Master’s Thesis 2013

Candidate: Maryna Zinchenko

Title: Determination of Particle Velocities in Pneumatic Conveying

Telemark University College

Faculty of Technology

M.Sc. Programme

MASTER'S THESIS, COURSE CODE FMH606

Student: **Maryna Zinchenko**

Thesis title: **Determination of Particle Velocities in Pneumatic Conveying**

Signature: . . . .

Number of pages: 64

Keywords: **pneumatic conveying, solids velocity, high-speed video**

Supervisor: Chandana Ratnayake sign.: . . . . ………..

2nd Supervisor: <name> sign.: . . . .

Censor: <name> sign.: . . . .

External partner: Tel-Tek, Dept. POSTEC sign.: . . . .

Availability: <Open/Secret>

Archive approval (supervisor signature)**:** sign.: . . . . **Date :** . . . .

Abstract:

The main objective of this investigation was to formulate a technique for particle velocity determination in pneumatic conveying system. Plastic pellets were transported in a pneumatic conveying experimental rig. A large number of pneumatic conveying tests have been carried out under various experimental conditions. Experimental data was captured by pressure transmitters and analysed. The high-speed video of pneumatic conveying of plastic pellets in horizontal pipe element was recorded by high-speed camera.

Mathematical model was developed for solids velocity determination of plastic pellets in horizontal pneumatic conveying.

Based on the results of measurement and calculated solids velocity for horizontal conveying of plastic pellets, a model for solids velocity estimation was formulated with a material dependent constant.

Telemark University College accepts no responsibility for results and conclusions presented in this report.

Table of Contents

Preface

The experimental investigation described in this thesis has become an interesting part of my real life. First of all I would like to thank to my supervisor Chandana Ratnayake for the helpful hints and encouragement and interesting discussions throughout the work. I would like to thank to all employees of POSTEC group for their technical and social support for my investigation.

Nomenclature

A	pipe cross-sectional area	[m^2]
A'	projected area normal to flow	[m^2]
C_D	drag coefficient	[-]
$C_{D\infty}$	drag coefficient for undisturbed and unbounded fluid	[-]
d	particle diameter	[m]
d_v	volume diameter of a particle	[m]
D	Pipe inner diameter	[mm]
F	drag force	N
g	acceleration of gravity	[m/s^2]
Ga	Galileo number	[-]
k	material dependent constant	[-]
$K_{P_1P_2}$	cross-correlation function	[-]
l	distance	[m]
L	length of pipe section	[m]
$\dot{m}_s$	mass flow rate of solids	[kg/s]
$\dot{m}_f$	mass flow rate of gas	[kg/s]
n	number of particles	[-]
p	pressure	[N/m$_2$]
p_0	atmospheric pressure	Pa, bar
P	local static pressure	Pa, bar
Re	Reynolds number	[-]
Re_p	Reynolds number related to particle diameter	[-]
Re_{pf}	Reynolds number related to terminal velocity of particle	[-]
S	surface area of a particle	[m^2]
t	time	[s]
T	absolute temperature	[K]
v	velocity	[m/s]
V	volume	[m^3]

V_L	volume of a pipeline element	[m^3]
V_ε	actual gas velocity	[m^2/s]
w	relative velocity between gas an solid	[m^2/s]
w_s	slip velocity	[m/s^2]
w_T	terminal velocity	[m/s^2]

Greek Symbols

Δp_g	Gauge pressure	Pa, bar
ε	voidage	[-]
η	dynamic viscosity	Pa
λ_s	solids friction factor	[-]
π	dimensionless number	[-]
ρ	density	[kg/m^3]
ρ^*	apparent bulk density	[kg/m^3]
ρ_{ds}	dispersed solid density	[kg/m^3]
ρ_{sus}	suspension density	[kg/m^3]
τ	time delay	[s]
ψ	sphericity	[-]

Subscripts

a	air
D	drag
p	particle
s	solids

1 Introduction

The world 'pneumatic' comes from the Greek word 'pneumatikós' and means pertaining to air, breath, wind. In technology it means process containing or operated by air or gas under pressure [1]. The pneumatic conveying is one of the most common and popular technique of material transportation in industry.

This chapter gives understanding and design of pneumatic conveying systems. The definition, history, basic types, advantages and disadvantages of pneumatic conveying presented in the next sections of the chapter. The thesis structure is also provided in the end of the chapter.

1.1 History of Pneumatic Conveying

Pipeline transportation of solids is not a modern invention. The history of its use dates back to antiquity. The Greek physicist and engineer Hero of Alexandria who lived around 10 – 85 AD in his work Pneumatica explained the basic principles of pneumatics [2]. Furthermore in a prehistoric time the Romans used lead pipes for water supply and sewage disposal and Chinese used bamboo tubes to transport natural gas. Negative and positive pressure systems of grain conveying were common in 1920's. The first system of vacuum conveying of grain was used in the late nineteenth century [3].

During the First World War (1914 – 1918), was a difficult situation because of the high demand for foods, labour scarceness and the risks of explosion were too high. All this factors influenced on the development of pneumatic conveying, which were the best solution for solving the problem. In the post-war period, pneumatic conveying systems were used for transportation coal and cement in the industry [4].

One of the earliest printed page references can be considered a case of grain unloading from ships in Russia. In 1923 - 1924 the researcher and practitioner J. Gasterstadt have presented some basic studies in pneumatic conveying, investigated the linear relationship between pressure drop and mass flow rate for dilute phase flow and presented some experimental results of conveying in 100 m long horizontal pipe. In the same time the beginning of pneumatic conveying was in Japan and Germany [5].

In the late 1950's through the 1960's raised the activity in USA. An experimental work with a simple vacuum cleaner did by Fred Zens was the first development in pneumatic conveying in the United States. He presented plots of pressure drop versus gas flow rates which were named after him and are still in use. His book with Othmer on Fluidization and Fluid Particle Systems from 1960 is a big investigation and is a classic of pneumatic conveying [5].

Nowadays, pneumatic conveying is one of the most popular techniques of material transportation in industry.

1.2 Definition of Pneumatic Conveying

The pneumatic conveying is a transportation system, where bulk particles of a various powdered and granular solids are moved within a piping system in a gas stream. Usually the gas is air and the piping system represented by vertical and horizontal pipes and bends. To convey the materials through the piping system high, low or negative pressure can be used. After that the solids are separated from the gas stream for storage in the desired destination [3]. Most conveying systems can work completely automatically.

A general setup of a pneumatic conveying system is shown in Figure 1-1.

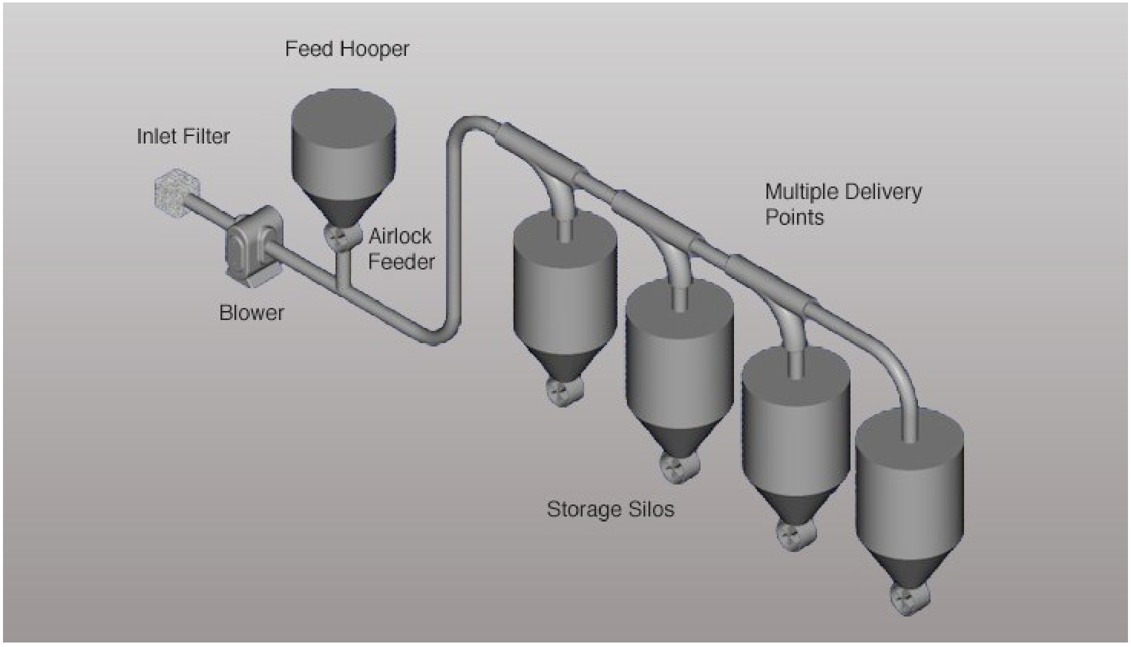

Figure 1-1Setup of a pneumatic conveying system [6]

A wide range of powdered and granular form materials can be transported through pneumatic conveyors in different industries. The main industrial fields where it has definitely been used are [7]:

- Agricultural industry
- Chemical process industry
- Mining industry
- Pharmaceutical industry
- Food processing industry
- Mineral industry

Lists of more than 250 materials which have been successfully conveyed pneumatically are presented in "Pneumatic Conveying of Solids: a theoretical and practical approach" [3] and by D. Mills in "Pneumatic Conveying Design Guide" [8].

1.3 Advantages and Limitations of Pneumatic Conveying

One of the main limitations in the use of pneumatic conveyors is the transported material, but conveying distance or conveying rate can also be determinant factors.

The main advantages of pneumatic conveyors are [3] [9]:

- Flexibility in routing. Due to bends in the pipeline conveying can be horizontal and vertical. It takes a little floor space and pipeline can be easily mounted across the roof.
- Low manpower and low maintenance costs.
- Lower raw material cost due to bulk delivery, lower storage costs and reduced storage area, reduced product losses.
- Dust-free transportation of a variety of products and improved working environment.
- Ease of automation and control.
- Multiple uses of the pipelines.
- Distribution to different areas in a plant and possibility to pick-up materials from several areas.
- Possibility to convey toxic and hazardous to health materials. Negative pressure pneumatic system is the best solution for this option.

Always against advantages there are certain disadvantages which are listed below [9] [3]:

- Erosion of the plant by the conveyed product
- Particle degradation
- Explosion risk with certain products
- High power consumption
- Limited distance

But despite all limitations pneumatic conveying has seen increased use in many industrial sectors.

1.4 The main components of Pneumatic Conveying System

A pneumatic conveying system consists of four zones that are listed below. In turn, each of the zones is represented by special equipment which is required for the successful plant operation. The schematic diagram of pneumatic system components is shown in Figure 1-2.

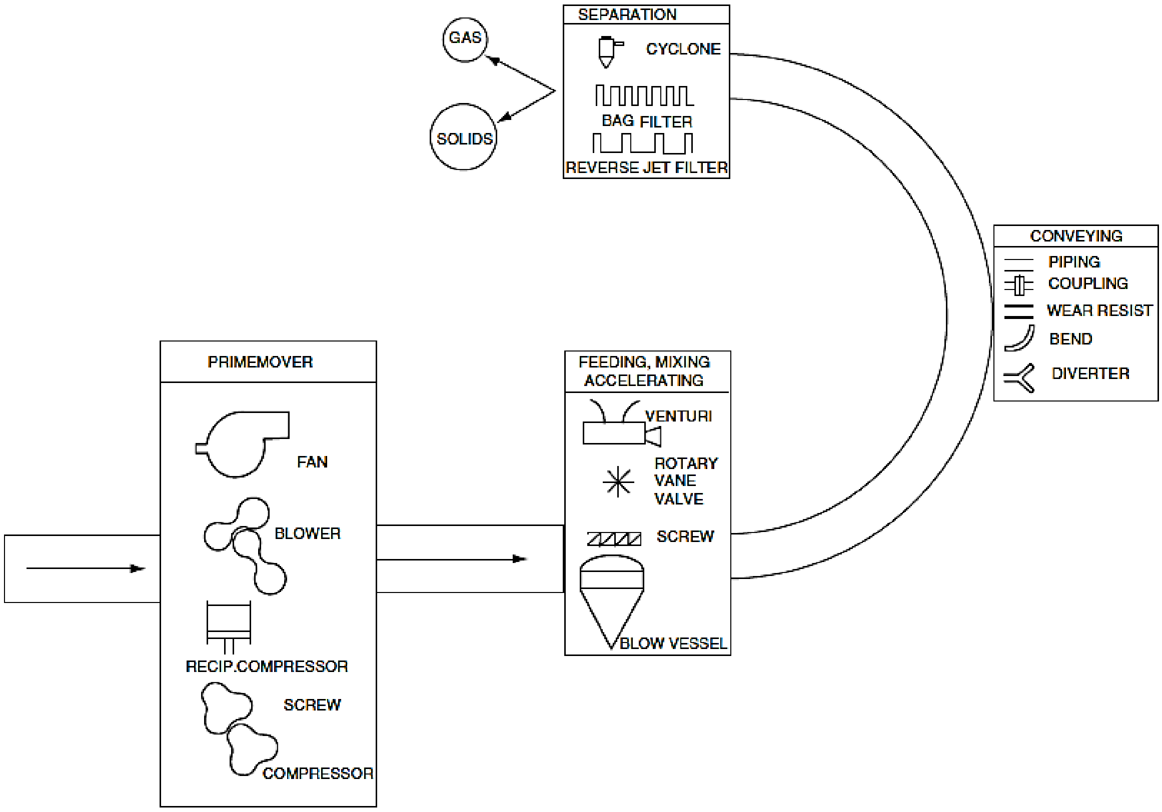

Figure 1-2Schematic diagram op pneumatic conveying system components [3]

1. **The gas supply zone (the prime mover)** consists of a wide range of compressors, vacuum pumps and blowers that are used to provide the necessary energy to conveying gas.
2. **Feeding, mixing and acceleration zone** consists of rotary valves, screw feeders and other equipment which introduce the solids into the conveying line.
3. **The conveying zone** consists of a number of horizontal and vertical pipes, bends and diverter valves.
4. **Gas-solids separation zone** consists of bag filters, cyclones and electrostatic precipitators which are used to separate the solids from the gas stream in which they have been transported.

1.5 Basic types of Pneumatic Conveying Systems

There are few different classifications of pneumatic conveying systems which are described in this Section. One of them are classifying in terms of the system pressure and the other one in terms of the conveying mode.

1. **Positive pressure system**, which is shown in Figure 1-3 is probably the most common of all pneumatic conveying systems.

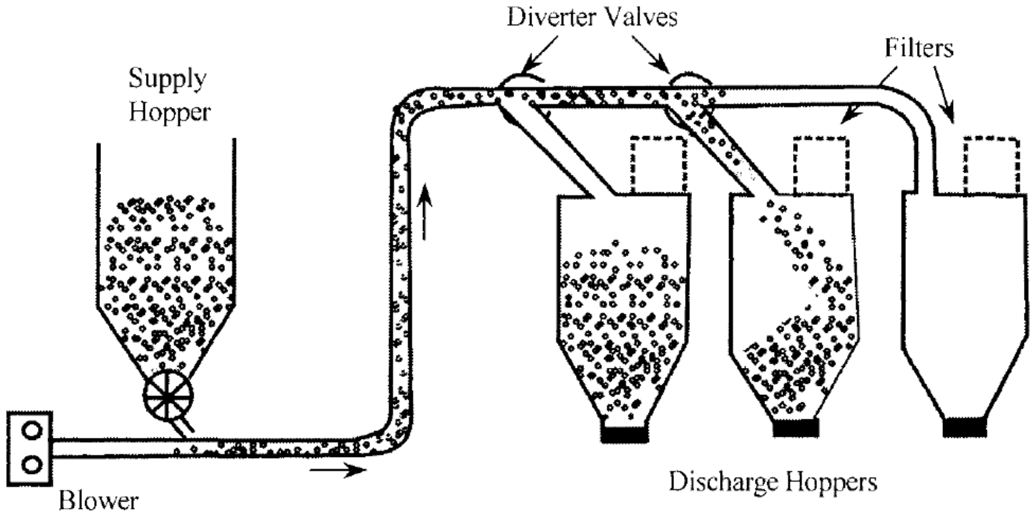

Figure 1-3Positive pressure conveying system [7]

In these systems, materials with the help of the air from the fan or blower are delivered to the pipeline. The systems are good to multiple discharge application; they are able to pick up material from the single point and delivered to several receiving points. The main characteristic of positive pressure systems is that the absolute pressure of conveying gas inside the pipeline is always greater than atmospheric pressure [4].

2. **Negative pressure system**, which is shown in the Figure 1-4, is commonly used to transport material from several feeding points to one receiving point. The principle of work of these systems is the same like in a domestic vacuum cleaner. The characteristic of the system is that the absolute gas pressure inside the system is lower than atmospheric pressure [4].

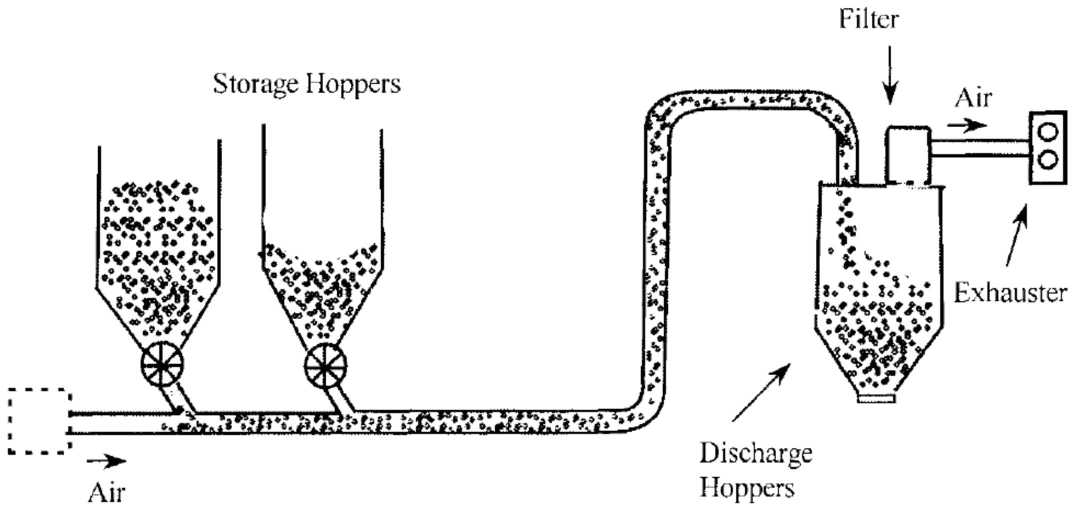

Figure 1-4Negative pressure conveying system [7]

These systems are widely used to transport toxic and hazardous materials because the all gas leakage is inner [7].

3. **Combined Negative – Positive pressure systems** are often referred to as "suck-blow" systems. These systems are able to provide the multiple intakes and multiple discharge of a number of products. They are used in many industries [3]. The example of the system is shown in Figure 1-5.

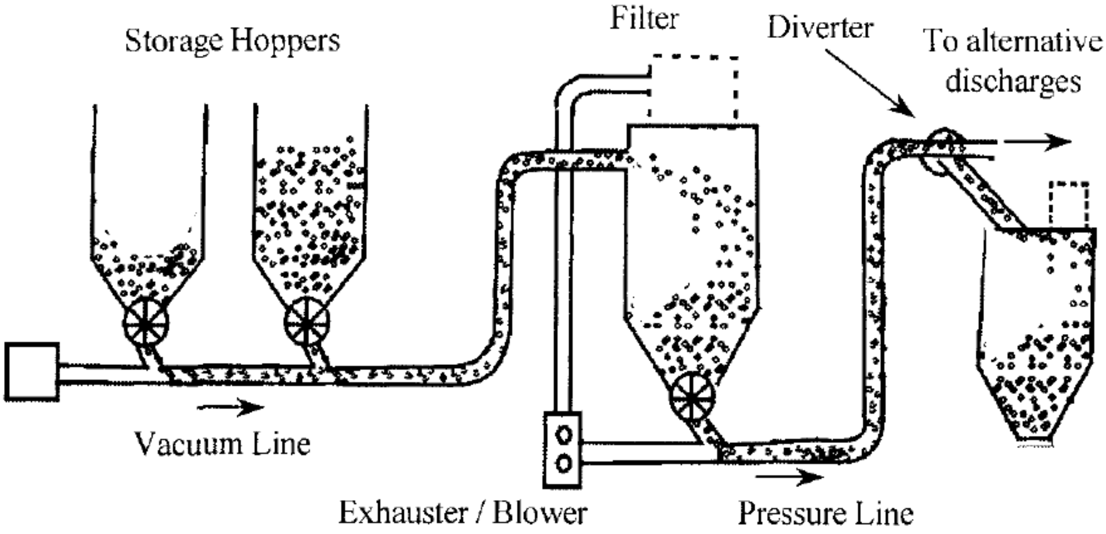

Figure 1-5Combined Negative-Positive pressure conveying system [7]

As was mentioned above, the pneumatic conveying systems can be classified in terms of the conveying mode. All the systems described above can operate into two different categories:

- **Dilute phase systems** are the most widely used systems and almost any material can be conveyed in dilute phase [8]. These systems employ large volume of gas at high velocities. According to this mode the material is transported by a gas stream of sufficient velocity to entrain and re-entrain it for a distance, which is dependent on the available pressure [9]. Typical dilute phase conveying system is shown in Figure 1-6.

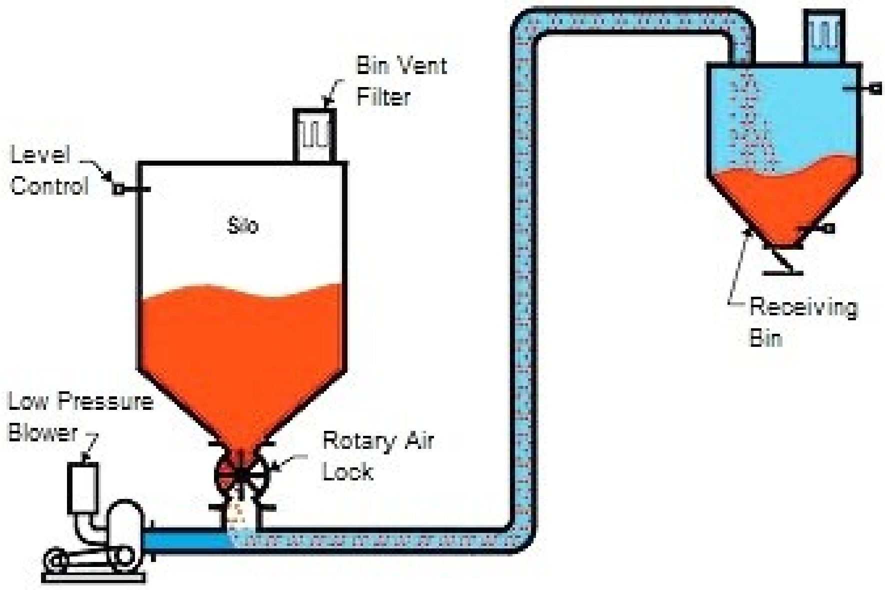

Figure 1-6Schematic diagram of a dilute phase conveying system [10]

- **Dense phase systems** is a system in which the material as plug or as a moving bed is pushed through a pipeline for a distance dependent on the available pressure. In some cases to re-fluidize the material or re-separate the plug additional air can be added along the length of the pipeline [9]. The next modes of flow are recognised in dense phase system: moving bed flow and slug or plug flow. Moving bed flow is only possible for fine powdered materials with a mean particle size in the range of approximately 40–70 µm which have good air retention characteristics. Plug type flow is only possible for mono-sized materials with good permeability [8]. Typical dense phase conveying system is shown in Figure 1-7.

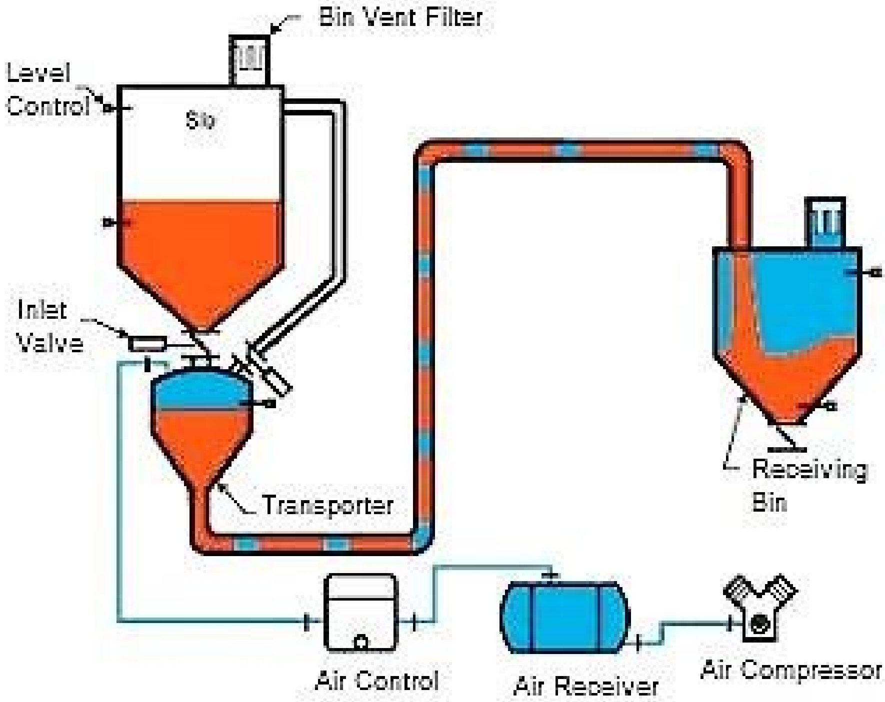

Figure 1-7Schematic diagram of a dense conveying system [11]

1.6 Operation of Pneumatic Conveying system

Inside a pipeline of each pneumatic conveying system there are various flow regimes that could be explained easily in terms of variations of gas velocity, solids mass flow rate and system pressure drop. By the way, the particle size and particle size distribution also have influence on the flow patterns inside the pipelines [4].

1.6.1 Geldart's Powder Classification

The type of materials to be transported is one of the important characteristics that should be considered to choose the right type of pneumatic conveying. Working on the field of fluidization, in 1973 Geldart classified powders into four different groups and showed their fluidization behaviour as a function of the mean particle size (x-axis) and density difference between particles and fluid (y-axis) [12] [13]. This classification is shown in Figure 1-8.

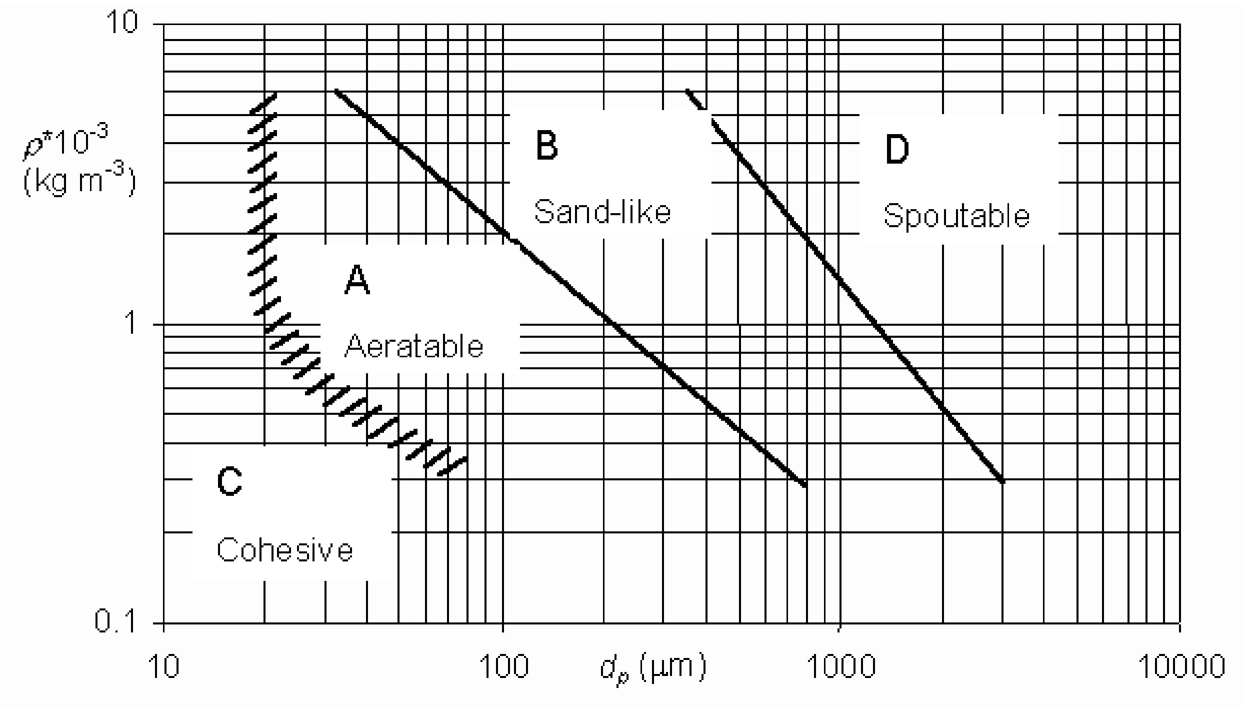

Figure 1-8Geldart's classification of powders [14]

1. **Group A powders** are aeratable and characterized by the small diameter and low particle density. They are ideal powders for dense phase conveying [9]. Beds of powders considerably expand before bubbling starts. Bubble size reduced by either using a wider particle size distribution or reducing the average particle diameter. When the gas supply is turned off the bed collapses slowly. The examples of powders belongs to group A are FCC (face centred cubic crystals), milk flour [15].
2. **Group B powders** are coarser than powders from group A and cannot be fluidized homogeneously. They are suitable for dilute phase conveying. Bubbles form at a minimum fluidizing velocity and the bed expansion is very small [12]. At the turned off gas supply the bed collapses rapidly. An example is sand [15].
3. **Group C powders** are characterized by strong cohesive forces and the mean size smaller than 20 μm. These powders are difficult to fluidise, they lifts the whole bed as a plug. Thus they are not recommended for dense phase conveying and usually transported in dilute phase [13]. The examples are flour, cement.
4. **Group D powders** are the coarsest powders with high superficial velocities at fluidization. Some of these powders can be transported in dense phase, but generally dilute phase conveying is more suitable [9].

1.6.2 State Diagram

State diagram is the best way to introduce the gas-solid conveying. This diagram is a plot of the pressure gradient at any point of the pipeline versus the superficial gas velocity. Various cross-sectional diagrams are able to illustrate the state of the conveying pipeline at a specific point in the state diagram, but the state diagrams which are shown in Figure 1-9 and in Figure 1-10 can illustrate the whole spectrum from dilute phase to dense phase [3].

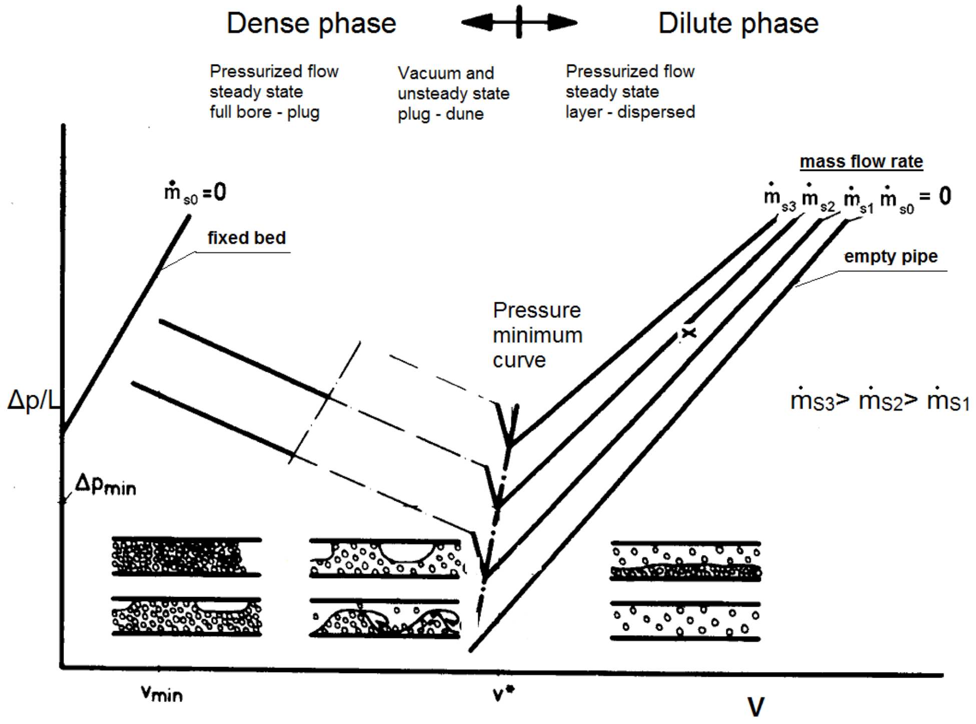

Figure 1-9State diagram for horizontal conveying [3]

The curves in the both figures show the different constant solids mass flow rates at various conveying gas velocity and system pressure drop. The empty pipe shows the pressure drop versus gas velocity curve, which is characteristically a single phase flow [4]. When the solid particles at a constant feed rate are introduced into the pipeline the pressure drop increases to a higher value than in case of empty pipe due to drag on particles and due to solids friction [3].

Further decreasing the gas velocity leads to the pressure drop decreasing to a certain point where the minimum pressure drop is experienced. The critical gas velocity corresponding to this point is called the 'saltation velocity'. These points for different solids flow rate values are connected by the pressure minimum curve. So, the flow regime up to this point characterised as the dilute phase flow. Further reduction of gas velocity leads to a to particle deposition in pipe bottom which in turn leads to the dense phase conveying. After an unsteady state region the plug flow appears and in case of further reduction of gas velocity the pipeline can be totally blocked [4].

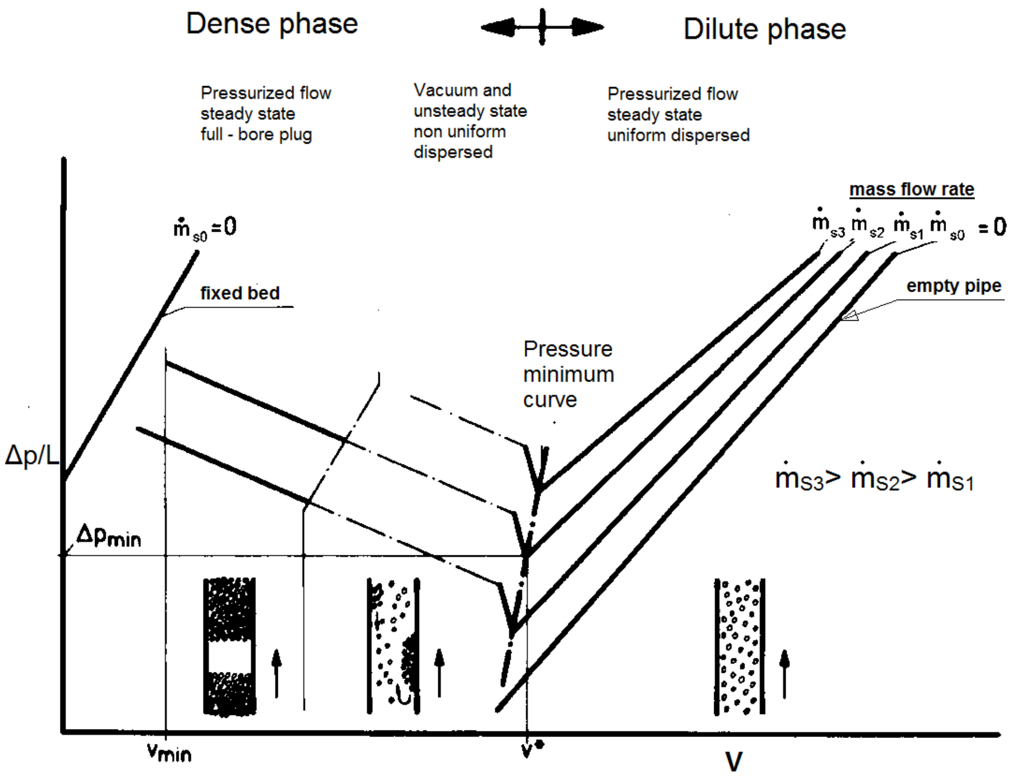

Figure 1-10State diagram for vertical conveying [3]

In terms of the definition of saltation velocity for horizontal conveying, a similar point is used to define the minimum transport velocity for vertical conveying – the choking velocity. This point is usually called the choking point [3].

1.7 Aim of the Project

It is well known that the pneumatic conveying is an important technique used for transportation of powders and particulates across plenty of industries and characterised by a large number of advantages described in sections above. But despite all advantages the pneumatic conveying systems operated in the dilute-phase regime at a high air velocity, causes a high power consumption, particle degradation and pipe erosion. The best solution for this problem is to operate at a low conveying velocity. To realize this, it is necessary to reveal the behaviours of particles in the range of low conveying velocity which means to determine particle velocity in pneumatic conveying. But, as per today, there is no solid explanation or scientific method of determining particle velocity, thus motivating the present work.

The main objectives of the subsections of the investigation are listed below:

1. To formulate a technique for the particle velocity determination in pneumatic conveying system.
2. Pressure signals analysis to determine the particle velocity at different types of powders transportation.

3. High speed video and image processing for particle velocity determination.

1.8 Structure of the Report

This report contains five chapters and each chapter is divided further into sections and subsections. Chapter 1 is an introductory part to the whole thesis and presents in the details historical developments, advantages, limitations and basic types of pneumatic conveying systems. Operation of pneumatic conveying systems and the main goal of this experimental investigation are also described under this chapter.

Chapter 2 provides the background and literature review of the current problem, the available mathematical models and various methods of solids velocity determination.

Experimental setup, all instruments on it and the experimental procedure are described in Chapter 3.

Experimental results, results from the pressure data analysis and image processing are discussed in Chapter 4.

Chapter 5 contains the final conclusions and suggestions for the future improvements. The list of references sited in this thesis is given at the end before the Appendices, which contain project description and MatLab codes.

2 Background and review of literature

Millions of particles are transported by pneumatic conveying systems to the desired destination. A detailed analysis of the behaviour of the single particle in a conveying gas stream and determination of minimum conveying velocity at which the solids can be conveyed steadily through the pipeline is necessary for successful operations of pneumatic transport. The theoretical and experimental investigation of particle velocity determination, signal analysis and cross correlation techniques are described in the current chapter.

2.1 Determination of minimum conveying velocity

Minimum conveying gas velocity is the lowest safe gas velocity for the horizontal transport of solids; usually the gas velocity at the start of the pipeline is the lowest in the all conveying system [4]. The conveying gas velocity is one of the most important parameters in pneumatic conveying and it need to be controlled fairly precisely. Uncontrolled gas conveying velocity causes many operational problems in conveying systems. If in a dilute phase conveying system, the velocity is too low there is a risk that the solids will drop out of suspension and block the pipeline; if the velocity is too high, bends in the pipeline will erode and fail if the solids are abrasive, there is also a possibility of material degradation [7].

Such terms as suspension velocity, pickup velocity, saltation velocity and critical velocity were used to refer to minimum conveying velocity. Usually these terms were used to indicate some transition in the way along the pipeline where particles are moving or begin to move [4].

2.2 Law of continuity

One of the main problems in pneumatic conveying is gas expansion, when the gas velocity and gas density change downstream from the product intake until the end of the conveying pipe. The different situation is for the air, if it is alone in the pipe the mass flow rate is constant for the all length and is given by the Equation 2-1 [16].

$$\dot{m}_f = \dot{V}_a \cdot \rho = A \cdot V_a \cdot \rho = constant \qquad 2\text{-}1$$

Where

$$\rho = \frac{p}{RT} \qquad 2\text{-}2$$

R is the gas constant (for the air R = 287.3 J/kg K) and T is the absolute temperature

$$T = (273 + t)K \qquad 2\text{-}3$$

t is the ambient temperature in °C.

The local static pressure p is given by Equation 2-4

$$P = p_0 \pm \Delta p_g \qquad 2\text{-}4$$

Where p_0 is barometric pressure and Δp_g is gauge pressure [16].

2.3 Determination of air velocity and terminal particle velocity

The local air velocity can be calculated from the air mass flow rate Equation 2-1 [16]

$$v_a = \frac{\dot{m}_a}{A \cdot \rho} \qquad 2\text{-}5$$

The simplest dynamic of the particle are when the steady state is established and only a gravitational forces are acting. At these conditions the terminal particle velocity w_T can be determined, which is a free fall velocity of the particle. For a spherical particle it can be estimated by equating drag and buoyancy forces with gravitation force, as shown by the equation (2-8). Drag force F is expressed by the equation below [16],

$$F = C_{D\infty} \frac{\rho}{2} w^2 A' = C_{D\infty} \frac{\rho}{2} w^2 \frac{\pi d^2}{4} \qquad 2\text{-}6$$

Where A' the projected area normal to flow, d the diameter of the particle, w is the relative velocity between the gas and the solid and $C_{D\infty}$ a drag coefficient is a function of the particle Reynolds number [16],

$$Re_p = \frac{wd\rho}{\eta} \qquad 2\text{-}7$$

$$C_{D\infty} \frac{\rho}{2} w_T^2 \frac{\pi d^2}{4} = (\rho_P - \rho_a) \frac{g\pi d^3}{6} \qquad 2\text{-}8$$

Or

$$C_{D\infty} = \frac{4\rho d^3(\rho_P - \rho_a)g}{3\eta^2 Re_{pf}^2} = \frac{4d(\rho_P - \rho_a)}{3w_T^2 \rho} g \qquad 2\text{-}9$$

$$w_T = \left(\frac{4}{3} \frac{d}{C_{D\infty}} \frac{\rho_P - \rho_a}{\rho_a} g\right)^{0.5} \qquad 2\text{-}10$$

General equation for estimation terminal velocity for a single sphere can be derived combining the equation (2-9) and (2-10) [16]:

$$Ga = 18Re_{pf}\left(1 + 0.15Re_{pf}^{0.687}\right) + \frac{0.351Re_{pf}^2}{\left(1 + 4.25 \cdot 10^4 Re_{pf}^{-1.16}\right)} \qquad 2\text{-}11$$

Where Reynolds number related to terminal velocity of the particle is defined as

$$Re_{pf} = \frac{w_T d\rho}{\eta} \qquad 2\text{-}12$$

η is dynamic viscosity and Galileo number Ga is given by

$$Ga = \frac{\rho(\rho_P - \rho_a)gd^3}{\eta^2} = \frac{\rho_a \Delta\rho g d^3}{\eta^2} \qquad 2\text{-}13$$

For the various Reynolds numbers and different flow regimes the next calculation procedures which are shown in Table 2-1can be applied.

Table 2-1Calculations of terminal particle velocity at various flow regimes [16]

Flow regime	Reynolds numbers	Calculation procedure
Stokes law regime	$Re_T < 2.0$	$w_T = \frac{d^2(\rho_P - \rho_a)g}{18\eta}$
Intermediate regime	$0.5 < Re_T < 500$	$w_T = \frac{0.153g^{0.71}d^{1.14}(\rho_P - \rho_a)^{0.71}}{\rho_a^{0.29}\eta^{0.43}}$
Newton's regime	$500 < Re_T < 2 \cdot 10^5$	$w_T = 1.74\left[\frac{d(\rho_P - \rho_a)g}{\rho_a}\right]^{0.5}$
Supercritical regime	$Re_T > 2 \cdot 10^5$	$w_T = 3.65\left[\frac{d(\rho_P - \rho_a)g}{\rho_a}\right]^{0.5}$

For the non-spherical particles procedure of free fall velocity calculation is the same as for the spherical particles with the same volume and some corrections for shape. Corrections for shape effect can be applied in one of the next two ways [16]:

- To determine the ratio $(w_T)_\psi/(w_T)_{sphere}$ with the help of Figure 2-1. Where $(w_T)_\psi$ is a free fall velocity of particle with sphericity of ψ and $(w_T)_{sphere}$ is a free fall velocity of spherical particle of same volume.

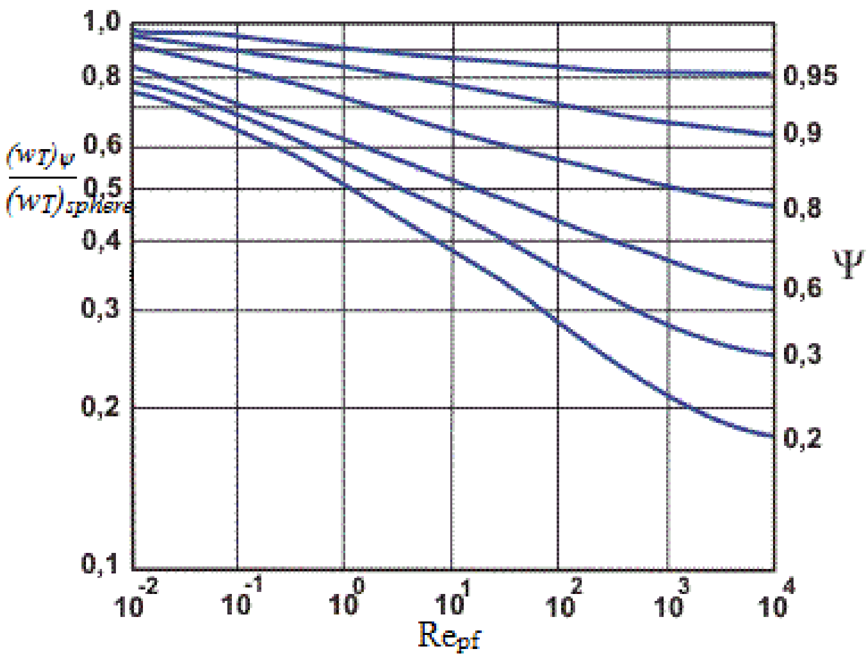

Figure 2-1Effect of particle shape on terminal settling velocity [16]

Shape factor ψ is a sphericity of a particle which can be defined by:

$$\psi = \frac{surface\ area\ of\ sphere\ with\ the\ same\ volume\ as\ particle}{surface\ area\ of\ particle} = \frac{\pi d_v^2}{S} \qquad \textit{2-14}$$

Where d_v indicates the equivalent volume diameter of a particle and S is the surface area of the particle. Data on sphericity for some materials are given in Table 2-2.

Table 2-2Data on sphericity ψ [16]

Material	Sphericity, ψ
Sand	0.534 – 0.861
Iron catalyst	0.578
Bituminous coal	0.625
Pulverized coal	0.696
Celite cylinders	0.861
Broken solids	0.63
Silica	0.554 – 0.628

- To determine the ratio $(w_T)_\psi/(w_T)_{sphere}$ with the help of the empirical equation below

$$\frac{(w_T)_\psi}{(w_T)_{sphere}} = 0.843\, log\, \frac{\psi}{0.065} \qquad \textit{2-15}$$

Equation (2-15) is also valid for solid-liquid systems [16].

2.4 Determination of voidage and slip velocity

According to Klinzing et al. [17] the parameters of voidage and slip velocity are closely related. The voidage is possible to derive from the volume element *dL* with the number of particles *n*. The voidage can be considered a number of particles in a given volume element as shown in Figure 2-2 [17].

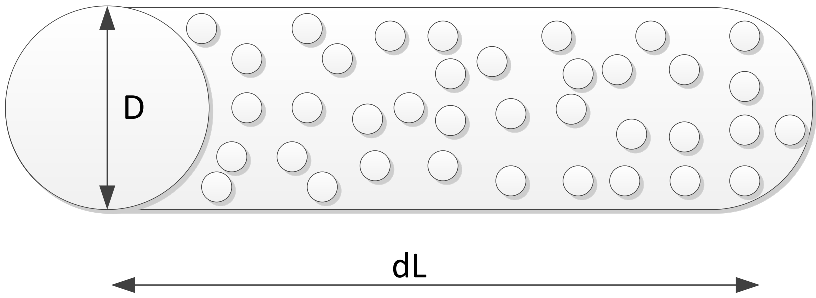

Figure 2-2Volume element dL with n number of particles [17]

Consider V_L the volume of the pipeline element and V_s the volume of the enclosed particles. The voidage $\mathcal{E}$ can be determined by

$$\varepsilon = \frac{V_L - V_s}{V_L} = 1 - \frac{V_s}{V_L} \qquad \textit{2-16}$$

Where

$$V_s = n \cdot V_p = \frac{\dot{m}_s}{\rho_p v_s} \Delta L \qquad \textit{2-17}$$

So,

$$\varepsilon = 1 - \mu \frac{\rho_a}{\rho_p} \frac{V_\varepsilon}{v_s} = 1 - \frac{\rho^*}{\rho_p} \qquad \textit{2-18}$$

Where ρ^* is the apparent bulk density and $V_{\mathcal{E}}$ is an actual gas velocity between the particles or velocity of porosity wave and can be found by

$$V_\varepsilon = \frac{v_a}{\varepsilon} \qquad \textit{2-19}$$

Where v_a is the superficial gas velocity based on the tube diameter [17]. The particle velocity can be found similarly to the Equation 2-18 upon condition that the voidage, mass flow ratio and density are known [17].

The slip velocity for a single particle in a gas stream is defined as the difference between the gas velocity and the particle velocity and it is the resultant velocity between the fluid and the solid caused by particle – particle and particle – wall interactions [17].

$$w_s = V_\varepsilon - v_s = \frac{v_a}{\varepsilon} - v_s \qquad \textit{2-20}$$

It is possible to assume, that for fine particles with the diameter less than 40 µm, the particles and the gas velocity are approaching one another in dilute flow and their difference is given by equation below:

$$w_T = v_a - v_s \qquad \textit{2-21}$$

2.5 Determination of particle velocity

According to Klinzing et al. [17] which referred to the earlier works by Hinkle, particle velocity can be found by the empirical correlation given below.

$$v_s = v_a\left(1 - 0.68d^{0.92}\rho_p^{0.5}\rho_a^{-0.2}D^{-0.54}\right) \qquad 2\text{-}22$$

The main idea of this correlation is that the particle velocity is just a function of system parameters.

Referring to Yang was proposed another empirical correlation which is shown below.

$$v_s = \frac{v_a}{\varepsilon} - w_T\left(1 + \frac{\lambda_s v_s^2}{2gD}\varepsilon^{4.7}\right)^{0.5} \qquad 2\text{-}23$$

Where λ_s is a solids friction factor and for various models can be determined from Table 2-3.

Table 2-3Solids friction factor for various models [17]

Investigator	**Solids friction factor, $\lambda_s/4$**
Stemerding	0.003
Reddy and Pei	$0.046\ c^{-1}$
Capes and Nakamura	$0.048\ c^{-1.22}$
Yang, vertical	$0.00315\frac{1-\varepsilon}{\varepsilon^3}\left(\frac{(1-\varepsilon)w_T}{V_\varepsilon - v_s}\right)^{-0.979}$
Yang, horizontal	$0.0293\frac{1-\varepsilon}{\varepsilon^3}\left(\frac{(1-\varepsilon)V_\varepsilon}{(gD)^{0.5}}\right)^{-1.15}$

Not so many studies were reported on solid particle velocity in horizontal dilute phase pneumatic conveying. Wei et al. [18], in his experimental study on the solid velocity in horizontal dilute phase pneumatic conveying, had showed that the particle velocities are different in the upper and lower part of the cross-section in the horizontal pipe. The velocity difference will decrease with the increasing gas velocity, and increases with the solid mass flow rate. This difference is usually no more than 2 m/s. According to the experimental results the implicit correlation based on Yang's Unified Theory gives the best prediction of particle velocity among existing studies.

New method of velocity measurement of pneumatically conveyed particles through digital imaging was proposed by Song et al. [19]. This method based on the traveling wave equation method that has been used to estimate the motion blur length and hence the particle velocity. The simulation studies presented by Song et al. have demonstrated that one can build a mathematical model of the blurred particle images to estimate the motion blur length and they proved that the digital imaging method is a reasonable approach to particle velocity measurement.

An indirect method of solid velocity [20] and slip velocity [21] estimation in vertical and horizontal pneumatic conveying has been presented by Raheman and Jindal. Rough rice, milled rice and soybean were transported by pneumatic conveying and experimental results indicated that solid velocity is a function of air velocity, solid flow rate, solid – flow – air ratio and particle diameter. Based on solids flow rate and dispersed solids density solid velocity was calculated. This method was estimated based on the theory that average solid velocity is equal to zero when the limiting value of the air velocity is equal to the terminal velocity of the particles [20]. In this case the dispersed solids density was measured by special mechanical trapping device which was installed at the end of the pipeline. The mass of the trapped sample were collected and weighed and the dispersed solid density was calculated by dividing the weight of the sample collected by volume of pipe section. The solid velocity was indirectly determined using equation below

$$v_s = \frac{\dot{m}_s}{A \cdot \rho_{ds}} \qquad 2\text{-}24$$

Where m_s is solid flow rate, A is cross-sectional area of the pipe and ρ_{ds} is the dispersed solid density which is influenced by grains shape and size. It was also reported that for materials like sand and catalyst the dispersed solid density is dependent on the air velocity and solid flow rate. Based on the experimental data of this study was developed the equation for dispersed solid density estimation [20].

2.6 Cross – correlation technic for particle velocity estimation

Uses of transducers is essential in the control process of pneumatic conveying system. The pressure waves measured by the pressure transducers and fluctuations behaviour of a gas - solid flow can provide useful information about the flow condition within the pipe line. The main idea is that transducers can give a pressure directly or provide a signal to be analysed in different ways. That is why careful monitoring of the pressure signals can prevent plugging of the system [22].

Of late, cross – correlation of signals has been available for two – phase flow and mostly in the field of turbulence [22]. Basically, in signal processing the cross – correlation is used to measure the similarity of two signals as a function of a time delay between them. Cross – correlation of signals $P_1(t)$ and $P_2(t)$ from two transducers, that are placed on a fixed distance from each other, can be defined as

$$K_{P_1P_2} = \int_{-\infty}^{\infty}[P_1(t) * P_2(t+\tau)]dt \quad \text{2-25}$$

where τ represents the delay time between two signals. Time delay is usually determined by the argument of the maximum of the cross-correlation function that corresponds to the point in time where the signals are best aligned. The application of this principle to a simple signal is shown in Figure 2-3.

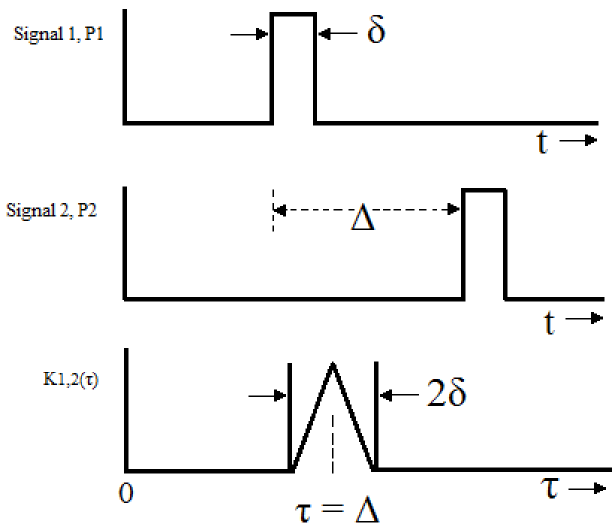

Figure 2-3Cross-correlation technique [22]

Since the distance between the measuring signals is a known parameter, the particle velocity of the solids in pneumatic conveyor can be found using

$$v_s = \frac{l}{\tau} \quad \text{2-26}$$

Where l represents distance between signal $P_1(t)$ and $P_2(t)$ and τ represents time at maximum $K_{P_1P_2}$ [22].

One of the advantages of the cross-correlation procedure is the possibility to use different signal devices such as hot wire, hot film anemometers and laser Doppler velocimetry (LDV), which can detect flow fluctuations that generally arise from pneumatic conveyer. Nowadays there is the possibility to produce a cross-correlator unit for any kind of electronic signals.

Another advantage of this type of signal measurement is that it can be performed electronically and can be incorporated into a control system for pneumatic conveyors [22].

3 Experimental setup and instrumentations

As mentioned early, the main aim of the investigation is to determine the solids velocity in pneumatic conveying. The experiment was carried out in the test rig which is available in the powder research laboratory of the Department of POSTEC of Tel-Tek. Pneumatic conveying of the plastic pellets that are shown in was conducted under various experimental conditions. One of the horizontal pipe sections was transparent. Pneumatic transportation of the plastic pellets through the transparent section was recorded by the high-speed camera. In addition to this, pressure transducers, flow transducers, thermometers and humidity meters are also mounted on the pipeline in order to achieve the desired measurements. The pressure and air flow rate data were collected using user friendly software program of the Lab VIEW package. The following chapter will give the explanations about different test units used in the investigation and experimental procedure.

3.1 Pneumatic conveying test rig

This section will give an introduction to the components used for the experiment. The schematic view of the conveying test rig is shown in Figure 3-1.

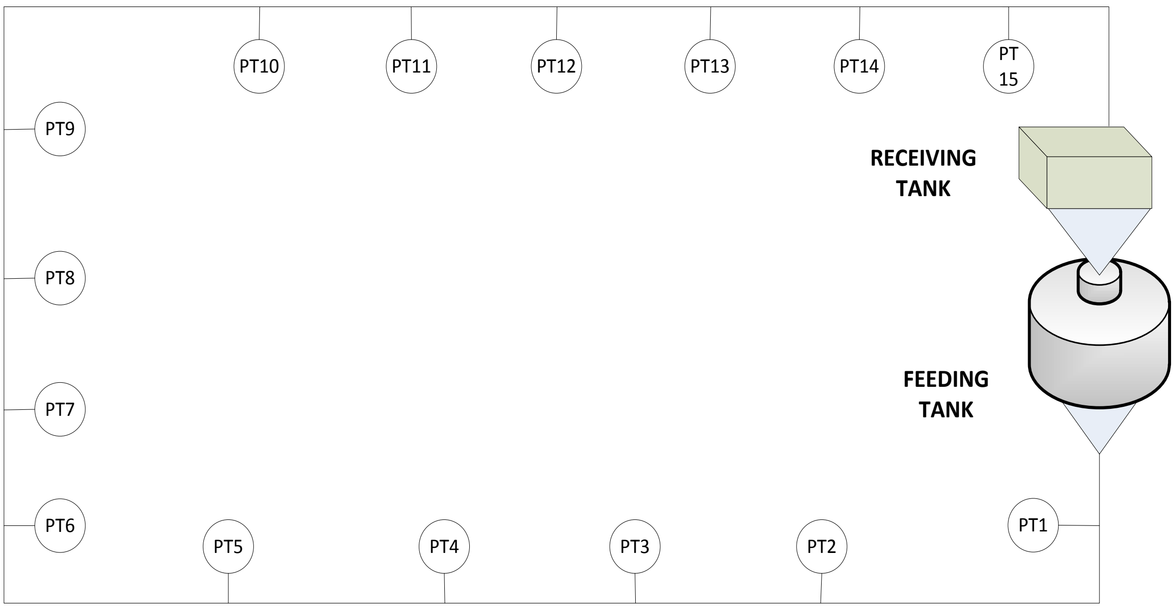

Figure 3-1Schematic view of the conveying test rig

Test rig was designed and built in POSTEC Powder Hall with the aim to conduct the research activities on dilute phase conveying. The layout of the experiment is shown in Figure 3-2.

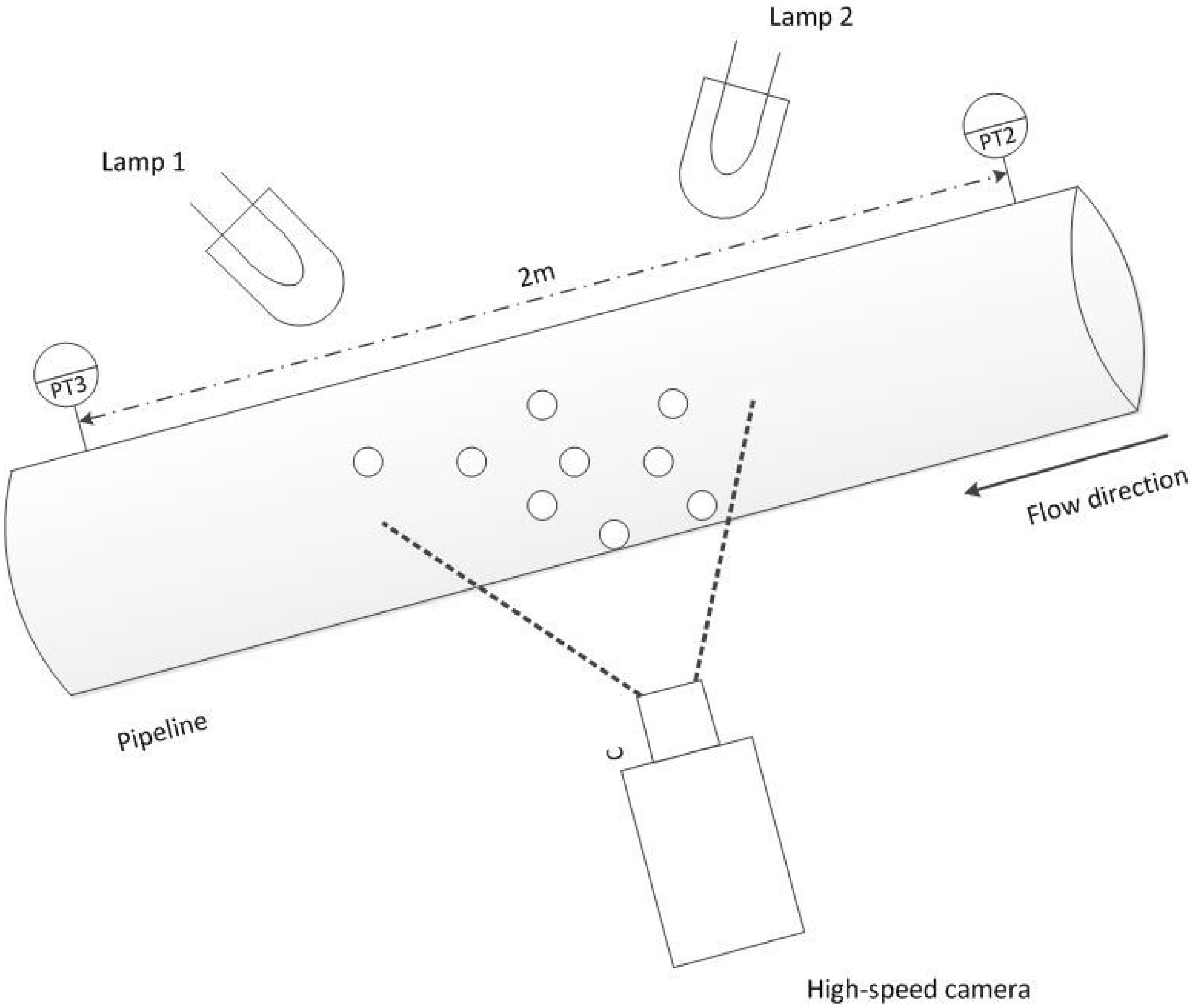

Figure 3-2 The pipe section

The test rig consists of a discharge tank with the capacity of 2.5 m^3, a receiving tank, which is mounted on a special arrangement of load cells to record the weight accumulation during the experiment and thus to get the information on solids transport rate, pipeline of 75mm diameter and approximately 40m length. The feeding from discharge tank to conveying pipeline was arranged through a feeding valve. The pipeline is presented by horizontal and vertical pipe sections of different bore sizes and lengths, an inclined pipe section and various types of bends.

By placing the receiving tank on top of the blow tank the conveying line forms a closed loop so that the solids under testing can be repeatedly transported without taking them out of the test rig. The snapshot of the receiving tank and the blow tank is shown in Figure 3-3.

Figure 3-3The blow tank and the receiving tank

The air supply was received from a combination of a screw type air compressor and a dryer-cum-air cooler. The pressure and volume flow rate of supply air could be controlled by a regulator. To achieve the desired measurements a number of pressure transducers, flow transducers, thermometers and humidity meters are also mounted on the transport line.

The transport rig is equipped with facilities for continuous online data logging and visualising of data like air pressure at various locations, air flow rate, air temperature, material transport rate, on a real time basis.

3.2 Test material

Plastic pellets provided by INEOS AS were used as a test material for pneumatic conveying. Pellets are made from low density polyethylene (LDPE) and are shown in Figure 3-4.

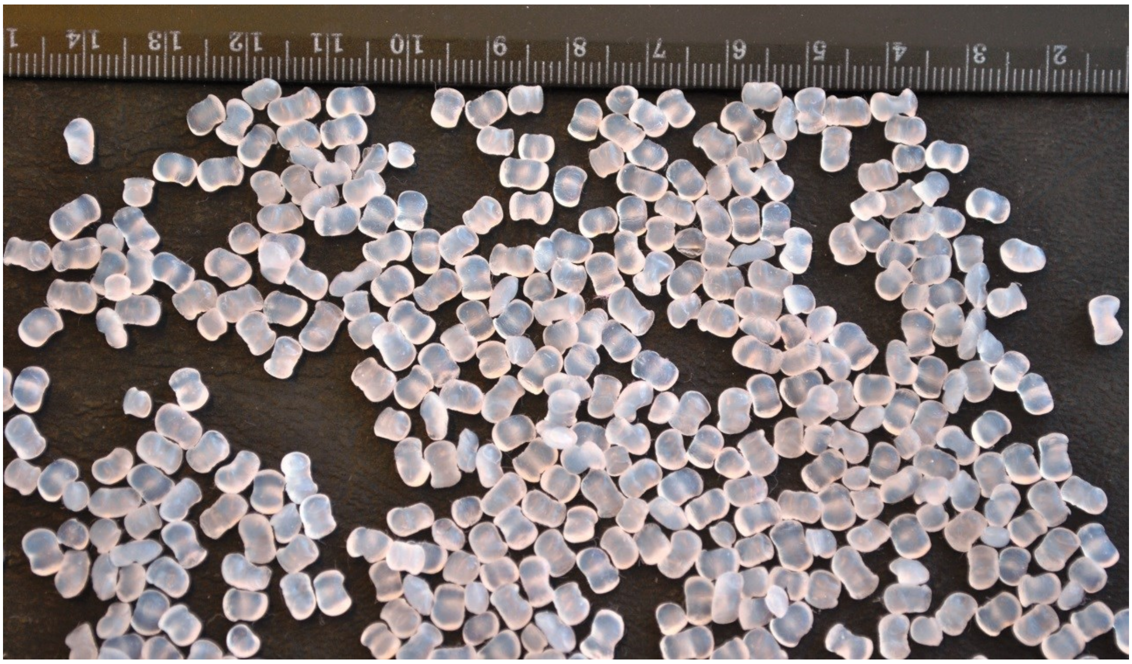

Figure 3-4Transported material - plastic pellets

The properties of plastic pellets are given in Table 3-1.

Table 3-1Properties of the solids

№	Property	Plastic pellets
1	Material	Low density polyethylene (LPDE)
2	Measured solids density, kg/m^3	911

3.3 Pressure transducers

A large number of pressure transducers have been used in the experimentations to monitor the pressure at different points on the pipeline, as shown in Figure 3-5.

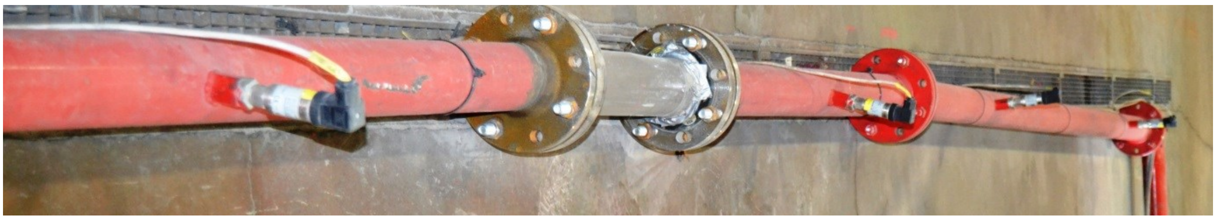

Figure 3-5Pressure transducers mounted on the pipeline

The type of pressure transmitter used in this investigation is called Druck PTX1400 Industrial Pressure Sensor. These pressure sensors have been designed for use with aggressive pressure media found in many industrial and process applications. They are feature compact, rugged design with field proven electronics to ensure long term reliable measurement and low cost of ownership [23]. The technical details of the pressure transducers are given below [23]:

- Current output: 4 - 20 mA
- Pressure range: 0 - 6 bar
- Supply voltage: 9 - 28 VDC
- Accuracy: ±0.15% typical

3.4 Air flow meter

To measure the total air flow rate through the conveying line, a vortex flow meter is mounted on the exhaust line as shown in Figure 3-6.

Figure 3-6Air flow meter

The technical specifications of the vortex type flow meter used in the experiment are given below [4]:

- Manufacturing Company: Yokogawa Electric
- Model: YF108
- Capacity: 1000 Nm^3/h
- Allowable max/min flow rates: 1142.2/ 59.4 Nm^3/h
- Supply voltage: 24 VDC
- Output current: 4…20 mA
- Accuracy: ±1.0% of reading (for velocity ≤ 35m/s)
  ±1.5% of reading (for 35 m/s < velocity ≤ 80 m/s)

3.5 High-speed video

In order to investigate the particle velocity during the pneumatic conveying of the plastic pellets, a high-speed camera was used. The type of the camera used is OLYMPUS model i-SPEED 3. This camera is designed to capture video of high speed events, store the captured video in internal memory and subsequently replay the video at slower speeds. A picture of the camera is shown in Figure 3-7.

Figure 3-7High-speed camera

The video has been captured in the transparent pipe section 53 cm length. The pipe is made from the Plexiglas and shown in Figure 3-8.

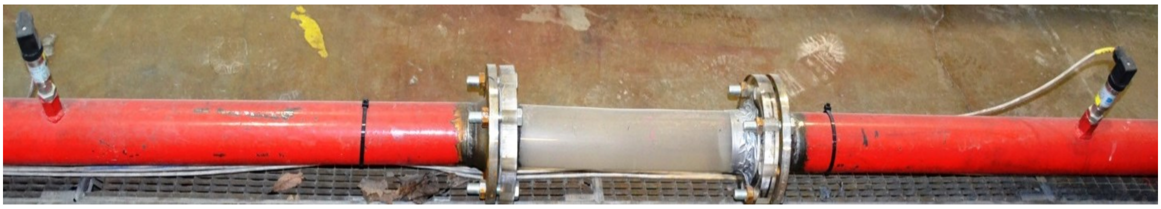

Figure 3-8Pipeline section

3.6 Particle density analyser

The Telemark University College laboratory is equipped with a particle density analyser of the Micromeritics 1320 model which is shown in Figure 3-9. The Micromeritics 1320 model is suitable for measuring the density of porous particles and is completely automated and operates by compression and expansion cycles of the chamber that contains the material. The density was determined by placing the known mass of the material in the autopycnometer chamber, the weight of the material was dialled on the chamber, and the run button was pushed. Then the volume of the material was determined by the instrument and density was calculated and displayed on the instrument.

Figure 3-9Particle density analyser

3.7 Experimental procedure

For current investigation, as a test material plastic pellets made from low density polyethylene have been used. The material was transported with a given supply air pressure and using various volumetric air flow rate and various rotary feeder frequency conditions. The test procedures were similar to each other. The experimental procedure can be divided into three parts: pre-test preparations, testing procedure and post-test analysis. Pre-test preparations cover setting up of the test rig and the high-speed camera. Post-test analysis includes the test data averaging, high-speed video analysis and other relevant analysis. The general procedure of experiments is explained in detail in the following section.

For each test, approximately 200 kg of plastic pellets were used for testing. Before testing in the pneumatic conveying rig, the particle density of representative sample of the material was measured in the laboratory. The first step of the each test was to fill up the blow tank with the test material by opening the supply valve. After the blow tank was full the supply valve was closed. The supply air pressure was adjusted to a predetermined pressure. When the pressure was stabilised, the rotary feeder was switched on and material was introduced to the pipeline. The number of test runs has been carried out by varying the volumetric air flow rate and the material feeding rate.

When the solid-air flow was stabilised the data acquisition programs, such as LabVIEW program and high-speed video, were simultaneously started. The duration of data capture by LabVIEW program was approximately 1 – 2 min and the duration of high-speed video was 3 - 4 sec.

The end of the conveying cycle was determined by checking the amount of material collected in the receiving tank that was digitally displayed on a control panel. Then, the rotary feeder was switched off and the pipeline was supplied with some additional compressed air to clean the pipeline from any residual materials. After that, the blow tank was let to depressurise and then, the materials were taken down to the blow tank for the next test run.

Since the experiment was finished the test rig was switched off and electricity supply was switched off. The different signals recorded during the test were then analysed and the solids velocity was calculated.

4 Results and Discussion

This chapter consists of four sections. Introduction to the chapter is presented in Section 4.1. The experimental results from the pressure data analysis and high speed video analysis are described in Section 4.2 and Section 4.3 respectively. Comparison of solids velocity calculated from a data captured by pressure transducers and solids velocity calculated from the high-speed video is presented in Section 4.4.

4.1 Introduction

Thirty experiments of pneumatic conveying of the plastic pellets have been performed by varying the material feeding rate and the volumetric flow rate of conveying air.

For each test run pressure data was recorded by transducers PT3 and PT4 which are placed on the pipeline on 2 m distance from each other. In addition to the pressure data, air flow rate and solids flow rate were also recorded. The solids flow rate was recorded on the basis of recorded data of accumulation of solids in the receiving tank measured over a period of time during every test run. An example of collected data is shown in Appendix 2. The high-speed video of pneumatic conveying of plastic pellets was also recorded for each test run.

Pressure data and high speed footage were collected from eight experiments. The experimental results summarized in Table 4-1.

Table 4-1Experimental criteria for pneumatic conveying of the plastic pellets

Test number	**Frequency of the rotary feeder, Hz**	**Air flow rate, Nm^3/h**	**High speed film**	**Pressure data**
Test 1	50	200	×	×
Test 2	60	200	×	×
Test 3	70	200	×	×
Test 4	80	200	×	×
Test 5	50	300	×	×
Test 6	60	300	×	×
Test 7	70	300	×	×
Test 8	80	300	×	×

The data is corrected so that all measurements start at zero, so video time and conveying time start at the same time zero.

4.2 Pressure data analysis

As mentioned early, one of the main objectives of the current investigation was to determine the solids velocity in horizontal pneumatic conveying of plastic pellets in 79 mm inside diameter and 2 m length pipe.

As explained above, it was possible to record the pressure signals PT, air volume flow signals FT and weight accumulation rates during testing. A typical variation of different signals during a conveying test is shown in Figure 4-1.

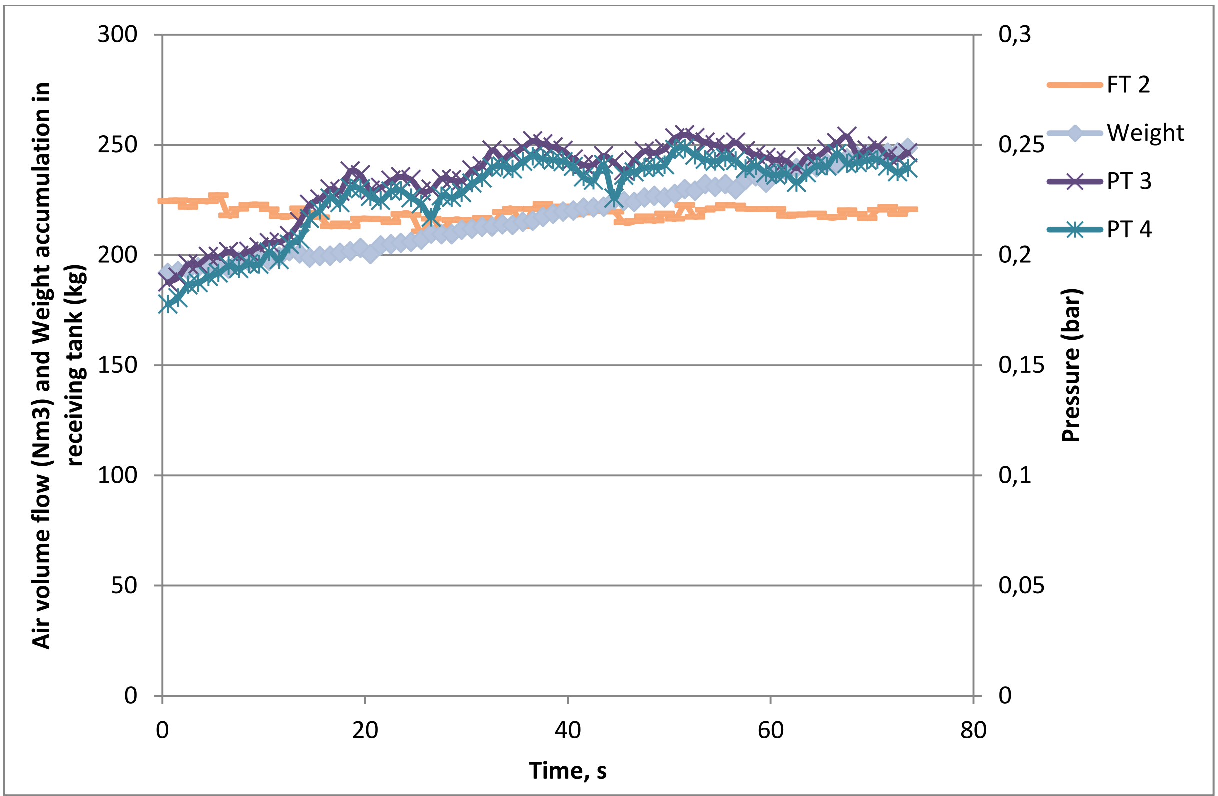

Figure 4-1Variation of different signals during conveying test run

Based on experimental data, cross-correlation technique was applied to determine the velocity of solids. Cross-correlation technic for particle velocity estimation is explained in Section 2.6. The cross-correlation function was computed for each of the signals in MatLab programme and the results for Test 7 are shown in Figure 4-2. MatLab code for cross-correlation function is presented in Appendix 2. It is based on the pressure data of first 10 s of the conveying. This graph of cross-correlation function K_{P3P4} shows a clear maximum at sample № 12 which corresponds to the time $\tau = 1.1$ s.

The solids velocity had been calculated using Equation 4-3 and the resulting magnitude was unexpectedly small. The same procedure was applied to all the tests and the magnitudes of the solids velocities were not acceptable. Probably the main reason for this problem is that the pressure signals were not good enough. It can be caused by not enough sensitive pressure transducers, too light plastic pellets or too low solids feed rate.

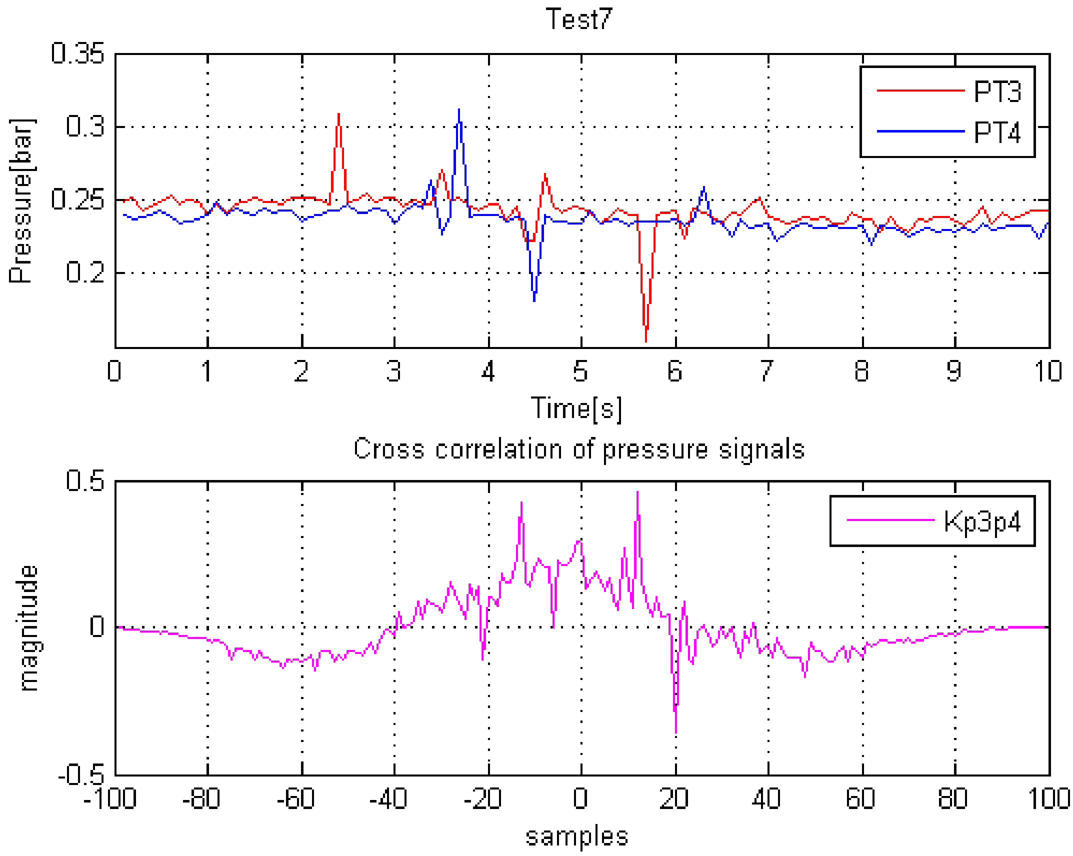

Figure 4-2Cross-correlation of two pressure signals based on data from Test 7

To control the pneumatic conveying it is important to monitor process parameters. The variation of pressure, volumetric air flow rate and weight accumulation during various test runs in horizontal line configuration are shown in figures from Figure 4-3 to Figure 4-10.

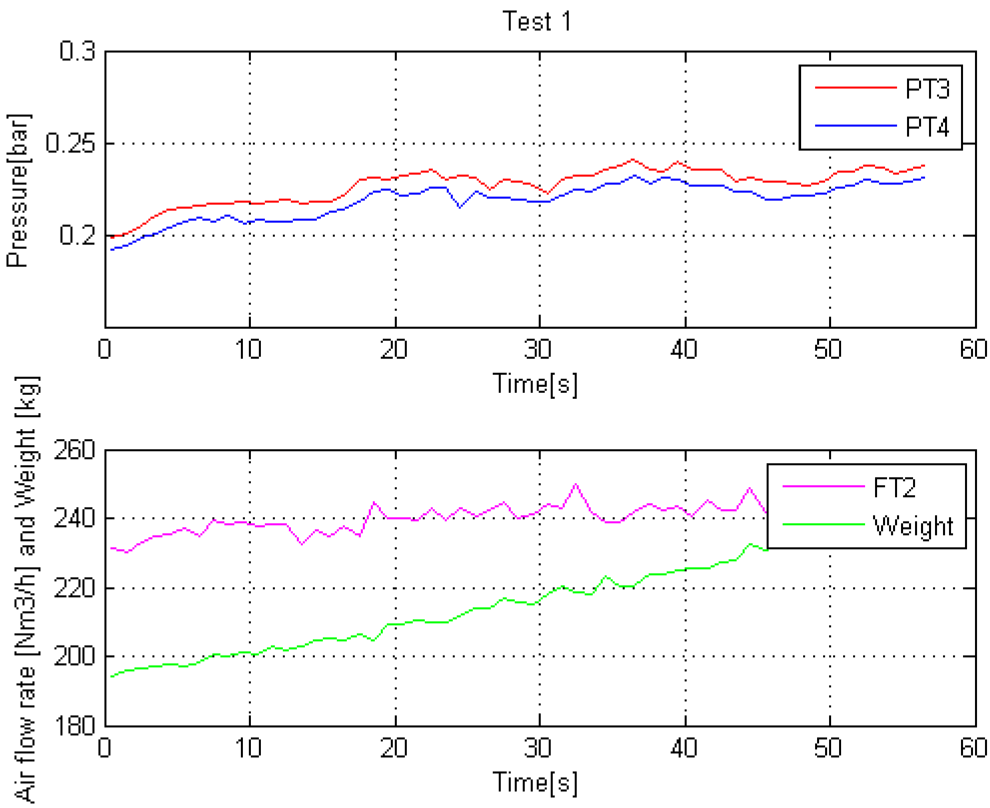

Figure 4-3Variation of pressure signals, air flow rate and weight accumulation during Test 1

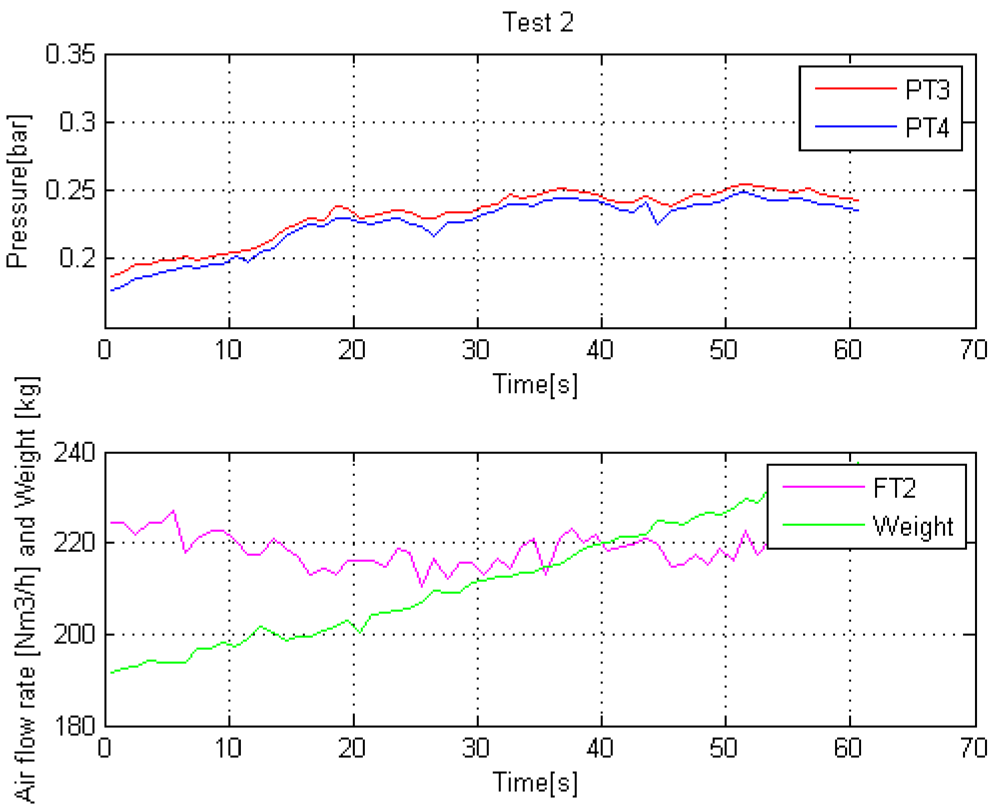

Figure 4-4Variation of pressure signals, air flow rate and weight accumulation during Test 2

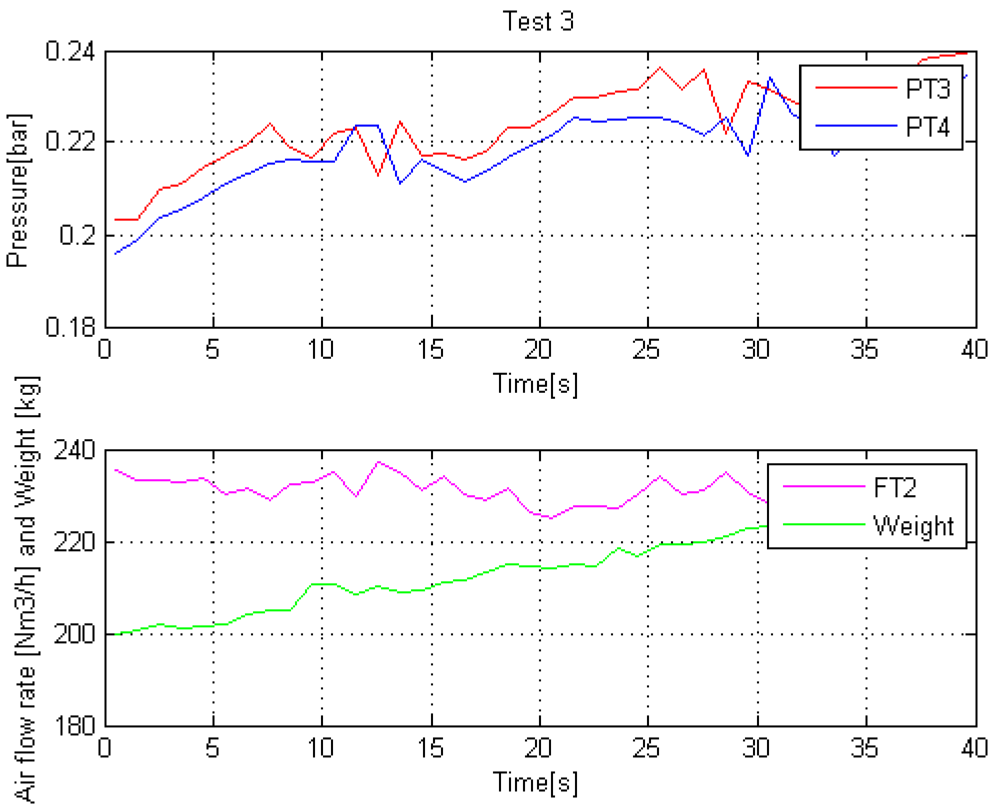

Figure 4-5Variation of pressure signals, air flow rate and weight accumulation during Test 3

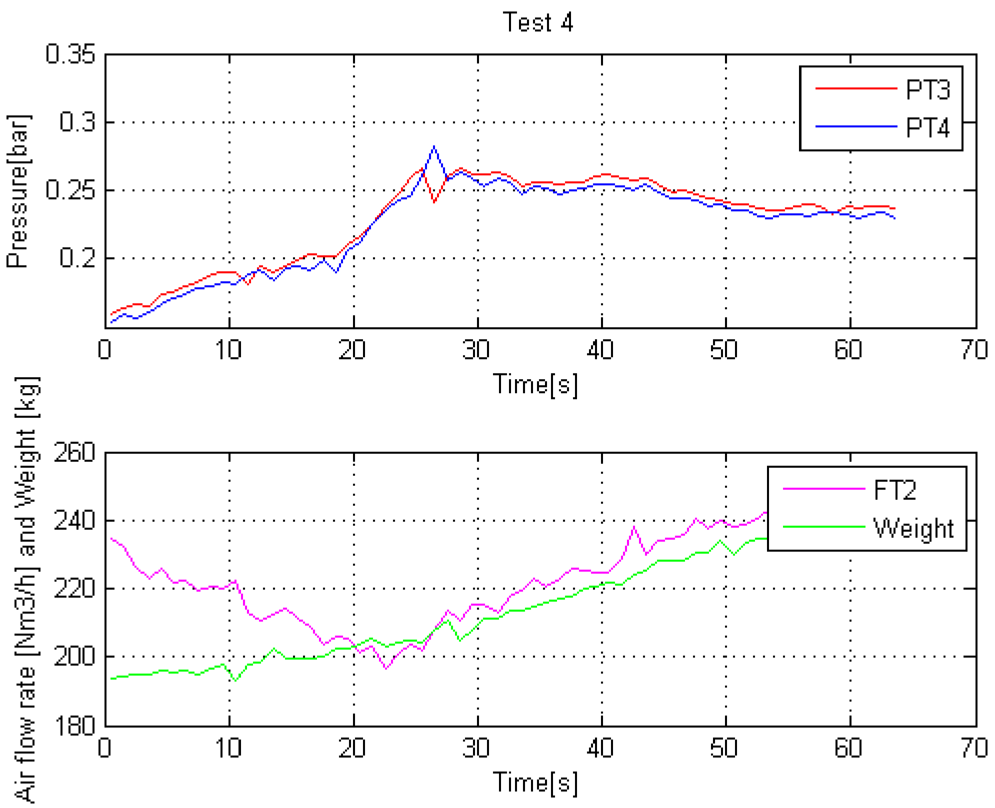

Figure 4-6Variation of pressure signals, air flow rate and weight accumulation during Test 4

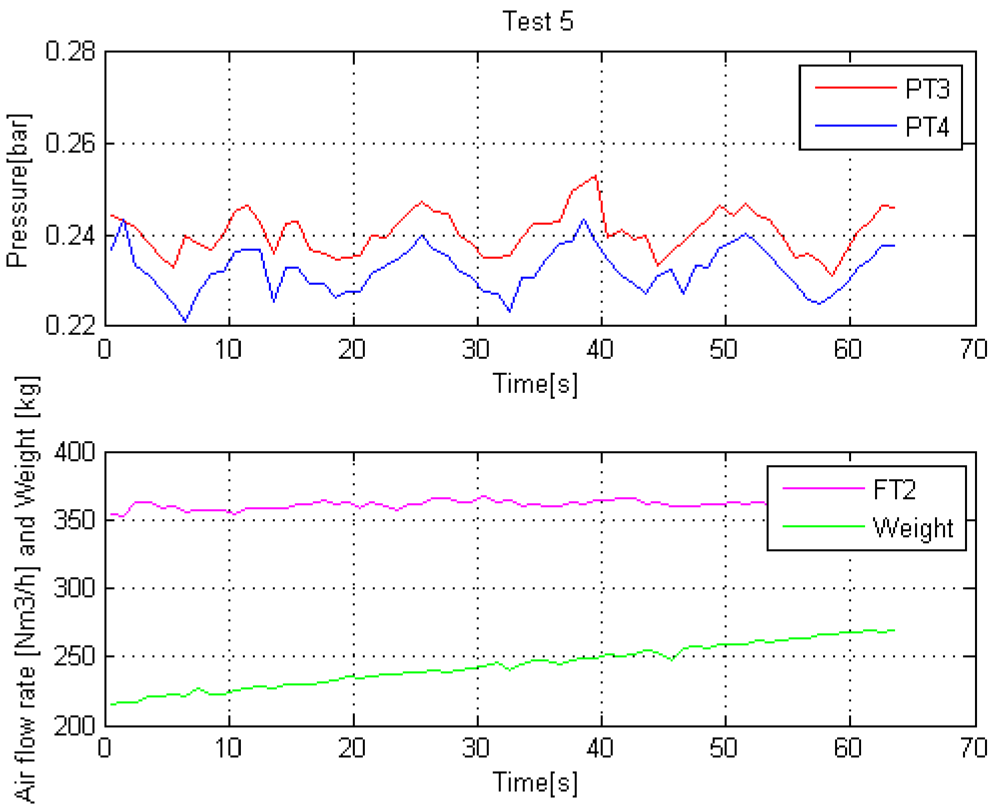

Figure 4-7Variation of pressure signals, air flow rate and weight accumulation during Test 5

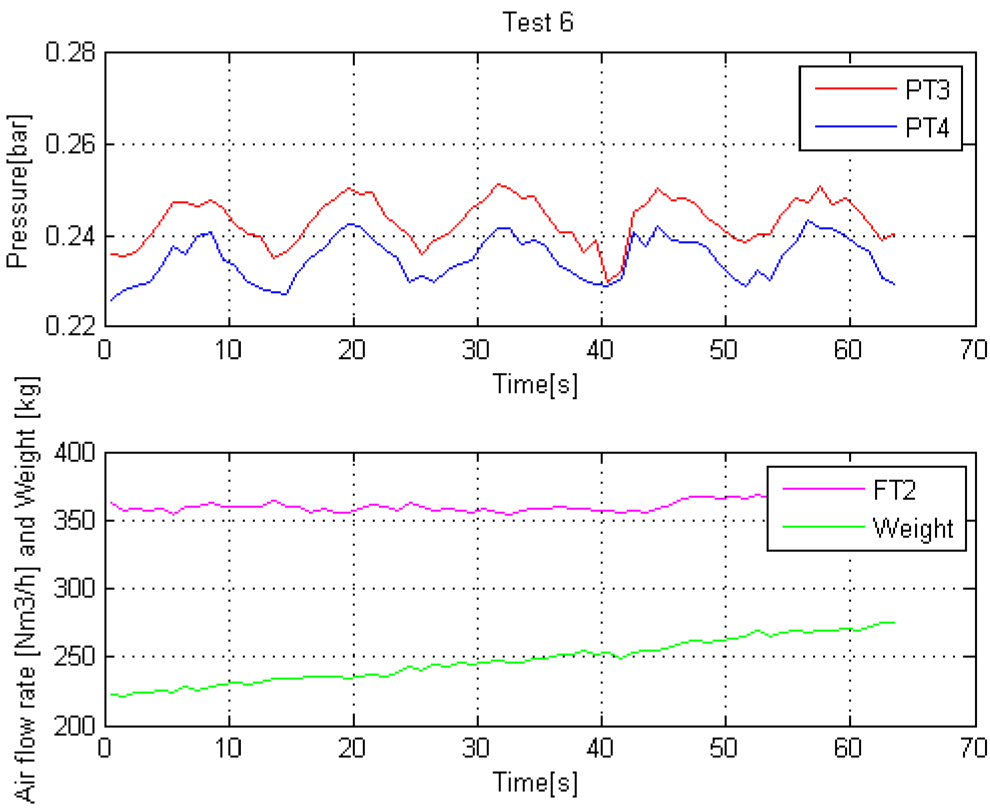

Figure 4-8Variation of pressure signals, air flow rate and weight accumulation during Test 6

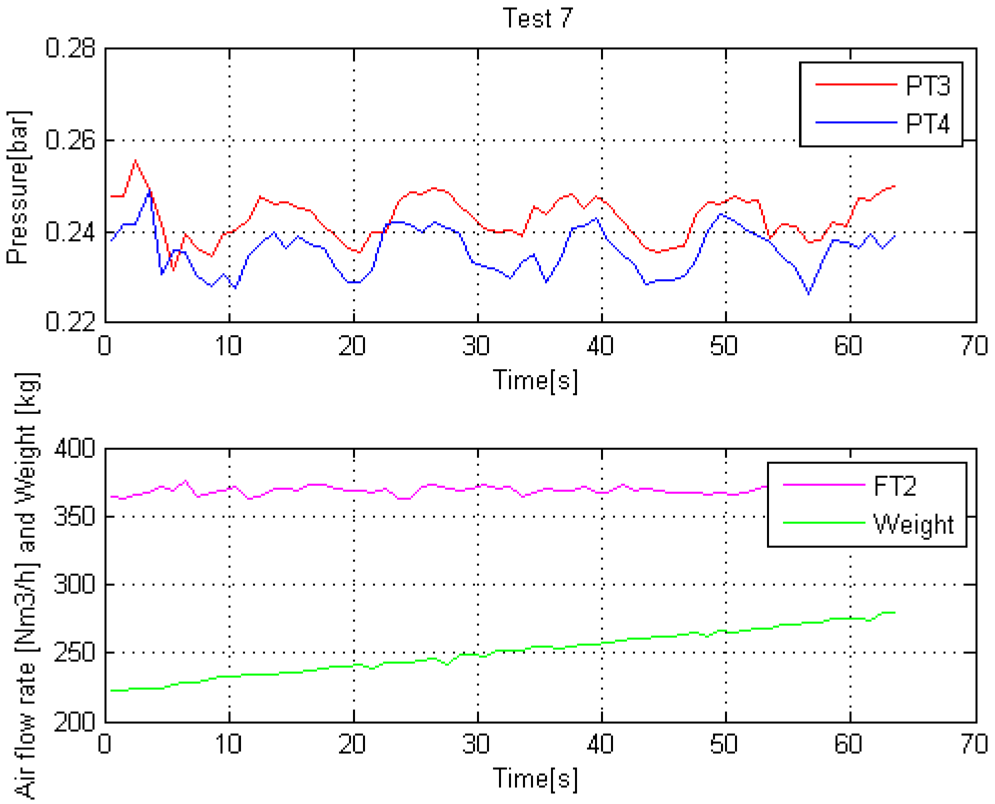

Figure 4-9Variation of pressure signals, air flow rate and weight accumulation during Test 7

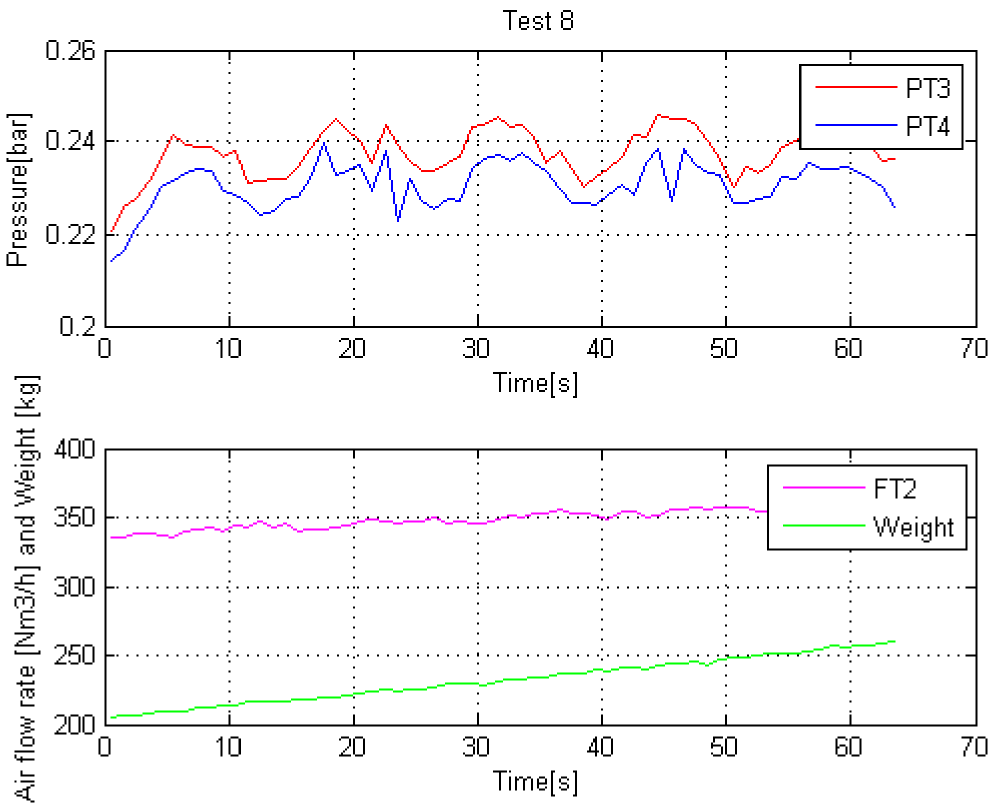

Figure 4-10Variation of pressure signals, air flow rate and weight accumulation during Test 8

From these figures, it is clear that the pressure signals were quite stable during a conveying run and they lead each other well. The higher variations in pressure signals could be observed under conveying runs with low air volume flow rates. It is easy to see that the pressure difference during tests 1 – 4 is not significant and much smaller than the pressure difference during tests 5 – 8. Reduction of air volume supply leads to plug formation and blocking the pipeline. Under higher air volume flow rates, quite stable conveying could be observed. It was also noticed that when the air volume flow rate remains stable during a considerably long time interval, the pressure signals behaviour are quite stable. When feeding rate of conveying materials was changed by varying the frequency of the rotary feeder, different gradients could be seen in load cell signal. The air flow rate seems to be stable for all the experiments.

During the present investigation, it was examined that the equation for solids velocity estimation, used by Raheman and Jindal [20], could be modified for the two phase flow in a short pipe element. Basically, the solid suspension density (ρ_{sus}) was introduced to Equation 2-24, instead of ρ_{ds} dispersed solids density measured by a mechanical sample-trapping device. When a short pipe element is considered the suspension density (ρ_{sus}) can be defined as the mixture density using below [4]

$$\rho_{sus} = \frac{\dot{m}_s + \dot{m}_a}{V_s + V_a} \qquad \textit{4-1}$$

Where $\dot{m}_s$ is solids mass flow rate, $\dot{m}_a$ are air mass flow rate, V_s and V_a are solids volume flow rate and volumetric air flow rate respectively. The solids density (ρ_s) was measured by using particle density analyser, which was described in Section 3.6.

The final equation for solids velocity determination can be presented in the following way.

$$v_s = \frac{\dot{m}_s}{A \cdot \rho_{sus}} \qquad \textit{4-2}$$

Air velocity was found by

$$v_a = \frac{V_a}{A} \qquad \textit{4-3}$$

The relationship between calculated solids velocity and measured superficial air velocity in 79 mm diameter pipe are shown in figures below for horizontal conveying of plastic pellets for different test run condition.

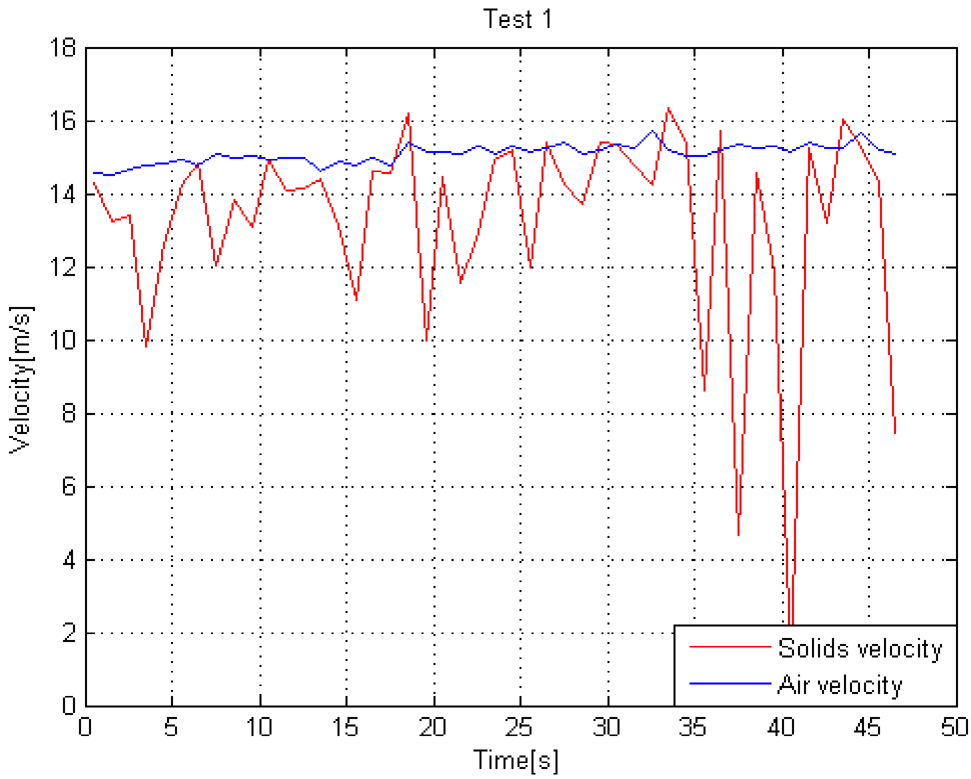

Figure 4-11Variation of calculated solid velocity and measured superficial air velocity during Test 1

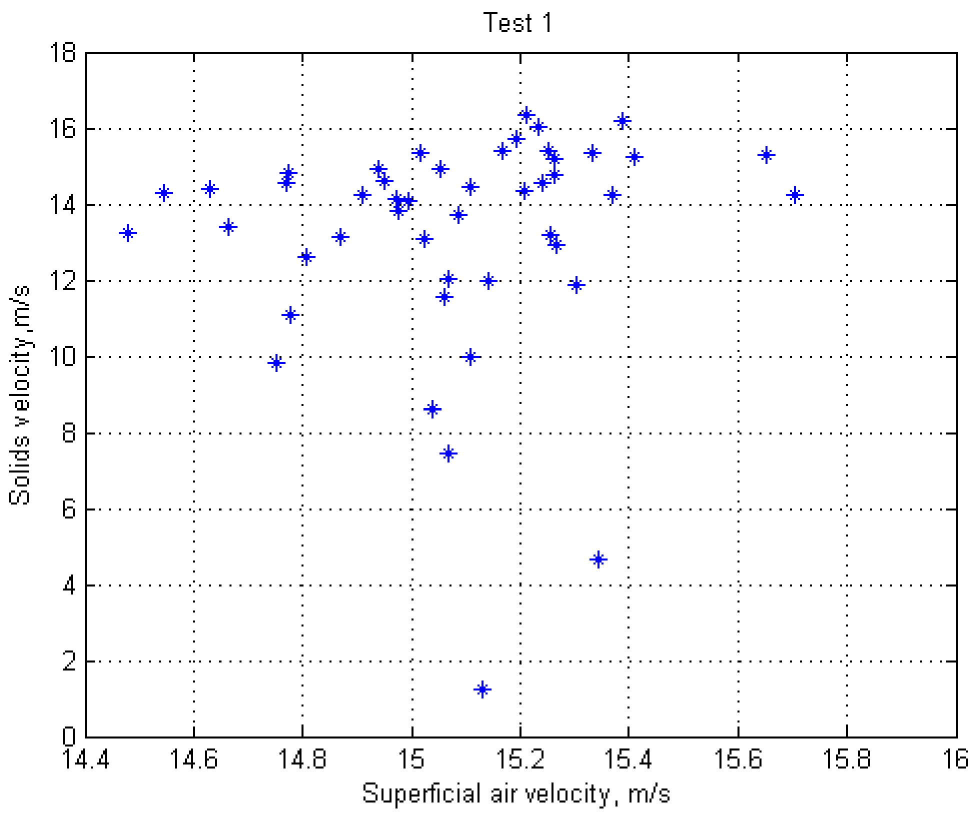

Figure 4-12Solid velocity as a function of air velocity in horizontal conveying of plastic pellets during Test 1

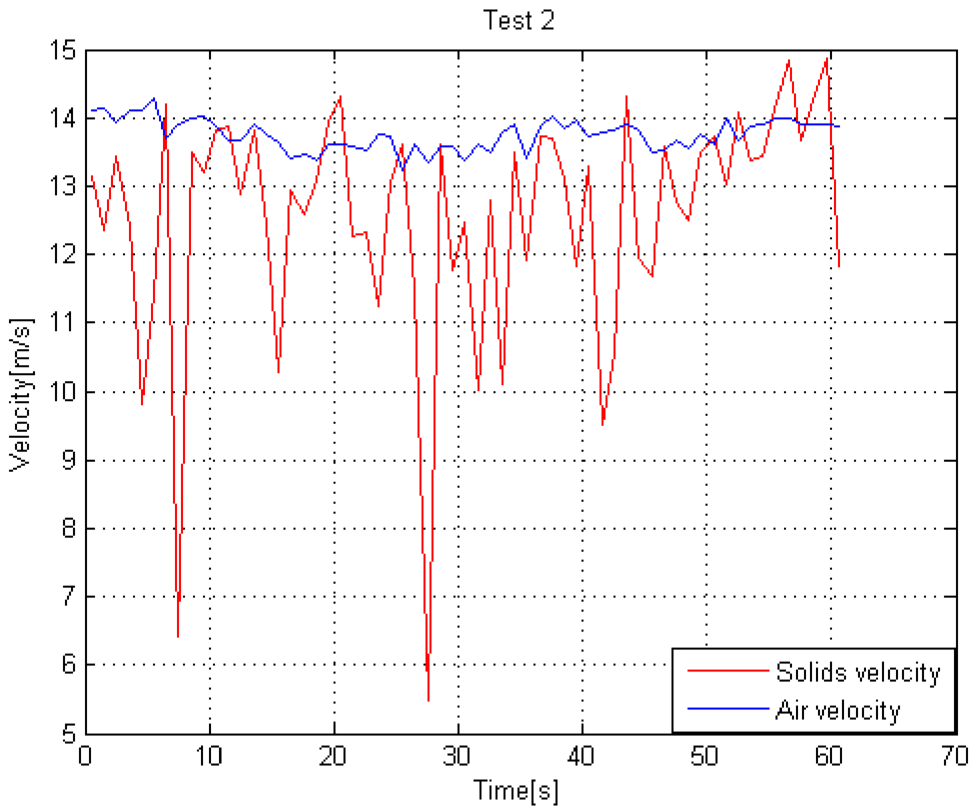

Figure 4-13Variation of calculated solid velocity and measured superficial air velocity during Test 2

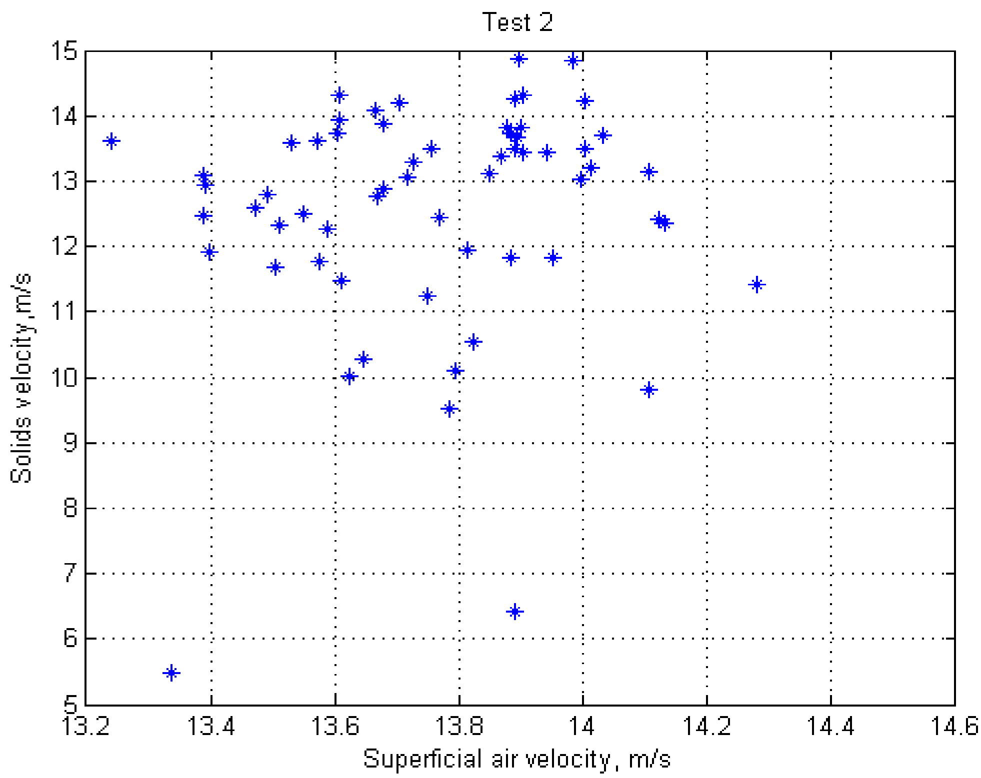

Figure 4-14Solid velocity as a function of air velocity in horizontal conveying of plastic pellets during Test 2

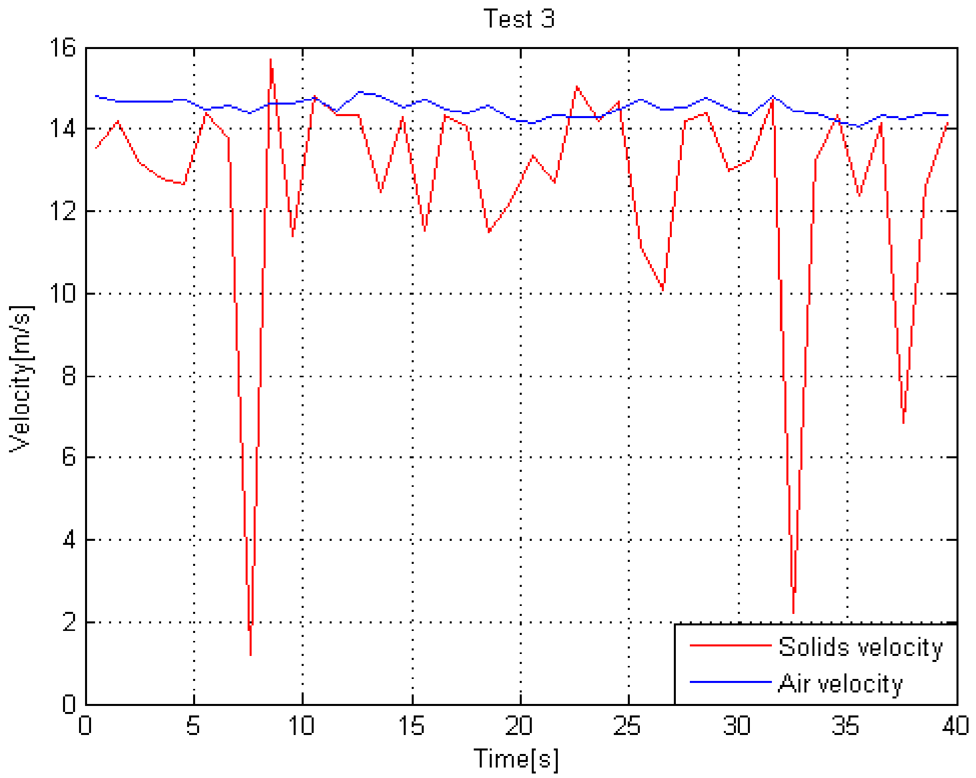

Figure 4-15Variation of calculated solid velocity and measured superficial air velocity during Test 3

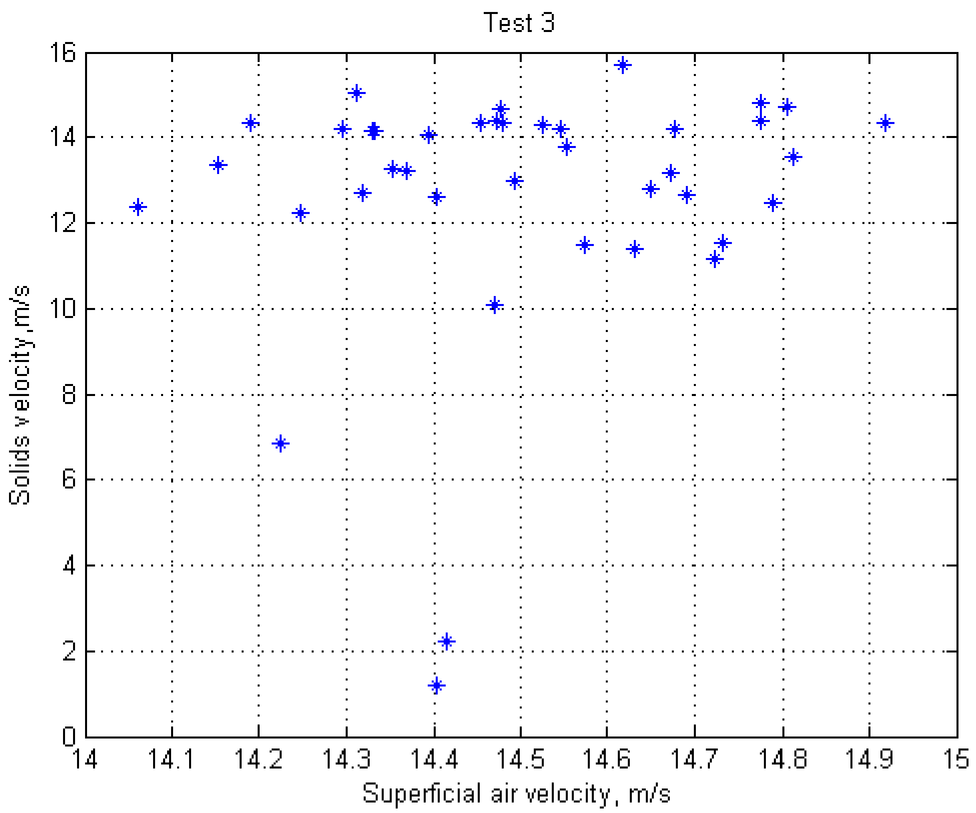

Figure 4-16Solid velocity as a function of air velocity in horizontal conveying of plastic pellets during Test 3

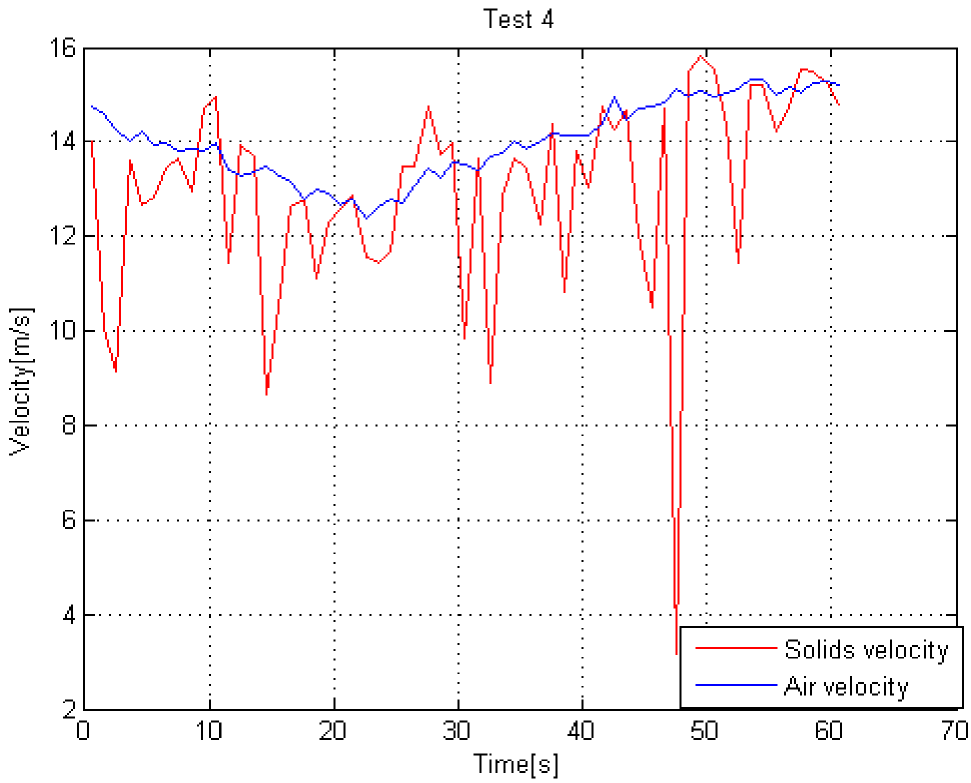

Figure 4-17Variation of calculated solid velocity and measured superficial air velocity during Test 4

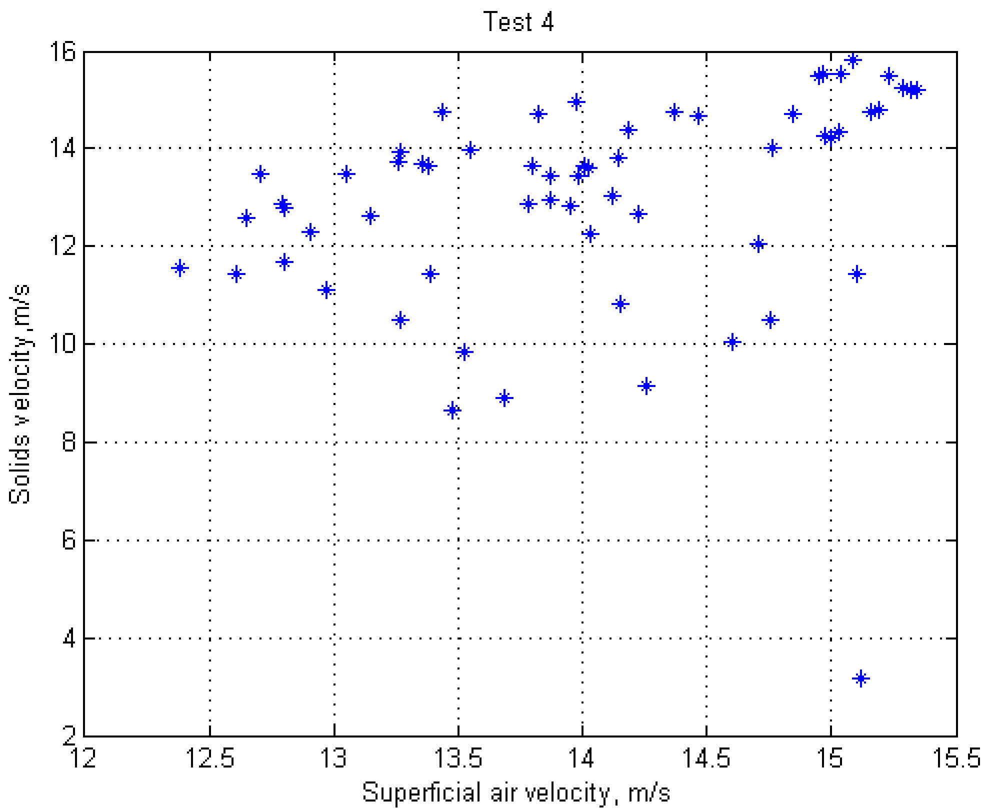

Figure 4-18Solid velocity as a function of air velocity in horizontal conveying of plastic pellets during Test 4

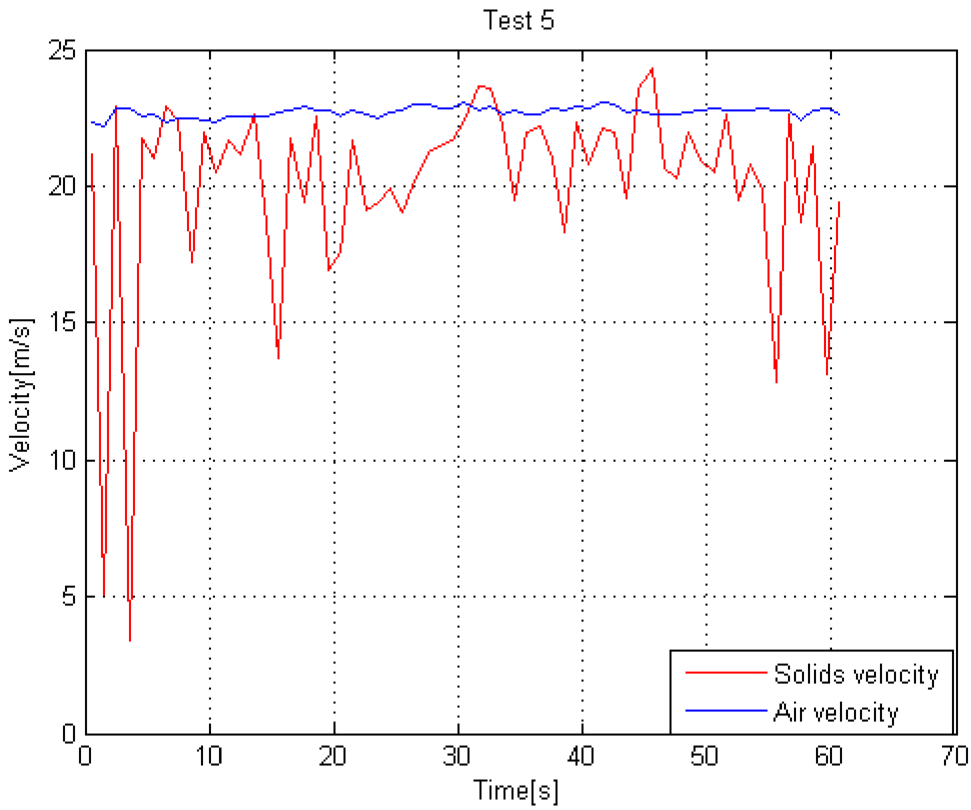

Figure 4-19Variation of calculated solid velocity and measured superficial air velocity during Test 5

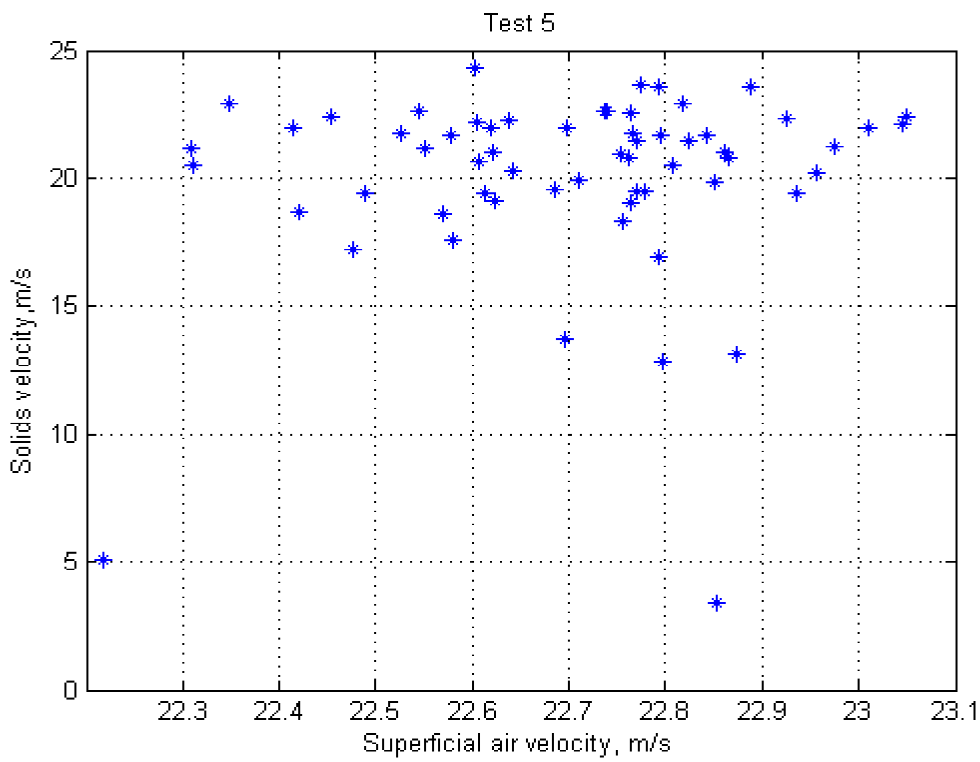

Figure 4-20Solid velocity as a function of air velocity in horizontal conveying of plastic pellets during Test 5

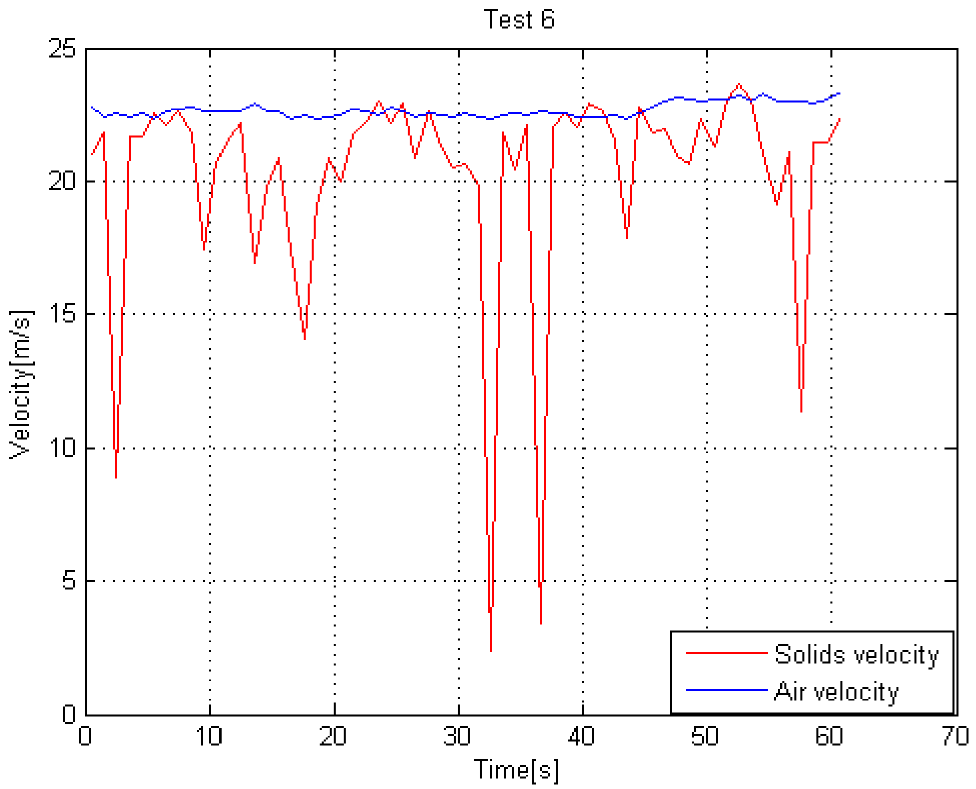

Figure 4-21Variation of calculated solid velocity and measured superficial air velocity during Test 6

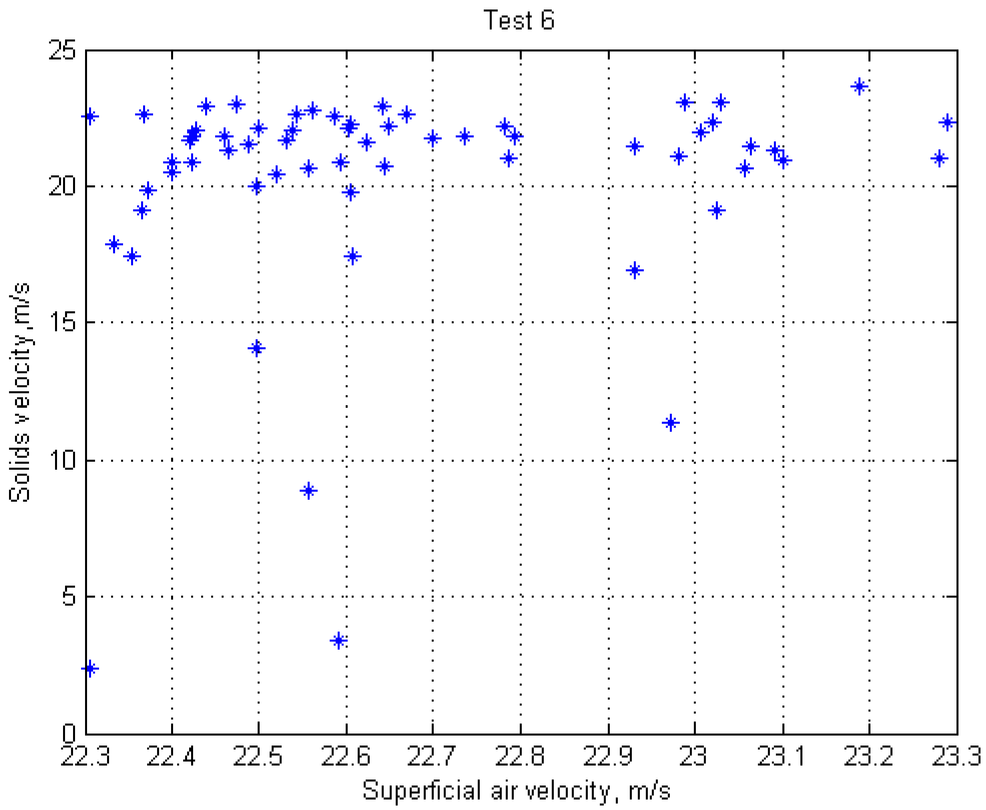

Figure 4-22Solid velocity as a function of air velocity in horizontal conveying of plastic pellets during Test 6

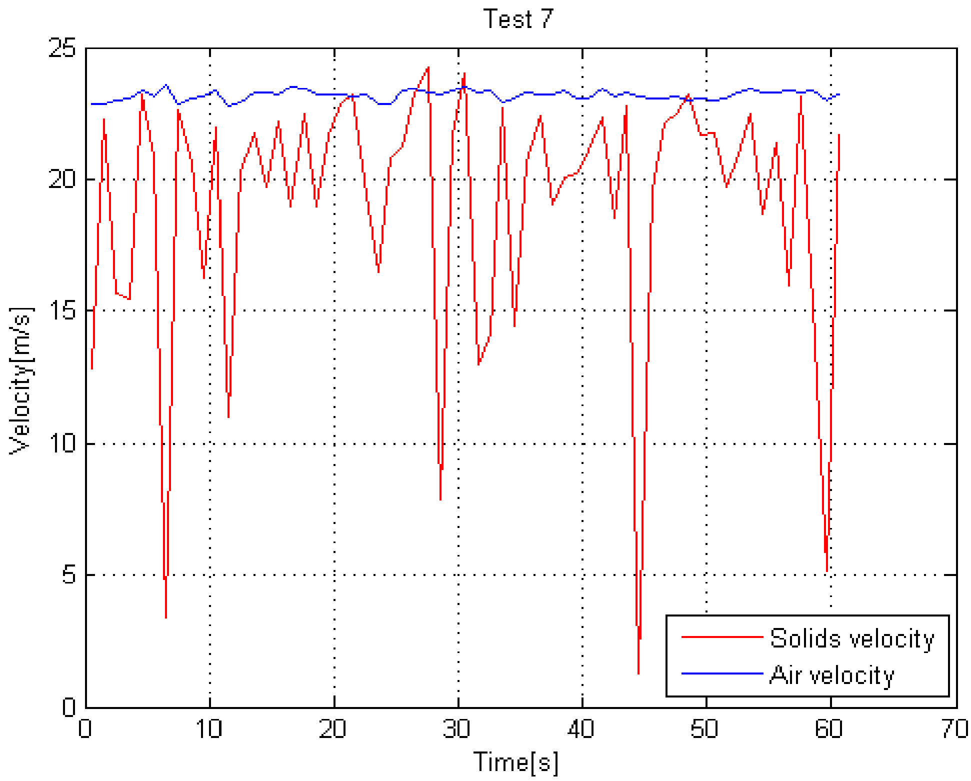

Figure 4-23Variation of calculated solid velocity and measured superficial air velocity during Test 7

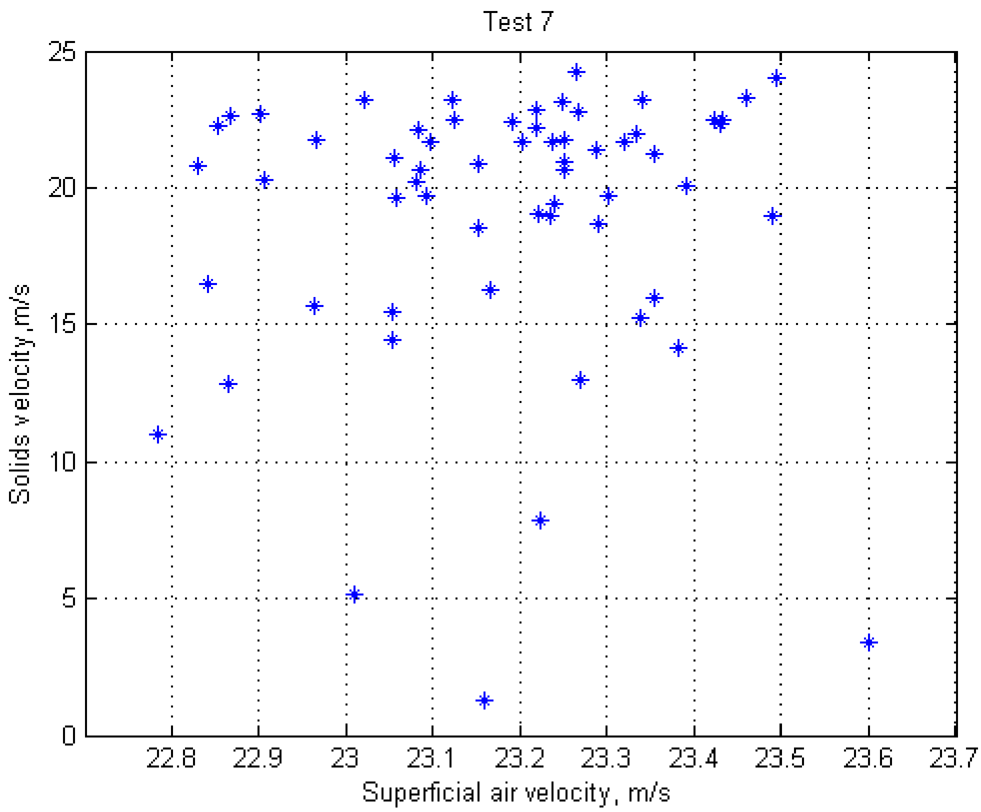

Figure 4-24Solid velocity as a function of air velocity in horizontal conveying of plastic pellets during Test 7

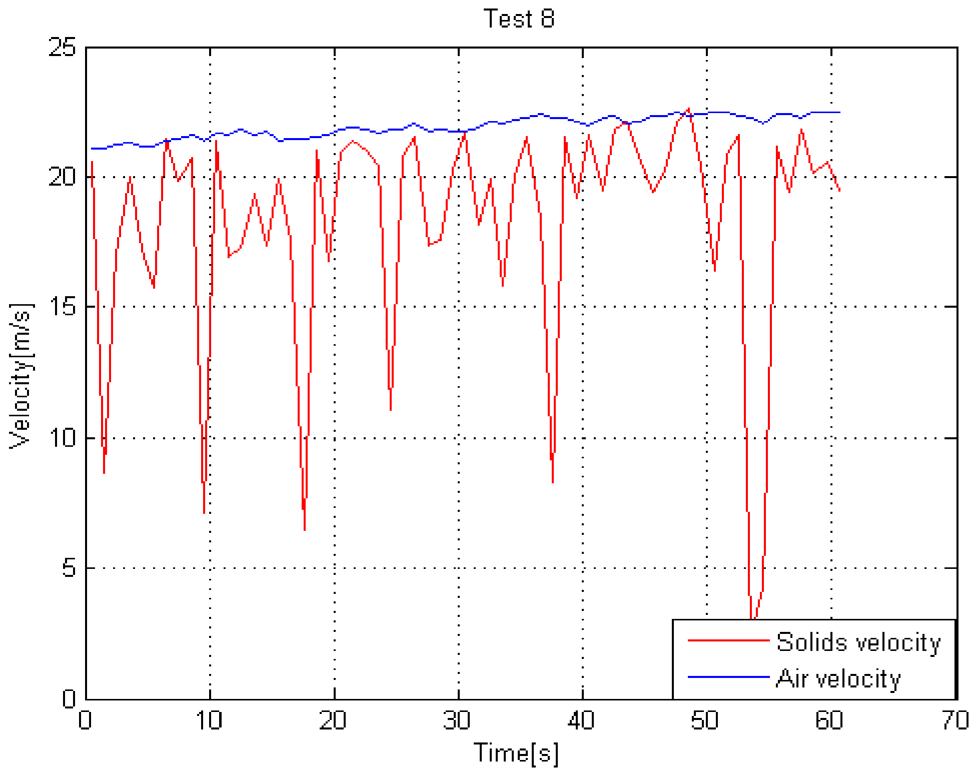

Figure 4-25Variation of calculated solid velocity and measured superficial air velocity during Test 8

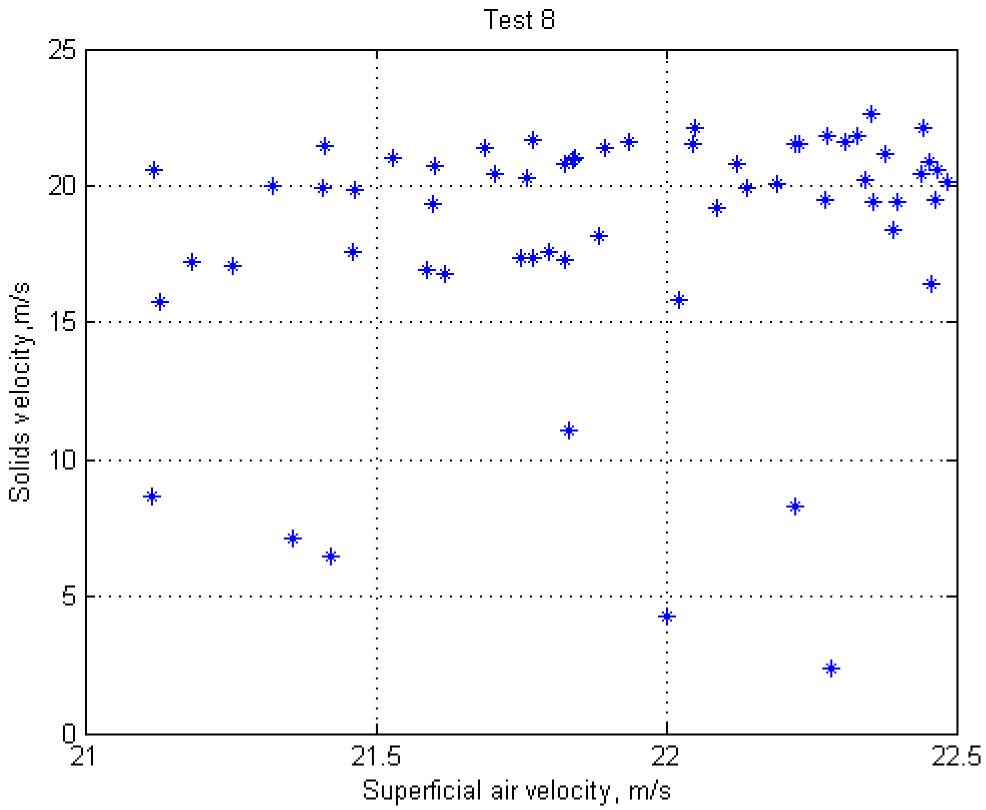

Figure 4-26 Solid velocity as a function of air velocity in horizontal conveying of plastic pellets during Test 8

From these figures, it is clear that solid velocity is a function of air velocity; the results of calculated solids velocity are widely dispersed. From this it could be concluded that experimental data or calculations are not so accurate. In other studies [21] it was also shown, that the solid velocity is also a function of particles diameter, solid flow rate and solid-to-air ratio. In general, the particle velocity is lower than the superficial air velocity. High variation of solids velocity can be observed from the graphs, which could be caused by unstable air volume flow rate and different solid concentrations in the conveyed flow. Possible contribution from electronic noise of pressure signals may also be quite high.

4.3 High-speed video analysis

To evaluate the particle velocity of the plastic pellets in horizontal conveying by digital imaging method, a series of high-speed video were undertaken during experimentation. As was mention in Chapter 3, high-speed footage of the experimental tests, which were conducted in a transparent pipe section 53 cm length, was made by the high-speed camera.

A typical example of a motion image captured by the high-speed camera is illustrated in Figure 4-27.

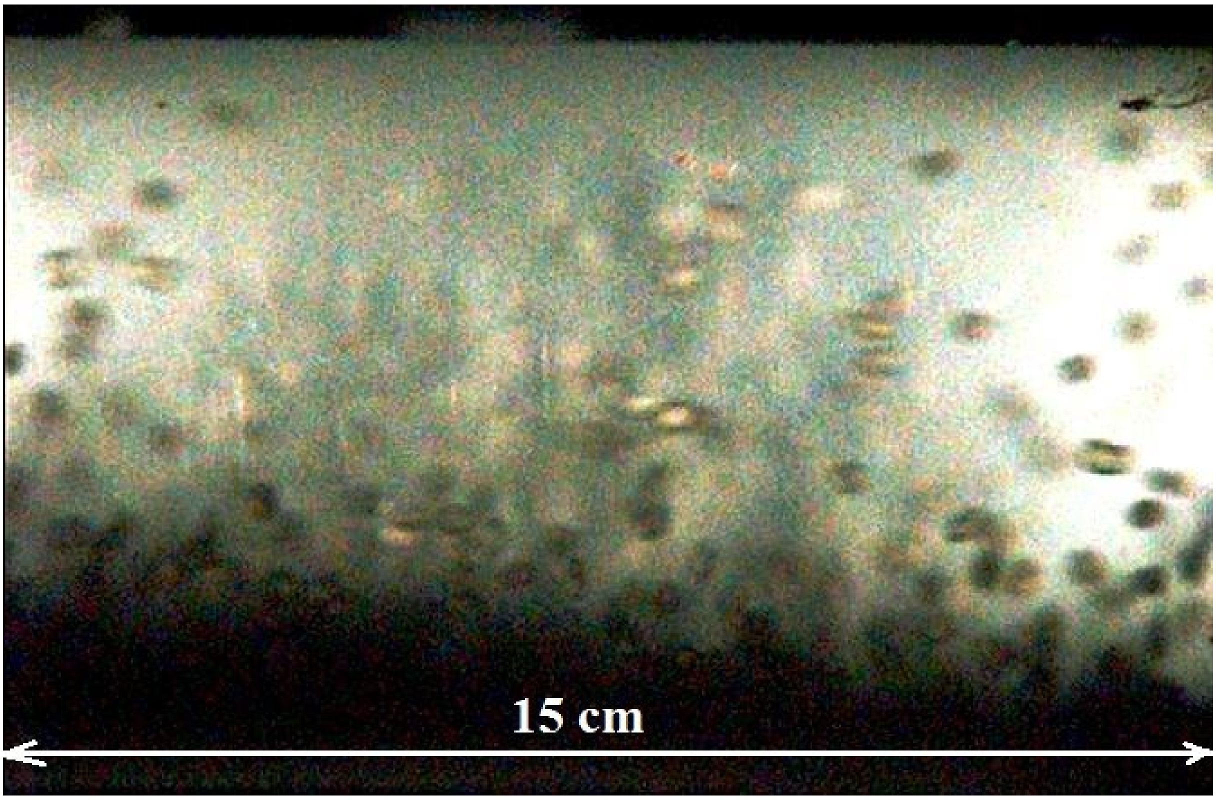

Figure 4-27Example of an image captured by high-speed camera

The operational conditions of digital imaging are presented in Table 4-2.

Table 4-2Operational conditions of digital imaging

Test number	**Video length, frames**	**Frame rate, fps**	**Time of the one frame , s**	**Length of the visual window, m**
Test 1	4204	1500	0.000667	0.15
Test 2	5957	1500	0.000667	0.15
Test 3	4438	1500	0.000667	0.15
Test 4	4188	1500	0.000667	0.15
Test 5	5033	1500	0.000667	0.15
Test 6	5057	1500	0.000667	0.15
Test 7	4421	1500	0.000667	0.15
Test 8	3562	1500	0.000667	0.15

Each high-speed video was analysed with the help of MatLab program, which has divided the video on frames. MatLab code is presented in Appendix 2. Then the particle motion was followed manually and the amount of the frames for each particle, which has travelled the distance of 15 cm, was estimated. Then the travelling time was calculated and solids velocity was found using equation below

$$v_s = \frac{l}{t} \qquad 4\text{-}4$$

Where l is a travelling distance of the particle and according to current experiment is 15 cm, t is a time which particle needs to cross the distance 15 cm.

The typical procedure is shown in Figure 4-28. Two particles were marked in blue and red colours to simplify the tracking. The number of frames during which the particle needs to travel the distance of 15 cm was found. The experimental results of solids velocity calculation are shown in Table 4-3.

Table 4-3The experimental results of solids velocity calculation

Test number	Average particle movement, frames	Calculated time of the particle movement, s	Solids velocity, m/s
Test 1	33	0.02	6.82
Test 2	32	0.02	7.03
Test 3	31	0.02	7.26
Test 4	30	0.02	7.5
Test 5	20	0.01	11.25
Test 6	19	0.01	11.84
Test 7	19	0.01	11.84
Test 8	18	0.01	12.5

As it could be seen from Table 4-3 that in the tests, which were conducted under higher air flow rate, the solids velocity are higher than under a lower one.

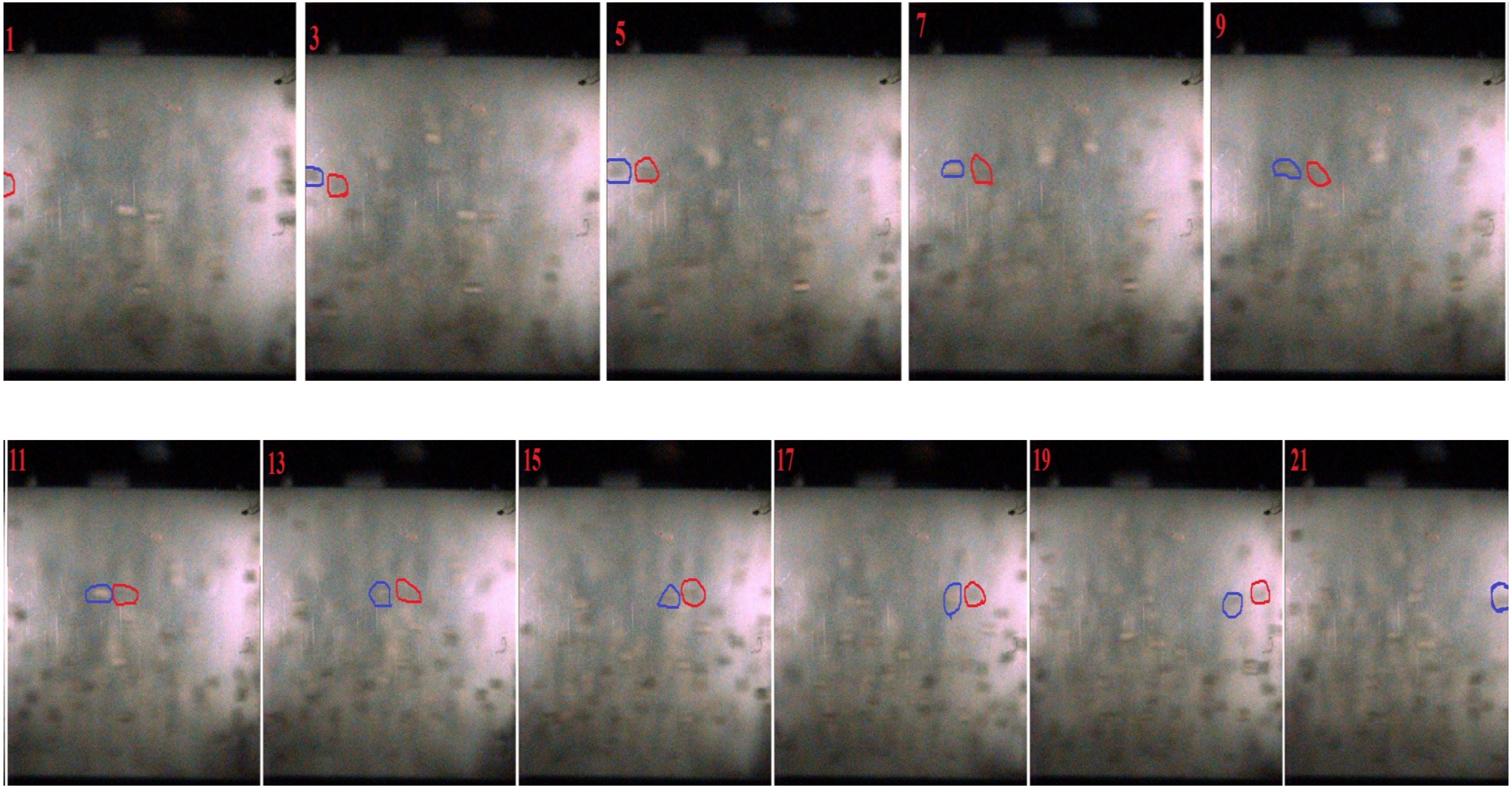

Figure 4-28Procedure of a high-speed video analysis

4.4 Comparison between calculated and measured solids velocity

Comparison between calculated average solids velocity based on pressure data and measured solids velocity based on high-speed video is presented in Table 4-4.

Table 4-4Comparison between measured and calculated solids velocity

Test number	Calculated solids velocity, m/s	Measured solids velocity, m/s
Test 1	13.87	6.82
Test 2	12.88	7.03
Test 3	13.14	7.26
Test 4	13.51	7.5
Test 5	20.15	11.25
Test 6	20.16	11.84
Test 7	20.35	11.84
Test 8	19.51	12.5

As it could be seen from the experimental results in the Table 4-4, the velocity found by the digital imaging method is consistently lower than that calculated based on pressure data. It is clear that the measured velocity is approximately two times lower than calculated velocity. The same phenomenon was observed in the investigation of particles on a free fall particle flow rig and pneumatically conveying test rig [19].

This was thought to be due to the fact that the solid concentration in the pipe cross-section of the horizontal dilute phase pneumatic conveying is non-uniform. As a result, the upper particle velocities are higher than the lower ones at given superficial gas velocity and solids feed rates.

Based on the results of measurement and calculated solids velocity for horizontal conveying of plastic pellets, the equation for solids velocity estimation, which was used in current report, could be presented in the following way

$$v_s = k \frac{\dot{m}_s}{A \cdot \rho_{sus}} \qquad 4\text{-}5$$

where k is material dependent constant that could be dependent on particle properties and flow conditions. The electronic noises in the pressure signals could also be a reason and could influence on the accuracy of the calculation.

According to the experimental results a value for material dependent constant could be suggested as shown below.

$$k = 0.5 \tag{4-6}$$

According to a new model presented by Equation 4-5 the results of calculated solids velocity are corrected with the material dependent constant and presented in Table 4-5.

Table 4-5Comparison between calculated solids velocity corrected with k and measured solids velocity

Test number	Calculated solids velocity, m/s	Measured solids velocity, m/s
Test 1	6.94	6.82
Test 2	6.44	7.03
Test 3	6.57	7.26
Test 4	6.76	7.5
Test 5	10.08	11.25
Test 6	10.08	11.84
Test 7	10.18	11.84
Test 8	9.76	12.5

The comparison between measured and calculated solids velocity corrected with the material dependent coefficient is presented in Figure 4-29.

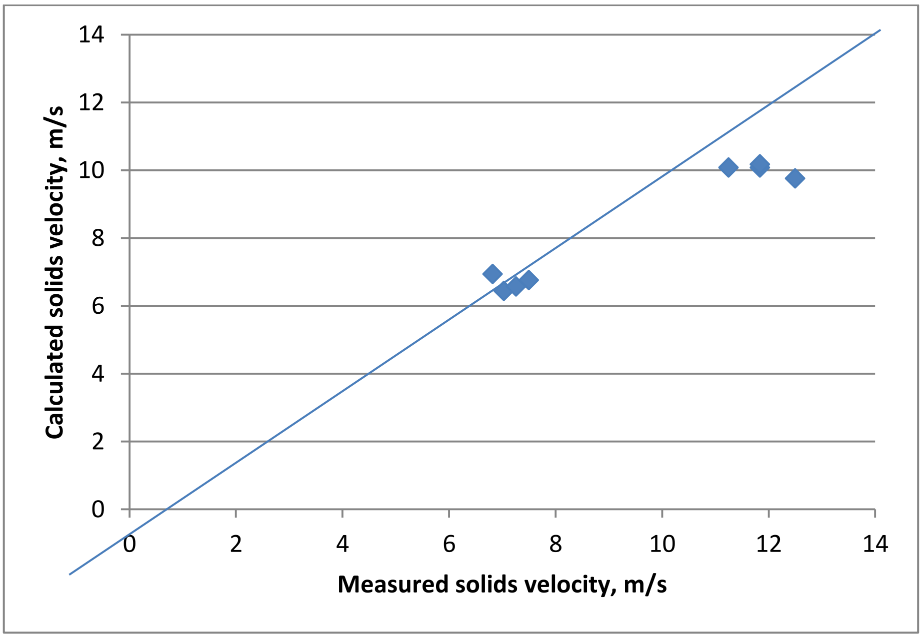

Figure 4-29Comparison between calculated and measured solids velocity

As it could be seen from Figure 4-29 the results are dispersed which could be caused by not accurate experimental data or not accurate calculations.

5 Conclusion and suggestions for further works

As discussed in details under Chapter 1, the main aim of the present investigation was to determine solids velocity in horizontal pneumatic conveying of plastic pellets. Few different methods for experimental estimation of solids velocity were proposed. First, cross-correlation of pressure signals, which were measured by pressure transmitters, was applied. Unfortunately, the results were not satisfactory. The main reason could be an instrumentation error and not good enough pressure signals, which in turn, are caused by not enough sensitive pressure transducers, too light plastic pellets or too low solids feed rate.

The next technique that can be used to determine solid velocity for the two phase flow in a short pipe element, based on suspension density estimation, was proposed. Solids velocity for different flow conditions was calculated and from the experimental results it is clear that solid velocity is a function of air velocity.

High-speed video of pneumatic conveying of plastic pellets in horizontal pipeline was recorded by high-speed camera and analysed partly with the help of MatLab program and partly manually. From the experimental results it could be seen that the measured solids velocity found from the high-speed video is consistently lower than the calculated based on the pressure data. This was thought to be due to the fact that the solid concentration in the pipe cross-section of the horizontal dilute phase pneumatic conveying is non-uniform. As a result, the upper particle velocities are higher than the lower ones at given superficial gas velocity and solids feed rates.

Based on the results of measurement and calculated solids velocity for horizontal conveying of plastic pellets, current model for solids velocity estimation was corrected by material dependent constant that could be dependent on particle properties and flow conditions.

As it could be seen from the stated above there are still many aspects and areas where further scientific studies and investigations would further improve the solids velocity estimation in pneumatic conveying. The followings are some suggestions for future studies.

- It requires more details about the material properties, especially particle diameter and particle shape
- The influence of particles diameter and solid-to-air ratio would be interesting to investigate
- Different types of conveying materials could to be tested
- More sensitive pressure transmitter could be used

References

[1] Oxford Dictionaries, «Oxford Dictionaries,» [Internett]. Available: http://oxforddictionaries.com/definition/english/pneumatic. [Funnet 2 February 2013].

[2] E. Papadopoulos, «Heron of Alexandria,» Department of Mechanical Engineering, National Technical University of Athens, 2007. [Internett]. Available: http://nereus.mech.ntua.gr/pdf_ps/heron.pdf. [Funnet 3 February 2013].

[3] G. E. Klinzing, F. Rizk, R. Marcus og L. S. Leung, «An overview of Pneumatic Conveying System,» i *Pneumatic Conveying of Solids*, 2010, pp. 1 -54.

[4] C. Ratnayake, «A Comprehensive Scaling Up Technique forPneumatic Transport Systems,» Telemark University College, Porsgrunn, 2005.

[5] G. E. Klinzing, «Historical Review of Pneumatic Conveying and Solids Processing World Wide,» University of Pittsburgh, [Internett]. Available: http://www.engineering.pitt.edu/GeorgeKlinzing/. [Funnet 3 February 2013].

[6] Jenike og Johanson, «Testing - Pneumatic Conveying,» Jenike & Johanson, 2010. [Internett]. Available: http://www.jenike.com/Services/Testing_PneumaticConveying.html. [Funnet 4 February 2013].

[7] D. Mils, M. G. Jones og V. K. Agarwal, Handbook of Pneumatic Conveying Engineering, New York: Marcel Dekker, Inc, 2004.

[8] D. Mills, Pneumatic Conveying Design Guide, Great Britain: Elsevier Butterworth-Heinemann, 2004.

[9] S. R. De Silva, «Transport of Particulate Materials, Dilute Phase Pneumatic Transport,» Telemark Technological Centre, Porsgrunn.

[10] P. S. &. Design, « Process Systems & Design,» Process Systems & Design, 2013. [Internett]. Available: http://www.processsystemsdesign.com/equipment-dilute-phase-pneumatic-conveying-material.html. [Funnet 8 February 2013].

[11] P. S. &. Design, «Process Systems & Design,» Process Systems & Design, 2013. [Internett]. Available: http://www.processsystemsdesign.com/equipment-dense-phase-conveying-material.html. [Funnet 8 February 2013].

[12] S. De Silva, «Characterization of particulate solids,» Telemark Technological Centre, Porsgrunn, 1995.

[13] S. De Silva, «Fluidization, de-aeration and their effect on systems selection and design,» Telemark Technological Centre, Porsgrunn, 1994.

[14] A. C. Hoffmann, «Manipulating fluidized beds by using internals fluidization with baffles,» Stratingh Institute for Chemistry and Chemical Engineering , Groningen, The Netherlands, 2000.

[15] J. R. Van Ommen og N. Ellis, «JMBC/OSPT course Particle Technology 2010,» 2010. [Internett]. Available: http://www2.msm.ctw.utwente.nl/sluding/TEACHING/ParticleTechnology/vanOmmen_Fluidization.pdf. [Funnet 9 February 2013].

[16] G. E. Klinzing, F. Rizk, R. Marcus og L. S. Leung, «Fluid and Particle Dynamics,» i *Pneumatic Conveying of Solids*, 2010, pp. 55 -70.

[17] G. E. Klinzing, F. Rizk, R. Marcus og L. S. Leung, «Fundamentals,» i *Pneumatic Conveying of Solids: A theoretical and practical approach*, Springler Science , Business Media B.V., 2010, pp. 81 - 151.

[18] W. Wei, G. Qingliang, W. Yuxin, Y. Hairui, Z. Jiansheng og L. Junfu, «Experimental study on the solid velocity in horizontal dilute phase pneumatic conveying of fine powders,» *Powder Technology,* vol. 212, nr. 3, p. 403–409, 2011.

[19] D. Songa, L. Penga, G. Lua, S. Yanga og Y. Yanb, «Velocity measurement of pneumatically conveyed particles through digital imaging,» *Sensors and Actuators A: Physical,* vol. 149, p. 180–188, 2009.

[20] H. Raheman and V. K. Jindal, "Solid Velocity Estimation in Vertical Pneumatic Conveying of Agricultural Grains," *Applied Engineering in Agriculture,* vol. 17(2), pp. 209 - 214, 2001.

[21] H. Raheman and V. K. Jindal, "Slip Velocity in Pneumatic Conveying of Agricultural Grains," *Powder handling & processing,* vol. 5, no. 1, pp. 15 - 20, 1993.

[22] G. E. Klinzing, F. Rizk, R. Marcus og L. S. Leung, «Instrumentation,» i *Pneumatic Conveying of Solids*, Springler, 2010, pp. 475 - 508.

[23] C. L. Group, «Cuthbertson Laird Group,» [Internett]. Available: http://www.cuthbertsonlaird.co.uk/Detail.asp?tbl_Model=ptx&ProdID=733. [Funnet 15 April 2013].

[24] G. E. Klinzing, F. Rizk, R. Marcus og L. S. Leung, Pneumatic Conveying of Solids: A theoretical and practical approach, Springler Science , Business Media B.V., 2010, pp. 1-2.

Appendices

Appendix 1: Project description

Appendix 2: MatLab code for cross-correlation

Appendix 3: MatLab code for high-speed video analysis

Appendix 1: Project description

Telemark University College
Faculty of Technology

FMH606 Master's Thesis

Title: Determination of Particle Velocities in Pneumatic Conveying

TUC supervisor: Chandana Ratnayake

External partner: Tel-Tek, Dept. POSTEC

Task description:

During this experimental and theoretical investigation, attempts will be made to determine particle velocity based on pressure signals of gas-solids flow (pneumatic conveying of particulate materials). It is widely believed that the fluctuations of pressure signals have a direct relationship to conveying mode. Signal analysis and cross correlation techniques will be used to determine particle velocity. The findings will be used in increasing accuracy of on-line, non-intrusive, mass flow measuring technique that in turn will be used in feedback control system for pneumatic conveying systems.

Task background:

Pneumatic conveying is commonly used for transportation of powders and particulates across industries. Flexibility in pipeline routing, ability to collect and distribute materials from multiple sources to multiple destinations, elimination of material loss and dust pollution, low risk of product contamination, and relative easiness of automation and control are among the main advantages of pneumatic conveying over the other methods of powder transport.
Particle velocity has been identified as a very important parameter in pneumatic conveying systems. Even though conveying air velocity can be determined based on air volume flow measurements, it is difficult to determine particle velocity, which has a big effect on product degradation, pipe wall erosion, etc. Many pressure drop determination models/techniques will also be benefitted with accurate measurement of particle velocity.
In pneumatic conveying the solid particle velocity always lags behind the air velocity. The difference between these two velocities, called the slip velocity, plays an important role in the design of pneumatic conveying systems. Velocity of solid is generally determined by knowing the air velocity and slip velocity, which has been discussed in many research studies. But, as per today, there is no solid explanation or scientific method of determining slip velocity or

Adress: Kjølnes ring 56, NO-3918 Porsgrunn, Norway. **Phone:** 35 57 50 00. **Fax:** 35 55 75 47.

particle velocity. Although some success stories has been published by POSTEC and Applied Chemometrics Research Group (ACRG) at TUC based on acoustic measurements techniques with big pellets, their applicability for fine powder systems is questionable.
As explained under “Task description”, direct or indirect accurate measuring technique for particle velocity will benefit for pneumatic conveying system design, optimisation, troubleshooting and also on-line mass flow measurement technique, which was developed and patented to POSTEC.

Student category:

The study is best suited for PT or EET student (partly matches for SCE students also)

Practical arrangements:

POSTEC Powder hall has a semi industrial scale pneumatic conveying rig with necessary measuring sensors and also other bench scale testing devices. The experiments and data collection will be carried out at POSTEC, but TUC will provide the necessary office space.

Signatures:

Student (date and signature): Maryna Zinchenko 25.01.13

Supervisor (date and signature): [illegible] 25.01.13

Appendix 2: MatLab code for cross-correlation

```
% Read the data range from excel
t1 = xlsread(filename,t1_xlRange);
PT3 = xlsread(filename,PT3_xlRange);
PT4 = xlsread(filename,PT4_xlRange);

% Plot the graphs
subplot(2,1,1)
plot(t1,PT3,'r');
xlabel('Time[s]')
ylabel('Pressure[bar]')
grid on

hold on

subplot(2,1,1)
plot(t1,PT4,'b');
legend('PT3','PT4')
title('Test7')
xlabel('Time[s]')
ylabel('Pressure[bar]')
grid on

%// Normalize signals to zero mean and unit variance
s1 = (PT3 - mean(PT3)) / std(PT3);
s2 = (PT4 - mean(PT4)) / std(PT4);

%// Compute time lag between signals
[c, lags] = xcorr(s1, s2, 'coeff');     %// Cross correlation

lag = mod(find(c == max(c)), length(s2)) %// Find the position of the peak

% Find at what time maximum will appear
d=c;
[o1,o2] = sort(d);
d(o2(1:end-1))=0;
sz=1;
for N=1:101
    if d(N)>0
        index(sz)=N;
        sz=sz+1;
    end
end
d

% Plot cross-correlation
subplot(2,1,2)
plot(lags,d,'m');
% plot(lags,c,'m');
legend('Kp3p4')
title('Cross correlation of pressure signals')
xlabel('samples')
ylabel('magnitude')
grid on
```

Appendix 3: MatLab code for high-speed video analysis

```
mov=mmreader('70_300.avi'); %read a movie
frames=read(mov,[1 4000]); %read each frames, from the 1st to 4000th frames

for ii=1:4000
    sequence=num2str(ii);
    tempstr=strcat(sequence,'.jpg'); %formate into string
    imwrite(frames(:,:,:,ii),tempstr);
end

for ii=2:4000
    sequence=num2str(ii);
    tempstr=strcat(sequence,'.jpg'); %formate into string
    im2=imread(tempstr);
    im2=im2-im;
    imwrite(im2,tempstr);
end
```