main pipe with high solid volume fraction, while the bypass pipeline still maintains with lower solid volume fraction.

Fig 5.23 Simulation of solid volume fraction of longitudinal plane

![Fig 5.23 Simulation of solid volume fraction of longitudinal plane](image)

Fig 5.24 Simulation of solid volume fraction at different cross-sections around flute 7 and 8 (unit for intervals: mm)

![Fig 5.24 Simulation of solid volume fraction at different cross-sections around flute 7 and 8 (unit for intervals: mm)](image)
Fig 5.25 shows the simulation velocity profiles at the longitudinal plane. Fig 5.26 shows the simulation velocity vectors at longitudinal plane around flute 7 and 8. In this test, the solid mass flow rate was 2.54 kg/s with an air mass flow rate 0.021 kg/s.

As shown in Fig 5.25 and Fig 5.26, velocity within the bypass pipeline is much higher than the main pipe. The flute opening in the bypass pipe has an orifice plate, which generally creates turbulence and a higher pressure before the orifice. This geometry and pressure combination forces the air back into the pipeline through downstream opening. In this way, the material full bore dune can be disturbed and aerated which generally reduces the dunes into ones with smaller size. This basic behaviour correlates well with the work of Zhang et al [49]. Zhang used CFD to analyse the pneumatic conveying in bypass pipe and found that the air velocity in the bypass pipeline is much higher than the velocity in the main pipe for places where there appeared full bore dunes. The simulation results fit well with the experiment result.

![Fig 5.25 Simulation velocity profiles at the longitudinal plane (m/s)](image)

5.6.2 Solid volume fraction distribution along with velocity magnitude

The profiles of volume fraction obtained from simulation within time interval 0.1s are shown in Fig 5.27. In the beginning, an increase in height of material occurs due to the influence of air injection from the inlet of the pipe. There is obviously a material full bore dune located around flute 8 and 9 at $t=0$s. Air is forced into the bypass pipeline through flute 7 and then is forced back to the main pipeline through flute 8 to disturb the
sand dune. At $t=0.05s$, it is obvious that the sand dune moves to the right after flute 8. At $t=0.1s$, the sand dune moves forward between flute 8 and 10. In this way, the dunes for denser flows can continuously form, deform and convey as the material is continually aerated via the bypass flutes.

The sketch for geometry and position of flute 7 and 8 are shown in Fig 5.28. Flute 7 is 2.6m away from the pipeline inlet, while Flute 8 is 3.0m away from the pipeline inlet. Along the center of bypass pipeline, a broken line ABCD which runs through the orifice plate is also presented: point A is 2.4m away from the pipeline inlet, point B is 2.6m away from the pipeline inlet, point C is 3.0m away from the pipeline inlet and point D is 3.2m away from the pipeline inlet.
The gas velocity magnitude variation along broken line ABCD is shown in Fig 5.29. The gas velocity right after flute 8 is much larger than gas velocity right after flute 7 due to the full bore sand dune deforming around flute 8. This is because air is forced back into the main pipe at flute 8 and disturbs the sand build-up otherwise causing a blockage in a conventional pipe. As such, the air at flute 8 in the bypass pipeline is accelerated accordingly. In addition, kinetic energy is transferred from air to sand and the air velocity reduced gradually from 25m/s to 4m/s during period of 0s to 0.1s. As there is no sand fully filling the pipe around flute 7, the material conveys the same as in the conventional pipe, the gas velocity shows only a small change between 3m/s to 9m/s. Moreover, due to the influence of orifice plate, the velocity has a sudden increase right after flute 7. Similarly, a sudden increase in gas velocity can be observed right after flute 8, with a much larger increment.
5.6.3 Velocity magnitude around flute 8

In order to illustrate more clearly the air velocity variation around the bypass flutes, flute 8 was chosen to investigate the airflow into a full bore dune of material. As such polygon FEGF’ is defined with coordinates at the longitudinal plane, as shown in Fig 5.30.

Fig 5.31 shows gas velocity magnitude variation for EG around flute 8. For profiles of 0.0s to 0.06s, flute 8 has a very dense layer below (in the main pipe) associated with a full bore dune formation. The velocity magnitudes in this period show the same profile shape with a steady decrease in time, probably due to a slow reduction in solids concentration of the dune below the flute. These gas velocity profiles increase quickly.
and reaches the maximal at the centre of EG, i.e. through the orifice, then decreases to 5m/s. This is consistent with the movement of the full bore plug of material below the flute, causing the air to flow through the bypass.

For profile of 0.07s, material starts to be disturbed sufficiently for increased aeration into the main pipe, thereby reducing bypass gas velocity. As such there is a smaller gas velocity rise from 1.5m/s to 6m/s and then it keeps relatively stable for position just before and after the orifice plate. The gas velocity then drops to 5m/s, which is the same for the earlier time periods, as the full bore dune is still dominant at this location.

For velocity profiles of 0.08s to 0.1s, the full bore material dune around flute 8 has totally disappeared, and velocity magnitudes just before the orifice plate flutes increase slowly from 1m/s to 2.5m/s. For the position right after flute 8, velocity magnitude climbs up dramatically to 10m/s, 17m/s and 20m/s at 0.08s, 0.09s and 0.1s respectively. This is most likely due to the preferential airflow into the bypass pipe from the main pipe, behind the full bore dune as it passes the flute.

![Fig 5.31 Velocity magnitude for position EG around flute 8](image)

Fig 5.32 shows the gas velocity magnitude variation for EF around flute 8. For profile times of 0.0s to 0.05s, flute 8 is semi-blocked with a material dune flow past the flute. The gas velocity along EF in the bypass pipeline shows little change in profile, but a slow decrease in magnitude of velocity, probably due to the amount of material from the
dune below decreasing in height. Profile 0.06s to 0.07s, the increase in gas velocity along EF in the bypass pipeline shows the diversion of air into the main pipe, probably due to a significant change in the amount of material below the flute. For profiles of 0.08s to 0.1s, the gas velocity profile and magnitude before orifice plate as well as between bypass pipeline and main pipeline behaves very similarly. In this period, the material full bore dune has past the main pipe, with an increase in air velocity entering the main pipe from the flute.

The reason for the velocity reduction along EF is because the air is firstly accelerated for this position due to the increasing aeration into the main pipe, then the air velocity drops to low value since there is a full bore passing the flute and there will be a greater cross sectional area for the gas to flow in the main pipe (i.e. not accelerated near the orifice plate).

![Velocity magnitude for position EF around flute 8](image)

**Fig 5.32 Velocity magnitude for position EF around flute 8**

Fig 5.33 shows velocity magnitude variation for F’G. From 0s to 0.06s, again the velocity profile shape is the same, but the magnitude decreases, again associated with the change in material concentration below the flute. When time is 0.07s, the velocity increases to 18m/s and then decreases to 5m/s with time. After that, from 0.08s to 0.1s, the velocity magnitude rises right after flute 8 and then gradually decreases. Right after flute 8, the velocity magnitude of 0.08s is larger than 0.09s and 0.1s. Again, this shows quite dramatic gas velocity fluctuations associated with the flute geometry.
5.6.4 Pressure profiles around flute 8

The pressure profiles on the longitudinal plane for a time interval of 0.1s are shown in Fig 5.34 where the pressure decay is evident along the pipeline. From $t=0s$ to $0.06s$, since there is a full bore dune at flute 8, the pressure at the left side of flute 8 is much larger than the right side, and the pressure in the bypass pipeline is larger than the main pipeline. When the full bore sand dune occurs, the air goes into the bypass pipeline through the last nozzle and is forced back into main pipeline thought the next nozzle, which leads to a higher pressure in the bypass pipeline. With the passage of time, more air goes into the main pipe through the nozzle and the dune becomes more aerated allowing increased air to flow through the main pipe. From $t=0.07s$ to $0.1s$, the pressure difference between the left side and right side of flute 8, as well as the pressure difference between the bypass pipeline and main pipeline become smaller.
Again, using the previously defined polygon FEGF’ (Fig 5.30), analysis of the pressure variation around flute 8 is conducted. Fig 5.35 shows the pressure variation with time for length EG. The pressure difference between point E and G is large from $t=0s$ to $t=0.06s$ due to the appearance of full bore sand dune, with the energy of air is transferred to the material gradually to disturb the sand dune. Nevertheless, when $t=0.07s$ to $t=0.1s$, the pressure is almost maintained at the same level as the sand dune has passed flute 8.
Fig 5.35 Gas pressure magnitude for position EG around flute 8

Fig 5.36 shows the pressure variation with time between point E and F. For pressure profiles of 0.0s to 0.06s, pressure decreases from the flute to the top of the main pipe, which shows the airflow direction will be predominantly flowing into the main pipe. While for profiles of 0.07s to 0.1s, pressure has little change, indicating more dilute period of conveying around flute 8.

Fig 5.36 Gas Pressure for position EF around flute 8

Fig 5.37 shows the pressure variation with time between point F’ and G. For pressure profiles of 0.0s to 0.06s, pressure gradually decreases from the top of the main pipe to
the flute. For profiles of 0.07s to 0.1s, pressure almost has no change. On the other hand, for the same position, the absolute pressure increase gradually from $t=0s$ to $t=0.06s$. But from $t=0.07s$ to $t=0.1s$, there is only little increase for absolute pressure.

As a summary, when there appears a material full bore dune, for position EG which represents the location before and after the orifice plate through the flute, the pressure magnitude continuously decreases from the time profile 0s to 0.06s, and then maintains the same from 0.7s to 0.1s. For position EF which represents the location through the bypass pipeline to the main pipeline, the pressure magnitude slowly decreases for the time period of 0s to 0.06s, and then has almost no change for profiles of 0.7s to 0.1s. For position F’G which represents the location through the main pipeline to the bypass pipeline, the pressure magnitude continuously goes down from the time profile 0s to 0.06s, and then keeps the same from 0.7s to 0.1s.

5.6.5 Summary for detailed analysis of simulation case Sand-6

Both of the general and detailed solid volume fraction distributions on the longitudinal plane within in time period of 0.1s was conducted for this analysis in this subchapter. The behaviour of sand powders with dune formation and deformation clearly represents the mechanism of bypass pneumatic conveying as was observed during the experimental testing.
The analysis conducted on the airflow and pressure around flute 8 with the existence of a full bore sand dune highlighted the fluctuating and turbulent nature of the flow. For instance, the velocity variation and direction of the flow between main pipe and bypass pipe represents the movement of air into the main pipe from the bypass pipe to disturb the formation of full bore length of material that would otherwise block the pipe. Moreover, the pressure changes show that the movement of air is generally from the bypass pipe into the main pipe, especially when a full bore dune is formed.

All the above analysis for Sand-6 shows how CFD simulations can provide detailed information of the flow behaviour associated with bypass pneumatic conveying, especially for the turbulent flow conditions around the bypass flutes. In particular, the solids volume fraction, velocity magnitudes and pressure behaviour in bypass pneumatic conveying for dense sand flow with dune formations can be investigated, which may be used to optimise flute geometries, in the future.

5.7 Conclusion

Firstly, different flow regimes including dilute regime, intermediate regime and dense regime were defined and described for bypass pneumatic conveying of flyash, alumina and sand. In contrast to sand, flyash and alumina have more distinct boundaries between different regimes. That is because sand is the type of material to be conveyed generally in dilute phase only and tend to either be suspended in a dilute stream or deposit at the bottom of pipeline. Sand dunes will only form and move forward due to the enhanced aeration mechanism within a bypass pneumatic conveying system, as seen in the experimental and associated CFD modelling discussed in this chapter.

Secondly, a frictional-kinetic model for dense phase gas-solid flow have been reviewed and summarised. It was found that frictional-kinetic model was widely applied to investigate dense phase gas-solid flow behaviour in fluidised bed and spouted beds. Few studies applied frictional-kinetic model in the numerical study of dense phase pneumatic conveying. Thus, the conventional frictional-kinetic model has been primarily chosen to conduct simulation for pressure drop prediction with different types of material in this chapter. Moreover, the packing limit and frictional packing limit were modified according to the test results of tapped bulk density and fluidised bulk density particular to each material type for the preparation of simulation.
Thirdly, the conventional updated frictional-kinetic model was utilised for CFD based pressure drop prediction with flyash, alumina and sand powders. The simulation results can be summarised with the following aspects:

- For flyash, pressure drop simulation results from applying kinetic theory and conventional frictional-kinetic model are the same. Cases Flyash-1 and Flyash-21 have been carried out as examples for less dense flows and denser flows. These two cases help to present that there was no improvement on solid volume fraction and pressure profiles distribution by conventional frictional-kinetic model. This is due to the solids volume fraction never attaining a value high enough to initiate the frictional resistance component, the reason for which is not immediately clear. As such, in its current form, the frictional-kinetic model has shown no improvement compared with the kinetic model on pressure drop prediction for flyash.

- For alumina, the frictional-kinetic model provides large improvement of pressure drop prediction compared with results from kinetic theory, especially for denser flows with large SLR and low air mass flow rate. Cases Alumina-3 and Alumina-15 have been carried out as two examples for less dense flows and denser flows. It has been found that conventional frictional-kinetic model has almost no improvement on pressure drop prediction for Alumina-3, as the flow is very dilute. However, the conventional frictional-kinetic model improves the pressure drop prediction for Alumina-15 and the relative error drops from 73% to 61%. Thus, the inclusion of the frictional stress in the CFD simulations plays important role in the prediction capability for dense bypass pneumatic conveying for alumina.

- For sand, by using frictional-kinetic model, all the simulation cases were able to obtain convergence of the solution and a significant improvement for pressure drop prediction was shown. The results of experiment and simulation show good agreement. Cases Sand-2 and Sand-8 have been carried out as two representative cases for less dense flows with high air mass flow rate and denser flows with low air mass flow rate. For Sand-2, the relative error drops to 42%. While for Sand-8, the simulation gets converged and the relative error is about 63%. The solid volume fraction distribution and absolute pressure profiles are more reasonable by applying conventional frictional-kinetic model for these two cases.
Again, the inclusion of the frictional stress in the CFD simulations plays important role in the prediction capability for dense bypass pneumatic conveying for sand.

Finally, because most of material powders in Sand-2 and Sand-8 settle down as a thick layer at the bottom of pipeline without moving forward, Sand-6 which has high SLR was selected as an example to conduct further analysis of bypass flute behaviour for denser flows. The general solid volume fraction and velocity magnitude within in time period of 0.1s was presented to show how the full bore dune formation and deformation of sand and bypass flutes interact. It was shown that in the short time period (0 to 0.1 seconds) that high fluctuations and variation in pressure and gas velocity occur, the gas velocity vectors indicate a high degree of air penetration from the flute into the bypass pipe. It is exactly this behaviour which provides an aeration mechanism for the gas to flow into the conveyed material in the main pipe. This aeration mechanism is what makes the bypass system work and allows non-dense phase material to be conveyed in a dense mode of flow.
CHAPTER 6 MODIFIED FRICTIONAL-KINETIC MODEL

In this chapter, a different frictional-kinetic model is proposed and then modified in order to use for pressure drop prediction of flyash, alumina and sand in the bypass pneumatic conveying system. This chapter can be divided into following aspects:

The modified frictional pressure model is based on the conventional Johnson-Jackson frictional-kinetic model. The critical value of solids volume fraction $\alpha_{s,min}$ and maximum packing limit $\alpha_{s,max}$ are modified according to the solid volume fraction obtained from fluidised bulk density and tapped bulk density, respectively. Since the frictional pressure tends towards infinite value when the solid volume fraction approaches the maximum packing limit with the original Johnson-Jackson frictional pressure model, an offset solid volume fraction $\alpha_{s,off}$ is introduced into the frictional pressure model. This offset solid volume fraction $\alpha_{s,off}$ is introduced into the radial distribution functions which are the correction factor to modify the probability of collisions between particles when solid phase becomes dense.

Based on the modified frictional pressure model mentioned above, a sensitivity analysis is conducted for the CFD case studies for the Johnson-Jackson modified parameters of $\alpha_{s,off}$, $Fr$, $n$, and $p$. Flyash-20 (SLR=148.78), Alumina-18 (SLR=147.44) and Sand-6 (SLR=82.49) which are representative of dense phase flows have low air mass flow rates as well as high SLR are chosen as the examples to conduct the sensitivity analysis. The solid volume fraction and pressure contours distribution on the longitudinal plane are investigated graphically to show the influence of $\alpha_{s,off}$, $Fr$, $n$, and $p$ on gas-solid flow behaviour in the CFD simulation for the different types of material.

Subsequently, from the sensitivity analysis, new constants in the modified frictional-kinetic model were introduced to the CFD simulation for the pressure drop prediction. The pressure drop prediction results are then summarised and compared with results obtained from kinetic theory and conventional frictional-kinetic model. Based on the research above and from Chapter 4 and Chapter 5, guidance for choosing an appropriate friction model to predict pressure drop for different types of material conveyed in bypass pneumatic conveying systems is proposed.
6.1 Review for frictional-kinetic model

Based on the experiment conducted in fully developed flow down an inclined chute with granular material of glass beads, Johnson and Jackson [2, 3] derived constitutive expressions for frictional contribution to the total stress. The Coulomb relationship between frictional shear $S_f$ and normal shear $N_f$ is shown as equation (6-1). 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 (6-2).

\[
S_f = N_f \sin \varphi \tag{6-1}
\]

\[
N_f(\alpha) = \begin{cases} 
Fr \frac{(\alpha_s - \alpha_{min})^p}{(\alpha_{max} - \alpha_s)^n} & \text{if } \alpha_s > \alpha_{min} \\
0 & \text{if } \alpha_s \leq \alpha_{min}
\end{cases} \tag{6-2}
\]

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

Savage [107] assumed that stress tensor $\tilde{\tau}$ is the sum of the kinetic stress tensor $\tilde{\tau}_k$ and the frictional stress tensor $\tilde{\tau}_f$, which encapsulates the yield and flow behaviour of granular materials, as shown in equation (6-3).

\[
\tilde{\tau} = \tilde{\tau}_k + \tilde{\tau}_f \tag{6-3}
\]

The kinetic stress tensor $\tilde{\tau}_k$ is modelled by kinetic theory of granular flows while frictional stress tensor $\tilde{\tau}_f$ is defined by equation (4-6). The stress assumption proposed by Savage [107] as shown in equation (6-3) has been employed by many researchers to pursue improved simulation results for dense granular flows. The corresponding shear viscosity $\mu_s$ for solids phase can be described as the same as stated in equation (4-12), where $\mu_{s,f}$ can be defined by equation (5-1). The corresponding solid pressure $p_s$ is also different than the solids pressure defined in the conventional frictional-kinetic model as the friction term has changed. The new solids pressure equation is defined in equation (6-4) which includes both of the kinetic and friction contributions.
Syamlal et al. [4] 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, switching between two entirely different constitutive relations was coded in MFIX shown as following:

\[
\tau = \begin{cases} 
\tau_{s-\text{kinetic}} I + \tau_{s-\text{kinetic}} & \text{if } \varepsilon_s < \varepsilon_{s-\text{critical}} \\
\tau_{s-\text{friction}} I + \tau_{s-\text{friction}} & \text{if } \varepsilon_s \geq \varepsilon_{s-\text{critical}} 
\end{cases}
\]  

(6-5)

The frictional stress \( P_s \) is:

\[
P_s = \begin{cases} 
0 & \text{if } \varepsilon_s < \varepsilon_{s-\text{critical}} \\
10^{25} (\varepsilon_s - \varepsilon_{s-\text{critical}})^{10} & \text{if } \varepsilon_s \geq \varepsilon_{s-\text{critical}} 
\end{cases}
\]  

(6-6)

And the frictional viscosity \( \mu_{s,fr} \) is calculated by equation (5-1).

Srivastava and Sundaresan [101] 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 (6-3). Kinetic theory was used for expressing kinetic stress, while frictional stress and frictional viscosity described by Schaeffer [104] as shown in equation (6-7) and (5-1), respectively, was 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 (6-8). 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.

\[
P_{c}(v) = \begin{cases} 
Fr \left( \frac{\alpha_s - \alpha_{s,\text{min}}}{\alpha_{s,\text{max}} - \alpha_s} \right)^p & \text{if } \alpha_s > \alpha_{s,\text{min}} \\
0 & \text{if } \alpha_s \leq \alpha_{s,\text{min}} 
\end{cases}
\]  

(6-7)

\[
\frac{\tau_f}{p_c(v)} = 1 - \sqrt{2} \sin \varphi \frac{s}{\sqrt{s^2 + r^2}}
\]  

(6-8)
Tardos et al [5] proposed a new expression for average solid shear stress as shown in equation (6-9) and (6-10). Makkawi and Ocone [108] 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<\text{Re}<3000.

\[ \tau_{s-Tardos} = P_s \sin \phi \tanh \left( \frac{a\sqrt{\pi}}{2} \right) \quad (6-9) \]
\[ a = \frac{(du_s/dy)}{2\sqrt{2\sigma}} \quad (6-10) \]

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

Yassir et al [109] 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 [110] 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 (6-3). The simulation results from Wu and Arun [110] were compared with experimental data from He et al [111]. 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 [112] 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 [2] and a modified frictional shear viscosity model [4], as shown in equation (6-11). 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.

\[ \mu_{\text{friction}} = F_r \frac{(\alpha_s - \alpha_{s,\text{min}})^n \sin \phi}{\alpha_s (\alpha_{s,\text{max}} - \alpha_s) \sqrt{I/2b}} \quad \text{if} \quad \alpha_s > \alpha_{s,\text{min}} \quad (6-11) \]

Ng et al [1] 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 (6-12), 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 [104] with solids pressure provided by Lun et al [87], 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.

\[ \tilde{T} = \tilde{T}_{\text{kin}} + A^* \times \tilde{T}_{fr} \quad (6-12) \]

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

Wang et al [113] and Lu et al [114] 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 [2], equation (6-2), and the frictional shear viscosity model from Schaeffer [104] 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 [111], 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 [115, 116] 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 [117] 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 [2], Syamlal et al [4] and Srivastava and Sundaresan [101] were applied in the simulation to compare with the results from classical kinetic theory of granular flow. The frictional pressure for Srivastava and Sundaresan [101] model is the same as Johnson and Jackson [2]. The frictional viscosity was as equation (6-13). 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.

\[ \mu = \frac{P_{friction} \sqrt{2 \sin \varphi_f}}{2 \left( \frac{S_2 - S_3}{d_p} \right)} \]  

Pu [105] 2010 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 [2] and a modified frictional shear viscosity model of Syamlal et al [4] were adopted for friction stress. The simulation result at cross section agreed well with experiment results from electrical capacitance tomography (ECT) image. The influences of superficial velocity on solid concentration distribution were analysed. The formation and motion process of slug flow was similar to the visualization photographs by 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 very important role in many dense phase gas-solid flows. However, the frictional stress model applied in fluidised beds, mixer or horizontal pipe is 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 obtained from the results of experiments conducted with only two types of material, glass beads and polystyrene beads. Many researchers have adopted the Johnson and Jackson’s frictional stress model and applied the constants proposed from these two materials directly in their investigation 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 6.1.

Johnson and Jackson [2, 3] derived the model based on experiments carried out with plate shear and inclined-plane shear flow, as shown in Fig 6.1 and Fig 6.2, respectively. Materials were in consolidated state and frictional stress appeared between different layers inside the material. Johnson and Jackson model [2, 3] 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 $Fr$, $n$, $p$, $\alpha_{\text{min}}$ and $\alpha_{\text{max}}$ were applied directly without physical verification.

Figure 6.1 Nomenclature for plane shear of a horizontal layer [2]

Figure 6.2 Inclined-plane shear flow [3]
### Table 6.1 Semi-empirical constants that have been used by different investigators

<table>
<thead>
<tr>
<th>Author</th>
<th>Materials</th>
<th>$d_p$ (um)</th>
<th>$\rho$ (kg/m³)</th>
<th>$\alpha_{\text{max}}$</th>
<th>$\alpha_{\text{min}}$</th>
<th>$n$</th>
<th>$p$</th>
<th>Fr</th>
</tr>
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<tbody>
<tr>
<td>Johnson and Jackson[2]:</td>
<td>Glass beads</td>
<td>1800</td>
<td>2980</td>
<td>0.63</td>
<td>0.5</td>
<td>2</td>
<td>5</td>
<td>0.05</td>
</tr>
<tr>
<td>Inclined chute</td>
<td>Polystyrene beads</td>
<td>1000</td>
<td>1095</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang et al [112, 113, 118]:</td>
<td>From He</td>
<td>1410</td>
<td>2503</td>
<td>0.593</td>
<td>0.5</td>
<td>2</td>
<td>5</td>
<td>0.05</td>
</tr>
<tr>
<td>Spouted beds</td>
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<td></td>
</tr>
<tr>
<td>Lu et al [114]:</td>
<td>From He</td>
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<td>2503</td>
<td>0.593</td>
<td>0.5</td>
<td>2</td>
<td>5</td>
<td>0.05</td>
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<td>Spouted beds</td>
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<td></td>
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<tr>
<td>Srivastava et al [101]:</td>
<td>Geldart A particles</td>
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<td>2900</td>
<td>0.63</td>
<td>0.5</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Bin discharge and rising bubble</td>
<td>Geldart B particles</td>
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<td></td>
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<tr>
<td>Darelius et al [119]:</td>
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<td>740</td>
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<tr>
<td>Wang et al [116]:</td>
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<td>3589</td>
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<td>0.5</td>
<td>2</td>
<td>5</td>
<td>0.05</td>
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<td>Fluidised beds</td>
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<td></td>
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<td></td>
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<tr>
<td>Pu et al [105]:</td>
<td>Pulerized coal</td>
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<td>1350</td>
<td>0.63</td>
<td>0.1</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Sun et al [102]:</td>
<td>Glass beads</td>
<td>196.5</td>
<td>2467</td>
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<td>2</td>
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<td>0.05</td>
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<tr>
<td>Sun et al [120]:</td>
<td>From He</td>
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<td>0.5</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Ocone et al [103]:</td>
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<td>2500</td>
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<td>0.5</td>
<td>2</td>
<td>3</td>
<td>0.05</td>
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<td>Duct of arbitrary inclination</td>
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<tr>
<td>Johnson et al [121]:</td>
<td>Glass beads</td>
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<td>2900</td>
<td>0.63</td>
<td>0.5</td>
<td>2</td>
<td>5</td>
<td>0.05</td>
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</tr>
<tr>
<td>Johnson and Jackson[2]:</td>
<td>Glass beads</td>
<td>1800</td>
<td>2980</td>
<td>0.63</td>
<td>—</td>
<td>0</td>
<td>40</td>
<td>$3.65 \times 10^{32}$</td>
</tr>
<tr>
<td>Plane shearing</td>
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<td></td>
</tr>
<tr>
<td>Johnson and Jackson[2]:</td>
<td>Poly-styrene beads</td>
<td>1000</td>
<td>1095</td>
<td>0.63</td>
<td>—</td>
<td>0</td>
<td>40</td>
<td>$4.0 \times 10^{32}$</td>
</tr>
</tbody>
</table>
As shown in Fig 6.3, 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 $\tau_f$ between particles at the bottom is still continual. The constants in equation (6-2) 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 (6-2) 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.

6.2 Modified frictional models

Since Johnson and Jackson frictional model [2] was derived from soil mechanics, the critical value of solids volume fraction and packing limit in the model are modified according the actual condition of pneumatic conveying where material is flowing and aerated. Also, an offset solid volume fraction is proposed and introduced into the Johnson and Jackson frictional pressure equation. In this way, the frictional pressure
equation may be modified for simulation of gas-solid flow for flyash, alumina and sand, respectively.

**6.2.1 Definitions of \( \alpha_{s,\text{min}} \) and \( \alpha_{s,\text{max}} \)**

Johnson and Jackson frictional model [2] has been widely used to describe frictional pressure for dense flow. However, the Johnson and Jackson model for frictional pressure as shown in equation (6-2) 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 (6-14), the minimum solids volume fraction, \( \alpha_{s,\text{min}} \) is the critical value of solids volume fraction when frictional stress can be added to the stress predicted by kinetic theory, of which \( \alpha_{s,\text{min}} \) is set to 0.5 as default. In addition, the default value for maximum material packing limit, \( \alpha_{s,\text{max}} \) 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 solids 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 [99]. As such, the solid volume fraction of material would not exceed the value obtained from the tapped bulk density approach. Therefore it is proposed that the constants of \( \alpha_{s,\text{min}} \) and \( \alpha_{s,\text{max}} \) are redefined to fit with the actual flow conditions in pneumatic conveying, where \( \alpha_{s,\text{min}} \) can be calculated from material fluidized state and \( \alpha_{s,\text{max}} \) can be calculated from material tapped state. For different materials, \( \alpha_{s,\text{min}} \) and \( \alpha_{s,\text{max}} \) can be written as equation (6-14) and (6-15).

\[
\alpha_{s,\text{min}} = \frac{\rho_{fb}}{\rho_p}
\]  
(6-14)

\[
\alpha_{s,\text{max}} = \frac{\rho_{tb}}{\rho_p}
\]  
(6-15)
where $\rho_{fb}$ is the fluidized bulk density, $\rho_p$ is the particle density, $\rho_{tb}$ is the tapped bulk density. Based on the test results from Chapter 3.2, $\alpha_{s,min}$ and $\alpha_{s,max}$ for different materials are summarized in Table 6.2.

<table>
<thead>
<tr>
<th>Materials</th>
<th>$\rho_{fb}$ (kg/m³)</th>
<th>$\rho_{tb}$ (kg/m³)</th>
<th>$\rho_p$ (kg/m³)</th>
<th>$\alpha_{s,min}$</th>
<th>$\alpha_{s,max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flyash</td>
<td>505</td>
<td>992</td>
<td>2093</td>
<td>0.24</td>
<td>0.47</td>
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<td>863</td>
<td>1115</td>
<td>4088</td>
<td>0.21</td>
<td>0.27</td>
</tr>
<tr>
<td>Sand</td>
<td>1247</td>
<td>1703</td>
<td>2600</td>
<td>0.47</td>
<td>0.63</td>
</tr>
</tbody>
</table>

After modifying the packing limit $\alpha_{s,min}$ and frictional packing limit, $\alpha_{s,max}$ for different types of material to fit with the actual solid volume fraction distribution in pneumatic conveying, the Johnson and Jackson frictional model can be rewritten as equation (6-16) to (6-18).

Flyash: 
$$P_{friction} = \begin{cases} 
F_T \frac{(\alpha_s-0.24)^n}{(0.47-\alpha_s)^p} & \text{if } \alpha_s > 0.24 \\
0 & \text{if } \alpha_s \leq 0.24
\end{cases} \quad (6-16)$$

Alumina: 
$$P_{friction} = \begin{cases} 
F_T \frac{(\alpha_s-0.21)^n}{(0.27-\alpha_s)^p} & \text{if } \alpha_s > 0.21 \\
0 & \text{if } \alpha_s \leq 0.21
\end{cases} \quad (6-17)$$

Sand: 
$$P_{friction} = \begin{cases} 
F_T \frac{(\alpha_s-0.47)^n}{(0.63-\alpha_s)^p} & \text{if } \alpha_s > 0.47 \\
0 & \text{if } \alpha_s \leq 0.47
\end{cases} \quad (6-18)$$

### 6.2.2 Definition of $\alpha_{s,off}$

In the original Johnson and Jackson frictional model [2], as stated previously, 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 (6-16) to (6-18) 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 (6-16) to (6-18) 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 (6-16) to (6-18) 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 6.4. The frictional pressure is relatively lower in value when $\alpha_s$ 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 consolidate 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 6.4 Frictional pressure with and without $\alpha_{s,off}$ as function of solid fraction](image)

Fig 6.4 Frictional pressure with and without $\alpha_{s,off}$ as function of solid fraction
By applying $\alpha_{s,off}$ and combining with $\alpha_{s,min}$ and $\alpha_{s,max}$ obtained from subchapter 6.1.1, the Johnson and Jackson frictional pressure equation for flyash, alumina, and sand can be modified as equation (6-19) to (6-21):

Flyash:  
$$P_{friction} = \begin{cases}  
Fr \frac{(\alpha_s - 0.24)^n}{(0.47 + \alpha_{s,off} - \alpha_s)^p} & \text{if } \alpha_s > 0.24 \\
0 & \text{if } \alpha_s \leq 0.24 
\end{cases}$$  
(6-19)

Alumina:  
$$P_{friction} = \begin{cases}  
Fr \frac{(\alpha_s - 0.21)^n}{(0.27 + \alpha_{s,off} - \alpha_s)^p} & \text{if } \alpha_s > 0.21 \\
0 & \text{if } \alpha_s \leq 0.21 
\end{cases}$$  
(6-20)

Sand:  
$$P_{friction} = \begin{cases}  
Fr \frac{(\alpha_s - 0.47)^n}{(0.63 + \alpha_{s,off} - \alpha_s)^p} & \text{if } \alpha_s > 0.47 \\
0 & \text{if } \alpha_s \leq 0.47 
\end{cases}$$  
(6-21)

where $Fr$, $n$, and $p$ are constants. As summarized in table 6.1, $Fr=0.05$, $n=2$ and $p=5$ are the parameters chosen for most of the research conducted for pneumatic conveying and are the constants obtained from soil mechanics and defined in Fluent theory guide. In Pu’s investigation [105], $Fr$ equal to 0.1 was used, however no explanation is provided why this value was chosen. The frictional pressure increases dramatically to infinite when the solids volume fraction is close to the packing limit 0.63. However, in bypass pneumatic conveying with modified packing limit and frictional packing limit, it is impossible for frictional pressure to reach the infinite value, as material is flowing and aerated. Thus, the pressure drop could be extremely over predicted near the maximum packing limit with original constants obtained by soil mechanics, especially with constant $p=5$ in the denominator. So, as suggested by Ocone et al [103], $p=3$ will be used for this chapter as it dampens the quick increase in pressure near the maximum packing limit.

Moreover, within the numerical model, the radial distribution function acts as a correction factor to modify the probability of collisions between particles, when the solid phase becomes dense. As such, this function requires re-definition for different materials accordingly due to the change in $\alpha_{s,off}$, therefore, the radial distribution functions defined in equation (4-12) are modified as shown in equations (6-22) to (6-24) for flyash, alumina and sand, respectively.

Flyash:  
$$g_{0,ss} = \left[1 - \left(\frac{\alpha_s}{0.47 + \alpha_{s,off}}\right)^3\right]^{-1}$$  
(6-22)
6.3 Analysis of $\alpha_{s,off}$ for modified frictional models

$\alpha_{s,off}$ has been added into the modified frictional pressure equation. However, the values of $\alpha_{s,off}$ are different for various types of material. This is because gas-solid flow behaviours for different types of material powders are dissimilar due to their particle properties, i.e. particle density, tapped bulk density and fluidised bulk density. Therefore, $\alpha_{s,off}$ is a very important parameter to the determination of modified frictional pressure equation, and it will be studied in this subchapter.

6.3.1 Sensitivity analysis of $\alpha_{s,off}$ for flyash

The sensitivity analysis of $\alpha_{s,off}$ for flyash is conducted. Different values of $\alpha_{s,off}$ are applied in the pressure drop prediction for bypass pneumatic conveying, and the results are summarised. In addition, the CFD case study for Flyash-20 with different values of $\alpha_{s,off}$ is presented to show the influence of $\alpha_{s,off}$ on solid volume fraction and pressure contours distributions for flyash in bypass pneumatic conveying.

6.3.1.1 Pressure drop prediction by varying $\alpha_{s,off}$ for flyash

By using different values of $\alpha_{s,off}$ in equation (6-19), when $Fr=0.05$, $n=2$ and $p=3$, the variation of frictional pressure with solid volume fraction was obtained in Fig 6.5. In Fig 6.5, it appears that the frictional pressure increases sharply when solid volume fraction increases from 0.24 to 0.245 where the frictional pressures are still low. When $\alpha_s>0.245$, the frictional pressure increases gradually until the solid volume fraction reaches about 0.445. When solid volume fraction continuously increases from 0.445 to packing limit 0.47, the frictional pressure rises largely. Moreover, with the same value of solid volume fraction, the frictional pressure climbs up more sharply with a decrease in $\alpha_{s,off}$, and it is more obvious in the range of $\alpha_s=0.445 \sim \alpha_s=0.47$ where material is close to packing limit.
Moreover, during conveying the lower the value of $\alpha_{s,off}$, the closer flyash powders to the packing limit of 0.47 are so that flyash powders will have more chance to have sustained contact. Thus, for dense flows with lower value of $\alpha_{s,off}$, the pressure drop of bypass pneumatic conveying with flyash increases accordingly.

![Fig 6.5 Frictional pressure with different $\alpha_{s,off}$ for flyash](image)

Case Flyash-20 is chosen for the investigation of $\alpha_{s,off}$ as it is dense flow with low air mass flow rate (0.0157kg/s) as well as high SLR (148.78). Moreover, the pressure drop prediction results with kinetic theory and conventional frictional-kinetic model for Flyash-20 are much lower than the experimental result as described in Chapter 4 and 5, and the relative error is about 72%.

CFD simulations were conducted by applying the kinetic theory combined with the modified frictional pressure equation (6-19), and adopting $Fr=0.05$, $n=2$ and $p=3$ as summarised in subchapter 6.1 and varying $\alpha_{s,off}$ for Flyash-20. It was found that only when $\alpha_{s,off} \geq 0.0009$ that the simulations converged. By applying different values of $\alpha_{s,off}$, the simulated pressure drops for the pipeline for Flyash 20 show no change, as shown in Fig 6.6. In fact, all the flyash results showed no change, which is as expected as the friction model appears to have no effect. For all converged cases always show no variation.
6.3.1.2 CFD flow description case studies of $\alpha_{s,off}$ for flyash

By applying modified frictional-kinetic model on simulation of Flyash-20, cases with $\alpha_{s,off}=0.0009$ and $\alpha_{s,off}=0.01$ are selected as two examples to show the effect of $\alpha_{s,off}$ on solid volume fraction distribution and pressure contours for dense flow.

For simulation with $\alpha_{s,off}=0.0009$, the solid volume fraction distribution for Flyash-20 on the longitudinal plane is shown in Fig 6.7. It has been found that the maximum solid volume fraction of flyash across the pipeline is much lower than the minimum packing limit 0.24.
Fig 6.7 Solid volume fraction distribution on the longitudinal plane for Flyash-20 with modified frictional-kinetic model ($m_a$=0.0157kg/s, $m_s$=2.3358kg/s, $\alpha_{s,off}$ =0.0009)

The pressure contours for Flyash-20 with $\alpha_{s,off}$=0.0009 at the longitudinal plane is shown in Fig 6.8. The absolute pressure contours on the longitudinal plane at different durations from $t$=0s to $t$=0.1s show a dilute phase behaviour of even pressure decay.

Fig 6.8 Pressure contours on the longitudinal plane for Flyash-20 with modified frictional-kinetic model ($m_a$=0.0157kg/s, $m_s$=2.3358kg/s, $\alpha_{s,off}$ =0.0009)

For simulation with $\alpha_{s,off}$=0.01, the solid volume fraction distribution for Flyash-20 at the longitudinal plane is shown in Fig 6.9. The maximum solid volume fraction of flyash across the pipeline is still found to be much lower than the minimum packing limit of 0.24. By increasing the value of $\alpha_{s,off}$ from 0.0009 to 0.01, solid volume
fraction distribution has no change, as expected. Thus, changing $\alpha_{s,off}$ from 0.0009 to 0.01 does not make frictional stress play an unimportant role on the simulation.

$t=0s$

$t=0.02s$

$t=0.04s$

$t=0.06s$

$t=0.08s$

$t=0.1s$

Fig 6.9 Solid volume fraction distribution on the longitudinal plane for Flyash-20 with modified frictional-kinetic model ($m_a=0.0157kg/s$, $m_s=2.3358kg/s$, $\alpha_{s,off}=0.01$)

For the sake of completeness, the simulation with $\alpha_{s,off}=0.01$, the pressure contours for Flyash-20 on the longitudinal plane is shown in Fig 6.10. The pressure contours have exactly same distribution and tendency as shown in Fig 6.8 from $t=0s$ to $t=0.1s$. There is no influence on pressure contours distribution by changing value of $\alpha_{s,off}$.

$t=0s$

$t=0.02s$

$t=0.04s$

$t=0.06s$

$t=0.08s$

$t=0.1s$

Fig 6.10 Pressure contours on the longitudinal plane for Flyash-20 with modified frictional-kinetic model ($m_a=0.0157kg/s$, $m_s=2.3358kg/s$, $\alpha_{s,off}=0.01$)
6.3.1.3 Summary for sensitivity analysis of $\alpha_{s,off}$ for flyash

$\alpha_{s,off}$ in equation (6-19) represents how $\alpha_s$ of flyash powders could be close to $\alpha_{s,max}$ while conveying. The lower $\alpha_{s,off}$ means the closer of $\alpha_s$ to $\alpha_{s,max}$. Nevertheless, by changing $\alpha_{s,off}$ from 0.0009 to 0.01, the solid volume fraction and pressure contours distribution for Flyash-20 are the same. This is because of the fact that the maximum $\alpha_s$ obtained from simulation is much lower than $\alpha_{s,min} = 0.24$. As such, the simulation case studies for flyash will not be repeated in this chapter. Only the sensitivity of the other modified frictional stress model parameters ($Fr$ and $n$) will be investigated for flyash.

6.3.2 Sensitivity analysis of $\alpha_{s,off}$ for alumina

The sensitivity analysis of $\alpha_{s,off}$ for alumina was conducted and the results are summarised. In addition, the CFD case study for Alumina-18 with different values of $\alpha_{s,off}$ is presented to show the influence of $\alpha_{s,off}$ on solid volume fraction and pressure.

6.3.2.1 Pressure drop prediction by varying $\alpha_{s,off}$ for alumina

By applying different values of $\alpha_{s,off}$ in equation (6-20), when $Fr=0.05$, $n=2$ and $p=3$, the relationship between frictional pressure and solid volume fraction is presented in Fig 6.11. In Fig 6.11, the frictional pressure again rises quickly when solid volume fraction increases from 0.21 to 0.215. However, the values of frictional pressure are still relatively low. Subsequently frictional pressure increases gradually until the solid volume fraction becomes 0.255. When solid volume fraction increases from 0.255 to packing limit 0.27, the frictional pressure rises much more quickly. Moreover, with the same solid volume fraction, as shown in Fig 6.11, the frictional pressure goes down with decrease of $\alpha_{s,off}$, especially for the range between $\alpha_s=0.255$ and $\alpha_s=0.27$ where material is close to packing limit.

Moreover, during conveying the lower the value of $\alpha_{s,off}$, the closer flyash powders to the packing limit of 0.27 are so that flyash powders will have more chance to have sustained contact. Thus, with lower value of $\alpha_{s,off}$, the pressure will become larger.
As the test case Alumina-18 represents a dense flow with low air mass flow rate (0.0157 kg/s) and high SLR (147.44), and the pressure drop prediction result with kinetic theory and conventional frictional-kinetic model are much lower than the experimental result as stated in Chapter 4 and 5, and the relative error is about 68%. Thus, case Alumina-18 study is chosen for investigation of $\alpha_{s,off}$.

By using modified frictional-kinetic model with equation (6-20), a group of simulations with different values of $\alpha_{s,off}$ for alumina were conducted, and the results are presented in Fig 6.12. The simulation results of full pipeline pressure drop are illustrated with $\alpha_{s,off} = 0.005$ to $\alpha_{s,off} = 0.01$, while cases with $\alpha_{s,off} = 0$ to $\alpha_{s,off} = 0.004$ are un-converged. As shown in Fig 6.12, the pressure drop decreases with the increase of $\alpha_s$. When $\alpha_{s,off} = 0.005$, the simulation pressure drop, which is about 15.65 kPa, is the closest to experimental result 17.16 kPa.
6.3.2.2 CFD flow description case studies of $\alpha_{s,\text{off}}$ for alumina

By applying modified frictional-kinetic model on simulation of Alumina-18, cases with $\alpha_{s,\text{off}}=0.005$ and $\alpha_{s,\text{off}}=0.01$ are selected as two examples to show how $\alpha_{s,\text{off}}$ influences solid volume fraction distribution and pressure contours for alumina.

Fig 6.13 shows the solid volume fraction distribution of fully developed flow at longitudinal plane for Alumina-18 with $\alpha_s=0.005$. There is a thick layer of material at the bottom of pipeline. There are also many slugs along the whole pipeline with air gaps in between. These slugs move forward due to the mechanisms associated with bypass pneumatic conveying, as previously described. That is to say, air is forced into bypass pipeline due to the existence of a full bore of material and then forced back to main pipeline with much higher velocity to disturb the slug. In this way, the material is continually aerated and moves forward accordingly. Meanwhile, there is also dynamic behaviour of the alumina slugs merging and separating. For instance, the air gap 1 between slug A and slug B becomes larger from $t=0s$ to $t=0.1s$, and slug B gradually moves forward. Meanwhile, the air gap 2 between slug B and C becomes smaller with the passage of time, and these two slugs tend to merge into a much longer slug. Furthermore, the air gaps of 3 and 4 at the second half of the pipeline are very large and there are not as many alumina slugs in this part. These simulations show the dynamic
behaviour of the flow within a bypass pneumatic conveying of alumina, as has been observed by high speed video.

![Image](image.png)

**Fig 6.13 Solid volume fraction distribution on the longitudinal plane for Alumina-18 with modified frictional-kinetic model ($m_a=0.0157\text{kg/s}$, $m_s=2.3147\text{kg/s}$, $\alpha_{s,off}=0.005$)**

The pressure contours distribution at longitudinal plane for Alumina-18 with $\alpha_{s,off}=0.005$ are shown in Fig 6.14, where the largest absolute pressure is shown at the pipeline inlet, and then gradually decreases to the lowest value at the outlet. For the pressure difference between inlet and outlet, it firstly decreases from $t=0s$ to $t=0.02s$, and then increases from $t=0.02s$ to $t=0.06s$. After that, the pressure difference declines from $t=0.06s$ to $t=0.1s$. 
Fig 6.14 Pressure contours on the longitudinal plane for Alumina-18 with modified frictional-kinetic model ($m_a=0.0157$ kg/s, $m_s=2.3147$ kg/s, $\alpha_{s,off}=0.005$).

Fig 6.15 shows the solid volume fraction distribution at longitudinal plane for Alumina-18 with $\alpha_{s,off}=0.01$. There is a long material dune formation at the first half part of pipeline and four slugs at the second half part of the pipeline. Compared with Fig 6.13, there is thinner material layer at the bottom of pipeline in Fig 6.15. According to equation (6-20) the highest solid volume fraction is less close to the modified alumina packing limit at lower values of $\alpha_{s,off}$; hence there are less chances for alumina powders to have sustained contact during conveying, as such a thinner material layer is present.
The pressure contours distribution at longitudinal plane for Alumina-18 with $\alpha_{s,\text{off}}=0.01$ are shown in Fig 6.16. The pressure difference between inlet and outlet firstly increases from $t=0s$ to $t=0.04s$, and then decreases from $t=0.04s$ to $t=0.1s$. Compared with Fig 6.14, Fig 6.16 shows less pressure difference between inlet and outlet in other words the chances for sustained contact are reduced. That is to say, the conveying causes less pressure drop across the pipeline.
6.3.2.3 Summary for sensitivity analysis of $\alpha_{s,off}$ for alumina

$\alpha_{s,off}$ in equation (6-20) represents how $\alpha_s$ of alumina powders could be close to $\alpha_{s,max}$ while conveying. With lower $\alpha_{s,off}$, $\alpha_s$ is closer to $\alpha_{s,max}$. By changing $\alpha_{s,off}$ from 0.005 to 0.01, the solid volume fraction and pressure contours distribution for Alumina-18 are quite different. When $\alpha_{s,off}=0.005$, there is thicker alumina layer at the bottom of pipeline compared with results obtained from $\alpha_{s,off}=0.01$. Furthermore, the pressure drop prediction results with $\alpha_{s,off}=0.005$ is much larger than results from $\alpha_{s,off}=0.01$. This is because with lower $\alpha_{s,off}$, more alumina powders accumulated at the bottom of pipeline where the sustained contact between particles become larger, and the pressure drop between inlet and outlet increases as a result. As the pressure drop prediction result obtained from $\alpha_{s,off}=0.005$ is close to the experiment result, it could be utilised in equation (6-20) to modify the frictional-kinetic model and conduct further sensitivity analysis of $Fr$, $n$ and $p$.

6.3.3 Sensitivity analysis of $\alpha_{s,off}$ for sand

The sensitivity analysis of $\alpha_{s,off}$ for sand is conducted. Different values of $\alpha_{s,off}$ are applied in the pressure drop prediction for bypass pneumatic conveying, and the pressure drop prediction results are summarised. Again, a CFD case study for Sand-6 with different values of $\alpha_{s,off}$ is presented to show the influence of $\alpha_{s,off}$ on solid volume fraction and pressure contours distributions.

6.3.3.1 Pressure drop prediction by varying $\alpha_{s,off}$ for sand

By using different values of $\alpha_{s,off}$ in equation (6-21), when $Fr=0.05$, $n=2$ and $p=3$, the relationship between frictional pressure and solid volume fraction is presented in Fig 6.17. In Fig 6.17, the frictional pressure seems to rise rapidly when solid volume fraction increases from 0.47 to 0.475. Then, the frictional pressure increases gradually until the solid volume fraction reaches 0.63. Moreover, at the same solid volume fraction, the frictional pressure increases with reducing value of $\alpha_{s,off}$, especially in the range of $\alpha_s=0.585$ to $\alpha_s=0.63$ where material concentration is close to packing limit.
Case Sand-6 is chosen for investigation of $\alpha_{s,off}$, since this case represents a dense flow with a low air mass flow rate (0.0317kg/s) and high SLR (82.49). Additionally, this case only gets converged by applying conventional frictional-kinetic model in which the pressure drop is under-predicted. By using the modified frictional-kinetic model with equation (6-21), a series of simulations with different values of $\alpha_{s,off}$ for sand were conducted, and the results are shown in Fig 6.18.

In Fig 6.18, the simulation results of pressure drop across the bypass pipeline were presented with $\alpha_{s,off}=0.05$ to $\alpha_{s,off}=0.09$. Cases with $\alpha_{s,off}=0$ to $\alpha_{s,off}=0.04$ were un-converged. As shown in Fig 6.18, the pressure drop almost maintained its level as $\alpha_{s,off}$ increases from 0.05 to 0.06. Then pressure drop goes down gradually when $\alpha_{s,off}$ rises from 0.06 to 0.09. The simulation pressure drop was the highest when $\alpha_{s,off}=0.05$. 

**Fig 6.17 Frictional pressure with different $\alpha_{s,off}$ for sand**
Fig 6.18 Simulation pressure drop with different $\alpha_{s,\text{off}}$ for sand

6.3.3.2 CFD flow description case studies of $\alpha_{s,\text{off}}$ for sand

By applying modified frictional-kinetic model on simulation of Sand-6, cases with $\alpha_{s,\text{off}} = 0.05$ and $\alpha_{s,\text{off}} = 0.09$ are selected as two examples to show how $\alpha_{s,\text{off}}$ influences solid volume fraction and pressure contour distributions.

Fig 6.19 shows the solid volume fraction distribution in the longitudinal plane for Sand-6 with $\alpha_s = 0.05$. There is a thick layer of sand at the bottom of pipeline. It is obvious that material forms a dune like structure rather than a slug structure that was seen in the case of alumina. These dunes move forward with the passage of time due to the aeration mechanism of bypass pneumatic conveying. For example, the moving distance for dune 2 from $t=0s$ to $t=0.1s$ is about 300mm. In the mean time, air gap 1 becomes much larger with the passage of time, as the material dune 1 almost stays at the same place and there is not enough energy for the air to move this dune, however the dune shows separation during this time period. In addition, the sand layer between dune 1 and 2 becomes thinner within the same time period. Moreover, some dunes merge and some air gaps vary in size by time. For instance, the air gap 2 gradually becomes smaller from $t=0s$ to $t=0.1s$, and dune 3 and 4 gradually merge into a single dune with a longer length.
Fig 6.19 Solid volume fraction distribution on the longitudinal plane for Sand-6 with modified frictional-kinetic model ($m_a=0.0317\text{kg/s}$, $m_s=2.6149\text{kg/s}$, $\alpha_{s,off}=0.05$)

The pressure contour distributions at longitudinal plane for Sand-6 with $\alpha_{s,off}=0.05$ are shown in Fig 6.20, where the largest absolute pressure is shown at the pipeline inlet, and then gradually decreases to the lowest value at the outlet. The pressure drop between pipeline inlet and outlet decreases from $t=0\text{s}$ to $t=0.1\text{s}$.

Fig 6.20 Pressure contours on the longitudinal plane for Sand-6 with modified frictional-kinetic model ($m_a=0.0317\text{kg/s}$, $m_s=2.6149\text{kg/s}$, $\alpha_{s,off}=0.05$)

Fig 6.21 shows the solid volume fraction distribution at longitudinal plane for Sand-6 with $\alpha_{s,off}=0.09$. Compared with Fig 6.19, there are sand dunes with longer length, such as dune 1, and there is thinner sand layer 1 at the bottom of pipeline. Moreover,
dune 1 and dune 2 moves forward at the same time, while the air gap 1 between these two sand dunes keeps almost the same length.

**Fig 6.21 Solid volume fraction distribution on the longitudinal plane for Sand-6 with modified frictional-kinetic model ($m_a=0.0317\text{kg/s}$, $m_s=2.6149\text{kg/s}$, $\alpha_{s,\text{off}}=0.09$)**

The pressure contours distribution at longitudinal plane for Sand-6 with $\alpha_{s,\text{off}}=0.09$ are shown in Fig 6.22. Compared with Fig 6.20, Fig 6.22 shows lower pressure difference between inlet and outlet. With larger $\alpha_{s,\text{off}}=0.09$, material cannot pack up as close as $\alpha_{s,\text{off}}=0.05$, and less sand material particles can have sustained contact. So lower pressure drops are obtained accordingly.

**Fig 6.22 Pressure contours on the longitudinal plane for Sand-6 with modified frictional-kinetic model ($m_a=0.0317\text{kg/s}$, $m_s=2.6149\text{kg/s}$, $\alpha_{s,\text{off}}=0.09$)**
6.3.3.3 Summary for sensitivity analysis of $\alpha_{s,off}$ for sand

How $\alpha_s$ of sand powders could be close to $\alpha_{s,\text{max}}$ while conveying depends on the value of $\alpha_{s,off}$ in equation (6-21). When $\alpha_{s,off}$ is lower, $\alpha_s$ is closer to $\alpha_{s,\text{max}}$. Different solid volume fraction and pressure contours distribution for Sand-6 are shown by changing $\alpha_{s,off}$ from 0.05 to 0.09. Compared with results obtained from $\alpha_{s,off}=0.1$, there is thicker sand layer at the bottom of pipeline for $\alpha_{s,off}=0.05$. Moreover, in simulation with $\alpha_{s,off}=0.05$, the pressure drop across the pipeline in the simulation is much larger than the results from $\alpha_{s,off}=0.09$, as more sand powders settle down at the bottom of pipeline with lower $\alpha_{s,off}$.

The modified packing limit obtained from tapped bulk density for sand powders is equal to the original material packing limit 0.63. In addition, sand is the type of material only suitable to be conveyed in dilute phase. That is to say, during conveying for dense flows, most of the sand powders closely pack together at the bottom of pipeline where $\alpha_s=0.63$, and the sand powders are not aerated and are in non-aerated consolidated state. However, with applying $\alpha_{s,off}=0$, the simulation for sand is un-converged, as the frictional pressure tends to infinite with equation (6-21). The minimum available $\alpha_{s,off}$ for the simulations to obtain convergence is 0.05. Although the pressure drop is considerably under-predicted, $\alpha_{s,off}=0.05$ is still chosen to conduct the sensitivity analysis of $Fr$, $n$ and $p$ with equation (6-21).

6.4 Analysis of Fr for modified frictional models

The constant $Fr$ is a very important parameter to the Johnson-Jackson frictional pressure model, and the most common empirical values of $Fr$ adopted by other researchers are summarised in table 6.1. However, the Johnson-Jackson frictional pressure model has been modified into equation (6-19) to (6-21) based on the actual gas-solid flow behaviour in pneumatic conveying. Thus, further investigation of $Fr$ for the modified frictional pressure model is going to be conducted in this subchapter.

6.4.1 Sensitivity analysis of Fr for flyash

As the CFD simulations for flyash do not exhibit dense phase conveying, the sensitivity analysis is still conducted for the Johnson and Jackson modified model. Different values
of $Fr$ are applied in the pressure drop prediction for bypass pneumatic conveying, and the results are summarised.

For flyash, the original value for $Fr$ used in Johnson and Jackson model [2, 3] is 0.05. Investigation of $Fr$ in equation (6-19) are conducted and $Fr$ varied from 0.01 to 0.5, while using $n=2$, $p=3$ and $\alpha_{s,off}=0.0009$. It can be observed from Fig 6.23 that when $0.24 \leq \alpha_s \leq 0.245$, the frictional pressure maintains with low values. By increasing $\alpha_s$ from 0.245 to 0.458, the frictional pressure gradually rises up. When $\alpha_s$ increases from 0.458 to 0.47, there is a large increase in frictional pressure. Moreover, for the same value of $\alpha_s$, frictional pressure climbs up gradually with the increase in $Fr$ from 0.01 to 0.5. This finding again shows that the frictional pressure increases as solids concentration increases, culminating at a maximum solids concentration which strongly retards the flow.

![Image of Fig 6.23 Frictional pressure with different $Fr$ for flyash](image_url)

Fig 6.23 Frictional pressure with different $Fr$ for flyash

### 6.4.2 $Fr$ for alumina

The sensitivity analysis of $Fr$ for alumina is conducted as follows. Different values of $Fr$ are applied in the pressure drop prediction for alumina in bypass pneumatic conveying, and the results are summarised. In addition, the CFD case study for Alumina-18 with different values of $Fr$ is presented to show the influence of $Fr$ on solid volume fraction and pressure contour distributions in bypass pneumatic conveying.
6.4.2.1 Pressure drop prediction by varying $Fr$ for alumina

For alumina, investigation of $Fr$ in equation (6-20) were conducted and $Fr$ varied from 0.01 to 0.5, while adopting $n=2$, $p=3$ and $\alpha_{S,off}=0.005$, as showed in Fig 6.24. When $0.21 \leq \alpha_s \leq 0.215$, the frictional pressure maintains low values. By increasing $\alpha_s$ from 0.215 to 0.27, the frictional pressure rises up slowly. For the same value of $\alpha_s$, frictional pressure goes up gradually with the increasing of $Fr$ from 0.01 to 0.13.

![Frictional pressure with different Fr for alumina](image)

**Fig 6.24 Frictional pressure with different Fr for alumina**

By adopting some different values of $Fr$ and applying equation (6-20) in the simulation, the pressure drops were predicted and the results are shown in Fig 6.25. Simulation cases are un-converged when $Fr > 0.05$. For those converged cases, the pressure drop of bypass pneumatic conveying increases with the increase of $Fr$. At $Fr=0.05$, the pressure drop prediction result is about 15.65kPa, which is closest to the experimental result 17.16kPa.
6.4.2.2 CFD flow description case studies of \( Fr \) for alumina

The solid volume fraction and absolute pressure contour distributions for \( Fr=0.05 \) are exactly the same as shown in Fig 6.13 and 6.14. Thus, the simulation results for Alumina-18 with \( Fr=0.01 \) are only shown here.

Fig 6.26 shows the solid volume fraction distribution flow in the longitudinal plane for Alumina-18 when \( \alpha_{s,off}=0.01 \). Fig 6.26 shows continuous thinner alumina layer at the bottom of pipeline compared with Fig 6.13. For example, slug 1 moves forward for a distance “L” within 0.1s. Moreover, air gaps vary with time as well: gap 1 slowly becomes larger from \( t=0 \)s to \( t=0.1 \)s; air gap 1, 2 and 3 merges into a large air gap “A” within 0.1s.

![Fig 6.25 Simulation pressure drop with different Fr for alumina](image-url)
The pressure contours distribution at longitudinal plane for Alumina-18 with \( Fr=0.01 \) are shown in Fig 6.27, where the largest absolute pressure is shown at the pipeline inlet, and then gradually decreases to the lowest value at the outlet. For the pressure difference between inlet and outlet, it gradually decreases from \( t=0s \) to \( t=0.1s \).

Fig 6.26 Solid volume fraction distribution on the longitudinal plane for Alumina-18 with modified frictional-kinetic model \( (m_a=0.0157\text{kg/s}, m_s=2.3147\text{kg/s}, \alpha_{s,off}=0.005, Fr=0.01) \)

Fig 6.27 Pressure contours on the longitudinal plane for Alumina-18 with modified frictional-kinetic model \( (m_a=0.0157\text{kg/s}, m_s=2.3147\text{kg/s}, \alpha_{s,off}=0.005, Fr=0.01) \)
6.4.2.3 Summary for sensitivity analysis of $Fr$ for alumina

By changing $Fr$ from 0.01 to 0.05, the solid volume fraction and pressure contours distribution for Alumina-18 are shown. When $Fr=0.05$, there is a thicker alumina layer at the bottom of pipeline compared with results obtained for $Fr=0.01$. Furthermore, the pressure drop across the pipeline in simulation with $Fr=0.05$ is much larger compared to the results for $Fr=0.01$. It is seen that the pressure drop prediction results for $Fr=0.05$ is about 15.65kPa, which is much closer to the experimental result of 17.16kPa compared to Fr=0.01. As such, a value of $Fr=0.05$ is chosen for further investigation of $n$ and $p$.

6.4.3 $Fr$ for sand

The sensitivity analysis of $Fr$ for sand is conducted. Different values of $Fr$ are applied in the pressure drop prediction. The CFD case study for Sand-6 with different values of $Fr$ is presented to show the influence of $Fr$ on solid volume fraction and pressure contours distributions.

6.4.3.1 Pressure drop prediction by varying $Fr$ for sand

For sand, investigation of $Fr$ in equation (6-21) were conducted and $Fr$ varied from 0.01 to 0.5, while adopting $n=2$, $p=3$ and $\alpha_{s,off}=0.05$, as showed in Fig 6.28. When $0.47 \leq \alpha_s \leq 0.475$, the frictional pressure maintains low values. By increasing $\alpha_s$ from 0.475 to 0.63, the frictional pressure gradually increases. For the same value of $\alpha_s$, frictional pressure goes up gradually with the increasing of $Fr$ from 0.01 to 0.25.
By adopting different values of $Fr$ and applying equation (6-21) in the simulation, the pressure drop prediction results for sand are shown in Fig 6.29. Simulation cases could only obtain convergence when $Fr \leq 0.05$. The results show that the full pipeline pressure drop rises with an increase in $Fr$. With $Fr = 0.05$, the pressure drop prediction result is about 27.7kPa. Although simulation with $Fr = 0.05$ still under-predicts the pressure drop, it provides a much better result than cases with other values of $Fr$. 
6.4.3.2 CFD flow description case studies of $Fr$ for sand

Fig 6.30 shows the solid volume fraction distribution along the longitudinal plane for Sand-6 with $Fr=0.01$. The solid volume fraction distribution for Sand-6 with $Fr=0.05$ has already been shown in Fig 6.19. Compared with Fig 6.19, Fig 6.30 shows continuous thinner layer at the bottom of pipeline.

![Solid volume fraction distribution](image)

Fig 6.30 Solid volume fraction distribution on the longitudinal plane for Sand-6 with modified frictional-kinetic model ($m_a=0.0317\text{kg/s}$, $m_s=2.6149\text{kg/s}$, $\alpha_{s,\text{off}}=0.05$, $Fr=0.01$)

Fig 6.31 shows the pressure contours distribution for Sand-6 with $Fr=0.01$, while the pressure contours distribution for Sand-6 with $Fr=0.05$ has already been shown in Fig 6.20. Compared with Fig 6.20, a lower pressure drop is shown in Fig 6.31. When $Fr=0.05$, the pressure drop prediction result $\Delta P=27.70\text{kPa}$, which is still under-predicted pressure drop across the bypass pipeline.
Fig 6.31 Pressure contours on the longitudinal plane for Sand-6 with modified frictional-kinetic model \((m_a=0.0317\text{kg/s}, m_s=2.6149\text{kg/s}, \alpha_{s,off}=0.05, Fr=0.01)\)

### 6.4.3.3 Summary for sensitivity analysis of \(Fr\) for sand

The solid volume fraction and pressure contours distribution for Sand-6 are shown with respect to time for \(Fr\) 0.01 and 0.05. There is a thicker sand layer at the bottom of pipeline when \(Fr=0.05\) compared to the case \(Fr=0.01\). In addition, the pressure drop across the pipeline in simulation for \(Fr=0.05\) is much larger than the results obtained for \(Fr=0.01\). The pressure drop predicted for \(Fr=0.05\) is about 27.70kPa, which is the closest one to the experimental finding of 84.04kPa. Although simulation cases for \(Fr=0.05\) significantly under-predicts the pressure drop, \(Fr=0.05\) is chosen for further investigation of \(n\) and \(p\).

### 6.5 Analysis of \(n\) for modified frictional models

The most common empirical value of \(n\) adopted by other researchers in the Johnson-Jackson frictional pressure model are summarised in table 6.1. However, the Johnson-Jackson frictional pressure model has been modified into equation (6-19) to (6-21) for different types of material, further investigation of \(n\) needs to be conducted in this subchapter.

#### 6.5.1 \(n\) for flyash

Only one sensitivity analysis of \(n\) for flyash is conducted as the CFD in its current form does not seem to be suitable for the simulation of dense phase solids concentrations for
flyash. Different values of $n$ are applied in the pressure drop prediction for bypass pneumatic conveying, and the results are summarised.

For flyash, The original value for $n$ that is 2 was used in Johnson and Jackson model [2, 3] equals 2. Investigation of $n$ in equation (6-19) is conducted and $n$ varied from 1.4 to 2.5. Since in the above investigation $Fr$ has no influence on pressure drop prediction for flyash, $Fr=0.05$ is adopted here to study the effect of $n$ on frictional pressure drop prediction, while $p=3$ and $\alpha_{s,off}=0.0009$. Similar to the previous examples, in the range $0.24 \leq \alpha_s \leq 0.245$ the frictional pressure shows a quick increase as it is seen in Fig 6.32 reflecting the commencement of sustained contacts occurring in the flow. When $\alpha_s$ increases from 0.245 to 0.458, the frictional pressure gradually rises up suggesting that sustained contacts dominate. When $\alpha_s$ increases from 0.458 to 0.47, there is a great increase in frictional pressure which reflects an incipient blockage type resistance at this concentration. Moreover, for the same value of $\alpha_s$, frictional pressure climbs up gradually with the increasing of $n$ from 1.4 to 2.5.

![Graph showing frictional pressure with different $n$ for flyash](image)

**Fig 6.32 Frictional pressure with different $n$ for flyash**

6.5.2 $n$ for alumina

The sensitivity analysis of $n$ for alumina is conducted as follows. Different values of $n$ are applied in the pressure drop prediction for alumina in bypass pneumatic conveying,
and the results are summarised together. Plus, CFD case study for Alumina-18 with different values of $n$ is presented to show the influence of $n$ on solid volume fraction and pressure contours distributions in bypass pneumatic conveying.

### 6.5.2.1 Pressure drop prediction by varying $n$ for alumina

As shown Fig 6.33, when $Fr=0.05$, $p=3$ and $\alpha_{s,off}=0.005$, by increasing the solids volume fraction from 0.21 to 0.215 in equation (6-20), the frictional pressure increases quickly. Then frictional pressure climbs up gradually when solids volume fraction increase from 0.215 to 0.27. For the same volume fraction, by varying the value of $n$ from 2.5 to 1.4, the frictional pressure increases accordingly within the volume fraction range of 0.21 to 0.27.

![Frictional pressure with different $n$ for alumina](image)

**Fig 6.33 Frictional pressure with different $n$ for alumina**

Pressure drop prediction of bypass pneumatic conveying with different $n$ value in equation (6-20) for alumina is conducted. By changing $n$ from 2.5 to 1.4, a series of pressure drop prediction result are obtained, as shown in Fig 6.34. It is found that simulation cases are un-converged when $n<2$. By decreasing $n$, the pressure drop in bypass pneumatic conveying system for alumina goes up gradually. When $n=2$, the pressure drop prediction result for alumina is the largest, which is very close to the experimental result.
6.5.2.2 CFD flow description case studies of $n$ for alumina

Fig 6.35 shows the solid volume fraction distribution of fully developed flow at longitudinal plane for Alumina-18 with $n=2.5$. The solid volume fraction of Alumina-18 with $n=2$ has already been shown in Fig 6.13. Generally, a comparison between these two figures shows that there is thinner layer at the bottom of pipeline in Fig 6.35 compared with Fig 6.13. Otherwise, similar transient dense phase slug like flow is observed.
Fig 6.35 Solid volume fraction distribution on the longitudinal plane for Alumina-18 with modified frictional-kinetic model ($m_\alpha=0.0157\text{kg/s}$, $m_s=2.3147\text{kg/s}$, $\alpha_{s,off}=0.005$, $n=2.5$)

Fig 6.36 shows the pressure contours at longitudinal plane for Alumina-18 with $n=2.5$, while the pressure contours of Alumina-18 with $n=2$ has already been shown in Fig 6.14. When $n$ is larger, the frictional pressure is lower. Thus, less pressure drop is shown in Fig 6.36 compared with Fig 6.14. Moreover, for the pressure difference between inlet and outlet, Fig 6.36 shows gradual decrease from $t=0s$ to $t=0.1s$.

Fig 6.36 Pressure contours on the longitudinal plane for Alumina-18 with modified frictional-kinetic model ($m_\alpha=0.0157\text{kg/s}$, $m_s=2.3147\text{kg/s}$, $\alpha_{s,off}=0.005$, $n=2.5$)
6.5.2.3 Summary for sensitivity analysis of \( n \) for alumina

By changing \( n \) from 2 to 2.5, the solid volume fraction and pressure contours distribution for Alumina-18 are shown. When \( n=2 \), there is thicker alumina layer at the bottom of pipeline compared with results obtained from \( n=2.5 \). In addition, the pressure drop across the pipeline in the simulation with \( n=2 \) is much larger than results from \( n=2.5 \). Compared with results from applying \( n=2.5 \), the pressure drop prediction results with \( n=2 \) is much closer to the test measurement. Thus, \( n=2 \) is chosen for further investigation of \( p \).

6.5.3 \( n \) for sand

The sensitivity analysis of \( n \) for sand is conducted. Different values of \( n \) are applied in the pressure drop prediction for bypass pneumatic conveying, and the pressure drop prediction results are summarised. The CFD case study for Sand-6 with different values of \( n \) is presented to show the influence of \( n \) on solid volume fraction and pressure contours distributions for sand in bypass pneumatic conveying.

6.5.3.1 Pressure drop prediction by varying \( n \) for sand

As shown Fig 6.37, \( Fr=0.05 \), \( p=3 \) and \( \alpha_{s,off}=0.05 \), by increasing the solids volume fraction from 0.47 to 0.485 in equation (6-21), the frictional pressure increases sharply. Then frictional pressure increases gradually when solids volume fraction increase from 0.485 to 0.63. For the same volume fraction, by varying the value of \( n \) from 1.4 to 2.5, the frictional pressure decreases accordingly.
Pressure drop prediction of bypass pneumatic conveying with different $n$ values in equation (6-21) for sand is conducted. By changing $n$ from 1.4 to 2.5, a series of predictive result are obtained for pressure, as shown in Fig 6.38. Again, it was found that only when $n \geq 2.0$, simulation cases get converged. By increasing $n$, the pressure drop of bypass pneumatic conveying for sand goes down gradually. When $n$ is 2.0, the pressure drop prediction result for sand is the largest.
6.5.3.2 CFD flow description case studies of $n$ for sand

Fig 6.39 shows the solid volume fraction distribution on longitudinal plane for Sand-6 with $n=2.5$, while the solid volume fraction of Sand-6 with $n=2.0$ has already been shown in Fig 6.19. Compared with Fig 6.19, Fig 6.39 shows thinner layer at the bottom of pipeline. Otherwise, the transient dune type flow is still observed.

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**Fig 6.39 Solid volume fraction distribution on the longitudinal plane for Sand-6 with modified frictional-kinetic model ($m_a=0.0317\text{kg/s}, m_s=2.6149\text{kg/s}, \alpha_{s,off}=0.05, n=2.5$)**

Fig 6.40 shows the pressure contours in the longitudinal plane for Sand-6 with $n=2.5$, while the pressure contours of Sand-6 with $n=2$ has already been shown in Fig 6.20. It is clear that when $n$ is larger, the frictional pressure is lower. Thus, lower pressure drop is shown in Fig 6.40.
6.5.3.3 Summary for sensitive analysis of $n$ for sand

The solid volume fraction and pressure contours distribution for Sand-6 are shown by changing $n$ from 2.0 to 2.5. Compared with results obtained from $n=2.5$, there is a thicker sand layer at the bottom of pipeline when $n=2.0$. In addition, the pressure drop across the pipeline in simulation with $n=2.0$ is much larger than results from $n=2.5$. Compared with results from applying $n=2.5$, the pressure drop prediction results with $n=2.0$ is about 27.70kPa, which is the closest estimation to the experimental result of 84.04kPa. Although simulation cases with $n=2.0$ under-predicts the pressure drop, $n=2.0$ is still be chosen for further investigation of $p$.

6.6 Analysis of $p$ for modified frictional models

The most common empirical value of $p$ adopted by other researchers in the Johnson-Jackson frictional pressure model are summarised in table 6.1. However, the Johnson-Jackson frictional pressure model has been modified into equation (6-19) to (6-21) for different types of material, further investigation of $p$ needs to be conducted in this subchapter.

6.6.1 $p$ for flyash

As was the case for the other Johnson-Jackson model parameters, only one sensitive analysis of $p$ is conducted for flyash. Different values of $p$ are applied in the pressure drop prediction for bypass pneumatic conveying, and the results are summarised.
For flyash, the original value for $p$ used in Johnson and Jackson model [2, 3] is 5. Investigation of $p$ in equation (6-19) is conducted and $p$ varied from 2.80 to 3.20. Since in the above investigation, $\alpha_{s,off}$, $Fr$ and $n$ has no influence on pressure drop prediction for flyash, $\alpha_{s,off} = 0.0009$, $Fr=0.05$ and $n = 2$ are used here to conduct the study of $p$ on pressure drop prediction. Fig 6.41 is obtained from equation (6-19). As shown in Fig 6.41, the pressure behaviour is generally the same with an initial increase, steady increase and a final steep increase in frictional pressure for an increase in solids friction. For the parameter $p$, the frictional pressure generally increases with increasing value of $p$ from 2.80 to 3.20.

![Frictional pressure with different $p$ for flyash](image)

**6.6.2 $p$ for alumina**

The sensitivity analysis of $p$ for alumina is conducted as follows. Different values of $p$ are applied in the pressure drop prediction for alumina in bypass pneumatic conveying, and the results are summarised together. Plus, CFD case study for Alumina-18 with different values of $p$ is presented to show the influence of $p$ on solid volume fraction and pressure contours distributions for alumina in bypass pneumatic conveying.
6.6.2.1 Pressure drop prediction by varying $p$ for alumina

As shown Fig 6.42, when $a_{s,off}=0.005$, $Fr=0.05$ and $n=2$, by increasing the solids volume fraction from 0.21 to 0.215 initial fast increase in pressure occurs followed by a sustained gradual increase in pressure. Unlike the flyash, there is no sudden increase in frictional resistance close to the highest solids concentration. Generally, as $p$ increases from 2.80 to 3.20, the frictional pressure increases.

![Frictional pressure with different $p$ for alumina](image)

**Fig 6.42 Frictional pressure with different $p$ for alumina**

Pressure drop prediction of bypass pneumatic conveying with different $p$ values in equation (6-20) for alumina was conducted. By changing $p$ from 2.80 to 3.20, a series of prediction result were obtained, as shown in Fig 6.43. It was found when $p > 3.05$, simulation cases were un-converged. By increasing value of $p$, the pressure drop of bypass pneumatic conveying for alumina climed up, as shown in Fig 6.43. When $p$ is 3.05, the pressure drop prediction result for alumina is the largest which is closest to the experimental result.
6.6.2.2 CFD flow description case studies of $p$ for alumina

Fig 6.44 shows the solid volume fraction distribution in the longitudinal plane for Alumina-18 with $p=2.80$. The solid volume fraction of Alumina-18 with $\alpha_{s,off} =0.0009$, $Fr =0.05$, $n=2$ and $p=3$ has already been shown in Fig 6.13. Compared with Fig 6.13, there are less discrete plugs in motion and that the pipeline appears to be blocked at the start in Fig 6.44.

![Pressure drop graph](image)

**Fig 6.43 Simulation of pressure drop with different $p$ for alumina**

![Solid volume fraction distribution](image)

**Fig 6.44 Solid volume fraction distribution on the longitudinal plane for Alumina-18 with modified frictional-kinetic model ($m_a=0.0157$kg/s, $m_s=2.3147$kg/s, $\alpha_{s,off} =0.0009$, $p=2.80$)**
Fig 6.45 shows the pressure contours in the longitudinal plane for Alumina-18 with $p=2.80$, while the pressure contours for Alumina-18 with $p=3$ has already been shown in Fig 6.14. It has been found that when $p$ is smaller, the frictional pressure decreases. Thus, lower pressure drop is shown in Fig 6.45 compared with Fig 6.14.

$\begin{array}{c}
t=0s \\
t=0.02s \\
t=0.04s \\
t=0.06s \\
t=0.08s \\
t=0.1s \\
\end{array}$

Fig 6.45 Pressure contours on the longitudinal plane for Alumina-18 with modified frictional-kinetic model ($m_a=0.0157\text{kg/s}, m_s=2.3147\text{kg/s}, \alpha_{s,off}=0.0009, p=2.80$)

Fig 6.46 shows the solid volume fraction distribution at longitudinal plane for Alumina-18 with $p=3.05$. Compared with Fig 6.44 where $p=2.80$ and $t=0.1s$, air gap gradually becomes larger, air gap 2 slowly disappears. In the same time period, slug 1 and slug 2 mixes into one slug, and slug 3 turns into full bore material dune. This shows that when $p=3$ or 3.05, the simulation shows dynamic slug movement representative of the transient flow seen in the high speed video images when conveying alumina.
Fig 6.46 Solid volume fraction distribution on the longitudinal plane for Alumina-18 with modified frictional-kinetic model ($m_a=0.0157$ kg/s, $m_s=2.3147$ kg/s, $\alpha_{s,off} =0.0009$, $p=3.05$)

In Fig 6.47, at first the pressure difference between inlet and outlet increases from $t=0$ s to $t=0.06$ s, and then decreases from $t=0.06$ s to $t=0.1$ s. Compared with Fig 6.44 when $p=2.8$ and Fig 6.14 when $p=3$, the pressure drop in Fig 6.47 where $p=3.05$ is much larger.

Fig 6.47 Pressure contours on the longitudinal plane Alumina-18 with modified frictional-kinetic model ($m_a=0.0157$ kg/s, $m_s=2.3147$ kg/s, $\alpha_{s,off} =0.0009$, $p =3.05$)
6.6.2.3 Summary for sensitive analysis for $p$ with alumina

By changing $p$ from 2.80 to 3.05, the solid volume fraction and pressure contour distributions for Alumina-18 are shown. The pressure drop across the pipeline in simulation with $p=3.05$ is much larger than results from $p=2.80$ and $p=3$. Compared with results from applying $p=2.8$ and $p=3$, the pressure drop prediction results with $p=3.05$ is much closer to the experimental result, with the alumina still exhibiting the expected transient flow behaviour. Thus, $p=3.05$ is chosen for equation (6-20).

6.6.3 $p$ for sand

The sensitivity analysis of $p$ for sand is conducted. Different values of $p$ are applied in the pressure drop prediction for bypass pneumatic conveying, and the pressure drop prediction results are described. The CFD case study for Sand-6 with different values of $p$ is presented to show the influence of $p$ on solid volume fraction and pressure contours distributions.

6.6.3.1 Pressure drop prediction by varying $p$ for sand

$\alpha_{s,off} = 0.05$, $Fr=0.05$ and $n=2$ are used here for sensitivity analysis of $p$ in equation (6-21). As shown in Fig 6.48, the behaviour of pressure increase is the same as seen for the alumina with an initial fast increase in pressure followed by a gradual increase as solids volume concentrations increase. Again, as $p$ increases, frictional pressure increases across most of the range of $\alpha_s$ used for the analysis.
The pressure drop prediction of bypass pneumatic conveying with different $p$ values in equation (6-21) for sand was conducted. By changing $p$ from 2.85 to 3.20, a series of prediction result were obtained. It was found only when $p \leq 3.0$ that the simulations obtained convergence. Thus, the results are summarised in Fig 6.49. By decreasing value of $p$, the pressure drop for sand in bypass pneumatic conveying decreases gradually.

![Graph showing pressure drop vs. $p$]

**Fig 6.49 Simulation of pressure drop for different values of $p$ for sand**

### 6.6.3.2 CFD flow description case studies of $p$ for sand

Fig 6.50 shows the solid volume fraction distribution when $p=2.85$. The solids volume distribution when $p=3$ has already been presented in Fig 6.19. Compared with Fig 6.19, Fig 6.50 generally shows a slightly thinner layer at the bottom of pipeline. Material dune 1 almost maintains at the same place within 0.1s, while material dune 2 to dune 7 gradually move forward with the passage of time. It is obvious that dune 3 becomes smaller from $t=0$s to $t=0.1$s, as part of the sand powders in dune 3 slowly migrate towards air gap 1. Within the same time period, air gap 2 becomes much shorter, as material dune 4 and 5 gradually merge into one sand dune which is much longer.
Fig 6.50 Solid volume fraction distribution on the longitudinal plane for Sand-6 with modified frictional-kinetic model \( (m_a=0.0317\, \text{kg/s}, \, m_s=2.6149\, \text{kg/s}, \, \alpha_{s,off} = 0.05, \, p=2.85) \)

Fig 6.51 shows the pressure contour for sand-6 when \( p=2.85 \). Compared with Fig 6.20 where \( p=3 \), the pressure drop between pipeline inlet and outlet in Fig 6.51 for Sand-6 is much larger.

Fig 6.51 Pressure contours on the longitudinal plane for Sand-6 with modified frictional-kinetic model \( (m_a=0.0317\, \text{kg/s}, \, m_s=2.6149\, \text{kg/s}, \, \alpha_{s,off} = 0.05, \, p=2.85) \)
6.6.3.3 Summary of sensitivity analysis of \( p \) for sand

The solid volume fraction and pressure contours distribution for Sand-6 are shown by changing \( p \) from 2.85 to 3. Compared with results obtained from \( p=3 \), there is thinner sand powders layer at the bottom of pipeline when \( p=2.85 \). Moreover, the pressure drop across the pipeline in the simulation with \( p=3 \) is much larger than results from \( p=2.85 \). Compared with results from applying \( p=2.85 \), the pressure drop prediction results with \( p=3 \) is about 27.70kPa, which is the closest to the experimental result of 84.04kPa, however, still significantly under predicting pressure.

6.6 Summary of sensitivity analysis of modified frictional-kinetic model

After conducting the sensitivity analysis above, the most suitable choices of \( \alpha_{s,off}, Fr, n \) and \( p \) in modified frictional-kinetic model for pressure drop prediction of flyash, alumina and sand in bypass pneumatic conveying are summarised in table 6.3.

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<th>Alumina</th>
<th>Sand</th>
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<tr>
<td>( p )</td>
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Table 6.3 \( \alpha_{s,off}, Fr, n \) and \( p \) for different materials

For flyash, there is no significant influence on pressure drop prediction for all the case studies as the solids 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 \( \alpha_{s,off} \geq 0.005 \) for Alumina-18. 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. Particularly, it was found that when \( Fr=0.05 \), \( n=3 \) and \( p=2 \), the pressure drop prediction result 17.75kPa for Alumina-18 is the closest to the experimental result 17.16kPa.
For sand, simulation gets converged only when $\alpha_{s,off} \geq 0.05$ for Sand-6. With the decrease of $\alpha_{s,off}$, increase of $Fr$, decrease of $n$ and increase of $p$, the pressure drop across the pipeline climbs up and the sand powders layer at the bottom of pipeline is much thicker. However, the pressure drops across the pipeline are always underpredicted no matter how much $\alpha_{s,off}$, $Fr$, $n$ and $p$ vary. All the convergence conditions for pressure drop prediction by applying modified frictional-kinetic model with different values of $\alpha_{s,off}$, $Fr$, $n$ and $p$ are summarized in tale 6.4. As such, a guidance for choosing appropriate constants in modified frictional-kinetic model to obtain simulation convergence is provided.

### Table 6.4 Convergence for modified frictional-kinetic model with different values of $\alpha_{s,off}$, $Fr$, $n$ and $p$

<table>
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<th>Alumina</th>
<th>Sand</th>
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</table>

### 6.7 Pressure drop prediction with modified frictional-kinetic model

The pressure drop prediction for alumina and sand is conducted by applying modified frictional-kinetic model with modified critical value of solids 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 Chapter 6, table 6.3. Thus, the modified frictional pressure equation can be written as equation (6-25) to (6-27), and modified radial distribution functions can be written as equation (6-28) to (6-30).
Flyash:  
\[ P_{friction} = \begin{cases} 
0.05 \frac{(\alpha - 0.24)^2}{(0.47 + 0.0009 - \alpha)^3} & \text{if } \alpha > 0.24 \\
0 & \text{if } \alpha \leq 0.47
\end{cases} \]  
(6-25)

Alumina:  
\[ P_{friction} = \begin{cases} 
0.05 \frac{(\alpha - 0.21)^2}{(0.27 + 0.005 - \alpha)^3} & \text{if } \alpha > 0.21 \\
0 & \text{if } \alpha \leq 0.21
\end{cases} \]  
(6-26)

Sand:  
\[ P_{friction} = \begin{cases} 
0.05 \frac{(\alpha - 0.47)^2}{(0.63 + 0.05 - \alpha)^3} & \text{if } \alpha > 0.47 \\
0 & \text{if } \alpha \leq 0.47
\end{cases} \]  
(6-27)

Flyash:  
\[ g_{0,ss} = \left[ 1 - \left( \frac{\alpha}{0.24 + 0.0009} \right)^{1.3} \right]^{-1} \]  
(6-28)

Alumina:  
\[ g_{0,ss} = \left[ 1 - \left( \frac{\alpha}{0.27 + 0.005} \right)^{1.3} \right]^{-1} \]  
(6-29)

Sand:  
\[ g_{0,ss} = \left[ 1 - \left( \frac{\alpha}{0.63 + 0.05} \right)^{1.3} \right]^{-1} \]  
(6-30)

The simulation results by applying equation (6-28) to (6-30) are compared with results from kinetic theory (Chapter 4 analysis) and conventional frictional-kinetic model (Chapter 5 analysis), and they are presented as follows.

### 6.7.1 Pressure drop prediction with modified frictional-kinetic model for alumina

The pressure drop prediction with modified frictional-kinetic model for alumina through CFD simulations was conducted. The simulation results are summarized in Fig 6.52 and compared with results calculated by kinetic theory and the conventional frictional-kinetic model. However, pressure drop prediction results for most of the alumina cases are still under-predicted with the modified frictional-kinetic model, since the shear viscosity \( \mu_{s,coi} \) in equation (4-13), kinetic viscosity \( \mu_{s,kin} \) (4-14), frictional viscosity \( \mu_{s,fr} \) (4-15) and bulk viscosity \( \lambda_s \) are slightly reduced with \( \alpha_{s,off}=0.005 \) compared with \( \alpha_{s,off}=0 \). Nevertheless, it is still found that results from 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 of alumina transporting in bypass pneumatic conveying system.
Compared with results obtained from kinetic theory and conventional frictional-kinetic model, the simulation with modified frictional-kinetic model shows a great improvement on the pressure drop prediction results.

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

The pressure drop prediction with modified frictional-kinetic model for sand is conducted. The simulation results are summarized in Fig 6.53 and compared with simulation results obtained from kinetic theory and conventional frictional-kinetic model. Although all simulation cases numerically converged with 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 6.52 Experimental pressure drop Vs simulation pressure drop with different simulation models for alumina
The original idea for frictional pressure model is that the frictional pressure increases quickly when the solid volume fraction reaches the packing limit. However, sand is the type of material only to be conveyed in dilute phase, most of the sand powders closely pack at the bottom of pipeline during conveying. The material packing limit obtained from tapped bulk density in equation (6-14) and (6-15) is 0.63 which equals to the original value of packing limit in Fluent. Nevertheless, simulation with modified frictional-kinetic model only gets converged only when $\alpha_{s,off} = 0.05$, 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 (6-21) where solid volume fraction is close to the packing limit is largely under-predicted, and the correction factor in equation (6-24) for radial distribution function is also under-predicted. As a result, the shear viscosity $\mu_{s,col}$ in equation (4-13), kinetic viscosity $\mu_{s,kin}$ (4-14), frictional viscosity $\mu_{s,fr}$ (4-15) and bulk viscosity $\lambda_s$ are largely reduced with $\alpha_{s,off}=0.05$. As a result, the pressure drop prediction results are largely under-predicted.

Therefore, conventional frictional-kinetic model with 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.

### 6.8 Simulation models for different flow modes

As shown in Chapter 3, Fig 3.9 to Fig 3.12, 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 fluidised dense phase mode of flow. Flyash has same pressure drop prediction results from 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 model for flyash. Thus, it is proposed that the modified frictional-kinetic model can be applied to conduct pressure drop prediction for material with fluidised dense phase capable. For sand which represents materials to be conveyed in dilute phase only, the frictional stress plays 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 3.9 to Fig 3.12 can be used to show which frictional model can be used in the CFD simulations, as shown in Fig 6.54 to Fig 6.57. This may now provide guidance on what frictional approach to use for CFD analysis of powders in a bypass pneumatic conveying system.
Fig 6.54 Geldart fluidisation chart of sand with flow modes boundaries

Fig 6.55 Molerus fluidisation chart of sand with flow modes boundaries
6.9 Conclusion

Adopting the test results from basic parameter methods for three types of materials from Chapter 3, a modified frictional kinetic-model was proposed. The critical volume
fraction and close packing limit are defined according to fluidized bulk density and tapped bulk density. The constants in the modified frictional-kinetic model were analysed. For all three kinds of materials, the frictional pressure can be varied by changing those constants.

By combining all the simulation results from applying kinetic theory, conventional frictional-kinetic model and modified frictional-kinetic model, the conclusions can be summarised as following:

- For flyash, the solid volume fraction distribution and pressure contours from simulation by using modified frictional-kinetic model show the same results when applying the conventional frictional-kinetic theory. The reason for this is due to the low solids volume fractions never initiating frictional resistance component within the simulation. As shown in Fig 3.9 to Fig 3.12, flyash naturally conveys in fluidised dense phase where the particle-particle collision plays the dominant role. The influence of frictional stress should occur. It would appear that the very fine powders like flyash require other aspects of the CFD analysis to be investigated to improve the predictive capability.

- For Alumina, the modified frictional-kinetic model showed the largest improvement on pressure drop prediction results compared with results obtained from applying kinetic theory and conventional frictional-kinetic model, especially for denser flows with low air mass flow rate and high SLR. That means the influence of frictional stress between particles is well established in the simulations. In addition, the solids volume investigation of CFD simulations show a strong comparison to the actual flow conditions in the pipe, as transient slug type flow of the alumina is observed.

- For sand, only four cases with low SLR were converged by applying kinetic theory, and the pressure drop is largely under-predicted. By applying conventional frictional-kinetic theory, dramatic improvement has been shown. All the simulation cases were converged, and the simulation results are more accurate. With the modified frictional-kinetic pressure model, all the simulations were converged; however the pressure drop significantly under-predicted. With regards to the solids flow investigations, like alumina, both the conventional and the modified frictional kinetic models show the transient dune like flow for sand, which is reflective of the actual flow conditions within the bypass conveying
pipeline system. For the modified friction based model, the offset solid volume fraction $\alpha_{s,off}=0.05$ is too large, and the frictional pressure in equation (6-21) where solid volume fraction is close to the packing limit is largely under-predicted, with the correction factor in equation (6-24) radial distribution function is also under-predicted. As a result, the shear viscosity $\mu_{s, col}$ in equation (4-13), kinetic viscosity $\mu_{s, kin}$ (4-14), frictional viscosity $\mu_{s, fr}$ (4-15) and bulk viscosity $\lambda_s$ are largely reduced with $\alpha_{s,off}=0.05$. Consequently, the pressure drop prediction results are largely under-predicted with modified frictional-kinetic model. In summary, the conventional frictional-kinetic model provides a significantly more accurate frictional model for sand.

The methods to choose appropriate simulation models for different types of material with diverse flow modes were proposed: all the theories show the same pressure drop predictive capability for Flyash; the modified frictional-kinetic model should be applied for pressure drop prediction of alumina which represents those material with marginal fluidised dense phase capability; the conventional frictional-kinetic model should be applied for pressure drop prediction of sand which represents the material conveying in dilute phase.
CHAPTER 7 CONCLUSIONS AND OUTLOOK

This thesis was focused on gaining a better understanding of gas solid flow behaviour in the bypass pneumatic conveying system through the use of Computational Fluid Dynamic 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 investigate the pressure drop prediction from the CFD simulations as the pressure drop is an important design parameter for pneumatic conveying system selection. The final form of this thesis also found that not all the aspects of the CFD simulation have been fully resolved, therefore an outlook for more completely understanding gas-solid flow behaviour in bypass pneumatic conveying system as well as further develop numerical model to predict pressure drop more accurately is also presented at the end of this chapter.

7.1 Summary for pressure drop test

The basic parameters including particle size, particle density and bulk density were described and characterised by basic parameter methods and air-particle characterisation methods. Based on these basic parameters, the flow modes for different types of material were determined. Then, bypass pneumatic conveying testing was conducted on three powder materials; Flyash, Alumina and Sand, with the pressure drop measured and analysed. From this analysis it was found that:

- Flyash had the widest particle size distribution and smallest particle diameter, sand had the narrowest particle size distribution and the largest particle diameter, while alumina had the particle size distribution and particle diameter in between. Furthermore, alumina had the heaviest particle density, with sand the next heaviest, while flyash had the lightest particle density. Moreover, the loose poured bulk density, tapped bulk density and fluidised bulk density were tested and the parameters measured for future use. Based on the parameters obtained as above, the modes of flow for the different types of materials were classified. It was found that flyash is in the fluidised dense phase region; sand is in the dilute only region;
alumina is in near the boundary between these region so has a small dense phase capability.

- The general arrangement of the bypass pneumatic conveying system, detailed configurations of conveying pipeline and instrumentation were described, and the computational domain for CFD numerical simulation was determined accordingly. Based on the experimental test procedure and test programme, the pressure drop of bypass pneumatic conveying was measured. It was found that the pressure drop decreased with increasing air mass flow rate within different solid mass flow rate ranges for all three types of materials. In addition, the pressure drop generally increased with increasing solid mass flow rate when the same air mass flow rate was used.

### 7.2 Summary for simulation with kinetic theory

The kinetic theory was utilised to undertake CFD based simulations in the bypass pneumatic conveying system to predict pressure drop for the three material types transporting. The solid volume fraction and pressure contours were also presented and then compared with experimental images of the pneumatic conveying flow captured by high speed camera.

- 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, cases with lower pressure drop provided good predicting results by applying kinetic theory. Nevertheless, for cases with large pressure drop, the pressure drop was largely under-predicted. For sand, only a few cases obtained numerical convergence for the pressure drop prediction by applying kinetic theory.

- Images captured by high speed camera demonstrated that solids distribution for denser flows was un-uniformed compared with less dense flows. Thick layers at the bottom of pipeline were shown for all three types of material for denser flows with high experimental pressure drop and low air mass flow rate. Therefore, indication of sustained contact between particles in the thicker layers was proposed. It was further proposed that frictional stress should play an important role for particles transported in denser flow regimes within bypass pneumatic conveying.
7.3 Summary for simulation with conventional frictional-kinetic model

The conventional frictional-kinetic model was utilised to conduct the CFD simulation based pressure drop prediction. The solid volume fraction and pressure contours for different types of material were 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. Interestingly, the case study of Flyash-21 with conventional frictional-kinetic model showed that the maximum solid volume fraction is much lower than the minimum frictional packing value (0.24) required to initiate frictional resistance within the CFD simulation. 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 thesis. 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.
• A specific case Sand-6 which has high SLR and low air mass flow rate was carried out to express the mechanism of bypass pneumatic conveying, especially to show how the full bore dune formation and deformation of sand and bypass flutes interact. It was found that high fluctuations and variation in pressure and gas velocity occurred in the short time period (0 to 0.1 seconds). Moreover, the gas velocity vectors indicated a high degree of air penetration from the flute into the bypass pipe. In this way, an aeration mechanism for the gas to flow into the conveyed material in the main pipe was shown. This work highlighted the bypass pipeline mechanism which aerated the material along the pipeline, therefore providing a passive flow enhancement mechanism.

7.4 Summary for 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). The 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 (7-1), the pressure drop was predicted and compared with results from kinetic theory and conventional frictional-kinetic model.

$$P_{friction} = \begin{cases} Fr \frac{(\alpha_s - \alpha_{s, min})^n}{(\alpha_{s, max} + \alpha_{s, off} - \alpha_s)^p} & \alpha_s > \alpha_{s, min} \\ 0, & \alpha_s \leq \alpha_{s, min} \end{cases}$$ (7-1)

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 the sensitivity analysis of the modified friction results, the pressure drop prediction results varied quite differently by changing $\alpha_{s,off}$ and the constants in modified frictional pressure equation. 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 maintained the same. Again this
was due to the maximum solid volume fraction from simulation being always 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 to experimental result by choosing appropriate $\alpha_{s,off}$ and constants. It is clear that frictional stress plays 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 the frictional pressure as well as the correction factor for radial distribution function was 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.

- The methods to choose appropriate simulation models for different types of material with diverse flow modes were proposed. The modified frictional-kinetic model was proposed to be applied for pressure drop prediction for material having a well-defined fluidised dense phase conveying potential. The modified frictional-kinetic model was also proposed to be applied for pressure drop prediction for material that has some marginal fluidised dense phase capability. The conventional frictional-kinetic model was proposed to be applied for pressure drop prediction for material that is classified as dilute phase only capable in a conventional pipeline.

### 7.5 Flow chart for simulation of bypass pneumatic conveying

Based on all the research described above, a flow chart for the CFD simulation methodology of bypass pneumatic conveying is proposed and shown in Fig 7.1. In this figure, the most important outcomes and the associated design guide to choose appropriate models for simulation of bypass pneumatic conveying are symbolised with colour. First step is to get 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-Language can be applied. Based on the numbers and status of phases, the types of
Euler-Euler multiphase model can be decided. If the flow is with 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 gas phase turbulence in this thesis. Moreover, the dispersed turbulence model is decided to be used to simulate the turbulence of solid phase. Then, 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 included additionally, then the conventional frictional-kinetic model is chosen. Or if the modified frictional viscosity is included additionally, then the modified frictional-kinetic model is selected. Plus, based on the experimental and numerical investigation of bypass pneumatic conveying flow modes with flyash, alumina and sand, the simulation models for pressure drop 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 7.1 Proposed flow chart for simulation of bypass pneumatic conveying
7.6 Outlook

It is understood that there are still aspects in this thesis that have not been fully investigated and solved. Some areas need further investigations to get 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 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 than 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 phenomenon is against to what was observed from high speed camera, as there was thick layer at the bottom of pipeline with denser flows. Therefore, it indicated that the frictional packing limit and critical solid volume fraction might be actually be even much lower than the results calculated from fluidised bulk density. Further investigation of frictional packing limit and critical solid volume fraction needs to be conducted.

- The pressure drop prediction with different types of material in this thesis was only conduct 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 thesis, 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.

- Based on the pressure drop prediction, by only adopting three types of material in this thesis, the predictive chart in Chapter 7 were obtained accordingly. However, more types of material which to these modes of flow types will help re-enforce the findings and solutions presented in this thesis. 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 thesis, the gas-solid flow was assumed as 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 system 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 simulation for this thesis. 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 about choosing appropriate models for simulation with gas-solid flow behaviour needs to be further developed.
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