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Abstract

A wide range of industrial processes involve multiphase granular flows. These include catalytic reactions in fluidized beds, the pneumatic conveying of raw materials and gas-particle separators. Due to the complex nature of multiphase flows and the lack of fundamental understanding of the phenomena in a multiphase system, appropriate design and optimized operation of such systems has remained a challenging field of research. Design of these processes is hampered by difficulties in upscaling pilot scale results, the difficulties involved in experimental measurements and in finding reliable numerical modelling methods. Significant work has been carried out on numerical modelling of multiphase systems but challenges remain, notably computational time, appropriate definition of boundary conditions, relative significance of effects such as lift and turbulence and the availability of reliable model validation.

The work presented in this thesis encompasses experimental and numerical investigations of horizontal pneumatic conveying. In the experimental work, carefully controlled experiments were carried out in a 6.5 m long, 0.075 m diameter horizontal conveying line with the aid of the laser Doppler anemometry (LDA). Initially, LDA measurements were performed to measure the gas velocity in clear flow. Good agreement was observed between the theory and experimental measurements. For two-phase experiments, spherical and non-spherical particles with different sizes and densities were used to study the effect of particle size and solid loading ratio on the mean axial particle velocity. Three different sizes of spherical glass beads, ranging from 0.9 mm to 2 mm and cylindrical shaped particle of size 1×1.5 mm were employed. It was found that by increasing the particle size and solid loading ratios, the mean axial particle velocity decreased. Turbulence modulation of the carrier phase due to the presence of spherical particles was also investigated by measuring fluctuating gas velocity for clear gas flow and particle laden flow with different particle sizes and solid loading ratios. Results suggested that for the size ranges of particles tested, the level of gas turbulence intensity increased significantly by adding particles, and the higher the solid loading ratio, the higher the turbulence intensity.
With the rapid advancement of computer resources and hardware, it is now possible to perform simulations for multiphase flows. For a fundamental understanding of the underlying phenomena in pneumatic conveying, the coupled Reynolds averaged Navier-Stokes and discrete element method (RANS-DEM) was selected. The aim of the modelling section of this study was to evaluate the abilities of coupled RANS-DEM to predict the phenomena occurring in a research-sized pneumatic conveying line. Simulations for both one-way and two-way RANS-DEM coupling were performed using the commercial coupled software FLUENT-EDEM in an Eulerian-Lagrangian framework, where the gas is simulated as a continuum medium, while solid phase is treated as a discrete phase. In one-way coupling simulations, a considerable discrepancy in mean axial particle velocity was observed compared to the experimental results, meaning two-way coupling was required. It was further found that the inclusion of Magnus lift force due to particle rotation was essential to reproduce the general behaviour observed in the experiments. Turbulence modulation also was investigated numerically.

Experimental and simulation results of gas and particle velocities were compared showing that the RANS-DEM method is a promising method to simulate pneumatic conveying. However, some discrepancy between simulation and experimental results was observed.

Most studies in two-phase flow fields have focused on spherical particles. However the majority of particles encountered in industry involve non-spherical granules which show considerably different transportation behaviour compared with spherical particles. Further modelling of cylindrical particles was conducted using a multi-sphere model to represent cylindrical particles in the DEM code. Drag and lift forces and torque equations were modified in the code to take the effect of particle orientation into account. The framework developed was evaluated for two test cases, indicating a good agreement with the analytical and experimental results. The transportation of isometric (low-aspect-ratio) non-spherical particles in pneumatic conveying was also modelled. The simulation results of mean axial particle velocity agreed well with the experimental measurements with the LDA technique.
Declaration

I declare that this thesis has been composed by myself and was not submitted in any form at another university. It is the original work of the author except where otherwise stated.

Mohammadreza Ebrahimi
April 2014
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Dissemination

The results of the current study have been presented in several conferences and PARDEM meetings. Moreover, some of the outcomes of the study have been published and others are in the process of being published. The list of publications is as follows:


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# Nomenclature

## Latin symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Particle cross section</td>
</tr>
<tr>
<td>A</td>
<td>Transformation matrix</td>
</tr>
<tr>
<td>b</td>
<td>Cylinder half length</td>
</tr>
<tr>
<td>CD</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>CL</td>
<td>Coefficient of Magnus lift force</td>
</tr>
<tr>
<td>C_{e3}</td>
<td>Empirical constant</td>
</tr>
<tr>
<td>D_l</td>
<td>Laser beam diameter</td>
</tr>
<tr>
<td>D_{pipe}</td>
<td>Pipe diameter</td>
</tr>
<tr>
<td>d_e</td>
<td>Equal volume sphere diameter</td>
</tr>
<tr>
<td>d_f</td>
<td>Beam waist diameter</td>
</tr>
<tr>
<td>d_n</td>
<td>Equal projected area circle diameter</td>
</tr>
<tr>
<td>d_p</td>
<td>Particle diameter</td>
</tr>
<tr>
<td>d_x, d_y, d_z</td>
<td>Measurement volume</td>
</tr>
<tr>
<td>E</td>
<td>Beam expansion factor</td>
</tr>
<tr>
<td>e</td>
<td>Coefficient of restitution</td>
</tr>
<tr>
<td>F</td>
<td>Force</td>
</tr>
<tr>
<td>F_l</td>
<td>Lens focal length</td>
</tr>
<tr>
<td>f</td>
<td>Ratio of the drag coefficient to Stokes drag</td>
</tr>
<tr>
<td>f_d</td>
<td>Frequency shift</td>
</tr>
<tr>
<td>G</td>
<td>Shear Modulus</td>
</tr>
<tr>
<td>I</td>
<td>Moment of inertia</td>
</tr>
<tr>
<td>k</td>
<td>Turbulent kinetic energy</td>
</tr>
<tr>
<td>l_e</td>
<td>Integral length scale</td>
</tr>
<tr>
<td>m</td>
<td>Particle mass</td>
</tr>
<tr>
<td>N</td>
<td>Number of samples</td>
</tr>
<tr>
<td>N_f</td>
<td>Number of fringes</td>
</tr>
<tr>
<td>N_t</td>
<td>Total number of sample points of the particle</td>
</tr>
<tr>
<td>n_c</td>
<td>Number of sample points contained within the mesh cell</td>
</tr>
<tr>
<td>n_m</td>
<td>Number of particles in a mesh</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
</tr>
<tr>
<td>r</td>
<td>Particle radius or Distance from the pipe centre</td>
</tr>
<tr>
<td>S</td>
<td>Volumetric particle-fluid interaction force</td>
</tr>
<tr>
<td>S_n</td>
<td>Normal stiffness</td>
</tr>
<tr>
<td>S_t</td>
<td>Tangential stiffness</td>
</tr>
<tr>
<td>S_kp, S_dp</td>
<td>User defined source terms</td>
</tr>
<tr>
<td>T</td>
<td>Torque</td>
</tr>
<tr>
<td>T_R</td>
<td>Rayleigh time</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
</tr>
<tr>
<td>\bar{U}_p</td>
<td>Mean particle velocity</td>
</tr>
</tbody>
</table>
Particle velocity $u$

Fluctuating particle velocity $u'$

Particle volume $V_p$

Normal component of the relative velocity between two particles $V_{n\text{rel}}$

Tangential component of the relative velocity between two particles $V_{t\text{rel}}$

Mean gas velocity $\bar{V}$

Maximum value of $\bar{V}$ $\bar{V}_{\text{max}}$

Fluctuating gas velocity $v'$

Fluctuating gas root mean square (RMS) velocity $V'_{\text{rms}}$

Gas velocity $v$

The distance between the centre of pressure and the centre of mass $x_{cp}$

Young’s modulus $Y$

Particle major axis $z'$

Greek symbols

Angle between the particle major axis and the relative velocity vectors $\alpha$

Fringe distance $\delta y$

Normal overlap $\delta n$

Tangential overlap $\delta t$

Dissipation rate $\varepsilon$

Porosity $\varepsilon_{\text{mesh}}, \varepsilon_f$

Euler’s four parameters $\varepsilon_1, \varepsilon_2, \varepsilon_3$

and $\eta$

Angle between two beams $\theta$

Aspect ratio $\Lambda$

Wavelength of the laser light $\lambda$

Fluid viscosity $\mu$

Coefficient of rolling friction $\mu_r$

Coefficient of static friction $\mu_s$

Turbulent viscosity $\mu_t$

Poisson’s ratio $\nu$

Fluid density $\rho$

Turbulence intensity $\sigma$

Turbulence intensity of the clear gas $\sigma_f$

Turbulence Prandtl numbers $\sigma_k, \sigma_\varepsilon$

Turbulence intensity of the particle laden flow $\sigma_{f\text{p}}$

Fluid viscous stress tensor $\tau$

Time scale of turbulence $\tau_e$

Particle response time $\tau_p$

Stokesian response time $\tau_V$

Rolling friction $\tau_r$
\( \phi_p \) \hspace{2em} \text{Particle volume fraction} \\
\( \psi \) \hspace{2em} \text{Sphericity} \\
\( \omega \) \hspace{2em} \text{Angular velocity} \\
\( \omega_c \) \hspace{2em} \text{Fluid vorticity} \\

**Non-dimensional numbers**

- \( Ar \) \hspace{2em} \text{Archimedes number} \\
- \( Re \) \hspace{2em} \text{Reynolds number} \\
- \( Re_p \) \hspace{2em} \text{Particle Reynolds number} \\
- \( Re_\Omega \) \hspace{2em} \text{Particle rotation Reynolds number} \\
- \( St \) \hspace{2em} \text{Stokes number} \\

**Subscripts**

- \( i,j \) \hspace{2em} \text{Indices} \\
- \( p \) \hspace{2em} \text{Particle} \\
- \( f \) \hspace{2em} \text{Fluid}
Chapter 1.
Introduction

In this chapter a brief introduction to pneumatic conveying is presented. The aim and scope of this study is also described as well as the outline of this thesis.

1.1 Pneumatic conveying fundamentals and flow regimes

Pneumatic conveying is a widely employed system for transportation of granular media in various contexts such as the chemical, agriculture, pharmaceutical and food industries. Particles are propelled by gas, usually air in a conveying line which can be installed in horizontal, vertical or inclined configurations.

In general, different flow regimes may occur depending on the conveying gas flow rate, particle characteristics and pneumatic conveying system geometry. These flow regimes can be broadly classified as dilute or dense conveying (Lim et al. (2006)). In the former, the gas velocity and particle properties form a regime in which most of the particles are dispersed in the conveying gas. In comparison, the particles in the latter regime are not fully suspended in the gas and, as a result, the particles are conveyed as a plug. The dilute mode has the advantages of low pressure fluctuation and is a more stable mode compared with the dense regime. However, it suffers from high power consumption, product degradation and wear of equipment as a result of high gas velocity (Baker and Klinzing (1999)). In comparison, dense flow regime is the preferred method for conveying materials which are sensitive to abrasion. In addition, high mass flow rate can be conveyed with great energy efficiency (Levy (2000)). However, the dense mode suffers from high pressure fluctuation; as a result the system may be prone to blockages and instabilities (Sturm et al. (2010)). Beside these two main flow regimes, in horizontal pneumatic conveying some other flow regimes can be formed due to the effects of gravity. These flow modes may be referred to as stratified and moving dunes flow regimes. In the stratified flow regime, a thin layer of particles is transported along the lower pipe wall. The particle
concentration is higher near the lower pipe wall and decreases toward the upper wall of pipe. In the moving dune flow regime, stable particles clusters are formed, but these clusters do not combine to form a plug. In this regime, a large portion of particles are conveyed above these dunes (Lim et al. (2006), Rao et al. (2001)). In inclined pneumatic conveying systems, other flow regimes such as reverse flow, half ring and unsteady reverse flow with pulsating waves may also take place (Zhang et al. (2007)).

The boundary between different flow patterns is not well defined. However, to distinguish the flow regimes in a pneumatic conveying system, phase diagrams have been presented. Molerus (1996) showed a phase diagram based on the pressure drop and gas velocity for horizontal pneumatic conveying of polystyrene. Lim et al. (2006) presented phase diagrams for vertical and horizontal pneumatic conveying based on the solid flow rate and gas velocity, derived from simulation studies. Kuang and Yu (2011) also established a phase diagram for horizontal pneumatic conveying by analyzing the forces governing the flow of particles in micro and macro scales such as particle-particle, particle-fluid and particle-geometry forces. They also mentioned that their diagram could be applied regardless of the particle properties and operational conditions.

1.2 Forces in pneumatic conveying

Pneumatic conveying consists of two distinct phases. Two phases interact with each other and as a result various particle-fluid interaction forces are generated. Moreover, particle-particle and particle-geometry forces play an important role in pneumatic conveying systems. For very fine particles, non-contact forces such as electrostatic charges, and the van der Waals force also need to be considered. The magnitude and importance of each of these forces depend on the nature of the flow studied.

1.2.1 Particle-fluid interaction

During fluid-particle interaction, forces are exchanged between phases. These forces may include particle-fluid drag force, lift forces, buoyancy force, Basset force and virtual mass force.
Generally, empirical or numerical approaches are used to determine particle-fluid drag force. Examples include Ergun (1952), Wen and Yu (1966), Di Felice (1994), Hill et al. (2001) and Choi and Joseph (2001). The drag force acting on a single isolated particle is well established and the drag coefficient, $C_D$, depends on particle Reynolds number, $Re_p$. The effect of the presence of neighbouring particles is usually incorporated to the drag models in terms of local porosity.

In a multiphase flow, spherical particles may experience two different types of lift force, usually referred to as the Magnus and Saffman forces. Magnus lift force arises due to the particle rotation. Particle rotation may be caused by a particle-wall contact, particle-particle contact or by a velocity gradient. Saffman lift force develops due to the non-uniform pressure distribution on the surface of a particle. Generally, drag and lift forces are the dominant aerodynamic forces in a horizontal pneumatic conveying.

Other aerodynamic forces such as virtual mass force, which is the force required to accelerate the surrounding fluid and Basset force which is the force due to the lagging boundary layer development with changing relative velocity are usually negligible compared to the drag and lift forces (Zhu et al. (2007)).

1.2.2 Particle-particle and particle-geometry interaction

During motion, a particle may interact with neighbouring particles or the system geometry. Usually in dense particle flows, particle-particle interactions control the particle flow. In extremely dilute systems this may be negligible compared with the aerodynamic forces.

1.3 Objective of the thesis

The general aim of this study is to improve the understanding of two-phase flow in horizontal pneumatic conveying. This will be addressed experimentally by performing detailed experiments by laser Doppler anemometry (LDA) and numerically by the aid of coupled RANS-DEM simulations. Gas and particle velocities for different particle sizes, and SLRs will be measured and then
simulations corresponding to the experiments will be conducted using the commercial FLUENT-EDEM software with additional functionality introduced by means of Applications Programmer Interface (API) coding. It also will be attempted to provide a detailed and comprehensive data set for a wide range of operational conditions which can be applied for code validations. It also can be claimed that this research study is one of the first applications of new interface of coupled FLUENT-EDEM enabling customized solutions for coupled particle-fluid flow simulations. Moreover, for first time, a regime which is between dilute and dense regimes is investigated in a horizontal pneumatic conveying in this study. In the current research, the following points will be thoroughly investigated

- How does the turbulence level change due to the addition of particles in the studied flow regime? and what is the influence of turbulence modulation on the simulation results?
- How well can RANS-DEM represent pneumatic conveying?
- What is the influence of the particle shape on the simulation and pneumatic conveying behaviour?

1.4 Thesis outline

In the current chapter, a brief introduction to pneumatic conveying of particles was presented. Previous findings of experimental and numerical modelling studies of pneumatic conveying are summarized in chapter 2. In chapter 3, the experimental system, measurement procedures, material specification and experimental conditions are reviewed. Chapter 4 represents the experimental measurement results for spherical particles. The effect of particle size and particle solid loading ratio (SLR) on the particle velocity is addressed. Moreover, the carrier phase turbulence modulation phenomenon is also investigated experimentally in this section. Chapter 5 covers the governing equations applied in the simulations. The RANS-DEM code employed is also verified by two test cases in this chapter. The importance of the lift force in the current study, the level of coupling and the comparison between experimental and simulation results of the carrier phase turbulence modulation are presented in chapter 6. Simulation results of mean gas and particle velocities are compared with the experimental measurements in chapter 7. In chapter 8, the
pneumatic conveying of isometric non-spherical particles is presented. A framework for non-spherical particles in the coupled FLUENT-EDEM is also introduced and applied to test cases. In chapter 9, conclusions and recommendations for future research studies are presented.
Chapter 2.

Background and literature review

In this chapter, the experimental measurement techniques and numerical modelling approaches in multiphase flows are described. Then the previous experimental and numerical studies of pneumatic conveying are reviewed. The main focus is on experimental measurements with the laser Doppler anemometry (LDA) technique and RANS-DEM modelling of pneumatic conveying systems. The turbulence modulation phenomenon also is introduced in this chapter and the motion of nonspherical particles in two-phase flow is reviewed.

2.1 Experimental measurement techniques in gas-solid flows

Many physical phenomena which happen in working pneumatic conveying systems, such as particle concentration, carrier phase turbulence level change, blockage and transition in flow patterns cannot be easily determined by conventional measurement approaches such as the measurement of bulk properties, pressure drop and velocity, because of the diversity and complexity of the gas-particle behaviour. Therefore, more reliable and accurate measurement techniques are needed to analyze gas-particle flows (Brown et al. (1996)). Various accurate non-intrusive measurement techniques have been introduced and applied successfully for gas-particle flows such as particle tracking velocimetry (Sommerfeld and Huber (1999)), particle image velocimetry (PIV) (Kadambi et al. (1998)), photographic image techniques (Li and Tomita (2000)), CCD cameras (Caicedo et al. (2003)), phase Doppler anemometry (PDA) (van de Wall and Soo (1994)), electrical capacitance tomography (ECT) (Ostrowski et al. (2000), Azzopardi et al. (2008)), laser Doppler anemometry (LDA) (Lee and Durst (1982), Frank et al. (1996)), and radioactive particle tracking (Roy et al. (1994)). Detailed information from these measurement techniques provides useful insight on system design and optimization.
In this study the LDA technique has been applied. Therefore, the principles of LDA and its application in pneumatic conveying are reviewed in the next sections. LDA technique is one of the most commonly used experimental tools for use in gas and particle velocity measurements. The major reasons are that LDA is a non-intrusive optical measurement and it can handle velocity components with high temporal and spatial resolution even in highly turbulent flows. The LDA technique can only be used for a relatively dilute system, the reason being that, in order to measure the particle velocity correctly, each individual particle should be seen and detected in the pipe. Moreover, data acquisition takes place at one position at a time; therefore to map the fluid flow field for a specific cross section with LDA many runs would be required.

2.1.1 The principles of LDA

The components of a LDA system are displayed in Figure 2-1.

![Figure 2-1: The schematic diagram of LDA system (Dantec Reference Guide (2000)).](image)

In LDA, the light is emitted from a laser source with a specific wavelength toward the measurement point. When particles or seeding particles which are used to represent the fluid flow pass through the laser light, the light is scattered. The
scattered light has a different frequency due to the motion of the moving particle; this phenomenon is called the Doppler effect (frequency shift). The Doppler effect depends on the angle between the incident and scattered light and the moving particle velocity. It may be expressed as follows:

\[ f_D = \frac{u_p \cdot (e_s - e_i)}{\lambda} \]  

(2-1)

Where \( e_i \) and \( e_s \) are the unit vectors in the direction of incoming and scattered lights and \( \lambda \) is the wavelength of the light. In practice this frequency change can only be measured directly for very high particle velocity. Therefore, practical LDA systems are based on a dual-beam principle where the scattered light is a mixture of two intersecting laser beams. At the intersection point, the interference of the beams produces parallel planes of light and darkness known as fringes which can be seen in Figure 2-2.

The distance between the fringes, \( \delta_f \), is determined by the angle between the two beams, \( \theta \), and the wavelength of the laser light \( \lambda \) as follows:

\[ \delta_f = \frac{\lambda}{2\sin(\theta/2)} \]  

(2-2)

The particle velocity normal to the plane of the fringe, \( u_{p,\perp} \), can be obtained as:

\[ u_{p,\perp} = \delta_f f_D = \frac{f_D \lambda}{2\sin(\theta/2)} \]  

(2-3)
Measurements take place in the intersection between the two incident laser beams, which may be referred to as the measurement volume. The measurement volume is defined as the volume within which the modulation depth is higher than $e^{-2}$ times the peak core value. The measurement volume has an ellipsoidal shape because of the Gaussian intensity distribution in the beams as seen in Figure 2-3 (Dantec Reference Guide (2000)).

![Figure 2-3: The measurement volume (Dantec Reference Guide (2000)).](image)

The size of the measurement volume can be calculated with knowing the beam waist diameter, $d_f$, and the angle between the two beams. The beam waist is the point where beam cross section attains its smallest value. It can be expressed as:

$$d_f = \frac{4 F_l \lambda}{\pi E D_l}$$  \hspace{1cm} (2-4)

where $F_l$ is the lens focal length, $E$ is the beam expansion factor and $D_l$ is the laser beam diameter in front of the lens. The three dimensions of measurement volume are then calculated as:

$$d_x = \frac{d_f}{\cos(\theta/2)}, \quad d_y = d_f, \quad d_z = \frac{d_f}{\sin(\theta/2)}$$  \hspace{1cm} (2-5)

By knowing the height of the measurement volume, $d_z$, and the fringe spacing, the number of fringes can be calculated.

$$N_f = \frac{d_x}{\delta_f} = \frac{2d_f}{\lambda} \tan(\theta/2)$$  \hspace{1cm} (2-6)
This number of fringes is passed by a particle moving straight to the centre of a measurement volume along the x-axis. If a particle follows any other passage through the control volume it will pass fewer fringes as a result there will be fewer periods in the recorded signal from which to estimate the Doppler frequency. To ensure reliable LDA measurement, the control volume should have a sufficiently high number of fringes. Typical LDA systems produce between 10 to 100 fringes (Dantec Reference Guide (2000)).

The light scattered from the particles passes through receiving lens and is collected on a photodetector, usually a photomultiplier. The scattered light is focused and converted into a voltage signal. A typical LDA signal (which is called burst) has a high frequency part i.e. Doppler signal and a low frequency part i.e. the pedestal, which can be filtered. The modulation contains the actual Doppler signal and is used as input into the signal processor. The processor receives the analogue signal from the photodetector and calculates the frequency of the signal and the velocity is measured (Romani Fernández (2012)). It should be taken into account that, in LDA technique, it is not actually the velocity of fluid that is measured, but the velocity of small particles dispersed in the flow. Thus, to measure fluid flow, seeding particles are used. The motion of these is used to represent the fluid flow in total, and thus they should be small enough to follow the fluid flow accurately. Seeding particles also should scatter the light sufficiently and be generated conveniently. For a more comprehensive explanation of LDA principles the reader is referred to the Dantec Reference Guide (2000).

With the LDA technique, mean gas and particle velocities and the root mean square velocities can be measured. The mean velocity for either gas or particle at a sample point $(x, y, z)$ is calculated based on the equation below:

$$
\bar{U}_p = \frac{1}{N} \sum_{i=1}^{N} u_{p,i}
$$

(2-7)
where \( u_{pi} \) is the instantaneous particle velocity component, \( \bar{u}_p \) is the mean particle velocity, \( v_i \) is the instantaneous gas velocity component and \( \bar{V} \) is the mean gas velocity. \( N \) is the number of samples at the measurement point. The fluctuating gas root mean square (RMS) velocity is calculated by the following equation:

\[
V'_{rms} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (v_i - \bar{V})^2} 
\]

(2-9)

By having the mean and root mean square velocities the carrier phase turbulence intensity can be expressed as:

\[
Turbulence\ intensity\ (\sigma) = \frac{V'_{rms}}{\bar{V}} 
\]

(2-10)

### 2.1.2 Application of LDA technique in pneumatic conveying systems

LDA measurements have previously been applied to investigate gas-solid flows in pneumatic conveying systems. The influence of particles on the carrier phase turbulence intensity, which is usually referred to as turbulence modulation, can also be investigated by this technique. Table 2-1 lists the studies in which the LDA technique has been applied to investigate pneumatic conveying systems. Brief key results of each study also are presented in this table.

In the current study, the gas velocity, particle size and flow rates are different from those experiments presented in Table 2.1. Compared to the available experiments, a different flow regime is investigated in this study, which is a conveying mode between dilute and dense regimes. Moreover, the measurements are performed at three different cross sections along the pneumatic conveying line (compared to the usual single cross section measurements performed in most of the literature), which
is done firstly to provide a comprehensive data set for code validation and secondly to investigate how the dynamic behaviour of gas and particle flows changes from one cross section to another cross section.

Table 2-1: The application of the LDA technique for pneumatic conveying

<table>
<thead>
<tr>
<th>Reference</th>
<th>Experimental rig</th>
<th>Test solid and flow conditions</th>
<th>Key results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsuji and Morikawa (1982)</td>
<td>Horizontal glass pipe</td>
<td>• Plastic particles, 0.2 mm and 3.4 mm</td>
<td>1. The effects of the solid particles on air flow turbulence intensity varied heavily with the particle size. The 3.4 mm particles increased the carrier phase turbulence intensity while the 0.2 mm ones reduced it 2. With adding the particle, the maximum gas velocity shifted upward from the pipe centre</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Air conveying velocity 6 to 20 m/s</td>
<td></td>
</tr>
<tr>
<td>Laín et al. (2002b)</td>
<td>Horizontal channel</td>
<td>• Five kinds of glass beads with mean size of 0.06, 0.1, 0.195, 0.625, 1 mm</td>
<td>1. Measured gas and particle velocities were used to validate numerical results</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Air velocity up to 30 m/s</td>
<td></td>
</tr>
<tr>
<td>Datta et al. (2007)</td>
<td>Horizontal and vertical pipe</td>
<td>• Polyamide chips, approximate 3 mm long, 3 mm wide and 1 mm thick</td>
<td>1. The LDA technique was used to validate ECT measurements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Air velocity 1 to 5 m/s</td>
<td></td>
</tr>
<tr>
<td>Laín and Sommerfeld (2008)</td>
<td>Horizontal channel</td>
<td>• Glass beads, with diameter between 0.06 and 0.625 mm</td>
<td>1. Mean and fluctuating air velocity were measured in the presence of particles 2. Carrier phase turbulence intensity was attenuated due to the presence of 0.13 and 0.195 mm glass beads</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Gas velocity, 20 m/s</td>
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### Vertical pneumatic conveying

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2. Particle velocity exceeded the gas velocity near the wall

1. The amplitude of turbulent fluctuations of particle velocity in the axial direction was much higher than that in the radial direction
2. The axial and radial fluctuations of particle velocity depended greatly on the particle loading
3. The presence of particles in the gas phase reduced the level of gas turbulence

1. Mean gas and particle velocity profiles and gas turbulence intensity were measured within the bend
2. An acceptable consistency between experimental and numerical results was reported

1. The lighter particle, i.e. glass beads, reached a higher velocity than the heavier particles
2. Flat profiles were observed for the mean axial particle velocity
3. By increasing the particle volume fraction, the axial particle velocities increased for zirconium oxide. However the same effect was not seen for the glass beads

2.2 Numerical modelling of multiphase gas-solid flows

Numerical simulation of gas-solid systems has a significant role in the understanding and visualization of the dynamics of these complex systems as well as in the prediction of the flow behaviour of such systems. The use of computer simulation enables determination of several properties such as particle-particle interaction forces, magnitude of particle-fluid interaction forces and porosity which remain extremely demanding or even impossible to measure experimentally. Furthermore, computer simulations have predictive abilities which means several design options and operational conditions can be tested (Deen et al. (2007)).
Generally, multiphase gas-solid flows can be modelled by two different numerical methods which are the Eulerian-Eulerian and Eulerian-Lagrangian approaches. Usually, for large industrial scale simulations, the Eulerian-Eulerian model which also may be referred to as the two fluid model (TFM) is applied. In this modelling approach, both the solid and gas phases are treated as inter-penetrating continua exchanging momentum and for each phase a momentum conservation equation is solved. The interaction between gas and solid is modelled by drag force correlations. Correlations for the solid phase pressure and viscosity also need to be specified.

In the Eulerian-Lagrangian model, particles are described as discrete entities and Newton’s equations of motion are solved to track each individual particle. Similar to the Eulerian-Eulerian method, the continuous phase is described by the Navier-Stokes equations. Eulerian-Lagrangian methods could be roughly divided into resolved discrete particle model (RDPM) and unresolved discrete particle model (UDPM) approaches. (Van der Hoef et al. (2008), Zhu et al. (2007)). In RDPM which often referred to as direct numerical simulation (DNS), the fluid is simulated using an Eulerian grid by solving the Navier-Stokes equations with no empirical closure assumption for drag or turbulence. The Eulerian grid is usually an order of magnitude smaller than the particle size (Van der Hoef et al. (2008)). This grid covers the interstitial volume between the solid particles, and the fluid is fully resolved. The fluid interacts with the particles at their no-slip boundaries. Immersed boundary (IB) method is one of the most common approaches in this category.

In UDPM approach which usually termed as Reynolds averaged Navier-Stokes (RANS), the fluid is unresolved and the Eulerian grid covers the entire domain. The size of the grid is larger than the size of the individual particle; therefore particles act as sinks of momentum. The drag force on the DEM particles is modelled using correlations that have been obtained by experiments or by fully resolved simulations.

Another alternative approach for simulation resolved gas-particle flow is Lattice-Boltzmann (LB) method. This method is based on the discretised model of the Boltzmann equation in which the fluid field is modelled at scales smaller than the
size of the solid particles. LB method in fact is a method between molecular and continuum description of fluid flow.

Based on the explanation in the previous paragraphs, it can be concluded that TFM model cannot model the particle level phenomena. However this model is computationally faster compared to the Eulerian-Lagrangian models, in which each individual particle is tracked. RDPM methods are computationally expensive due to the requirement of parallel computation. However, DNS is the most accurate way of numerical study of turbulent flows (Fokeer et al. (2004)). Due to the non-availability of a computer facility to perform RDPM simulations within this project, this study mainly covers the UDPM approach, where the interstitial fluid is unresolved and the solid particles are individually modelled using discrete element method (DEM). This allows the model to capture the particular characteristics of a granular material, while being applicable to a wider range of problems and more complex particle-fluid flows than a fully resolved simulation. However, at this stage of development, the computational effort required to track each particle in the dense flows or large systems limits the application of the UDPM approach. A summary of different approaches for numerical modelling of turbulent particle laden flows can be found in Elghobashi (1994), Crowe et al. (1996), Fokeer et al. (2004) and Zhu et al. (2007).

In a numerical description of a multiphase flow, the level of coupling between gas and particle can be performed through two approaches, usually referred to as one-way or two-way coupling (Crowe et al. (1996)). One-way coupling relies on the particle volume fraction being very low and the presence of particles having a negligible effect on the flow field of the carrier phase. On the other hand, when the particle volume fraction is increased, both the effect of gas flow on the solid motion and the effect of particles on the gas flow pattern become important and two-way coupling is necessary in a simulation. In this case, a momentum source term is added to the carrier phase momentum equation to take into account the particle presence. One-way coupling has an advantage of faster computational time. However, the accuracy of this method is lower than two-way coupling since the influence of the solid phase on the carrier phase is neglected (Wong et al. (2009)).
2.2.1 Governing equations in the RANS-DEM approach

In the RANS-DEM approach, unresolved fluid phase is modelled based on the averaged Navier-Stokes equations derived by Anderson and Jackson (1967). By applying their averaging method to the Navier-Stokes equations, the following continuity equation in terms of averaged variables is derived:

$$\frac{\partial (1 - \phi_p)\rho}{\partial t} + \nabla \cdot (1 - \phi_p)\rho \vec{v} = 0$$

(2-11)

where $\rho$ is the fluid density and $\phi_p$ is the particle volume fraction in an Eulerian grid. The corresponding momentum equation is given by

$$\frac{\partial (1 - \phi_p)\rho \vec{v}}{\partial t} + \nabla \cdot (1 - \phi_p)\rho \vec{v} \vec{v} = -\nabla p + \nabla \cdot \left( (1 - \phi_p)\tau \right) + \nabla \left( (1 - \phi_p)\tau' \right) + (1 - \phi_p)\rho g - S$$

(2-12)

$\tau$ is the fluid viscous stress tensor, $\tau'$ is the Reynolds stress tensor and $S$ is the volumetric particle-fluid interaction force acting on each mesh cell. The equations governing the translational and rotational motions of particle $i$ are described as

$$m_i \frac{du_{p,i}}{dt} = m_i g + \sum_{j=1}^{k_i} F_{c,i,j} + F_{interaction,i}$$

(2-13)

$$I_i \frac{d\omega_{p,i}}{dt} = \sum_{j=1}^{k_i} T_{ij}$$

(2-14)

where $F_{c,i,j}$ is the contact force and $F_{interaction,i}$ shows the particle-fluid interaction. $u_{p,i}$ and $\omega_{p,i}$ are the linear and angular particle velocities. $m_i$, $I_i$, and $T_i$ denote the mass, the moment of inertia of the particle and torque acting on a particle respectively. $k_i$ is the number of particles interacting with particle $i$. 
2.2.2 Simulation results of pneumatic conveying

With regard to the advantages of numerical simulation mentioned, in this section the results of previous pneumatic conveying modelling are reviewed. The main focus will be on the application of RANS-DEM in pneumatic conveying simulation.

In one of the first attempts to apply DEM for numerical modelling of pneumatic conveying, Tsuji et al. (1992) applied 1D CFD and 3D DEM simulation for a dense conveying flow regime in a horizontal pipe. The Ergun equation was applied to model the fluid force acting on particles inside the plug. Due to the CPU time limitations, they used large particles ($d_p = 10$ mm) and a small number of particles in a short pipe. The plug velocity and the height of the stationary layer predicted by the model were in good agreement with the experiment. Lun and Liu (1997) performed a RANS-DEM modelling for a dilute horizontal particle laden channel flow for a low particle volume fraction in order of $10^{-3}$. They concluded that the particle-particle collisions and Magnus lift force had crucial effects to keep particles suspended in the channel. The authors ignored the influence of the dispersed phase on the carrier phase turbulence, and a conventional $k$-$\varepsilon$ was applied in the simulation. Fraige and Langston (2006) developed Tsuji’s model (Tsuji et al. (1992)) by correcting the pressure drop calculation in pneumatic conveying for 1D CFD and 3D DEM simulation. It was assumed that the fluid flow to be at steady state condition for each time step. The model could then successfully reproduce various flow patterns.

Li et al. (2005) developed a 2D RANS-DEM model to investigate plug formation and flow. The CFD package PHOENICS was employed in their simulations. The plug and settled layer of particles were created initially. They reported that, as the plug moved along the pipe, some particles were picked up from the settled particles by the plug and, on the other hand, at the end of the plug some particles fell into the bottom part of the pipe and formed the stationary layer. The simulation findings were also confirmed by recorded video footages.

In a 2D RANS and 3D DEM simulation for a narrow horizontal particle laden
channel flow, Kuang et al. (2008) also captured the exchange of particles between the particle settled layer and a moving plug. They also performed a force analysis on particles in a plug. Di Felice (1994) drag model was used in the simulations. The results showed that the axial particle-fluid interaction force was bigger than the radial particle-fluid force. In addition, the plug flow was driven by axial gas-solid and particle-wall interactions and the particle-particle interaction caused a plug to pick particles from the settled layer. Plug formation, plug flow and plug collapse also were investigated in Xiang and McGlinchey (2004)’s research in a 2D RANS-DEM simulations. Lim et al. (2006) applied RANS-DEM approach to reproduce various types of solid flow patterns in vertical and horizontal pipes. The numerically predicted flow regimes showed good consistency with the previously reported experimental observations by Rao et al. (2001) and Zhu et al. (2003). Stratified, moving dune, dense and dilute flow regimes were reproduced numerically for diverse operational conditions in horizontal pneumatic conveying; in vertical pneumatic conveying dilute and dense flow patterns were obtained.

Kuang and Yu (2011) could also predict the various flow regimes in 3D horizontal pneumatic conveying. However, the authors did not consider the gas phase turbulence alteration due to the presence of the dispersed phase. They also analyzed the magnitude of different forces acting on particles in each flow regime. Sturm et al. (2010) used an in-house DEM code coupled with the FLUENT CFD software to simulate a dense vertical pneumatic conveying and a dilute conveying in a 90° pipe elbow in 3D. For vertical pneumatic conveying, porosity distribution, plug velocity and pressure distribution were investigated. Plug velocity was over-predicted by the simulation compared to the experimental work by Niederreiter (2006) which was attributed to the particle-wall coefficient of friction and the drag model implemented. The model was also able to predict the particle roping i.e. the region with much higher solid concentration compared to the remainder of the pipe, and particle velocity reduction in the elbow.

Formation of the particle rope in an elbow was also found in the Yilmaz and Levy (2001) and Chu and Yu (2008) studies. Zhang et al. (2007) investigated the flow
regimes in a 45° inclined pneumatic conveying line. The Di Felice (1994) drag model was applied in the simulations and the fluid flow was assumed to be laminar which seems unrealistic for the experiments performed in their studies. Their RANS-DEM model could replicate the various flow regimes including dilute flow, reverse flow and half ring flow which were observed experimentally by PIV and ECT techniques. The effect of major forces i.e. drag force, electrostatic force, gravity and friction force acting on each individual particle was analysed for three different flow regimes. Results showed that the drag force was the dominant force in the dilute regions of different flow regimes. It was also shown that Coulombic electrostatic force was significant in the dense region of reverse flow and half ring flows. The authors concluded that the formation of reverse flow and half ring flow regimes might be attributed to electrostatic force.

Lun (2000) compared simulation results of mean gas and particle velocities and carrier phase turbulence intensity with the experimental measurements of Tsuji et al. (1984) for a dilute steady state flow in vertical pneumatic conveying. A modified $k-\omega$ turbulence model was used to take into account the effect of particles on the fluid phase turbulence level. Drag model suggested by Clift and Gauvin (1971) was applied in the simulations. The model could predict reasonably the mean gas and particle velocities. However, it only could capture the gas turbulence level trend qualitatively in the pipe. Fan et al. (1997)’s models could also predict the mean gas and particle velocities and gas turbulence intensity satisfactorily when compared with experimental results for dilute vertical pneumatic conveying. The gas phase assumed to be steady state and turbulence modulation was considered by adding source term to turbulence kinetic energy and dissipation terms in $k-\varepsilon$ model. Lain et al. (2002b) applied Reynolds-averaged conservation equations in connection with a full Reynolds stress turbulence model to describe the fluid phase. Particle-particle collisions were modelled using a stochastic approach (Sommerfeld (2001)) and the wall roughness was also taken into account to simulate the particle-wall collisions (Sommerfeld and Huber (1999)). Good agreement between experimental results by PDA and simulation results for the mean and RMS velocities of gas and particles in a
2D horizontal channel was observed. It was concluded that development of particle distribution in the channel depends strongly on the wall roughness and inter-particle collisions. This result was also mentioned in other studies by Huber and Sommerfeld (1998) and Sommerfeld (2003). Lain and Sommerfeld (2008) applied the model developed by Lain et al. (2002b) to investigate the pressure drop and gas and particle interaction in a 2D dilute horizontal channel. Turbulence reduction by 130 and 195 μm particles was captured by model with reasonable consistency with the experiments. They also concluded that the pressure drop increased by increasing the particle mass loading, particle size and wall roughness due to the increased particle-wall collision frequency. Lain and Sommerfeld (2012) also used the model developed by Lain et al. (2002b) for 3D particle laden flow in a pipe and a narrow channel with the same hydraulic diameter and length, to investigate the effect of conveying line geometry. Both $k-\varepsilon$ and Reynolds stress models were applied in the simulations. Results showed that the modulation of gas turbulent kinetic energy was more significant in the pipe than in the channel. Moreover, the pressure drop in the pipe was noticeably higher than the channel in the case of high wall roughness. This implied that higher energy is needed to transport the same amount of particles in a pipe than in a channel.

With the advancement of computer resources, RDPM approaches such as IB and LB have also been applied for three-dimensional systems containing particles collection up to several thousands. Examples include Ten Cate et al. (2004), Kajishima et al. (2001), Uhlmann (2005), García-Villalba et al. (2012) and Gao et al. (2013). Uhlmann (2008) applied the IB method to simulate a dilute turbulent particle laden flow in a vertical channel consisting of 4096 spherical particles. The simulation showed that the particles strongly altered the flow and led to the formation of a very large streamwise-elongated flow structure. The author pointed out the computational challenges for increasing the domain size with the presented algorithm. Yan and Koplik (2009) used the LB method to model particle laden flow in horizontal channel in a very low Reynolds number and for a very short length of channel. A stratified flow regime was modelled successfully. However, no precise comparison was made.
with the experiments. Shao et al. (2012) modelled particle laden turbulent flow in a horizontal channel for large and heavy particles for a relatively large solid volume fraction (up to 7%). They found that when the settling effect (gravity) is taken into account, most particles settle to the bottom wall where the particles accumulated in the low speed flow region.

The TFM modelling approach has also been applied to model pneumatic conveying systems particularly in dense flow regime. Examples include Pakhomov et al. (2007), Henthorn et al. (2005), Levy (2000), Bilirgen et al. (1998), Levy et al. (1997). However, as mentioned before, this method is not the main focus of this study. Therefore, the reader is referred to those studies for more details about application of TFM in pneumatic conveying modelling.

### 2.3 Turbulence modulation in particle laden flows

The carrier phase turbulence structure changes as the particulate phase is added to the clear fluid phase. This phenomenon is known as turbulence modulation in the literature (Elgobashi and Abou-Arab (1983)). Turbulence level alteration of the fluid phase is important because any change in the continuous phase turbulence has a direct influence on the fluid mean velocity, the effective viscosity of the fluid, the heat and mass transfer as well as particle mixing and dispersion (Kenning and Crowe (1997), Lightstone and Hodgson (2004), Fokeer et al. (2004)). It has also been pointed out that in a dilute phase particle laden flow the turbulence modulation impacts drastically on the conveying line pressure drop (Curtis and van Wachem (2004)). Lain et al. (2002a) highlighted the influence of the turbulence modulation on the prediction of the hydrodynamic behaviour of a bubble in a bubble column. Therefore, it seems that understanding the interaction between dispersed phase and fluid phase turbulence is one of the crucial steps in understanding the complex characteristics of two-phase systems.

Both attenuation and augmentation of fluid phase turbulence have been reported in previous studies; some researchers also reported both an increase and decrease in turbulence intensity by the addition of particles. Despite much research focused on
this topic, there is no generally proven explanation for the influence of the solid phase on the carrier phase (Crowe (2000), Mandø (2009)). In general, it is recognizable from previous studies that the small particles tend to suppress the carrier phase turbulence level while the large particles increase the fluid phase turbulence. Previous observations reveal that small particles (particle diameter, $d_p < 200 \, \mu m$) follow the fluid flow and as a result these particles may break the eddies. These small particles may be accelerated by eddies (dissipation of energy), and so extract kinetic energy from eddies leading to the reduction in the turbulence level of the fluid flow (Lightstone and Hodgson (2004), Geiss et al. (2004)). On the other hand, fluid flow turbulence augmentation by large particles can be explained as a result of the wake generated behind the particles. This wake creates an additional disturbance to the flow which may increase the level of turbulence. These phenomena are considered to be the core reasons of turbulence reduction and enhancement (Bolio and Sinclair (1995)).

In addition to these two predominant mechanisms, other factors such as fluid flow turbulence modification due to the particle-particle interaction, and changing the continuous phase velocity gradient are believed to be other influential reasons for turbulence modification (Yuan and Michaelides (1992)). However these mechanisms may be negligible in a dilute particle suspension. Lightstone and Hodgson (2004) also mentioned the influence of the crossing trajectory, i.e. large relative mean velocity between the particles and the turbulence eddies, as another source of gas phase turbulence generation. Some researchers have tried to formulate turbulence modulation based on the observation of experimental results (Crowe (2000), Mandø (2009)). However these formulations are valid only for the specific range of solid loading ratios and system specifications observed in each case.

### 2.4 Non-spherical particles in two-phase flow

In contrast to spherical particles, the motion of a non-spherical particle is dependent on the particle orientation, and particle shape can play a significant role on the particle-fluid interaction and particle dispersion in a two-phase flow. The motion of particles which are mathematically describable have been the subject of investigation
in literature. These shapes encompass cylinders, ellipsoids, cubes, disks and cones. It is desirable to define a single shape factor which can be used to describe all possible non-spherical particles. Some of the commonly used shape factors are Corey shape factor, roundness and sphericity (Mando et al. (2007)). Corey shape factor is defined as the ratio of the shortest particle axis to the square root of the product of the other two axes. Roundness is expressed as the ratio of the average radius of the curvature of the corners to the radius of the largest inscribed circle. The most widely applied of these shape factors is sphericity ($\psi$) which was suggested initially by Wadell (1933). It is defined as the ratio between surface of a sphere with the same volume as the particle and the surface area of the actual particle.

Non-spherical particle free fall has been subject of some studies. One of the first attempts was carried out by Jeffery (1922) in the Stokes regime. He theoretically calculated the torque acting along the ellipsoid principle axes. Bretherton (1962) and Brenner (1963) developed Jeffry’s finding for an arbitrary shape of particles in a creeping flow. Becker (1959) carried out a research on the effect of $Re_p$ on the non-spherical particle sedimentation. He observed for $5 < Re_p < 200$, particles oriented themselves in a direction in which drag force was maximum. For higher $Re_p$, the particle was settling while wobbling, rotating or a combination of both. Marchildon et al. (1964) studied a cylindrical particle settling in water over a wide range of aspect ratios, from 1.34 to 35 and $Re_p$ up to 1000. They observed for $Re_p < 0.05$ there was no preferred orientation for particles. For $0.05 < Re_p < 100$ particles oriented themselves in a direction in which the largest particle cross section was normal to the direction of particle motion. For the range of $100 < Re_p < 1000$ particles experienced secondary motion and for higher $Re_p$ fully developed secondary motion was observed. They also suggested that the particle frequency of oscillation might be related to cylindrical particle size and the ratio between fluid and particle densities.

Field et al. (1997) observed four different dynamic behaviours during the settlement of a disk-like particle, these being steady, tumbling, chaotic and periodic motion as a function of particle Reynolds number and dimensionless moment of inertia.
Background and literature review

\[ I^* = \frac{\pi \rho_p t_{disk}}{64 \rho d_{disk}} \]  

(2-15)

Here, \( t_{disk} \) is the disk thickness and \( d_{disk} \) is disk diameter.

Yin et al. (2003) studied the sedimentation of a cylindrical particle in a stagnant fluid experimentally and numerically. The particle motion recorded by a digital camera was used to evaluate the developed numerical code. The numerically predicted particle position during sedimentation and settling velocity agreed well with the experimental results.

Transportation of non-spherical particles in a pipe and channel was also investigated in a few studies. In a dilute vertical pneumatic conveying, Henthorn et al. (2005) measured a significantly higher pressure drop for flake-like particles (Sphericity = 0.39) compared to the spherical particles with the same equal volume sphere diameter and density. They concluded this was as a result of the higher drag force associated with the non-spherical particles.

Black and McQuay (2001) experimentally investigated the influence of particle shape on the particle dispersion in a vertical co-axial jet and swirling flow. Spherical and non-spherical particles had a same material and similar size distribution. By the aid of phase Doppler particle analyser (PDPA), for fine particles (30-70 \( \mu \)m) and solid loading ratio (SLR)=0.01 they observed that non-spherical particles responded faster to the changes in the gas flow. They concluded that for both co-axial and swirling flows particle shape had a significant effect on the particle velocity profile for regions with a high velocity gradient. However, for other locations with low velocity gradient, velocity profiles were almost the same for spherical and non-spherical particles.

Zhang et al. (2001) examined the transportation and deposition of very fine ellipsoidal particles in a dilute turbulent channel flow by means of DNS-DEM, in one way coupling simulation. They investigated the effect of parameters such as
particle aspect ratio, turbulence eddies and hydrodynamic forces on the deposition velocity in the near wall regions. Mortensen et al. (2008b) applied the same approach as Zhang et al. (2001) to simulate ellipsoidal particles in a turbulent shear flow. They found that in the near wall regions, the ellipsoidal particles tend to align themselves with the mean flow direction as reported previously by Zhang et al. (2001). This alignment increased with increasing the particle aspect ratio. In another study, Mortensen et al. (2008a) extended the Zhang et al. (2001) study for a larger geometry and finer mesh and provided the particle statistics for the whole cross section in a turbulent channel flow. They reported that the aspect ratio did not have a significant effect on the translational motion of ellipsoidal particles. However, both mean and fluctuating spin components depended critically on it.

Rosendahl (2000) also showed that the trajectories of cylindrical and ellipsoidal particles are different from spheres in a horizontal combustor. Hilton and Cleary (2009) and Hilton and Cleary (2012) investigated the effect of particle shape on flow regime in pneumatic conveying. They concluded that the particle shape had a significant influence on the bulk flow. They reported that, for a specific pressure gradient, a stable plug was formed for spherical particles while the plug formation was not seen for ellipsoidal particles.

Laín and Sommerfeld (2007) performed a study on the dilute pneumatic conveying of non-spherical particles in a horizontal channel. Phase Doppler anemometry technique was used to measure gas and particle velocities. They assumed the particles to be isometric, namely the ratio of the maximum length to the minimum length is below 1.7 (Mandø et al. (2007)); particle rotation and particle-particle interaction were neglected and lift force was not modelled. A qualitatively good comparison between experimental data and numerical simulation was observed.

Readers are referred to Lin et al. (2003)’s study for more information regarding the motion of non-spherical particles in a shear flow, during sedimentation and turbulent flow. A comprehensive review of the modelling of motion of non-spherical particles in a two-phase flow also was summarized by Mandø et al. (2007). Generally, it is
well known that the terminal velocity and drag coefficient of a non-spherical particle are dependent on the particle shape and orientation (Mandø et al. (2007)). Therefore, it is expected that a complete formulation of drag coefficient would be described as: 

\[ C_D = f(Re_p, \text{Shape}, \text{Orientation}) \]

Sørensen et al. (2007) and Hölzer and Sommerfeld (2008) presented formulae for \( C_D \) in which the particle orientation is also taken into account. Hölzer and Sommerfeld (2008) derived the \( C_D \) equation based on Leith (1987), Ganser (1993) and Tran-Cong et al. (2004) studies for an arbitrary particle. Sørensen et al. (2007) derived the model based on the sedimentation of a cylindrical particle in a stagnant flow. However, to have a less complex description of \( C_D \) in most of the formulations the orientation dependency of \( C_D \) is ignored. Examples include Hartman et al. (1994), Haider and Levenspiel (1989), Ganser (1993), Swamee and Ojha (1991), Thompson and Clark (1991) and Tran-Cong et al. (2004). Chhabra et al. (1999) did a comprehensive study on the drag coefficient for non-spherical particles such as cylinder, cone, disk and cube, concluding that overall best performance for a variety of shapes and orientation of a free falling particles was given by the Haider and Levenspiel (1989) and Ganser (1993) drag coefficients. The drag coefficient suggested by Haider and Levenspiel (1989), and Ganser (1993) are given in equations (2-16) and (2-18) respectively.

\[
C_D = \frac{24}{Re_p} \left(1 + ARe_p^B\right) + \frac{C}{D} \left(1 + \frac{1}{Re_p}\right)
\]

(2-16)

where

\[ A = \exp(2.3288 - 6.4581\psi + 2.4486\psi^2) \]
\[ B = 0.0964 + 0.5565\psi \]
\[ C = \exp(4.905 - 13.8944\psi + 18.4222\psi^2 - 10.2599\psi^3) \]
\[ D = \exp(1.4681 + 12.2584\psi - 20.7322\psi^2 + 15.8855\psi^3) \]

(2-17)
where $Re_p$ is calculated based on the equal volume sphere diameter, i.e. $d_e = \sqrt[3]{6V_p/\pi}$

$$C_D = \frac{24}{Re_pK_1} \left\{ 1 + 0.1118 (Re_pK_1K_2)^{0.6567} \right\}$$

$$+ \frac{0.4305}{1 + 3305/Re_pK_1K_2}$$

(2-18)

here again $Re_p$ is calculated based on the equal volume sphere diameter, and $K_1$ and $K_2$ are function of sphericity, and are calculated as:

$$K_1 = \left[ (d_n/3d_p) + (2/3)\psi^{-0.5} \right]^{-1}$$

$$K_2 = 10^{1.8148(-\log\psi)^{0.5743}}$$

(2-19)

where $d_n$ is the equal projected area circle diameter.
Chapter 3.

Experimental setup and conditions, gas velocity measurement and material specification

3.1 Introduction

In this chapter, an overview is presented about the pneumatic conveying apparatus used in this study. The specifications of the available laser Doppler anemometer (LDA) system are also presented. Data acquisition with LDA technique is discussed and clear gas velocity measurement results are presented. Moreover, particle specifications and experimental conditions are summarized.

3.2 Experimental setup and LDA specifications

Figure 3-1 displays the schematic sketch of the horizontal pneumatic conveying apparatus. As can be seen, the y negative direction is on the gravity direction, z positive axis is along the side of the pipe and the x positive direction is outward the paper. The pneumatic conveying system consists of a hopper, fan, cyclone and conveying line. The particles are pushed by a screw feeder from the hopper into the inclined pipe (inclined at 45°) which is connected to the horizontal pipe. The length of the inclined pipe is 0.35 m. Once inside the horizontal pipe, the fan sucks both the air and the particles into the cyclone, where the gas and particles are separated. The horizontal section is 6.5 m long and is connected to the vertical section (1.2 m) by a bend. The pipe internal diameter is 0.075 m. The measurements were carried out for three different cross sections in the horizontal section (shown by red arrows) at distances of 1 m, 2 m and 3 m from the point where the particles are introduced to the horizontal section. These cross sections are called z=1 m, z=2 m and z=3 m respectively. Air is used to transport particles in the pneumatic conveying. The particle flow rate can be regulated by adjusting the screw feeder revolutions per minutes (RPM) and air flow rate can also be regulated, these make it possible to obtain the desired solid loading ratio(SLR = solid mass flow rate/ gas mass flow rate)
in the conveying line. The three different mass loading ratios in this study are 2.3, 3 and 3.5.

When particles are transported through the glass pipe, static electricity is generated. This will have an effect on the particle flow in the conveying line. To reduce this effect the line has been earthed at three different locations at distances of 0.15 m, 1.75 m and 3.35 m from the point where the particles are introduced to the horizontal section. Pipes made from opaque materials (such as steel) cannot be used due to the laser-based technique.

![Figure 3-1: Schematic of pneumatic conveying system.](image)

In this work, the LDA technique is used to measure the mean axial gas and particle velocity components and axial fluctuating gas root mean square (RMS) velocity. The LDA system applied in the experiments is one-dimensional, which means only one velocity component can be measured in each experiment. The wavelength of the laser light is equal to 514 nm. The backscatter mode is used for all the experiments. The transmitting and receiving lens focal lengths are 800 mm. LDA system characteristics are presented in Table 3-1. More information about the LDA principles and specifications can be found in the Dantec Reference Guide (2000).
Experimental setup and conditions, gas velocity measurement and material specification

Table 3-1: LDA system specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam diameter (m)</td>
<td>2.2×10^{-3}</td>
</tr>
<tr>
<td>Beam half angle (°)</td>
<td>5.153</td>
</tr>
<tr>
<td>Number of fringes</td>
<td>42</td>
</tr>
<tr>
<td>Fringe spacing (m)</td>
<td>2.864×10^{-6}</td>
</tr>
<tr>
<td>Measurement volume $dx$ (m)</td>
<td>0.123×10^{-3}</td>
</tr>
<tr>
<td>Measurement volume $dy$ (m)</td>
<td>0.133×10^{-3}</td>
</tr>
<tr>
<td>Measurement volume $dz$ (m)</td>
<td>1.36×10^{-3}</td>
</tr>
</tbody>
</table>

The laser beams are refracted while passing through the pipe curved wall. As a result, there would be a deviation between the actual beams intersection point and the expected position (Lu (2009) and Doukelis et al. (1996)). Lu (2009) calculated and presented the deviation between the actual intersection point of the beams and the expected point in the horizontal and vertical planes for the present system at different probe angles, which is presented in Figure 3-2. As seen in Figure 3-2, generally for all measurement points and all probe angles the vertical deviation is smaller than the horizontal deviation. These graphs have been applied in the current study to find the measurement points precisely.

![Figure 3-2: Horizontal and vertical deviation of the intersection point for different probe angles, (Lu (2009)).](image)

The LDA system is mounted on a 3D traverse system allowing measurement in different locations. It should be noted that the LDA can only collect data at one point.
Experimental setup and conditions, gas velocity measurement and material specification

at a time. However, by moving the measurement point along the cross section, a profile measurement for a cross section is achieved. The first velocity measurement was at the pipe centre, and then the probes were moved horizontally or vertically to measure the gas and particle velocities for other measurement points across the pipe. The distance between every two measurement points was 5 mm for particle laden flow measurements.

The measurement reproducibility was checked by repeating the measurements three times, and each measurement was carried out for 50 seconds. The maximum number of samples for each measurement point was set to 100,000 and 5,000 for clear gas experiments and particle laden flows respectively.

3.3 Data acquisition with the LDA technique

To measure the gas velocity, the carrier phase is impregnated by seeding particles in the form of incense smoke. Smoke is added to the air at the beginning of the horizontal line. The particle velocity measurement can be performed separately by adding particles to the pneumatic conveying. Figure 3-3 shows an example of a set of raw results for particle velocity. The horizontal axis shows the measured particle velocity and the vertical axis represents the total of particle velocity count for each specific velocity range during the experiments. The raw data of axial velocity is used for the statistical analysis. The mean axial velocity for either particle or gas and the fluctuating gas RMS velocity at a sample point \((x, y, z)\) are calculated based on equations (2-7), (2-8) and (2-9). At each measurement point, a large number of samples are measured to obtain statistically reliable measurements of the mean and fluctuating velocity components of each phase.
Simultaneous measurement of gas and particle velocities can also be carried out. For this, incense smoke and particles are injected into the pipe simultaneously. For the present study, the size difference between the incense smoke particles and the test particles is considerable, mandating that only one velocity can be measured at any given time. In fact, the large size of test particles compared to the seeding particles ensures the clearly distinguishable measurement of either gas or particle velocity. Figure 3-4 shows a typical set of raw results for simultaneously measured gas and particle velocities. The velocity probability density function (PDF) with the higher velocity represents the gas velocity measured during the experiment and the PDF with the lower velocity shows the particle velocity values. The horizontal axis shows either gas or particle velocity and the vertical axis represents the total of particle or gas velocities count for each specific velocity range during the experiments. In the post-processing of the acquired data, the velocity filtering approach is applied on the velocity probability density function. Therefore, the velocities of the two phases can be distinguished and the requested information for gas or particle phase is derived.
Errors associated with the velocity and carrier phase turbulence intensity measurements are presented by error bars based on the standard deviation (Std) in this study. These errors can be estimated as follows (Berendsen (2011)):

\[
\text{Uncertainty} = \left( \frac{\text{Std}(\sigma)}{\sigma} \right)^2 + \left( \frac{\text{Std}(V_{rms})}{V_{rms}} \right)^2
\]

### 3.5 Clear gas velocity measurement

Single phase gas flow dynamic was investigated by injecting incense smoke into the system, which acts as a tracer. The size of the incense particles is less than 10 μm (Fang et al. (2002)). This size is in the range of the tracer particles size suggested by Dantec Dynamics, the manufacturer of the LDA system. In the current study by altering the fan speed three different gas velocities are produced inside the transportation line. It is known that the turbulent velocity profile in a circular pipe can be expressed by the empirical equations, power law equation, as follows (Benedict (1924)):
Experimental setup and conditions, gas velocity measurement and material specification

\[
\frac{V}{V_{\text{max}}} = \left(1 - \frac{r}{R}\right)^{1/n}
\]

(3-1)

\[
\frac{V}{V_{\text{max}}} = \frac{2n^2}{(n + 1)(2n + 1)}
\]

(3-2)

where \(V_{\text{max}}\) is the maximum value of \(V\) in the pipe cross section and \(R\) is the pipe radius; \(r\) is the distance from the pipe centre and \(n\) is the empirical exponent factor dependent on Reynolds number. The value of \(n\) is six when the Reynolds number is equal to 4000, and \(n=7\) when \(Re=110,000\). With regards to the air velocity in the experiments \(Re\) number at the pipe centre for three different motor speeds are much higher than 4000, therefore \(n=7\) is selected in this study (Benedict (1924)). In order to compare the cross-sectional data of air velocity with the empirical profile estimated by equation (3-1), the experimental data and the empirical profile are plotted together in Figure 3-5. The point \(r/R=0\) indicates the pipe centre. Comparison of the experimental data with the empirical velocity profile indicates that they have a good agreement and a similar shape, the average error being around 3\% with the maximum deviation, for one point only, being 11\%. By using equation (3-2), the average gas velocity is calculated for three different motor speeds which are 9.5, 8.5 and 7 m/s respectively.
Experimental setup and conditions, gas velocity measurement and material specification

The clear gas velocity measurements at cross sections $z=1$ m and $z=3$ m are presented in Appendix A.

3.6 Particle specification

The particles selected in this study are spherical glass beads and cylindrical polyamide6. Particles chosen for experiments with the laser technique need to reflect light and not be degraded during the experiments. Glass beads in three different sizes (0.9 mm, 1.5 mm and 2 mm) with density 2540 kg/m$^3$, and cylindrical polyamide6 with the size of 1×1.5 mm with density of 1140 kg/m$^3$ were chosen in this study. The
0.9 mm glass beads particles have a wide size distribution, with particle sizes ranging between 0.8 mm to 1 mm with a mean particle size of 0.9 mm. These particle sizes give a reasonable time step in the numerical work and guarantee a reasonable computational time; their sizes also diminish issues such as cohesion and agglomeration associated with very fine powder. For spherical glass beads, the particle flow rates were set to 0.1128 kg/s, 0.1277 kg/s and 0.1329 kg/s. For cylindrical Polyamide6, particle flow rates were fixed at 0.0296 kg/s and 0.04467 kg/s. Particle mass flow was measured by weighing particles before starting the experiments and the particles were separated from the flow in the cyclone at the end of the rig for reuse.

3.7 Experimental conditions

By combining the three different mean gas velocities with fine adjustments of the screw feeder speed, different SLRs were produced. For spherical glass beads, the resulting SLRs were 2.3, 3 and 3.5. It is worth mentioning that for a particle size 2 mm and SLR=3.5, the pneumatic conveying mode changed from dilute to dense and as a result the LDA technique could not be applied. For cylindrical polyamide6, SLRs were equal to 0.6, 1, 1.2. Details of the experimental conditions are summarized in Table 3-3. In all experiments with spherical particles the mean gas and particle velocities as well as the carrier phase turbulence intensity were measured in horizontal and vertical profiles. Horizontal profile of mean particle velocity was also measured for cylindrical polyamide6 particles.
Table 3-3: Summary of experimental conditions

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<th>Case 3</th>
<th>Case 4</th>
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<td>Spherical</td>
<td>Spherical</td>
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<td>Spherical</td>
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<td>9.5</td>
<td>8.5</td>
<td>7</td>
<td>9.5</td>
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<td>0.1128</td>
<td>0.1329</td>
<td>0.1277</td>
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<th>Case 10</th>
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</tr>
</thead>
<tbody>
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<td>Cylindrical</td>
<td>Cylindrical</td>
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<td>Particle size (mm)</td>
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<td>1×1.5</td>
<td>1×1.5</td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
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<td>7</td>
<td>9.5</td>
<td>8.5</td>
<td>7</td>
</tr>
<tr>
<td>Particle mass flow rate (kg/s)</td>
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<td>0.1277</td>
<td>0.0296</td>
<td>0.04467</td>
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<td>0.6</td>
<td>1</td>
<td>1.2</td>
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</table>
Chapter 4.

Experimental results of particle laden flow with spherical particles

4.1 Introduction

In this chapter the experimental results for horizontal and vertical profiles of mean axial particle and gas velocities are presented. The fluctuating gas RMS velocity ($V'_{rms}$) is also measured in the axial direction which is used to calculate the carrier phase turbulence intensity values. Turbulence intensity for clear gas and particle laden flow are compared to determine the influence of the presence of the particles on the gas turbulence intensity. Generally the aim of this chapter is to investigate the influence of the solid loading ratio and particle size on the particle velocity and carrier phase turbulence intensity as well as to collect a detailed data set for use in RANS-DEM model validation.

4.2 Effect of solid loading ratio and particle size on the horizontal profile of particle velocity

In this section the effect of solid loading ratio (SLR) and particle size on the mean axial particle velocity for three different cross sections are investigated. In all figures in this chapter Radius=0 shows the pipe centre, a positive radius shows the measurement points toward one side of the pipe wall and radius in the negative direction shows the measurement points toward the other side of the pipe. All error bars shown on the graph in this chapter are calculated as per the methods explained in section 3.4.

In Figure 4-1, horizontal profile of mean axial particle velocity for different SLRs are shown at $z=1$ m. From Figure 4-1 it can be seen that, by increasing the SLR, the mean particle velocity decreases. This was expected since, based on the definition of SLR, a higher SLR means a higher particle flow rate and/or a lower gas velocity. Generally, the mean axial particle velocity profiles seen in Figure 4-1 are flat at the
Experimental results of particle laden flow with spherical particles

pipe centre and decrease slightly toward the pipe wall as previously reported by Mathiesen et al (1999). This tendency is more observable for 2 mm glass beads and a clear decrease in particle axial velocity is seen close to the wall (right hand side).

Figure 4-2 shows the influence of particle size on the horizontal profile of mean axial particle velocity at z=1 m. It is seen that at a constant SLR, the 0.9 mm glass beads achieves the highest velocity, since these particles are lighter compared with the other two sizes of particles used in the experiments.
Experimental results of particle laden flow with spherical particles

Figure 4-1: Effect of solid loading ratio on the horizontal profile of mean axial particle velocity, $z=1$ m.
Figure 4-2 Effect of particle size on the horizontal profile of mean axial particle velocity, \(z=1\) m.

Measurements similar to those in Figure 4-1 and Figure 4-2 were performed for \(z=2\) m and \(z=3\) m as can be seen in Figure 4-3, Figure 4-4, Figure 4-5 and Figure 4-6. The influence of SLR and particle size on the horizontal profile of mean axial particle velocity at these cross sections was similar to what was observed for cross section \(z=1\) m. From Figure 4-3 and Figure 4-5 it is seen that the particle velocity profiles reduced slightly when approaching the pipe wall and mean axial particle velocities decreased with increasing SLRs. From Figure 4-4 and Figure 4-6 it is concluded that, for a constant SLR, 0.9 mm particles reached the highest particle velocity, showing that the lighter the particle, the higher the particle velocity.
Figure 4-3: Effect of solid loading ratio on the horizontal profile of mean axial particle velocity, \( z=2 \) m.
Figure 4-4: Effect of particle size on the horizontal profile of mean axial particle velocity, z=2 m.
Figure 4-5: Effect of solid loading ratio on the horizontal profile of mean axial particle velocity, z=3 m.
Experimental results of particle laden flow with spherical particles

As can be seen from Figure 4-1 to Figure 4-6, horizontal profiles of mean axial particle velocity are not completely symmetrical. This can be explained by the fact that the particles enter to the inclined pipe from the right hand side of the pipe.
Experimental results of particle laden flow with spherical particles

(considered from the positive x direction) where the screw feeder has been installed, which leads to an uneven distribution of particles across the conveying line. Therefore, it is highly possible that the number of particles in one side of the pipe is different from the number of particles in another side.

Comparison between the mean axial particle velocities at different cross sections are shown in Figure 4-7 to Figure 4-9. These figures reveal that the particle velocity increases noticeably from cross section $z=1$ m to $z=2$ m, showing that particles are still in the accelerating zone. However, as can be seen in these figures, the particle velocities between cross sections $z=2$ m and $z=3$ m are close for SLR=2.3 and SLR=3, demonstrating that particles are entering into the steady-state zone where the flow is fully developed. This dynamic behaviour is seen for all particle sizes. This is less obvious for SLR=3.5 for all particle sizes.

For a turbulent single phase gas flow, a fully developed velocity profile occurs when pipe length/pipe diameter $> 40$ (Benedict (1924)); in fact pipe length is the only criterion needed to reach to the fully developed flow. Mandø (2009) mentioned that, in contrast to the single phase gas flow, the pipe length is not a sufficient criterion that a particle laden flow can be claimed as a fully developed flow, since the particle fluctuating velocity is strongly dependant on the pipe roughness and the initial condition. Govan et al. (1989) carried out an experiment on a 20 m vertical transportation line, with $D_{\text{pipe}}=0.032$ m. He concluded that the fully developed flow was not observed after 19 m. Therefore, it seems that to achieve to a fully developed particle laden flow, a pipe length is required which may be difficult to fit it in the laboratory. Since the final objective of this work is to provide a data set to validate the RANS-DEM code, the length of the conveying line was selected in a range that enables computer modelling in a reasonable time frame. However, the fact that the particles as measured remain in the acceleration zone must be taken into account in the simulation work described in Chapter 6 and Chapter 7.
Figure 4-7: Horizontal profiles of mean axial particle velocity at different cross sections, 0.9 mm.
Figure 4-8: Horizontal profiles of mean axial particle velocity at different cross sections, 1.5 mm.
Experimental results of particle laden flow with spherical particles

Figure 4-9: Horizontal profiles of mean axial particle velocity at different cross sections, 2 mm.

4.3 Effect of solid loading ratio and particle size on the vertical profile of particle velocity

Figure 4-10 demonstrates the vertical profiles of mean axial particle velocity for different SLRs at z=1 m. It can be seen that the particle velocity is smaller at the bottom of the pipe where more particles are transported compared with the pipe upper section. Particle velocity increases from the bottom toward the pipe centre and reaches a maximum value in the pipe upper section. It then decreases again in the areas near the upper wall of the pipe. This trend is more obvious for 0.9 mm glass beads. Moreover, for all particle sizes, the particle velocity decreases by increasing SLRs, similar to what was seen in the horizontal profile of mean axial particle velocity in section 4.2.
Experimental results of particle laden flow with spherical particles

Figure 4-10: Effect of solid loading ratio on the vertical profile of mean axial particle velocity, z=1 m.

In Figure 4-11 vertical profiles of mean axial particle velocity for different particle sizes at a constant SLR at z=1 m are shown. It is seen that, for most of the measurement points, the smaller the particle size the higher the particle velocity.
However, at the bottom of the pipe, particle velocities for different particle sizes are relatively close. For SLR=3 and SLR=3.5, the 0.9 mm glass beads velocity is smaller than 1.5 mm glass beads velocity for the measurement points close to the bottom of the pipe. This can be attributed to the number of particles transported at the constant SLR. The number of particles at the bottom of the pipe is noticeably higher for 0.9 mm particles compared to 1.5 mm particles. This can lead to the tighter packing of the particles and higher particle-particle collisions leading to the smaller particle velocity for 0.9 mm particles.
To investigate the influence of SLR and particle size on the vertical profiles of mean axial particle velocity at other pipe cross sections, measurements similar to those in Figure 4-10 and Figure 4-11 were performed at $z=2$ m and $z=3$ m. Measurement results can be seen in Figure 4-12 to Figure 4-15. Vertical profiles of mean axial particle velocity at these cross sections show similar trends to those observed for the cross section $z=1$ m. The mean particle velocity is smaller at the lower section of the pipe. Particle velocity peaks at a point in the pipe upper section and decreases near the pipe upper wall. It is also seen that by increasing the SLR the particle velocity decreases (Figure 4-12 and Figure 4-14). From Figure 4-13 and Figure 4-15, it is seen that the particle velocities for various particle sizes are very close at the bottom of the pipe. Obviously at a constant SLR the number of particles of 0.9 mm particles is more than the number of particles of 1.5 and 2 mm particles. As a result, at the bottom of the pipe, there are more particle-particle and particle-wall contacts for 0.9 mm particles than for 1.5 mm and 2 mm particles, which lead to the noticeable particle velocity drop for 0.9 mm particles. Therefore, although 0.9 mm glass beads are lighter than 1.5 and 2 mm particles but they are transported with almost the same velocity as 1.5 and 2 mm glass beads at the bottom of the conveying line.
Experimental results of particle laden flow with spherical particles

Figure 4-12: Effect of solid loading ratio on the vertical profile of mean axial particle velocity, $z=2$ m.
Figure 4-13: Effect of particle size on the vertical profile of mean axial particle velocity, $z=2$ m.
Experimental results of particle laden flow with spherical particles

Figure 4-14: Effect of solid loading ratio on the vertical profile of mean axial particle velocity, z=3 m.
The vertical profiles of mean axial particle velocities at different cross sections for a specific particle size are compared in Figure 4-16 to Figure 4-18. These figures show that particle velocity increases from cross section \(z=1\) m to \(z=3\) m for all particle sizes. However, as mentioned in the previous section, the particle velocity increase
Experimental results of particle laden flow with spherical particles

between cross sections $z=2$ m and $z=3$ m is smaller than the particle velocity increase between cross sections $z=1$ m and $z=2$ m (except for 0.9 mm, SLR=3.5). Again it may be concluded that particles are in the acceleration zone between cross section $z=1$ m and $z=2$ m. The close particle velocity profiles at $z=2$ m and $z=3$ m may imply that particles are entering the steady state zone for SLR=2.3 and SLR=3.
Figure 4-16: Vertical profiles of mean axial particle velocity at different cross sections, 0.9 mm.
Experimental results of particle laden flow with spherical particles

Figure 4-17: Vertical profiles of mean axial particle velocity at different cross sections, 1.5 mm.

Figure 4-18: Vertical profiles of mean axial particle velocity at different cross sections, 2 mm.
4.4 Experimental measurements of turbulence modulation due to the presence of spherical particles

4.4.1 Introduction

In this section, turbulence alteration due to addition of spherical glass beads is investigated.

According to the explanation regarding the turbulence modulation presented in section 2.3, it seems that particle size, particle concentration (loading), fluid velocity and ratio of particle to fluid length scale are important parameters to evaluate the turbulence modulation. These four parameters may be expressed as mass/volumetric solid loading, the ratio of particle diameter to the fluid turbulence length scale, particle Reynolds number ($Re_p$) and Stokes number ($St$) (Fokeer et al. (2004), Mandø (2009), Yarin and Hetsroni (1994) and Gouesbet and Berlemont (1998)). In the following sections, firstly the influence of each of these parameters on the turbulence modulation is elucidated and the experimental results are checked against these criteria. Afterwards, the experimental results related to turbulence modulation obtained by LDA are discussed. To examine the turbulence modulation experimentally, the particles are added to the carrier phase and the continuous phase turbulence level in the presence of particles is compared with the turbulence level of the clear flow (particle free flow) while all other parameters such as gas velocity are kept constant for both cases.

4.4.2 Particle mass/volumetric loading

Particle loading is one of the important parameters that has a direct influence on the degree of the turbulence modulation (Fan et al. (1997)). The magnitude of turbulence modulation is proportional to the particle loading. Elghobashi (1994) presented a graph providing the importance of the interaction between solid phase and turbulence. The graph is plotted based on the particle volume fraction $\phi_p$ versus the ratio of the particle response time to the relevant time scale of turbulence, $\tau_p/\tau_e$, as is seen in Figure 4-19.
Experimental results of particle laden flow with spherical particles

Figure 4-19: Map of regimes of interaction between particles and turbulence (Elghobashi (1994)).

For particle volume fraction less than $10^{-6}$, the influence of particles on the fluid phase turbulence is weak. For particle volume fraction in the range $10^{-6} < \phi_p < 10^{-3}$, the particles can augment or attenuate the carrier phase turbulence depending on the ratio of $\tau_p/\tau_e$. For $\tau_p/\tau_e < 1$, the turbulence is reduced by the particle presence while for $\tau_p/\tau_e > 1$ the carrier phase turbulence is enhanced. Elghobashi (1994) also explained turbulence augmentation due to the wake formation. For higher particle volume fractions, $\phi_p > 10^{-3}$, particle-particle collision plays a crucial role in the particle dispersion and the turbulence level of the continuous phase is influenced by particle collision.

It is necessary to consider particle density and particle size, as these parameters determine the number of particles interacting with the fluid phase. Geiss et al. (2004) reported that the turbulence modulation was observed only when the minimum required particle loading is passed. For instance for 120 $\mu$m particles, a number density of 30-40 particles/cc corresponding to a particle volume fraction of $\phi_p = 2.8 \times 10^{-5}$ to $3.7 \times 10^{-5}$ and a mass fraction of 0.058 to 0.077 was found to be the threshold to observe carrier phase turbulence modulation. Fan et al. (1996) also reported turbulence modulation to be strongly dependent on the mass loading and particle diameter.
4.4.3 Effect of length scale ratio

Gore and Crowe (1989) reviewed the wide range of experimental data for pipe and jet flows and suggested that the ratio of particle diameter ($d_p$) to the integral length scale ($l_e$) may be used as a criterion to examine the augmentation or attenuation of turbulence level. The summary of their study was presented in a graph as can be seen in Figure 4-20. Turbulence intensity and percentage change in turbulence intensity are calculated as follows

$$Turbulence\ intensity\ (\sigma) = \frac{V'_{rms}}{\bar{V}}$$

(4-1)

$$The\ percentage\ change\ in\ turbulence\ intensity = \frac{\sigma_{TP} - \sigma_{F}}{\sigma_{F}} \times 100$$

(4-2)

Here $\sigma_{TP}$ denotes the turbulence intensity of the particle laden flow and $\sigma_{F}$ is the turbulence intensity of the clear gas.

As seen in the graph, the length scale ratio 0.1 is a distinguishing point for the turbulence modulation; for a length scale ratio $d_p/l_e < 0.1$, turbulence intensity decreases while for $d_p/l_e > 0.1$, particles tend to increase the turbulence intensity.

Figure 4-20: Change in turbulence intensity vs length scale ratio, (Gore and Crowe (1989)).
The integral length scale for a fully developed turbulent flow in a pipe over different Reynolds numbers can be expressed as $l_e = 0.1D_{pipe}$ (Hutchinson et al. (1971)). So for a pipe flow, the length scale ratio depends only on the pipe diameter. Overall, the graph in Figure 4-20 implies that small particles decrease and large particles amplify the turbulence intensity.

### 4.4.4 Effect of particle Reynolds number ($Re_p$)

Another criterion to evaluate the increase or decrease of the fluid phase turbulence intensity was proposed by Hetsroni (1989) and is based on the particle Reynolds number.

$$Re_p = \frac{\rho(v - u_p)d_p}{\mu}$$

(4-3)

He investigated various experimental data for horizontal and vertical two-phase pipe flows and concluded that particles with $Re_p$ higher than 400 tend to increase the turbulence intensity due to vortex shedding (detachment of eddies created in the wake of particles (Geiss et al. (2004))) from particles, while particles with $Re_p$ less than 400 tend to suppress the turbulence intensity. Yuan and Michaelides (1992) also noted that a wake behind a particle is formed for $Re_p > 20$ and for $Re_p > 400$ vortices are shed behind the solid particles. Lun (2000) also reported that turbulence modulation depends significantly on $Re_p$; however he found vortex shedding occurs when $Re_p$ is around 300. He observed that particles tend to attenuate the carrier phase turbulence when $Re_p < 300$, whilst on the other hand if the $Re_p$ is more than a critical $Re_p$, turbulence enhances.

### 4.4.5 Effect of Stokes number ($St$)

Another important parameter to investigate the turbulence modulation phenomenon is Stokes Number ($St$), which represents the ratio of solid response time to a time scale of the fluid. $St$ may be defined as follows:

$$St = \frac{\tau_p}{\tau_e} = \frac{\tau_v/f}{l_e/V_{rms}}$$

(4-4)
Here $\tau_p$ is the particle response time and $\tau_e$ is the eddy turnover time. $\tau_v$ is the Stokesian response time defined by equation (4-5); $f$ is the ratio of the drag coefficient to the Stokes drag.

$$\tau_v = \frac{\rho_p d_p^2}{18 \mu}$$

As can be seen in Figure 4-19, for $10^{-6} < \phi_p < 10^{-3}$, particles with a $St$ value bigger than 1.0 tend to increase the fluid phase turbulence and particles with $St$ smaller than 1.0 tend to decrease the fluid phase turbulence. In fact, small particles with $St$ smaller than 1.0 follow the fluid and eddy kinetic energy is transferred to those particles with the result that turbulence is attenuated. On the other hand, particles with high $St$ number are less affected by the fluid field (Tang et al. (1992)).

Although many of the experimental measurements match well with the 4 criteria mentioned in sections 4.4.2 to 4.4.5, Mandø (2009) and Geiss et al. (2004) commented that turbulence modulation is a more complex phenomenon than can be evaluated only by $Re_p$, $St$ or length scale ratio. For instance, Mandø (2009) reported turbulence suppression for spherical particles ($d_p = 0.9$, 1.3 and 1.8 mm) even for $d_p/l_e > 0.1$ in a vertical jet flow. He also experimentally observed that for a $Re_p$ smaller than 400, both turbulence augmentation and attenuation could happen, which is not correlated well with the criterion stated by Hetsoni (1989).

**4.4.6 Experimental data evaluation**

Experimental data obtained by the LDA technique in this study are used to calculate length scale ratio, $Re_p$ and $St$ at the pipe centre. The purpose of this section is to predict whether turbulence augmentation or attenuation is expected in the current study before detailed investigation of carrier phase turbulence modulation phenomenon in the next section.
Experimental results of particle laden flow with spherical particles

Length scale ratios for the experimental conditions in the present study (close to the centre of the pipe) are summarized in Table 4-1. As mentioned by Hutchinson et al. (1971) for the region close to the pipe centre the integral length scale $l_e = 0.1D_{pipe}$.

<table>
<thead>
<tr>
<th>Particle diameter (mm)</th>
<th>Length scale ratio $d_p/l_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.27</td>
</tr>
<tr>
<td>1.5</td>
<td>0.2</td>
</tr>
<tr>
<td>0.9</td>
<td>0.11-0.13</td>
</tr>
</tbody>
</table>

Comparing to the Gore and Crowe (1989) criterion, which was mentioned in section 4.4.3, the calculated length scale ratios are higher than 0.1, implying that the particles in this study tend to enhance the turbulence intensity of the carrier phase flow. For 0.9 mm particles, the length scale ratio is close to the threshold of 0.1.

Gas and particle velocities are measured at the pipe centre to calculate $Re_p$. The gas density and viscosity are 1.2 kg/m³ and 1.78×$10^{-5}$ Pa.s respectively. The $Re_p$ was calculated for three different cross sections and for three different particle sizes. The $Re_p$ ranges from around 340 for 0.9 mm particle at the cross section $z=3$ m for SLR=3.5 to 1200 for 2 mm particle at the cross section $z=1$ m for SLR=2.3. As can be seen in Table 4-2, the value of $Re_p$ is close to 400 for the 0.9 mm particles at all cross sections. For 1.5 and 2 mm particles, $Re_p$ is greater than 400 at all measurement points. Therefore, based on the Hetsroni (1989) criterion, carrier phase turbulence augmentation should be observed for these experimental conditions.

<table>
<thead>
<tr>
<th></th>
<th>2 mm, $z=1$ m</th>
<th>2 mm, $z=2$ m</th>
<th>2 mm, $z=3$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLR=2.3</td>
<td>1208</td>
<td>1164</td>
<td>1135</td>
</tr>
<tr>
<td>SLR=3</td>
<td>1117</td>
<td>1089</td>
<td>1072</td>
</tr>
<tr>
<td>1.5 mm, $z=1$ m</td>
<td>875</td>
<td>821</td>
<td>821</td>
</tr>
<tr>
<td>SLR=2.3</td>
<td>819</td>
<td>792</td>
<td>789</td>
</tr>
<tr>
<td>SLR=3</td>
<td>690</td>
<td>682</td>
<td>668</td>
</tr>
<tr>
<td>0.9 mm, $z=1$ m</td>
<td>489</td>
<td>461</td>
<td>457</td>
</tr>
<tr>
<td>SLR=2.3</td>
<td>458</td>
<td>437</td>
<td>433</td>
</tr>
<tr>
<td>SLR=3</td>
<td>399</td>
<td>364</td>
<td>341</td>
</tr>
</tbody>
</table>
Experimental results of particle laden flow with spherical particles

Gas and particle velocities at the pipe centre are used to calculate the $St$, as is summarized in Table 4-3 for 0.9 mm particle. As seen the $St$ is much greater than unity for the 0.9 mm particles in the current study. Obviously the corresponding $St$ numbers for 1.5 and 2 mm particles are higher than the values in Table 4-3, implying that the turbulence production is expected in the current study based on the $St$ number criterion.

<table>
<thead>
<tr>
<th>SLR=2.3</th>
<th>0.9 mm, z=1 m</th>
<th>0.9 mm, z=2 m</th>
<th>0.9 mm, z=3 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>48</td>
<td>42</td>
<td>54</td>
</tr>
<tr>
<td>SLR=3</td>
<td>51</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>SLR=3.5</td>
<td>61</td>
<td>62</td>
<td>65</td>
</tr>
</tbody>
</table>

Based on the initial evaluation of the experimental results, we may conclude that the turbulence intensity is expected to increase in this study in agreement with previous research. Almost all the values calculated in these sections confirm that the turbulence level augmentation is expected.

To investigate the turbulence modulation phenomenon with more details, turbulence intensity and percentage change in turbulence intensity are calculated in the next sections.

4.4.7 LDA measurements of horizontal profile of mean axial gas velocity and turbulence modulation in particle laden flow

To evaluate the turbulence modulation phenomenon, spherical glass beads were added to the carrier phase. The carrier phase turbulence intensity (equation (4-1)) was calculated twice- first for particle free air flow and then for particle laden flow while experimental conditions such as gas flow rate were kept similar for both types of experiment. As explained before, the velocity difference between the fluid phase and glass beads is large enough that the discrimination between LDA signals for each phase is easily recognisable (Tsuji and Morikawa (1982)). The particle characteristics were varied by changing the particle size and solid loading ratios. The mean axial gas velocity and fluctuating gas velocity in axial direction are the most significant velocity components. Therefore the evaluation of turbulence modulation
Experimental results of particle laden flow with spherical particles

is based solely on these parameters (Mandø (2009)). The turbulence intensity and the percentage change in turbulence intensity are calculated based on equations (4-1) and (4-2)).

In the following sections turbulence intensity, percentage change in turbulence intensity and the influence of particles on the mean axial gas velocity are presented for different particle sizes and SLRs at cross section z=2 m. Further measurements for other cross sections are presented in Appendix A.

As it can be seen in Figure 4-21 (a), for both particle free and particle laden flows, turbulence intensity increases gradually from the centre of the pipe toward the pipe wall. Moreover, it is seen that by adding particles into the clear flow, turbulence intensity enhances. Percentage change in the turbulence intensity of around 35% is seen at the pipe centreline (Figure 4-21 (b)). Turbulence intensity changes are not the same for the two sides of the pipe, showing that particles are not distributed evenly which is related to the way that particles are introduced into the pneumatic line. The horizontal profile of mean axial gas velocity plotted in Figure 4-21 (c), demonstrates that mean axial gas velocity decreases by the addition of particles to the clear gas flow. The particle acceleration is extracted from the fluid momentum leading to a decrease in the gas velocity. The mean axial gas velocity profile for the particle laden flow becomes flat in comparison to the clear gas flow.
Experimental results of particle laden flow with spherical particles

For the same cross section ($z=2$ m) and particle size 0.9 mm, the turbulence intensity, percentage change in the turbulence intensity and horizontal profile of mean axial gas velocity were plotted for SLR=3 and SLR=3.5 in Figure 4-22 and Figure 4-23.
respectively. Similar trends are seen in these figures as explained before for Figure 4-21. A percentage change in turbulence intensity of more than 100% is seen close to the pipe centre for both SLR=3 and SLR=3.5.

Figure 4-22: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR =3, z=2 m.
Figure 4-23: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR =3.5, z=2 m.

Turbulence intensity for three different clear gas flows and turbulence intensity of particle laden flows with three different SLRs in the presence of 0.9 mm glass beads at z=2 m are summarized in Figure 4-24. As it can be seen for all of the measurement
points, the higher the SLR the higher the carrier phase turbulence intensity. This is more obvious when turbulence intensity of particle laden flow with SLR=2.3 is compared with the turbulence intensity of particle laden flow with SLR=3.5. This behaviour is in the good agreement with the previously reported results by Lightstone and Hodgson (2004) in which for large particles, increasing the particle volume fraction enhances the turbulence level of the flow. Curtis and van Wachem (2004) also mentioned that an increase in SLR for large particles tends to further increase the gas turbulence intensity.

Percentage changes in the turbulence intensity with 0.9 mm glass beads at z=2 m for three different SLRs also are summarized in Figure 4-25 and Table 4-4. It is seen that in all of the measurement points, the maximum percentage changes occur for the SLR=3.5 and the minimum percentage changes occur for SLR=2.3.

![Figure 4-24: Effect of SLR on the turbulence intensity, 0.9 mm glass beads, z=2 m.](image)
Figure 4-25: Effect of SLR on the percentage change in turbulence intensity, 0.9 mm glass beads, z=2 m.

Table 4-4: Percentage change in the turbulence intensity, 0.9 mm glass beads, z=2 m

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>SLR=2.3</th>
<th>SLR=3</th>
<th>SLR=3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.030</td>
<td>31</td>
<td>67</td>
<td>95</td>
</tr>
<tr>
<td>-0.025</td>
<td>37</td>
<td>74</td>
<td>88</td>
</tr>
<tr>
<td>-0.020</td>
<td>17</td>
<td>82</td>
<td>91</td>
</tr>
<tr>
<td>-0.015</td>
<td>21</td>
<td>63</td>
<td>117</td>
</tr>
<tr>
<td>-0.010</td>
<td>39</td>
<td>80</td>
<td>116</td>
</tr>
<tr>
<td>-0.005</td>
<td>36</td>
<td>75</td>
<td>105</td>
</tr>
<tr>
<td>0</td>
<td>35</td>
<td>90</td>
<td>111</td>
</tr>
<tr>
<td>0.005</td>
<td>50</td>
<td>113</td>
<td>123</td>
</tr>
<tr>
<td>0.010</td>
<td>45</td>
<td>111</td>
<td>140</td>
</tr>
<tr>
<td>0.015</td>
<td>55</td>
<td>82</td>
<td>129</td>
</tr>
<tr>
<td>0.020</td>
<td>50</td>
<td>81</td>
<td>112</td>
</tr>
<tr>
<td>0.025</td>
<td>24</td>
<td>76</td>
<td>78</td>
</tr>
<tr>
<td>0.030</td>
<td>34</td>
<td>67</td>
<td>100</td>
</tr>
</tbody>
</table>

The same measurements which were performed for turbulence modulation in the presence of 0.9 mm glass beads at cross section z=2 m are carried out for particle laden flows with 1.5 mm and 2 mm glass beads at the cross section z=2 m which can be seen in Figure 4-26 to Figure 4-34. The same results for turbulence intensity level and mean axial gas velocity are obtained for particle laden flow with 1.5 and 2 mm glass beads as described for particle laden flows with 0.9 mm glass beads at cross section z=2 m. The gas turbulence intensity increases from the pipe centre toward the pipe wall for both clear gas flow and particle laden flows for different SLRs, as can be seen in Figure 4-26 (a), Figure 4-27 (a) and Figure 4-28 (a) for the conveying of
Experimental results of particle laden flow with spherical particles

1.5 mm glass beads and Figure 4-31 (a) and Figure 4-32 (a) for the conveying of 2 mm glass beads. It is also seen from these figures that the carrier phase turbulence intensity level increases by adding particles into the clear gas flow. The percentage change in the turbulence intensity is presented in Figure 4-26 (b), Figure 4-27 (b) and Figure 4-28 (b) for conveying of 1.5 mm glass beads and Figure 4-31 (b) and Figure 4-32 (b) for conveying of 2 mm glass beads. As can be observed in Figure 4-26 (c), Figure 4-27 (c) and Figure 4-28 (c) for 1.5 mm glass beads and Figure 4-31 (c) and Figure 4-32 (c) for 2 mm glass beads, the mean axial gas velocity decreases in the particle laden flow for all SLRs compared to the mean axial gas velocity in particle free flows. Moreover, the horizontal profiles of mean axial gas velocity become flat by adding particles to the clear gas flows.
Experimental results of particle laden flow with spherical particles

Figure 4-26: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 1.5 mm glass beads, SLR = 2.3, z = 2 m.
Experimental results of particle laden flow with spherical particles

Figure 4-27: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 1.5 mm glass beads, SLR = 3, z = 2 m.
Experimental results of particle laden flow with spherical particles

Figure 4-28: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 1.5 mm glass beads, SLR =3.5, z=2 m.

Turbulence intensity for three different clear gas flows and particle laden flows with three different SLRs for 1.5 mm glass beads and 2 mm glass beads at the cross section z=2 m are summarized in Figure 4-29 and Figure 4-33, respectively. As can be seen for most of the measurement points in Figure 4-29, by increasing the SLR the turbulence intensity increases.

Percentage changes in the carrier phase turbulence intensity due to the presence of 1.5 mm glass beads and 2 mm glass beads at the cross section z=2 m for three different SLRs also are summarized in Figure 4-30 and Table 4-5, and Figure 4-34 and Table 4-6. From Figure 4-30 and Table 4-5 it is seen that for almost all of the measurement points the highest percentage changes occur for SLR=3.5.
Experimental results of particle laden flow with spherical particles

Figure 4-29: Effect of SLR on the turbulence intensity, 1.5 mm glass beads, \( z = 2 \text{ m} \).

Figure 4-30: Effect of SLR on the percentage change in turbulence intensity, 1.5 mm glass beads, \( z = 2 \text{ m} \).
Experimental results of particle laden flow with spherical particles

Table 4-5: Percentage change in the turbulence intensity, 1.5 mm glass beads, z=2 m

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>SLR=2.3</th>
<th>SLR=3</th>
<th>SLR=3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.030</td>
<td>65</td>
<td>49</td>
<td>131</td>
</tr>
<tr>
<td>-0.025</td>
<td>47</td>
<td>31</td>
<td>48</td>
</tr>
<tr>
<td>-0.020</td>
<td>42</td>
<td>22</td>
<td>43</td>
</tr>
<tr>
<td>-0.015</td>
<td>34</td>
<td>9</td>
<td>73</td>
</tr>
<tr>
<td>-0.010</td>
<td>87</td>
<td>61</td>
<td>95</td>
</tr>
<tr>
<td>-0.005</td>
<td>58</td>
<td>96</td>
<td>145</td>
</tr>
<tr>
<td>0</td>
<td>76</td>
<td>89</td>
<td>151</td>
</tr>
<tr>
<td>0.005</td>
<td>48</td>
<td>87</td>
<td>151</td>
</tr>
<tr>
<td>0.010</td>
<td>33</td>
<td>80</td>
<td>116</td>
</tr>
<tr>
<td>0.015</td>
<td>27</td>
<td>53</td>
<td>98</td>
</tr>
<tr>
<td>0.020</td>
<td>63</td>
<td>60</td>
<td>204</td>
</tr>
<tr>
<td>0.025</td>
<td>59</td>
<td>139</td>
<td>135</td>
</tr>
<tr>
<td>0.030</td>
<td>89</td>
<td>109</td>
<td>131</td>
</tr>
</tbody>
</table>

![Graph](image-url)
Figure 4-31: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 2 mm glass beads, SLR = 2.3, z = 2 m.
Experimental results of particle laden flow with spherical particles

Figure 4-32: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 2 mm glass beads, SLR = 3, z = 2 m.

Figure 4-33: Effect of SLR on the turbulence intensity, 2 mm glass beads, z = 2 m.
Figure 4-34: Effect of SLR on the percentage change in turbulence intensity, 2 mm glass beads, z=2 m.

Table 4-6: Percentage change in the turbulence intensity, 2 mm glass beads, z=2 m

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>SLR=2.3</th>
<th>SLR=3</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.030</td>
<td>65</td>
<td>48</td>
</tr>
<tr>
<td>-0.025</td>
<td>35</td>
<td>54</td>
</tr>
<tr>
<td>-0.020</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>-0.015</td>
<td>40</td>
<td>27</td>
</tr>
<tr>
<td>-0.010</td>
<td>58</td>
<td>46</td>
</tr>
<tr>
<td>-0.005</td>
<td>72</td>
<td>82</td>
</tr>
<tr>
<td>0</td>
<td>63</td>
<td>91</td>
</tr>
<tr>
<td>0.005</td>
<td>54</td>
<td>85</td>
</tr>
<tr>
<td>0.010</td>
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</tr>
<tr>
<td>0.015</td>
<td>27</td>
<td>61</td>
</tr>
<tr>
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<td>36</td>
<td>41</td>
</tr>
<tr>
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<td>60</td>
<td>40</td>
</tr>
<tr>
<td>0.030</td>
<td>78</td>
<td>121</td>
</tr>
</tbody>
</table>

4.4.8 LDA measurements of vertical profile of mean axial gas velocity and turbulence modulation in particle laden flow

In this section, the vertical profile of turbulence modulation and alteration in the mean axial gas velocity due to the presence of particles are investigated. As it is seen in Figure 4-35 (a), adding the particle to the clear gas flow increases the carrier phase turbulence intensity at all measurement points. However, the turbulence intensity in the lower section of the pipe, where more particles are distributed because of gravity, is higher. The maximum turbulence intensity occurs near the bottom pipe wall. Turbulence intensity augmentation is less noticeable in the pipe upper parts due to
the lower particle concentration, except for a measurement point very close to the pipe upper wall where gas velocity drops. Percentage change in the turbulence intensity is shown in Figure 4-35 (b). Gas phase turbulence intensity changes around 150% to 200% in the pipe lower half while percentage change of turbulence intensity is considerably lower in the upper half of the pipe section. Mean axial gas velocity in Figure 4-35 (c) shows that the gas velocity decreases by addition of particles into the clear gas in the lower section of the pipe and increases in the upper section of the pipe. In the pipe lower section, where particle concentration is higher, particles are accelerated by the gas momentum, leading to a decrease in the gas velocity. In the upper section of the pipe, particle concentration is low and since the available cross section for gas flow has decreased, the gas velocity increases. It also can be seen that the maximum gas velocity moved upward by adding particles to the clear gas flow. This behaviour was previously reported by Tsuji and Morikawa (1982).
Figure 4-35: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR = 2.3, z = 2 m.

Turbulence intensity, percentage change in the carrier phase turbulence intensity and mean axial gas velocity in the presence of the 0.9 mm glass beads at z=2 m for SLR=3 and SLR=3.5 are shown in Figure 4-36 and Figure 4-37 respectively. Similar trends are observed to those explained for Figure 4-35.
Experimental results of particle laden flow with spherical particles

Figure 4-36: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR =3, z=2 m.
Figure 4-37: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR =3.5, z=2 m.
Turbulence intensity for three different clear gas flows and particle laden flows with three different SLRs for 0.9 mm glass beads is shown in Figure 4-38 at the cross section $z=2$ m. As is seen in Figure 4-38 in the lower section of the pipe the turbulence intensity increases by increasing the SLR. For the upper section of the pipe the turbulence intensity values are close for the different SLRs. However, in the pipe upper section the carrier phase turbulence intensity for SLR=2.3 has slightly higher values showing that the number of particles in those regions decreases slightly by increasing the SLR. From Figure 4-39 and Table 4-7, it is seen that in the lower section of the pipe, for most of the measurement points, the highest percentage changes occur for SLR=3.5, and the lowest percentage changes happen for SLR=2.3. In the pipe upper section, the percentage changes in the turbulent intensity are close for the various SLRs. However, for some points the turbulence intensity changes for SLR=2.3 have the maximum values.

Figure 4-38: Effect of SLR on the turbulence intensity, 0.9 mm glass beads, $z=2$ m.
Experimental results of particle laden flow with spherical particles

Figure 4-39: Effect of SLR on the percentage change in turbulence intensity, 0.9 mm glass beads, z=2 m.

Table 4-7: Percentage change in the turbulence intensity, 0.9 mm glass beads, z=2 m

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>SLR=2.3</th>
<th>SLR=3</th>
<th>SLR=3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.030</td>
<td>105</td>
<td>87</td>
<td>105</td>
</tr>
<tr>
<td>-0.025</td>
<td>38</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>-0.020</td>
<td>34</td>
<td>28</td>
<td>14</td>
</tr>
<tr>
<td>-0.015</td>
<td>37</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>-0.010</td>
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</tr>
<tr>
<td>-0.005</td>
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<tr>
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<td>86</td>
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<td>0.010</td>
<td>101</td>
<td>146</td>
<td>136</td>
</tr>
<tr>
<td>0.015</td>
<td>139</td>
<td>155</td>
<td>181</td>
</tr>
<tr>
<td>0.020</td>
<td>195</td>
<td>214</td>
<td>209</td>
</tr>
<tr>
<td>0.025</td>
<td>172</td>
<td>210</td>
<td>245</td>
</tr>
<tr>
<td>0.030</td>
<td>155</td>
<td>150</td>
<td>243</td>
</tr>
</tbody>
</table>

The same measurements were performed for particle laden flows with 1.5 mm and 2 mm glass beads at the cross section z=2 m for different SLRs. Similar trends for mean axial gas velocity and turbulence intensity were observed as explained for particle laden flows with 0.9 mm glass beads in Figure 4-35 to Figure 4-39. Experimental results can be seen in Figure 4-40 to Figure 4-48. Table 4-8 and Table 4-9 show the percentage change in the turbulence intensity for particle laden flows with 1.5 mm and 2 mm glass beads for various SLRs. As is seen in tables, in the lower section of the pipe, the highest percentage change happens for the highest SLR, at almost all of the measurement points.
Experimental results of particle laden flow with spherical particles

Figure 4-40: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 1.5 mm glass beads, SLR = 2.3, z = 2 m.
Figure 4-41: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 1.5 mm glass beads, SLR = 3, z=2 m.
Experimental results of particle laden flow with spherical particles

Figure 4-42: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 1.5 mm glass beads, SLR = 3.5, z=2 m.
Experimental results of particle laden flow with spherical particles

Figure 4-43: Effect of SLR on the turbulence intensity, 1.5 mm glass beads, z=2 m.

Figure 4-44: Effect of SLR on the percentage change in turbulence intensity, 1.5 mm glass beads, z=2 m.
Table 4-8: Percentage change in the turbulence intensity, 1.5 mm glass beads, z=2 m

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>SLR=2.3</th>
<th>SLR=3</th>
<th>SLR=3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.030</td>
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<td>90</td>
<td>81</td>
</tr>
<tr>
<td>-0.025</td>
<td>23</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>-0.020</td>
<td>25</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>-0.015</td>
<td>51</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>-0.010</td>
<td>95</td>
<td>39</td>
<td>24</td>
</tr>
<tr>
<td>-0.005</td>
<td>78</td>
<td>49</td>
<td>54</td>
</tr>
<tr>
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<td>106</td>
</tr>
<tr>
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<td>76</td>
<td>81</td>
<td>137</td>
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</tr>
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<td>73</td>
<td>115</td>
<td>132</td>
</tr>
<tr>
<td>0.020</td>
<td>82</td>
<td>110</td>
<td>185</td>
</tr>
<tr>
<td>0.025</td>
<td>133</td>
<td>182</td>
<td>168</td>
</tr>
<tr>
<td>0.030</td>
<td>127</td>
<td>142</td>
<td>238</td>
</tr>
</tbody>
</table>

(a) Clear gas  
(b) Particle laden flow
Experimental results of particle laden flow with spherical particles

Figure 4-45: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 2 mm glass beads, SLR = 2.3, z = 2 m.
Figure 4-46: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 2 mm glass beads, SLR =3, z=2 m.

Figure 4-47: Effect of SLR on the turbulence intensity, 2 mm glass beads, z=2 m.
Experimental results of particle laden flow with spherical particles

Figure 4-48: Effect of SLR on the percentage change in turbulence intensity, 2 mm glass beads, z=2 m.

Table 4-9: Percentage change in the turbulence intensity, 2 mm glass beads, z=2 m

<table>
<thead>
<tr>
<th>Radius (m)</th>
<th>SLR=2.3</th>
<th>SLR=3</th>
</tr>
</thead>
<tbody>
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<tr>
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<td>3</td>
</tr>
<tr>
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<td>17</td>
</tr>
<tr>
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<td>52</td>
<td>19</td>
</tr>
<tr>
<td>0.005</td>
<td>83</td>
<td>46</td>
</tr>
<tr>
<td>0</td>
<td>72</td>
<td>71</td>
</tr>
<tr>
<td>0.005</td>
<td>73</td>
<td>106</td>
</tr>
<tr>
<td>0.010</td>
<td>77</td>
<td>139</td>
</tr>
<tr>
<td>0.015</td>
<td>66</td>
<td>102</td>
</tr>
<tr>
<td>0.020</td>
<td>134</td>
<td>186</td>
</tr>
<tr>
<td>0.025</td>
<td>171</td>
<td>186</td>
</tr>
<tr>
<td>0.030</td>
<td>124</td>
<td>177</td>
</tr>
</tbody>
</table>

4.5 Flow regime in the current study

The experimental measurements of the mean gas and particle velocities and the experimental observations prove that particle concentration varies on the vertical profile. Particle concentration is higher in the pipe lower section and decreases toward the pipe upper section on the vertical profile. Therefore, the pneumatic conveying mode cannot be called a dilute regime. However, the majority of particles are dispersed in the conveying gas. On the other hand, a thin layer of particles is not formed at the bottom of the pipe. Therefore, the flow regime cannot be referred as a
Experimental results of particle laden flow with spherical particles

stratified regime. With regards to this explanation, one may conclude that the pneumatic conveying regime in the current study is a flow regime between dilute and stratified regimes for all particle sizes and SLRs.

**4.6 Conclusion to Chapter 4**

In this chapter the experimental measurements were presented and the following results were obtained.

- The horizontal profile of the particle velocity showed a flat profile at the pipe centre with a slight decrease close to the pipe wall. It was also observed that the higher the SLR and particle size the lower the particle velocity.

- Particle velocity was observed to be higher in the upper section of the pipe compared with the particle velocity in the lower section of the pipe. Increasing the solid loading ratio also decreased the vertical profile of particle velocity. Furthermore, an increase in the particle size decreased the particle velocity in the pipe upper section. However, the particle velocities were close for the different particle sizes in the lower section of the pipe.

- Relation between 1) mass/volumetric solid loading 2) the ratio of particle diameter to the fluid turbulence length scale 3) particle Reynolds number and 4) Stokes number with turbulence modulation was presented and it was concluded that turbulence augmentation occurs due to the presence of particles under the conditions tested.

- Both the horizontal and vertical profiles of the carrier phase turbulence intensity augmented due to the addition of particles. Moreover, it was observed that, by increasing the SLR, the horizontal profile of the carrier phase turbulence intensity further increased in most of the measurement points. The vertical profile of the carrier phase turbulence intensity was also
further enhanced by increasing the SLR, as was observed at most of the measurement points in the lower section of the pipe.

- The horizontal profiles of mean axial gas velocity decreased by adding particles to the clear gas flow. Moreover, the horizontal profiles of the mean axial gas velocity in particle laden flows became flat compared to the horizontal profiles of mean axial gas velocity in particle free flows.

- The vertical profiles of mean axial gas velocity of particle laden flows increased in the pipe upper section and decreased in the pipe lower section compared to the vertical profiles of mean axial gas velocity in particle free flows. In addition, the maximum gas velocity shifted upward from the pipe centre in the particle laden flows.
Chapter 5.
Numerical modelling fundamentals and code validation

5.1 Introduction
With the advent of increased computational power, fluid-particle flows can be modelled with a multiphase modelling strategy (van der Hoef et al. (2004)). Deciding which strategy is to be employed is mostly a trade-off between the desired level of modelling detail and computational expense. However, the ability of the numerical model to simulate the dynamic behaviour of system needs to be addressed with a series of validation test cases. In this chapter, the mathematical fundamentals of the numerical simulation applied to simulate the particle laden flow of air and particles in a pneumatic line are described. The various forces which arise due to the interaction between gas and particles, particle-particle and particle-geometry in pneumatic conveying are explained in this chapter along with a discussion of the magnitude and importance of each of these forces. Special attention will be paid to drag and lift models. The turbulence modulation correlations are also presented and discussed. These models can be categorized in standard, consistent, theoretical or hybrid models based on the original equation used to develop the model. Then two verification test cases including the single particle sedimentation (SPS) and constant porosity block (CPB) sedimentation are explained to evaluate the ability of the code to simulate simple systems before implementing model codes to detail study of pneumatic conveying.

5.2 Fundamentals of multiphase modelling
Generally multiphase systems such as pneumatic conveying and fluidised beds can be described by two different numerical models, namely Eulerian-Eulerian (E-E) or Eulerian-Lagrangian (E-L) approaches. As explained before, the particle concentration, the nature of the studied system and the level of information that
needs to be obtained from the results decide the appropriate method for the simulation.

In this study an Eulerian-Lagrangian method is used which may be referred to as coupled computational fluid dynamics and discrete element method (RANS-DEM). In this approach the averaged Navier-Stokes equations (Anderson and Jackson (1967)) are coupled with the Lagrangian approach. RANS-DEM provides the particle level information, which enables simulation of laboratory scale of two-phase flow. In this approach, the conservation equations (continuity and momentum) are integrated over the Eulerian grid that covers the entire domain.

In the Discrete Element Method (DEM) (Cundall and Strack (1979)) translational and rotational motion of each particle is tracked by solving Newton's equations of motion. In these equations, the impact forces of particle-particle and particle-wall interactions are included. Other forces such as van der Waals and electrostatic forces can also be incorporated (Chauveil (2012)). Particle collisions generally can be described by two common types of approach - the hard-sphere model and the soft-sphere model (Zhu et al. (2007) and Deen et al. (2007)). In the hard-sphere model, the interactions between particles are assumed to be binary and instantaneous. The particle trajectories are calculated by solving the momentum equation in the collision. This model is generally used for diluted suspensions since multiple collisions are not taken into account at the same instant. In the soft-sphere approach, particles trajectories are determined by integrating the force balance for each particle. When two particles collide, particles are allowed to overlap. The contact and repulsive forces are calculated as a function of overlap. The soft-sphere approach is time-driven and, as a result, the time step needs to be selected for calculating the contact force. Multiple contacts may happen for a particle during a time step, and the net contact force is calculated by summing all the pair interactions.

In the context of two-phase modelling, the aerodynamic forces play a crucial role on the particle trajectories. Therefore it is necessary that these forces are included in the DEM equations. These forces can be drag, lift and buoyancy forces. To calculate the
Numerical modelling fundamentals and code validation

Aerodynamic forces, it is necessary to have fluid field data such as velocity, pressure, density and viscosity of the flow in the computational domain. This data are calculated by the RANS solver and is transferred to the DEM solver. Particle momentum and position are then needed to be passed to the RANS solver to solve the Navier-Stokes equations. The presence of the particles in the computational domain is taken into account by mesh porosity ($\varepsilon_{\text{mesh}} = 1 - \phi_p = 1 - V_p / \Delta V_{\text{mesh}}$) and a momentum sink term which is added to the fluid momentum equation. Therefore, coupling between DEM and RANS solver is needed which may be depicted as follows:

![Figure 5-1: RANS-DEM coupling cycle (DEM Solutions Ltd (2010)).](image)

Based on the Figure 5-1, firstly the flow field is determined by the RANS solver. Then the particle motion is calculated with the DEM solver and the net force acting on each particle including particle-particle, particle-geometry and aerodynamic forces is calculated. Aerodynamic forces are calculated by the information transferred from the RANS solver. At the end of the DEM calculation, particle position and velocities are updated. Lastly, the fluid flow will be computed again considering the influence of the particles as an additional momentum sink term in the momentum equations. This loop continues until the end of the requested computation time.
In the following section the mathematical formulation of RANS-DEM is presented.

5.3 Mathematical formulation

In this study, simulations were carried out using the commercial software Ansys FLUENT version 12.1 and EDEM version 2.4 in an Eulerian-Lagrangian framework, in which particles are tracked individually. The averaged Navier-Stokes equations are solved in FLUENT for the carrier phase; Navier-Stokes equations are solved by using a finite volume discretisation scheme and applying an iterative solution procedure based on the SIMPLE algorithm. The motion of discrete phase in the simulation is described by solving Newton’s laws of motion in EDEM. The two software are then coupled with full momentum exchange between the solid and fluid phases.

5.3.1 Mathematical formulation of the fluid

In the present study, the averaged Navier-Stokes equations derived by Anderson and Jackson (1967) in connection with the $k$-$\varepsilon$ turbulence model are solved by FLUENT to model the fluid flow. The time dependent three dimensional mass and momentum conservation equations may be written as follows:

$$\frac{\partial (1 - \phi_p) \rho}{\partial t} + \nabla \cdot (1 - \phi_p) \rho \vec{v} = 0$$  \hspace{0.5cm} (5-1)

$$\frac{\partial (1 - \phi_p) \rho \vec{v}}{\partial t} + \nabla \cdot (1 - \phi_p) \rho \vec{v} \vec{v} = -\nabla p + \nabla \cdot \left( (1 - \phi_p) \tau \right)$$

$$+ \nabla \cdot \left( (1 - \phi_p) \tau' \right) + (1 - \phi_p) \rho g - S$$  \hspace{0.5cm} (5-2)

$$S = \frac{\sum_{i}^{nm} F_{interaction,i}}{\Delta V_{mesh}}$$  \hspace{0.5cm} (5-3)

$\tau$, $nm$, $\Delta V_{mesh}$ are the fluid viscous stress tensor, the number of particles in the considered computational cell and the computational cell volume respectively. $S$ is the volumetric force acting on each mesh cell and $F_{interaction}$ includes drag and lift forces in this study. In the FLUENT-EDEM coupling, three drag models are
available as in-built drag models: the modified Stokes model, the Di Felice model (Di Felice (1994)) and the Ergun and Wen & Yu model (Ergun (1952), Wen and Yu (1966)). However, there is the possibility to add any other drag models in the coupled FLUENT-EDEM as User defined functions (UDFs). The equations for drag and lift forces will be presented in sections 5.5.1 and 5.5.2 respectively.

To calculate \( \varepsilon_{\text{mesh}} \), it is necessary to calculate the volume fraction of the CFD mesh cell occupied by the solid. In the coupled FLUENT-EDEM, regular sample points are created within the bounding box of a particle as shown in Figure 5-2.

![Sample points within a particle (DEMSolutions Ltd (2010)).](image)

Each point is checked to determine the CFD mesh cell within which it lies. The solid volume fraction within a particular mesh cell is therefore the percentage of the number sample points that lie within that mesh cell as given by:

\[
\varepsilon_{\text{mesh}} = 1 - \sum_{\text{particles}} \frac{n_c}{N_t} V_p
\]

(5-4)

where \( n_c \) is the number of sample points contained within the mesh cell and \( N_t \) is the total number of sample points of the particle. \( V_p \) is the volume of the particle.

The general \( k-\varepsilon \) turbulence model equations in FLUENT are as follow (Launder and Spalding (1972)):

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k v_i) = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{C_\mu} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_b - \rho \varepsilon + Y_M + S_{kp}
\]

(5-5)
\[
\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon v_i) = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{e1} \frac{\varepsilon}{k} (G_k + C_{e3} G_b) - C_{e2} \rho \frac{\varepsilon^2}{k} + S_{ep}
\]  

(5-6)

\( \mu = \rho C_{\mu} k^2/\varepsilon \) is the turbulent viscosity, \( \sigma_k \) and \( \sigma_\varepsilon \) are turbulent Prandtl numbers and \( S_{kp} \) and \( S_{ep} \) are user defined source terms. The model constants have values as set out in Table 5-1.

<table>
<thead>
<tr>
<th>( C_{\mu} )</th>
<th>( C_{e1} )</th>
<th>( C_{e2} )</th>
<th>( \sigma_k )</th>
<th>( \sigma_\varepsilon )</th>
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<td>0.09</td>
<td>1.44</td>
<td>1.92</td>
<td>1</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Generally to simulate the turbulent multiphase flows, \( S_{kp} \) and \( S_{ep} \) source terms are modified to take into account the presence of the solid phase in the fluid. The proposed models for these source terms are explained in the next section.

5.3.2 Numerical modelling of turbulence modulation

In this section, modelling of the turbulence modulation phenomenon is discussed. Generally, the single flow equations for turbulent kinetic energy and dissipation are modified to take into account the presence of the solid phase. Some research has been conducted to formulate source terms to include the effects of particles on the fluid turbulence structure (Gouesbet and Berlemont (1998), Geiss et al. (2004), Rao et al. (2012)). These source terms mainly depend on the turbulence model used to close the fluid’s momentum equation (Lain and Sommerfeld (2003)). Since the \( k-\varepsilon \) model is one of the most common turbulence models in single phase flow modelling, consequently most of the source terms are derived for turbulent kinetic energy and dissipation equations of this model (Pakhomov et al. (2007), Fan et al. (1997), Chen and Wood (1985)). However, source terms for other turbulence models like Reynolds stress turbulence model and \( k-\omega \) have also been introduced (Lain and Sommerfeld (2008), Lun (2000)). These source terms can be divided into three main sections based on the original equations that these source terms have been derived from.
Numerical modelling fundamentals and code validation

(Boulet and Moissette (2002), Lain et al. (2002a) and Mandø (2009)). These are categorized as standard, consistent and theoretical methods. A new approach was also recently introduced by Geiss et al. (2004) and Mandø (2009) which is a hybrid method that is the combination of standard and consistent methods. These categories are explained for \( k-e \) turbulence model in the following sections.

5.3.2.1 Standard method

The instantaneous momentum equation is used as a starting point in this method. The interaction between the two phases is taken into account by a momentum sink. Reynolds decomposition is applied to the momentum equation, the resultant is multiplied by the fluctuating gas velocity and then Reynolds averaging is applied. (Gouesbet and Berlemont (1998), Chen and Wood (1985)). Finally, a source term in the turbulent kinetic energy equation is obtained which is due to the dispersed phase. The general form for the source term in the kinetic energy equation may be expressed as

\[
S_{kp} = S'_{pv_i}v_i' \tag{5-7}
\]

where \( S'_{pv_i} \) is the fluctuating momentum exchange term. If it is assumed that the interaction between the two phases occurs only due to the drag force, then equation (5-7) can be written as

\[
S_{kp} = \phi_p \rho_p \left( \bar{u}'_{pi}v_i' - v_i'v_i' \right) \tag{5-8}
\]

Here \( \phi_p \) is the particle volume fraction, \( v_i' \) is fluctuating gas velocity and \( u'_pi \) is particle fluctuating velocity. \( v_i'v_i' \) is modelled as for the clear gas phase as used in the standard \( k-e \) model which is \( v_i'v_i' = 2k \). However \( u'_pi v_i' \) requires to be modelled (Lightstone and Hodgson (2004)). Some models have been presented in Lightstone and Hodgson (2004) for the \( k-e \) model. As stated by Boulet and Moissette (2002), \( u'_pi \) arises from particle-particle and particle-wall interaction, and is often smaller than \( v_i' \) resulting in \( S_{kp} \) being negative. Therefore, this approach can only predict the
dissipation of the carrier phase turbulence (Lain et al. (2002a), Mandø (2009) and Boulet and Moissette (2002)). One may conclude that this method is not suitable for the modelling of turbulence modulation due to large particles which enhance turbulence intensity.

5.3.2.2 Consistent method

Another formulation for the turbulent kinetic energy source term due to particles is based on the Crowe (2000) study. This method starts with the mechanical energy equation for the fluid phase. The source term equation obtained by considering the drag force as the only interaction force is expressed as:

$$S_{kp} = \frac{\phi_p \rho_p}{\tau_p} \left( |\bar{v}_i - \bar{u}_p| \right)^2 + \left( \bar{u}_p - \bar{u}_i \right)^2$$  \hspace{1cm} (5-9)

The first contribution may be explained as the kinetic energy production due to the particle drag. In fact this term takes into account turbulence generation due to the particle wake. The second term (redistribution) is attributed to the transfer of the kinetic energy of the particle motion into the kinetic energy of the continuous phase. The second term has a negligible effect in the dilute suspensions.

As can be seen in equation (5-9), the first term is positive for all conditions and increases as the particle density or size increases. Generally, the generation due to the particle drag has a larger magnitude than the redistribution term. As a result one may notice that models based on this approach are capable of capturing the fluid phase turbulence augmentation only and may not be suitable to be applied for turbulence modulation due to small particles.

For both standard and consistent approaches, the dissipation term due to the presence of particles, $S_{ep}$, is assumed to be proportional to $S_{kp}$ and the ratio $\varepsilon/K$.

$$S_{ep} = C_{\varepsilon} \frac{\varepsilon}{K} S_{kp}$$  \hspace{1cm} (5-10)
The empirical constant $C_\varepsilon$ does not have a unique value and various values have been proposed ranging from 1.0 to 2.0 (Zhang and Reese (2003)). Boulet and Moissette (2002) reported that $C_\varepsilon$ depends mainly on particle concentration and diameter and it is not a universal constant. Boulet and Moissette (2002) also mentioned that the method of derivation of the $S_{kp}$ leads to a different value for $C_\varepsilon$. Zhang and Reese (2003) reported that, for large and heavy particles with the ratio of the particle relaxation time to time scale of the large eddies around 10, $C_\varepsilon$ was decreased by increasing the mass loading. They proposed a model for $C_\varepsilon$ that is dependent on the particle volume fraction:

$$C_{\varepsilon, c} = \left[ 1 - \left( \frac{6\phi_p}{\pi \phi_{pm}} \right)^{1/3} \right] C_\varepsilon$$  \hspace{1cm} (5-11)

Where $\phi_{pm}$ is the random close-packing particle volume fraction, which is assumed to be 0.64. As can be seen from the equation (5-11), $C_{\varepsilon, c}$ depends on the initial selection of $C_\varepsilon$. The authors selected the value of 1.95 for $C_\varepsilon$ based on the Tsuji and Morikawa (1982) experiments. They also showed the predicted turbulent kinetic energy depended significantly on the value of $C_\varepsilon$.

Lain et al. (2002a) used a value of 1.8 in the simulation of a bubble column. Boulet and Moissette (2002) applied 1.8 for modelling a vertical gas-particle flow, they showed the fluid phase turbulence value depended strongly on the value of $C_\varepsilon$. They also showed a small change in the $C_\varepsilon$ value (from 1.8 to 1.85 or 1.8 to 1.81) could change the simulation results considerably. They also showed the dependency of the value of $C_\varepsilon$ on the particle volume fraction. They concluded that the value of $C_\varepsilon$ which gives the best result for one example may not be suitable for another example if there is a change in the volume fraction. Although equation (5-10) is controversial and restricted, this equation has been successfully applied in some studies (Geiss et al. (2004) and Mandø (2009)).
5.3.2.3 Theoretical method

To explain and model the turbulence generation or dissipation due to the presence of the dispersed phase, some simplified physical descriptions have also been proposed. Yuan and Michaelides (1992) attributed turbulence generation and reduction to the particle wake and work performed by eddy to accelerate a particle, respectively. To derive the model only the drag model was considered and the kinetic energy production was assumed to be a function of the wake size and shape. The proposed model was capable of predicting the turbulence augmentation and attenuation due to the presence of large and small particles when compared to the experimental results for vertical pipe and jet flows. Following the Yuan and Michaelides (1992) study, Bolio and Sinclair (1995) developed a model to capture the turbulence modulation due to the presence of large particles. Instead of the ellipsoidal shape for particle wake proposed by Yuan and Michaelides (1992), a more detailed wake shape approximation was used. The model was developed for a steady-state two phase flow in a vertical pipe. Similar to the standard and consistent methods, $S_{dp}$ was assumed to be proportional to $S_{dp}$ and $\varepsilon/k$ and the value of 1.2 was selected for $C_\varepsilon$. Yarin and Hetroni (1994) also explained the turbulence modulation with the same idea as the Yuan and Michaelides (1992) study. The model was developed based on the momentum balance equations of a single particle and fluid element. A more detailed expression for the wake was suggested and the developed model was able to predict both turbulence generation and reduction.

Kenning and Crowe (1997) proposed a model for turbulence modulation based on a simple energy balance. They assumed that turbulence was generated by the work done by particle drag, and dissipation happened due to the work done by the fluid phase to oscillate the solid phase. To model the dissipation, a new hybrid length scale based on the inter-particle spacing was introduced. A comparison of the theoretical results with available experimental data for turbulence modulation in a vertical pipe showed good agreement.
Although these theoretical models successfully captured the augmentation and attenuation of turbulence intensity, as mentioned by Boulet and Moissette (2002) and Mandø (2009), contrary to the results of the standard and consistent approaches, they cannot be simply introduced in a conventional closure model for turbulence. Another drawback of the theoretical method is that its equations are derived for a simple interaction between a fluid phase and a single particle. Therefore, when these models are applied for a particle laden flow, their accuracy is not guaranteed.

### 5.3.2.4 Hybrid method

With regard to the limitations of the previous methods, the hybrid method was suggested by Geiss et al. (2004). The source term for the $k-\varepsilon$ model can be seen in equation (5-12). Only the drag force was considered as a gas-solid interaction force and the influence of particle-particle collisions on the turbulence modulation was neglected.

$$S_{kp} = \frac{\phi_p \rho_p}{\tau_p} \left( |\vec{v}_i - \overline{u_{pi}}|^2 + (u'_{pi} u'_{pi} - v'_{i} v'_{i}) \right) \quad (5-12)$$

This source term can also be derived by adding the standard and consistent method source terms (Mandø (2009)). As mentioned in the consistent approach, the first term represents the conversion of mechanical energy by the drag force into turbulent kinetic energy. The fluctuating particle velocity in the second term is important only in the case of dense flows or for the regions close to the wall. As a result, this term can be omitted for simplicity (Geiss et al. (2004)). As mentioned in the standard approach $v'_i v'_i$ can be replaced by $2k$, meaning that equation (5-12) can be written as

$$S_{kp} = \frac{\phi_p \rho_p}{\tau_p} \left( |\vec{v}_i - \overline{u_{pi}}|^2 - 2k \right) \quad (5-13)$$

This formulation can predict both the increase and decrease of carrier phase turbulence intensity. For small particles travelling at almost the same velocity as the carrier phase, the effect of the first term is negligible and overall the source term decreases the turbulence intensity. For large particles, on the other hand, the first
contribution is significantly bigger than the second term leading to turbulence augmentation. Geiss et al. (2004) investigated the capability of this model for a very dilute vertical wind tunnel. Mando (2009) also derived the same equation as equation (5-13) by using the Vreman (2007) study. He showed the ability of the proposed model by implementing it in a 2D and 3D CFD code and evaluated its ability against several experimental results for dilute vertical gas-particle flows for a various range of SLRs, particle sizes and $Re_p$. A good agreement between the turbulence intensity measured experimentally and calculated by the model was observed for large and small particles. The dissipation source term is calculated by the equation (5-10), and as mentioned before, $C_{\varepsilon 3}$ does not have a unique value. Geiss et al. (2004) applied the value of 1.87 for $C_{\varepsilon 3}$ while Mando (2009) obtained good results by setting the constant to 1.00.

The hybrid source term was implemented in the coupled FLUENT-EDEM via UDF to take into account the effect of the dispersed phase on the carrier phase turbulence intensity.

### 5.3.3 Mathematical formulation of the DEM

Translational and rotational motions of particles in EDEM software are described by the equations below.

\[
m_i \frac{du_{p,i}}{dt} = m_i g + \sum_{j=1}^{k_i} F_{c,i,j} + F_{interaction,i}
\]  

\[
l_i \frac{d\omega_{p,i}}{dt} = \sum_{j=1}^{k_i} T_{ij}
\]

Where $F_{c,i,j}$ is the contact force and $F_{interaction,i}$ includes drag and lift forces. $u_{p,i}$ and $\omega_{p,i}$ are the linear and angular particle velocities. $m_i$, $l_i$, and $T_i$ denote the mass and the moment of inertia of the particle and torque acting on a particle respectively. Gravity has a significant effect on the particle transportation in a horizontal flow and
makes particles to settle in the lower section of the pipe depending on the weight of particles and gas flow.

In the current study, to model the particle-particle and particle-geometry contacts, a non-linear Hertz-Mindlin contact model, which is a non-linear soft-sphere model, is applied. The program can distinguish particles from the wall and can conduct particle-particle or particle-wall contact (Favier et al. (1999)). A contact will be registered if the distance between the centre of two neighbouring particles with the radius of R1 and R2 is less than the sum of their radii (Favier et al. (1999)). Contact between two particles is shown in Figure 5-3.

![Figure 5-3: Contact between two particles (Romani Fernández (2012)).](image)

Normal components of the contact force can be expressed as follows, and are functions of normal overlap $\delta_n$, equivalent Young’s modulus $Y^*$ and equivalent radius $R^*$.

\[
F_n = \frac{4}{3} Y^* \delta_n^{3/2} \sqrt{R^*} \tag{5-16}
\]

\[
\frac{1}{Y^*} = \frac{(1 - \nu_i^2)}{Y_i} + \frac{(1 - \nu_j^2)}{Y_j} \tag{5-17}
\]

\[
\frac{1}{R^*} = \frac{1}{R_i} + \frac{1}{R_j} \tag{5-18}
\]

$Y$, $\nu$ and $R$ are Young’s modulus, Poisson’s ratio and particle radius respectively. $i$ and $j$ represent the particles in contact. The normal damping force is given by
Numerical modelling fundamentals and code validation

\[ F_n^d = -2\sqrt{\frac{5}{6}} \gamma \sqrt{S_n m^* V_n^\text{rel}} \]  \hspace{1cm} (5-19)  

\[ S_n = 2Y^* \sqrt{R^* \delta_n} \]  \hspace{1cm} (5-20)  

and  

\[ \gamma = \frac{\ln e}{\sqrt{\ln^2 e + \pi^2}} \]  \hspace{1cm} (5-21)  

\[ \frac{1}{m^*} = \frac{1}{m_i} + \frac{1}{m_j} \]  \hspace{1cm} (5-22)  

where \( m^* \) is the equivalent mass, \( e \) is the coefficient of restitution, \( S_n \) is the normal stiffness, and \( V_n^\text{rel} \) is the normal component of the relative velocity between the particles.

Tangential force and damping are calculated by the following equations (Mindlin and Deresiewicz (1953)):

\[ F_t = -S_t \delta_t \]  \hspace{1cm} (5-23)  

\[ S_t = 8G^* \sqrt{R^* \delta_n} \]  \hspace{1cm} (5-24)  

\[ F_t^d = -2\sqrt{\frac{5}{6}} \gamma \sqrt{S_t m^* V_t^\text{rel}} \]  \hspace{1cm} (5-25)  

\( \delta \) is the tangential overlap, \( S_t \) is the tangential stiffness and \( G^* \) is the equivalent shear modulus. \( V_t^\text{rel} \) denotes the tangential component of the relative velocity between two particles.

The tangential force is limited by the Coulomb friction \((\mu_s F_n)\) where \( \mu_s \) represents the static friction coefficient. If the net tangential force reaches the frictional force then sliding occurs. The rolling friction is accounted for by applying a torque to the contacting surfaces which is a function of normal force \( F_n \) and coefficient of rolling friction \( \mu_r \):

\[ \tau_{r,i} = -\mu_r F_n R_i \omega_i \]  \hspace{1cm} (5-26)
As it can be seen from the equations in this section, some parameters such as the Young’s modulus, coefficient of restitution and coefficient of static friction need to be determined before commencing the numerical modelling. These parameters are barely measurable and are usually selected from literature. However, in relatively dilute transportation systems, the particle-particle and particle-wall collisions are not the main sources of solid phase stress, so in these simulations the results are not significantly dependant on these parameters (Zhang and Reese (2003)).

In the current study, the cohesion and adhesion of particles to each other or to the wall also are excluded in the simulation since in this study particles are dry and large enough that these forces are negligible (Zhu et al. (2007)).

5.4 Choosing the time step

The equations of motion, equations (5-14) and (5-15), are integrated over the time step in EDEM. It is assumed that the forces acting on each particle are constant during the time step. The time step in EDEM is calculated based on the Rayleigh time, which is the time taken for a shear wave to propagate across a particle. In fact, Rayleigh time is the largest time step which can be used.

\[ T_R = \frac{\pi R \sqrt{\rho_p G}}{(0.1631v + 0.8766)} \]  

(5-27)

As it is seen from equation (5-27), \( T_R \) is inversely proportional to shear modulus, \( G \), and therefore the harder particles require a smaller time step. In order to avoid numerical instability, it is suggested to set the time step around 30% of \( T_R \) (DEMSolutions Ltd (2010)).

However, in a two-phase simulation context, time scales such as the time required for a particle to pass a control volume, particle response time and integral time scale of turbulence need to be checked against the Rayleigh time step and the smallest time step should be chosen. The Eulerian time step which dictates the temporal resolution
of the fluid field generally is selected to be larger than the Lagrangian time step (Lain et al. (2002a)). Typically a ratio of 100 between Eulerian and Lagrangian time steps is suggested i.e. $\Delta t(\text{Eulerian})/\Delta t(\text{Lagrangian})=100$.

5.5 Aerodynamic forces

In the previous sections, the mathematical formulations for gas and particle phases were presented separately. In the next sections aerodynamic forces - including the drag force, lift forces, Basset and virtual forces (which are arisen from the gas and particle interactions) - are discussed.

5.5.1 Drag force model

Drag force, $F_D$, on a single spherical particle in an infinite fluid domain and creeping flow (i.e. no inertial fluid forces) is expressed as follows:

$$F_D = 3\pi \mu d_p (v - u_p) \tag{5-28}$$

Defining a drag coefficient $C_D$ and using the cross sectional area of the particle, $A$, Stokes drag force can be rearranged as

$$F_D = \frac{1}{2} C_D \rho A \left| (v - u_p) \right| (v - u_p) \tag{5-29}$$

For very low $Re_p$ number, $C_D=24/Re_p$ and for high $Re_p (Re_p >> 1000)$ the drag coefficient is approximately constant at 0.44.

One of the earliest drag laws is attributed to Ergun (1952), who proposed a drag force for fluid flow through a packed bed.

$$\beta = 150 \frac{(1 - \varepsilon_f)^2 \mu}{\varepsilon_f d_p^2} + 1.75 (1 - \varepsilon_f) \frac{\rho}{d_p} \left| (v - u_p) \right| \tag{5-30}$$

$$F_D = \frac{V_p \beta}{1 - \varepsilon_f} (v - u_p) \tag{5-31}$$
where $\mu$ is the fluid viscosity and $\varepsilon_f$ is porosity. This drag force is valid for a homogeneous and isotropic distribution of spherical particles in the dense particle density regime, which is normally defined as $\varepsilon_f < 0.8$.

For multiple particles, the flow and pressure effects from neighbouring particles are modelled by the addition of voidage function $f(\varepsilon_f)$. Wen and Yu (1966) have proposed a voidage function of $f(\varepsilon_f) = \varepsilon_f^{-4.7}$ for dilute fluid-particle regimes with $\varepsilon_f > 0.8$.

$$\beta = \frac{3 C_D}{4 d_p} \rho (1 - \varepsilon_f) \varepsilon_f^{-2.7} |v - u_p|$$  \hspace{1cm} (5-32)

$$F_D = \frac{V_p \beta}{1 - \varepsilon_f} (v - u_p)$$  \hspace{1cm} (5-33)

The combination of Wen & Yu’s drag law for $\varepsilon_f > 0.8$ and Ergun’s for $\varepsilon_f < 0.8$ is one of the most popular choices for $F_D$ in the literature. However, as noted by Kafui et al. (2002), the resultant drag force function in terms of the porosity contains a undesirable discontinuity at $\varepsilon_f = 0.8$. This can be avoided by using an appropriate smooth transitioning function or by simply using the minimum value of $\beta$ in equation (5-30) or (5-32) (Deen et al. (2007)).

The drag force proposed by Di Felice (1994) is another commonly used drag law that is applicable for both the dense and the dilute regimes. Di Felice uses a modified version of the single particle drag force, equation (5-29), and defines the voidage function as

$$\xi = 3.7 - 0.65 \exp \left( - \frac{(1.5 - \log_{10} Re_p)^2}{2} \right)$$  \hspace{1cm} (5-34)

$$f(\varepsilon_f) = \varepsilon_f^{-\xi}$$  \hspace{1cm} (5-35)

$$F_D = \frac{1}{2} C_D A \rho |(v - u_p)| (v - u_p) f(\varepsilon_f)$$  \hspace{1cm} (5-36)
$C_D$ in the Di Felice drag model (equation (5-36)) is calculated based on following equation.

$$C_D = \left(0.63 + \frac{4.8}{Re_p^{0.5}}\right)^2$$  \hspace{1cm} (5-37)

Li and Kuipers (2003) compared a number of different drag forces, including the forces by Di Felice, Ergun and Wen & Yu and the combination of the latter two. They found that the Di Felice, Wen & Yu and the combined Ergun and Wen & Yu drag forces all produced similar predictive capabilities in simulations of gas-solid fluidized beds, while the Ergun alone tended to over-predict the drag force.

As mentioned before, the modified Stokes drag model is another in-built drag model in the coupled FLUENT-EDEM. This drag model is calculated based on equation (5-29) and $C_D$ is calculated based on the equation below.

$$C_D = \begin{cases} 
\frac{24}{Re_p} & \text{if } Re_p \leq 0.5 \\
\frac{24(1 + 0.15Re_p^{0.687})}{Re_p} & \text{if } 0.5 < Re_p \leq 1000 \\
0.44 & \text{if } Re_p > 1000 
\end{cases}$$ \hspace{1cm} (5-38)

### 5.5.2 Lift force model

Lift force is another important force in pneumatic conveying system. Lift force may happen due to the particle rotation (Magnus lift force) or due to flow velocity gradient (Saffman lift). The high velocity gradient induces a pressure difference across the particle surface, causing lift. Matsumoto and Saito (1970), Sommerfeld (2003) and Lun and Liu (1997) mentioned in their research that in dilute horizontal pneumatic conveying, particles acquire very high angular velocities when they collide with the wall. Matsumoto and Saito (1970) reported particle rotational velocities as high as 1800 revolutions per second in a pipe flow due to particle-wall collision. Sommerfeld (2003) collected the research papers up to the year 2000 which included lift force in the modelling, and highlighted the importance of lift force in the
dilute conveying of particles in a circular pipe or channel. Table 5-2 shows the research after the year 2000 including the lift force.

Table 5-2: Summary of numerical work including lift force after 2000

<table>
<thead>
<tr>
<th>Reference</th>
<th>Flow configuration</th>
<th>Gas velocity (m/s)</th>
<th>size of particles (mm)</th>
<th>Lift force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lun (2000)</td>
<td>Horizontal pipe</td>
<td>5-15</td>
<td>0.5</td>
<td>Saffman and Magnus</td>
</tr>
<tr>
<td>Lain et al. (2002b)</td>
<td>Horizontal channel</td>
<td>Up to 30</td>
<td>0.06 to 1</td>
<td>Saffman and Magnus</td>
</tr>
<tr>
<td>Sommerfeld (2003)</td>
<td>Horizontal channel</td>
<td>18</td>
<td>0.03 to 0.7</td>
<td>Saffman and Magnus</td>
</tr>
<tr>
<td>Gupta and Pagalthivarthi (2006)</td>
<td>Horizontal channel</td>
<td>15</td>
<td>Various sizes</td>
<td>Saffman and Magnus</td>
</tr>
<tr>
<td>Kuan et al. (2007)</td>
<td>Horizontal pipe and bend</td>
<td>10</td>
<td>0.077</td>
<td>Saffman</td>
</tr>
<tr>
<td>Lain and Sommerfeld (2008)</td>
<td>Horizontal channel</td>
<td>20</td>
<td>0.06 to 0.625</td>
<td>Saffman and Magnus</td>
</tr>
<tr>
<td>Lain et al. (2009)</td>
<td>Horizontal pipe</td>
<td>10</td>
<td>0.2</td>
<td>Saffman and Magnus</td>
</tr>
<tr>
<td>Brosh and Levy (2010)</td>
<td>Horizontal pipe</td>
<td>6.1-50.8</td>
<td>5.45</td>
<td>Saffman and Magnus</td>
</tr>
<tr>
<td>Lain and Sommerfeld (2012)</td>
<td>Horizontal pipe and channel</td>
<td>20</td>
<td>0.13</td>
<td>Saffman and Magnus</td>
</tr>
</tbody>
</table>

Gupta and Pagalthivarthi (2006) did a comparative study to investigate the influence of different lift coefficients on the particle trajectory in a horizontal channel. They concluded that the effect of shear lift (Saffman lift) was relatively very small in comparison with the Magnus lift force. Therefore, Saffman lift force was excluded in the simulation in the current study.

The Magnus lift force equation applied in this work is based on the Oesterlé and Dinh (1998) research:

\[
F_{\text{Magnus}} = 0.125\pi d_p^3 \rho \frac{R_{ep}}{R_{e\Omega}} C_L \left[ (\omega_p - 0.5 \omega_c) \times (v - u_p) \right] \quad (5-39)
\]

\[
C_L = 0.45 + \left( \frac{R_{ep}}{R_{e\Omega}} + 0.45 \right) \exp(-0.0568 R_{e\Omega}^{0.4} R_{ep}^{0.3}) \quad (5-40)
\]

where \( C_L \) and \( \omega_c \) are coefficient of Magnus lift force and fluid vorticity, respectively. \( R_{e\Omega} \) is a particle rotation Reynolds number.
\[ Re_\Omega = \frac{\rho |\omega_p - 0.5\omega_c| d_p^2}{\mu} \] (5-41)

In the simulation section, the influence of the Magnus lift force on the particle trajectories in the pneumatic conveying will be investigated in more details.

### 5.5.3 Basset and virtual mass forces

Two other forces in gas-particle flows are Basset and virtual mass, which are due to the acceleration of the relative velocity. Both of these forces become insignificant when \( \rho_p / \rho > 1000 \) and these forces are usually negligible compared to the drag and lift force in the pneumatic conveying (Zhu et al. (2007)). Therefore, these forces are not considered in this study.

### 5.6 FLUENT-EDEM code verification

Codes are generally tested with a series of verification test cases before implementing model codes to study more complex systems. In this section, two test cases are described to evaluate the ability of coupled FLUENT-EDEM to correctly model the dynamics of two-phase flows and the interaction between phases before being used for the pneumatic conveying simulation. Two sedimentation test cases are studied here: single particle sedimentation (SPS) and a constant porosity block (CPB). Single particle sedimentation checks the drag force implementation (calculation and integration) for a single particle falling through different fluid media, in this case air, water and water-glycerol. These results can be compared to creeping flow single particle approximations in the Stokesian regime. The CPB checks the drag model implementation for a constant porosity field and a simple velocity field.

#### 5.6.1 Simulation setup of test cases

The simulation domain and solid particle properties for the verification cases are shown in Table 5-3. The domain comprises a column under gravity (negative z direction) with a no-slip boundary condition at the bottom and side walls (Figure 5-6).
The fluid properties are summarized in Table 5-4.

Table 5-4: Fluid properties and particle relaxation time

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Air</th>
<th>Water</th>
<th>Water-Glycerol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid density (kg/m³)</td>
<td>1.1839</td>
<td>1000</td>
<td>1150</td>
</tr>
<tr>
<td>Fluid viscosity (Pa.s)</td>
<td>1.86×10⁻⁵</td>
<td>8.9×10⁻⁴</td>
<td>8.9×10⁻³</td>
</tr>
</tbody>
</table>

The CPB is created using a regular grid of DEM particles that are separated by a constant distance (Δr), as seen in Figure 5-6. Δr is calculated as follows:

\[ Δr = \left( \frac{V_p}{1 - \varepsilon_f} \right)^{1/3} \]  

(5-42)

The DEM particle positions are fixed relative to each other during the simulation. To implement this for the CPB test, the drag force calculated for each particle is summed over the CPB and then divided equally among all its component particles, thus ensuring each particle experiences an equal drag force (Robinson et al. (2014) and Ebrahimi et al. (2013)). For the simulation of the CPB, the fluid mesh is created with respect to the distance between the particles, giving 8 particles in each fluid cell, placed symmetrically. This means that each particle would ‘experience’ equal porosity except for the boundary particles which would experience a reduced porosity than the rest of the block at certain times (hence the need for averaging the drag force over all particles).

5.6.2 Single particle sedimentation (SPS) results

This section describes simulation results for SPS. In the Stokesian or creeping flow regime (\( Re_p < 0.5 \)), the following analytical equation can be solved to calculate the terminal velocity:
\[ u_p(t) = \frac{(\rho_p - \rho)V_p g}{b} \left(1 - e^{-bt/m}\right) \]
\[ b = 3\pi \mu d_p \]

(5-43)

The buoyancy force acting on a particle is taken into account by the following equation.

\[ F_B = \rho V_p g \]

(5-44)

Figure 5-4 gives the simulation results for single particle sedimentation in air, water and a water-glycerol solution using the modified Stokes drag model (equations (5-29) and (5-38)) in comparison with the analytical solution. RANS-DEM results for terminal velocity are within 1% error for water-glycerol, 3% error for water and 5% error for air.
Figure 5-4: Comparison between analytical and simulation results of sedimentation velocity for SPS in different media.

As can be seen in Figure 5-5, simulation shows a lateral velocity (magnitude $10^{-11}$) which can be attributed to numerical errors due to discretization schemes. These errors come primarily from the buoyancy calculations (pressure calculations updated only at the fluid step). These numerical errors are fluctuating and do not accumulate with time. $t_d$ in Figure 5-5 is the ratio of particle mass ($m$) to $b$ in equation (5-43). Lateral velocity is scaled by the single particle sedimentation velocity.

RANS-DEM calculates porosity based on the mesh cell volume, and hence predicts lower porosity for finer mesh size. This can lead to unphysical low porosity even for a single particle in the domain. Usual RANS-DEM methodology states that the minimum cell size should be sufficiently larger than the largest DEM particle.
diameter in order to reduce these unphysical porosities (Anderson and Jackson (1967)).

![Figure 5-5: Simulation results for the fluctuating numerical error in the lateral velocity.](image)

**5.6.3 Constant porosity block (CPB)**

The second test case models the sedimentation of the CPB in water. The initial position of CPB is displayed in Figure 5-6 from two different views.

![Figure 5-6: Schematic of the domain and constant porosity block (CPB), $\varepsilon_f = 0.8$.](image)

The simulation domain is otherwise identical to the SPS test case. Using the Di Felice drag (equation (5-36)), the expected terminal velocity of the block is calculated by the following equation, based on the $Re_p$.

$$0.392Re_p^2 + 6.048Re_p^{1.5} + 23.04Re_p - 1.333Ar\varepsilon_f^{1+\xi} = 0 \quad (5-45)$$
Where $Ar = \frac{d^3 \rho (\rho_p - \rho) g}{\mu^2}$ is the Archimedes number. Figure 5-7 shows the scaled average terminal velocity plotted with respect to porosity ranging from 0.7 to 0.9. A close agreement between analytical and simulation results is observed and the maximum discrepancy is limited to 8%. High porosity cases tend to have lower error compared with low porosity cases. This trend can be explained by the fact that analytical solution does not consider the effects of interstitial fluid velocity and the porosity is assumed to be constant throughout the block. However in the simulations, the DEM particles at the edge of the block experience a lower porosity.

Figure 5-7: Average terminal velocity (scaled by the expected terminal velocity of single particle calculated by equation (5-43)) for CPB in water, for varying porosities.

**5.7 Conclusion to Chapter 5**

In this chapter, the governing equations applied in the coupled FLUENT-EDEM were presented. Forces acting on a particle due to the particle-particle or gas-particle interactions were introduced and the mathematical equations for these forces were presented. Mathematical formulations of the carrier phase turbulence modulation were also discussed. To test the RANS-DEM approach explained in this chapter, two verification test cases were performed i.e. single particle sedimentation and constant porosity block sedimentation. Simulation results agreed well with the analytical solutions for both test cases.
Chapter 6.

Numerical simulation of the pneumatic conveying system

In this chapter, the important parameters in the simulation of the experimental pneumatic system are discussed. Firstly, the steps which have been taken to choose the appropriate mesh sizes and boundary conditions are explained. Then the influence of the Magnus lift force on the particle trajectories is studied by the aid of the RANS-DEM approach. One-way coupling simulation of pneumatic conveying is also presented in order to determine the importance of the mutual momentum exchange between gas and particles in the current study. The effect of hybrid source terms on the numerical results of the carrier phase turbulence intensity is also evaluated using some of the experimental measurements presented in Chapter 4.

6.1 Meshing procedure, boundary conditions and particle initial position

In the previous chapter the importance of the mesh size was highlighted and here in this section the meshing procedure is explained in more detail. RANS method is a finite volume mesh based method. Therefore, the mesh size and quality have a direct influence on the simulation convergence, computational time and simulation accuracy. Moreover, RANS is coupled with DEM and therefore the results for fluid phase at each time step have a direct effect on the DEM side.

With the aid of the experimental results, a suitable mesh size which produces accurate results and reasonably fast simulation was selected. Simulation results from FLUENT (for clear gas flow) were compared with the experimental results to choose the appropriate simulation mesh size. The gas velocity at the cross sections z=1 m, z= 2 m and z=3 m were measured experimentally. Then, a 3D pipe which represents the 5.5 m of the pneumatic conveying pipe length was simulated. For this geometry, the gas velocity profile which was measured by LDA experimentally was set as boundary condition. Then, different mesh sizes were tested for the pipe (noting that
Numerical simulation of the pneumatic conveying system

in the RANS-DEM coupling method, the size of mesh should be larger than the particle size for smooth convergence). The list of mesh sizes tested is summarized in Table 6-1. To check the mesh quality, the simulated gas velocity at the z=2 m was compared with the experimental results as can be seen in Figure 6-1. For clarity, only Cases 1, 4 and 5 are shown. Simulation results for Cases 4 and 5 are relatively close. The error between the predicted gas velocities with these two cases is around 2% at the pipe centre. Simulation results with these mesh sizes show a relatively good agreement with the experimental results. The error between the predicted gas velocity in Case 5 and the experimental measurements is around 6% at the pipe centre and the error between the predicted gas velocity in Case 4 and the experimental measurements is around 8% at the pipe centre. However, the simulation for Case 4 was much faster than Case 5; therefore this mesh size is chosen. This mesh size is considerably larger than the particle size and is smaller than the system dimensions which satisfies the mesh size criterion in the RANS-DEM method (Anderson and Jackson (1967)).

In all simulations in this study, 2.15 m of the conveying pipe is simulated to decrease the computational time. Boundary conditions for this geometry are determined from the previous simulation for clear gas for the 5.5 m pipe. A no slip boundary condition was set at the wall for the gas phase.

![Table 6-1: Different mesh sizes tested for gas flow](image)

<table>
<thead>
<tr>
<th>Case</th>
<th>Min element size (m)</th>
<th>Max element size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.0075</td>
<td>0.015</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.0045</td>
<td>0.015</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.0075</td>
<td>0.012</td>
</tr>
<tr>
<td>Case 4</td>
<td>0.0045</td>
<td>0.012</td>
</tr>
<tr>
<td>Case 5</td>
<td>0.0045</td>
<td>0.009</td>
</tr>
</tbody>
</table>
Particles in the simulations are created in the inclined pipe attached to the horizontal pipe (Figure 3-1) with the initial velocity of 0.0635 in the x direction. This initial velocity is given to the particles to replicate the screw feeder effects, since the screw feeder is not modelled in this study. Then the particles roll down the inclined pipe and are pulled down by the effect of gravity into the horizontal pipe, where they experience a gas flow similar to the experiments.

6.2 Importance of lift force in the simulation

In this section, two different simulations were carried out to investigate the influence of the Magnus lift force on particle trajectory in the horizontal transportation line in order to estimate whether or not the lift force can be neglected. All simulation parameters were kept similar for both simulations except in one of the simulations lift force was included whilst the other simulation was carried out without lift force. A 3D geometry similar to the experiment was built (as mentioned before only 2.15 m of the conveying line) and the mesh size and particle initial positions are selected as explained in the previous section. Table 6-2 shows the parameters used for the simulations.
Table 6-2: Pneumatic conveying simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle diameter (m)</td>
<td>0.0015, 0.002</td>
</tr>
<tr>
<td>Particle density (kg/m$^3$)</td>
<td>2540</td>
</tr>
<tr>
<td>Coefficient of restitution (glass beads-wall)</td>
<td>0.97</td>
</tr>
<tr>
<td>Coefficient of restitution (glass beads-glass beads)</td>
<td>0.9</td>
</tr>
<tr>
<td>Coefficient of friction</td>
<td>0.154</td>
</tr>
<tr>
<td>Solid mass flow rate (kg/s)</td>
<td>0.1128</td>
</tr>
<tr>
<td>Drag force</td>
<td>Ergun and Wen &amp; Yu</td>
</tr>
<tr>
<td>Lift force</td>
<td>Magnus</td>
</tr>
</tbody>
</table>

To investigate the influence of Magnus lift force, the horizontal pipe was divided into 4 sections vertically (as can be seen in Figure 6-2) and the number of particles in the top section was counted during the simulation time for both simulations.

![Figure 6-2: side and front view of the pneumatic conveying divided into 4 sections.](image)

As illustrated in Figure 6-3 qualitatively and Figure 6-5 quantitatively, the number of particles in the top section of the pipe increases noticeably by the inclusion of Magnus lift force, demonstrating the importance of lift force in the simulation in order to model the particle trajectory correctly.

Figure 6-3 (a) displays that, for the simulation without lift force, a dense layer of particles is formed at the bottom of the pneumatic conveying line, such a behaviour not being seen in the experiments. On the other hand, Figure 6-3 (b) shows the simulated particle distribution with the Magnus lift term included, this being similar to the distribution observed in the experiments. A snapshot of the experiment in comparison with the simulation including the Magnus lift force is seen in Figure 6-4.
Figure 6-5 illustrates that the average number of particles in the top section increases from 2 where lift force was not applied to 14 particles by inclusion of Magnus lift force. Therefore, this force should not be neglected in simulations.

![Figure 6-3: Qualitative comparison of particle distribution without lift force (a) and with lift force (b).](image1)

(a)                                                                                      (b)

![Figure 6-4: Experiment snapshot (a) in comparison with the simulation included Magnus lift force (b).](image2)

(a)                                                                                      (b)

Figure 6-5: The effect of the Magnus lift force on the particle trajectory of 1.5 mm glass beads, SLR=2.3, z=1 m.

![Figure 6-5: The effect of the Magnus lift force on the particle trajectory of 1.5 mm glass beads, SLR=2.3, z=1 m.](image3)

To clarify the reason of the significant effect of Magnus lift force in the current horizontal pneumatic conveying, angular velocity in the simulation was determined in the 7 ‘bins’ as shown in Figure 6-6.
Numerical simulation of the pneumatic conveying system

Figure 6-6: Position of different bins to measure the particles angular velocity.

While particles are passing through each of these bins, the particles angular velocities are recorded and averaged. Bins 1, 2 and 3 are before particle-wall collision, bin 4 is just after the point where particles first collide with the wall and bins 5, 6 and 7 are at the distance of 0.5, 1 and 1.2 m from the point where particles are introduced to the horizontal pipe. As can be seen in Figure 6-7, for 2 mm glass beads, the particle angular velocity is around 70 rad/s for the first three bins and particle angular velocity increases significantly after collision with the wall in bin 4 and then reaches around 250 rad/s toward the end of the simulation time. The increase in angular velocity confirms that collision with the wall is the main reason of high angular velocity. For Bins 5, 6 and 7 we have the same trend as for bin 4, but the angular velocity at bin 4 is higher at the beginning compared to other bins. However, all particles in these bins achieve almost the same angular velocity by the end of simulation. This high angular velocity clearly explains why Magnus lift force has such a predominant effect in the pneumatic conveying simulation. For 1.5 mm glass beads, the same trend as 2 mm glass beads is seen, but particles at bins 4, 5, 6 and 7 acquire lower angular velocities by the end of the simulation.
In order to extract the magnitude of the lift force in the present pneumatic conveying simulation, a custom property is defined in the coupled FLUENT-EDEM. Then, force balances between the lift and drag forces, and the lift and gravity forces are calculated. The magnitude of the lift force can be extracted for any arbitrary particles or for a bunch of particles passing through a specific region of the geometry, as can be seen in Figure 6-8.

Figure 6-7: Angular velocity in different bins, 2 mm glass beads, SLR=2.3 (a), 1.5 mm glass beads, SLR=2.3 (b).
As it is seen in Table 6-3, for 2 mm glass beads, the magnitude of lift force is very close to the magnitude of the drag force and the ratio between drag and lift forces is almost one. For 1.5 mm glass beads, the value of the lift force is almost half of the drag force. The comparison between lift and gravity forces also shows that the lift force is not much smaller than the gravity force. Therefore, it is concluded that the Magnus lift force should be included in the simulation of the pneumatic conveying in the current study.

6.3 One-way coupling simulation

In this section, a one-way coupling simulation of the pneumatic conveying is presented to investigate whether or not one-way coupling is a suitable way of simulation in the current study.

In the one-way coupled FLUENT-EDEM, first, Navier–Stokes equations are solved for a single gas phase in FLUENT, then the cell centre information, including the gas velocity and vorticity are exported to EDEM. However, since it is a one-way simulation, these values are assumed to be constant for whole simulation time. These
Numerical simulation of the pneumatic conveying system

fluid flow values are used to calculate the drag and Magnus lift forces at each time step. The geometry, mesh and particle initial positions are similar to those explained in section 6.1 to simulate the experimental apparatus. The simulation parameters presented in Table 6-2 also are used in this section.

To compare simulation results with experimental results, it is necessary to explain how the particle information is extracted from the simulation. As explained in the experimental section, particle velocity was measured for 15 points of a cross section in the horizontal direction and 15 points of a cross section in the vertical direction. Therefore, in the simulation post processing, the pneumatic conveying line cross section is divided into 15 “grid bins” in the horizontal direction and 15 grid bins in the vertical direction such that each of these grid bins has 5 mm length. In fact each of these grid bins represents a measurement point in the experiment. The grid bins are shown in Figure 6-9. When a particle is passing through a specific grid bin, the particle velocity is recorded for that grid bin and at the end of the simulation time a temporally averaged velocity is obtained for all the particles passed through the specific grid bin. This temporally averaged velocity then is compared with the experimentally measured particle velocity.
Figure 6-9: Horizontal and vertical grid bins in the pneumatic conveying.

Figure 6-10 shows the comparison between the experimental and one-way coupling simulation results of the horizontal profile of mean axial particle velocity. The grid bin number 8 represents the pipe centre. As it can be seen in Figure 6-10, horizontal profile of mean axial particle velocity calculated by one-way coupling is over-predicting the experimental results and a considerable discrepancy is seen. This can be explained by the fact that, in one-way coupling, the fluid phase velocity remains unchanged. But, as it was shown in the experimental section (section 4.4.7), the horizontal profile of gas velocity became flat due to addition of particles to the system and the gas velocity in the particle laden flow decreased noticeably compared to the clear gas flow. So it may be concluded that, for the present study, the one-way coupling method is not capable of capturing the real gas-particle behaviour and, as a result, the two-way coupling method needs to be used in the current study. Therefore, all simulations presented from this point are carried out with the two-way coupling method.
6.4 Comparison between experimental and simulation results of turbulence intensity

In this section, some of the experimental results of the carrier phase turbulence intensity presented in Chapter 4 are compared with the simulation results to address the importance of the inclusion of the effects of the dispersed phase on the carrier phase turbulence level.

As mentioned before, the averaged Navier-Stokes equations in connection with the $k$-$\epsilon$ turbulence model (equations (5-1), (5-2), (5-5) and (5-6)) are solved by using Ansys FLUENT software version 12.1 to model the fluid flow. $S_{kp}$ and $S_{\epsilon \rho}$ in equations (5-5) and (5-6) are replaced by the model suggested by Geiss et al. (2004) and Mandø (2009) (equations (5-13) and (5-10)). In the current study the value of $C_{\epsilon 3}$ is assumed to be constant regardless of the particle concentration in the pneumatic conveying line and its value is calibrated by comparing the simulation results versus experimental measurements of carrier phase turbulence intensity. This assumption is made to simplify the model, moreover there is no proven equation for the dependency of $C_{\epsilon 3}$ to particle concentration. The source terms are implemented in the RANS-DEM code by the User Defined Functions (UDFs), in order to take into account the influence of the dispersed phase on the carrier phase. At the beginning of
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each time step, the source terms are calculated using the particle information provided by EDEM from the previous time step. The mesh size and particle initial position are similar to that explained in the section 6.1. All parameters used in the pneumatic conveying simulation in FLUENT-EDEM are summarized in Table 6-4. The particle property values are selected from DEMSolutions Ltd (2010).

Table 6-4: Numerical parameters for pneumatic conveying simulation

<table>
<thead>
<tr>
<th>Simulation method</th>
<th>RANS-DEM (Eulerian-Lagrangian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling method</td>
<td>Two-way coupling</td>
</tr>
</tbody>
</table>

**FLUENT**

<table>
<thead>
<tr>
<th>Air density (kg/m³)</th>
<th>1.225</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air viscosity (pa.s)</td>
<td>$1.78 \times 10^{-5}$</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>$k$-$\varepsilon$ model with the hybrid source terms</td>
</tr>
</tbody>
</table>

**EDEM**

<table>
<thead>
<tr>
<th>Particle creation</th>
<th>Created in the inclined pipe with the initial velocity similar to the experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle flow rate (kg/s)</td>
<td>0.1128, 0.1329</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.24</td>
</tr>
<tr>
<td>Shear modulus (pa)</td>
<td>$2.62 \times 10^{10}$</td>
</tr>
<tr>
<td>Particle-Particle, Particle-wall contact model</td>
<td>Non-linear Hertz-Mindlin</td>
</tr>
<tr>
<td>Particle diameter (m)</td>
<td>0.0015, 0.002</td>
</tr>
<tr>
<td>Particle density (kg/m³)</td>
<td>2540</td>
</tr>
<tr>
<td>Coefficient of restitution (glass beads-wall)</td>
<td>0.97</td>
</tr>
<tr>
<td>Coefficient of restitution (glass beads-glass beads)</td>
<td>0.9</td>
</tr>
<tr>
<td>Coefficient of static friction</td>
<td>0.154</td>
</tr>
<tr>
<td>Time step</td>
<td>$3 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

**Gas-Particle interactions**

<table>
<thead>
<tr>
<th>Drag model</th>
<th>Ergun and Wen &amp; Yu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift model</td>
<td>Magnus lift force</td>
</tr>
</tbody>
</table>

Firstly, the simulation results for single phase turbulence intensity are compared with the experimental measurements. As seen in Figure 6-11 and Figure 6-12, the simulations give close agreement with the single phase experimental measurements. However, the turbulence intensity profile shapes predicted by the simulations are generally different from the turbulence intensity profile shapes measured experimentally.
To determine whether or not the $C_{\varepsilon3}$ value had a significant effect on the simulation results, four different values for $C_{\varepsilon3}$, all reported in the literature, were selected. Results for horizontal profile of turbulence intensity at $z=2$ m for SLR=2.3 and SLR=3 in the presence of 2 mm glass beads are shown in Figure 6-13 and Figure 6-14. It is seen that the turbulence intensity values depend strongly on the $C_{\varepsilon3}$. For both cases, by increasing the $C_{\varepsilon3}$ values from 1.1 to 1.89, turbulence intensity drops noticeably. This is in a good agreement with Zhang and Reese (2003) study that they reported that the $C_{\varepsilon3}$ values had a significant effect on fluctuating gas velocity.

Figure 6-11: Horizontal profile of gas turbulence intensity for pure gas flow, gas velocity 9.5 m/s.

Figure 6-12: Vertical profile of gas turbulence intensity for pure gas flow, gas velocity 8.5 m/s.
also seen that the horizontal profile of turbulence intensity is more or less flat except for regions close to the wall where turbulence intensity increases significantly.

Figure 6-13: Effect of $C_{x3}$ on the horizontal profile of turbulence intensity, 2 mm glass beads, SLR=2.3, $z=2$ m.

Figure 6-14: Effect of $C_{x3}$ on the horizontal profile of turbulence intensity, 2 mm glass beads, SLR=3, $z=2$ m.

Figure 6-15 shows the vertical profile of turbulence intensity of air in the presence of 2 mm glass beads at $z=2$ m for SLR=2.3. These results also indicate that the turbulence intensity values change considerably by changing $C_{x3}$. It is also seen that the higher the $C_{x3}$ value, the lower the turbulence intensity. Moreover, it is seen that
the turbulence intensity value is not symmetrical; it is higher in the lower section of the pipe because the number of particles here is higher and lower in the pipe upper section where the particle concentration is much lower. This trend was previously observed experimentally by Tsuji and Morikawa (1982).

If the simulation results presented in Figure 6-13 and Figure 6-14 are summarized in one graph, the influence of SLR on the turbulence intensity for a constant $C_\varepsilon$ can be seen (Figure 6-16). For instance, if turbulence intensity for SLR=2.3, $C_\varepsilon=1.7$ is compared with SLR=3, $C_\varepsilon=1.7$, it becomes clear that the turbulent intensity increases with increasing the SLR. The same trend is seen when SLR=2.3, $C_\varepsilon=1.8$ is compared with SLR=3, $C_\varepsilon=1.8$. It shows that the turbulence intensity increases by increasing the SLR for a constant $C_\varepsilon$ as was previously reported in Curtis and van Wachem (2004).

The results from Figure 6-13 to Figure 6-16 confirm that the new source terms added to the $k-\varepsilon$ turbulence model are capable of predicting previous findings.
In order to evaluate the influence of the source terms added to the standard $k$-$\varepsilon$ turbulence model, simulation results were compared with experimental results. The results for horizontal and vertical profiles of carrier phase turbulence intensity in the presence of 1.5 mm glass beads with SLR=3 are shown in Figure 6-17 and Figure 6-18 respectively. It is seen that turbulence intensity decreases with increasing the $C_\varepsilon$. In the horizontal profile, the $k$-$\varepsilon$ model with the source terms and $C_\varepsilon=1.8$ is under-predicting the experimental results considerably due to the overestimating the dissipation. Obviously, the turbulence intensity predicted by the $k$-$\varepsilon$ turbulence model with the source terms with $C_\varepsilon=1.1$ is over-predicting the turbulence intensity compared to the experimental results in the central section of the pipe. The experimental turbulence intensity trend is captured only very generally by the model in the horizontal profile, and the model shows significant turbulence intensity increase only for regions very close to the pipe wall. In the vertical profile, similar to the experimental measurements, the model predicts higher turbulence intensity values in the lower half of the pipe where more particles are concentrated because of the gravity, and lower values in the pipe upper section where fewer particles are transported. For both horizontal and vertical profiles, the discrepancy between experimental and simulation results increases toward the walls as previously observed by Boulet and Moissette (2002) in vertical pneumatic transportation. The capacity of RANS-DEM to simulate the near-wall flow is generally limited, as the
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The fluid mesh cannot be resolved finely enough for this due to the requirement for it to be significantly larger than the particle diameter. Moreover, in the implemented hybrid source terms the effect of the particle fluctuating velocity i.e. $u'_{p1}u'_{p1}$ was omitted for model simplicity. However, for near-wall regions it can be imagined that the gas phase turbulence intensity can be alerted due to the significant increase of particle fluctuating velocity due to the increased particle-wall collisions. The minimum discrepancy between experimental and simulation results in the central section of the pipe is obtained by using $C_3=1.7$ or $C_3=1.5$.

Simulation and experimental results of carrier phase turbulence intensity in the presence of 1.5 mm glass beads, SLR=2.3 are shown in Figure 6-19 and Figure 6-20. In the horizontal profile and close to the pipe centre, the $k-\varepsilon$ turbulence model with the source terms over-estimates the turbulence intensity (except for $C_3=1.8$). Similar to Figure 6-17, the model is not capable of capturing the detail of the experimental results. In the vertical profile, the turbulence intensity trend is also captured generally by the model. In some measurement points in the central section of the pipe, the simulations with $C_3=1.7$ are closest to the experimental results.

![Figure 6-17: Effect of $C_3$ on the horizontal profile of turbulence intensity and comparison between simulation and experimental results, 1.5 mm glass beads, SLR= 3, z=2 m.](image_url)
Figure 6-18: Effect of $C_{\varepsilon 3}$ on the vertical profile of turbulence intensity and comparison between simulation and experimental results, 1.5 mm glass beads, SLR= 3, $z=2$ m.

Figure 6-19: Effect of $C_{\varepsilon 3}$ on the horizontal profile of turbulence intensity and comparison between simulation and experimental results, 1.5 mm glass beads, SLR= 2.3, $z=2$ m.
Comparison between experimental and simulation results of horizontal and vertical profiles of gas phase turbulence intensity in the presence of 2 mm glass beads for SLR=2.3 are presented in Figure 6-21 and Figure 6-22. As can be seen, the simulation results with $C_{\varepsilon}=1.8$ or $C_{\varepsilon}=1.7$ are close to the experimental results in the central section of the pipe in both horizontal and vertical profiles. However, the discrepancy increases for the measurement points closer to the pipe walls.

Figure 6-20: Effect of $C_{\varepsilon}$ on the vertical profile of turbulence intensity and comparison between simulation and experimental results, 1.5 mm glass beads, SLR= 2.3, $z=2$ m.

Figure 6-21: Effect of $C_{\varepsilon}$ on the horizontal profile of turbulence intensity and comparison between simulation and experimental results, 2 mm glass beads, SLR= 2.3, $z=2$ m.
Figure 6-22: Effect of $C_{\varepsilon_3}$ on the vertical profile of turbulence intensity and comparison between simulation and experimental results, 2 mm glass beads, SLR=2.3, $z=2$ m.

Figure 6-23 shows the carrier phase turbulence intensity for the particle laden flow with 2 mm glass beads, SLR=3. A very good agreement between the simulation with $C_{\varepsilon_3}=1.8$ and experimental results in the horizontal profile is observed, except for the measurement points close to the pipe walls. In the vertical profile, a good agreement is also observed between the experimental results and simulation results with $C_{\varepsilon_3}=1.8$ in the central parts of the pipe (Figure 6-24).

Figure 6-23: Effect of $C_{\varepsilon_3}$ on the horizontal profile of turbulence intensity and comparison between simulation and experimental results, 2 mm glass beads, SLR=3, $z=2$ m.
6.5 Carrier phase turbulence impact on the particle velocity

The influence of the $C_{\varepsilon}$ values on the horizontal and vertical profiles of mean particle velocity is examined in Figure 6-25 to Figure 6-32 for 1.5 mm and 2 mm particles and different SLRs. As is seen, in all figures the $C_{\varepsilon}$ values have a negligible influence on the particle velocity and the particle mean velocity is almost the same for all different values of $C_{\varepsilon}$ which is due to the high particle response time.
Figure 6-26: Effect of $C_{3,3}$ on the horizontal profile of particle velocity, 1.5 mm glass beads, SLR=3, $z=1$ m.

Figure 6-27: Effect of $C_{3,3}$ on the horizontal profile of particle velocity, 2 mm glass beads, SLR=2.3, $z=1$ m.
Figure 6-28: Effect of $C_{\varepsilon}$ on the horizontal profile of particle velocity, 2 mm glass beads, SLR=3, $z=1$ m.

Figure 6-29: Effect of $C_{\varepsilon}$ on the vertical profile of particle velocity, 1.5 mm glass beads, SLR=2.3, $z=1$ m.
Figure 6-30: Effect of $C_{d3}$ on the vertical profile of particle velocity, 1.5 mm glass beads, SLR=3, $z=1$ m.

Figure 6-31: Effect of $C_{d3}$ on the vertical profile of particle velocity, 2 mm glass beads, SLR=2.3, $z=1$ m.
6.6 Conclusion to Chapter 6

In this chapter, the meshing procedure and boundary conditions in this study were explained. Then the effect of Magnus lift force on the particle trajectory was highlighted with the aid of simulation. It was concluded that the inclusion of lift force in the simulation changed the particle distribution in the pipe, demonstrating the significance of this force to the realistic simulation of particle distribution within the pipe. High angular velocities (up to 250 rad/s) that resulted from particle-wall collisions were identified as the main reason for having a high Magnus lift force. Afterwards, it was shown that for the SLRs investigated; one-way coupling cannot be used to simulate the particle velocity precisely in the conveying line, over-predicted particle velocity being observed. Hybrid source terms were added to the $k-\varepsilon$ turbulence model. In summary, from the simulation results of turbulence intensity, the following points were concluded:

- The higher the $C_\varepsilon$, the lower the turbulence intensity
- The higher the SLR, the higher the turbulence intensity
- $C_\varepsilon$ had a negligible influence on the mean particle velocity, because of the large particle size
In the next chapter, the mean gas and particle velocities measured experimentally will be compared with the simulation results. With regard to the results obtained in this chapter, the simulations in the next chapter will be performed with a two-way RANS-DEM approach. The Magnus lift force will be implemented to all simulations, and the source terms are incorporated to the $k$-$\varepsilon$ turbulence model to take into account the effect of particles on the turbulence structure.
Chapter 7.

Comparison between simulation and experimental results for pneumatic conveying of spherical particles

7.1 Introduction

In this chapter, a comparison between the experimental and simulation results is presented. The experimental measurements presented previously are used to validate the coupled FLUENT-EDEM code. Firstly, the numerical model and applied parameters are presented and then the simulation results of horizontal and vertical profiles of particle and gas velocities are compared with the experimentally measured data. The comparison of numerical and experimental results showed that RANS-DEM could capture gas and particle dynamic behaviours in horizontal pneumatic conveying. Flat profiles were predicted for horizontal profiles of mean gas and particle velocities. Moreover, in vertical profiles, the maximum gas and particle velocities were predicted in the upper section of the pipe as previously seen in the experiments. RANS-DEM approach could also predict gas and particle velocity values in pneumatic conveying relatively close to those measured in the experiments. However, both the gas and particle velocities predicted numerically in both horizontal and vertical profiles over-estimated the experimental results.

7.2 Numerical model and applied parameters

In this section, the standard simulation approach applied is presented based on the findings from the previous chapters and preliminary simulations. A complete comparison was attempted between experimental and simulation results which includes the horizontal and vertical mean gas velocity profiles, and horizontal and vertical mean particle velocities under different operating conditions. It was also attempted to address the limitation of the current numerical models by analysing the discrepancy between simulation and the corresponding experimental results.
In the previous chapters, the effects of some simulation parameters such as mesh size, coupling method, time step, Magnus lift force and turbulence modulation were investigated on the horizontal pneumatic conveying using the coupled FLUENT-EDEM. More details about these codes can be found in the coupled FLUENT-EDEM user guides DEMSolutions Ltd (2010). The findings from our previous simulations are used in this section to simulate the horizontal pneumatic conveying.

In the following paragraphs the numerical method and parameters used in the simulations are summarized briefly. A 2.15 m length of the pneumatic conveying line is simulated in a 3D geometry and the mesh sizes are selected as explained in section 6.1. The hybrid source terms introduced in section 5.3.2.4 are added to the standard k-ε model to take into account the influence of the discrete phase on the carrier phase turbulence. As explained, these source terms are implemented into the k-ε model via UDFs. Gas and particle flow rates in the simulations are matched with the experiments to make SLRs 2.3, 3 and 3.5.

Particles are assumed to be spherical in the current chapter. The nonlinear Hertz-Mindlin contact model for particle-particle and particle-geometry is used in all simulations. Particles are created in the inclined pipe with the initial velocity $u_x = 0.0635$ to replicate the screw feeder as mentioned in section 6.1. Time step equals to 30% of Rayleigh time is chosen for particle time step which is in $10^{-7}$ range and Eulerian time step is set to 100 times the particle time step.

In all computer simulations in this section, the Ergun and Wen & Yu drag models (section 5.5.1) are used otherwise stated. The influence of the lift force on the particle trajectory was explained in section 5.5.2. Therefore, Magnus lift force is included in the pneumatic conveying simulations. It should be noted that Buoyancy force is not included in the simulations in this chapter. All parameters used in the pneumatic conveying simulation in FLUENT-EDEM are summarized in Table 6-4. In addition to the parameters in Table 6-4, Particle diameter 0.9 mm was also considered in the simulations. The 0.9 mm particle size is defined with a normal
distribution and the mean particle size is set to be 0.9 mm. The $C_{\epsilon_3}$ value was selected equal to 1.7 according to the calibration performed in section 6.4. As mentioned the equation (5-10) is controversial and the value of $C_{\epsilon_3}$ may change based on the particle concentration in the system. However for the sake of the simplicity of the model and lack of the availability of the other established models to correlate the particle concentration to $C_{\epsilon_3}$, constant value of $C_{\epsilon_3}=1.7$ is selected in the current simulations.

Various particle-particle and particle-geometry coefficients of restitution have been used in literature for glass beads, which are usually close to unity. Tartan and Gidaspow (2004) used 0.98, 0.89 and 0.95 for 530 μm glass beads. Mathisen (2010) and Lu (2009) used the value of 0.95 and 1 for the coefficient of restitution respectively. Patil et al. (2005) selected the value 0.9 for glass beads. In this study particle-wall and particle-particle collisions are assumed to be almost elastic as seen in Table 6-4. A coefficient of restitution of 0.8 also was tested but no clear difference was observed on the particle transportation behaviour.

As mentioned in the section 3.2, experimental measurements were performed at the cross sections $z=1$ m, $z=2$ m and $z=3$ m. However, to reduce the computational time only 2.15 m of the pipe is modelled, therefore measurement data at $z=3$ m is not used in the comparison between experiments and simulations. Horizontal and vertical mean particle velocity profiles are obtained by dividing the pipe cross sections into 15 grid bins in either horizontal or vertical directions as explained in the section 6.3. Gas simulation results are extracted by defining a line at the chosen cross section in horizontal or vertical directions. When the defined line crosses a control volume (mesh) the requested data from that mesh is extracted and can be plotted in the post-processing section. Obviously, if the information for a whole cross section is needed a plane can be defined to extract fluid information.

As mentioned before, simulations with coupled RANS-DEM methods are notoriously slow since the particle position and momentum need to be transferred to
the fluid domain at each time step. Moreover, aerodynamic forces are needed to be calculated by the information passed from RANS solver to the DEM solver in order to calculate the particle position. The large simulation domain compared to the particle size and tracking individual particle also increases the computational time. Therefore, due to the very high CPU time, it is not possible to carry out the simulation in a similar time to that of the experiments. In this study, the simulations are carried out for around 1.8 seconds. It has been seen that by performing a simulation of 1.8 seconds, sufficient information is acquired for the comparison with the experimental results.

7.3 Comparison between simulation and experiments for particle velocity

In this section, horizontal and vertical profiles of particle velocity are compared with the experimental results.

Before starting the comparison between experiment and simulation results, the influence of the drag force model on the particle velocity is investigated because the drag force is the dominant force in the pneumatic conveying and this force mainly determines the particle velocity. Two widely used drag models in the pneumatic conveying simulations namely Ergun and Wen & Yu and Di Felice (section 5.5.1) are applied.

The experimental results showing horizontal and vertical profiles of particle velocity, the simulation results with Ergun and Wen & Yu drag models, and the simulation results with Di Felice drag model are presented in Figure 7-1 to Figure 7-4 for 2 mm glass beads, SLR=2.3 and 3 at z=1 m. In all cases, it is clearly observed that the Di Felice drag model predicts higher particle velocity than the Ergun and Wen & Yu drag model, which means the discrepancy between experimental and simulation results increases considerably by using the Di Felice drag model compared to that of Ergun and Wen & Yu.

Numerous correlations for calculating the drag coefficient of gas–solid systems have been reported in literature, including Syamlal and O’brien (1989), Gidaspow (1994),
and Beetstra et al. (2007), all of which can be implemented into the FLUENT-EDEM code. However, even if a drag model giving more accurate results for this study were found, it would not be possible to conclude that this would be appropriate in other pneumatic conveying simulations with different particle sizes and flow regimes. Therefore and as mentioned before, Ergun and Wen & Yu drag model is used in this study. However, the particle velocity simulated by Ergun and Wen & Yu drag model is also over-estimating the experimental results.

Figure 7-1: Effect of the drag model on the horizontal profile of particle velocity, 2 mm glass beads, SLR=2.3, z=1 m.

Figure 7-2: Effect of the drag model on the vertical profile of particle velocity, 2 mm glass beads, SLR=2.3, z=1 m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-3: Effect of the drag model on the horizontal profile of particle velocity, 2 mm glass beads, SLR=3, z=1 m.

Figure 7-4: Effect of the drag model on the vertical profile of particle velocity, 2 mm glass beads, SLR=3, z=1 m.

To determine whether or not the simulation time had a significant effect on the simulation results the particle velocity profiles for 1.8s and 4s simulations are compared for 1.5 mm glass beads, SLR=2.3 at z=1 m. As seen in Figure 7-5, the horizontal profile of particle velocity does not change considerably by increasing the computational time from 1.8s to 4s. The average particle velocity change is around 2%. The vertical profile of particle velocity also increases only slightly by extending the simulation time from 1.8s to 4s (Figure 7-6). The average particle velocity change is around 3%. Therefore, based on this comparison it seems that the particle velocity has reached the steady state condition during 1.8s of simulation and there is
therefore no need to carry out the simulation for longer simulation time. This helps to reduce the CPU time noticeably because the CPU time for a 4s simulation increases significantly compared to the CPU time of a 1.8s simulation. As a result, the simulations are carried out for around 1.8s for all graphs presented in this section unless stated.

![Figure 7-5: Effect of the simulation time on the horizontal profile of particle velocity, 1.5 mm glass beads, SLR=2.3, z=1m.](image1)

![Figure 7-6: Effect of the simulation time on the vertical profile of particle velocity, 1.5 mm glass beads, SLR=2.3, z=1m.](image2)

The horizontal and vertical profiles of the particle velocity are shown in Figure 7-7 and Figure 7-8 for 2 mm glass beads, SLR=3. For the horizontal profile, similar to the experimental results, a relatively flat mean particle velocity profile is obtained in the central parts of the pipe. However, the particle velocity decrease close to the pipe
wall is not seen in the simulation results, and obviously, the model is not capable of predicting the particle velocity decrease close to the pipe wall. The discrepancy between experimental and simulation results increases for the measurement points closer to the pipe wall. The average relative error between simulation and experimental results (relative error = \( \frac{(u_{p,simulation} - u_{p,experiment})}{u_{p,experiment}} \times 100 \)) for the measurement points in the central parts of the pipe is around 35%.

As seen in the vertical profile of particle velocity (Figure 7-8), the particle velocity increases from the lower section of the pipe and reaches a maximum point in the upper section of the pipe and again decreases toward the upper pipe wall. This behaviour is also observed in the experimental results. However, the model cannot capture the noticeable particle velocity decrease close to the pipe wall accurately. The average relative error around 35% is also seen for the vertical profile.

As it is seen for both horizontal and vertical profiles the simulation results are over-predicting the experimental results. Although a discrepancy is seen between experimental and simulation results, the general particle velocity trend is captured (except for the close to wall regions) by the RANS-DEM method showing the ability of this method in pneumatic conveying simulation.

![Figure 7-7: Particle velocity comparison between experiment and simulation for horizontal profile of 2 mm glass beads, SLR=3, z=1 m.](image)
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-8: Particle velocity comparison between experiment and simulation for vertical profile of 2 mm glass beads, SLR=3, z=1 m.

Figure 7-9 and Figure 7-10 display the comparison between experimental and simulation results for 2 mm particles, SLR=2.3 for horizontal and vertical profiles. Comparable to Figure 7-7, horizontal profile of mean axial particle velocity shows a relatively flat profile (Figure 7-9). Similar to what was explained for Figure 7-8 the particle velocity in the vertical profile reaches a maximum point in the pipe upper section. For the both profiles, the particle velocity over-prediction is also seen and generally the particle velocity reduction close to the pipe wall is not predicted by the simulations particularly for the horizontal profile of particle velocity. The average relative errors for horizontal and vertical profiles are around 22% and 25% respectively.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-9: Particle velocity comparison between experiment and simulation for horizontal profile of 2 mm glass beads, SLR=2.3, z=1 m.

Figure 7-10: Particle velocity comparison between experiment and simulation for vertical profile of 2 mm glass beads, SLR=2.3, z=1 m.

Figure 7-11 to Figure 7-16 present the horizontal and vertical profiles of mean particle velocity for 1.5 mm particles, SLR=2.3, 3 and 3.5. Similar to what was discussed for 2 mm glass beads, a flat mean particle velocity profile is obtained for the horizontal profile (Figure 7-11, Figure 7-13 and Figure 7-15). In the vertical profile, particle velocity is smaller in the lower section of the pipe, it increases to a maximum value and decreases again toward the upper pipe wall (Figure 7-12, Figure 7-14 and Figure 7-16). The noticeable particle velocity decrease in the experimental results is not seen in the simulation results for the region close to the pipe wall. As a
result, discrepancy increases between experiments and simulations results for the measurement points close to the pipe wall.

As mentioned in section 2.2, in the RANS-DEM method the mesh size needs to be larger than the particle size \((\text{Anderson and Jackson (1967)})\). Therefore, the fluid flow is not resolved well close to the walls. This issue decreases the accuracy of the fluid flow calculation in these regions and consequently will increase discrepancies between simulation and experimental results. Again, the numerically predicted particle velocity is over-predicting the experimental results. The average relative error for 1.5 mm particles with the SLR=2.3 is around 25% in the horizontal and vertical profiles, and the average relative errors are around 38% and 33% for 1.5 mm particles with the SLR=3 in the horizontal and vertical profiles respectively. For 1.5 mm particles, SLR=3.5 (Figure 7-15 and Figure 7-16) the average relative error in the horizontal profile is around 55% and for the vertical profile it is around 36%.

Figure 7-11: Particle velocity comparison between experiment and simulation for horizontal profile of 1.5 mm glass beads, SLR=2.3, \(z=1\) m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-12: Particle velocity comparison between experiment and simulation for vertical profile of 1.5 mm glass beads, SLR=2.3, z=1 m.

Figure 7-13: Particle velocity comparison between experiment and simulation for horizontal profile of 1.5 mm glass beads, SLR=3, z=1 m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-14: Particle velocity comparison between experiment and simulation for vertical profile of 1.5 mm glass beads, SLR=3, z=1 m.

Figure 7-15: Particle velocity comparison between experiment and simulation for horizontal profile of 1.5 mm glass beads, SLR=3.5, z=1 m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-16: Particle velocity comparison between experiment and simulation for vertical profile of 1.5 mm glass beads, SLR=3.5, z=1 m.

Figure 7-17 and Figure 7-18 show the horizontal and vertical profiles of mean axial particle velocity for 0.9 mm particles with SLR=2.3. Similar to 1.5 mm and 2 mm particles, a flat particle velocity profile is observed for the horizontal profile (Figure 7-17). Particle velocity in the vertical profile increases noticeably from the lower section of the pipe toward the upper part of the pipe (Figure 7-18). The average relative errors between experimental and simulation results are around 40% and 36% for the horizontal and vertical profiles respectively.

Figure 7-17: Particle velocity comparison between simulation and experiment for horizontal profile in the presence of 0.9 mm glass beads, z=1 m, SLR=2.3.
As observed in all figures in this section, the numerically predicted particle velocity over-predicted the experimental results. A reason for over-estimation of the particle velocity can be the inaccurate prediction of drag force. Drag model correlations should be employed with caution as they are usually derived for an isolated single particle and for a specific flow condition. For instance, the Di Felice (1994) drag model was derived for particle sedimentation and the Ergun (1952) drag correlation was derived based on the empirical correlations for pressure drop in a packed bed. They are then corrected to take into account the effect of neighbouring particles in a bulk suspension. However, these drag coefficients cannot be used universally for all simulations and flow conditions, and there is no general agreement about the modelling of gas-particle drag (Goldschmidt et al. (2004)). This shows that more research needs to be performed in this field (Sturm et al. (2010)). Such research is however beyond the scope of this thesis as discussed in the beginning of this section.

The obvious explanation for the discrepancy observed in this study is that the drag model of Ergun (1952) and Wen & Yu (1966) used over-predicts the drag force in the simulations, which can lead to the higher particle velocity compared to the experimental data. Successful implementations of this drag model for simulating the pneumatic conveying have been reported previously (Xiang and McGlinchey (2004), Xiang and McGlinchey (2010)) though these were mainly for dense flow regimes.
In addition, the fluid velocity at the particle location needs to be determined from the grid information to calculate the relative velocity and drag force. However, in the coupled FLUENT-EDEM, fluid velocity is not interpolated to the particle location, and all particles in a mesh experience the same fluid velocity regardless of the particle position, indicated by the quantity $v_f$ in Figure 7-19. This inaccuracy in the calculation of the drag force can be another source of mismatch between experimental and simulation results. Interpolation methods suggested by Xiao and Sun (2011), Sommerfeld et al. (1993) or Elghobashi (1994) could, given time, be implemented in the FLUENT-EDEM code.

![Figure 7-19: Schematic of 2D mesh and particle position within a mesh.](image)

To clarify the significance of the interpolation scheme in calculating the relative velocity and drag force, a simple example was performed with a MATLAB code. A 2D structured mesh was created in 8 rows and 4 columns, as can be seen in Figure 7-20. The mesh size chosen was almost 5 times and 3 times the particle size in the x and y directions respectively, corresponding closely to the mesh size in the FLUENT-EDEM simulations.
The gas velocity at the cell centres was assigned similar to the gas velocity obtained in the simulation of the particle laden flow in the presence of 2 mm glass beads and with SLR=2.3 in a pipe flow which ranged from 7.2 to 11.45 m/s along the y axis. Particles were created randomly in the mesh domain. The particle velocity was also assigned randomly in the range of 2.62 to 2.9 m/s, values obtained from the simulation of particle laden flow in the presence of 2 mm glass beads and with SLR=2.3 in a pipe flow. Then, the relative velocity and drag force were calculated twice. In the first case, no interpolation scheme was used, and the relative velocity and drag force were calculated based on the fluid velocity at the cell centre. This is the method used in the coupled FLUENT-EDEM software. In the second case, the interpolation scheme proposed by Xiao and Sun (2011) was implemented with a weight function inversely proportional to the distance between the particle position and the cell centre. The “cut-off” distance was assumed to be 1.1 times that of the largest dimension of the mesh. Table 7-1 shows the mean error of the relative velocity and drag force for the two cases explained above, at a specific time.
Table 7-1: Mean error of the relative velocity and drag force for the cases with and without interpolation scheme

<table>
<thead>
<tr>
<th>Number of particle</th>
<th>Solid volume fraction range</th>
<th>Mean relative velocity error (%)</th>
<th>Mean drag force error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-0.011</td>
<td>1.3</td>
<td>2.3</td>
</tr>
<tr>
<td>2</td>
<td>0-0.011</td>
<td>1.11</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>0-0.011</td>
<td>1.93</td>
<td>3.4</td>
</tr>
<tr>
<td>10</td>
<td>0-0.033</td>
<td>2.19</td>
<td>3.9</td>
</tr>
<tr>
<td>20</td>
<td>0-0.044</td>
<td>1.88</td>
<td>3.38</td>
</tr>
<tr>
<td>30</td>
<td>0-0.077</td>
<td>2.05</td>
<td>3.66</td>
</tr>
<tr>
<td>50</td>
<td>0-0.1</td>
<td>1.84</td>
<td>3.32</td>
</tr>
</tbody>
</table>

As can be seen from Table 7-1, the calculated drag force with and without interpolation scheme shows around 2 to 4% error for different particle numbers and solid volume fractions. This error in the drag force calculation can certainly lead to a discrepancy between simulation and experimental results during a simulation time, though it clearly does not account alone for the entire discrepancy between observed and simulated particle velocities in the FLUENT-EDEM simulations, which ranged from 22% to 55%.

The above example and the errors demonstrated in Table 7-1 show a general example of the interpolation scheme issue. Obviously, depending on the particles positions in the meshes, the error values vary. Moreover, this example was performed only for a specific time and it needs to be extended for the whole simulation time to study whether the errors are accumulated. The interpolation scheme needs further investigation in future studies using coupled FLUENT-EDEM.

Another reason for discrepancies noticed between simulation and experimental results can be attributed to the neglecting of Buoyancy in the coupled FLUENT-EDEM which is a software bug and needs to be resolved by the software provider. Neglecting the Buoyancy force makes the coupling between the gas and solid phases inaccurate. In other words, by neglecting the Buoyancy force in the simulations, the interaction between phases is not modelled correctly which can result in error on the prediction of the gas and particle dynamic behaviour in the pneumatic transportation
of particles. The magnitude and influence of Buoyance force in the pneumatic transportation of particles needs to be investigated.

Figure 7-21 and Figure 7-22 show the effect of SLR on the horizontal profile of particle velocity for 1.5 mm and 2 mm particles at z=1 m respectively. These figures show that the particle velocity decreases with increasing the SLR. This trend was also observed in the experiments. However, the particle velocity decrease due to increasing the SLR from SLR=2.3 to SLR=3 is more considerable in the experiments as seen in Figure 4-1. The particle velocity decrease which was predicted in the simulation with increasing SLR from 3 to 3.5 (Figure 7-21) is in the range of experimental results. The average particle velocity decrease with increasing SLR from 3 to 3.5 is around 0.4 m/s for both experimental and simulation results.

Figure 7-21: Effect of solid loading ratio on the horizontal profile of particle velocity, 1.5 mm glass beads, z=1m.
Figure 7-22: Effect of solid loading ratio on the horizontal profile of particle velocity, 2 mm glass beads, z=1 m.

Figure 7-23 and Figure 7-24 present the effect of SLR on the vertical profiles of particle velocity for 1.5 mm and 2 mm particles. It is seen from the simulation results that by increasing the SLR the particle velocity decreases as previously observed in the experiments. The average particle velocity decrease by increasing SLR in the experiments and simulations is relatively similar in Figure 7-23 and Figure 4-10. However, for Figure 7-24 the average particle velocity decrease by increasing SLR is higher in the experiments compared to the simulation results.

Figure 7-23: Effect of solid loading ratio on the vertical profile of particle velocity, 1.5 mm glass beads, z=1 m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

The effect of particle size on the horizontal and vertical profiles of particle velocity is illustrated in Figure 7-25 and Figure 7-26 for SLR=2.3 at z=1 m. For both profiles, the particle velocity decreases with increasing particle size for all measurement points. This trend was also observed in the experimental data. The difference between particle velocity of 0.9 mm particles and particle velocity of 1.5 mm and 2 mm particles predicted by the simulation is higher than the difference between particle velocity of 0.9 mm particles and particle velocity of 1.5 mm and 2 mm particles measured experimentally, as can be seen from Figure 4-2 and Figure 4-11.

Figure 7-27 and Figure 7-28 show the influence of particle size on the horizontal and vertical profiles of particle velocity for SLR=3 at z=1 m. It is seen that the particle velocity for 2 mm particle is smaller than the particle velocity for 1.5 mm particles in all measurement points. RANS-DEM Simulations predict the average particle velocity in both horizontal and vertical profiles to decrease by around 0.36 m/s with increasing the particle size.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-25: Effect of particle size on the horizontal profile of particle velocity, SLR=2.3, z=1 m.

Figure 7-26: Effect of particle size on the vertical profile of particle velocity, SLR=2.3, z=1 m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-27: Effect of particle size on the horizontal profile of particle velocity, SLR=3, z=1 m.

Figure 7-28: Effect of particle size on the vertical profile of particle velocity, SLR=3, z=1 m.

7.4 Comparison between simulation and experiments for gas velocity

In this section, simulation results of the mean gas velocity profiles in the presence of glass beads are compared with the experimental measurements.

Figure 7-29 shows the horizontal profile of the simulated and measured mean gas velocity in the presence of 1.5 mm particles, SLR=2.3. The simulation predicts a flat mean gas velocity profile (in the central parts of the pipe) for the particle laden flow compared to the parabolic mean gas velocity of clear gas flow. This trend was also seen in the experimental results. Comparison of the numerical results with the
corresponding experimental data indicates that numerically predicted gas velocity is over-predicting the experimental results.

Comparison between simulation and experimental results of vertical profiles of mean gas velocity in the presence of 1.5 mm glass beads, SLR=2.3 is seen in Figure 7-30. Both experimental and simulation results show that the maximum gas velocity shifted upward from the pipe centre because the flow resistance due to particles is lower in the pipe upper section. Generally, the mean gas velocity is smaller in the lower section of the pipe where more particles are transported. Similarly to that observed for the horizontal profile of mean gas velocity, the mean gas velocity predicted by the simulation is higher than the experimental measurements at all measurement points. However, numerical and experimental results are relatively close.

Figure 7-31 to Figure 7-40 present the comparison between simulation and experimental results of horizontal and vertical profiles of mean gas velocity in the presence of 1.5 mm glass beads and SLR=3, 1.5 mm glass beads and SLR=3.5, 2 mm glass beads and SLR=2.3, 2 mm glass beads and SLR=3 and 0.9 mm glass beads and SLR=2.3. Similar trends as explained for mean gas velocity in the presence of 1.5 mm glass beads and SLR=2.3 were observed in all these graphs. A flat mean gas velocity profile is predicted for the horizontal profiles (in the pipe central regions). For the vertical profiles, mean gas velocity increases from the lower section of the pipe to a maximum in the pipe upper section and decreases again toward the pipe upper wall. In all graphs the numerically predicted gas velocity over-predicts the experimental data.

For all graphs (Figure 7-29 to Figure 7-40) presented in this section, a reasonably close agreement between simulation and experimental results was observed, and the RANS-DEM method also captured the gas velocity trend.

Generally, as observed for all graphs in this section, the gas velocity predicted in the simulation over-predicted the experimental results. It seems that the model cannot
capture the details of the effect of particles on the gas profile accurately it can be attributed to the fluid discretization. As mentioned in section 2.2, the fluid mesh has to be larger than the particle scale for good enough statistics for averaging. The size of the computational cells may not be small enough to replicate the fluid pattern accurately.

The simulation results of mean gas velocity profiles are arguable because it seems that the gas phase mass is not conserved in the coupled FLUENT-EDEM simulations. As observed previously, horizontal and vertical profiles of particle velocities were predicted higher in simulations compared to the experimental measurements. These higher predicted particle velocities in the simulations means the lower predicted solid volume fraction in the simulated pneumatic conveying system compared to the experiments. Lower predicted solid volume fraction or in other words higher predicted porosity means that more space is provided for gas phase to flow in the simulations compared to the experiments and, as a result, lower simulated gas velocities are expected in comparison with the experiments. However, as observed in this section, the gas velocities were also predicted higher in the FLUENT-EDEM simulations compared to the measured gas velocities which shows that the gas phase mass is not conserved in the simulations. More investigation related to the mass conservation in the coupled FLUENT-EDEM simulation is required to answer this inconsistency.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-29: Gas velocity comparison between simulation and experiment for horizontal profile in the presence of 1.5 mm glass beads, SLR=2.3, z=2 m.

Figure 7-30: Gas velocity comparison between simulation and experiment for vertical profile in the presence of 1.5 mm glass beads, SLR=2.3, z=2 m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-31: Gas velocity comparison between simulation and experiment for horizontal profile in the presence of 1.5 mm glass beads, SLR=3, z=2 m.

Figure 7-32: Gas velocity comparison between simulation and experiment for vertical profile in the presence of 1.5 mm glass beads, SLR=3, z=2 m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-33: Gas velocity comparison between simulation and experiment for horizontal profile in the presence of 1.5 mm glass beads, SLR=3.5, z=2 m.

Figure 7-34: Gas velocity comparison between simulation and experiment for vertical profile in the presence of 1.5 mm glass beads, SLR=3.5, z=2 m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-35: Gas velocity comparison between simulation and experiment for horizontal profile in the presence 2 mm glass beads, SLR=2.3, z=2 m.

Figure 7-36: Gas velocity comparison between simulation and experiment for vertical profile in the presence of 2 mm glass beads, SLR=2.3, z=2 m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-37: Gas velocity comparison between simulation and experiment for horizontal profile in the presence of 2 mm glass beads, SLR=3, z=2 m.

Figure 7-38: Gas velocity comparison between simulation and experiment for vertical profile in the presence of 2 mm glass beads, SLR=3, z=2 m.
Comparison between simulation and experimental results for pneumatic conveying of spherical particles

Figure 7-39: Gas velocity comparison between simulation and experiment for horizontal profile in the presence of 0.9 mm glass beads, SLR=2.3, z=2 m.

Figure 7-40: Gas velocity comparison between simulation and experiment for vertical profile in the presence of 0.9 mm glass beads, SLR=2.3, z=2 m.

7.5 Conclusion to Chapter 7

A series of simulations corresponding to the experimental data were carried out. Horizontal and vertical profiles of gas and particle velocities for different SLRs were investigated numerically by the use of coupled FLUENT-EDEM. Conclusions can be deduced from the comparison of numerical and experimental data as follows:
- The RANS-DEM method could model the gas and particle velocity trends observed experimentally. However, a discrepancy between simulation and experimental results was observed. Similarly to the experiments, simulated horizontal profile of mean gas and particle velocities showed a flat profile in the pipe central parts. In the vertical profile, the simulation results showed that the gas and particle velocities increased from the lower section of the pipe reaching to a maximum value in the pipe upper section and decreased again toward the upper pipe wall, as observed experimentally. The particle velocity decrease close to the pipe wall is not captured accurately by the simulation.

- Both gas and particle velocities predicted in the simulations over-estimated the experimental data.

- The discrepancy between simulation and experimental results of mean particle and gas velocities can be attributed to the combination of errors and inaccuracies described in this chapter, which are as follows: 1) The applied drag model may not be the most suitable drag model for the turbulent particle laden flow 2) The interpolation scheme is ignored in the code 3) The Buoyancy force is ignored in the coupled FLUENT-EDEM which is a software bug 4) The gas phase mass is not conserved in the coupled FLUENT-EDEM.
Chapter 8.

Pneumatic transportation of multi-sphere particle

8.1 Introduction

The majority of works related to gas-particle interaction are restricted to spherical particles because of the extreme complexity of the alternatives in numerical work. However, in reality the particles encountered in real applications are not always spherical and as a result the orientation of particles plays a significant role on the particle motion in the fluid. In this chapter, initially, the conveying of the isometric particles (aspect ratio around 1.5) in a pneumatic conveying was examined. The particle velocity was measured by LDA technique and simulation results were compared with the experimental data. A reasonably close agreement between experimental and simulation data was observed. Then, the commercially available coupled FLUENT-EDEM code was modified in order to take into account the effect of the orientation of the particles on the torque, drag and lift forces. Two different test cases were used to validate the framework developed for multi-sphere (cylindrical) particles which are one-dimensional particle rotation and single particle sedimentation. Good agreement between the analytical/experimental results and the simulation results was observed.

8.2 Transportation of isometric particles

In this section, the transportation of isometric particles in turbulent horizontal pneumatic conveying is investigated. The purpose of this section is to evaluate how accurate drag models proposed for non-spherical particles could predict the particle velocity in a turbulent flow. Particle velocity was measured experimentally with the aid of LDA technique and then simulations corresponding to the experiments were carried out.
8.2.1 Experimental measurements of isometric particle mean axial velocity

Isometric particles were pneumatically conveyed in the same experimental setup as explained for the spherical particles in section 3.2. The horizontal profiles of particle velocity were measured at two cross sections $z=1$ m and $z=2$ m. The particle characteristics and experimental conditions are summarized in Table 8-1.

<table>
<thead>
<tr>
<th>Table 8-1: Isometric particle characteristics and experimental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle material</td>
</tr>
<tr>
<td>Particle diameter (m)</td>
</tr>
<tr>
<td>Particle length (m)</td>
</tr>
<tr>
<td>Particle density (kg/m³)</td>
</tr>
<tr>
<td>Aspect ratio</td>
</tr>
<tr>
<td>Particle sphericity</td>
</tr>
<tr>
<td>Particle flow rate (kg/ m³)</td>
</tr>
<tr>
<td>Gas velocity (m/s)</td>
</tr>
<tr>
<td>SLR</td>
</tr>
</tbody>
</table>

Aspect ratio is defined as a ratio of particle length to the particle diameter. All experimental conditions explained in Chapter 3 were kept the same for these experiments. Experiments were carried out for three different SLRs, i.e. 0.6, 1, and 1.2. The horizontal profiles of mean axial particle velocity are shown in Figure 8-1 and Figure 8-2. A flat horizontal profile for particle velocity is observed as it was previously seen for spherical particles. It is also seen that by increasing the SLR the mean particle velocity decreases. Some of these measurements are used to evaluate the code for predicting the particle velocity of isometric non-spherical particles.
8.2.2 Simulation of isometric particle conveying within FLUENT-EDEM

In this section, the simulations corresponding to the experiments of transportation of isometric particles are presented. Generally, non-spherical particles in EDEM software are approximated with the overlapping spherical particles which are fixed in position relative to each other along the major axis of symmetry, as can be seen in Figure 8-3.
The major axis is a line which connects together the centre of the particle elements in a multi-sphere particle. The direction of major axis can be chosen when a multi-sphere particle is created. The contact search, contact detection and calculation of force are the same as those explained for single sphere particles. The contact detection between two multi-sphere particles is based on detection of contacts between their element spheres. The contact forces on elements are transferred to the centroid of the particle to which they belong (Favier et al. (1999) and Abbaspour-Fard (2000)). A comprehensive explanation about the calculation of the resultant force and momentum acting on each multi-sphere particle element and non-spherical particle due to particle-particle or particle-geometry contacts can be found in (Abbaspour-Fard (2000)).

As mentioned before, for isometric particles the ratio of the maximum length to the minimum length is below 1.7 (Mandø et al. (2007)). For these particles the influence of the particle orientation on the aerodynamic forces and torques is ignored. Drag force is calculated according to equations (5-29). $C_D$ is calculated based on Haider and Levenspiel (1989) or Ganser (1993) models for non-spherical particles (equations (2-16) and (2-18)) implemented in the coupled FLUENT-EDEM software via UDF. However $d_n$ in equation (2-19) is replaced by 1 for the isometric shape (Ganser (1993)). The projected area in the drag force calculation is determined based on the equal volume sphere diameter ($d_v$). To take into account the influence of the surrounding particles, the voidage function proposed by Di Felice (equation (5-35)) is used. $Re_p$ also is calculated by using the equal volume sphere diameter (Hilton and Cleary (2012)). Lift force is calculated based on equations (5-39) and (5-40).
literature contains nearly no information about the carrier phase turbulence modulation due to the non-spherical particles (Lain and Sommerfeld (2007)). Therefore, the conventional \( k-\varepsilon \) turbulence model is applied in the simulations. All parameters for simulating the pneumatic conveying of isometric particles are presented in Table 8-2. The particle property values are selected from DEMSolutions Ltd (2010).

### Table 8-2: Parameters for FLUENT-EDEM simulation of isometric particles

<table>
<thead>
<tr>
<th>Simulation method</th>
<th>RANS-DEM (Eulerian-Lagrangian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coupling method</td>
<td>Two-way coupling</td>
</tr>
<tr>
<td><strong>FLUENT</strong></td>
<td></td>
</tr>
<tr>
<td>Air density (kg/m³)</td>
<td>1.225</td>
</tr>
<tr>
<td>Air viscosity (pa.s)</td>
<td>1.78×10⁻⁵</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>( k-\varepsilon ) model</td>
</tr>
<tr>
<td><strong>EDEM</strong></td>
<td></td>
</tr>
<tr>
<td>Particle creation</td>
<td>Created in the inclined pipe with the initial velocity similar to the experiments</td>
</tr>
<tr>
<td>Particle flow rate (kg/s)</td>
<td>0.0296, 0.04467</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.35</td>
</tr>
<tr>
<td>Shear modulus (pa)</td>
<td>1.2×10⁸</td>
</tr>
<tr>
<td>Particle-Particle, Particle-wall contact model</td>
<td>Non-linear Hertz-Mindlin</td>
</tr>
<tr>
<td>Particle size (m)</td>
<td>0.001×0015</td>
</tr>
<tr>
<td>Particle density (kg/m³)</td>
<td>1140</td>
</tr>
<tr>
<td>Coefficient of restitution (Polyamide-wall)</td>
<td>0.5</td>
</tr>
<tr>
<td>Coefficient of restitution (polyamide-Polyamide)</td>
<td>0.45</td>
</tr>
<tr>
<td>Coefficient of static friction</td>
<td>0.5</td>
</tr>
<tr>
<td>Particle aspect ratio</td>
<td>1.5</td>
</tr>
<tr>
<td>Sphericity</td>
<td>0.8585</td>
</tr>
<tr>
<td>Time step</td>
<td>1.5×10⁻⁶</td>
</tr>
<tr>
<td><strong>Gas-Particle interactions</strong></td>
<td></td>
</tr>
<tr>
<td>Drag model</td>
<td>Ganser or Haider and Levenspiel</td>
</tr>
<tr>
<td>Lift model</td>
<td>Magnus lift force</td>
</tr>
</tbody>
</table>

In Figure 8-4 and Figure 8-5 the experimental and simulation results of horizontal profiles of mean axial particle velocity are compared. As seen the particle velocities predicted in the simulations under-predict the experimental results. However, the simulation results are relatively close to the experimental results. In Figure 8-4 and
Figure 8-5, the mean relative error is around 20% and 25% respectively for the simulations implementing the Ganser drag coefficient model (Ganser (1993)) and it is around 18% and 20% for the simulations with the drag coefficient model proposed by Haider and Levenspiel (1989) respectively.

Hölzer and Sommerfeld (2008) considered a large number of experimental data (665 values) for isometric particles in the Stokes region. They reported the mean relative errors between experimental values and the correlation formulas of Ganser (1993) and Haider and Levenspiel (1989) were around 6.46% and 6.65% respectively. Obviously applying the $C_D$ model proposed by Ganser (1993) and Haider and Levenspiel (1989) for a turbulent dynamic system such as pneumatic conveying can increase the relative error between experiment and simulation, because these drag coefficients have not been derived for such conditions.

![Figure 8-4: Mean axial particle velocity comparison between experiment and simulation for horizontal profile of isometric particle, SLR=0.6, z=1 m.](image)
8.3 Equations of motion for a multi-sphere (cylindrical) particle in two-phase flow implemented in FLUENT-EDEM

In this section, the equations of motion and forces acting on a multi-sphere (cylindrical) particle in an arbitrary flow are presented.

In this study, the particle diameter remains constant along the major axis; and the final multi-sphere particle can be approximated as a cylinder (Figure 8-7). Therefore, equations of motion for a cylindrical particle are explained briefly in this section. All equations used in this study have been adapted from Rosendahl (2000) and Yin et al. (2003) studies. This model involves the formulation of orientation dependent drag and lift forces. Equations of motion, aerodynamic forces and torques acting on particles are implemented via UDFs to the coupled FLUENT-EDEM software. The reader is referred to the Rosendahl (2000) and Yin et al. (2003) studies for more detailed explanations.

There are two coordinate systems in EDEM which are referred to the global $\vec{x} = [x, y, z]$ and local coordinates $\vec{x'} = [x', y', z']$. The origin of the local coordinate is at the particle mass centre and its axes are the principal axes of particles. The
translational and rotational equations of motion of a non-spherical particle are given by:

\[
m \frac{du_p}{dt} = \sum F
\]  

(8-1)

\[
I_{x'} \frac{d\omega_{x'}}{dt} - \omega_{y'}\omega_{z'}(I_{y'} - I_{z'}) = T_{x'}
\]

\[
I_{y'} \frac{d\omega_{y'}}{dt} - \omega_{x'}\omega_{z'}(I_{x'} - I_{z'}) = T_{y'}
\]

(8-2)

\[
I_{z'} \frac{d\omega_{z'}}{dt} - \omega_{x'}\omega_{y'}(I_{x'} - I_{y'}) = T_{z'}
\]

where \( F \) includes contact force, gravity force and aerodynamic forces. \([I_{x'}, I_{y'}, I_{z'}]\) are moments of inertia and for a cylinder can be expressed \( I_{x'} = I_{y'} = \frac{1}{4}mr^2 + \frac{1}{2}mb^2 \) and \( I_{z'} = \frac{1}{2}mr^2 \) (when \( z' \) is the major axis) where \( r \) is cylinder radius and \( b \) is the cylinder half length. Based on the Rosendahl (2000) and Yin et al. (2003) studies the angle between the particle major axis and the relative velocity vectors is a key parameter in calculating the torques, drag and lift forces. This angle is shown as \( \alpha \) in Figure 8-6. In EDEM, the particle major axis needs to be selected when particles are created; major axis is shown by \( z' \) in Figure 8-6. However, in this study, particles are created with a random orientation. Therefore, a transformation matrix is used to describe the time evolution of particle major axis.

Figure 8-6: Schematic of a cylindrical particle (Mandø (2009)).
In coupled FLUENT-EDEM, quaternions (Euler’s four parameters) are used to calculate the transformation matrix. According to Goldstein (1980), Hughes (1986) and Kuipers (1999) the transformation matrix it is given by:

\[
A = \begin{bmatrix}
1 - 2(\varepsilon_2^2 + \varepsilon_3^2) & 2(\varepsilon_1 \varepsilon_2 + \varepsilon_3 \eta) & 2(\varepsilon_1 \varepsilon_3 - \varepsilon_2 \eta) \\
2(\varepsilon_1 \varepsilon_2 - \varepsilon_3 \eta) & 1 - 2(\varepsilon_3^2 + \varepsilon_1^2) & 2(\varepsilon_2 \varepsilon_3 + \varepsilon_1 \eta) \\
2(\varepsilon_1 \varepsilon_3 + \varepsilon_2 \eta) & 2(\varepsilon_2 \varepsilon_3 - \varepsilon_1 \eta) & 1 - 2(\varepsilon_1^2 + \varepsilon_2^2)
\end{bmatrix}
\]  

(8-3)

where \( \varepsilon_1, \varepsilon_2, \varepsilon_3, \) and \( \eta \) are Euler’s four parameters. Therefore, the major axis vector at each time step is calculated by multiplying the transformation matrix and the major axis vector in the previous time step.

### 8.3.1 Drag and lift forces

For a multi-sphere particle, the particle projected area changes according to the particle orientation. The drag force is calculated based on equation (5-29). The projected area for a cylindrical particle is given by:

\[
A = \pi r^2 (\cos^2 \alpha + (4\Lambda/\pi)^2 \sin^2 \alpha)^{0.5}  
\]  

(8-4)

where \( \Lambda \) is the particle aspect ratio expressed as:

\[
\Lambda = b/r  
\]

(8-5)

The drag coefficient \( C_D \) is calculated based on equations (2-16) and (2-18). Lift force for a cylindrical particle is given by:

\[
F_L = \frac{1}{2} \rho A_L \frac{z' \cdot (v - u_p)}{|v - u_p|} \left[ z' \times (v - u_p) \right] \times (v - u_p)  
\]

(8-6)

\[
A_L = \pi r^2 (\sin^2 \alpha + (4\Lambda/\pi)^2 \cos^2 \alpha)^{0.5}  
\]

(8-7)

Lift coefficient is determined by the following expression

\[
C_L = C_D \cos \alpha \sin^2 \alpha  
\]

(8-8)
8.3.2 Torques on the particles

Two types of torque act on a cylindrical particle in the fluid field - namely torque due to the aerodynamic forces and torque due to resistance. The former torque arises because the centre of mass and the centre of pressure on a particle do not coincide; the latter torque is a frictional effect which acts to reduce the particle angular velocity.

For cylindrical particles, aerodynamic forces act in the centre of pressure rather than centre of mass as a result a torque arises on the particle. The distance between the centre of pressure and the centre of mass, $x_{cp}$ (as can be seen in Figure 8-6), is calculated as:

$$x_{cp} = 0.25b(1 - e^{3(1-\Lambda)} )[\cos^3 \alpha]$$ (8-9)

Then the torque due to the aerodynamic forces can be expressed as:

$$T_1 = (x_{cp}z') \times (F_D + F_L)$$ (8-10)

The simplified form of torques due to resistance can be expressed as follow:

$$T_{2,x} = \frac{1}{32} C_D \rho r (2b)^4 \omega_x^2$$ (8-11)

$$T_{2,y} = \frac{1}{32} C_D \rho r (2b)^4 \omega_y^2$$ (8-12)

$$T_{2,z} = \frac{1}{32} C_D \rho r (2b)^4 \omega_z^2$$ (8-13)

It should be noted that torques due to the particle-particle or particle-geometry contacts are also added to these two torques. Torques due to the aerodynamic forces and particle-particle contacts are converted to the local coordinate system by EDEM (Favier et al. (1999)).
8.4 Model verification

Equations for drag force, lift force and torques were implemented into the coupled FLUENT-EDEM software via UDFs. The computational algorithm is mainly the same as explained for spherical particles. However, the angle between the particle major axis and relative velocity is calculated before the calculation of aerodynamic forces and torques. The code developed for cylindrical particles was initially tested for an upward fluid jet flow in a one-way coupling framework by Wong et al. (2009). However, in this section the code was extended for a two-way coupling approach. To evaluate the code, two test cases were examined, for which the results are discussed below.

8.4.1 Multi-sphere particle rotation in one-dimension

To investigate the ability of the computer code to calculate the particle orientation precisely, multi-sphere particle rotation in one-dimension was investigated. For this, the particle major axis was set on the x axis in the initial state of the simulation, and then a 1 Nm torque in the z direction was imposed. As a result the particle started rotating. The angle between the particle major axis and the x axis is calculated at each time step showing the orientation of the particle. The parameters used in the simulation are shown in Table 8-3. Multi-sphere representation of a cylindrical particle is also shown in Figure 8-7.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial angle between the particle major axis and x axis</td>
<td>0</td>
</tr>
<tr>
<td>Moment of inertia (kg.m²)</td>
<td>5.14×10⁻⁶</td>
</tr>
<tr>
<td>Time step (s)</td>
<td>1×10⁻⁶</td>
</tr>
<tr>
<td>Torque (N.m)</td>
<td>1</td>
</tr>
<tr>
<td>Particle Size (m)</td>
<td>0.001×0.004</td>
</tr>
</tbody>
</table>

The analytical result is obtained by solving the rotational equation of motion (equation (8-2)). The analytical and simulation results have been compared in Figure 8-8 showing a very good agreement.
Multi-sphere particle sedimentation

For the second test case, single multi-sphere particle sedimentation was investigated. The experimental study was carried out by Yin et al. (2003). A PVC particle with a specific orientation was released in a container full of water. A digital video camera was used to track the particle trajectory. A simulation based on the Yin et al. (2003) experimental study was conducted. The parameters used in the simulation are illustrated in Table 8-4. The particle z-position during the sedimentation and the sedimentation velocities were compared with the experimental results. A schematic sketch of the container and non-spherical particle are shown in Figure 8-9. The simulation results for the particle z-position showed a very good agreement with the experiments as seen in Figure 8-10. Position z on the vertical axis of Figure 8-10 shows the vertical distance of the particle from the initial position. This close
agreement may imply a correct implementation and calculation of the hydrodynamic forces acting on particle. Both drag coefficient proposed by Ganser (1993) and Haider and Levenspiel (1989) were checked in the code and same results were obtained.

Yin et al. (2003) also reported that a considerable error was observed in that the experimental measurements of the particle y-position. Therefore, a comparison between FLUENT-EDEM simulation results and the experimental measurements for the particle position in the y direction is not presented here.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle density (kg/m³)</td>
<td>1366</td>
</tr>
<tr>
<td>Particle diameter (m)</td>
<td>0.00541</td>
</tr>
<tr>
<td>Particle length (m)</td>
<td>0.05</td>
</tr>
<tr>
<td>Sphericity</td>
<td>0.593</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>9.242</td>
</tr>
<tr>
<td>Eulerian angle</td>
<td>(\theta_0=60), (\Phi_0=\psi_0=0)</td>
</tr>
<tr>
<td>Container length (m)</td>
<td>0.475</td>
</tr>
<tr>
<td>Container width (m)</td>
<td>0.48</td>
</tr>
<tr>
<td>Container height (m)</td>
<td>1.5</td>
</tr>
<tr>
<td>Initial particle position, above the bottom of the container (m)</td>
<td>0.7</td>
</tr>
<tr>
<td>Fluid density (kg/m³)</td>
<td>1000</td>
</tr>
</tbody>
</table>

In Figure 8-11, the particle sedimentation velocity is presented. The red line shows the terminal velocity reported by Yin et al. (2003) which is -0.1265 m/s. As seen, the particle velocity acquired by simulation is relatively close to that reported by Yin et al. (2003). The average velocity calculated during the simulation is -0.1298 m/s. The sudden velocity increase during sedimentation happens when the particle projected area is minimum, since as a result the drag force acting on the particle is minimum. Therefore, the particle sedimentation velocity increases suddenly. However, particle wobbles during the sedimentation and again the sedimentation velocity decreases when the particle projected area and thus the drag force increase. Particle velocity in
the container width direction, $U_y$, is shown in Figure 8-12. As seen in contrast to spherical particles, the lateral velocity of a multi-sphere particle is also important.

![Figure 8-9: Schematic sketch of container and particle.](image)

![Figure 8-10: Particle position during the sedimentation.](image)
Figure 8-11: Calculated sedimentation velocity ($U_z$) during the particle sedimentation.

Figure 8-12: Calculated particle velocity in the container width direction ($U_y$).

8.5 Conclusion to Chapter 8

In most numerical studies related to the gas-particle interaction, particles are assumed to have a spherical shape because of the relatively great advantage of computational simplicity. However this cannot accurately represent particle-fluid behaviour in real systems. In this chapter, an attempt was made to evaluate the ability of the modified coupled FLUENT-EDEM to model non-spherical particles in two-phase system step by step. Pneumatic transportation of isometric particles was investigated experimentally and numerically. Some simulations corresponding to the
experimental data were performed. A reasonably good agreement between simulation and experimental results was observed. Then, the coupled FLUENT-EDEM code was modified in order to take into account the effect of the particle orientation on the torque, drag and lift forces. Two test cases, namely multi-sphere particle rotation in one-dimension and multi-sphere particle sedimentation were carried out to evaluate the capability of the code. Good agreement between the analytical/experimental results and the simulation results was observed. The obtained results in this chapter prove that FLUENT-EDEM is reasonably capable of modelling the non-spherical particles in the particle-fluid systems.
A horizontal pneumatic conveying system was investigated experimentally and numerically. The LDA technique was applied to measure mean gas and particle velocities as well as the carrier phase turbulence intensity. The RANS-DEM approach was used to simulate the pneumatic conveying system. The RANS-DEM simulations of multiphase flow were carried out with the coupled FLUENT-EDEM software.

9.1 Conclusions

Horizontal and vertical profiles of mean axial particle velocity for different particle sizes and SLRs were measured. Generally, horizontal profiles of mean axial particle velocity were flat profiles with a slight velocity decrease toward the pipe wall. On the other hand, the mean axial particle velocity in the vertical profile increased from the lower section of the pipe and reached a maximum point in the upper section of pipe and again decreased toward the upper wall of pipe. It was also found that by increasing the SLR, both horizontal and vertical profiles of mean axial particle velocities decreased. Moreover, the horizontal profiles of mean axial particle velocity decreased by increasing the particle size. On the vertical profile, an increase in the particle size decreased the particle velocity in the pipe upper section. However, the particle velocities were close for the different particle sizes in the lower section of the pipe.

Horizontal and vertical profiles of mean axial gas velocity as well as fluctuating gas root mean square (RMS) velocity in the presence of particles were also measured. Comparison between the mean axial gas velocity in particle laden flows and particle free gas flows showed that, in horizontal profiles, the mean gas velocity decreased by adding glass beads. Moreover, the mean gas velocity profile became flat in the presence of particles. On the vertical profile, the maximum mean gas velocity shifted
towards the upper section of the pipe away from the pipe centre with the addition of particles. The mean gas velocity increased in the upper section of pipe, where a lesser number of particles were transported and decreased in the lower section of the pipe, where a high number of particles were conveyed due to gravity.

The experimental measurements were used to calculate three influential parameters in the evaluation of the turbulence modulation, including length scale ratio, particle Reynolds number ($Re_p$) and Stokes number ($St$). The length scale ratio ranged from 0.11 to 0.27, $Re_p$ for most of the experimental measurements was larger than 400 and $St$ was higher than 1. These values indicated that an augmentation of turbulence should be expected due to adding the particles.

The experimental measurements were also used to calculate the carrier phase turbulence intensity and percentage change in turbulence intensity. For the horizontal profile, the gas flow turbulence level in the presence of particles increased compared to the clear gas flow. For most of the measurement points, the turbulence intensity and percentage change in the turbulence intensity increased by increasing the SLR. For the vertical profile, the turbulence intensity increased noticeably in the lower section of the pipe due to the large number of particles transported in this area. However, the turbulence intensity augmentation in the upper section was less considerable due to the lower particle concentration. Experimental measurement for the percentage change in the turbulence intensity showed an increase up to 240%, demonstrating the importance of the turbulence modulation phenomenon in the current study. Generally, the experimental results showed that the turbulence intensity level of the carrier phase increased for both the horizontal and vertical profiles by adding particles to the clear gas. This was in a good agreement with the previous experimental findings that large particles increase the turbulence intensity of the gas flow.

Coupled FLUENT-EDEM was used in the numerical investigation of the gas-particle flow. The code was firstly verified for two test cases i.e. a single particle sedimentation and constant porosity block (CPB) sedimentation. The terminal
velocity calculated for a single particle in air, water and water-glycerol agreed well with the analytical calculation. The average terminal velocity of the CPB in water for various porosities also showed an excellent consistency with the analytical solution.

Two similar simulations were performed with and without lift force to highlight the importance of the lift force on the particle distribution in the horizontal pipe. It was found that the Magnus lift force had a crucial effect in replicating the particle distribution seen in the experiments. Particle-wall collision was found to be the main reason for high particle angular velocity and, as a result, the high magnitude of the Magnus lift force. The ratios between drag and lift forces for 2 mm and 1.5 mm glass beads were found to be 1.0547 and 1.9333 respectively. The ratio between gravity and lift forces for 2 mm and 1.5 mm glass beads also were predicted to be 3.9386 and 2.9355 respectively.

A one way coupling simulation for 1.5 mm glass beads with SLR=2.3 was performed. It was found that a one-way coupling simulation could not predict the particle velocity correctly and a considerable deviation between experimental and simulation results was observed in the horizontal profile of mean axial particle velocity. This error was explained by the fact that the gas velocity was assumed to remain unchanged during the one-way coupling simulation but as was observed experimentally, the gas velocity decreased by adding particles to the clear flow.

The turbulence modulation phenomenon in horizontal pneumatic conveying was also studied numerically. Hybrid source terms proposed by Geiss et al. (2004) and Mandø (2009) were added to the $k-\varepsilon$ turbulence model via User Defined Functions (UDF) to take into account the influence of the dispersed phase on the gas flow turbulence level. Simulation results revealed that horizontal and vertical profiles of carrier phase turbulence intensity depended strongly on the empirical constant $C_3$. It was found that by increasing the $C_3$ ranging from 1.0 to 2.0, the carrier phase turbulence intensity decreased. The model could also predict the further enhancement in the gas flow turbulence intensity with the increasing of the SLR. These observations proved
that the model was capable of predicting the previous findings. Simulations with the hybrid source terms for 1.5 mm and 2 mm glass beads and SLR=2.3 and 3 showed that the best results in the performed simulations were obtained by \( C_{\varepsilon_3} = 1.7 \) or \( C_{\varepsilon_3} = 1.8 \). The turbulence intensity trend was captured only very generally by the model. The discrepancy between experimental and simulation results increased for the regions close to the pipe wall. Simulation results also confirmed that the carrier phase turbulence and \( C_{\varepsilon_3} \) values had a negligible influence on the mean axial particle velocity.

A series of the FLUENT-EDEM simulations corresponding to the experimental measurements were performed. The initial particle velocity and SLRs were the same as used in the experiments. The results showed that some of features of the horizontal pneumatic conveying observed experimentally could be captured by the model. These were:

- Horizontal profiles of mean axial particle velocity was a flat profile.
- Vertical profiles of mean axial particle velocity increased from the lower section of the pipe to a maximum value in the pipe upper section and decreased again toward the pipe upper wall.
- The higher the SLR, the lower the mean axial particle velocity.
- The mean axial particle velocity decreases by increasing the particle size.
- Simulation results showed that the maximum mean gas velocity in the particle laden flow shifted upward from the pipe centre.
- The horizontal profile of mean gas velocity profile was flattened by adding particles.

Simulation results showed that the numerically predicted mean gas velocity overestimated the experimental results. This discrepancy could be attributed to the mesh size which needs to be selected to be larger than particle size in the RANS-DEM approach. Simulation results for the mean particle velocity also over-predicted the experimental results. This deviation was explained due to the inexact prediction of
drag force or drag coefficient acting on each particle which could lead to the higher particle velocity compared to the experimental measurements. There is also no interpolation scheme in the coupled FLUENT-EDEM to interpolate the gas velocity at grid into the particle position to calculate the drag force. Moreover, Buoyancy was not considered in the code leading to inaccurate coupling between codes. It also was found that the gas phase mass was not conserved in the simulations. The combination of these errors can cause errors when simulation results are compared to the experiments.

The motion of non-spherical particles in a two-phase flow also was investigated. Initially, transportation of isometric particles in turbulent horizontal pneumatic conveying was investigated experimentally and numerically. In the simulation the influence of particle orientation on aerodynamic forces and torque was ignored. Comparison between experimental and simulation results for the horizontal profile of mean axial particle velocity showed a reasonably close agreement.

A framework for multi-sphere particles approximating a cylinder was developed for coupled FLUENT-EDEM. This was evaluated with two test cases i.e. multi-sphere particle rotation in one-dimension and multi-sphere particle sedimentation. In the first test case the accuracy of the model to predict the particle orientation for a simple one-dimensional case was investigated. Simulation results agreed well with the analytical results. The second test case checked the accuracy of the hydrodynamic force and torque calculation acting on the single multi-sphere particle during the sedimentation. Particle position during the sedimentation showed a very good agreement with the experimental results. Averaged particle sedimentation velocity predicted by FLUENT-EDEM was also in a favourable agreement with experimental results.

In summary, this work checks the applicability of the RANS-DEM approach to study the details of gas and particle dynamic behaviours including the mean gas and particle velocities as well as the carrier phase turbulence intensity level in research-
scale horizontal pneumatic conveying. It can be concluded that special attention needs to be paid before using the RANS-DEM approach:

- **Equations for flow and solid coupling** (currently incorrect with respect to buoyancy implementation)

- **Lift force**
  In strong shear flows and when the particles acquire high angular velocities lift force needs to be considered in the modelling.

- **Carrier phase turbulence modulation**
  The importance of the effect of the particle on the carrier phase turbulence needs to be gauged and according to the particle size, suitable source terms may be added to the turbulence model. The value of $C_\alpha$ in the $k-\varepsilon$ turbulence model dissipation source term needs to be calibrated.

- **Drag model**
  Numerous drag models have been introduced in literature which can be applied for pneumatic conveying simulation. However, it should be noted that there is no generally/universally accepted drag model in the multiphase context that can be used for all flow conditions. This field of research requires further development.

Other parameters such as the mesh cell size, fluid and particle time step also have influential effects on the simulation results.

The promising simulation results for non-spherical particles also demonstrate the ability of the RANS-DEM method to model real particle shapes in multiphase flows.
9.2 Future development

The full understanding of particle laden flows depends strongly on the development of more efficient simulation approaches and more comprehensive experimental techniques. Some suggestions for future studies are as follows:

- Simulation of transition between dense and dilute regimes has rarely been reported. Understanding the transition criteria from dilute to dense regimes, especially for transporting materials which are sensitive to collision or attrition could be extremely useful, and therefore more research in this area is necessary.

- Near-wall regions cannot be modelled accurately with the RANS-DEM method as the fluid mesh cannot be resolved finely enough for this due to the requirement for it to be significantly larger than the particle diameter. New algorithms need be developed to model near wall regions in the RANS-DEM modelling approach.

- In this study, the effect of the particle fluctuating velocity i.e. $\overline{u_{pi}' u_{pi}'}$ in the hybrid source terms was omitted for model simplicity. However, It can be imagined that the gas phase turbulence intensity increases due to the significant increase of particle fluctuating velocity for near-wall regions due to the increased particle-wall collisions. Further simulations considering this term need to be performed.

- Experimental and numerical studies of the turbulence modulation due to the presence of non-spherical particles have been rarely carried out. This phenomenon can be the subject of more research.

- The influence of lift force and particle-particle interaction also needs to be considered in derivation of source terms for turbulence models due to the presence of particles.
Conclusions and recommendations for further work

- In most of the studies to simulate pneumatic conveying, particles are considered to be spherical and mono-size, which is not realistic for most industrial applications. Modelling of non-spherical, poly-dispersed particle needs to be performed in future research to simulate the real process and meet real engineering needs. Multiphase systems such as reactors and fluidized beds are usually involved in heat and mass transfer. Heat and mass transfer equations could also be added to RANS-DEM code to investigate these phenomena. Heat transfer in a pneumatic conveying system could also be a next step in pneumatic conveying numerical studies.
Appendix A: Additional LDA Measurements

The rest of the LDA measurements for particle free flows and particle laden flows which were not presented in the main part of this thesis can be found in this appendix.
Figure A. 1: Gas velocity measurement vs empirical equation for three different motor speeds, at z=1 m.
Figure A. 2: Gas velocity measurement vs empirical equation for three different motor speeds, \( z=3 \) m.
Figure A. 3: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR = 2.3, z = 1 m.
Figure A. 4: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR =3, z=1 m.
Figure A. 5: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR =3.5, z=1 m.

Figure A. 6: Effect of SLR on the turbulence intensity, 0.9 mm glass beads, z=1 m.
Figure A. 7: Effect of SLR on the percentage change in turbulence intensity, 0.9 mm glass beads $z=1$ m.
Figure A. 8: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 1.5 mm glass beads, SLR = 2.3, z = 1 m.
Figure A. 9: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 1.5 mm glass beads, SLR =3, z=1 m.
Figure A. 10: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 1.5 mm glass beads, SLR =3.5, z=1 m.

Figure A. 11: Effect of SLR on the turbulence intensity, 1.5 mm glass beads, z=1 m.
Figure A. 12: Effect of SLR on the percentage change in turbulence intensity, 1.5 mm glass beads z=1 m.
Figure A. 13: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR = 2.3, $z$=3 m.
Figure A. 14: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR =3, z=3 m.
Figure A. 15: Turbulence intensity (a), percentage change in turbulence intensity (b) and mean axial gas velocity (c), 0.9 mm glass beads, SLR =3.5, z=3 m.

Figure A. 16: Effect of SLR on the turbulence intensity, 0.9 mm glass beads, z=3 m.
Figure A. 17: Effect of SLR on the percentage change in the turbulence intensity, 0.9 mm glass beads $z=3$ m.
References


DEMSolutions Ltd. 2010. EDEM-CFD coupling for FLUENT, User guide.


