AN INVESTIGATION INTO BLOW TANK PERFORMANCE AND SOLIDS FRICTION FOR PNEUMATIC CONVEYING OF FINE POWDERS

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Thesis

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Submitted by
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CERTIFICATION

I, Parmod Kumar, declare that this thesis report entitled ***"An investigation into blow tank performance and solids friction for pneumatic conveying of fine powders"***, 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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ABSTRACT

An accurate estimation of design parameters such as blow tank initial pressurization, blow tank aeration, total pipeline pressure drop and solids friction factor is important for reliable design of fluidized dense-phase pneumatic conveying systems. This report presents the results of an investigation carried out to provide these important design parameters for fluidized dense-phase conveying of cement. Cement (median particle diameter: 14 µm; particle density: 3060 kg/m^3; bulk density: 1070 kg/m^3) was 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, which showed a clearly defined pressure minimum curve for all the pipelines except for 69 mm I.D. × 24 m long pipeline. Two existing models of solids friction for horizontal straight pipe sections were compared with experimental results. Pressure drop across bends was obtained by using Chamber and Markus formula. A power function based model was developed for solids friction using the straight pipe pressure drop data of 54 mm I.D. × 24 m long pipeline and is evaluated for all other pipelines. Models were found to give good predictions for total pipeline pressure drop at higher solid discharge rates. Blow tank characteristics were plotted to study the effect of blow tank initial pressurization and aeration on material discharge rate. It has been found that material discharge rate increases with an increase in blow tank initial pressurization and mass flow rate of top and fluidization air. It is concluded that blow tank performance has huge impact on the overall performance of the pneumatic conveying systems.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

B:	Bend loss factor
D:	Internal diameter of pipeline [m]
Fr:	Froude number $\left[\frac{V}{\sqrt{gD}}\right]$
Fr_i:	Froude number at inlet of pipe
Fr_m:	Mean Froude number $\left[\frac{V_m}{\sqrt{gD}}\right]$
Fr_{sd}:	Froude number based on particle diameter $\left[\frac{w_{fo}}{\sqrt{gd}}\right]$
H:	Riser inlet height above gas distribution plate [m]
K:	Constant of power function equation
L:	Length of pipeline [m]
N:	Number of bends
Q_f:	Fluidization gas flow rate [m^3s^{-1}]
Q_p:	Pressurizing gas flow rate [m^3s^{-1}]
Q_s:	Supplemental gas flow rate [m^3s^{-1}]
P_i:	Pressure at pipe inlet [Pa]
V:	Velocity of air [ms^{-1}]
a:	Exponent of m^* in equation (5.1)
b:	Exponent of mean Froude number in equation (5.1)
d_s:	Particle size [m]
d_r:	Riser diameter [m]

d_{50}: Median particle diameter [m]

m_s: Solid mass flow rate [kgs^{-1}]

ρ: Density of air [kgm^{-3}]

ρ_{bo}: Density of air at bend outlet [kgm^{-3}]

ρ_{bl}: Loose poured bulk density [kgm^{-3}]

ρ_m: Mean density of air [kgm^{-3}]

ρ_s: Particle density [kgm^{-3}]

λ_f: Air only friction factor

λ_s: Solids friction factor

λ_{bs}: Solids friction factor for bends

ΔP: Pressure drop for straight pipe [Pa]

ΔP_b: Pressure drop across bends [Pa]

m^*: Solid to gas mass flow rate ratio

Abbreviations:

AIV: Air inlet valve

BTP: Blow tank pressure

HLI: High level indicator

I.D.: Internal diameter

LLI: Low level indicator

MC: Pulverized coal external moisture content

MDV: Material discharge valve

MIV: Material inlet valve

PCC: Pneumatic conveying characteristics

PS: Pressure switch

VV: Vent valve

CHAPTER 1: INTRODUCTION AND OBJECTIVES

1.1 Introduction

Pneumatic conveying is popularly used for conveying of bulk solids and powdered materials (such as cement, pulverized coal, fly ash, food products, chemical powders etc) through pipelines by using gas as the conveying medium (Mallick, 2010). The reasons for its widespread use are: flexibility of layout, less contamination of conveyed material, reduced material losses, ease of automation and control, less maintenance, and the possibility of having multiple feed and discharge points. The conventional mode of conveying has been dilute-phase (suspension flow), in which the gas velocities are sufficiently high to suspend the particles being conveyed in pipeline. This leads to low solid loading ratios, damage to the fragile materials, excessive wear of pipeline and bends, requirement of large sized bag filters and compressor, which in turn increases energy consumption and maintenance requirement of the system (Mills, 2004). Due to these drawbacks of conventional dilute-phase conveying, dense-phase pneumatic systems are getting increasing popularity. Dense-phase pneumatic conveying systems are characterized by non-suspension flows (non-uniform distribution of solids across the cross-section of pipeline), having high solid loading ratios and low velocities (less than saltation velocity of particles) at pipe inlet (Mills, 2004). A well designed dense-phase pneumatic conveying system operates at high solid loading ratios as high as 100 instead of small loading ratios (typically under 20) for dilute-phase, over the long distances, when Geldart Group A materials such as cement, fly ash etc, are being conveyed. In spite of the many advantages of dense-phase systems over dilute-phase, the installations of these systems are still limited, because, the reliable design of such system is difficult due to the highly turbulent and complex nature of non-suspension dunes (Mallick, 2010). Cement is an important and one of the most popular/in demand construction materials that comes under Geldart Group A category and thus it is an ideal candidate for fluidized dense-phase conveying systems (Klinzing et al., 2010). Cement plants need to transfer large quantities of cement often over long distances, from mills to storage facilities. Two important parameters that need to be accurately modeled and scaled-up for the reliable design of dense-phase pneumatic conveying systems for cement are total pipeline pressure drop and blow tank initial pressurization. In spite of being an important industrial product, only limited data has been presented to date on dense-phase pneumatic conveying of cement (Mills, 2004), compared to the large volume of information available for dense-phase conveying of fly ash (Mallick, 2010; Mills, 2004; Pan and Wypych, 1998; Keys and Chambers, 1993, 1995). Blow tank is one of the crucial elements of fluidized dense-phase conveying systems, which acts as feeder. The performance of the whole pneumatic conveying system depends upon the performance of blow tank, because it controls the amount of material being fed into conveying pipeline, which has significant effect on the total pipeline pressure drop. Wypych et al. (2006) have reported that blow tank regulates the material discharge rate (m_s) with the variation in conveying pipeline pressure drop. Blow tank consists of top air port and fluidization pads, to supply pressurization and fluidization air. In some of the blow tanks pressurization air may be supplied from side port instead of top. Blow tank initial pressurization and aeration has huge effect on material discharge rate (Xu et al., 2013). However sufficient research has not been carried out to relate the effects of blow tank top air, fluidization air and initial pressurization on the solid mass flow rate (m_s) and conveying pipeline pressure drop. Total pipeline pressure drop is also an important parameter that needs to be accurately modeled and scaled-up for the reliable design of dense-phase pneumatic conveying systems. Inaccurate estimation of this results in higher energy cost and wearing of pipeline in case of over prediction of pressure drop, whereas under-prediction of pressure drop results in low material discharge rate and gradual deposition of material in pipeline, leading to pipe blockage (Mallick, 2010). Total pipeline pressure drop includes pressure drop across straight horizontal, vertical sections and across bends. Although, the pressure drop must be accurately predicted for each section, but, then also accurate predictions across horizontal sections are necessary, because it constitutes of the major part of pipeline, thus maximum share in total pipeline pressure drop. Barth (1958) has given an equation (2.1) to predict the pressure drop across staright horizontal sections. This equation (2.1) is believed to be originally for dilute-phase conveying of coarse particles. However, this has been used by the different researchers such as Stegmaier (1978), Weber (1981), Pan (1992), Pan and Wypych (1998) and Jones and Williams (2003) to predict the pressure drop for fluidized dense-phase conveying of fine powders, such as fly ash and cement etc.

The challenging task of this equation is to model the solid friction factor for fluidized dense-phase conveying system due to its highly turbulent and complex nature of non-suspension flows. In the past decades, various models were given by different researchers (Jones and Williams, 2003; Stegmaier, 1978) for solid friction factor for gas solid interactions across the horizontal sections. Most of these models are product specific and related to particular flow conditions and pipeline configurations. Most of the existing models are empirical and have shown good agreement when applied to researchers own data, but these have not been examined for different products and pipeline configurations. Thus further research need to be carried out to accurately estimate solid friction factor and validate it for different products and pipelines. Also, the blow tank aeration characteristics are needed to be studied to maximize material discharge rates and co-relate these to conveying pipeline pressure drop.

1.2 Objectives

In view of the above mentioned research gaps, the following specific objectives are undertaken:

(i) To study the effect of blow tank initial pressurization on material discharge rates (steady discharge versus unsteady discharge);

(ii) To evaluate different solid friction factor models for predicting total pipeline pressure drop for different pipelines;

(iii) To develop solids friction factor model for cement to predict straight pipeline pressure drop.

CHAPTER 2: LITERATURE REVIEW

This chapter presents the studies and research carried out by different researchers on solids friction and blow tank characteristics. The initial part of this chapter is focused on the general concepts of pneumatic conveying systems and operation of blow tank. In the later sections different models of solids friction for straight pipe sections given by various researchers are presented. Along with that some specific literature related to blow tank characteristics is also presented.

2.1 Pneumatic conveying

Pneumatic conveying is the technique that involves the transportation of wide variety of powdered and bulk solid materials with the help of a compressed air stream. In most of the cases air is used as the medium of transportation, but in some special cases other inert gases can be used, where there are the risks of explosion, fire hazard, etc. Although, 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-fibre materials. However, with the development of new types of conveyors operating at low gas velocities, cohesive, abrasive and friable materials can also be handled. It has wide range of applications in the chemical process, pharmaceutical, mining and mineral industries (Ratnayake, 2005).

Pneumatic conveying system is getting enormous 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 reach economically with mechanical conveyors. This is because of its flexibility of installation (i.e. horizontal, vertical pipelines and bends can be installed easily) (Pan, 1992).

(b) The physical size of pneumatic conveying pipeline is usually smaller than that of belt conveyor and bucket elevators.

(c) Since pneumatic systems are completely enclosed, product contamination, material loss and dust emission (thus, environment pollution) are reduced or eliminated. Particularly, to convey hazardous materials, vacuum system is used (Ratnayake, 2005).

(d) Pneumatic conveying system can take the material feed from multiple sources. Also, it can have multiple discharge points (Ratnayake, 2005).

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

(f) Latest advancements in pneumatic conveying allow the friable products to transport at low velocities, which lead to less product degradation.

(g) These systems are easy to control and automate.

The use of pneumatic conveying is increasing significantly in many applications, however still there are some demerits of pneumatic conveying:

(a) In case of dilute-phase conveying, high power consumption, material degradation and system erosion are the major problems (Mallick, 2010).

(b) In case of dense-phase conveying, pipe vibrations and system blockages are experienced often in poor designed systems (Wypych, 1989).

(c) Because of complex flow phenomena, which take place in dense-phase systems, there is a requirement for high levels of skill to design, operate and maintain systems (Mills, 2004).

(d) Lack of standard procedures for the selection of an optimal system for a particular application.

2.2 Components of pneumatic conveying system

A pneumatic conveying system must comprise of four basic components as given below:

(1) *Gas supply system:*

In the pneumatic conveying systems, the major requirement of the gas is 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 (Klinzing et al., 2009). 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. To ensure this, gas supply system must be incorporated with filter and drying unit.

(2) *Feeding device:*

This is one of the crucial elements of pneumatic conveying systems, which feeds the material into conveying pipeline. The performance of the whole pneumatic conveying system depends upon the type of feeder employed. So, the selection of a feeder for particular application must meet both system as well as material requirements (Mills, 2004). Feeding devices are discussed in much detail in the coming sections.

(3) 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 (Pan, 1992). Although, almost all the materials can be conveyed through the steel pipelines, however rubber hoses are widely used in pneumatic conveying systems, both for bends and pipelines, where there is a 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 alloyed cast iron pipeline is preferred (Klinzing et al., 2009).

(4) Separation equipment:

Gases conveying the material need to be separated from the material before; it is fed to the storage facility. For this purpose, bag filters, cyclone separators and electrostatic precipitators are used. The selection of a particular type of separation equipment depends upon a number of factors; primary factor being the size of solid particles, flow rate required and collection efficiency (Mills, 2004).

2.3 Feeding devices

For the efficient operation of a pneumatic conveying system, the feeding of solid in the pipeline should be effective. For this purpose, different types of feeding devices are available. Other than the feeding of solid these performs the other functions also, such as, these provide seal between the conveying gas and material storage hopper. Klinzing et al. (2009) reported that these devices may accurately control the solids feed rate into the pipeline for process control features as in chemical plants. Ratnayake et al. (2008**)** reported that in most of pneumatic conveying systems, the feeding device is the component, which contributes to the largest pressure losses. All pneumatic conveying feeding devices normally involve the introduction of solids in an almost stationary mode into a fast moving gas stream, which is under pressure or vacuum. The rapid changes in momentum of particles, coupled with a large amount of gas–solid turbulence in the feeding area are the two predominant factors reported, which account for the large pressure losses in feeding devices.

2.4 Classification of feeding devices

Klinzing et al. (2009) has classified the feeding devices in following ways:

Based on pressure characteristics:

(a) *Low pressure feeding devices:* These systems are used in applications where pressure ranges from vacuum to 100 kPa. The venturi feeder, vacuum nozzles and rotary airlock comes under this category of feeders.

(b) *Medium pressure feeding devices:* These systems are used in applications where pressure ranges from 100 to 300 kPa. The fluid solid pump, the Mohno powder pump, vertical lift pump and double gate lock feeding device comes under this category of feeders.

(c) *High pressure feeding devices:* These systems are used in applications where pressure ranges from 300kPa to 1000 kPa. Blow tank comes under the category of high pressure feeders.

Based on system requirements:

(a) Continuous feeding: Two blow tanks are used in conjunction to get continuous supply of solids as shown in Figure 2.1.

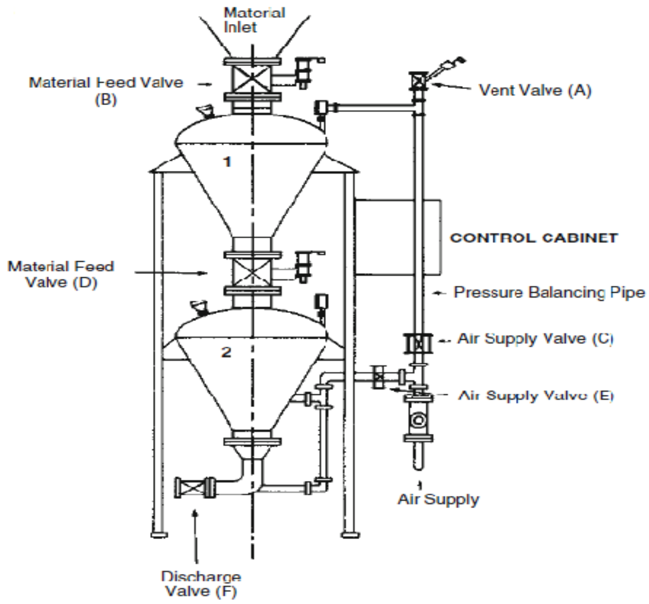

Figure 2.1: Vertical tandem blow tank system (Klinzing et al., 2009)

(b) *Batch feeding:* When single blow tank is used, then during feeding of material into tank and pressurization period of tank, there is no supply of material in conveying line.

2.5 Selection criteria for feeding devices

The considerations that are to be kept in mind while selecting a feeder for particular application are:

(1) Particle size, cohesive, friable, free flowing, whether degradation is of concern, whether required to operate at elevated temperatures, etc (Klinzing et al., 2009);

(2) Selection of feeder also depends upon the location and area or space availability;

(3) Cost influence the selection of feeder on the basis, whether the project is designed for short term or long term applications (Mills, 2004);

(4) Continuous or batch operation;

(5) System conveying pressure (Wypych et al., 2006);

(6) Accurate feeding control is required particularly for chemical process industry. For this purpose, sometimes the flow control arrangements are also used along with the feeders (Klinzing et al., 2009).

2.6 Commonly used feeding devices

A large number of feeding devices are available, but there are only few which find their applications in almost all industrial uses and are of major concern. These devices are discussed in the following.

Rotary Airlock: The most widely used of all pneumatic conveying feeding devices is the rotary airlock (rotary valve). This acts as feeder and provides pressure seal. The valve consists of a moving rotor and a stationary casing as shown in Figure 2.2. The rotor consists of segmented pockets that collects materials from an opening in the casing and deliver the material into the conveying gas stream. The casing is constructed in a manner so that it can take the material from feed hopper and can be coupled to the conveying pipe (Klinzing et al., 2009). Casing can also be fitted with a mechanism to adjust clearance between blade tips and the casing.

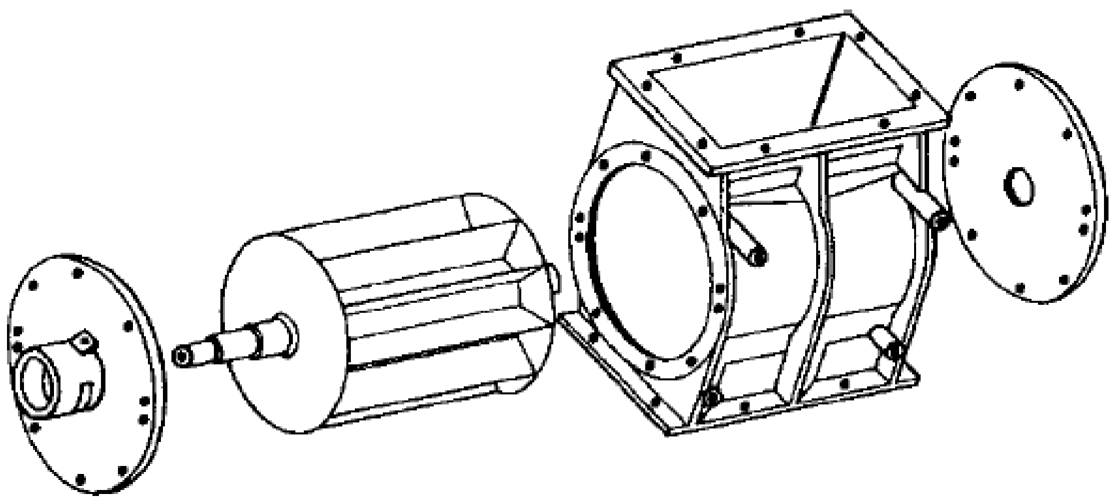

Figure 2.2: Rotary airlock (Klinzing et al., 2009)

All rotary airlocks, irrespective of their construction can leak air or gas. However, depending upon the construction, leakage rates can be minimized. There are basically three categories of leakages (Wypych et al., 2006) that are associated with rotary airlocks:

(a) *Carry-over leakage:* due to the return of empty pockets;

(b) *Labyrinth leakage:* due to losses through shaft seals in the casing;

(c) *Clearance leakage:* due to the clearance between the rotor tips and the casing.

Valve Configurations:

(a) *Drop through:* In the case of the drop-through valve the material is dropped into a transitional element (Figure 2.3) known as the feeding tee which links the valve to the pipeline.

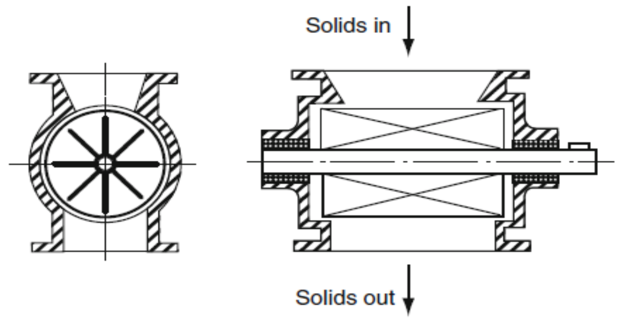

Figure 2.3: Drop through rotary airlock (Klinzing et al., 2009)

(b) *Blow through:* The blow-through configuration connects the conveying pipe directly to the valve casing. In such valves, the gas stream passes through the pockets, thereby ensuring complete removal of all material as shown in Figure 2.4. These valves are well suited to sticky materials.

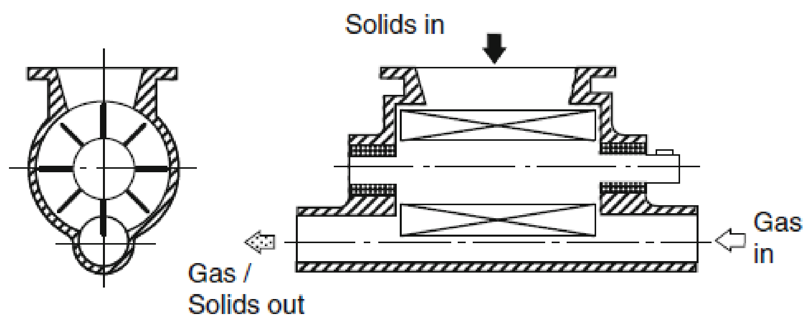

Figure 2.4: Blow through rotary airlock (Klinzing et al., 2009)

Blow Tank: Blow tank, also known as blow vessel, is a conical bottomed pressure vessel fitted with necessary valves and fittings to meet particular feeding requirements. Blow tank has the two basic configurations: Top Discharge and Bottom Discharge (Figure 2.5), reported by McLean (1985). The top discharge blow vessel relies on the efficient fluidization and entrainment of the material into the discharge pipe. These systems are now only used in situations where space requirements are limited. The bottom discharge blow vessel configuration appears to be more widely used.

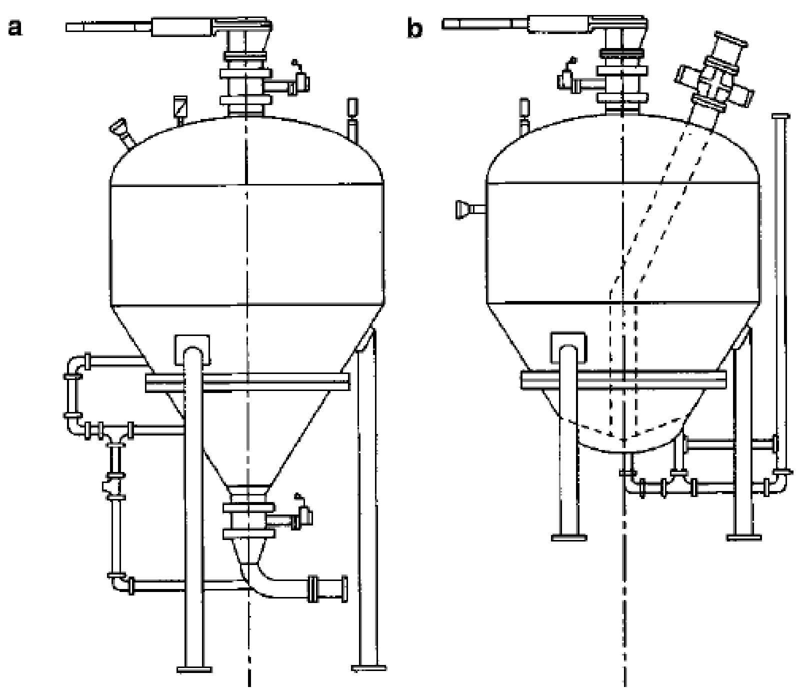

Figure 2.5: a) Bottom discharge blow tank, b) Top discharge blow tank (Klinzing et al., 2009)

Blow tank operation:

Blow tank is commonly designed for fully automatic operations because it contains number of valves and it becomes a tedious task to operate these valves manually. Due to the availability of the compressed air supply for conveying, the use of pneumatically actuated valves is preferred (Figure 2.6).

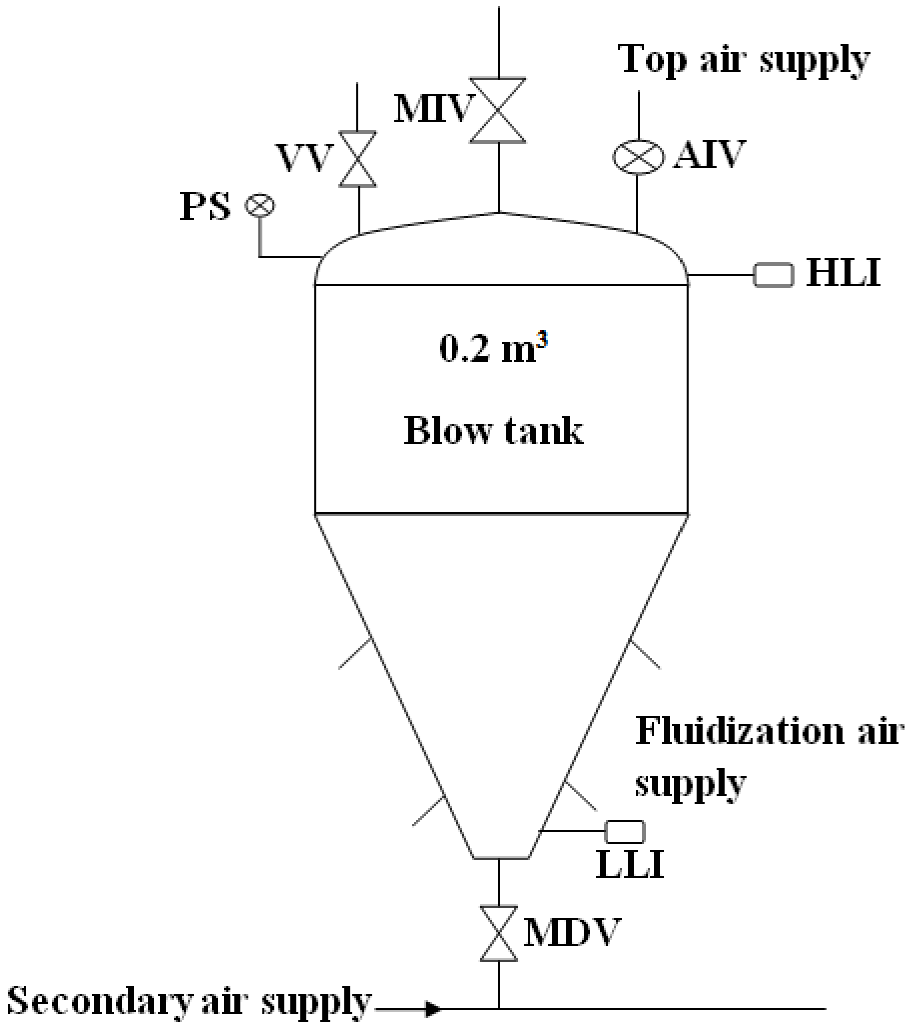

Figure 2.6: Bottom Discharge Blow Tank

For a fully automated blow tank, the following sequence of valve operations (Klinzing et al., 2009) is used:

(i) Vent valve (VV) is opened to depressurize the vessel.

(ii) After a short time delay, material feed valve (MIV) is opened and the filling process is initiated.

(iii) The material flows into the vessel until such time as the high-level indicator (HLI) is activated.

(iv) The high-level indicator activates a signal to close valves (VV) and (MIV).

(v) After a time delay, the air supply valve (AIV) is opened to supply air to the vessel.

(vi) Air is fed into the vessel until a pre-set pressure is attained in the vessel.

(vii) A pressure switch (PS) is activated, which in turn sends a signal to open the discharge valve (D). Now the air supply is also maintained open throughout the conveying cycle.

(viii) Material is conveyed until a low-pressure signal is detected on the pressure switch indicating that all material has been transported.

(ix) Normally the air supply is maintained for a short while to ensure that any material, which might be left in the pipe is transported to the receiving station.

(x) The cycle is then re-initiated.

Blow Tank Characteristics:

A pressure time curve obtained for bottom discharge blow tank fitted with discharge valve is shown in the following Figure. The blow tank is pressurized before opening the discharge valve. From the Figure 2.7, following observations can be made:

A–B: represents the vessel pressurizing cycle.

B: represents the initial vessel pressurization P_i.

B–C: represents the drop in pressure as a result of the opening of the discharge valve.

C: represents the average conveying pressure – a pressure which is attained by the gas–solids flowing in the conveying pipe.

C–D: represents the conveying cycle and is the time taken for discharging the bulk of the product.

D–E: is the clean-out time in which the last remaining material is transported through the pipeline.

C–E: is the total discharge time.

It can be seen that the sequence D–E represents a rapid depressurization of the vessel. This depressurization together with the small amount of material can result in a violent surge of high-velocity solids in a dilute concentration. This surge characteristic is necessary for the selection of an adequately sized air solids separation system on the receiving end (Klinzing et al., 2009). By introducing a low level indicator at the bottom of the vessel, the D–E sequence is replaced by a depressurization time.

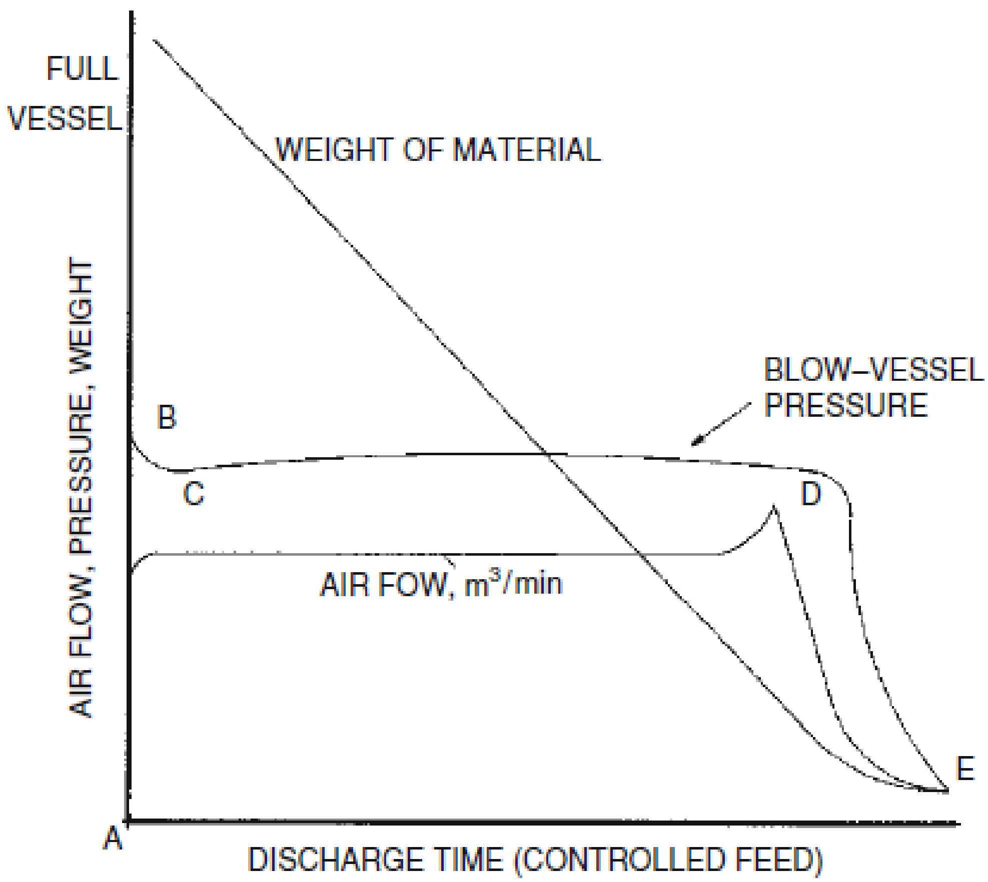

Figure 2.7: Blow tank characteristic curve (Klinzing et al., 2009)

Factors affecting blow tank performance:

McLean, (1985) reported the following three parameters that influence the performance of blow tank are:

(a) Cone angle

(b) Vessel volume

(c) Vessel pressure

If the cone angle of vessel is not designed suitably, it causes two problems, which are shown in Figure 2.8:

Ratholing: Formation of blow hole through material, which prevents any further material flow.

Bridging: Formation of a barrier across the outlet of vessel, which prevents any further material flow. This is also known as arching.

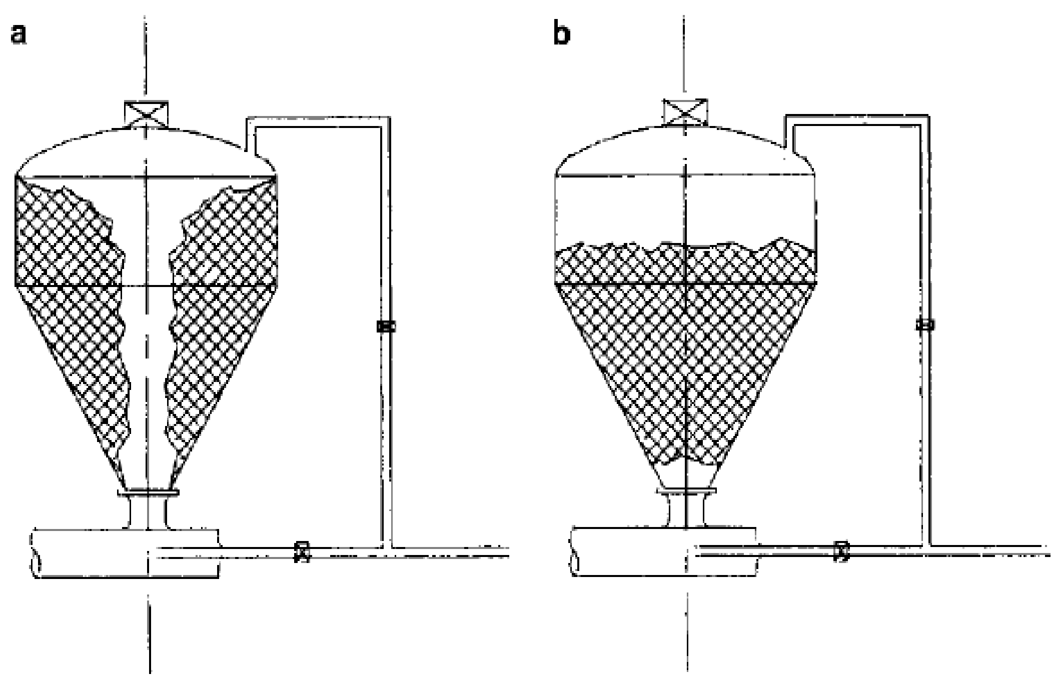

Figure 2.8: a) Ratholing, b) Bridging (Klinzing et al., 2009)

Vessel volumetric capacity is an important factor influencing blow vessel performance. In the case of products which are fluidizable, it is desirable to build the vessel as large as possible, because a large capacity blow vessel ensures large discharge time component in comparison to the pressurization and clean-out times. This improves the conveying efficiency. For materials, which have free flowing characteristics, they tend to flood the conveying line. In such cases, the volume of the vessel is selected such that on discharge, the conveying pipe cannot be overfilled and hence the risk of blockage is minimized. The increase in initial vessel pressure provides an opportunity to get higher material discharge rates and long conveying distances without doing any changes in the system.

2.7 Previous research work related to blow tank

Being one of the crucial components of pneumatic conveying systems blow tank plays an important role in overall performance of whole system. So, performance characteristics of blow tank must be accurately determined. Xu et al. (2013) studied the effects of riser inlet height above gas distribution plate (H), riser diameter (d_r), pulverized coal external moisture content (MC) and supplemental gas flow rate (Q_s) on the conveying characteristics of pulverized coal, such as mass flow rate (m_s) and solid to gas ratio. The experimental setup consisted of top discharge blow tank used under atmospheric pressure and nitrogen was used as carrier gas. The blow tank was made of plexiglass in order to have easy inspection of pulverized coal flow patterns. It was noticed that as H increased, the m_s and μ increased first and then decreased, respectively. This might have happened because at small H riser is close to the proximity of distributor plate so some of the fluidizing gas may escape directly through riser without participating in fluidization and at large H due increase in gap between distributor plate and riser inlet, part of gap remains unaffected by the fluidization. As the MC increased, the m_s and μ first increased and then declined, respectively. Supplemental gas could improve the continuity of conveying process but with increase in supplemental gas flow rate both m_s and m^* goes down. A model to predict m_s with an error of -25% to +15% is presented in this study.

Xu et al. (2012) studied the effect of fluidizing and pressurizing gas flow rates on powder mass flow rate (m_s), solid gas ratio (m^*) and voidage in a top discharge blow tank. Pulverized coal and glass beads were used to investigate the effect of powder properties on conveying performance. It was noticed that, as the fluidization gas flow rate (Q_f) increased the m_s and μ increased at first and then decreased. The explanation to this trend is that when small Q_f is supplied, the powder near riser inlet is partly fluidized. As pressurizing gas flow rate (Q_p) increased, the m_s increased gradually, while μ increased at first and then decline. The increase in Q_p could increase the blow tank pressure slightly, hence, m_f increases. The m_s and m^* for glass beads are higher than those for pulverized coal. This may be due to better flow ability of glass beads. There was a critical surface near the conjunction of cylindrical and conical part. When powder bed height was above critical surface and Q_f was low, funnel flow was observed. When Q_f was large enough, the flow pattern changed to mass flow. When the powder bed height was below the critical surface, the flow pattern was funnel flow. With further decrease of the powder height to near the riser inlet, the remaining powder was intensely fluidized and bubbles could be observed.

Ratnayake et al. (2008) obtained a relation to calculate the pressure drop at the entry section of pipeline from a top discharge blow tank in pneumatic conveying systems. Materials used in this study were: alumina, barite, cement, and ilmenite. In this study a theoretical model was obtained to predict the pressure drop at the entry section of pipe using Buckingham π theorem of dimensional analysis approach. The eleven variables were used for this purpose and a functional relationship was obtained between them. Then experimentation was done and factors that relate the different variables with pressure drop were found. After the relation for pressure drop was obtained, further experimentation was done by taking the pipes of different diameters and with different materials, pressure drops were recorded at the entry of pipe. For the same experiments pressure drop was also obtained theoretically by the previously obtained relation and validation of results was done. It was found that predicted values of pressure drop has an accuracy level of 15% for alumina, barite, and cement, while much better results of 10% was obtained for ilmenite.

Wypych et al. (2006) did the study of solid mass flow rate (m_s) capacity of drop through rotary valve and bottom discharge blow tank feeders through the common conveying line with same material. Mono sized poly pellets with properties: $d_s = 5$ mm, $\rho_{bl} = 565$ kg/m^3 and $\rho_s = 918$ kg/m^3 were used as material. For the rotary valve variable speed drive was used and it was found that m_s increased as the speed of rotor increased up to a certain speed of rotor and then it remained constant. The reason for m_s to not increase after certain value was found to be carryover losses and air leakages through casing and rotor tip of rotary valve. It was found that due carryover losses the pressurized conveying air reaches the discharge hopper and provides resistance to flow of material. Also, with increase in the speed pockets of valve will not get the sufficient time to get fill completely. Several experiments were also performed by varying top air and conveying air. It was found out that m_s obtained with blow tank are much higher than m_s obtained with rotary valve for same amount of air supply. A novel method for increasing the m_s of rotary valve was used in which it was found that by pressurizing the top side of rotary valve up to a pressure equal to the back pressure of conveying line, m_s of rotary valve can be increased but still it is less than the m_s of blow tank for same amount of air supply.

Wypych (1999) studied the design and requirements for long distance and large throughput pneumatic conveying. In this study the author has tried blow tank designs to provide an efficient and controlled material discharge; semi empirical techniques to predict pressure drop with better accuracy; optimization of stepped-diameter pipelines to minimize air flow, pressure, wear and power; and back-pressure unblocking techniques. Here three different pipeline configurations were used with three different blow tank designs and then experiments were performed with different fly ash samples. Also, six different configurations were used for stepped diameter pipelines and experiments were performed to find the optimal stepped pipeline configuration. It was found that blow tank with cone dosing valve systems provide an effective method to control and meter the discharge rate of material into the pipeline. It was seen that if stepped diameter pipeline configuration is designed properly tremendous amount of power can be saved. Also, the back pressure unblocking system used would reduce the downtime in the event of blockage.

Jones et al. (1987) did the comparison of performance of top and bottom discharge blow tank in this study. The experimentation was done on a pilot scale facility using a blow tank that could be arranged in both top and bottom discharge configurations by doing the certain modifications in pipeline geometry. Blow tank characteristics were presented for pulverized fuel ash in both top and bottom discharge configuration. The conveying plant used was batch type system. It was found that for top discharge configuration conveying characteristics covers a greater range of conveying conditions than bottom discharge configuration. Also, the much higher discharge is obtained with the top discharge arrangement than with bottom discharge arrangement. It was seen that there is no significant difference in pressure and energy required to convey a product through pipeline at a given product flow rate and phase density in both the configurations.

McLean (1985) used the design principles that are used for designing the gravity flow bins by modifying these in order to account for the pressure gradients that occur inside the blow tank, to systematically analyze blow tanks. The design principles presented were applied to both top discharge and bottom discharge blow tanks conveying both cohesive and non-cohesive bulk solid materials. It was noticed that the blow tank volumetric capacity, cone angle and outlet diameter have direct impact on the performance and different problems that occur in blow tanks, such as arching (bridging) and rat holing. In this study some design recommendations are also provided for the blow tank geometry design for both top and bottom discharge blow tanks. It is claimed by the author that application of these design recommendations will result in more efficient and less costly blow tank operations.

Tomita et al. (1978) studied the characteristics of top discharge blow tank conveying system experimentally. The test facility consisted of a semi cylindrical blow tank whose frontal plane is made up of transparent plate. The different materials tested were: cement raw materials, P.V.C. powder, phosphorus ore, glass beads, polyethylene pellets. It has been found that solids weight flow rate is related to the air velocity blown into the blow tank and is not influenced by the pressure drop characteristic of the pipeline. The tank pressure required for the transport is fixed by both pressure drop characteristic of pipeline and solids weight flow rate. The solids flow pattern in the blow tank is different for fine particles and granular solids. In case of fine particles solids flow into the pipe in a bloc. On the other hand, in granular solids, individual particles flow into the pipe continuously. At lower blowing air velocities, the solids weight flow rate increases in proportion to the velocity. With further increase in velocity the solids in the vicinity of nozzle are fluidized and with the occurrence of bubbling phenomenon the rate of increase of solid weight flow rate is slowed down.

Lech (2001) defined theoretical model to measure mass flow rate in vertical pneumatic conveying of solids and validated the calculated results with experimental results. The materials conveyed during testing are: sand, polyethylene cube and P.V.C. powder. The measurement method described is recommended for vertical conveyors transporting solid where measurement points were situated in a stable region of flow, for relatively high velocities and high solid concentrations.

Arakaki et al. (2010) presented a model to calculate mass flow rate of solids in pneumatic conveying systems, based on air flow and pressure measurements. The model is based on the principle of conservation of mass and is applied in a horizontal straight pipe section. The model has been validated with data from two different blow tank conveying systems in both dense and dilute-phase conveying. Different test materials used for validation of model were: alumina, barite, cement and dextrose. The assumptions made to derive the model are: isothermal conditions, no accumulation of mass in pipe section, steady state, one dimensional flow, velocity of mixture is same as the velocity of air only, uniform gas and solid velocity over the cross section of pipe and compressible flow.

2.8 Models for solids friction

An accurate estimation of total pipeline pressure drop is important for reliable design of pneumatic conveying systems. Equation (2.1) has been given by Barth (1958) to calculate the pressure drop for straight horizontal sections. The applicability of this equation was originally thought to be for dilute-phase conveying. However, this has been used by many researchers such as Stegmaier (1978), Weber (1981), Rizk (1982), Wypych (1989), Pan (1992), Pan and Wypych (1998) and Jones and Williams (2003) to predict the pressure drop for dense-phase flows. The large volume of data related to modeling of solids friction is available for fly ash, however not much work has been carried for cement till date. Hence, an effort is made to select some specific solids friction models for cement and evaluate these with experimental results. A new model for cement has also presented.

$$\Delta P = \left(\lambda_f + m^* \lambda_s\right)\left(\frac{L}{D}\right)\rho\left(\frac{V^2}{2}\right) \tag{2.1}$$

Jones and Williams (2003) conveyed different powders (iron powder, copper ore, pulverized fuel ash and flour) in fluidized dense-phase through a 53 mm I.D. and 50 m long pipeline having 9 bends. Using the back calculation method on the experimental data to obtain straight pipeline pressure drop, they developed a model for solid friction factor using straight pipe pressure drop data, as given in equation (2.2).

$$\lambda_s = 83\ (m^*)^{-0.9} {Fr_i}^{-2} \tag{2.2}$$

Stegmaier (1978) used the four dimensionless parameters ($m^*, Fr_m,\ Fr_i\ and\ \frac{D}{d_s}$) to obtain a power function based model for solid friction factor, as presented in equation (2.3). Model was obtained from the data of various fine and coarse particles such as fly ash, alumina, quartz powder and sand catalyst over the range of pipe sizes.

$$\lambda_s = 2.1\ (m^*)^{-0.3} {Fr_m}^{-2} {Fr_{sd}}^{0.5} (D/d_s)^{0.1} \tag{2.3}$$

Wypych and Arnold (1984) tested seven different materials to check their suitability of conveying in fluidized dense-phase. Authors found cement, fly ash and pulverized coal as the potential candidates for fluidized dense-phase conveying. They experimentally determined the blockage boundary for these powders using three different diameter and four different lengths pipelines.

Pan and Wypych (1998) conducted testing on four different fly ash samples using different test rig combinations. Combining the data of all the samples, two different models for straight pipe solids friction and bend solids friction were obtained, as given in equation (2.4) and (2.5), respectively.

$$\lambda_s = 3.2343 (m^*)^{-0.47} {Fr_m}^{-1.56} {\rho_m}^{-0.43} \tag{2.4}$$

$$\lambda_{bs} = 0.0097 (m^*)^{0.57} {Fr_{bo}}^{0.97} {\rho_{bo}}^{-0.62} \tag{2.5}$$

Chamber and Markus (1986) provided an expression to predict the pressure drop across bends. This equation (2.6) does not take particle properties, location and orientation of bends into account and its more of a general purpose model.

$$\Delta P_b = NB(1 + m^*)\rho V^2/2 \tag{2.6}$$

From the above studies, it can be concluded that the various models for solids friction given by different researchers were not evaluated under-scale up condition of lengths and diameters for their accuracy. Hence, it is evident that further studies are needed to be conducted to model the solids friction for such flows.

CHAPTER 3: EXPERIMENTAL WORK

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 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. Schematic of test facility used for cement conveying and to perform experiments at different blow tank initial pressures, is shown in Figure 3.1. The detailed schematic of blow tank showing its aeration is given in Figures 3.2 and 3.3. 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 was installed in compressed air line before blow tank to set the maximum pressure and to vary the air flow rates over 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 the material into conveying pipeline. 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, the 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^{o} bends of 1 m radius of curvature. Static pressure measurement point P4 was used to measure the total pipeline pressure drop.

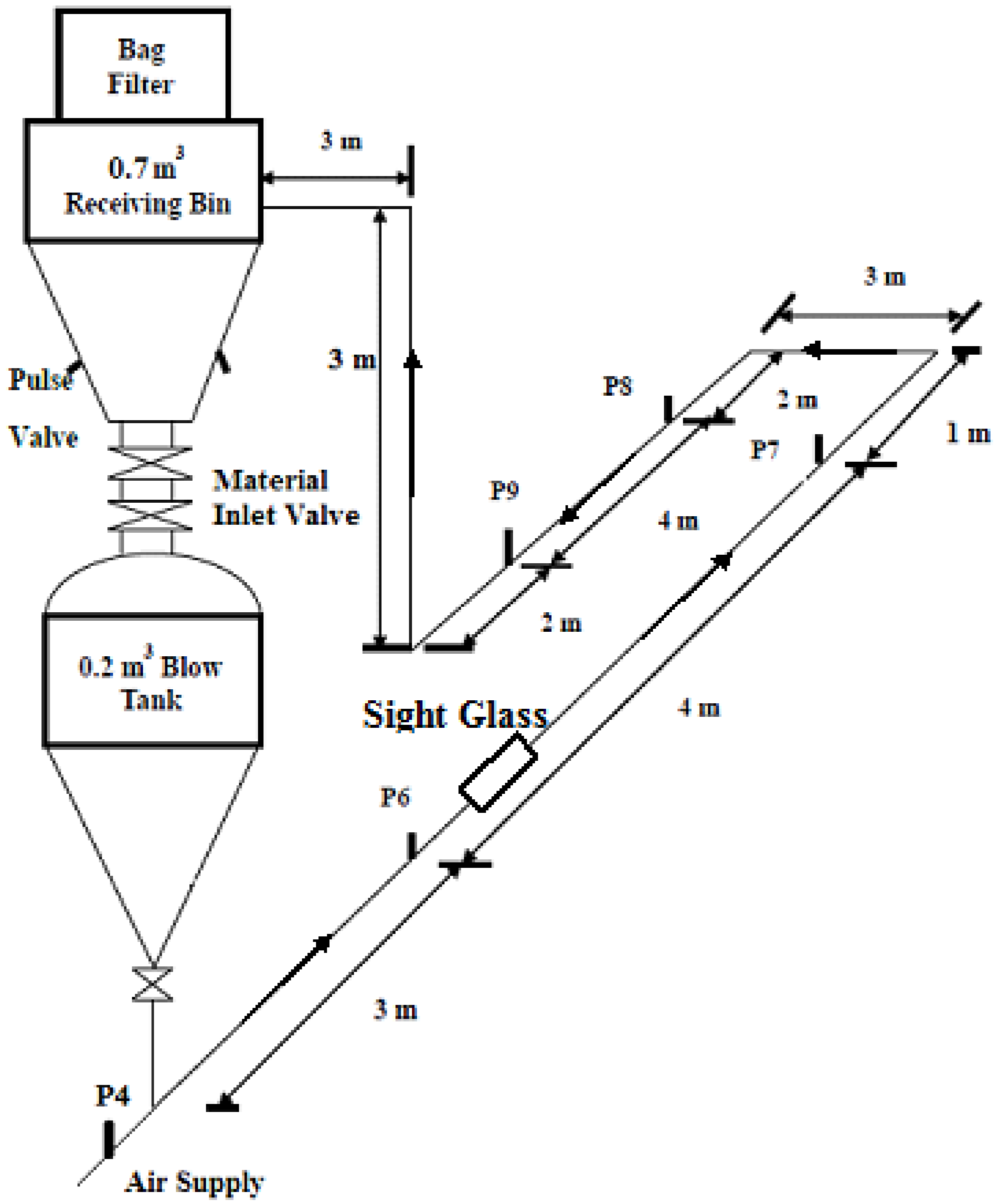

Figure 3.1: Schematic of experimental set up (54 mm I.D. × 24 m long pipe)

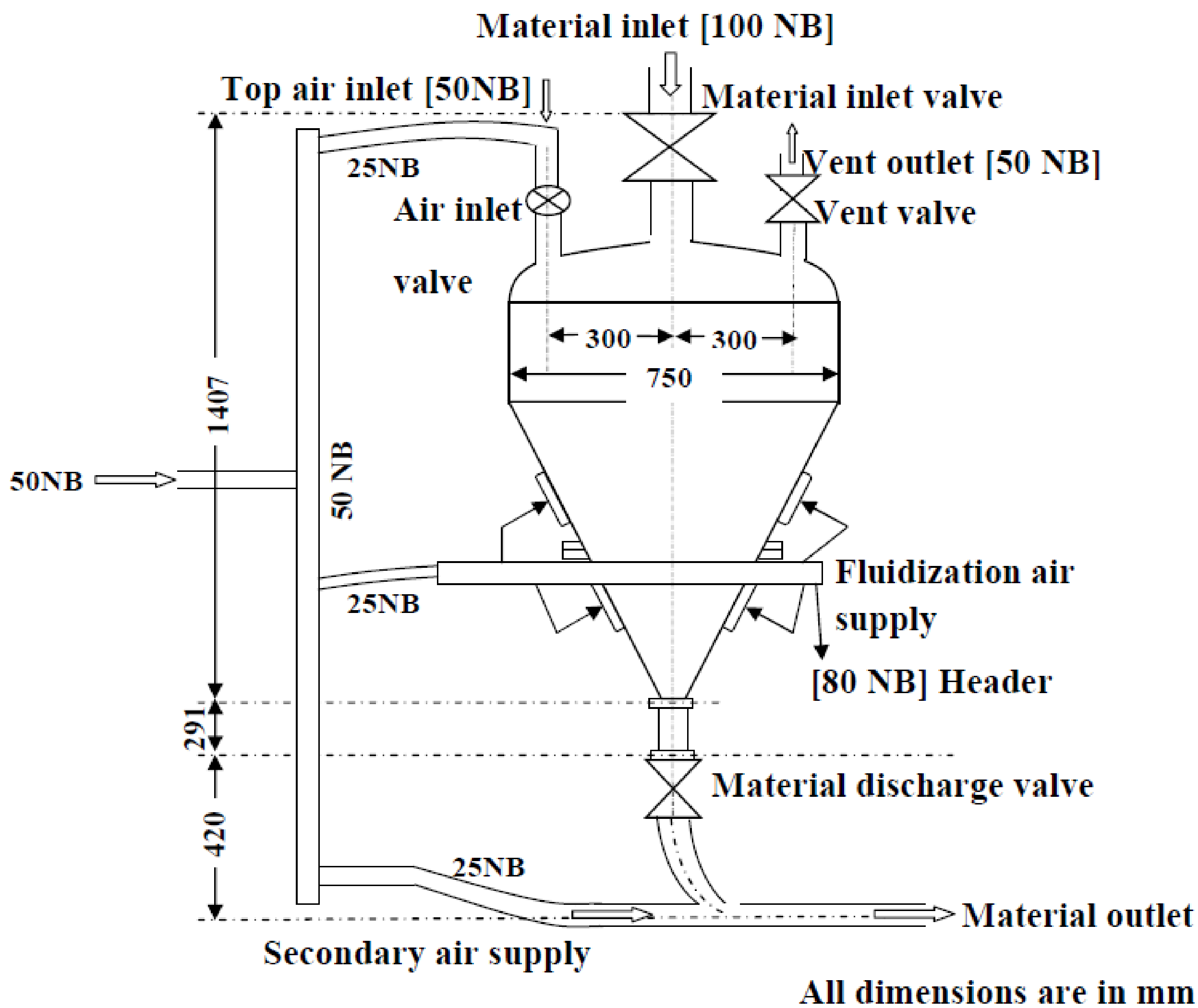

Figure 3.2: Schematic of blow tank

All other pressure transducer (P6 to P9) was 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 consist 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 channel 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 same material.

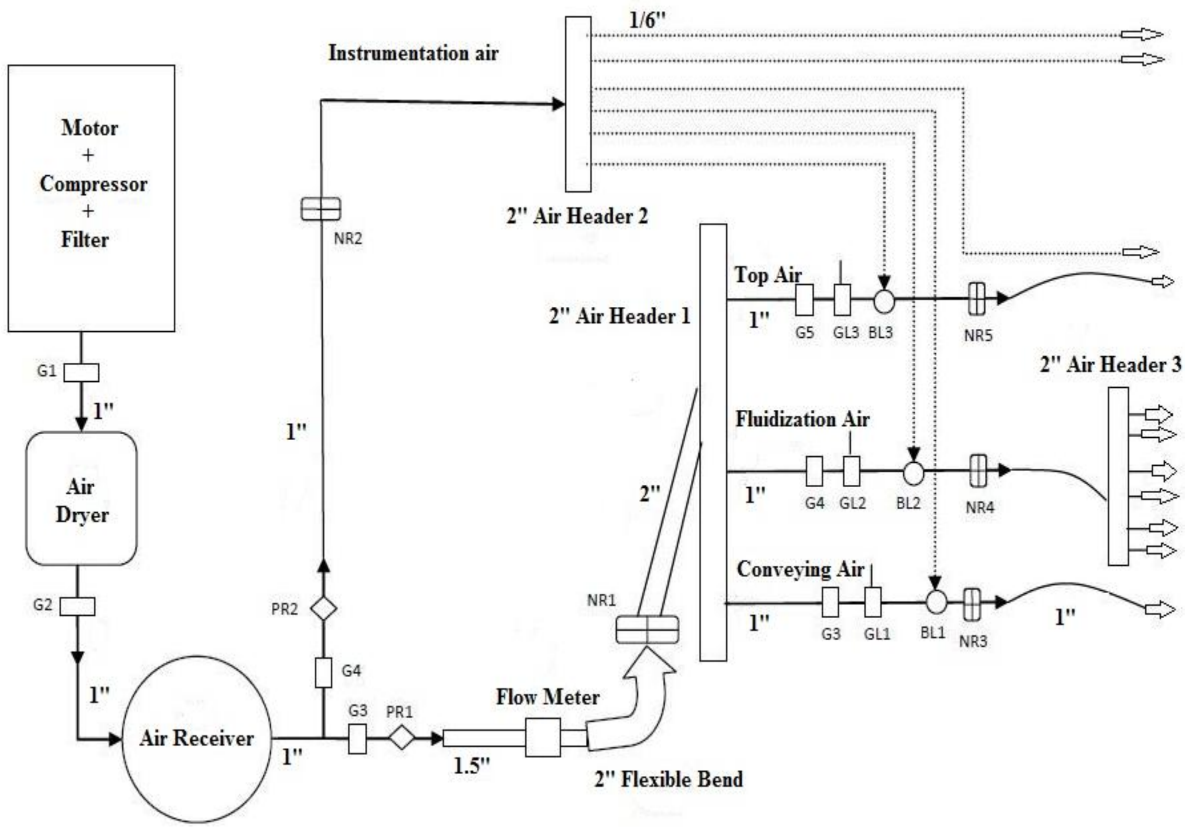

Figure 3.3: Piping and instrumentation diagram for compressed air

Cement was conveyed in all the pipelines for different air and solid mass flow rate. Flow visualization through sight glasses confirmed the fluidized dense-phase conveying of cement. 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, did not completely return to the 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.

Properties of test product:

Test data of cement was used for the purpose of modelling and evaluation of solid friction factor models. Blow tank characteristics were also developed based on same test data. Physical properties of cement are listed in Table 3.1.

Table 3.1: Physical properties of cement

Product	**ρ_s (kg/m^3)**	**ρ_{bl} (kg/m^3)**	**d_{50} (μm)**
Cement	3060	1070	14

Particle density was measured using pycnometer and particle size distribution was determined using laser diffraction analyzer.

3.2 Calibration Procedure

The load cells, pressure transducers and flow meter were calibrated before performing experiments using standard calibration procedure as described by Mallick (2010). Calibration graph for pressure transducer P4 and P6 are shown in Figure 3.4 and 3.5. 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.

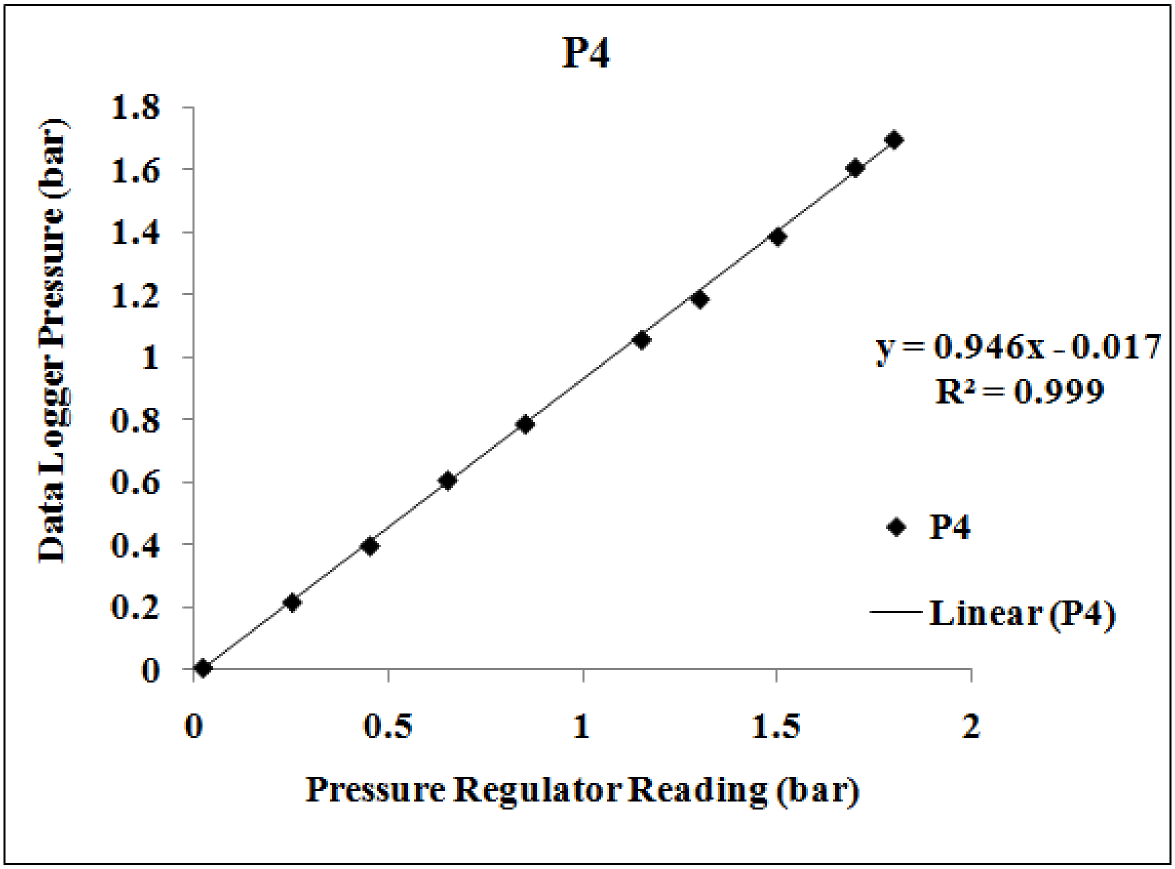

Figure 3.4: Calibration curve for pressure transducer P4

The standard calibration procedure for pressure transducers is given below:

(a) The pressure transducers were installed at desired locations along the pipeline and connected to the data logger.

(b) Conveying pipeline upstream of the receiver bin was closed by using a blind flange.

(c) The pipeline was checked for air leakages by passing the air through it and then ball valve was opened to release the air.

(d) Pressure regulator was set to desired pressure value (e.g. 50 kPa) and then conveying pipeline valve was opened.

(e) A pressure gauge was used to measure pressure in the pipeline and simultaneously pressure transducer reading was also recorded from data logger.

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

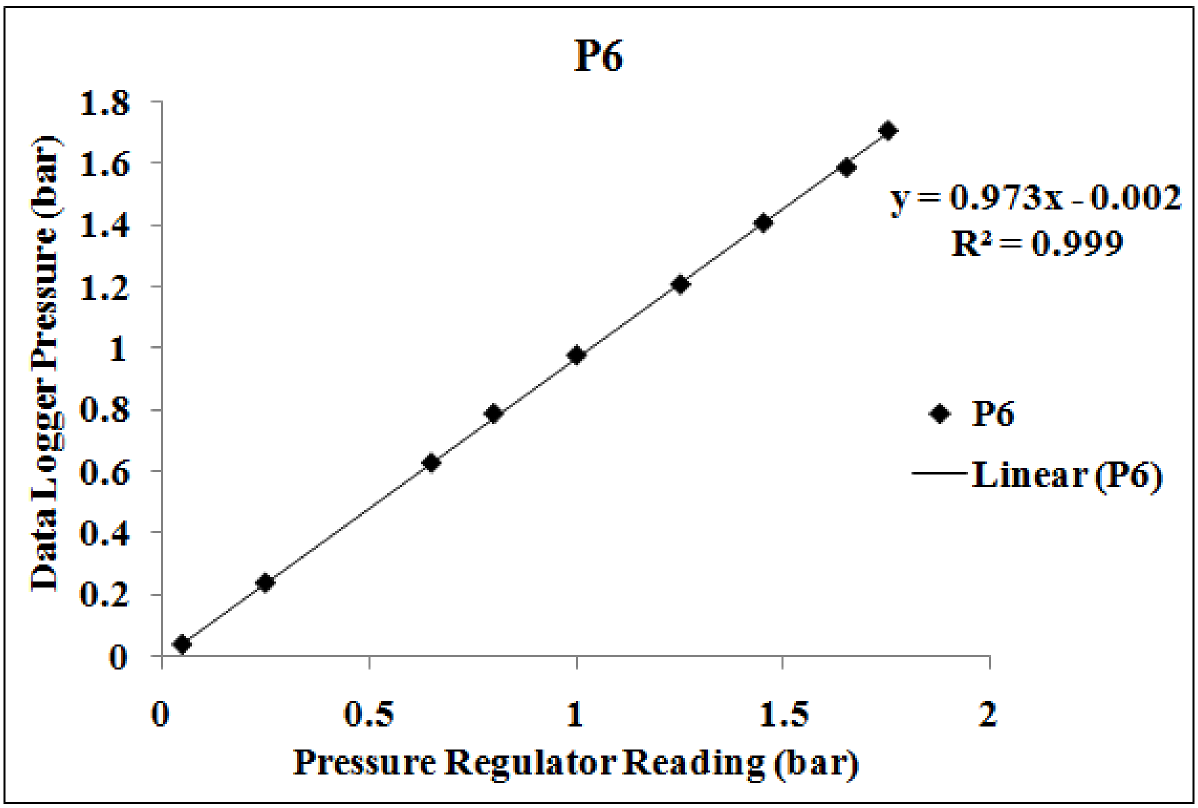

Figure 3.5: Calibration curve for pressure transducer P6

A vortex type air flow meter is used to measure the flow rate of supplied in a conveying cycle. This flow meter has a digital display, which shows the reading of volumetric flow rate of air, at the same time it also generates an analog signal, which is 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 is made in conveying pipeline and readings of flow meter were recorded simultaneously at its digital display and at data logger. Pressure data at inlet flow meter is 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. Calibration curve for flow meter is shown in Figure 3.6.

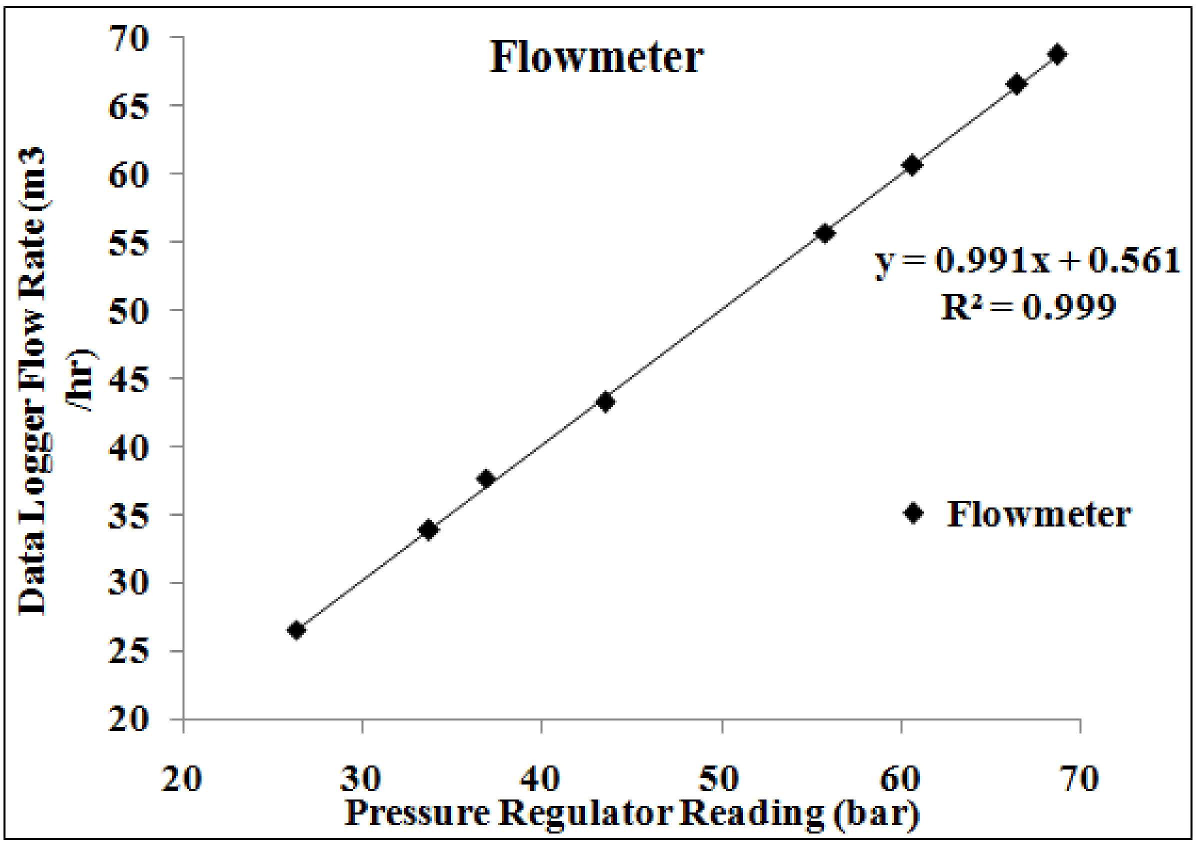

Figure 3.6: Calibration curve for flow meter

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

Each load cell has a maximum load bearing capacity of 500 kg. Four load cells were used to carry a combined weight of blow tank and material in it. Output from these four load cells were combined to give total load shared by each cell. The load cells generate a differential output voltage signal, which was fed to the data logger to calculate corresponding weight. Two such combinations were used to measure the material discharge rate. To calibrate the load cells, a known weight was put on the cells and its value is recorded by the data logger. Calibration curve for load cell 2 is given in Figure 3.7.

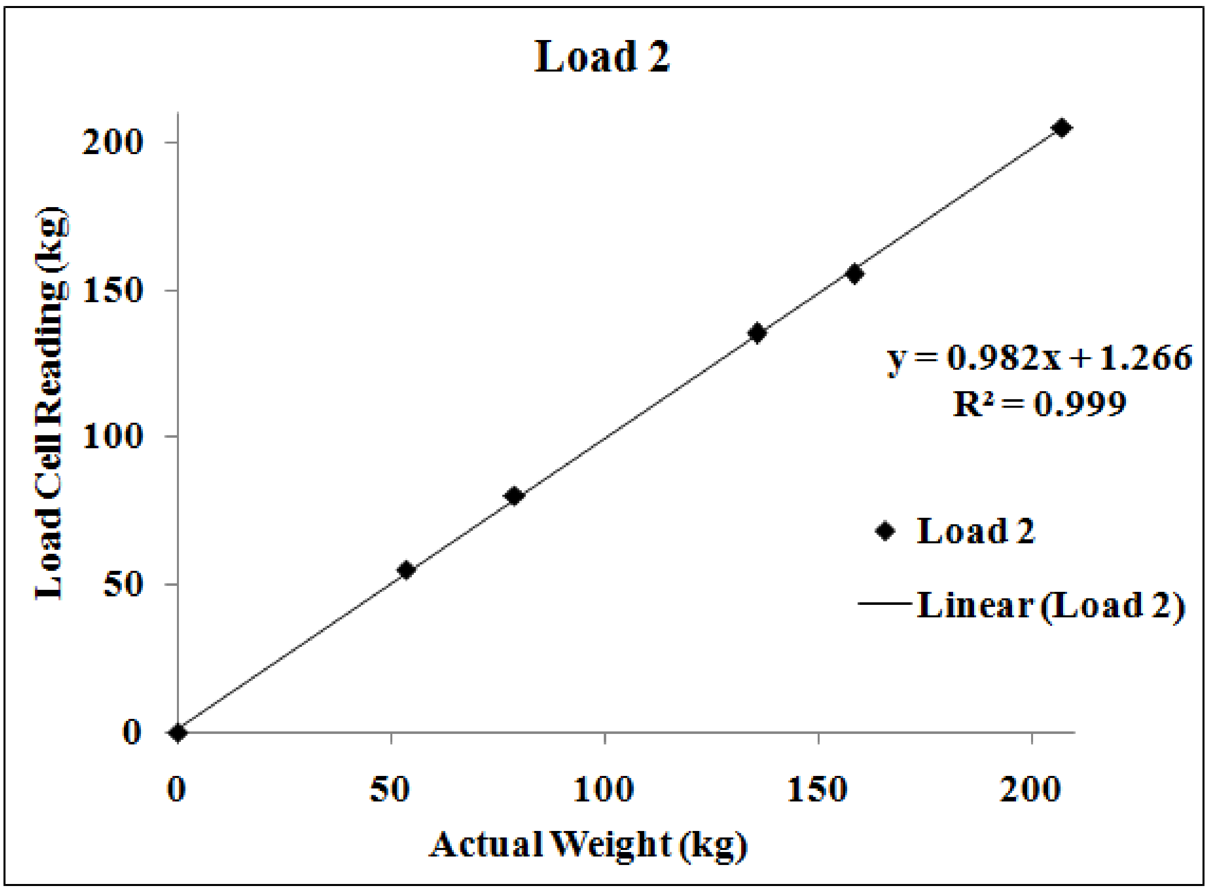

Figure 3.7: Calibration curve for load cell

3.3 Operational Procedure

A standard operational procedure was used to perform the experiments over 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 was 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) Compressor and drier were switched on and then air was allowed to reach the specified pressure in air storage tank.

(b) Now the process air and instrumentation air supply valves were turned on and the pressure of process air was set to desired value using pressure regulator, whereas, instrumentation air pressure was set to 5 bar (g).

(c) After that pneumatic panel and PLC panel were switched on and computer and data logger were checked for their functioning.

(d) All the transducers were calibrated before starting experiments.

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

(f) After the cycle was over, stop button was pressed in data logger and the pipeline was purged to clean it for next experiment.

(g) Globe valves settings were changed and the procedures were repeated to perform further experiments.

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

CHAPTER 4: BLOW TANK CHARACTERISTICS

Blow tank is an important component of any fluidized dense-phase pneumatic conveying system. The performance of whole pneumatic conveying system depends upon the performance of blow tank. As, blow tank controls the amount of material being fed into conveying pipeline, hence, it effects the pressure drop characteristics of pneumatic conveying systems because mass flow rate has significant effect on total pipeline pressure drop. Therefore, in the present study efforts have been made to present the effect of blow tank initial pressurization and aeration on solids mass flow rate for bottom discharge blow tank using cement as conveying material.

4.1 Effect of blow tank initial pressurization

Blow tank initial pressure has huge impact on the solids mass flow rate of material coming out of blow tank. Figures 4.1 to 4.4 shows the mass of solids in blow tank versus time at different blow tank initial pressures. It has been observed from Figure 4.1 that very high blow tank initial pressure has led to unsteady discharge of material from the blow tank. In this Figure, time span of 0 to 80 seconds represents the filling of blow tank and initial pressurization period and the remaining time on graph represents conveying period. During the conveying period four different slopes of mass versus time graph can be observed. In the time period between 80 to 100 seconds, about 80 kg of material was discharged from the blow tank, which led to very high tonnage of around 16.2 t/h, whereas from 98 to 125 seconds, about 6.2 t/h material discharge rate was obtained. This material discharge rate got further reduced as cycle time was increased. A very low tonnage of about 0.48 t/h was found near the end of conveying cycle. The high tonnage near the start of conveying was obtained due to flooding of materials at high blow tank pressures. The fluctuations in material discharge rate resulted in huge fluctuations in total pipeline pressure drop across the conveying cycle (Figure 4.5), causing very high total pipeline pressure drops near the start of conveying cycles.

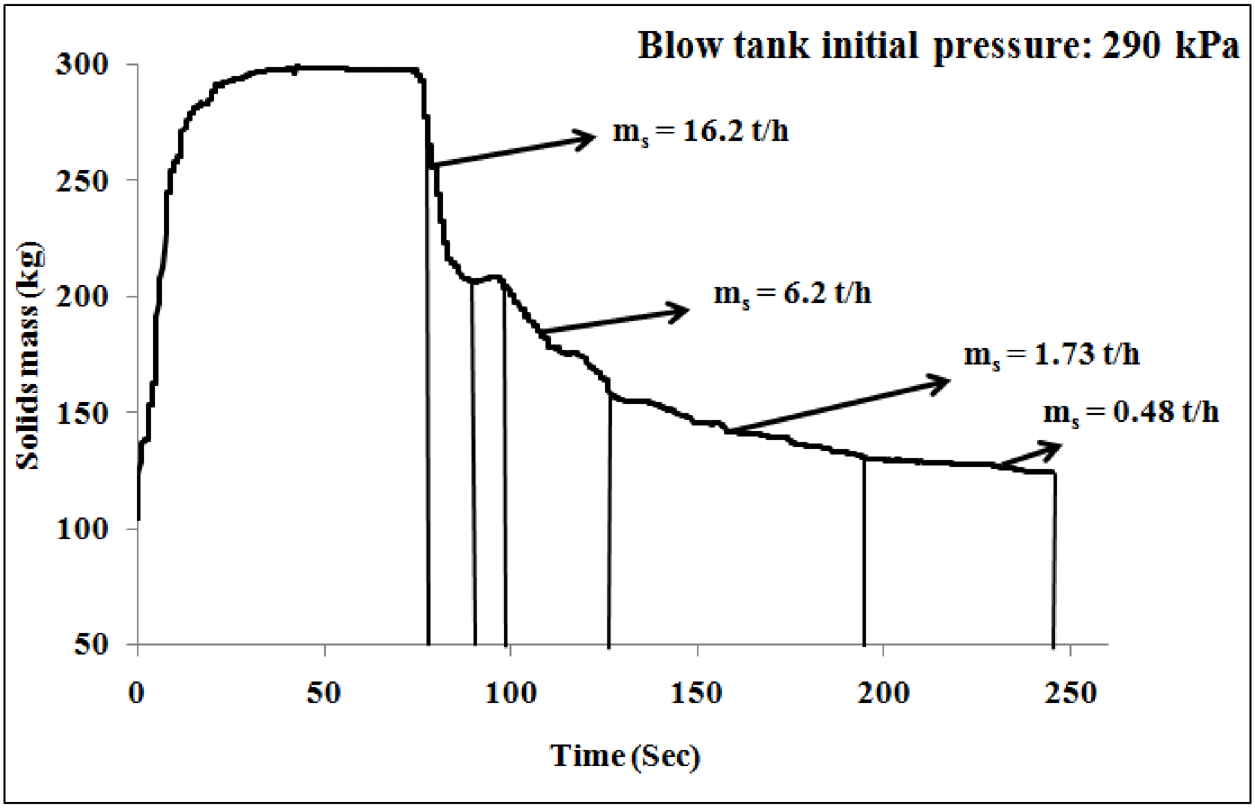

Figure 4.1: Solids mass versus time, cement, 54 mm I.D. × 70 m long pipeline, initial BTP: 290 kPa

The high tonnages during the start of conveying cycles ensured fluidized dense-phase conveying of cement, whereas, near the end of conveying cycles, low tonnages resulted in dilute-phase flow and led to excessive wear of pipelines. This increases the operational, maintenance and initial cost of the pneumatic conveying systems. Figure 4.2 shows the mass versus time graph for blow tank at blow tank initial pressure of 205 kPa. In this graph a smooth and steady discharge of material can be observed during the whole conveying cycle and a constant material discharge rate of about 4.13 t/h is obtained.

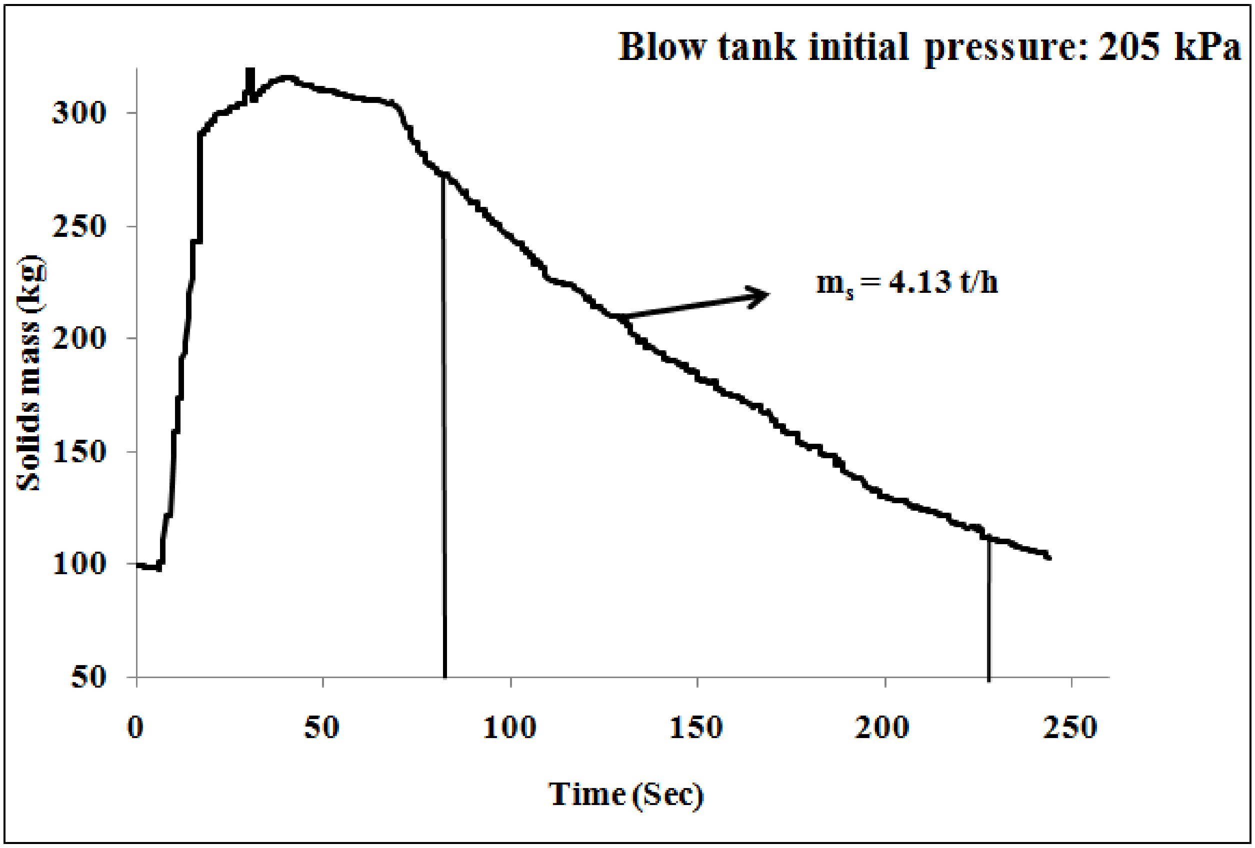

Figure 4.2: Solids mass versus time, cement, 54 mm I.D. × 70 m long pipeline, initial BTP: 205 kPa

It is observed from Figures 4.1 and 4.2 that in both cases, mass of about 180 kg was discharged from the blow tank, but in the first case it discharged with fluctuating tonnages, whereas in the second case relatively more uniform material discharge rate was observed. The constant material discharge rate in second case also resulted in smooth and steady variation of total pipeline pressure drop. From this discussion, it can be concluded that 205 kPa is the optimum blow tank initial pressure when 280 kg of cement is there in the blow tank, for the blow tank used in this study. It is also observed from Figures 4.3 and 4.4 that, this value is not constant under all the operating conditions. This value of blow tank initial pressure changes with alteration in amount of material in the blow tank.

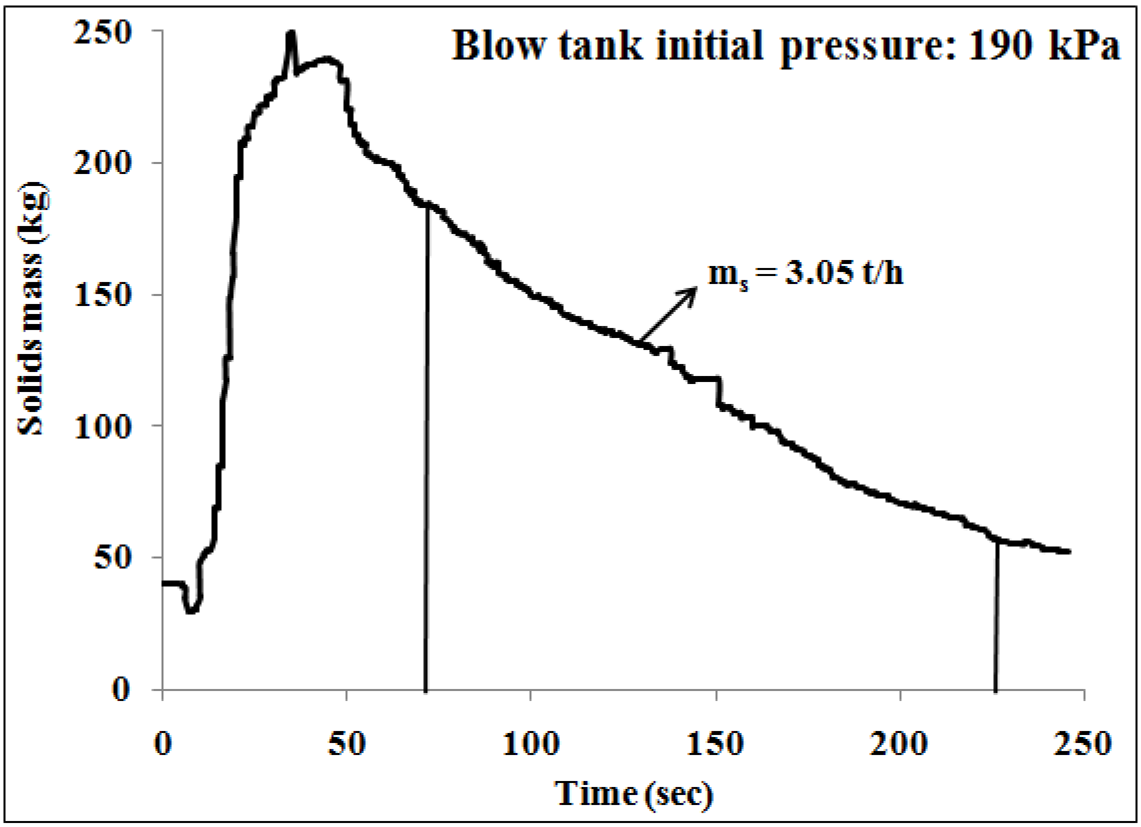

Figure 4.3: Solids mass versus time, cement, 54 mm I.D. × 70 m long pipeline, initial BTP: 190 kPa

In case of Figure 4.3 about 240 kg of cement was there in the blow tank and a smooth and steady material discharge rate of 3.05 t/h was obtained at blow tank initial pressure of 190 kPa, whereas, in Figure 4.4 mass of 160 kg was in blow tank, where blow tank initial pressure of 165 kPa gave constant material discharge rate of 2.95 t/h. It can also be concluded from this discussion that with decrease in blow tank initial pressure, material discharge rate also decreased.

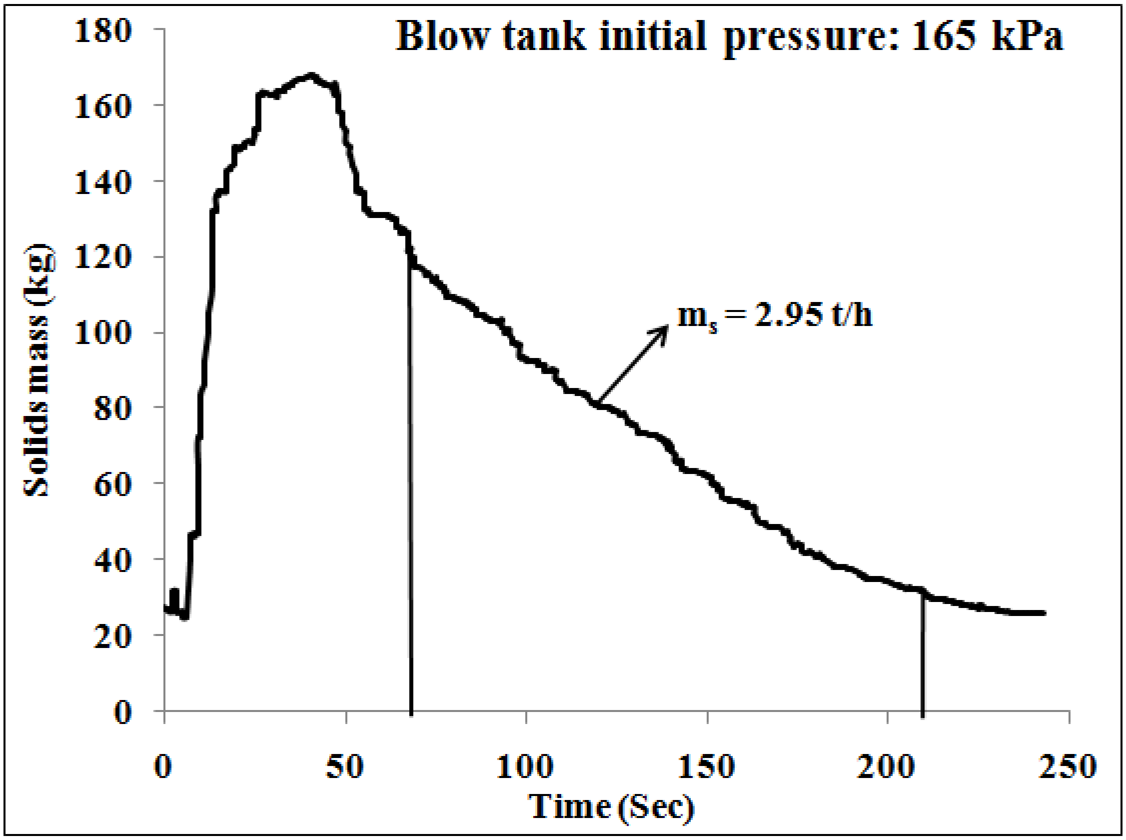

Figure 4.4: Solids mass versus time, cement, 54 mm I.D. × 70 m long pipeline, initial BTP: 165 kPa

4.2 Pressure fluctuations for steady versus unsteady discharge

Figure 4.5 shows the pressure fluctuations of total pipeline pressure drop for two different blow tank initial pressures (290 and 205 kPa).

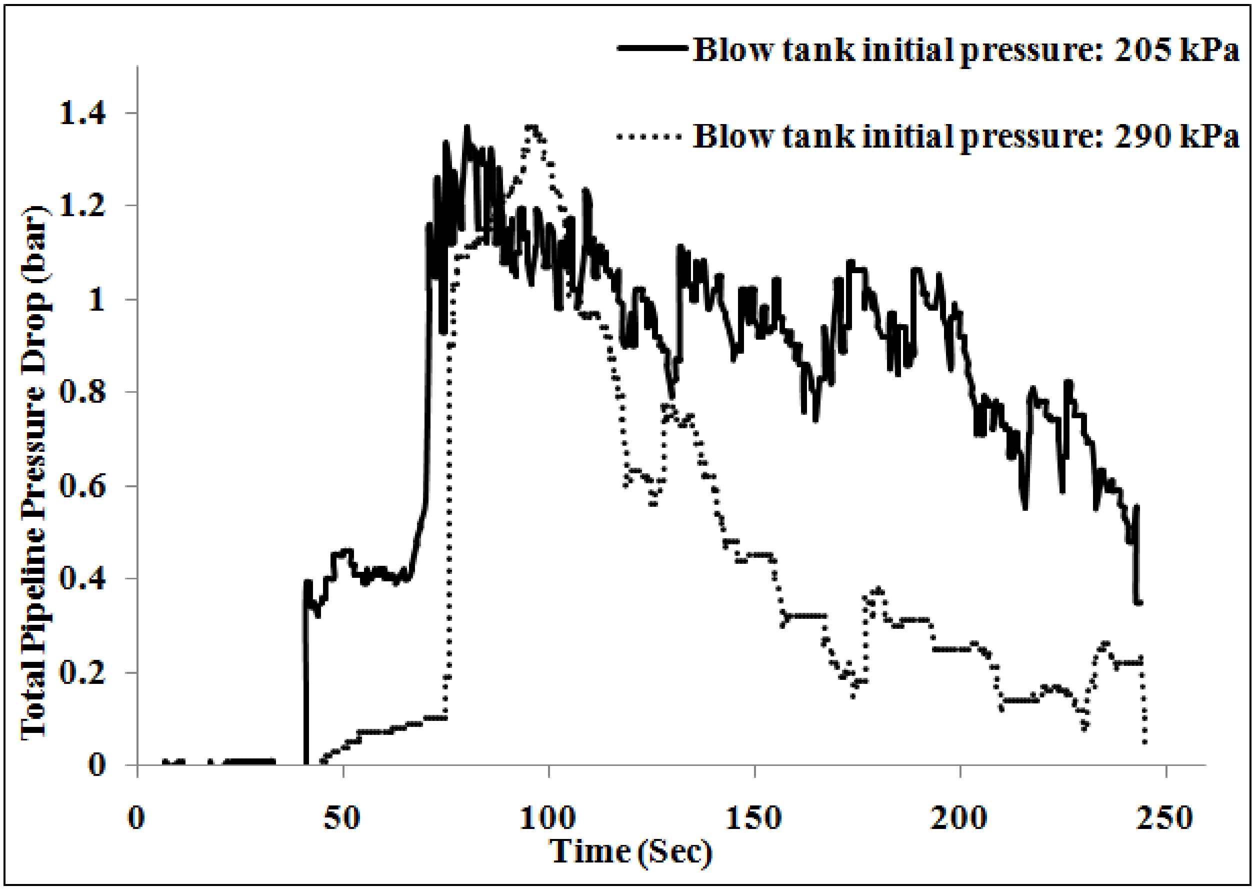

Figure 4.5: Comparison of pressure fluctuations for steady versus unsteady discharge of material

Pressure fluctuations at 205 kPa have shown more steady state in comparison to fluctuations obtained at 290 kPa. For the case of unsteady discharge (Figure 4.1) the total pipeline pressure has also shown decreasing trend with time, whereas for the second case pressure drop has remained almost constant and it was decreased near the end of cycle due to injection of more amount of air.

CHAPTER 5: MODELLING AND VALIDATION OF SOLIDS FRICTION FACTOR FOR CEMENT

Various empirical correlations were given by different researchers in past few decades for solids friction factor. Two such models given by Jones and Williams (2003) and Stegmaier (1978) were evaluated with experimental pneumatic conveying characteristics to predict total pipeline pressure drop for cement 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). Further a general power function based model was employed to model the solids fiction factor for straight pipes using straight pipe data of 54 mm I. D. × 24 m long pipeline and also evaluated for all other pipelines.

5.1 Modelling solids friction factor for straight horizontal pipe

A general power equation (5.1) based model was employed to model the solids fiction factor for straight pipes. This relation has the same format as used by Pan and Wypych (1998), Jones and Williams (2003) and Jones and Williams (2004) to model solids friction, hence used here. The relation is given in equation (5.1),

$$\lambda_s = K(m^*)^a {Fr_m}^b \tag{5.1}$$

where, K is the constant of the power function for a straight pipe, a and b are the exponents of the power function, and Fr_m is the mean Froude number of the flow. To obtain the exponents, testing of cement was performed at Laboratory for Particles and Bulk Solids Technologies, Thapar University, Patiala; through 54 mm I.D. × 24 m long pipeline. During testing, total pipeline pressure drop was recorded by conveying cement over wide range of air flows from fluidize dense-phase to dilute-phase. Straight pipe pressure drop was obtained using back calculation method by subtracting the vertical, acceleration and bend losses from total pipeline pressure drop. The back calculation method was used because this was used by the many previous researchers (such as Jones and Williams, 2003; William and Jones, 2004). Bend pressure losses were obtained by using Chamber and Markus (1986) formula. This straight pipe pressure drop data is further used to obtain the constants of equation (5.1), using regression analysis in Microsoft Excel. The obtained equation (5.2) is given as,

$$\lambda_s = 0.398(m^*)^{0.153} {Fr_m}^{-1.243} \qquad [R^2 = 0.955] \qquad (5.2)$$

The higher value of R^2 signifies good correlation of experimental data with model. This model was also used to predict total pipeline pressure drop for other three pipelines (43 mm I. D. × 24 m long, 54 mm I. D. × 70 m long and 69 mm I. D. × 24 m long) and evaluated with experimental results.

5.2 Evaluation of existing models for solids friction

For 54 mm I.D. × 70 m long pipeline:

Experimental PCC along with the total pipeline pressure drop lines predicted by different models (Jones and Williams, 2003; Stegmaier, 1978; New model) are shown in Figures 5.1 and 5.2 for

54 mm I.D. × 70 m long pipeline. It can be observed from Figure 5.1 that no model has shown agreement with experimental data at 1 t/h.

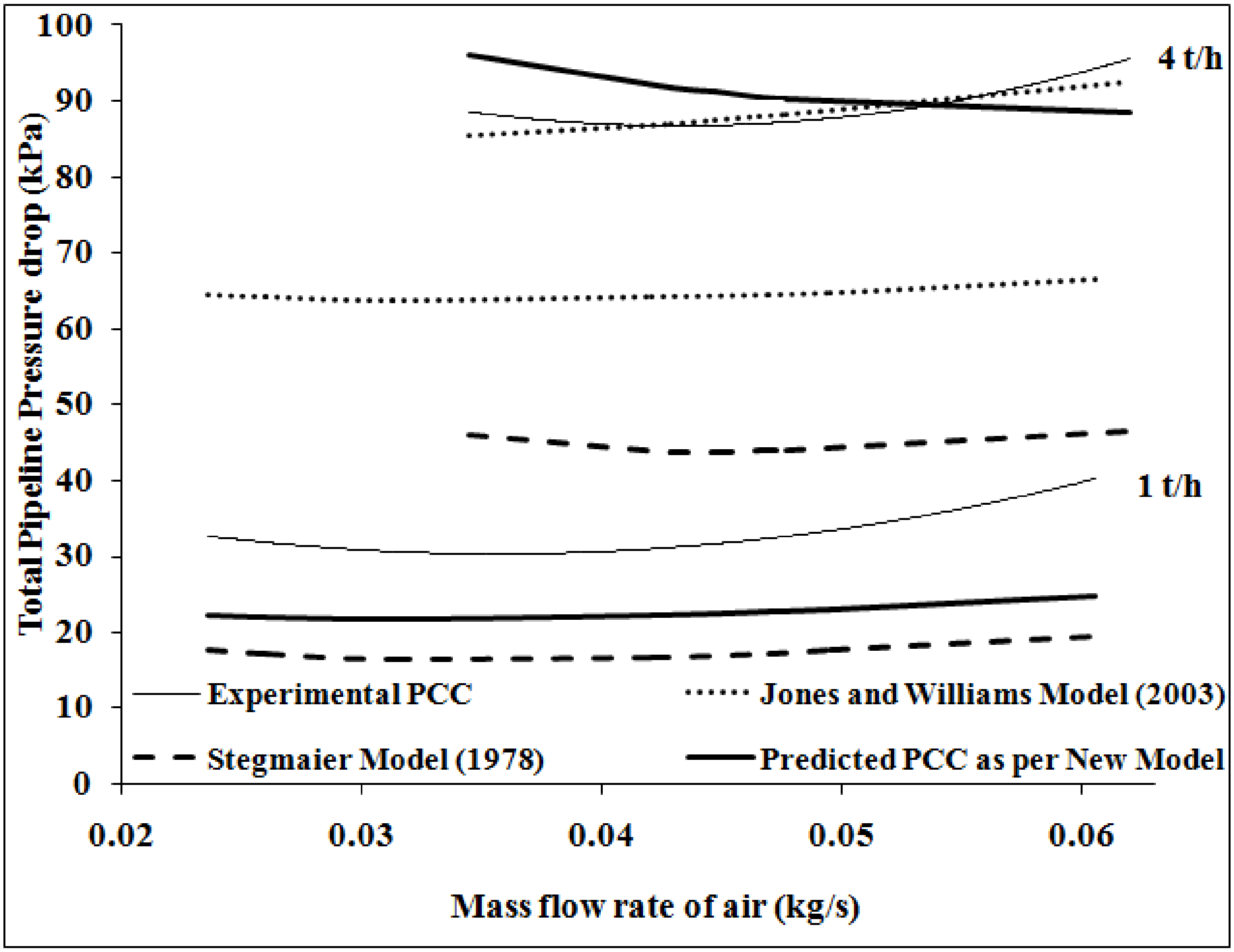

Figure 5.1: Experimental versus predicted PCC, cement, 54 mm I.D. × 70 m long pipe

Jones and Williams (2003) have over-predicted the pressure drop, whereas other two models have shown under-prediction, but still the new model provides results that are closest to the experimental predictions. Jones and Williams (2003) have also shown over-predictions at 2.5 t/h, but the margin of over-prediction is less in comparison to 1 t/h. New model has shown good predictions with percentage errors less than 5% at 2.5 t/h. Stegmaier (1978) has shown under-prediction at all three tonnages (Figures 5.1 and 5.2). The predictions by Jones and Williams (2003) have close agreement with experimental results at 4 t/h, whereas new model has shown over-prediction up to 0.053 kg/s air flow rate and under-prediction above this flow rate.

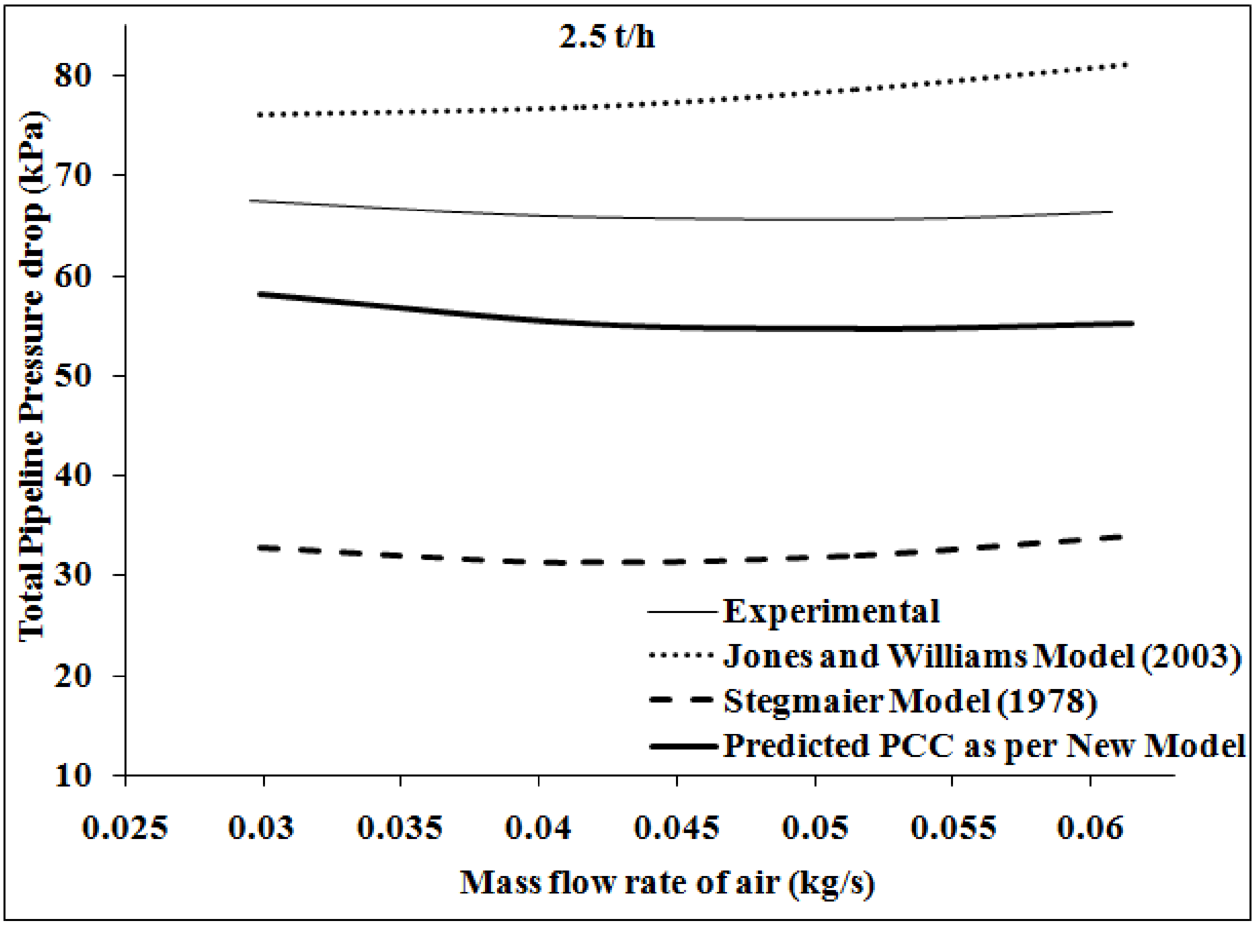

Figure 5.2: Experimental versus predicted PCC, cement, 54 mm I.D. × 70 m long pipe, 2.5 t/h

The maximum margin of over and under-prediction is 8.36 and 7.34%, respectively. Jones and Williams (2003) model has been developed from the data of powders having particle size (42 μm) greater than the size of product (cement: 19μm) tested in the study, so, this might have been the reason for deviation of results. It can also be observed from Figures 5.1 and 5.2 that, as the material discharge rate has been increased from 1 to 4 t/h, the margin of deviations between predicted and experimental results have decreased. The low tonnages in the present study might be the reason for deviations in results, because at low tonnages the self pushing effect of material does not come into effect and the total pipeline pressure drop goes up. Also, these small tonnages were obtained at same air flow rates as required for 4 t/h, so the mode of conveying might have transferred from dense to dilute-phase. As the models are empirical and specifically designed for dense-phase flows, thus the predictions from models have not shown agreement with experimental PCC.

For 69 mm I.D. × 70 m long pipeline:

Experimental PCC along with the total pipeline pressure drop lines predicted by different models are shown in Figure 5.3 for 69 mm I.D. × 24 m long pipeline. It can be observed that all the models have under-predicted the total pipeline pressure drop for both tonnages (i.e. 10 t/h and 13 t/h). Jones and Williams (2003) and Stegmaier (1978) have under-predicted the pressure drop by maximum margin of 60.2 and 58.66 %, respectively. New model has shown decreasing trend for total pipeline pressure drop with an increase in air flow rates. This model has shown good agreement with the experimental total pipeline pressure drop data near both sides of pressure minimum point for 10 t/h solids mass flow rate and same model also did similar predictions for solids mass flow rate of 13 t/h up to air mass flow rate of 0.04 kg/s. Jones and Williams (2003) and Stegmaier (1978) have shown similar trends with variations in air flow rates and the values predicted by these two models at all air flow rates are almost similar.

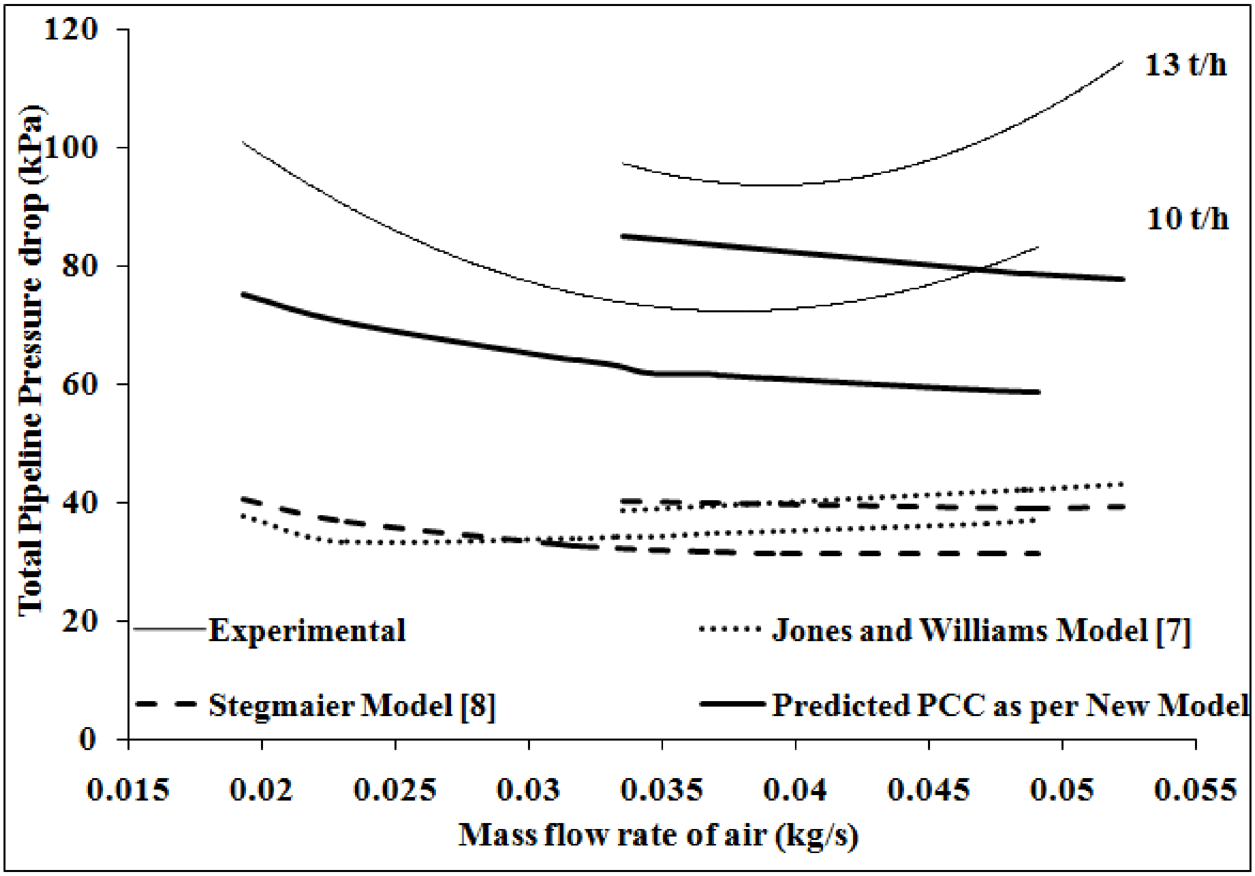

Figure 5.3: Experimental versus predicted PCC, cement, 69 mm I.D. × 24 m long pipe

The reasons for deviations in results with respect to experimental data might be the more number of bends in relatively small length pipeline, which influences the flow in straight pipeline sections and causes significant effect on straight pipeline pressure drop.

For 43 mm × 24 m long pipeline:

Experimental PCC along with the total pipeline pressure drop lines predicted by different models are shown in Figure 5.4 for 43 mm I.D. × 24 m long pipeline.

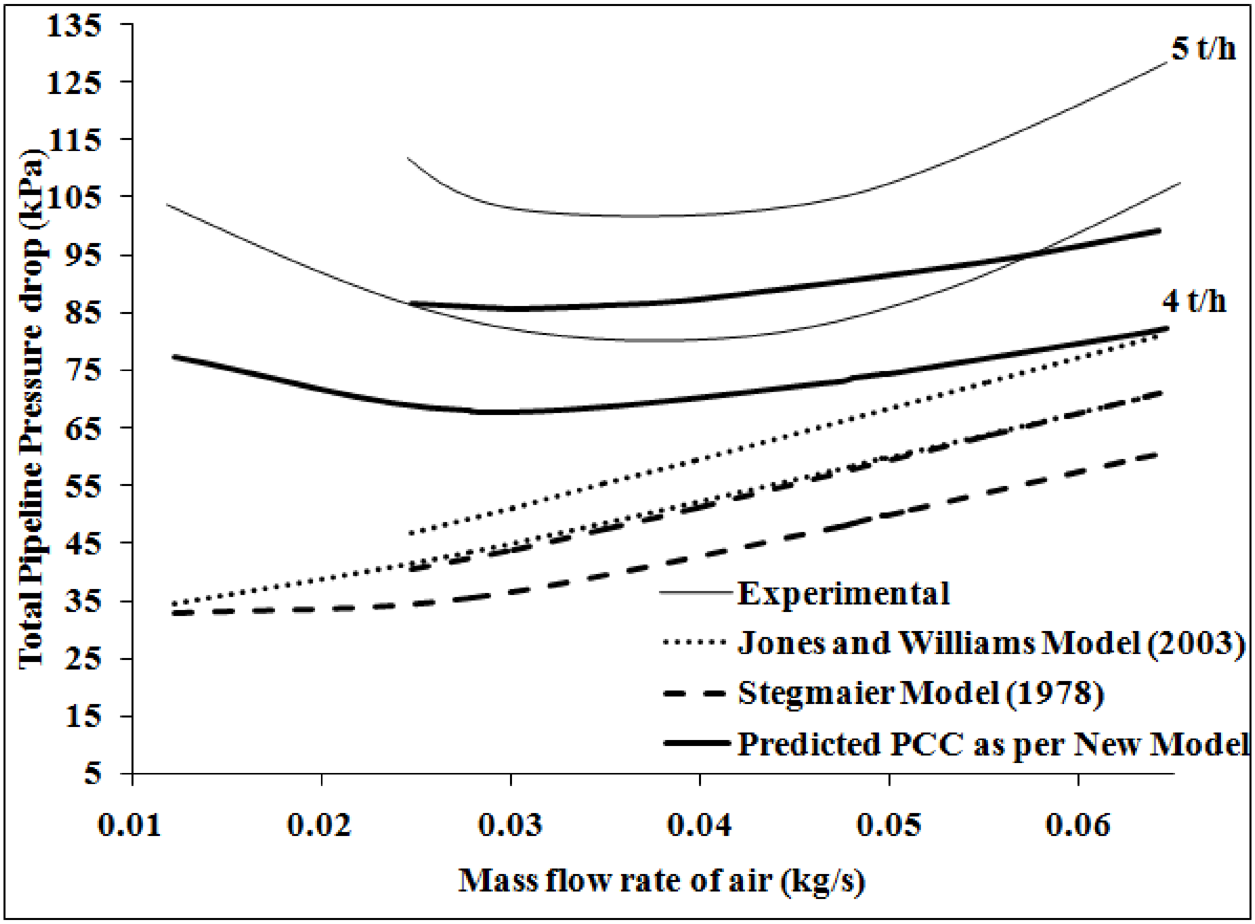

Figure 5.4: Experimental versus predicted PCC, cement, 43 mm I.D. × 24 m long pipe

It can be observed that all the models have under-predicted the total pipeline pressure drop for both tonnages (i.e. 4 and 5 t/h). Predictions by Jones and Williams (2003) and Stegmaier (1978) have shown increasing trend with increase in air mass flow rates, whereas, experimental pressure drop first decreased with increase in air flow rates, reached pressure minimum point and then again increased with increase in air flow rates above pressure minimum point. New model has shown similar trend to that of the experimental trend for both the solids mass flow rates. Predictions by this model were very close to the experimental results near both side of the pressure minimum point, whereas, same model has shown under predictions by great margin at low and high air flow rates. For 4 t/h solids mass flow rate, predictions by Stegmaier (1978) and Jones and Williams (2003) have shown close agreement between themselves up to the air flow rate of 0.025 kg/s. After this flow rate, Jones and Williams (2003) have predicted more total pipeline pressure drop in comparison to values predicted by Stegmaier (1978). Both Stegmaier (1978) and Jones and Williams (2003) have shown linearly increasing trends for total pipeline pressure drop with increase in air flow rates for solids mass flow rate of 5 t/h.

For 54 mm × 24 m long pipeline:

Experimental PCC along with the total pipeline pressure drop lines predicted by different models are shown in Figure 5.5 for 54 mm I.D. × 24 m long pipeline. It can be observed that all the models have under-predicted the total pipeline pressure drop for both tonnages (i.e. 5 t/h and 7 t/h) except new model. Jones and Williams (2003) have shown linearly increasing trend with increase in air mass flow rates for both solids mass flow rates. Stegmaier (1978) has also shown similar trend for solids mass flow rate of 7 t/h, whereas, same model has shown different trend at 5 t/h. Experimental total pipeline pressure drop curves have shown clearly defined pressure minimum point, similar point was shown by new model at same air flow rates. Jones and

Williams (2003) and Stegmaier (1978) have under-predicted the total pipeline pressure drop by maximum margin of 72.02 and 73.56%, respectively.

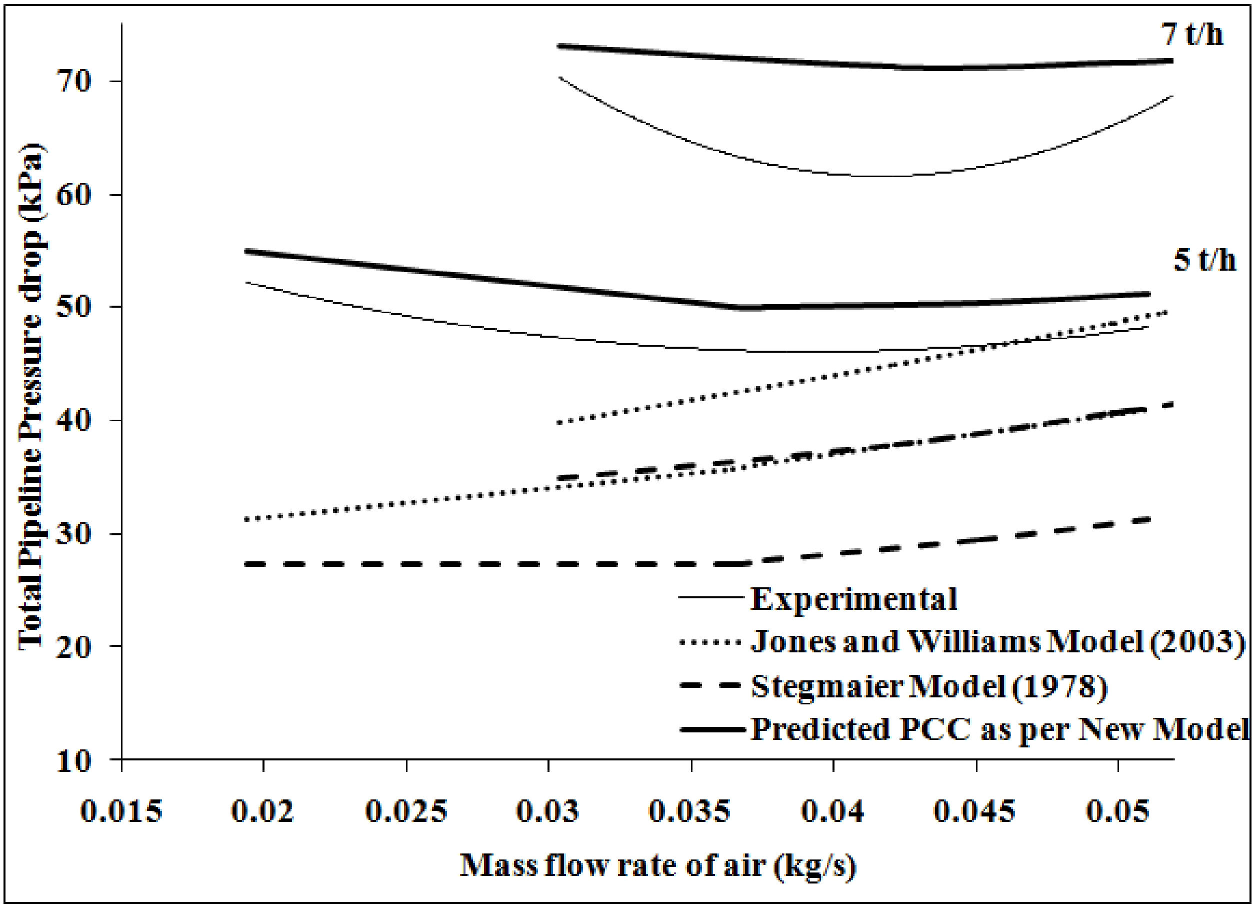

Figure 5.5: Experimental versus predicted PCC, cement, 54 mm I.D. × 24 m long pipe

Predictions by new model have provided good agreement with the experimental total pipeline pressure drop data. More deviations have been found near the experimental pressure minimum curve for solids mass flow rate of 7 t/h using new model. The new model has shown agreement with experimental results for this pipeline at both solids mass flow rates because this model was derived from the straight pipeline pressure drop data of same pipeline.

CHAPTER 6: CONCLUSION AND FUTURE SCOPE OF WORK

6.1 Conclusion

Two existing models and one new model for solids friction was compared with experimental total pipeline pressure drop PCC for cement using four different pipeline configurations. A pressure minimum point has been obtained in experimental total pipeline PCC for all the pipelines. It has been found that new model for solids friction has shown good agreement with experimental PCC for all the pipelines as compared to other existing models. Stegmaier (1978) has under-predicted the pressure drop for all the pipelines at different solids mass flow rates. Jones and Williams (2003) have shown good agreement with experimentally obtained total pipeline pressure drop for 54 mm I.D. × 70 m long pipeline at solids mass flow rate of 4 t/h, whereas for the same pipeline, this model has shown over-predictions at other material discharge rates. Same model has under-predicted the total pipeline pressure drop for all other pipelines at different material discharge rates. New model were found giving mixed predictions (i.e. over-prediction and under-prediction) for 54 mm I.D. × 70 m long pipeline, whereas same model has shown under-predictions for all other pipelines. It has been found that material discharge rate increases with increase in blow tank initial pressure. At the same time it has also been claimed that a very high blow tank initial pressure results in unsteady discharge of material from blow tank and very low blow tank pressure results in low material discharge rates, so blow tank must be pressurized to an optimum value of initial pressures.

6.2 Future scope of work

Further scope of work will include:

(i) The change in flow pattern along the length of pipeline is needed to be further investigated and its effect on solids friction must be included. Further studies should also need to be carried out to improve the models for solid friction factor for different products through different pipeline configurations for accurate and reliable design of pneumatic conveying systems.

(ii) An effort has been made to present the blow tank characteristics in this study, but, still there are many blow tank parameters such as side aeration, side discharge and relation of blow tank parameters with material properties and pressure drop characteristics, which can be investigated and adjusted to get maximum material discharge rates.

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APPENDIX: A1

Table A1: Pressure drop data, cement, 54 mm I.D. × 70 m long pipeline, 1 t/h

Air flow rate (kg/s)	Experimental pressure drop (kPa)	Jones and Williams (2003)	Stegmaier (1978)	New model
0.023583	38.29496	64.42418	17.58672	22.22605
0.026005	24.91	64.05699	17.0545	21.91775
0.031215	28.47059	63.73089	16.45468	21.61748
0.042068	40.06	64.04008	16.68296	22.06234
0.046952	25.52027	64.35343	17.19863	22.58812
0.049465	33.22162	64.65029	17.53585	22.91928
0.060508	40.5796	66.4772	19.47225	24.77056

Table A2: Pressure drop data, cement, 54 mm I.D. × 70 m long pipeline, 2.5 t/h

Air flow rate (kg/s)	Experimental pressure drop (kPa)	Jones and Williams (2003)	Stegmaier (1978)	New model
0.02988	58.5496	76.05491	32.80861	58.16854
0.041603	61.63	76.87024	31.26258	55.11616
0.051469	58.94776	78.67017	32.03389	54.62964
0.061455	58.76129	81.16802	33.85154	55.28437

Table A3: Pressure drop data, cement, 54 mm I.D. × 70 m long pipeline, 4 t/h

Air flow rate (kg/s)	Experimental pressure drop (kPa)	Jones and Williams (2003)	Stegmaier (1978)	New model
0.03447	88.6717	85.42277	46.00682	96.08552
0.042842	87.52679	86.91242	43.7837	91.73203
0.044688	82.2459	87.34759	43.78488	91.08363

0.046496	93.52137	87.80078	43.85299	90.53461
0.047606	84.20395	88.09765	43.92452	90.23668
0.06197	95.4578	92.5384	46.35428	88.45117

Table A4: Pressure drop data, cement, 69 mm I.D. × 24 m long pipeline, 10 t/h

Air flow rate (kg/s)	Experimental pressure drop (kPa)	Jones and Williams (2003)	Stegmaier (1978)	New model
0.019292	97.3	37.6715	40.71415	75.07957
0.023182	98.33333	33.42648	36.83405	70.40916
0.031191	67.34746	33.95573	32.81107	64.35173
0.031936	76.53191	34.04093	32.6	63.95373
0.03335	73.86364	34.21719	32.25241	63.25531
0.034608	71.2125	34.37298	31.99571	61.73126
0.037055	67.304	34.74113	31.61903	61.60762
0.039555	83.89286	35.15687	31.37492	60.80147
0.047245	80.875	36.59643	31.27894	59.1034
0.049133	80.45455	36.99055	31.36952	58.79824

Table A5: Pressure drop data, cement, 69 mm I.D. × 24 m long pipeline, 13 t/h

Air flow rate (kg/s)	Experimental pressure drop (kPa)	Jones and Williams (2003)	Stegmaier (1978)	New model
0.033528	97.21951	38.69003	40.18663	85.17052
0.048567	112.9538	42.15081	39.00352	78.65064
0.048603	105.7391	42.1605	39.00575	78.64165
0.04881	94.55263	42.18613	39.01879	78.59074
0.052311	115.243	43.14686	39.31502	77.75062

Table A6: Pressure drop data, cement, 43 mm I.D. × 24 m long pipeline, 4 t/h

Air flow rate (kg/s)	Experimental pressure drop (kPa)	Jones and Williams (2003)	Stegmaier (1978)	New model
0.012281	123.7838	34.63436	32.73314	77.41874
0.027871	71.93846	43.66316	35.4052	67.94781
0.047211	85.75	57.87857	47.81211	72.95042
0.048021	78.51376	58.49214	48.6042	73.66843
0.049576	83.91743	59.77742	49.7225	74.37468
0.049773	85.18571	59.92703	49.86438	74.46562
0.051056	78.59722	60.90415	50.79027	75.0758
0.063108	120.2748	70.15044	59.6651	81.32459
0.064616	122.8571	71.30645	60.78829	82.19383

Table A7: Pressure drop data, cement, 43 mm I.D. × 24 m long pipeline, 5 t/h

Air flow rate (kg/s)	Experimental pressure drop (kPa)	Jones and Williams (2003)	Stegmaier (1978)	New model
0.024747	121.514	46.787	40.62925	86.49437
0.030083	92.41176	51.20065	43.88838	85.7686
0.030147	95.192	51.25536	43.93183	85.76877
0.034954	95.64474	55.39376	47.3331	86.2619
0.039753	88.42708	59.56218	51.03219	87.45187
0.055226	123.4667	73.19383	63.64452	94.08202
0.064207	127.8624	81.06288	71.17921	99.26589

Table A8: Pressure drop data, cement, 54 mm I.D. × 24 m long pipeline, 5 t/h

Air flow rate (kg/s)	Experimental pressure drop (kPa)	Jones and Williams (2003)	Stegmaier (1978)	New model
0.019363	52.40206	31.28801	27.26228	54.97125
0.036457	41.37273	35.80194	27.37877	50.04054
0.037619	50.55952	36.18555	27.62207	50.01681
0.045152	47.28696	38.77565	29.51968	50.38458
0.051079	47.67257	40.93366	31.29212	51.13256

Table A9: Pressure drop data, cement, 54 mm I.D. × 24 m long pipeline, 7 t/h

Air flow rate (kg/s)	Experimental pressure drop (kPa)	Jones and Williams (2003)	Stegmaier (1978)	New model
0.030369	70.31405	39.81518	34.88743	73.09203
0.030369	70.31405	39.81518	34.88743	73.09203
0.04219	61.05455	44.9802	37.8218	71.1918
0.049765	66.62245	48.54715	40.5828	71.56752
0.049908	65.42222	48.61566	40.63886	71.5825
0.050311	68.18085	48.82788	40.79726	71.62599
0.051663	72.34641	49.47856	41.33571	71.78851
0.051915	63.6791	49.60005	41.43707	71.82064

COMMUNICATIONS

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