AN INVESTIGATION INTO RELIABLE TRANSPORT LIMITS AND SLIP VELOCITY FOR FLUIDIZED DENSE PHASE CONVEYING OF CEMENT

A

THESIS

Submitted in partial fulfillment of the requirements for the award of degree of

Master of Engineering

In
Thermal Engineering

Submitted by

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UNDER THE GUIDANCE OF

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July 2015

CERTIFICATION

I, **Gaurav Prakash Srivastava** , declare that this thesis report entitled "***An Investigation into Reliable Transport Limits and Slip Velocity for Fluidized Dense Phase Conveying of Cement***", submitted towards fulfillment of the requirements for the award of Master's Degree in Thermal Engineering, in Mechanical Engineering Department of Thapar University, Patiala, is entirely my own work. This document has not been submitted for any degree in any other institution.

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ACKNOWLEDGEMENT

Foremost, I would like to express my sincere gratitude to my supervisor Dr. S. S. Mallick for the continuous support of my Master of Engineering study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my study.

My sincere thanks also go to Mr. Atul Sharma for his support and inspiring suggestions have been precious for the development of this thesis content.

I am highly thankful to Thapar University, Patiala, for providing me such a great opportunity, support, exposure and atmosphere.

I am very much thankful to all the authors whose precious research works have been consulted and referred in this thesis work.

Last but not least, I am always grateful to my parents, family and friends for their unconditional love and support.

ABSTRACT

This report presents the results of an investigation into the minimum transport boundary of pneumatic conveying of cement and calculation of the slip velocity for pneumatic conveying of fly ash and cement. The properties of conveying materials used in experiments of this report are: cement (median particle diameter: 19 µm; particle density: 2910 kg/m^3; bulk density: 1080 kg/m^3) and fly ash (median particle diameter: 45 µm; particle density: 1950 kg/m^3; bulk density: 950 kg/m^3). These materials were conveyed through four different pipelines (viz. 43 mm I. D. × 24 m length, 54 mm I. D. × 24 m length, 54 mm I. D. × 70 m length and 69 mm I. D. × 24 m length) over the wide range of flow conditions (from fluidized dense phase to dilute phase flow). Pneumatic conveying characteristics based on total pipeline pressure drop were developed for all the pipelines.

To define the safe, reliable transport limits for cement Froude number based criteria were used at pipe inlet (Fr_i = 5 to 10). These limits are compared with one of the most popular model Mallick and Wypych (2010). For slip velocity, an investigation has been done for both fly ash and cement. A high resolution digital signal reflex camera is installed on a tripod to observe a detailed flow of material at a certain position of the sight glass section. The camera is capable to take video at 50 to 60 frames per second. These produced frames are further analyzed to estimate the slip velocity.

TABLE OF CONTENTS

Page No.

LIST OF FIGURES

Page No.

LIST OF TABLES

LIST OF SYMBOLS

A	Cross sectional area, m^2
D	Internal diameter of pipe, m
d	Median particle diameter, μm
Fr	Froude number
Fr_i	Froude number at pipe inlet
Fr_{min}	Minimum Froude number at the inlet to the pipe
Fr_s	Particle Froude number
g	Acceleration due to gravity, ms^{-2}
L	Total pipeline length, m
m_f	Mass flow rate of air, kgs^{-1}
m_s	Mass flow rate of solids, kgs^{-1}
$m^* = m_s/m_f$	Solids loading ratio
K	Constant of power function
L	Length of pipe or test section, m
P	Pressure, Pa
V_f	Superficial air/gas velocity, ms^{-1}
V_i	Velocity of air at pipe inlet, ms^{-1}
ρ_s	Particle density, kgm^{-3}
ρ_{bl}	poured bulk density, kgm^{-3}

Subscripts

Bl	Bulk
F	Fluid
i	Inlet condition
min	Minimum

Abbreviations

Bl	Bulk
ID	Internal diameter
PCC	Pneumatic conveying characteristics
PMC	Pressure minimum curve
MTB	Minimum transport boundary
PC	Pneumatic conveying
AFPC	Axial flow pneumatic conveying
SFPC	Swirl flow pneumatic conveying
ECT	Electrical capacitance tomography

CHAPTER 1: INTRODUCTION AND OBJECTIVES

1.1 Introduction

Pneumatic conveying is a method of conveying fine powders (e.g. cement, fly ash, wheat flour, etc.) and granular materials (crushed coal, grain, sugar) through a confined flow channel (pipeline) using a negative or positive pressure carrier gas (air, nitrogen, etc.) as a transport medium (Ratnayake, 2005; Marcus et al., 1986). This method is gaining popularity in many industries (such as cement, power plants, chemical, pharmaceutical, etc.) because of its benefits of safety, economical, layout flexibility, ease of automation, security, low maintenance, ease of installation, hygienic and environmentally safe method of transport (Pan, 1992). The conventional mode of pneumatic conveying is dilute-phase pneumatic conveying, in which the gas flow velocity is maintained sufficiently high to keep the particles suspended in the carrier gas during the flow. This high gas velocity can cause damage to fragile products or wear of the confined flow channel. Also, with high gas velocity there is a need of large sized compressors and bag filters resulting in high maintenance requirements (Setia et al., 2015). To overcome these drawbacks of conventional dilute-phase conveying, dense-phase pneumatic conveying is becoming popular (Mallick and Wypych, 2009). In dense-phase pneumatic conveying method the gas velocity is kept lower than the saltation velocity of particles travel in non-suspension mode (Setia et al., 2015).

An accurate estimation of minimum transport boundary is an important criterion to design dense-phase pneumatic conveying systems. Under-estimation of minimum transport boundary would result in unstable conveying, product build-up in the pipeline, and eventually pipeline blockage. Over-estimation would cause unnecessarily high velocities, which would lead to abolishing many of the advantages of low velocity dense phase conveying (Setia et al., 2015; Mallick and Wypych, 2009; Setia and Mallick, 2015; Mills, 2004). Although various models have been given by various researchers (such as Mallick and Wypych, 2009; Setia et al., 2015; Mills, 2004; Weber, 1981) to predict the blockage boundary, most of these models are empirical, product specific and have not been validated for other products and pipeline configurations. Generally in pneumatic conveying the velocity of particle is significantly lower than the velocity of transportation gas. This velocity difference between the particle and gas is called slip velocity and is an important variable for understanding the flow conditions in the pipe and the overall pressure drop of the system (Fuchs et al., 2008). The Weber A-4 model has used particle velocity and slip velocity to model the solids friction factor (Wypych et al., 1990). The particle velocity in the dense-phase conveying of powders is the function of superficial gas velocity, particle size and density (Fuchs et al.,2008). So the dynamics of two phase flow make the estimation of slip velocity is difficult.

1.2 Objectives

Specific objectives include:

1) To carry out an extensive test program on the fine powder (such as cement) through different pipelines (different diameter and lengths).
2) To develop minimum transport criteria for cement.
3) To determine slip velocity of the dunes through sight glass by using high speed camera.

CHAPTER 2: LITERATURE REVIEW

This chapter presents the research carried out by different researchers on minimum safe transport limits and slip velocity. The initial part of this chapter is focused on the general concepts of pneumatic conveying systems and different flow modes. In the later sections different researchers' work is presented related to minimum transport boundary and slip velocity estimation.

2.1 Pneumatic conveying

Pneumatic conveying system is an important method for conveying of bulk powders. Mechanical conveyors are used where pneumatic conveyors are not suited for one reason or another. Dry powders and granular products are produced in bulk to facilitate easy handling, transportation, transfer, storage, and blending or mixing as ingredients in the final product. Examples of types of products conveyed pneumatically are food ingredients, plastics, metal powders, propellants, small parts, etc. However, in most of the cases air is used as the medium of transportation, but in special cases where there are the risks of explosion, fire hazards, etc. other gases can be used (Pan, 1992). Under the action of pressurized air or gas stream, the material to be transported is forced through the pipelines and stored in the desired destination after separating the carrier gas from it. A wide range of materials can be conveyed by using this technique. The ideal materials for pneumatic conveying are free-flowing, non-abrasive and non-fibrous materials. It has a wide range of applications in the chemical process, pharmaceutical, mining and mineral industries.

Pneumatic conveying system is getting popularity these days, especially in the transportation of bulk solids mainly because of the following advantages:

a) This method is used to transport the materials to the remote locations that are difficult to be reached economically with mechanical conveyors. This is because of its flexibility of installation (Yi, 2001) i.e. horizontal, vertical pipelines and bends can be installed easily.

b) Pneumatic conveying of dry materials can be accomplished with dedicated equipment or multi-purpose equipment. A portable or central vacuum system can effectively be used for conveying dry materials and materials that have escaped a mechanical conveyor system at transfer points or vessel fill points.

c) The physical size of the pneumatic conveying pipeline is usually smaller than that of belt conveyor and bucket elevators (Wypych, 1989).

d) Pneumatic systems are completely enclosed so the product contamination, material loss and dust emission (thus, environment pollution) are reduced or eliminated (Yi, 2001). Particularly, they are good to convey hazardous materials.

e) Pneumatic conveying systems can take the material feed from multiple sources. Also, it may have multiple discharge points.

f) This system has low maintenance cost due to lesser number of moving parts.

g) Latest advancements in pneumatic conveying allow the friable products to be transported at low velocities, which lead to less product degradation.

h) These systems are easy to control and automation.

Although, the use of pneumatic conveying is increasing significantly in many industrial sectors, but still there are some major problems with it, which are listed below.

a) In case of dilute phase conveying, high power consumption, material degradation and system erosion are the major problems (Marcus, 1986).

b) In case of dense phase conveying, pipe vibrations and system blockages are experienced often.

c) Because of complex flow phenomena which take place, there is a requirement for high levels of skill to design, operate and maintain systems.

d) Lack of standard procedures for the selection of an optimal system for a particular application is also one of the major problems.

2.2 Components of pneumatic conveying system

Basic components of pneumatic conveying are broadly divided by Klinzing et al. (2009) into following four systems.

Air/Gas supply system:

In the pneumatic conveying systems, the major requirement of the gas is the transport of conveying materials. Apart from this, gas is also used for some other purpose, such as instrumentation gas, fluidizing gas and top gas in blow tank (blow tank aeration). Various types of prime movers, such as compressors, blowers, and vacuum pumps are used to supply gas depending upon the application and type of conveying. Before selecting a particular system, the gas flow and pressure requirements must be estimated to ensure reliable transportation. In most of the applications air is used as the conveying medium and it is taken from atmosphere so it needs to be filtered and dried before use (Mills, 2004). To ensure this, gas supply system must be incorporated with filter and drying unit.

Feeding device:

This is one of the crucial elements of pneumatic conveying system. This acts as a feeder (Wypych, 2006). The performance of the whole pneumatic system depends upon the type of feeder employed. So, the selection of a feeder for a particular application must meet both systems as well as material requirements.

Conveying line:

This consists of straight pipelines (horizontal and vertical), bends and other components, such as valves, flanges, etc., which provide the path for the gas and material to flow. Straight pipelines can be installed horizontally as well as vertically, depending upon the requirements. Bends provide a pneumatic conveying pipeline with considerable flexibility in routing. Although, almost all the materials can be conveyed through the steel pipelines, but rubber hoses are also widely used in pneumatic conveying systems, both for bends and pipelines, where there is requirement of flexibility. Rubber hoses can be used, particularly for reducing the erosive wear with abrasive materials and in minimizing the degradation of friable materials. For very abrasive materials spun alloy cast iron pipeline is preferred.

Separation equipment:

Gases convey the material need to be separated from the material in this zone. For this purpose, bag filters, cyclone separators and electrostatic precipitators are used (Wypych

2006). The selection of a particular type of separation equipment depends upon a number of factors, the primary factor being the size of solid particles, flow rate required and collection efficiency.

2.3 Minimum transport boundary

An accurate estimation of minimum transport boundary is an important criterion to design dense-phase pneumatic conveying systems. A deviation in accurate minimum transport boundary can cause either pipeline blockage or high velocities in the system (Mallick and Wypych, 2009; Mills, 2004).

Previous research work related to minimum transport boundary

Mallick and Wypych (2009) have analyzed minimum transport boundaries for pneumatic conveying of powders. In this paper effort is made to establish a generalized criterion for scaling-up the unstable boundary for the dense-phase pneumatic conveying of powders. Using the experimental data from twelve different powders conveyed over a wide range of pipe lengths and diameters, an improved design procedure has been developed in this study using a Froude number based criterion on the entry to the pipe. The physical significance of Froude number in representing the minimum transport boundary is also discussed. This model is obtained from experimental data, based on ESP dust and fly ash conveyed over range of pipe lengths and diameters, did not consider the effect of material properties.

Martinussen(1996) has developed a model to predict the minimum transport criteria by conveying products through a 53 mm diameter and 15m length horizontal pipeline

$$\mathrm{V_i}^2 = \mathrm{KDg}\frac{\rho_{\mathrm{bl}}}{\rho}\left[1 - \mathrm{m}^* \frac{\rho}{\rho_{\mathrm{bl}}}\right]^3 \qquad (2.1)$$

Where, K (geometrical factor) = Π/4 at the filling level of D/2. Martinussen (1996) also mentioned that this model could provide better predictions for fine materials than for coarse ones.

Setia et al. (2013) proposed a minimum Froude number based model to predict blockage boundary which incorporates the effect of solid loading ratio and particle properties (such as particle size and density) in addition to pipe diameter. This proves the reliable applicability of this model for different powders the model is developed from the data set obtained for 21 different products and 37 different pipelines configuration. The co relation is given in equation.

$$Fr_{min} = 23.5(m^*)^{-0.396}(F_s)^{0.131} \qquad (2.2)$$

The model is useful in predicting minimum conveying velocities to avoid pipeline-blockage and to ensure favorable operating point for industrial pneumatic conveying systems.

Mills (2004) proposed a constant velocity based criteria to represent the minimum transport boundary. He conveyed cement through 52.5 mm I.D. x 95m long pipeline and suggest an inlet velocity equal to 3 m/s, as minimum transport velocity. As this model is based on single pipeline data, so this does not account for diameter and length scale up effects.

Weber (1981) gave the following criteria to predict Froude number at feed point (minimum conveying velocity at pipe inlet) to avoid blockage. He did not provide details of products and pipe regarding applicability of the model.

$for \quad U_t \leq 3\, m/s$

$$F_{ri} = \left[7 + \left(\frac{8}{3}\right) U_t\right] (m^*)^{0.25} (d_s/D)^{0.1} \qquad (2.3)$$

$for \quad U_t \geq 3\, m/s$

$$F_{ri} = 15 (m^*)^{0.25} (d_s/D)^{0.1} \qquad (2.4)$$

2.4 Flow modes

These flows may be classified as following modes:

(a) Dilute phase

(b) Dense phase

(a)Dilute phase conveying**:** It is the most commonly used method of transporting bulk materials. This process uses a relatively high amount of air to convey a relatively low amount of material and at smaller pressures than the dense phase pneumatic conveying systems. The material is suspended in air and transported at higher velocities through the system.

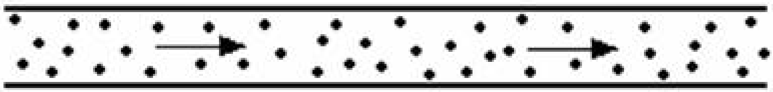

Fig 2.1: Dilute phase (suspension flow) (Yi, 2001).

This type of flow also referred as suspension flow because the particles are suspended in the air during conveying through the pipeline. A lot of materials can be conveyed by the dilute phase pneumatic conveying systems. Some examples are resins, fly ash, palletized products, food products, etc. The capital cost of dilute phase pneumatic conveying system is low in comparison to the other type of pneumatic conveying systems. The dilute phase system differs greater flexibility, and good reliability, but the high conveying velocity of this system causes some operational difficulties e.g. wear of pipelines, damage of the product, attrition of particle conveyed etc. Dilute phase system is generally classified into three types:-

i. Positive pressure system

ii. Negative pressure or vacuum system

iii. Combination of positive – negative system

i. Positive pressure system

The conveying line pressure in positive pressure pneumatic conveying system is above the atmospheric pressure. In this type of pneumatic conveying of materials from one or more than to single or multiple destination, over comparatively medium distances than other type of dilute phase pneumatic conveying system. This system has more capacity than vacuum systems (Ratnayake, 2005).

ii. Negative pressure system

The conveying line pressure in negative pressure pneumatic conveying system is under the atmospheric pressure. In this type of pneumatic conveying system materials from more than one point are convey to the storage vessels to one or more than one destinations (Ratnayake, 2005).

Vacuum systems are excellent for multiple product inlets through the use of simple diverter valves; however, it becomes costly to have multiple destinations because each must have its own filter receiver with the partial vacuum capability.

iii. Combination negative- positive pressure

This type of pneumatic conveying system is also called pull-push system which have the benefits of both negative and positive pneumatic conveying systems. This type of systems are used for more than one material inlet points and more than one outlet points (Ratnayake, 2005). Example of such type of system is the unloading of a standard railcar. Air is pulled from the outside, through the car (carrying the solids with it) to a filter, after the filter, a blower can be used to forward the solids to the final storage receiver.

Dilute phase systems are advantageous than dense phase pneumatic conveying system because of its flexibility in design and reliability. Due to the requirement of relatively high air volume and velocities the power requirement are also high for this system. The wear caused by the material on the pipelines of system is higher due to higher air velocities. Therefore the dilute phase pneumatic conveying system is not good for the products which are abrasive in nature and susceptible to damage (Klinzing, 2010). The friable products are not suitable for this system because during transport product can be crushed or deformed.

The lift or suspension in the air is the basic mechanism for dilute phase conveying. If during the conveying the velocity is reduced subsequently, the larger particles of material conveyed starts falling to the bottom of pipe. This velocity is called “saltation velocity” (Wypych and Hauser, 1990).

(b) Dense phase conveying system

Dissimilar to dilute phase pneumatic conveying system in dense phase pneumatic conveying system the advantage of efficiently pushing a higher density of bulk solids through the conveying pipeline at a relatively low velocity. The best definition for a system to be dense phase is whether the material conveyed in pipeline are having velocity below the saltation velocity.

Types of dense flow

1. Fluidized dense phase

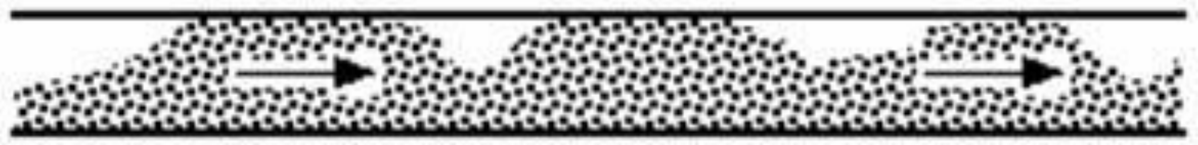

Fig 2.2: Fluidized dense phase (Wypych et al., 1995).

Example: fly ash, pulverized coal, crushed bauxite, lead dust

2. Low velocity slug flow

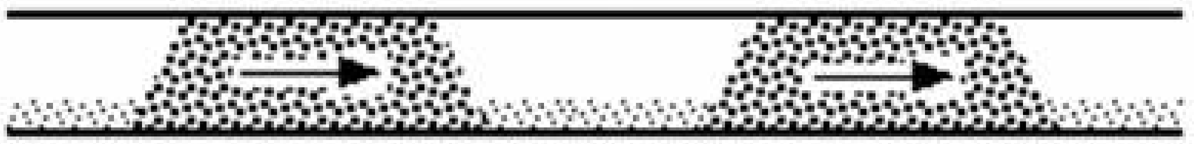

Fig 2.3: Low velocity slug flow (Wypych et al., 1990).

Example: friable and/or granular products (e.g. sugar, wheat, barley, peanuts, milled grain

3. Low–Velocity Plug Flow

Fig 2.4: Low velocity plug flow (Wypych et al., 1990).

This is suited for cohesive or sticky powders: full-cream milk powder, drinking chocolate and cocoa powder.

4. Single – Slug Conveying

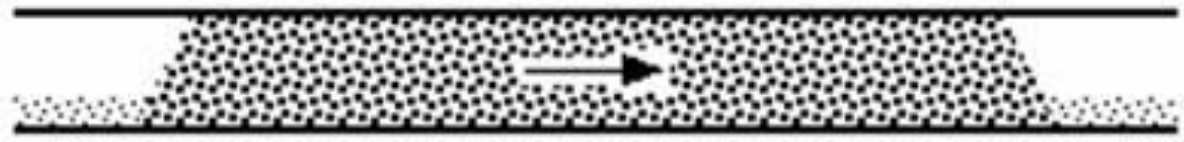

Fig 2.5: Single slug flow (Wypych et al., 1988).

Transportation of a limited batch of material per conveying cycle

Example: crushed coal, sand, grains, diamond ore, food products etc.

Applications: The low velocity in dense phase conveying is helpful in conveying of friable products such as meat lumps, softened grains and vegetables.

In the conveying of abrasive materials, the larger velocities associated with dilute phase pneumatic conveying system can lead to rapid pipeline wear. Many materials such as diamond, sand, alumina etc. are abrasive in nature. They can damage the conveying pipeline. The pipe wear can also result in a contamination of the product.

Plastics such as soft plastics (e.g. polypropylene and polyethylene) are not suitable for pneumatic conveying, because when the product conveyed these particles seamer onto the pipeline wall. It happens because of frictional heat when high speed product comes in contact to conveying pipeline and as a result a long thin layer of material formed. These plastic strips eventually collected inside the pipeline and result in pipeline blockage (Wypych, 2006). Dense phase is advantageous over dilute phase for conveying of such plastics.

Previous research work related to velocity calculation:

Pan (1999) developed a new flow mode diagram based on experimental results and theoretical analysis for the purpose of selecting the appropriate flow mode for a particular material. The particle/air interaction characteristics are a function of basic particle properties, such as particle size, density, size distribution, and the shape. From the developed flow mode model, they categorized the bulk solid materials into three groups PC1, PC2, PC3. Materials in group PC1 can be conveyed smoothly and easily from dilute to fluidized dense phase. Materials in group PC2 can be conveyed in dilute-phase unstable zone or slug-flow and materials in group PC3 are conveyed in dilute phase only. A good accuracy was achieved when many test results with the observed flow modes are superimposed on the developed flow mode diagram, but some exceptions can occur for bulk solids that displayed unusual particle and bulk properties, these bulk solid materials are transported in dilute-phase only.

Song et al (2009) proposed a new method for the measurement of particle velocity through digital imaging. The travelling wave equation method had been used to estimate the motion blur length and hence the particle velocity. The simulation studies presented in this paper have demonstrated that one can build a mathematical model of the blurred particle images to estimate the motion blur length. The experiments on the free-fall and pneumatic conveying test rigs have produced favourable results supporting that the digital imaging method is a viable approach to particle velocity measurement. Furthermore, the results have demonstrated that the travelling wave equation based method is insensitive to noise in the particle images.

Bilirgen (2010) found that the window overlapping technique was an efficient way of improving the accuracy of the instantaneous velocity calculations for relatively shorter data segments (shorter windows). This technique was found to be effective only for window sizes up to four times longer than the minimum window size. With the use of artificially generated signals, the optimum amount of window overlapping was found to be a function of window size and sample frequency. Due to the hardware limitations, it is not possible to sample data at frequencies high enough to capture the high frequency velocity fluctuations in a turbulent flow. Therefore, in this study, it was investigated that the velocity sampling frequency of a fibre optic probe could be enhanced by the window overlapping technique.

Li and Tomita (2000) analyzed concentration characteristics and particle velocity in a horizontal swirling flow dilute phase pneumatic conveying systems. Mean particle velocity of swirling flow pneumatic conveying systems (SFPC) was lower than the mean particle velocity in axial flow pneumatic conveying (AFPC) in high gas velocity range; however, the higher mean particle velocity in SFPC (swirl flow pneumatic conveying) can be obtained in a low gas velocity range. The uniform particle velocity profiles in SFPC were observed. The particle concentration profiles of SFPC have a symmetric distribution with respect to the pipe axis and the highest particle concentration appears near the wall under the acceleration region. In the developed region, the particle concentration profiles of the SFPC exhibit anti-symmetric distributions and the highest particle concentration appear at the bottom of the pipe. However, the particle concentrations of the SFPC at the bottom of the pipe are lower than that of AFPC. For particles having a higher floating velocity, the particle behaviour of the SFPC is almost the same as AFPC in developed region.

Shao et al. (2009) investigated into pneumatically conveyed particle velocity using intrusive electrostatic sensors. They used rod electrodes with a round cross section due to little effect on the induced sensor signal. The circular electrode detects a complex mix of signals produced by the particles around the inner pipe wall. The rod sensor is sensitive to localized flow information where the electrode is installed. The experimental results have also shown that both circular and rod sensors have excellent dynamic response, which is essential to track rapid changes in fuel particle velocity. It is concluded that the improved version of the electrostatic sensors could be helpful for a feedback loop for fuel flow control.

Fuchs et al. (2008) described the development of a gas-solid flow measurement setup based on an optical method to determine the particle velocity in the granular material flow. It is a gas-solids conveying rig for granular flow that is well-suited for demonstrative operation in teaching. A commercial turbine flow-meter is employed to obtain the gas velocity in the two-phase flow for a single phase air flow and a two phase gas-solid flow. The significant reduction of air velocity due to particles is shown. A camera-based measurement system is employed at three different positions along the piping system. The dependency of the sensor position along the piping system is demonstrated, showing the accelerating particle behaviour for a pipe section of more than ten pipe diameters of the presented conveying rig. The impact of bends on the velocity of individual particles is demonstrated. The use of the proposed setup in teaching allows students to gain insights into diverse research disciplines and presents a practical combination of materials handling, process instrumentation, and image-based measurement.

Ostrowski et al. (1999) conducted a real time visualization and analysis of dense phase powder conveying the flow regime within a pipeline, for a given particulate material, can often be controlled by variation of the air velocity. A pneumatic conveying system may simultaneously exhibit several flow regimes throughout its length. If unstable flow occurs, it can result in violent pressure surges which will increase both plant wear and product degradation problems. Electrical Capacitance Tomography (ECT) is gaining acceptance as an on-line tool to analyze multi-phase system. The visualization capability of ECT systems shows great potential for both increases our understanding the flow dynamics of particulate, and in the further development of empirical design methodologies for the conveying systems themselves. In addition, the use of statistical analysis of the pixel values within ECT images would appear to be a reliable method for the identification of both slow and fast slug flow regimes within dense phase conveying. This strategy can be incorporated as part of a control scheme for industrial conveyors to enable their efficient operation for various feedstocks, under conditions where attrition or power consumption can be minimized.

Williams (2008) determined the operating parameters and design considerations for dense phase conveying of fine powders. He used empirical steady- state modelling techniques. His thesis deals with three specific areas. Firstly, he predicts some material potential to dense phase conveying. Secondly, he obtained solid friction correlations and their subsequent effect on pressure drop prediction, and modelling the solid flow from a local prospective.

$$\Delta P_{fs} = \frac{A_2 D^{0.1} L}{A_3 - A_4 D^{0.1} L} \qquad (2.5)$$

$$\Delta P_{fs} = \frac{B_2 L}{D^{2.5}(B_3 L^3 + B_4)} \tag{2.6}$$

$$\Delta P_{fs} = \frac{-P_0 \sqrt{C_2 - C_3 L} - C_2^{0.5}}{\sqrt{C_2 - C_3 L}}. \tag{2.7}$$

The thesis also proposes a new continuum model which calculates the force balance between the conveying air flow, the resistance of the particles and geometric effect, e.g. bends.

Chapter 3: Test Facility and Experimental Procedures

The main objectives of this chapter are to provide the details of test facility, instrumentation, calibration and operational procedures. Standard calibration and operational procedures were used to perform experiments. Experiments were performed for a wide range of air flows and blow tank initial pressures through pipelines of different diameters and lengths.

3.1 Experimental setup

Conveying of cement was performed at the Laboratory for Particle and Bulk Solids Technologies of Thapar University, India. Schematic of test facility used for cement conveying is shown in Figs. 3.1 and 3.2. An electric powered rotary screw compressor (Make: Kirlosker, Model: KES 18-7.5) was used to supply compressed air having maximum delivery pressure 750 kPa and 0.056 m^3/sec of free air delivery. A pressure regulator and flow control valve were installed in compressed air line before the blow tank to set the maximum pressure and to vary the air flow rates over a wide range of air flows (0-0.6 kg/s). A vortex flow meter was installed for the measurement of air flow rates in compressed air flow line. Blow tank feeder of 0.2 m^3 water filled volume (Bottom discharge type) was used to feed material into the conveying pipeline. The air was supplied to blow tank with the help of orifice plate installed at its air inlet Blow tank was equipped with solenoid operated dome type material inlet, outlet and vent valves. On the top of the blow tank a receiver bin of 0.70 m^3 capacity was installed. It was fitted with bag filters having reverse pulse jet type cleaning mechanism. For the measurements of solid mass flow rates, blow tank and receiver bin were supported by shear beam load-cells. Four different mild steel pipelines of 43 mm I.D. × 24 m length, 54 mm I.D. × 24 m length, 69 mm I.D. × 24 m length and 54 mm I.D. × 70 m length were used to perform tests. All the pipeline configurations included a vertical lift of 3 m and 4 × 90° bends of 1 m radius of curvature. At different locations along the pipeline, various static pressure measurement point P4 was used to measure the total pipeline pressure drop. All other pressure transducers (P6 to P9) were installed to measure static pressure at their respective locations. The pressure transducers (Make/Model: Endress & Hauser/Ceraber PMC 131) had pressure range: 0-2 bar maximum pressure: 3.5 bar (abs.), current signal: 4-20 mA. A standard calibration procedure was followed to calibrate all the pressure transducers, load cells and flow meter (Mallick, 2010). A data acquisition system consists of a portable P.C. with compatible data logger was used to record the output signals from pressure transducer, flow meter and load cells, 16 different channels with 14 bit resolution were provided in data logger. 43 mm × 24 m pipeline was provided 150 mm long sight glass made of borosilicate material for flow visualization, whereas, remaining pipeline were provided two sets of 300 mm long sight glasses of the same material. Cement was conveyed in all the pipelines over the range of air and solid mass flow rate. Flow visualization through sight glasses confirms the fluidized dense phase conveying ability of cement.

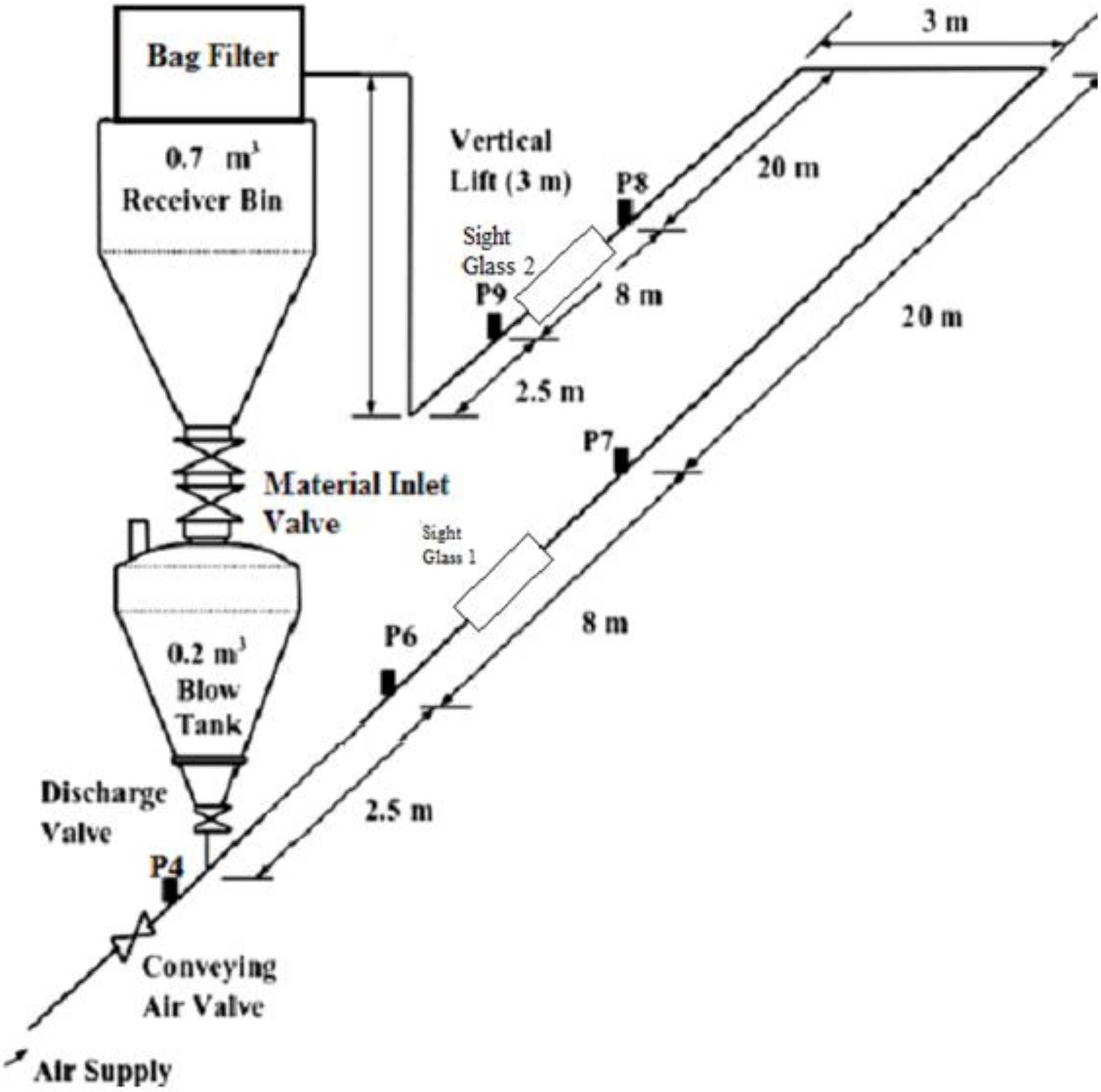

Fig. 3.1: Schematic of experimental set up (54 mm I.D. × 70 m long pipe).

Continuous dune flow was observed in conveying pipeline with gradual reduction of air flow, which in turn changed to discontinuous dune flow with further reductions in air flow rates. Even further reductions in air flow rates resulted in unstable conveying characterized by high pressure fluctuations and lead to complete pipeline blockage. In unstable conveying zone, amount of material pushed by blow tank into conveying pipeline, does not completely return to receiver bin, which leads to gradual deposition of material in the conveying line. As this gradual deposition of material would result in complete blockage of pipeline in few conveying cycles, hence, it is considered as the initiation of blockage in this study. Blow tank initial pressure was varied to vary the solid flow rates. To ensure the repeatability of data certain tests were performed multiple times.

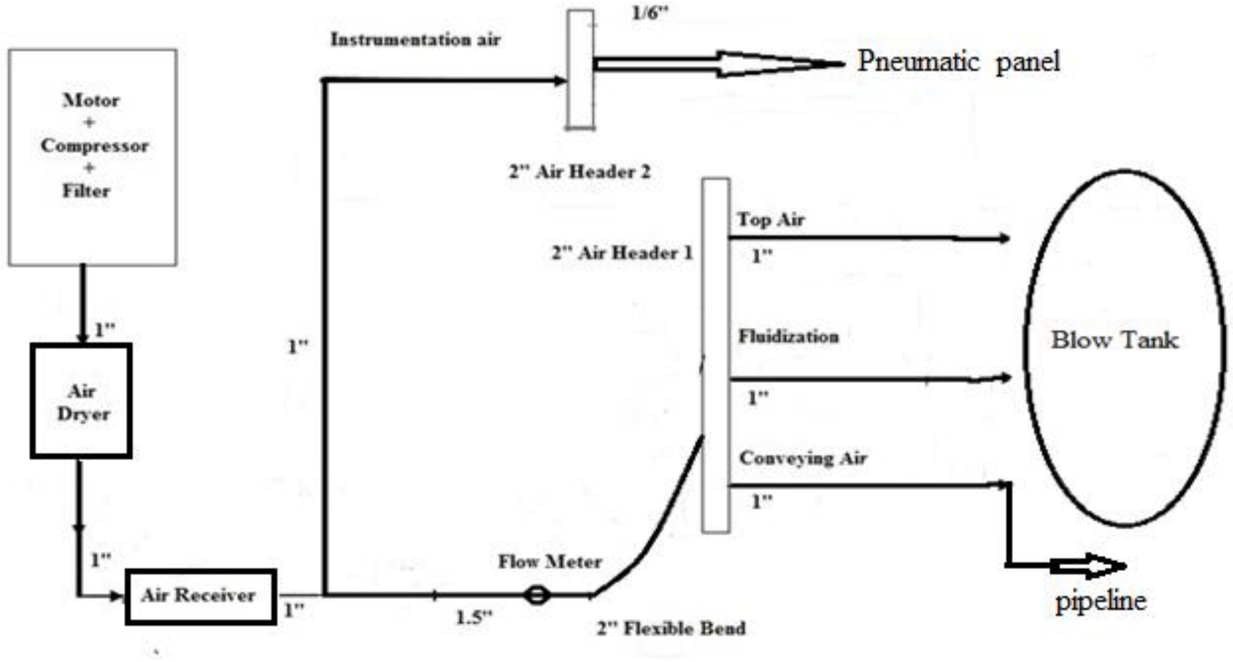

Fig. 3.2: Piping and instrumentation diagram for compressed air.

Fly ash test program:

Conveying of fly ash was also performed on the same experimental set-up of cement on the Laboratory for Particle and Bulk solids Technologies, Thapar Unversity, India. The pipeline 54mm I.D. x 70m length is used in the study of slip velocity calculation. This pipeline included a vertical lift of 3m and 4 × 90^{o} bends of 1 m radius of curvature. This pipeline was provided with two sets of 300 mm long sight glass of borosilicate material. A high resolution camera with tripod is used to capture the flow.

3.2 Properties of test product

The test powders for this report are fly ash and cement. These are the materials that, by virtue of their mean particle size and particle shape convey very well in dense phase at very low conveying velocities (Mills, 2004). There properties are specified in the following Table 3.1.

Table 3.1: Physical properties of material conveyed

Material	**ρ_s (kg/m^3)**	**ρ_b (kg/m^3)**	**d (µm)**
Fly ash	1950	950	45
Cement	3060	1070	14

Particle density was measured using water displacement method and particle size distribution was determined using laser diffraction analyzer.

3.3Calibration Procedure

Calibration of load cells, pressure transducers and flow meter were performed using the standard calibration procedure as described by Mallick (2010). All the pressure transducers were calibrated by maintaining constant static pressure in the conveying pipeline using blind flange and simultaneously recording the pressure signal from data logger. The standard calibration procedure for pressure transducers is given below:

a) All the pressure transducers were installed at desired locations along the pipeline and data logger was connected with these pressure transducers.

b) The pressure transducers were installed close to the pipeline upstream of the receiver bin using blind flange.

c) Pipelines were checked for air leakages, and rectify for any leakage found and open the vent valve to release the air from pipeline.

d) Pressure regulator was adjusted to desired value (e.g. 50 kPa) and open the conveying pipeline valve.

e) Pressure in the pipeline was measured using pressure gauge and the pressure of all the transducers recorded simultaneously from data logger.

f) the step (e) was repeated by adjusting the pressure regulator to different pressure readings.

Calibration graph for pressure transducer P4 and P6 are shown in Fig. 3.3 and 3.4.

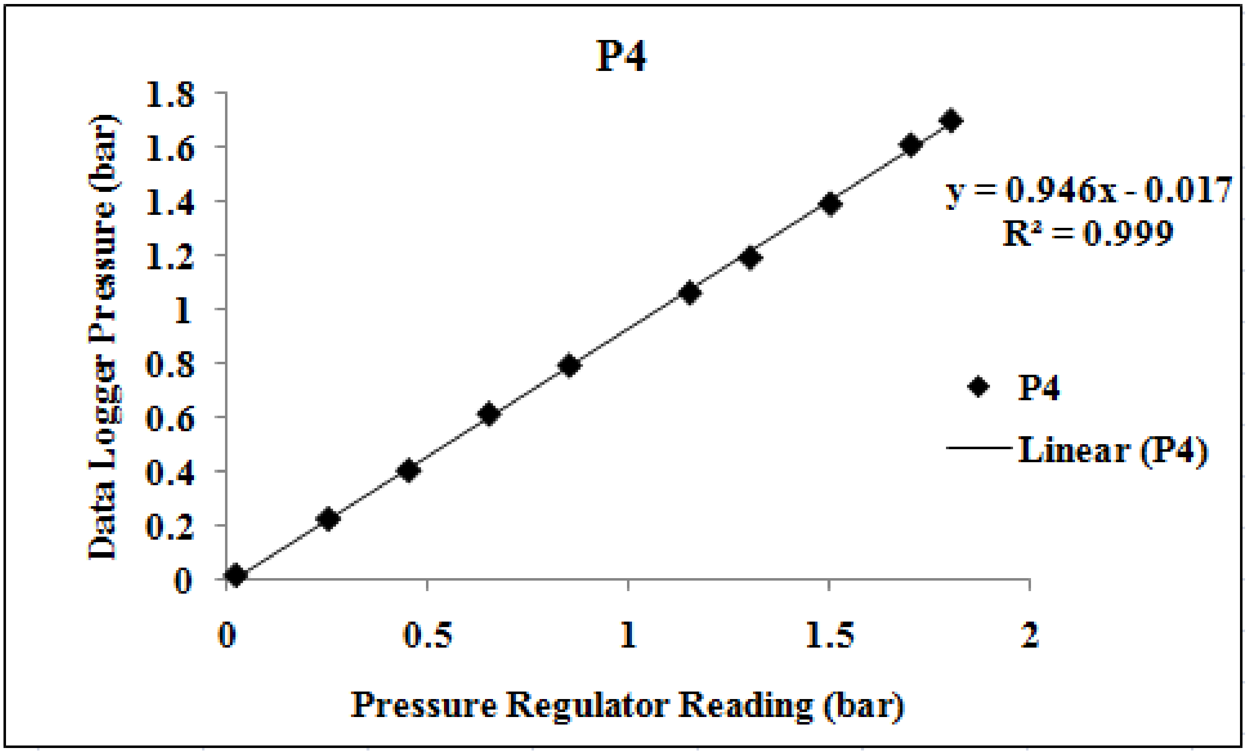

Fig. 3.3: Calibration curve for pressure transducer P4

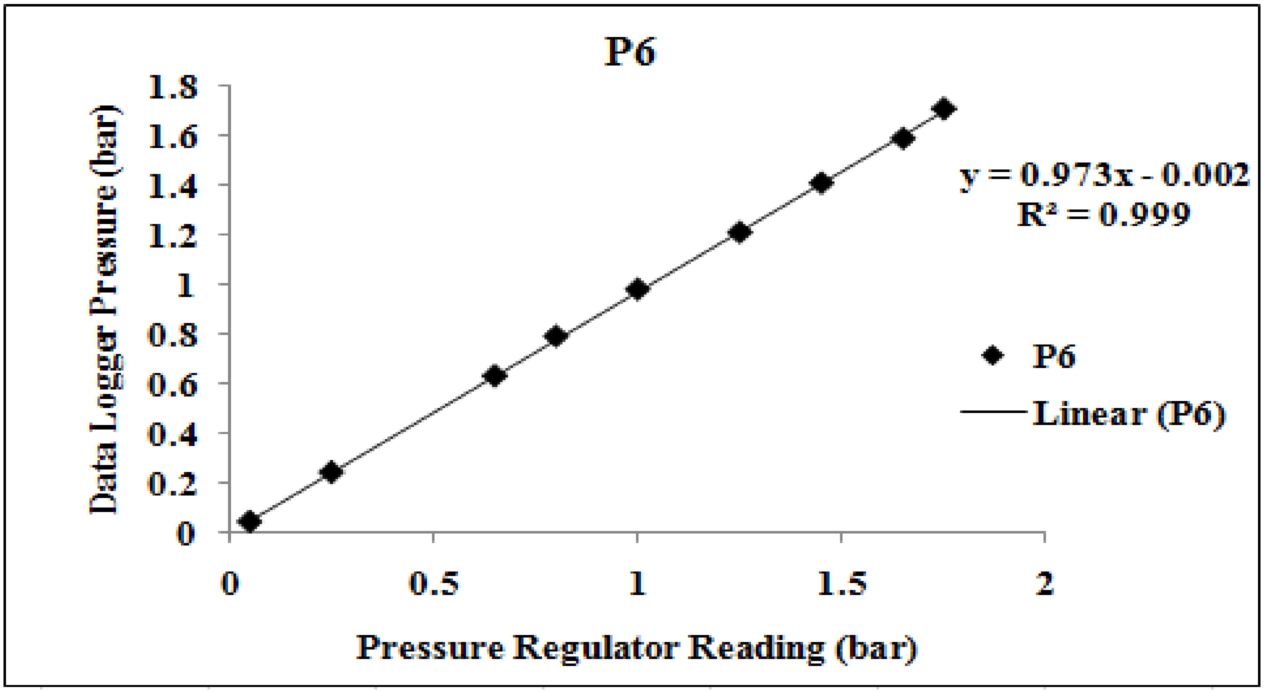

Fig. 3.4: Calibration curve for pressure transducer P6

A vortex type air flow meter was used to measure the flow rate of supply in a conveying cycle. This flow meter had a digital display which shows the reading of volumetric flow rate of air, at the same time it also generates an analog signal, which was fed to the data logger and after further processing of signal, data logger also displays the volumetric flow rate. To calibrate the flow meter a continuous supply of air was made in conveying pipeline and readings of flow meter were recorded simultaneously in its digital display and at data logger.

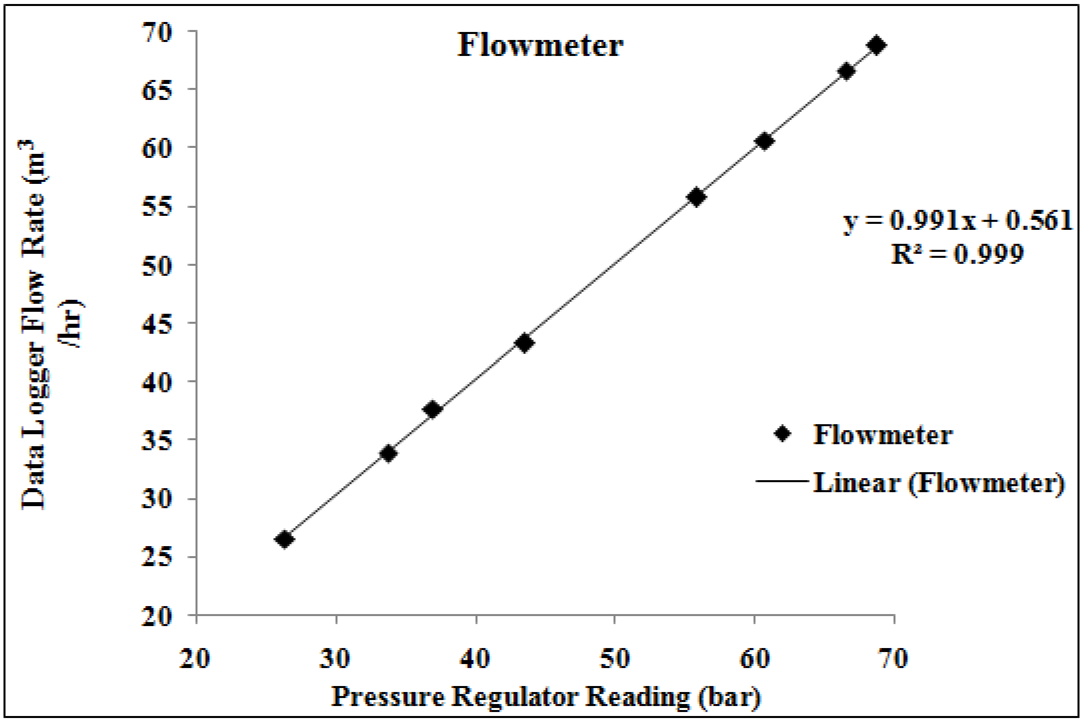

Fig. 3.5: Calibration curve for flow meter.

Pressure data in the inlet flow meter was recorded with the help of pressure transducer to calculate density of inlet air to flow meter, so that its mass flow rate can be obtained.

Load cells were used to calculate the mass of material accumulated in and discharged from receiver bin and hopper. Blow tank and receiver bin were placed on shear beam type load cells.

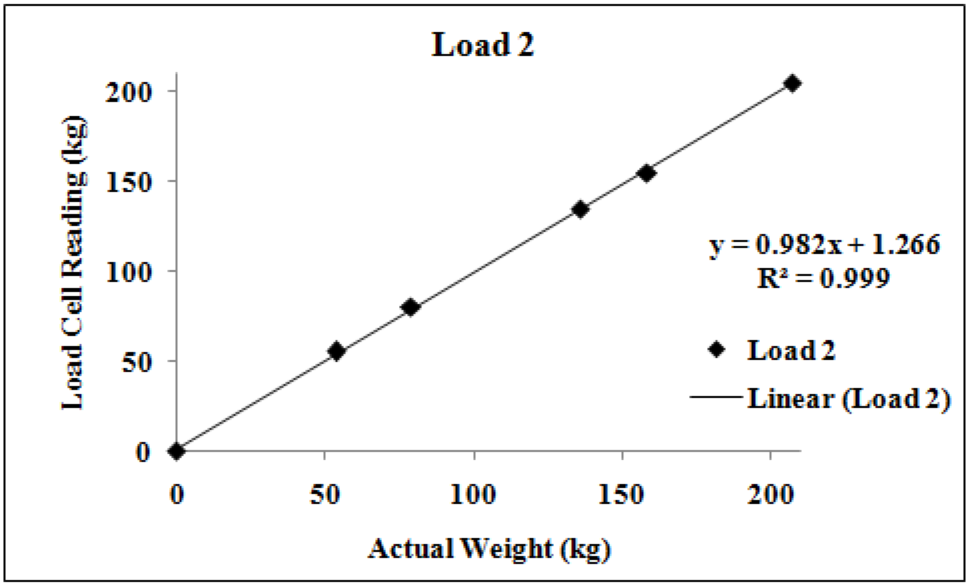

Fig. 3.6: Calibration curve for load cell

Each load cell used had the maximum load bearing capacity of 500 kg. Such four load cells were used to carry combined weight of blow tank and material, receiver bin and material. Output from these four load cells was combined to give a total load shared by each cell. The load cells generate a differential output voltage signal, which was fed into the data logger to calculate corresponding weight. Two such combinations were used to measure the material discharge rate. To calibrate load cells, a known weight was put on the structure and its value was recorded in the data logger.

3.4 Operational procedures:

A standard operational procedure was used to perform the experiments over a wide range of air and solid flow rates. Air flow rates were varied by changing the openings of globe valves installed in the pipeline, whereas solid mass flow rates were varied by changing the pre-pressurization of blow tank. There were two air lines in blow tank, one is top air line, which supplies the air for pre-pressurization of blow tank, other was fluidization air line, which was used to fluidize the material inside the blow tank and ensures that the materials would not stick to the walls of blow tank. Fluidization air line was also provided in receiver bin to prevent sticking of material.

The standard operational procedure to perform experiments is listed below;

a) The compressor and drier were turned on, and the air was allowed to reach the specified pressure in air storage tank.

b) The process air and instrumentation air supply opened. The pressure of process air was set to desired value using pressure regulator, whereas, the pressure of instrumentation air set to 5 bar (g).

c) Firstly pneumatic panel a PLC panel turned on. After that, computer started and the proper working of data logger was ensured.

d) After calibrating, all the pressure transducers, load cells and flow meter, experiments were started

e) Necessary settings were made of different globe valves and press the cycle start button from PLC panel. At the same time the run button in data logger was pressed.

f) When the cycle completed, the stop button was pressed in data logger and purge the pipeline to clean it for the next experiment.

g) The settings of globe valves were changed and the procedure to perform further experiments were repeated.

In each individual experiment data logger records the load cell, flow meter and pressure transducer readings with time. All these data points are plotted with time and steady state data is taken for further analysis, such as to obtain PCC, reliable transport limits and solid friction.

Tough borosilicate sight glasses were provided with all the pipelines at different locations, as shown in Fig. 1, for flow visualization. The products were conveyed in all the pipelines over the range of air and solid mass flow rates. Flow visualization done through sight glasses by a high resolution digital signal reflex camera which is installed on a tripod to observe a detailed flow of material at a certain position of the sight glass section.

Chapter4: Determination of Reliable Transport Boundary

4.1 Reliable transport boundary

Reliable design of pneumatic conveying systems requires an accurate estimation of reliable transport limits In this study an effort has been made to present the pneumatic conveying characteristics and reliable transport limits for cement conveyed through four different pipeline configurations.

Typical Pneumatic Conveying Characteristics (PCC) of Fluidized dense phase (FDP) is as follows:-

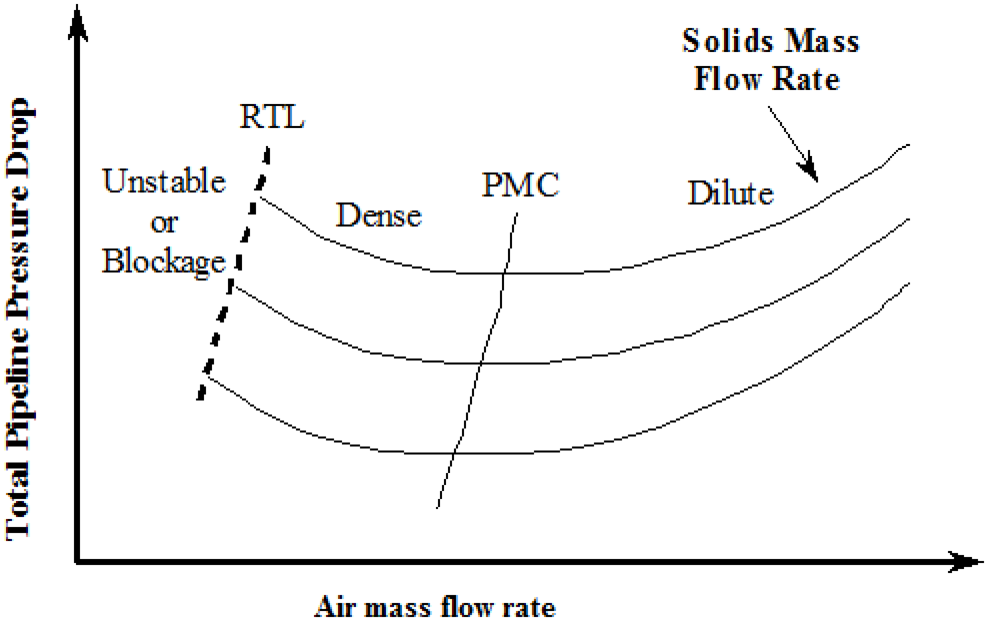

Fig 4.1: Typical PCC for fluidized dense-phase (PMC - Pressure minimum Curve, RTL - Reliable Transport Limit) (Wypych, Hastie, J. Yi, 2005)

For the correct design of fluidized dense-phase pneumatic conveying systems, it is important to precisely estimate blockage conditions which is also known as the minimum transport boundary.

Some fine powdered materials (such as cement, fly ash, etc.) that have appreciable air-retention property and they are able of being transported in the fluidized dense-phase conveying mode. Among all the different types of dense-phase pneumatic conveying, the fluidized dense-phase pneumatic conveying provides the largest solids to air mass ratio (up to 50) as compare to typical dilute-phase pneumatic conveying (having lesser solid loading ratio up to15). Due to such a higher solids concentration, larger solid discharge is achieved with smaller sized pipeline. The size requirement of the air-solids separation unit is also minimized. Other advantages include less operating and maintenance costs. Due to these advantages, the fluidized dense-phase pneumatic conveying of fine powders is assumed to be a significantly good alternative compare to traditional dilute-phase systems.

4.2 Pneumatic conveying characteristics and reliable transport limits

Pneumatic Conveying Characteristics (PCC) based on the total pipeline pressure drop are presented in Figs. 4.2 to 4.5 for all the four pipelines. PCC show the variation of total pipeline pressure drop versus air flow rates for different solids flow rates. PCC provides the useful information to design a pneumatic conveying system, as well as to upgrade an existing system. Experimental reliable transport limits and the predicted reliable transport boundary, obtained from Mallick and Wypych (2009) model, have been superimposed on the PCC. Mallick and Wypych (2009) proposed a Froude number based criteria ($Fr_i = 6$) at the pipe inlet as the reliable transport limit for fine powders that are suitable for fluidized dense-phase conveying. This model is obtained from the experimental data of ESP dust, fly ash, cement and several other materials (13 different materials) conveyed over range of pipe lengths (71 to 554 m) and diameters (52 to

105 mm). As this model is developed from several products data including cement, so it has been taken for validation in this study. All the PCC (Figures 5 to 8) have shown a pressure minimum curve and ‘U’-shaped nature of PCC. The ‘U’-shape is more prominent in Figures 4.2 and 4.5. A gradual rise in the total pipeline pressure drop PCC is observed with the variation in air flow rates (on both sides of PMC). The initiation of unstable conveying zone has been designated as the reliable transport limit in this paper. This is due to fact that at low air flow rates, sometimes blockage occurred at the low tonnage, whereas corresponds to same air rate; sometimes complete conveying of the material has taken place at higher tonnages. Similar observation is made by Mills (2004) also. Thus at low air flow rates, it is very difficult to ensure the repeatability of data near the blockage boundary. This happens due to the nature of product aeration in the blow tank that may vary from one conveying trial to another (even other conveying conditions remaining apparently similar).

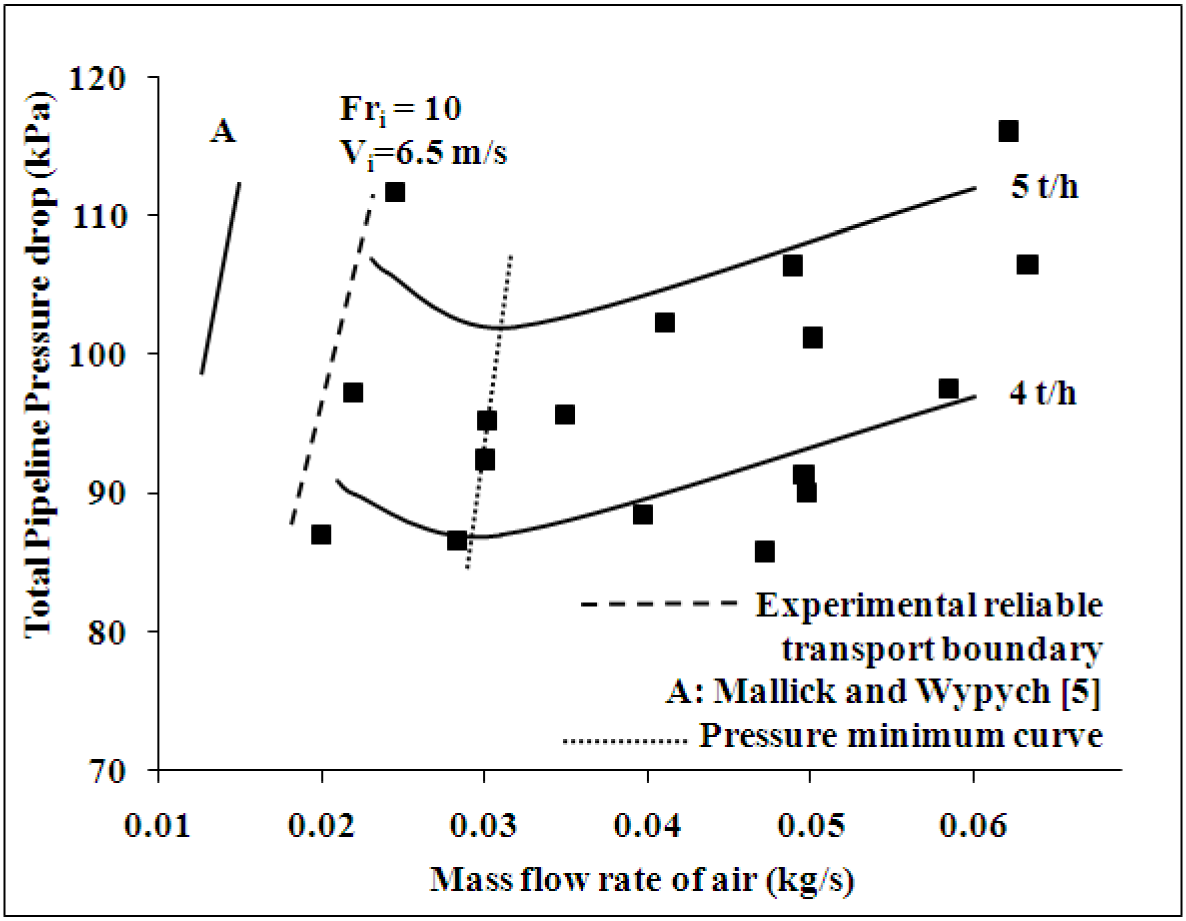

Fig 4.2: Pneumatic conveying characteristics, cement, 43 mm I.D. × 24 m long pipeline

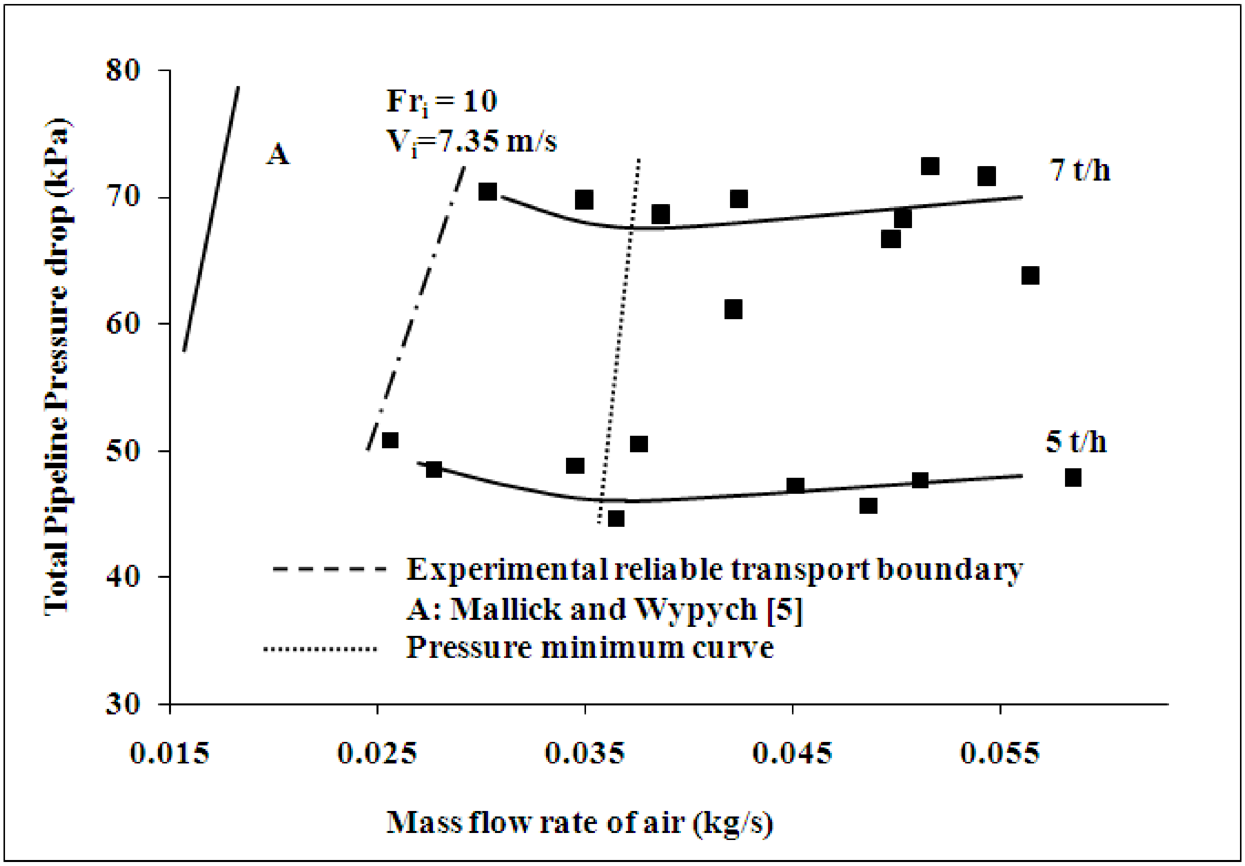

Fig 4.3: Pneumatic conveying characteristics, cement, 54 mm I.D. × 24 m long pipeline

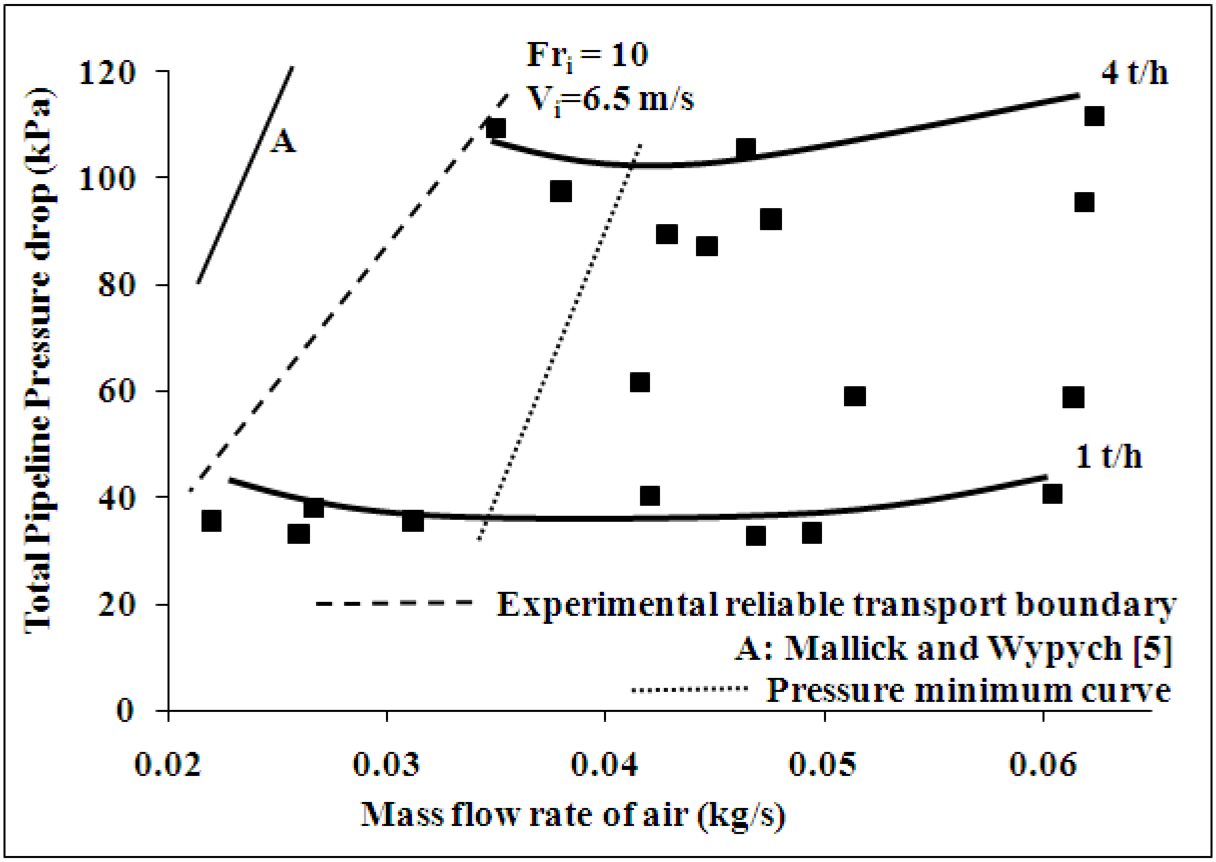

Fig 4.4: Pneumatic conveying characteristics, cement, 54 mm I.D. × 70 m long pipeline

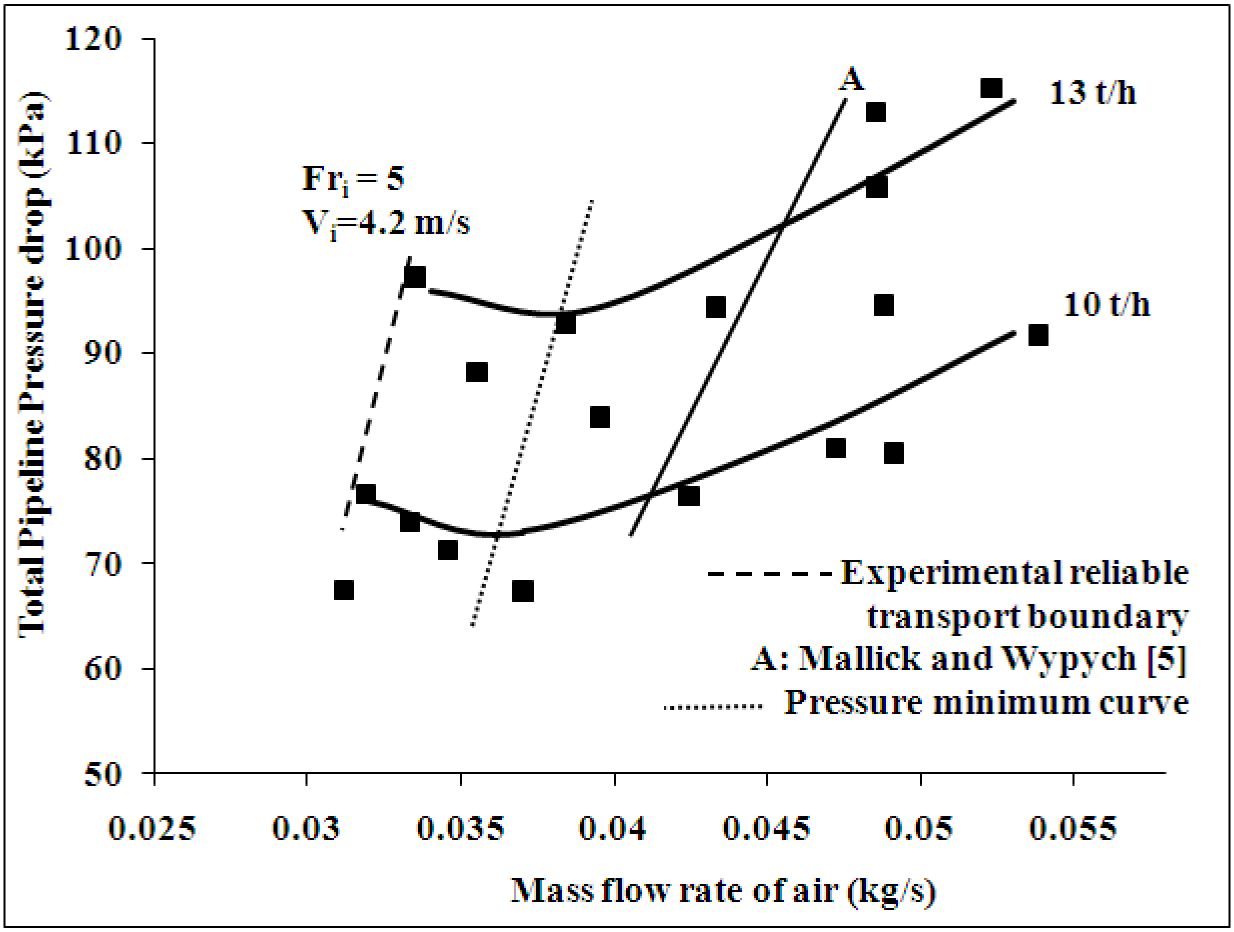

Fig 4.5: Pneumatic conveying characteristics, cement, 69 mm I.D. × 24 m long pipeline

Experimental reliable transport limits in Figures 4.2 to 4.4 are found to be corresponding to Fr_i = 10 (as shown by the dashed lines in Figures), whereas the same corresponds to Fr_i = 5 for Figure 8. This shows that with increase in material flow rate (above a lower limit), there is a reduction in gas flow rate requirement to sustain the flow. This is due to the self-pushing effect of the product at higher tonnages. As a result, while 10 to 13 t/h of product could be conveyed at Fr_i = 5 (Figure 4.5), 1 to 7 t/h of cement required Fr_i = 10. Similar requirement of higher conveying velocity at lower tonnages was observed by Mills (2004). As a result of the requirement of higher air flows at very low material flow rates to, Mallick and Wypych (2009) model has provided under predictions for the pipelines shown in Figures 5 to 7. Therefore, a designer estimating the minimum air flow requirement to conveying low tonnages in dense-phase should consider additional air flows to achieve stable conveying.

Chapter 5: Estimation of Slip velocity

5.1 Slip velocity

In a pneumatic conveying system the energy is taken from the carrier gas to accelerate and carry the solid particles in the two phase flow. The velocity of particle in this system is not only function of gas velocity, but it also depends on particle size and density. It has been observed in most of the applications that the velocity of particle is significantly lower than the velocity of the carrier gas (Tallon et al., 1998). This velocity difference between solid phase and gaseous phase is called slip velocity. The slip velocity is an important parameter for understanding the flow conditions in the pipelines and overall pressure drop of the system (Wypych et al., 1990). The slip velocity is helpful in determining the mean solids concentration for given mass flow rates and also determines the state of pneumatic conveying system (Tallon et al., 1998).

5.2 Assumptions

The following assumptions were made during analysis of slip velocity estimation.

1. The mass flow rate was assumed to be constant at each section of pipeline.
2. The effect of sight glass refraction was considered negligible during capturing the flow of material by a high speed camera.
3. The properties of air are different than that of ideal gas, but for calculations air was considered as an ideal gas.
4. Inaccuracy caused by missing one degree of freedom of particle movement due to the mapping of a 3D process onto a 2D image plane is considered negligible (Fuchs et al., 2008).

5. The effect of gravity is always present but in these experiment for the calculation of slip velocity, the influence of the gravity on the calculation of the particle velocity was considered negligible (Fuchs et al., 2008).

5.3 Methodology

The slip velocity is the difference of superficial air velocity and particle velocity (Fuchs et al., 2008). To estimate the slip velocity, particle velocity and the air velocity have to be calculated. The calculation of particle velocity for pneumatic conveying of cement and fly ash in all the experiments has been done by the help of high resolution camera. Different sets of video have been recorded by using the high resolution camera for a single setting of the parameter at the different sight glass. Each video was then converted into image frames (50 frames per second). For consecutive frames a void or layer pattern in flow has been traced. Now, tracking of the movement of a void or a layer pattern in the flow has been done by putting a virtual scale on the consecutive image frames. Particle velocity has been calculated by the help of distance travelled by a void or layer pattern in consecutive frames and known time between frames (i.e. 1/50 second).

The conveying air velocity was calculated by using eq 5.1 as given below follows

$$\text{Velocity of air } (\mathrm{v_{air}}) = \frac{\text{Volume flow rate of air } (\mathrm{V_f})}{\text{Area in which air flows during pnuematic conveying}} \quad \ldots\ldots.(5.1)$$

The volume flow rate ($\mathrm{V_f}$) was calculated with the help of mass flow rate of air ($\mathrm{m_f}$) and density of air (ρ_{air}). The value of $\mathrm{m_f}$ and ρ_{air} has been taken from the steady state pneumatic conveying data. This data was obtained from the analysis of the data recorded by the data logger. The area in which air flows during pneumatic conveying was calculated by the analysis of image frames generated from a different set of videos.

5.4 Superficial air velocity calculation

From the equation (5.1) for the calculation of superficial air velocity, the average area in which air flows during pneumatic conveying is required. For calculation of the average area in which air flows, the height of material bed is estimated with the help of a virtual scale as shown in figures 5.1, 5.2, 5.3 and 5.4. Some eexamples for the analysis of image frames generated from the respective video, for the calculation of average area of pipeline in which air flows have been shown in figure no. 5.1, 5.2 (for fly ash) and 5.3, 5.4 (for cement).

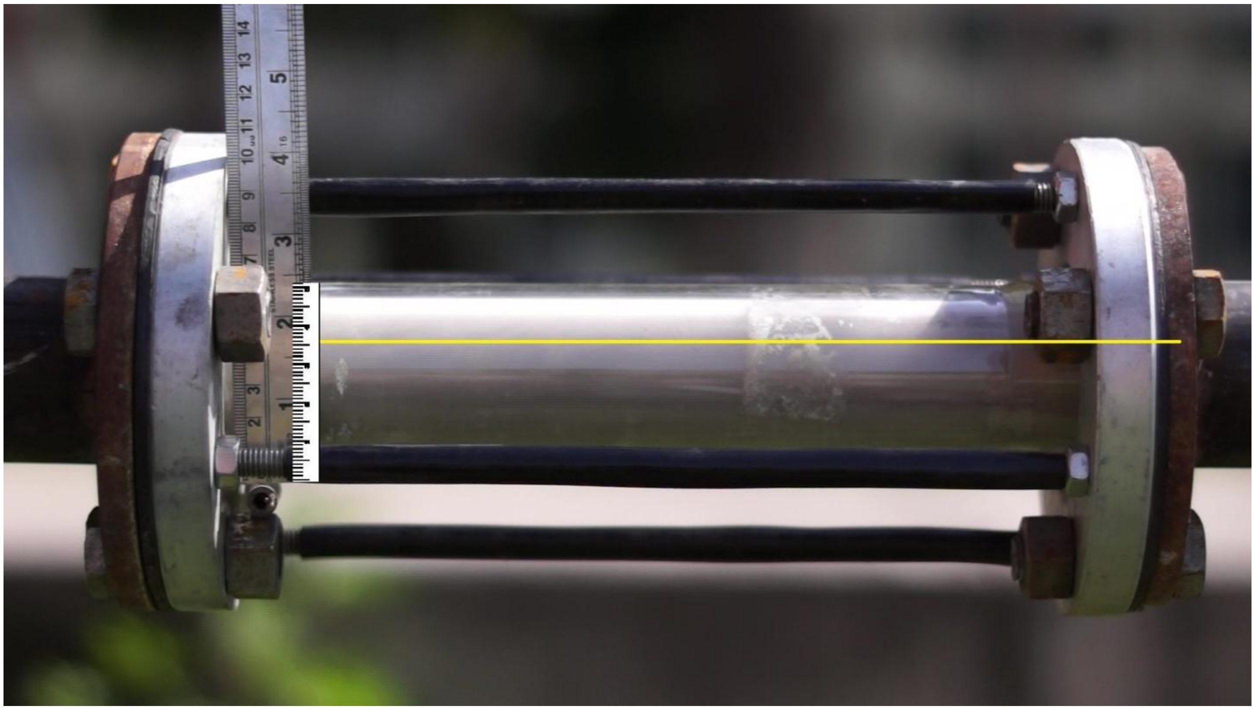

Fig 5.1: Sample image (18-613) for average area calculation of flyash .

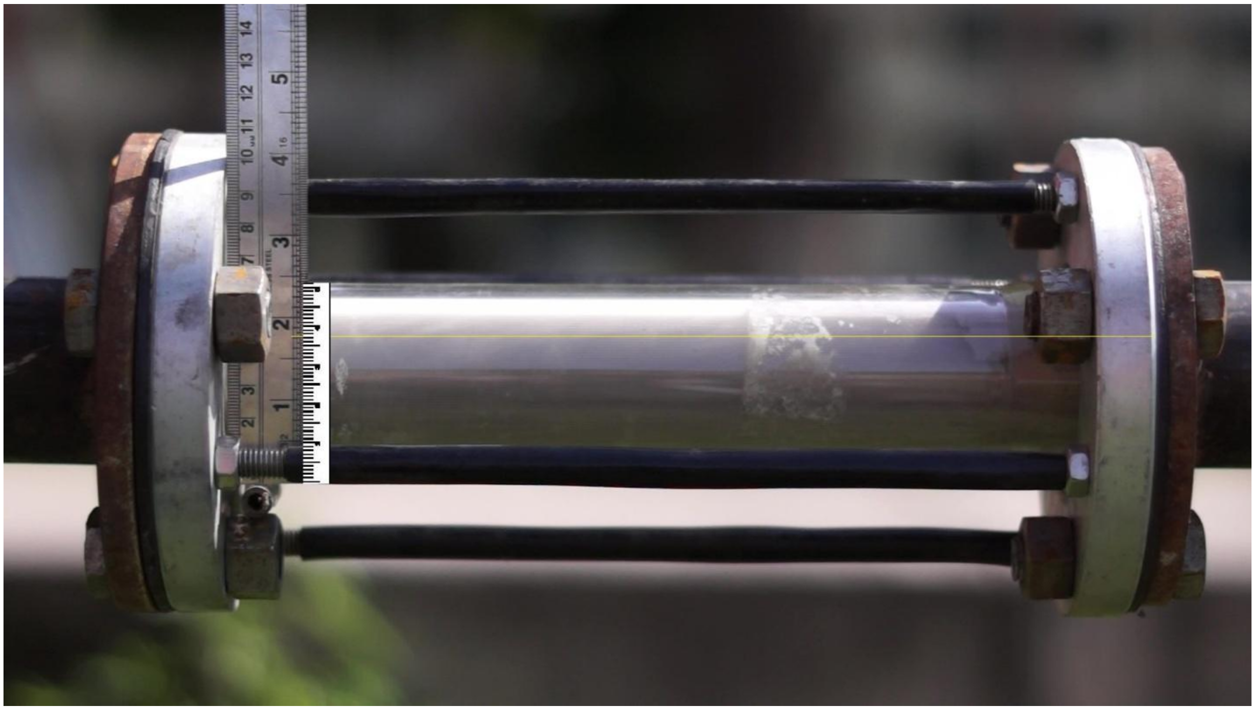

Fig 5.2: Sample image (18-963) for average area calculation of fly ash.

For cement sample of image analysis is given below:

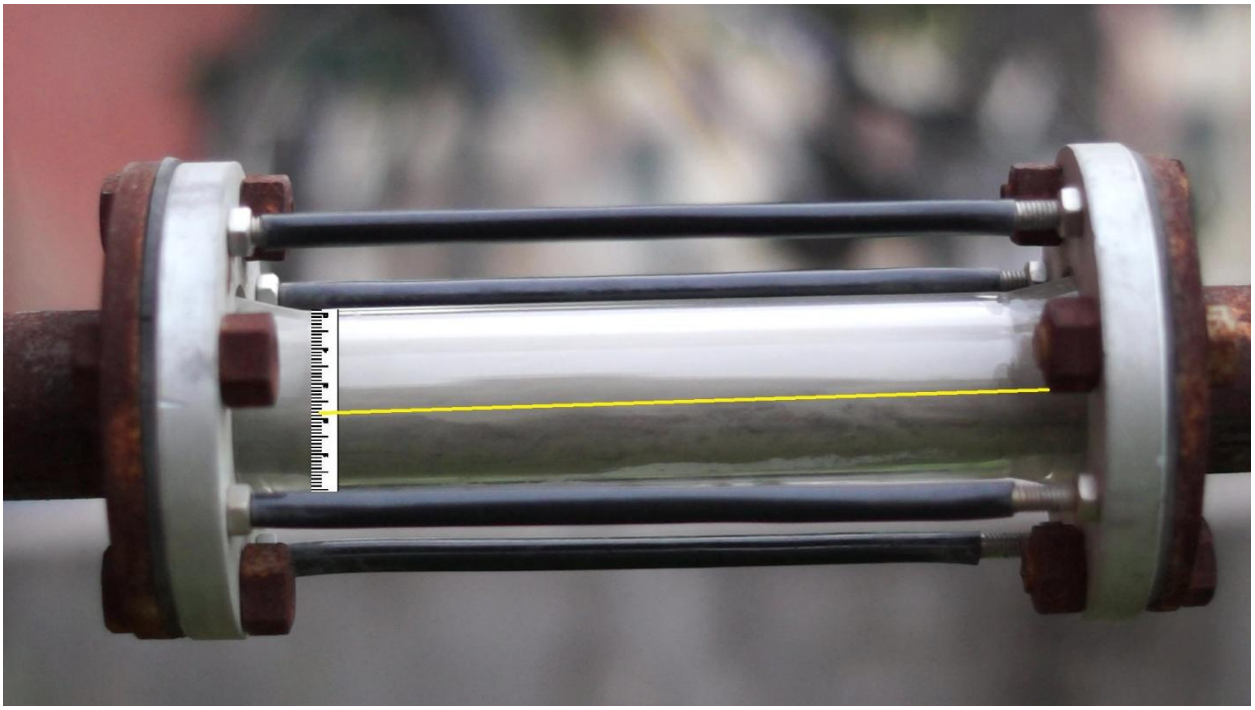

Fig 5.3: Sample of the image (00056-2305) for average area calculation of cement.

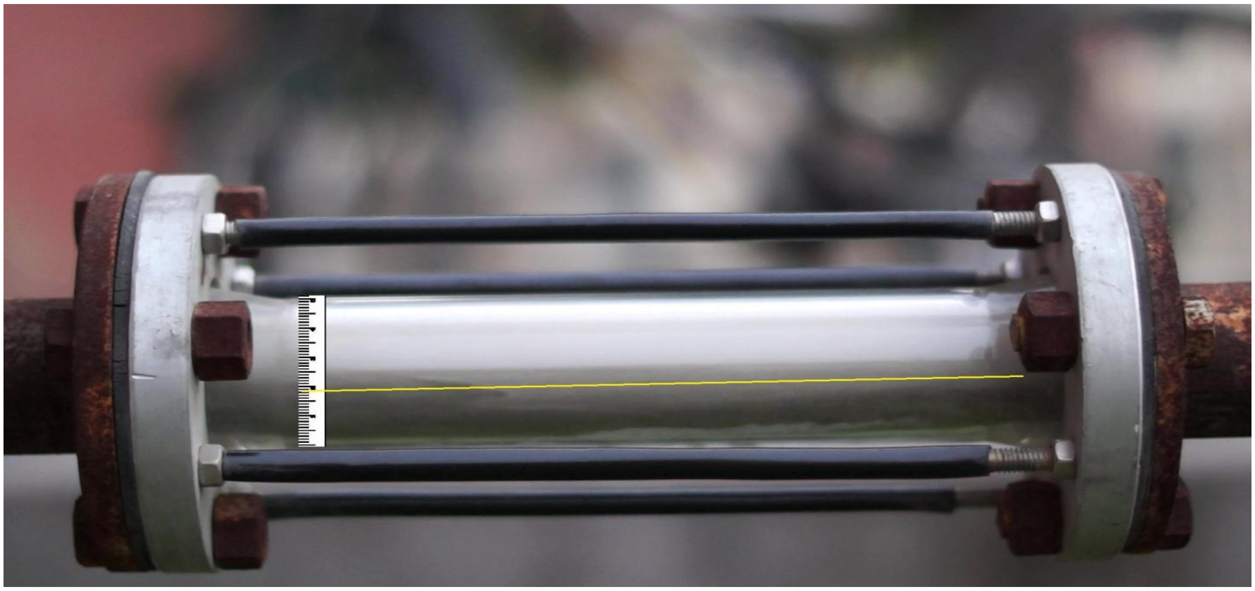

Fig 5.4: Sample of the image (00059-1904) for average area calculation of cement.

Similarly, all the images were analyzed and the average area in which air flows was calculated.

Table 5.1: Average area of air flow (for fly ash)

Video	**Average area (cm^2)**
15	3.89
17	8.47
18	1.67

Table 5.2: Average area of air flow (for cement)

Video	**Average area(cm^2)**
56	8.92
59	8.86
61	6.79

5.5 Particle velocity measurement

Tracking of the movement of a void or a layer pattern in the flow has been shown in the figure 5.5, 5.6, 5.7 for fly ash and 5.8, 5.9, 5.10 for cement.

For fly ash:

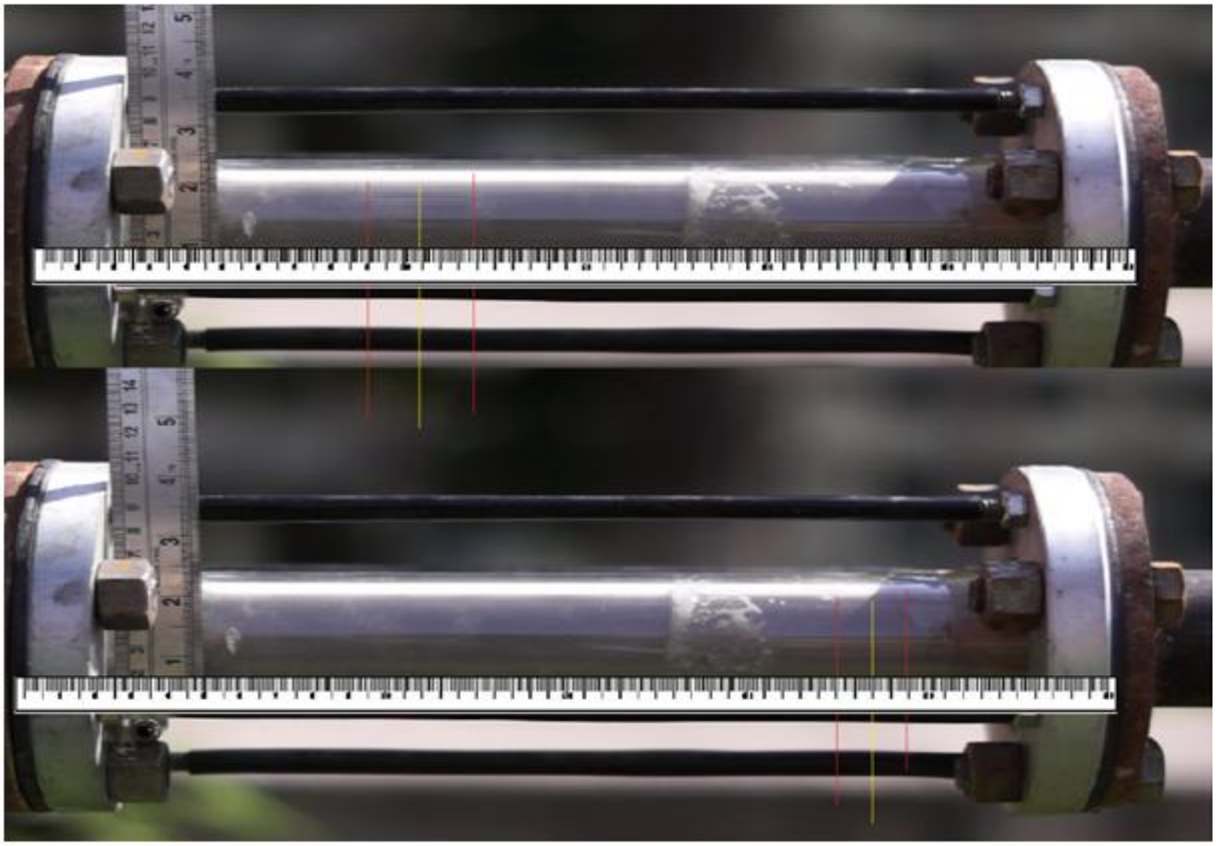

Fig 5.5: Image (18-98-99) for particle velocity calculation of fly ash.

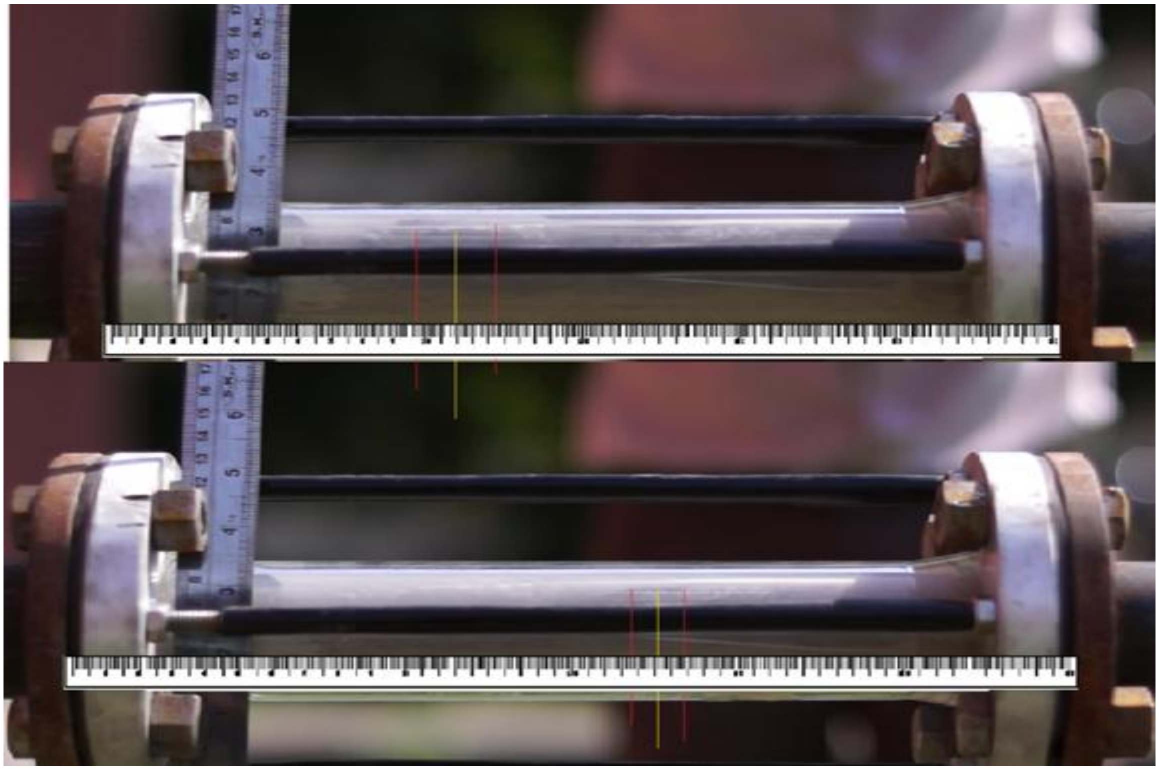

Fig 5.6: Image (17-1159-1160) for particle velocity calculation of fly ash

Fig 5.7: Image (15-93-94) for particle velocity calculation of fly ash

For cement:-

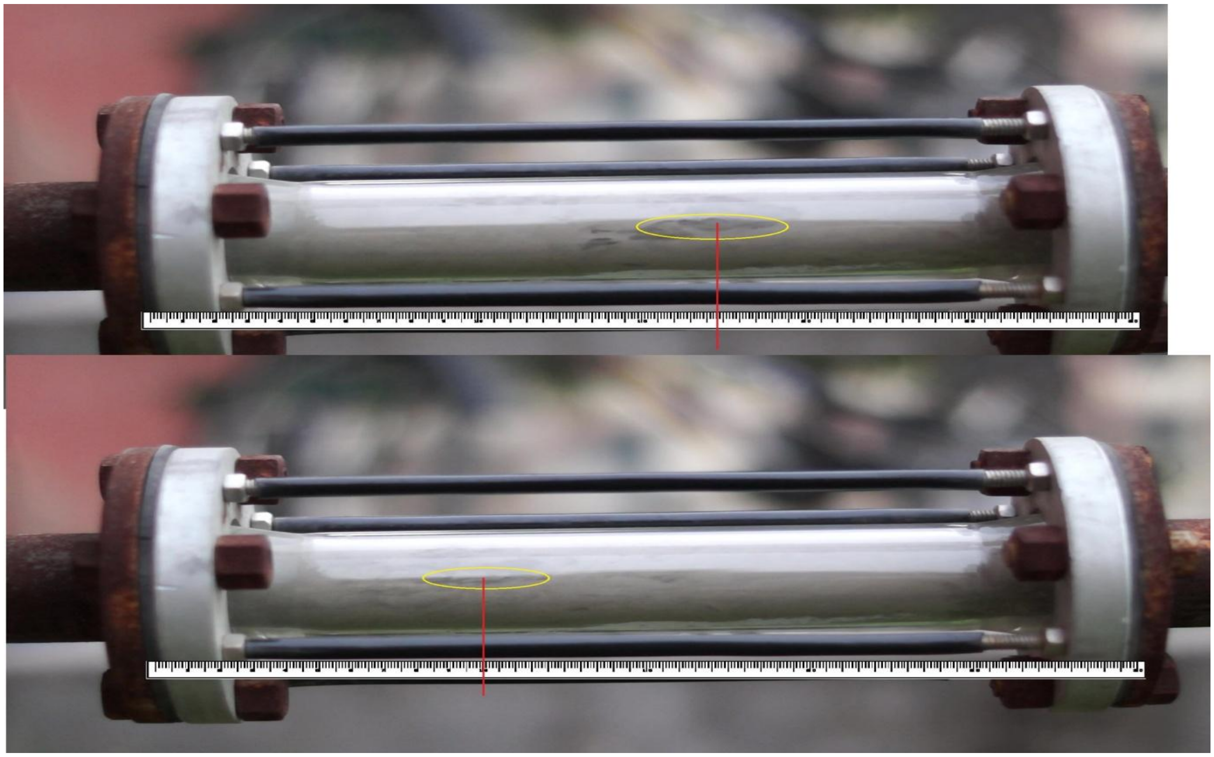

Fig 5.8: Image (56-236-237) for particle velocity calculation of cement.

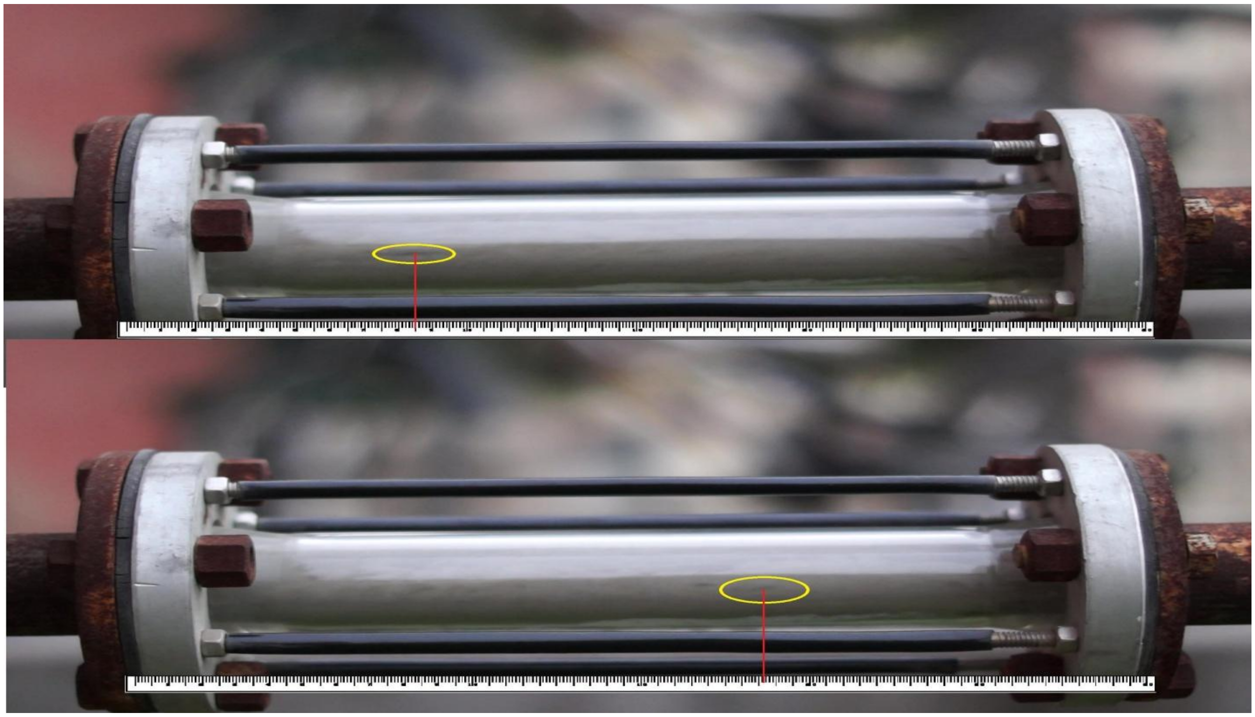

Fig 5.9: Image (59-1467-1468) for particle velocity calculation of cement.

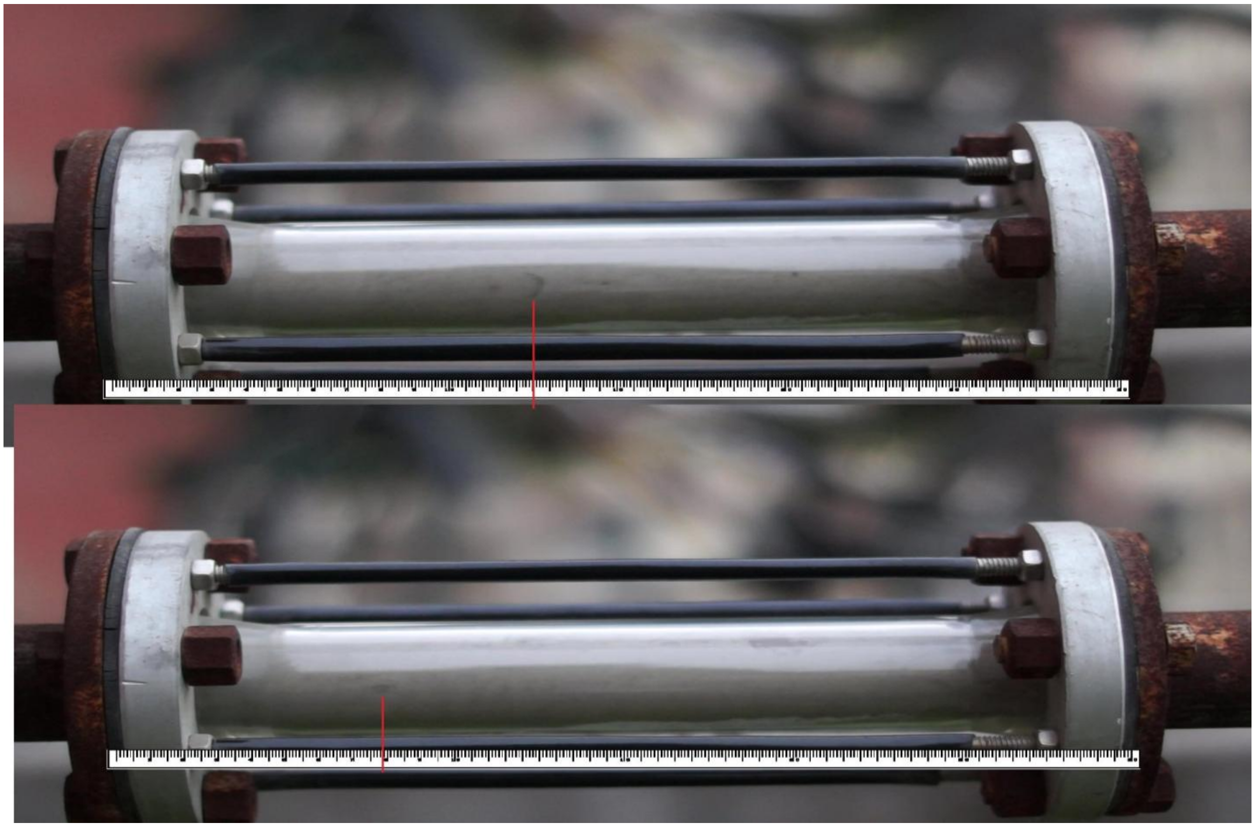

Fig 5.10: Image (61-273-274) for particle velocity calculation of cement.

5.6 Results for slip velocity calculation

After analyzing the average area in which air flows, the superficial velocity of the air is calculated with the help of steady state data. Now particle velocity for fly ash is calculated with the help of Figure 5.5, 5.6 and 5.7 and for cement particle velocity is calculated with the help of Figure 5.8, 5.9 and 5.10. All these results are summarized in the table no. 5.3 and 5.4.

Table 5.3 Results for slip velocity calculation (for fly ash)

Image	m_s **(kg/s)**	m_f **(kg/s)**	V_s **(m/s)**	V_f **(m/s)**	V_f-V_s **(m/s)**	V_s/V_f
Vid15	0.8446	0.020408	6.70	44.32	37.62	0.15
Vid17	0.508	0.015656	3.30	15.10	11.8	0.21
Vid18	0.478	0.010945	6.65	54.26	47.61	0.12

Table 5.4 Results for slip velocity calculation (cement)

Image	m_s **(kg/s)**	m_f **(kg/s)**	V_s **(m/s)**	V_f **(m/s)**	V_f-V_s **(m/s)**	V_s/V_f
Vid56	0.5798	0.049217	7.3	30.65	23.35	0.23
Vid59	0.7648	0.058173	10.1	35.34	25.24	0.28
Vid61	1.6298	0.04754	7.7	34.43	26.73	0.22

It has been found from above investigation, that the slip velocity of cement is less as compared to the slip velocity for fly ash for same material discharge rates. As shown in Table no. 3.1 particle size of cement is less than that of fly ash, hence the cement particles require lesser air velocity to convey in fluidized dense phase than that of fly ash particles.

Chapter 6: Conclusion and Future scope of work

6.1 Conclusion

The Mallick and Wypych (2009) model has shown under prediction of reliable transport boundary for smaller diameter pipelines. Whereas the same model has over predicted the reliable transport boundary for 69 mm I. D. × 24 m length pipeline. It was found that for very low tonnages, higher amounts of air flows are required ($Fr_i = 10$) compared to that required at higher tonnages ($Fr_i = 5$) to sustain the non-suspension dune movements of powders indicating that the product experiences a self pushing effect at higher material flow rates, which facilitates conveying.

The slip velocity of cement is found less as compared to the slip velocity for fly ash at same material discharge rates, whereas the gas flow rates were high for cement and low for fly ash. This is due to the particle size of cement (d= 19 µm), which is less than that of fly ash (d=45 µm) and because of better air retention property of cement due to which it flows easily. The slip velocity has not shown any particular trend with solids and air mass flow rates.

6.2 Future scope of work

I. Further work can be carried out by including specific material characteristics to model reliable transport limits.

II. The effect of varying concentration of solid particles in carrier gas, gravity, acceleration and deceleration of particles, geometry of piping system and bends should be considered in establishing a proper technique for particle velocity measurement.

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