AN INVESTIGATION INTO MODELLING SOLIDS FRICTION FOR DENSE PHASE PNEUMATIC CONVEYING SYSTEM

A

THESIS

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Submitted by

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CERTIFICATION

I, Deepak Kumar, declare that this thesis, submitted towards the fulfillment of the requirement of Master's degree in Thermal Engineering, in Mechanical Department, Thapar University, Patiala, is wholly my own work. This document has not been submitted for any degree at any other institution.

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ABSTRACT

This report presents the ongoing investigation for pressure drop in pipe for fluidized dense phase pneumatic conveying system of powders and granular particles. This thesis report includes the modeling of solid friction factor for straight pipes. The modeling is done on the basis of previous researches by considering the solid friction factor depends upon certain parameters, and these parameters are here modified with keeping in mind that the solid friction factor will remain dimensionless. The work is carried out by collecting data for pressure drop for 20different materials conveyed through different pipe configurations. The whole data is compiled at one place and an attempt is made to model a general solid friction factor which will work on any bulk material and on any pipe configuration used for dense or dilute phase pneumatic conveying system. The model so developed gives good predictions when compared with Pan (1992) data for pressure drop in total pipeline for Fly ash (particle density 2197 kg/m^3) and pulverized brown coal (particle density 1488 kg/m^3) in six different pipe configurations, but somehow gives very alarming results when it is done with the experimental data obtained at Thapar University, Patiala laboratory using Fly ash (particle density 1950 kg/m^3, median particle diameter 45μm) in three different pipe configurations.

Keywords: dense-phase, pneumatic conveying, pressure drop, straight pipe conveying characteristics, pressure minimum curve

TABLE OF CONTENTS

NOMENCLATURE

A	Cross-sectional area of the pipe
B	Bend loss factor
D	Internal diameter of pipe (m)
Fp	Particles friction coefficient
G	Acceleration due to gravity
L	Length of pipe
N	Total number of bends
P	Pressure (N/m^2)
Re	Reynolds number for the solid particles
V*	Volumetric loading ratio
V_f	Superficial air/gas velocity (m/sec)
V_t	Transport velocity
Wfo	Minimum fluidization velocity (m/sec)
d	Particle diameter (μm)
m*	Solid loading ratio
m_f	Mass flow rate of air (kg/sec)
m_s	Mass flow rate of solid (kg/sec)
r	Correlation coefficient
ε	Voidage in transporting line
λ_f	Air/gas friction factor
λ_s	Solid friction factor

ρ_f	Air Density (kg/m^3)
ρs	Bulk solid Density (kg/m^3)
ΔP_A	Pressure drop due to acceleration
ΔP_F	Pressure drop due to friction
ΔP_G	Pressure drop due to gravity
ΔPg	Pressure drop due to gas
ΔPs	Pressure drop due to solid
ΔP_{fs}	Pressure drop due to solid friction
ΔP_{hus}	Pressure drop due to holdup of solid

LIST OF FIGURES

LIST OF TABLES

Page No.

Chapter 1: Introduction and Objectives

1.1 Introduction

Pneumatic is the word originated from a Greek word '*pneumatikos'*, which means flow ofair. In science and technology it means the follow of pressurized air. The applications of pneumatic conveying system in industries and some domestic plants can be seen with variety of examples. Some feasible features like easiness in controlling and flexibilityin installation and environmental friendly nature (Ratnayke, 2005)in industrial and non industrial fields prefer it over other conveying methods.The Pneumatic Conveying System consists of transportation of bulk particulate material through pipes (includes the horizontal and vertical section) with the help of compressed air or gas in dense phase or dilute phase to the desired location where the gas or air is separated from the material with the help of filtration system.Pneumatic conveying system applications can be seen in various places, like domestic vacuum cleaners, ash conveying in power plants, pharmaceuticals, wheat flour industries, chemical process industries, mining and many more, where it is being implemented and showing great results.

Inspite of different available transport arrangements in the field of bulk solids handling and processing like mechanical conveyors (including belt and rope conveyors), using fluid such as water as a medium of transportation etc (Lech, 2001; Mills, 2004; Ratnayke, 2005), pneumatic conveying system has series of advantages over these methods and can be listed as under.

1) **Flexibility:** It provides a far more flexibility of installation and operation. It is quite easier for the industries to install such system in their working area with less

efforts. High skill for installation of such a system is not required and also due to automation it provides a very high flexibility in operation.

2) **Environmental friendly :** As the bulk solid is conveyed in a pure dry form through enclosed pipelines to remote locations the chances of spillage, contamination and dust emissions are negligible which further reduces the processing cost compared toif it were send through the mechanical conveyors. Also the maintenance cost is very less in such type of system as it contains less numbers of moving parts which are generally present in mechanical conveyors. Different materials can be transported with the same pipeline without laying down another stream to various destinations.

With the advantages of using pneumatic conveying system if it is not used properly then it will results in some drawbacks and thus prevails some major problems in its industrial employment. (Stoess Jr., 1983; Mills, 2003; Ratnayke, 2005; Arakaki, 2010; Bhatia, 2010).

1) **Power consumption**: This system utilizes high power of consumption in dilute phase transportation where the concentration of solid is very less in the system or with very low solid loading ratio.
2) **Product degradation**: Due to very high velocity used for transportation as in case of dilute phase there is always a chance of damage of material which is being transported. Also there is a chance of erosion at bends, pipelines etc.
3) **Selective nature**: This method is quite selective in nature for the materials to be transported as it is having different modes within itself for transportation like dense, dilute, dune etc. so it is necessary for any industry to have a good

knowledge of such systems while adopting the mode their use. For example one cannot use dilute phase for very fragile material, and one cannot go for dense phase for the materials which offers high resistance to the system. In dense phase system there are chances of unstable plugging phenomena, repeated blockages and severe vibrations is pipes. So it is quite necessary to use suitable mode of conveying depending on material.

In industries the pneumatic conveying system is used for transporting the bulk solids from one place to the desired location with the help of pressurized gas or air. For designing such system the measurement of the total pressure drop is required. The total pressure drop is calculated by considering different losses in pipeline like loss of pressure in bends, loss of pressure in straight pipes (vertical and horizontal), loss due to reacceleration of material etc. The pressure drop in straight pipe is due to thefriction offered by the air and solids respectively. The air friction factor and the solid friction factor are thus modeled for different materials for predicting the pressure drop in pipelines. This solid friction is difficult to predict due to the turbulence and the particle properties. The models for solids friction had beendeveloped by researchers such as Yang (1974), Weber (1982), Szikszay (1988), Pan et al. (1992) etc for predicting the straight pipeline pressure drop for different materials, which sometimes over predict the pressure drop and sometimes under predict the pressure drop, so to have an optimized system it is necessary to have further research in this field.

This thesis looks into the general formulation of the solids friction model which is used to predict the pressure drop in straight pipeline for any product. Solid friction factor depends upon various parameters like particle size and density, conveying velocity, pipeline dia and length etc. so for developing the solid friction model by first principle is quite difficult therefore the grouping of these parameters is done in such a way that the whole model remains dimensionless. The model is developed by collecting the data of large number of bulk solids, and there is no such work has been done so far.

1.2 Objectives

With the overall aim of improving the system for industries the following objectives are as under:

1) Development of unified model using suitable selection of parameter groupings for solids friction from a wide range of data.
2) Validation of the model with existing experimental data in different pipeline configurations with three different products.

Chapter 2: Literature Review

2.1 Components of Pneumatic Conveying System

This system is composed of different components to fulfill the objective of material transportation. There are different zones where different operations are carried out for the accomplishment of the objective, these zones have special equipments. Any pneumatic conveying system has four major components (Lech (2001), Mills (2003), Ratnayke (2005));

1. **Supply of energy to gas:** for pneumatic conveying system the required energy for transportation of material is provided to the gas or air by compressors, fans, vacuum pumps, and blowers, which act as prime movers.
2. **Feed mechanism:** for feeding the bulk solids into the system a feeding mechanism such as screw feeder, rotary valve, bucket feeder, blow tank, vibratory feeders etc is used.
3. **Conveying line:** pipes made up of different materials as per the quality of material being transported is used such as pipes of mild steel, galvanized iron pipelines, PVC pipelines etc, these pipeline consists of horizontal section, vertical section, bends and other auxiliary components such as valves.
4. **Filtration mechanism:** this consists of filters for separating the material from the gas or air; generally bag filters are used to fulfill this task. Other filtration techniques are cyclone separation, electrostatic precipitators etc.

2.2 Pneumatic Conveying System Classification

There are number of ways in which pneumatic conveying system can be classified, but mainly there are two ways in which this system can be broadly classified, these are according to the system pressure and other is the type of conveying. On the basis of system pressure there are mainly three types which are briefly describe as follows (Ratnayke 2005; Bhatia 2010):-

Positive pressure System: In this type of system the absolute pressure of conveying air in the pipeline is always greater than the atmospheric pressure. This type of system is found to be more useful especially for the multiple discharge applications where the material is picked from one source and delivered to more than one receiving stations. Being positive pressure in the pipeline there is chances of leakage of material when the pipe wears out or erodes out.

Negative pressure System: In this type of system the absolute pressure of conveying air or gas is lower than the atmospheric pressure. This system is also called as vacuum or suction system. The simplest example of such a system is the domestic vacuum cleaner and its applications vary from domestic to heavy duty industries which use some hazardous materials. In thermal power plants this system is used efficiently for conveying ash from the ESP to the silos.

Combined negative positive pressure system: In this type of system both negative and positive pressures are maintained for perfect transportation of bulk solid material. The advantages of both the above systems are incorporated in this type of arrangement. Thus it is suitable for multiple feeding as well as multiple discharge requirements.

According to the mode of conveying there are mainly two types of system that is dense phase and dilute phase system.

Dense phase system: In this type of system the material to be transported is having higher concentration into the conveying medium, i.e. the solid loading ratio is high. It is further classified as fluidized dense phase system, low velocity slug flow, low velocity plug flow, bypass conveying, single slug flow, and extrusion flow. This system has an advantage of transporting very heavy materials or which are bigger in size as compared to the materials being transported in dilute phase system. Examples of materials that can be easily transported through the dense phase system are, crushed coal, diamond ore aggregate, petroleum coke, food products, meat pallets, alumina, sugar, wheat, barley etc. (Bhatia, 2010). Since the conveying mode is dense in nature so the transportation velocity is low which provides an upper hand to this system over dilute phase system over power usage, this system requires less power consumption. Also due to low velocity there are less chances of material damage in this system. There is only one drawback of this system and that is; if not designed properly or if there are errors in modeling it will lead to frequent blocking conditions and which is very hectic for the operator and as well as for the industries. The main principle of dense phase conveying system is to slow down the velocity of product. This technology reduces the air or gas consumption by allowing the system to convey at maximum density. Due to the maximum conveying density small amount of particles are in contact with the pipe, hence there is less wear which is another step of low maintenance cost in this system. The schematic diagram of this type of system is shown in Figure 2.1.

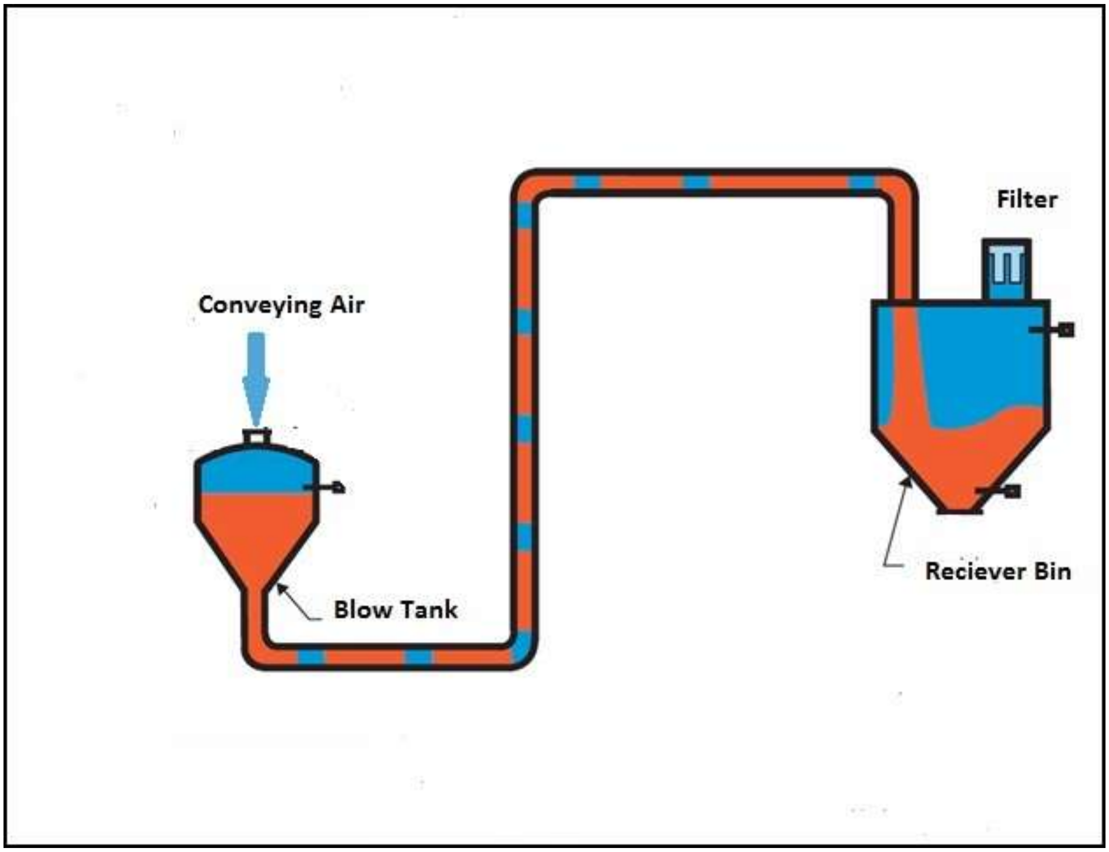

Figure 2.1: Schematic diagram of dense phase pneumatic conveying system

Dilute phase Pneumatic System: The most commonly used method of pneumatic conveying system is the dilute phase conveying. In this process a relatively large amount of air is used to transport a relatively small amount of material at very low pressure and high velocity. It is usually called a suspension flow as the particles are held in suspension in the air as they are blown or sucked through the pipeline (Bhatia, 2010). A relatively high velocity is required for this type of conveying and so the power requirement is high. There will be a contact between the material and the pipeline and due consideration must be given for the friable and abrasive materials. As also discussed earlier that with merits there also prevails some demerits of the system, this system also has demerits, it is not suitable for abrasive and friable materials as abrasive material cause very high wear and friable materials get damaged by transporting in this way. The schematic diagram that describes this system is shown in Figure 2.2.

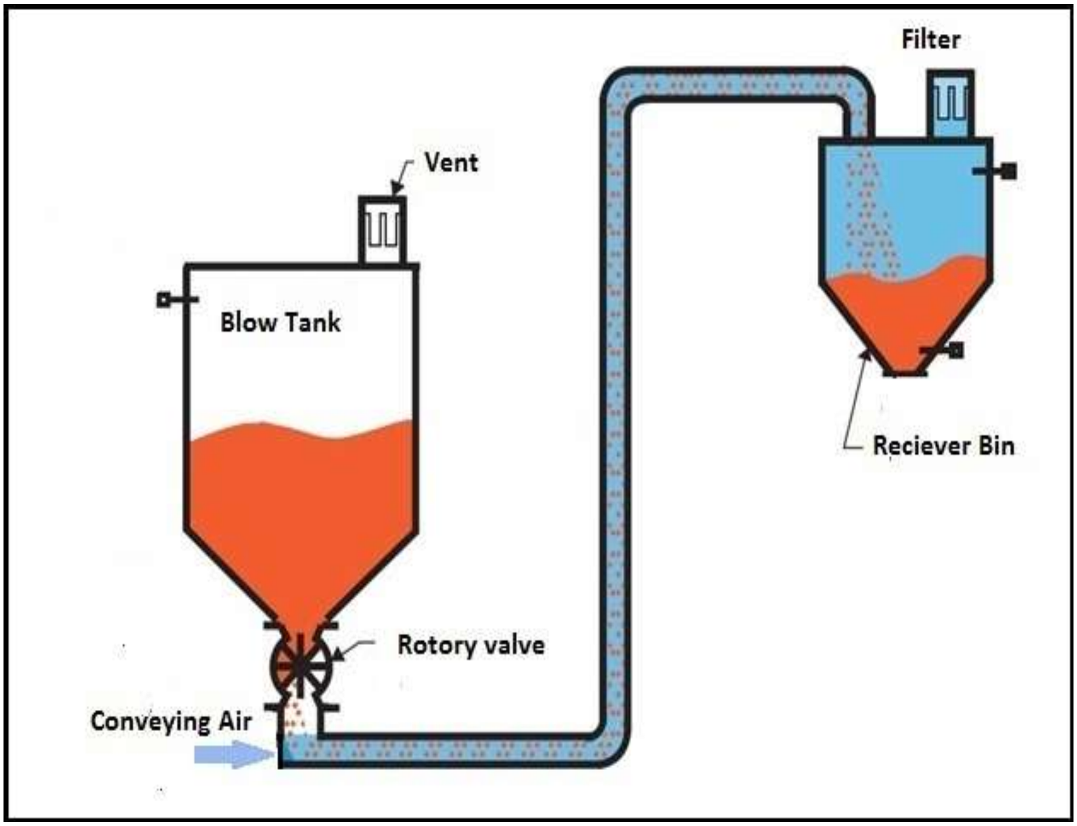

Figure 2.2: Schematic diagram of a typical dilute phase conveying system

2.3 Previous Research Work

Various experiments and researches on modeling pressure drop have been done on the bulk solid transportation pneumatically in dense and dilute phases, out of which many have been done on calculations and simulations for solid loading ratio, flow velocities, mass flow rate of air, fluidization of solid particles both in horizontal and vertical sections, flow pattern of solid particles in different mass flow rate of air, particle behavior, pressure drop across the section, etc. Previous woks that have been done in this field are briefly summarized under.

Chambers and Marcus (1986)had calculated the total pipeline pressure drop by considering the whole pipe-line into different components, i.e. by dividing the pipeline individually and calculating pressure drop in straight pipes, bend loss, vertical lift loss and losses due to the initial acceleration and finally add all components that were contributing in pressure drop.Followingrelationships for different components was presented as:

Acceleration loss: $$\Delta p_{accel} = \frac{\rho_f V^2 (1 + 2m * \frac{C}{V_f})}{2} \qquad (2.1)$$

Vertical loss: $$\Delta p_v = \frac{m * L_v g \rho_f V_f}{C} \qquad (2.2)$$

Straight pipe loss: $$\Delta p = \frac{(\lambda_f + m * \lambda_s) L \rho_f V_f^{\,2}}{2D} \qquad (2.3)$$

Bend loss: $$\Delta p_b = \frac{NB(1 + m*) \rho_f V_f^{\,2}}{2} \qquad (2.4)$$

Total loss: $$\Delta p_T = \Delta p_{accel} + \Delta p_v + \Delta p + \Delta p_b \qquad (2.5)$$

Theologos and Markatos (1994), had developed a mathematical model based on one dimensional, isothermal, steady state mass and momentum balance. The one dimensional differential equations had been solved for describing the drag force between the fluid and the particles and the pressure drop due to wall friction. For six different particles and 41 different operating conditions a parametric study had been carried out.. The results obtained had been compared with the experiments of Hariu and Molstad. One dimensional, isothermal and steady state, vertical pneumatic conveying described by four differential equations, i.e., the continuity and the momentum equations for each phase.

Gas continuity $\partial (\varepsilon w_{g)} / \partial z = 0.$

(2.6)

Particle continuity $\partial [(1- \varepsilon)w_p] / \partial z= 0$

(2.7)

Gas momentum $\partial (\varepsilon\rho_g w_g w_g) / \partial z = -\varepsilon\partial P/ \partial z + f_{gp}+ f_{gw}$

(2.8)

Particles momentum

$\partial[(1-\varepsilon)\rho_p w_p w_p] / \partial z = - (1-\varepsilon) \partial P/ \partial z + f_{pg}+ f_{pw}–(1- \varepsilon)(\rho_p- \rho_g)g$ (2.9)

Where w is the velocity, ρ the density for the phase considered, g is the gravitational acceleration, ε is the void fraction, and P is the pressure.

Drag force can be expressed by them as

$$F_D = 0.5C_D(\pi d_p^2 / 4)\ \rho_g(w_g - w_p)^2 \qquad (2.10)$$

Where C_D is the drag coefficient.

The wall friction consists of two parameters which are contributing in pressure drop one is due to gas and other one is due to solid particles therefore the frictional pressure drop due to the fluid alone is given be Fanning's equation as:

$$\Delta P_{Fg} = (f_g \rho_g w_g^2 L) / 2D$$

(2.11)

The wall friction due to solid particles is defined as:

$$\Delta P_{Fs} = [(1- \varepsilon) f_p \rho_p w_p^2 L] / 2D$$

(2.12)

With the help of computer programming these equations had been solved and based on the solutions of these equations results had been proposed in which it was found that for dilute phase using drag correlation particle accuracy can easily be predicted, it also predicts the choking conditions in the vertical pneumatic conveying system.

Pan and Wypych (1997) had presented a new test design procedure based on particle properties and data from a simple vertical test chamber, the pressure drop and slug velocity in low –velocity slug flow can be predicted accurately in large scale systems. Low velocity slug flow was used due to its low power consumption and low product damage. The predictions of pressure drop and slug velocity were compared with the experimental data obtained on large scale low velocity test rig. Ergun's test program was used in which it was shown that for a given granular product there was a good linear relationship between the ratio of pressure gradient to mean superficial air velocity(i.e. $\delta P_m / U_a$) and the air mass flow rate (i.e. m_f/A) and expressed it as:-

$$\delta P_m / U_a = a + b\,(m_f/A) \tag{2.13}$$

The test was performed on a vertical pipe of diameter 105.7 mm and a length of 1 m. The result concluded that the procedure used can be applied to bulk solid materials with regular, irregular and unusual physical properties

Hettiaratchi et al. (1998) had predicted the pressure drop in pneumatic conveying pipelines for design purpose and made a comparison between the pressure drop in horizontal and vertical pneumatic conveying pipelines. Their main concern was to predict the pressure drop for vertical pipe with the data obtained from horizontal pipe so as to reduce the test trials and to reduce the testing cost. Two materials used are polyethylene pallets and wheat flour in each case for vertical and horizontal pipeline sections and the data analyzed to provide a comparison of the pressure drop data obtained. They concluded that the pressure gradient has a considerable dependence on superficial air velocity.

Levy et al. (1998)had investigated theoretically air permeation through a plug, moving in a vertical pipe with constant velocity. The preliminary experiments confirmed the feasibility of Darcy- Forchheimer's law for air flow through plug. A theoretical model that predicts the air velocity, pressure drop and plug velocity for conveying a cohesive plug in vertical pipe was developed. Further experiments were conducted to characterize the conveying parameters of different particulate solids and to validate the theoretical model. The main aim of the experiment was to verify the applicability of the Darcy- Forchheimer law. The experimental analysis was used in the theoretical model only to describe the air permeation through the moving plug. The theoretical model was developed based on certain assumptions in which the flow was assumed to be in compressible, plug is moving with constant velocity, air is Newtonian and very low relative velocity between the air and the plug.

Molodtsof et al. (1998) had done experiments on characterization of pressure drops in dense phase pneumatic transport at very low velocity. Sand particles of diameter 0.2 mm were transported in horizontal pipes of diameter 20, 36, 50 and 53 mm and lengths up to 7 m using compressed air. Investigation of three different flow regimes (dunes I, dunes II and slug flow) was done. It was found that in long pipes a notable axial expansion was experienced by the carrier gas which resulted in showing that the pressure profile was no longer linear due to the evolution of flow along the pipe. A general pressure drop law was obtained which proved to be independent of both flow regimes and pipe diameter. This law was examined for all the three flow regimes keeping the superficial flow velocity lower than 0.2 m/sec. this pressure drop law contains eight dimensional constants. The law so obtained accounted for the separate effects of volumetric gas flow rate and mass flow rate of solids which were the only variables governing the local pressure gradients.

Rautiainen et al. (1999) have done an experimental study of vertical pneumatic conveying. This study uses a one dimensional equation system and experimental techniques to provide a comprehensive description of verticalgas–solid two-phase flow. The results from non-accelerating flow experiments conducted with a riser tube of bore 192 mm and height 16.2 m using spherical glass beads of average diameter 64 mm are presented.The frictional pressure drop was recognized to be an important component ofthe total pressure gradient in the riser. At low gas velocities, negative frictional pressure gradients occurred. The solids friction factor was found to be constant at high solids velocities and decrease to negative values as the solids velocity was reduced. The slip velocity was found to be always greater than the single-particle terminal velocity and to increase with decreasing gas velocity or increasing solids mass flux. According to them this is different to that which has usually been reported in literature, and is thought to be due to the large diameter of riser used. In addition, the slip velocity increased with increasing solid concentration. The gas friction factor was evaluated from standard empirical correlations and Moody charts and the solid friction factor was calculated by taking the difference of total wall shear stress and the wall shear stress due to the flow of gas only.

Ostrowski et al. (1999) made an investigation on control of flow phenomena in the pneumatic conveying of solids whichrequired a detailed knowledge of the flow regimesand a number of phase flow properties. Electrical capacitance tomography (ECT)was used as a robust tool,particularly in case of dense phase plug flow. The application of ECT to dense phase powder conveying in an experimental vacuum system was demonstrated and described, including the visualization of slug size, shape and velocity. Measured gas and solid flowrates were also analyzed in an attempt to ultimately provide a basis for comprehensive on-line analysis. A number of statistical estimatorswere selected and used in data processing, in order to distinguish between particular types of dense flow. The results show the potentialfor use of the method for the on-line control of dense phase pneumatic conveyors.

Lech (2001)had done experiments for the measurement of solid mass flow rate of in vertical pneumatic conveying system. The method was developed on the basis of parallel measurement of velocity of solid and pressure drop. A theoretical model was defined and validated by experiments. The total pressure drop was considered due to three main contributor's acceleration ΔP_a, gravity ΔP_g and friction ΔP_F. Pressure dropin the acceleration region was calculated by using Yang et al. model. The acceleration length of solid particles was calculated as proposed by Klinzing and Lech. According to the author for well developed steady flow where the solid would be in dynamic equilibrium with the gas flow total pressure drop can be written as:

$$\Delta P_T = \Delta P_s + \Delta P_g \quad (2.14)$$

$$\Delta P_T = \Delta P_{fs} + \Delta P_{hus} + \Delta P_{fg} + \Delta P_{hug} \quad (2.15)$$

Pressure drop due to solid is as follows:-

$$\Delta P_s = \Delta P_{fs} + \Delta P_{hus} \quad (2.16)$$

Where ΔP_{fs} is defined as

$$\Delta P_{fs} = f_p \rho_s U_p^2 (1-\varepsilon) L / 2D \quad (2.17)$$

Pressure drop due to hold up of solid was defined as :

$$\Delta P_{hus} = (M_s L g) / U_p A \quad (2.18)$$

The voidage ε in a given region of the transporting pipe was determined as:

$$\varepsilon = V_g / (V_s + V_g) = 1 - (M_s / U_p A \rho_s) \quad (2.19)$$

The concluded relation was then proposed as:

$$M_s = [\Delta P_s (A/L)] / [f_p(U_p/2D) + g/U_p] \quad (2.20)$$

Sanchez et al. (2003) worked on characterization of bulk solids to access dense phase pneumatic conveying system. Their work was concentrated to predict the feasibility of conveying particles in the dense phase mode by exploring particle characteristics in an assembly. The various suggested methods in previous literature were reviewed and comparisons were made withnew and existing data. Measurement of the permeability and de-aeration time of the particles was the key parameters to provide a predictivemodel. A multi-regression analysis had been carried out to provide a model which determe the ability of particles to be conveyed in dense phasepulsed piston operation.

Dhodopkar et al. (2005) worked on evaluation of models and correlations for pressure drop estimations in dense phase pneumatic conveying system. Various models and correlations for dense phase conveyingsystem had been tested toprovide guidance to the designer on the best pressure drop model. With the available data sets, it was concluded that the Mi (Konrad)-based model was found to be best forpredicting the pressure drop across dense phase plugs. A series of industrial scale tests were also made that also shows agreement with the Mi (Konrad)-based model. The different models that had been tested for best pressure drop were listed by the author, out of which the Mi (Konard)-based model was found to be the best. The various models that were tested for comparison consists of Muschelknautz's and Krambrock's model, Weber model, Ergun Model, Wen and Simon correlation, Konrad Model,Mi Model,Kano model,and the Molerus model.

McNamara et al. (2006) had done simulations on plug conveying along a vertical tube using a discrete element simulation approach for the granulate particles and pressure field approach for the gas. The result was compared with an experiment. The approach used provide access to important parameters like porosity and velocity of the granulate and the shear stress on the wall at relatively low computational cost. Pneumatic conveying of grain and gas had been observed through the model. The implementation of three dimensional; rotation and Coulomb friction were taken into account. The effectivefriction reflected the complex interplay between sliding, rolling and static friction. By using the model, large numbers of plugs could be studied, and their porosity, velocity, and size were measured as functions of height.

Arakaki et al. (2010) had developed a new and simple model which presented and described the calculation of mass flow rate of solids in pneumaticconveying systems, which was based on air flow and pressure measurements. The principle of the model was conservationof mass, and it was applied in a horizontal straight pipe section. Two tests were performed on the two different actualconveying rig.The validation of the model had been successfully done with the data taken from two different single blow tank conveying systemsand was tested in dense and dilute phase conveying. Four test materials were used for validation of the model: alumina, barite, cement and dextrose.

Chladek et al. (2011)had worked on the calculationof the effects of operating conditions and particle properties on performance of vertical air lift. The effect of the fluidization air flow rate and the transport air velocity on the solids mass flow rate and thepressure drop along the transport pipe was investigated in a vertical air-lift. Two different materials,glass (150 μm) and zirconium oxide (260 μm) particles (Geldart's B class), were studied to estimate the effect ofparticle properties on the air-lift performance. Different levels of the solids mass flow rate were obtained byvarying the fluidization air flow rate while keeping the transport air velocity constant. The solids loading ratiohad been varied between 2 and 16 for both particles. The pressure drop was non-linearly related to the solidsmass flow rate at most of the transport air velocities tested. State diagrams presenting the relationshipbetween the transport air velocity, the solids mass flow rate, and the pipeline pressure drop were constructedto characterize the flow pattern and to compare the behavior of the glass and zirconium oxide particles.With the larger size and higher density of the zirconium oxide particles they displayed higher pressure dropvalues than the glass beads and the minimum pressure drop shifted towards higher transport air velocities.The transition velocities between dilute and dense phase conveying had been found approximately in the range of7 to 10 m/s for glass beads and 10 to 12 m/s for zirconium oxide.

Cong et al. (2011)had made an experimental research on flow patterns and pressure signals in horizontal dense phase pneumatic conveying of pulverized coal. To understand the flow patterns and their variability was important for optimal design and trouble free dense phasepneumatic conveying of pulverized coal in a horizontal tube. The author had employed the electrical capacitancetomography (ECT), for quantitative analysis six flow patterns were identified and utilized which were based on thevalue and distribution of cross-sectional solid concentration. It was found that the dense-phase flow patterns in the horizontaltube of the pneumatic conveying system were somehow variable even when the operating conditions wereunchanged. The calculation results suggested that by changing multiple flow patterns with each of the seven sets of experimental conveying conditions, a finite change in thedominant flow pattern was observed with an increasing superficial gas velocity. The power spectral density(PSD) function and the Hurst exponent of the pressure signals of the pulverized coal were well correlated withits flow patterns in a horizontal tube. The relation with the flow pattern between PSD functions and probability density functions (PDFs) of the voidfraction signals from ECT was found to be in good agreement.

Guan et al. (2011)had studied the solid velocity in horizontal dilute phase pneumatic conveying of fine powders, the validation of calculation for pressure drop and gas–solid drag force in horizontal dilute phase pneumatic conveying correlation was done, especially for fine particles (such as pulverized coal and quartz sand). Consequently, in their work, a negative pressure pneumatic conveying test rig was set up and two kinds of powders with different sizes were adopted. Optical fiber probe (OFP) was used to measure the volumetric solid concentration and particle velocity. The volumetric solid concentration was also calculated by using the measured particle velocity. The results show that the solid concentrations obtained by the two methods had good agreement. It was found the particle velocities were different in the upper and lower part of the cross-section in the horizontal pipe. The difference was generally not more than 2 m/s. The velocity difference decreased with the increased gas velocity, and increased with the solid mass flow rate. By modifying the solid friction factor, an improved correlation of the particle velocity was obtained, which agrees better with the experimental data given in the present and literature studies.

2.4 Limitations of Present Status of Research

With the number of experiments and research works that have been already carried out in this field, still needs more research work to be carried out for finding the best model for pressure drop in straight pipeline for pneumatic conveying of bulk solids. As many researches' have been done for pressure drop calculations in horizontal pipes, bends and vertical pipe for different materials and different models for different materials have been proposed by authors which will give only pressure drop prediction for a particular material and may result in over prediction or under prediction of the pressure drop when it is being employed for other materials. Therefore it is quite necessary to have such model which will give best result for pressure drop prediction for designing the system.

Chapter 3:Experimental Setup and Test Work

For the experimental test the pilot plant is set up in the mechanical engineering department of Thapar University, Patiala (Initially known as TIET). This chapter gives a detailed experimental setup description and also about the experimental investigation for finding the pressure drops in the total pipeline. Four configurations of pipelines are used for testing the fly ash taken from Bhatinda Power Plant.

3.1 Test Facilities at Thapar University, Patiala laboratory

The test rig is designed and consulted by DST and CSIR grant with the objective of the research activities for dilute and dense phase conveying. It mainly consists of bottom discharge blow tank of capacity 0.2 m^3, which can withstand a maximum pressure of 10 bar gauge mounted on load cells, a receiver bin of 0.5m^3also mounted on load cells to monitor the weight accumulated during the experiments, conveying pipes of different bore size and lengths (38.1 mm I.D x 24 m, 50.8 mm I.D x 24 m, 50.8 mm I.D x 70 m, & 63.4 mm I.D x 24 m), bends of 1 m radius, compressor and air drier unit, air receiver tank of m3, different valves for operation, watch glass for having clear vision of particles that are being conveyed and a bag filter for separation of material from air.

The configuration of pipeline is such that it forms a close loop so that no material is discharged during the experiments. Pressure transducers at different location of pipeline are installed for calculating the pressure drop at different sections of the pipe. Flowmeter for measuring air flow during experiments, flexible hoses for making the pipeline free from contributing any load on load cells, data logger for recording the pressure and air flow. One of the setup layout is shown in Figure 3.1 below.

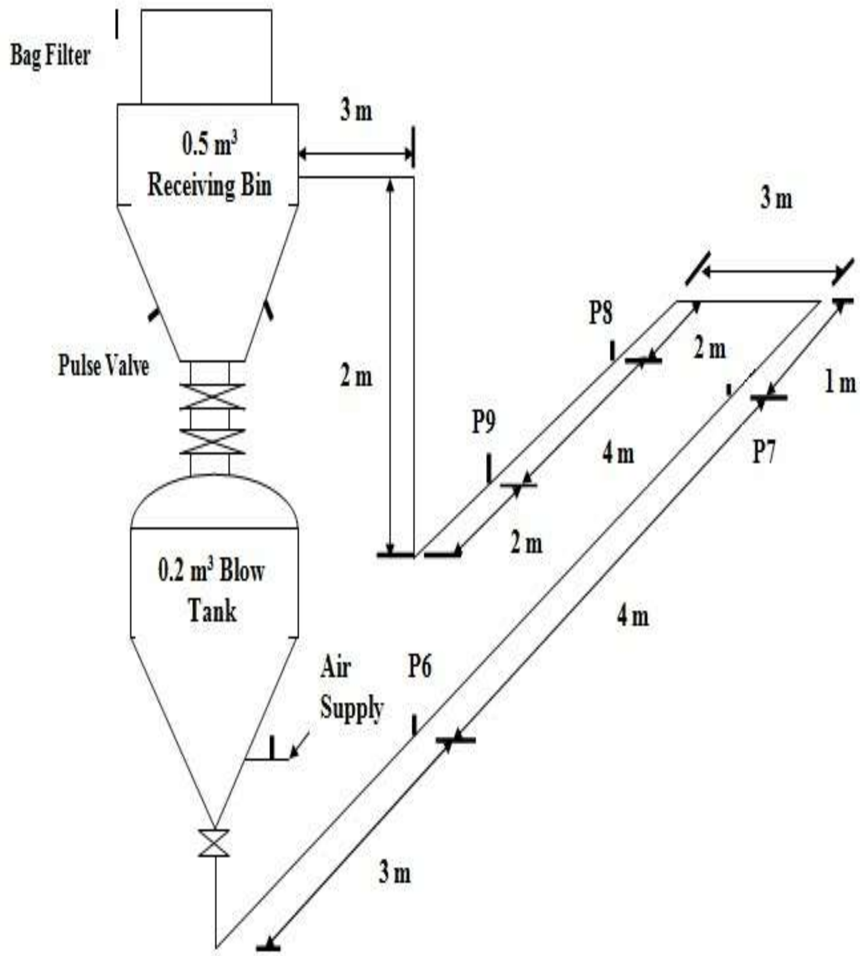

Figure 3.1 Test setup for Pneumatic conveying system in Thapar University

3.1.1 Air Compressor

Air being used as a conveying medium is compressed in compressor for attaining pressure above the atmospheric pressure. The compressor used here is a screw type compressor. To avoid excessive noise it is enclosed in a chamber that will reduce its sound. The picture of this arrangement is shown in Figure 3.2 below. The air is sucked from atmosphere through inlet valve and is then compressed in number of stages. The compressed air is then deliver to the air receiver tank through air drier unit. The technical specifications of air compressor are given below.

- Production Company : Kirloskar
- Model : KES18-7.5
- Maximum working pressure : 7.5 bar
- Maximum air flow rate : 3.37m^3/min
- Voltage/frequency : 415V/50 Hz
- Approximate thermal power : 18.5 kW

Figure 3.2 Air Compressor in TU laboratory

3.1.2 Air Dryer and Cooler

After air being compressed in the compressor it is passed through the air drier unit where the moisture present in the air is removed by cooling it to the dew point temperature. The air is passed through a refrigeration system contains R134 A refrigerant. This air is now useful for conveying and for pneumatically operated valves mounted on blow tank. The technical specifications of air drier are listed below.

- Type of Dryer : Refrigerated air cooled
- Working pressure : 5-13 bar
- Air Flow rate at outlet : 100 cfm
- Model : KRD100AC
- Supply Voltage : 230V/ 50Hz
- Dew point at line pressure : 3^o C

3.1.3 Air Receiver Tank

The function of air receiver tank is to store the compressed air for further supply to the required destination. From air receiver tank the air is going to different locations to perform different task. The air is supplied for pneumatically operated valves mounted on blow tank, for purging of bag filter mounted on receiver bin, for fluidization of receiver bin and blow tank, and for main conveying line. The mountings on air receiver tank area pressure gauge, and one safety valve that is set up to 10 bar. The technical specification of air receiver tank is listed below.

- Production Company : Kirloskar
- Design Pressure : 11.6 bar
- Hydraulic Test Pressure : 10.6 bar
- Model : KE29
- Capacity : $0.5m^3$

Figure 3.3 Air Receiver Tank in TU laboratory

3.1.4 Valves

After all these processing the air is being fed into the pipeline through a series of valves which includes pressure regulating valve, flow control valve, needle valve etc. This array is shown below in the process and instrumentation diagram below (P&ID). For controlling air flow in the main pipeline globe valves are used at different locations line in top air supply in blow tank, in boosting line for conveying material and in the line used for fluidization of blow tank. Different valves according to their use are shown in Figure3.4 below. For full shut off ball valves are used after compressor, dryer, and receiver tank named as G1, G2, and G3. These all are manually operated. After these valves, to regulate the line pressure, manually operated pressure regulatory valves are placed to attain the desired pressure in the line named as PR1 and PR2. NR1, NR2, NR3, NR4, and NR5 are non return valve to avoid any back pressure in the line also to avoid any back flow of material, otherwise valve functioning will be hampered. There are certain valves that are pneumatically operated named as BL1, BL2 and BL3, which are in operation only when the conveying cycle is running.

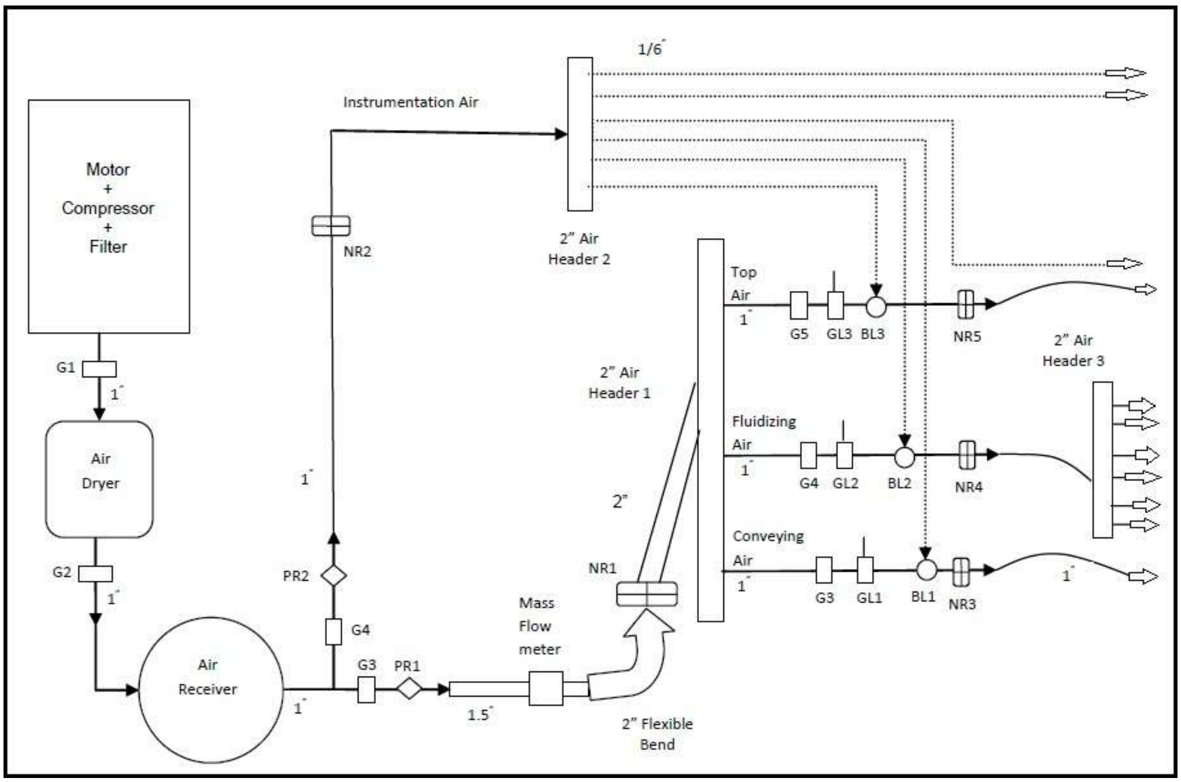

Figure 3.4 Schematic diagram of compressed air circuit

3.1.5 Control Panel

Control panel is used for running the conveying cycle PLC based. The logic is given to it with the help of ladder programming. The time lag of each valve is to be fed at the user interface for opening and closing of the valve and conveying cycle. Most of the experiments are done by setting the conveying cycle time in the range of 70 sec to 90 sec.

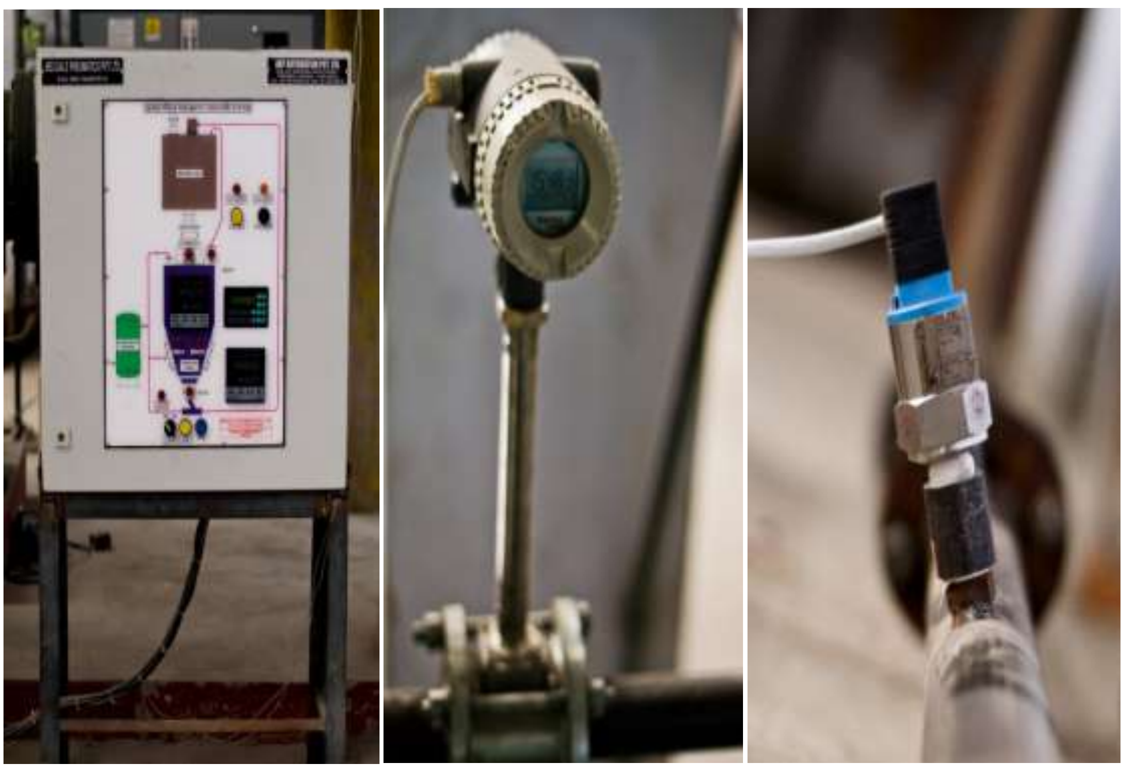

Figure 3.5 Control panel, flow meter and pressure transducer

3.1.6 Pressure Transducers

Pressure transducers are installed at different section of pipe keeping in mind that the difference between each transducer is minimum 3 meters so that there is no discrepancy between the two. Transducers of two different ranges are used during testing, one is of 0-2 bar range and other is having 0-4 bar measuring range. These transducers are calibrated at the laboratory by installing them to the main pipeline and blocking the pipeline at one end.The pressure transducers are placed at different locations of the pipe line. Calibration graph of transducers P7 and P9 are shown in Figure 3.6 (a) and (b) respectively. Other transducers are calibrated in same way.

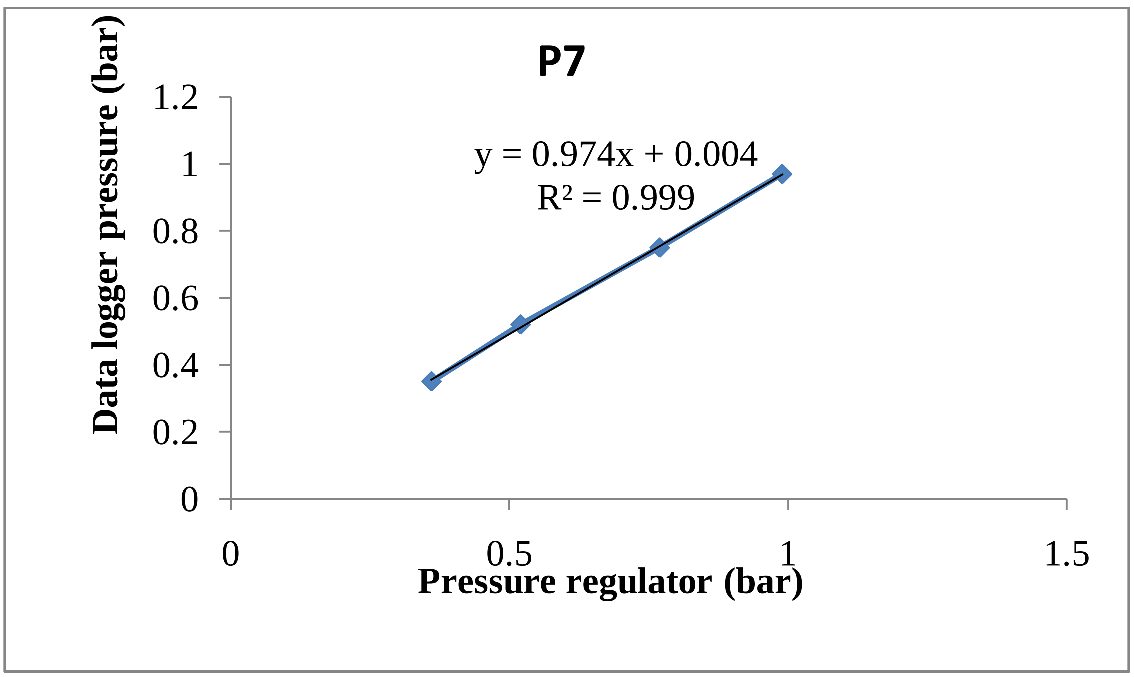

Figure 3.6 (a) Pressure Transducer Calibrations (P7)

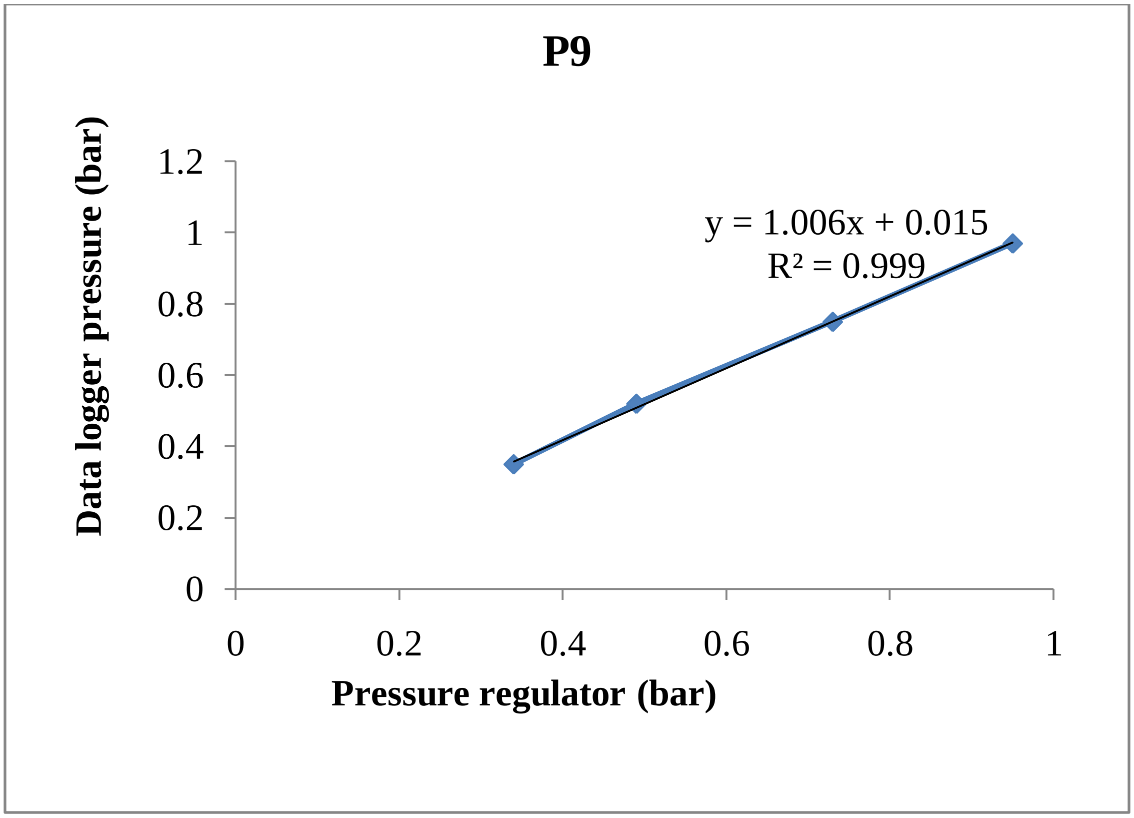

Figure 3.6 (b) Pressure Transducer Calibrations (P9)

3.1.7 Air Flow Meter

Air flow meter is used to measure the amount of air being conveyed during a cycle. This air flow meter is directly connected to the data logger and is recorded in the computer with the help of software provided by NIC Jaipur. This air flow meter also have a digital display on it which will show the amount of air passes through it and also the cumulative amount of air flow through it. It's a vortex type of flow meter, a vortex is created by the obstacle present in the path of air flow and is being converted into digital as well as analog signal that are being recorded in the data logger.

3.1.8 Load Cells

Load cells are used for calculating the amount of mass of material accumulated in the receiver bin and the blow tank. Receiver bin and blow tank are placed on these load cells, four numbers of load cell are placed below each corner of them and are then connected as such so that they will give the average reading of the load being transferred.Each of the load cells is calibrated before using it. The calibration of each load cell is done at the factory itself and at the laboratory.

3.1.9 Blow Tank and Receiver Tank

Blow tank is the device which acts as the collecting media for granular material, the material that has to be transported comes into the blow tank with the opening of inlet valve. This inlet valve is pneumatically controlled and is operated automatically during the conveying cycle. Blow tank is the device which will provide necessary air/gas for conveying the bulk material. There are two lines of conveying air connected to the blow tank, one is the top air that is required to built up initial pressure in the blow tank so that the bulk material can easily be transported and the other is the fluidization line which ensures that the material in the blow tank would not be settled or stick to any location inside it. When the outlet valve is opened, the material inside the blow tank falls in the conveying line and is being conveyed by the main air/gas. The capacity of blow tank is 0.2 m^3. The detailed specification of blow tank is given below;

On the other hand the receiver tank is the device that is used for collecting the material that is being conveyed and also acts as a separator in between the material and the conveying gas. Thus it allows the material to get stored in it and gas to leave it. The receiver tank used in our laboratory has a capacity of 0.5 m^3. Due to the closed system the material stored in this tank is fed to the blow tank for further conveying cycles. It is also provided with fluidization technique.

3.2 Product data & pipeline details

A table for various products that are used here for this thesis work is given below. This data is taken from the previous researchers work and the test carried out inThapar University, which include P.W.Wypych (1989), C.Ratnayake (2005), S.S.Mallick (2009), and Renhu Pan (1992).

Table 3.1 Product and pipeline details

Product	**Particle Density (ρ_s) (Kg/m^3)**	**Particle Bulk Density (ρ_{bl}) (Kg/m^3)**	**Particle mean dia (μm)**	**Pipe length (m)**	**Pipe I.D (mm)**
Pulverized coal	1600	760	30	25	52
Fly Ash (I)	2160	880	27.4	71	52

Fly Ash (II)	2350	500	19.6	71	52
Fly Ash (III)	2100	650	25.4	71	52
Fly Ash (IV)	2130	700	18.8	71	52
Fly Ash (V)	2250	1030	17.6	71	52
Fly Ash (VI)	2195	455	11.5	71	52
Fly Ash (VII)	2415	640	13.3	71	52
Fly Ash (VIII)	2300	700	30	168	105
PVC Powder I	1400	575	152.1	71	52
Screened Coke I	1940	985	529.7	25	52
Mixture of Fly Ash and Cement	2130 & 3100	700 & 950	19 & 20	162	60
Screened Coke II	1940	985	470	71	52
PVC Powder II	1400	575	135	160	105
Bentoninte	2500	--	25	72	75
Barytes	4200	--	12	66	75
Cement	3100	--	15.5	66	100
Illmenite	4600	--	9.5	68	125
Alumina	2800	--	86.7	130	75
ESP Dust	3637	610	76.6	168	69

White Powder	1600	620	55	148	69
Fly Ash (TU)	1950	950	45	70	63.4
Fly Ash (TU)	1950	950	45	70	50.8
Fly Ash (TU)	1950	950	45	24	50.8
Fly Ash (TU)	1950	950	45	24	38.1

Chapter 4: Modeling of Solid Friction Factor

4.1 Introduction

As discussed in previous chapters, pneumatic conveying is considered as one of the most efficient method for bulk particle material transportation. To ensure a good design of the pneumatic conveying system, two parameters will be determined accurately. These are the optimized air velocity for transporting material safely without blockage and the minimum pressure required for a given pipe length. The pressure head arises in the pipeline due to the two main reasons which are due to the gas/air only and other one is due to the solid material that is being conveyed.

4.2 Design consideration for pneumatic conveying system

For designing the pneumatic conveying system one must have to consider the pressure head required for the conveying of material, other factors also play an important role in designing of the required system but due to the scope of this thesis only pressure head is considered for the designing purpose. Barth (1958) proposed a relation between the pressure drop and the friction factors due to fluid and solid as,

$$\Delta p = \frac{(\lambda_f + m * \lambda_s) L \rho V^2}{2D} \tag{4.1}$$

This relation is mostly used for developing new models and here also the use of this correlation is made for developing the solid friction factor for straight pipes only.

4.3 Pressure Drop Determination

As discussed earlier that the total pressure drops in a pipeline is due to the flowing gas and due to the solid material being conveyed. The pressure drop due to the air or gas remains constant with different loadings of different materials. Thus we can say that

$$\Delta P_t = \Delta P_a + \Delta P_s \tag{4.2}$$

4.3.1 Pressure drop due to 'Air Only'

The pressure drop due to air can easily be determined by using the well established reliable mathematical models such as Darcy-Weisbach formula for single phase flow. It is given as;

$$\Delta Pa = \frac{4\lambda_f \rho_{aL} V^2}{2D} \tag{4.3}$$

The measure of shear stress that is exerted in turbulent flow on wall of a pipe is the friction factor. For laminar flow the friction factor is linearly dependent on Reynolds number, ($R \leq 2000$) and is calculated from the well known Hagen-Poiseuille equation:

$$\lambda_f = \frac{64}{R} \tag{4.4}$$

Where Reynolds number is defined as:

$$R = \frac{\rho VD}{\mu} \quad (4.5)$$

In turbulent flow for (R ≥ 4000), the friction factor depends upon the Reynolds number and the relative pipe roughness (k), in a smooth pipe this roughness factor is negligible and thus the friction factor is totally a function of Reynolds number. Nikuradse (1933) had proposed the following resistance equation:

$$\frac{1}{\sqrt{\lambda_f}} = 2 \log (R\sqrt{\lambda_f}) - 0.8 \quad (4.6)$$

In case of rough pipe the friction factor is the function of the pipe roughness (k) and is independent of Reynolds number (R). Von Karman (1979) derived the equation for finding the friction factor as;

$$\frac{1}{\sqrt{\lambda_f}} = 2 \log\left(\frac{D}{k}\right) + 1.74 \quad (4.7)$$

There is the state in between these two which is called as the transition state and in this state the friction factor depends upon both the Reynolds number and the pipe roughness and this is correlated by Colebrook and White (1937) as;

$$\frac{1}{\sqrt{\lambda_f}} = 2 \log \left[\frac{k/D}{3.7065} + \frac{2.5226}{R\sqrt{\lambda_f}}\right] \quad (4.8)$$

Based on this equation Moody (1944) prepared a chart for finding the friction factor for flow in pipes which has been used extensively for practical applications. Equation 4.8 covers both the region of smooth and rough pipes.In recent years there are several numbers of research have been done on modifying this friction factor correlation, these are listed in table 4.1 below;

Table 4.1 Different friction factor correlations

Researcher	**Correlations**
Wood (1966) for R> 10000 and 10^{-5}< k/D < 0.04	λ_f = a + bR^{-c} , where a = 0.53(k/D) + 0.094 $(k/D)^{0.225}$, b = 88$(k/D)^{0.44}$, c = 1.62$(k/D)^{0.134}$
Swamee and Jain (1976) for 5000 < R<10^7 and 0.00004 < k/D < 0.05	$\lambda_f = 0.25\, log\left[\frac{k}{D} + \frac{5.74}{R^{0.9}}\right]^{-2}$
Churchill (1977) for all R and k/D	$\lambda_f = 8\left(\left(\frac{8}{R}\right)^{12} + (A+B)^{-3/2}\right)^{1/12}$ where A=[-2log(((k/D)/3.7+ $(7/R)^{0.9}$))]^{16} and B=$(37530/R)^{16}$
Chen (1979) for all R and k/D	$\frac{1}{\sqrt{\lambda_f}}$ = -2log $\left[\frac{k}{3.7065\,D} - \frac{5.0452}{R}\, log\left(\frac{1}{2.8257}\left(\frac{k}{D}\right)^{1.1098} + \frac{5.8506}{R^{0.8987}}\right)\right]$
Round (1980)	$\frac{1}{\sqrt{\lambda_f}}$ = -1.8 log$\left(\frac{0.27k}{D} + \frac{6.5}{R}\right)$
Haaland (1983)	$\frac{1}{\sqrt{\lambda_f}}$ = -1.8 log$\left[\left(\frac{k}{3.7D}\right)^{1.11} + \frac{6.9}{R}\right]$
Manadilli (1997)	$\frac{1}{\sqrt{\lambda_f}}$ = -2log$\left(\frac{k}{3.7D} + \frac{95}{R^{0.983}} - \frac{96.82}{R}\right)$

These are the different models that are moreoften used to calculate the air friction factor when flowing in a pipe. For the calculation of the results Swamee and Jain's (1976) model is used here in this thesis to calculate the friction due to air only, which is further used for modeling the solid friction factor.

4.3.2 Pressure drop due to Solid particles

As discussed earlier that there are mainly two components that are contributing in total pressure drop in a two phase flow, one is due to air only and the other one is due to solid particles that are being conveyed. These solid particles have different properties and due to which the pressure drop due to them is still unpredictable, hence this topic is the main centre for the researchers to carry their researches around it. Likewise the air solid friction factor there exist the solid friction factor (λ_s). This factor depends upon number of variables as already discussed in Chapter 2. Various correlations developed for finding the solid friction factor are tabulated as under in table 4.2.

Table 4.2 Solid friction factor correlations

Researcher	Correlation
Yang (1974)	$\lambda_s = 0.117\frac{1-\varepsilon_s}{\varepsilon^2}\left[\frac{(1-\varepsilon)VRe_T}{(gD)^{0.5}Re_s}\right]^{-1.15}$
Szikszay (1988)	$\lambda_s = Fr^{x1}\mu^{x2}\left(\frac{d_s}{D}\right)^{x3}$ the coefficients x_i are to be found using empirical fittings.
Weber (1982)	$\lambda_s = x_1\mu^{-0.3}{Fr_a}^{-x2}{Fr_s}^{0.25}\left(\frac{D}{d_s}\right)^{0.1}$ where x_1 and x_2 are determined by empirical fittings.
Pan et al. (1992)	$\lambda_s = x_1\mu^{x_2}{Fr_m}^{x_3}{\rho_{am}}^{x_4}$ where x_i is determined by empirical fittings and this is valid only for a particular product.
Duckworth	$\lambda_s = x_1\left(\frac{d_p}{D}\right)^{x_2}\mu$
Arastoopour et al. (1979)	$\lambda_s = \frac{3}{8}\frac{\rho_a}{\rho_s}C_D\frac{D}{d_p}\left(\frac{V_a - V_s}{V_s}\right)^2$

Thus from above table it is clear that there are number of variables upon which the solid friction factor depends. These variables are selected on the basis of the particle properties and conveying method. To find the friction due to solid this solid friction factor is modified and has been modeled by selecting different variables.

4.4 Formulation of Solid Friction Factor model

As discussed earlier the objectives of this thesis, one of them is the developing a model for solid friction factor in straight pipes. From the first principle it is difficult to model the solid friction factor due to the unpredicted behavior of the particle as it goes into turbulent zone while being conveyed, so a an approach is made to model this solid friction factor by grouping different parameters on which it is supposed to be dependent and these parameters are volume loading ratio, particle free settling velocity, conveying air velocity, density of particle and air, pipe size and particle size. This can be expressed as;

$$\lambda_s = C(V^*)^a \left(\frac{W_{fo}}{V}\right)^b \left(\frac{d}{D}\right)^c \left(\frac{\rho_a}{\rho_s}\right)^d \quad (4.9)$$

Where C is the constant, V* is volume loading ratio,' W_{fo}' is the particle free settling velocityand can be found by a chart given by Clitt et al. (1978), as given in ANNEXURE-B, V is the conveying velocity, d is the particle diameter, D is the pipe diameter, ρ_a&ρ_s are the air density and particle density respectively, and a,b,c,d are the exponents which can be determined by simple regression tool in excel.

The parameters chosen for modeling the solid friction factor contributes in pressure drop when they are varied. With increase in volume loading ratio the flow become denser and hence it will have more pressure drop across the pipeline, particle free settling velocity also contributes in pressure drop as if the particle is heavier more air is required to suspend that particle and hence contributes towards the pressure drop, particle density also plays important role in pressure drop across the pipeline, if particle density is high it requires more pressurized air for conveying and thus results in more pressure drop, similarly if particle size is larger it will offer more friction due to increased surface area and thus results in pressure drop. Thus these parameters are grouped together for modeling the solid friction factor.

Air density at particular section of a pipe can be determined by using simple gas law which is stated as;

$$P=\rho_a RT \tag{4.10}$$

Where P is the total pressure drop across the pipe section, thus density of air can be written as;

$$\rho_a = \frac{P}{RT} \tag{4.11}$$

Where 'R' is the Specific gas constant and its value is taken as (0.287 KJ/KgK), and 'T' is the absolute temperature taken in Kelvin.

Density of air taken at inlet of pipe can be expressed as;

$$\rho_a \text{ (inlet)} = \frac{\Delta P + P_{atm}}{RT} \tag{4.12}$$

From continuity equation, amount of mass entering is equal to the amount of mass leaving a pipe section. And the equation for incompressible flow is expressed as

$$Q = AV \tag{4.13}$$

For compressible fluid flow the equation 4.13 can be expressed as;

$$Q = \rho_a AV \tag{4.14}$$

Here Q is the mass flow rate of air and will be written as $\mathbf{m_f}$ thus equation (4.14) can be rewritten as;

$$m_f = \rho_a AV \tag{4.15}$$

Here 'A' is the crossectional area and 'V' is the average velocity across the pipe section. For finding the inlet velocity at the pipe we can write from equations(4.12) and (4.15) as;

$$V_{inlet} = \frac{m_f}{\rho_{inlet} \ A} \tag{4.16}$$

For finding the dynamic viscosity of air we use the relation as

$$\mu_f = \frac{0.006515\left(\frac{T}{273}\right)^{1.5}}{T+105.6} \tag{4.17}$$

Reynolds number plays an important role for determining the flow to be in laminar, transient or turbulent mode, thus we can write;

$$\text{Re} = \frac{\rho VD}{\mu_f} \tag{4.18}$$

Thus from here we can find the air friction factor by using the Swamee and Jain's model as:

$$\lambda_f = 0.25\, log\left[\frac{k}{D} + \frac{5.74}{R^{0.9}}\right]^{-2} \tag{4.19}$$

Thus for calculating the total pressure drop in the straight pipe bend loss and vertical pipe loss have to be subtract from the total pipeline pressure drop. The bend loss and vertical loss will be calculated by using the Chambers and Marcus model as already discussed in the literature review chapter as:

$$\Delta p_b = \frac{NB(1+m^*)\rho_f V_f^{\,2}}{2} \tag{4.20}$$

$$\Delta p_v = \frac{m^* L_v g \rho_f V_f}{C} \tag{4.21}$$

Thus the total pipeline pressure can be written as:

$$\Delta \mathrm{P} = \Delta P_h + \Delta P_b + \Delta P_v \tag{4.22}$$

Now from equation (4.1)it can be written as:

$$\lambda_s = \left(\frac{\frac{2D(\Delta P_h)}{\rho_f L V^2} - \lambda_f}{m^*} \right) \tag{4.23}$$

From here the pressure loss in straight horizontal pipeline can be found. Now this pressure loss is used for finding the correlation between the solid friction factor and the depending variables by using simple regression tool in the Microsoft excel program, as depicted earlier in equation (4.9). The data is collected for various materials that are discussed in earlier Chapter3 under the heading of experimental setup and test work, in a one single sheet and find the pressure drop only in straight pipeline by using above methodology. The data for around 20 different materials has been collected for this work from previous research work. Through this data one single solid friction factor model is developed which will predict the pressure drop in straight pipe line for any material.The detailed data is provided in Annexure II for finding the solid friction factor correlation, and the results will be discussed in next chapter. From simple regression tool in Microsoft excel program the solid friction factor modeled as :

$$\lambda_s = 41.14(V^*)^{0.032} \left(\frac{W_{fo}}{V}\right)^{1.27} \left(\frac{d}{D}\right)^{-1.46} \left(\frac{\rho_a}{\rho_s}\right)^{1.8} \tag{4.24}$$

Chapter 5: Validation of model

5.1 Validation of model

For designing a system on the basis of the model developed, the model is to be validated with the experimental results so that the performance of the model can be evaluated for preventing further discrepancies in designing. The model is to be validated to found out if it is under predicting or over predicting so that due consideration would be taken into account while designing a system. Here in this thesis the solid friction factor that has been modeled is used for prediction of pressure drop in straight pipe for any size and length of pipe and for any material. The model is validated with the existing pneumatic conveying characteristics which are taken from Pan (1992) PhD thesis and the experiments done in Thapar University. The various plots are shown below.

5.1.1 Fly Ash(Pan(1992))

The prediction of pressure drop in the total pipeline using the straight pipe solid friction model is shown below in Figure 5.1. The pipeline diameter is 52.5 mm and the total length is 107 meter. The prediction is done for three differentmass flow rates of solid (1 kg/sec, 2 kg/sec and 3 kg/sec).On x-axis the mass flow rate of conveying air is taken and on the y-axis the total pipeline pressure drop is taken.

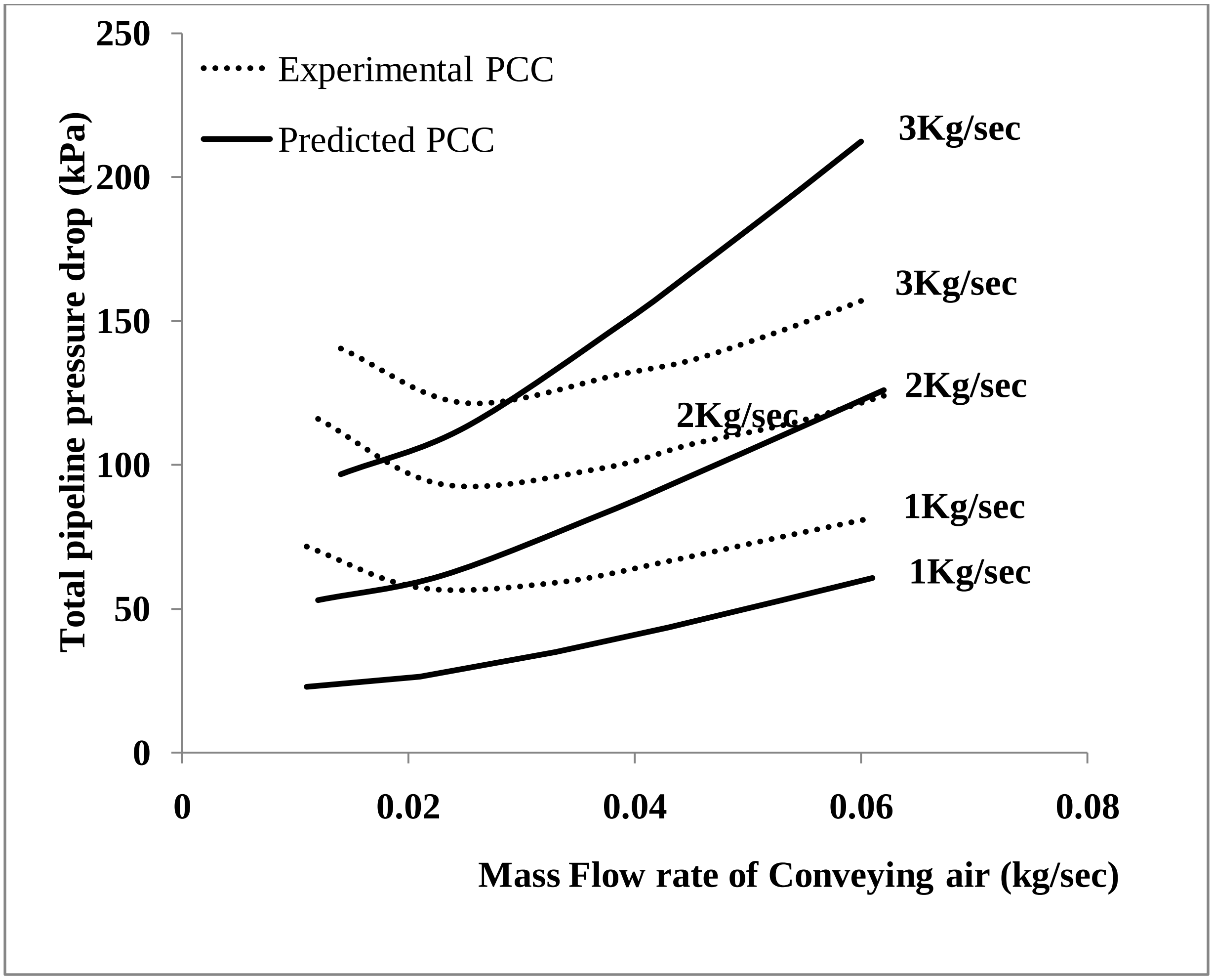

Figure 5.1 Experimental v/s Predicted PCC for Total Pipeline Pressure Drop for Fly Ash and 52.5 mm I.D x 107 m Pipe

It is seen from the Figure 5.1 that the model developed is showing good result with the intermediate mass flow rate of conveying air with all the solid mass flow rates. In the region of dense phase that is between mass flow of air from 0.01 kg/sec to 0.02 kg/secthe model is under predicting the pressure drop, as air mass flow rate increases the prediction for pressure drop also goes up towards the experimental values and in the region of dilute phase beyond the air mass flow rate of 0.06kg/sec the model over predicts the pressure drop. It can be concluded form the above Figure that if a system is to be designed by using this model than it will gives good result in intermediate regions of dense and dilute phase.

Another prediction is done on the same fly ash but with different configuration of pipe 52.5 mm I.D x 135 m total pipe length and having bends of 1 m radius is shown in Figure 5.2 below. Validation of model is done on three different mass flow rates of solid (1kg/sec, 2kg/sec, and 3 kg/sec).

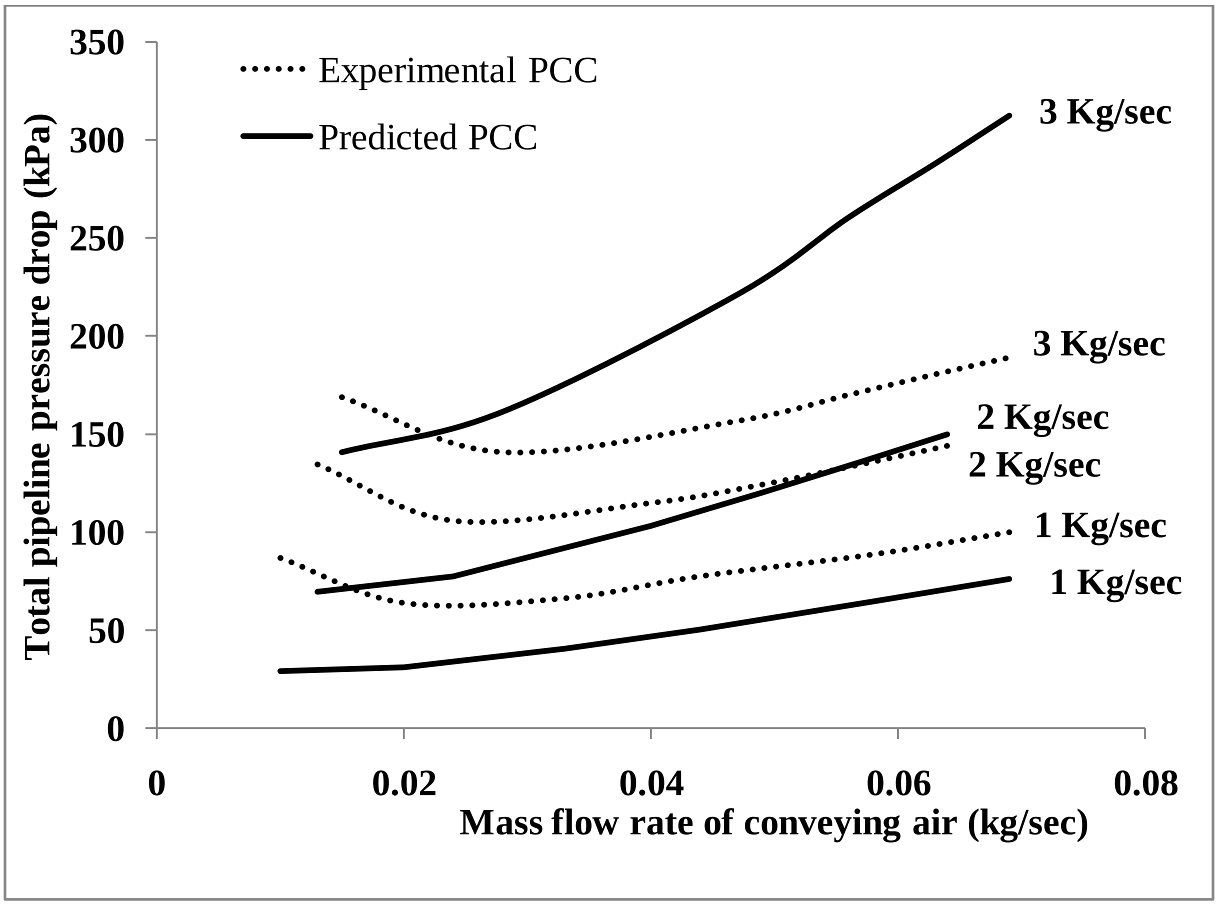

Figure 5.2 Experimental v/s Predicted PCC for Total Pipeline Pressure Drop for Fly Ash and 52.5 mm I.D x 135 m Pipe

This also shows that the model developed is showing good results with the intermediate mass flow rate of solid that is at 2 kg/sec, and gives under predicted results for pressure drop for 1kg/sec solid mass flow rate and over predicted pressure drop for 3 kg/ sec solid mass flow rate. It started with a lower value and at certain point crosses the experimental pressure drop. For the region of dense phase the predictions made by using this model are under the experimental values and in dilute phase with mass flow rate of solid 3 kg/sec it is over predicting the pressure drop.

The experimental PCCand the predicted PCC for total pipeline pressure drop for 80.5 mm I.D x 137 m and with bends of radius 554 mm is shown below in Figure 5.3. Pressure drop predictions are done for four different mass flow rates of solid (1, 2, 3 and 4 kg/sec) respectively.

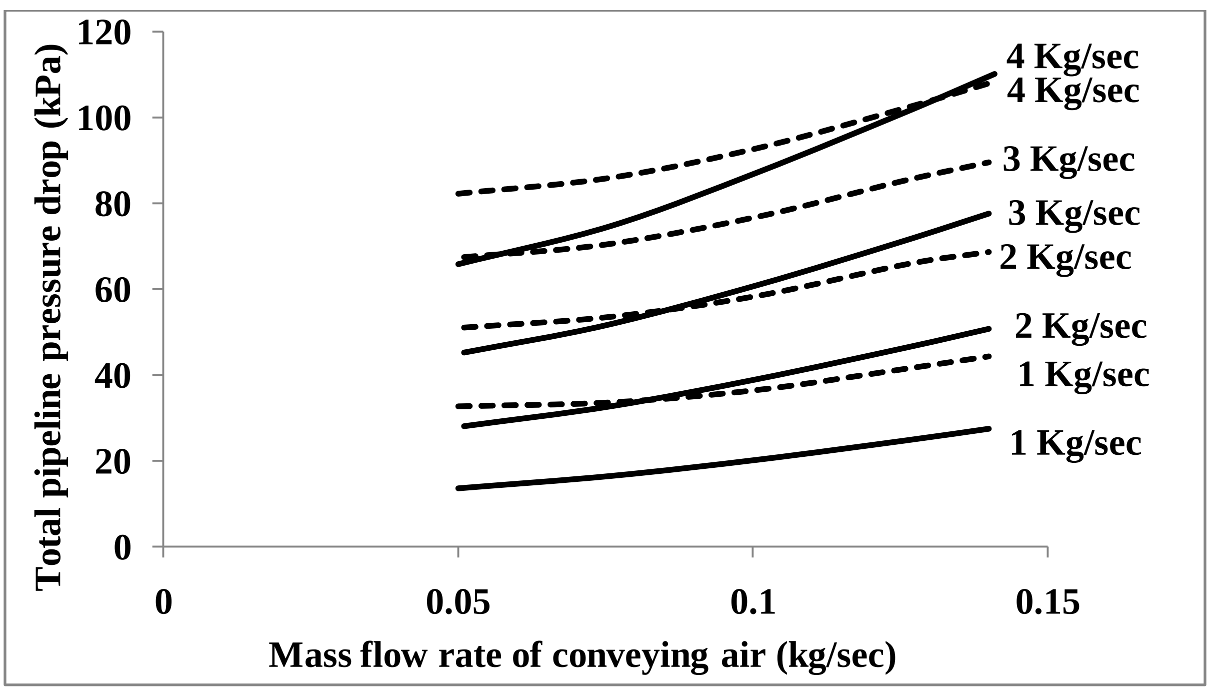

Figure 5.3 Experimental v/s Predicted PCC for Total Pipeline Pressure Drop for Fly Ash and 80.5 mm I.D x 137 m Pipe

Figure shown above it is seen that the model is predicting the total pipeline pressure drop is in good relation with the experimental values. The predictions are good due to the bend configuration used in this pipeline. Although the predictions for lower solid mass flow rate like 1 kg/sec is under the experimental values and thus it is not suitable for such mass flow rate of solids. The prediction shows that the model developed is not suitable for dilute phase as it is giving under prediction in dilute phase system and thus it will results in under sized design of the system. This model is giving good results for dense phase system.

The experimental and predicted PCC for pipeline 69 mm I.D x 170 m total length is shown below in Figure 5.4.Prediction of pressure drop is done for two different mass flow rates of solid (1 kg/sec and 2 kg/sec).

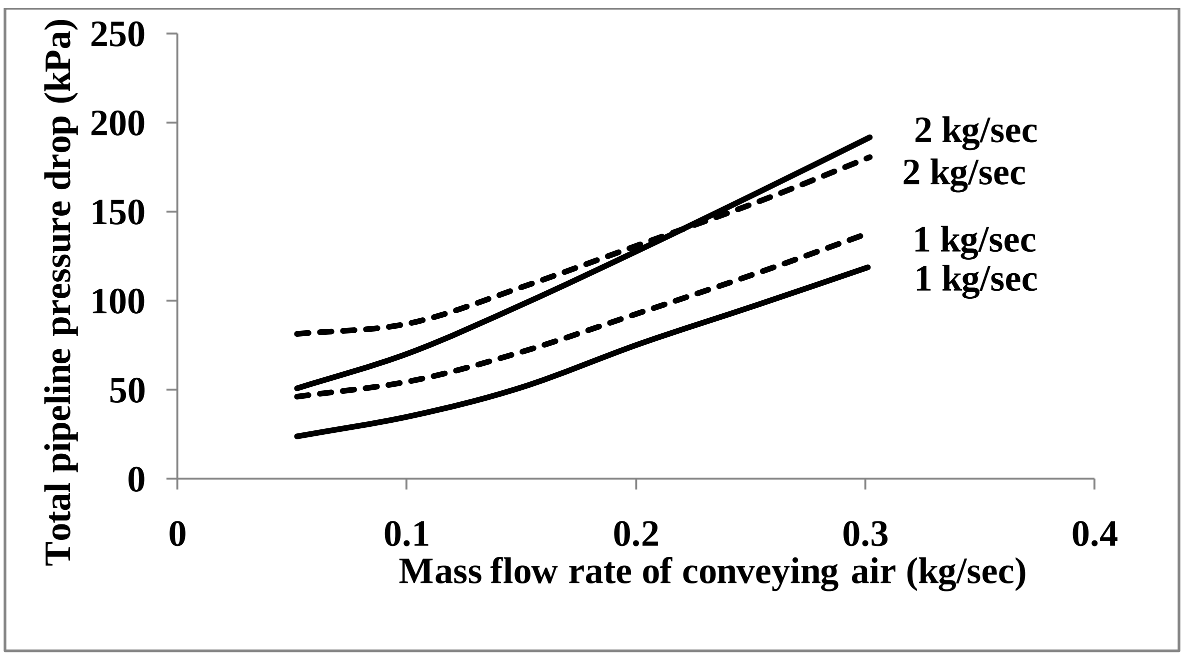

Figure 5.4 Experimental v/s Predicted PCC for Total Pipeline Pressure Drop for Fly Ash and 69 mm I.D x 172 m Pipe

In the Figure 5.4 it is shown that the model is giving a good result with the experimental values for two different solid mass flow rates. The prediction for total pipeline pressure drop is under the experimental values for solid mass flow rate of 1 kg/sec at all mass flow rate of conveying air and gives under prediction value in dense phase region of 2 kg/sec mass flow rate of solid but gives over prediction in dilute phase region. The difference between the experimental and predicted values is not very large for this configuration of pipeline

The configuration of pipeline for the prediction of total pipeline pressure drop used here is 69 mm I.D x 554 m total pipeline length with 1 m bend radius is shown in Figure 5.5 below

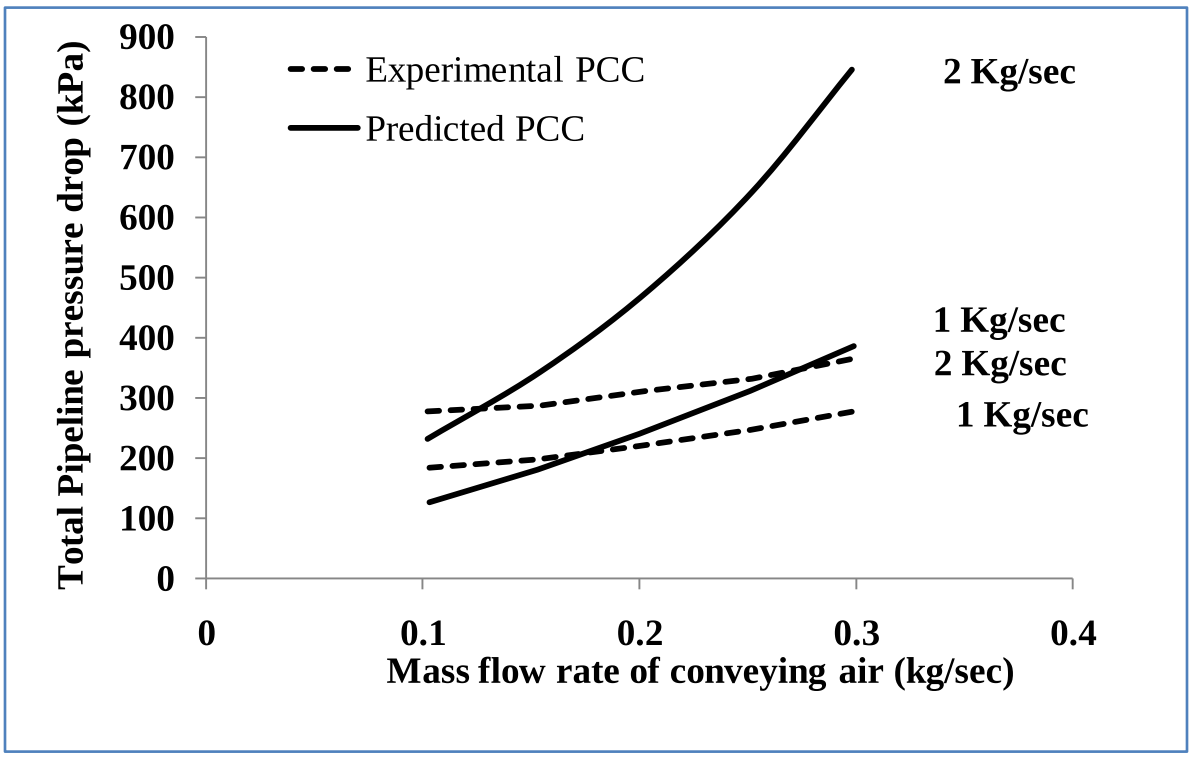

Figure 5.5 Experimental v/s Predicted PCC for Total Pipeline Pressure Drop for Fly Ash and 69 mm I.D x 554 m Pipe

Figure shows that the model used here for prediction gives alarming results as we go for dense phase system but gives a good relation when working in dilute phase. In going towards the dense phase the prediction is much higher and thus it is not suitable here for higher solid mass flow rate and for bigger lengths of pipe.

5.1.2 Brown Pulverized Coal (Pan (1992))

The prediction for brown pulverized coal for pipe configuration 69 mm I.D x 172 m total pipe length is shown below in Figure 5.6. The validation of model is done on two different mass flow rates of solid (1 kg/sec and 2 kg/sec). Mass flow rate of conveying air is taken on x-axis and total pipeline pressure drop is taken on y-axis and the experimental and predicted PCC are drawn. The Figure shows that the model used here gives under predicted values for pressure drop in total pipeline. It is further to be noticed that instead of giving good predictions in dense phase as it gives in earlier PCC here it gives under prediction for both dilute and dense phase and hence we can say that this model is not suitable for designing the system for such material and pipeline configuration. The error is not so big,it is in the controlled region but still this model is not showing good results here. It is also seen from the figure that if the predictions are done on solid mass flow rate more than 2 kg/sec the model will give over predicted values and thus it can be concluded that for higher solid mass flow rate for particles having lower density. For heavier particles the predictions are somewhat different than these predictions. Thus it is clear that model is sensitive for with the particle density.

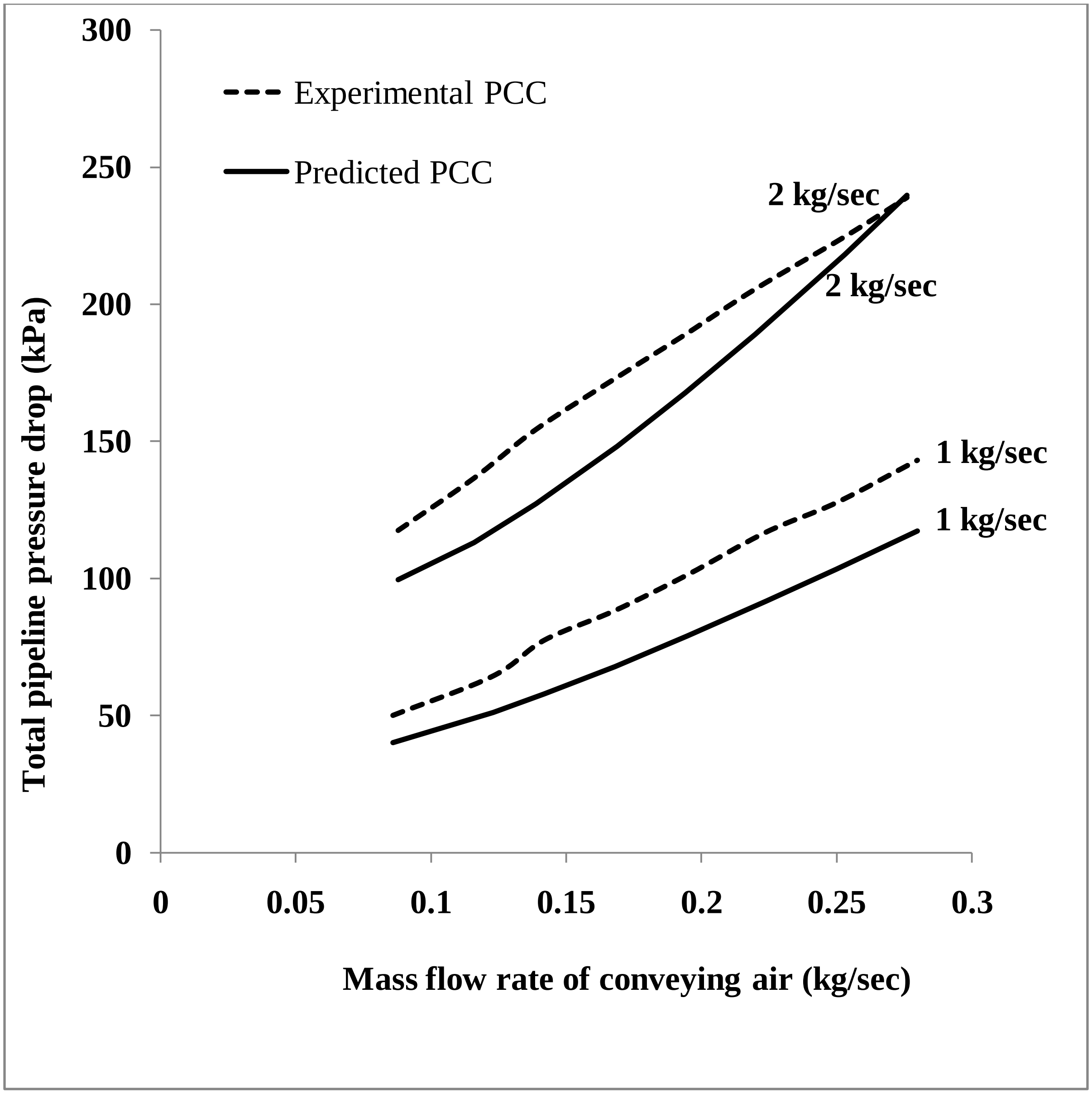

Figure 5.6 Experimental v/s Predicted PCC for Total Pipeline Pressure Drop for Brown Pulverized Coal and 69 mm I.D x 172 m Pipe

5.1.3 Fly Ash (Thapar University)

The prediction for total pipeline pressure drop is done on the PCC formed in Thapar University on experimental basis. The PCC were made by interpolation method and the model is validated with the experimental values in the form of bar chartsas shown in the following Figures.

Figure 5.7 shows the bar chart for 38.1 mm x 24 m pipeline length, validation is done on two mass flow rates of solid (1tph and 2 tph), Figure shows different pressure drops at different air mass flow rates in the form of bar chart.

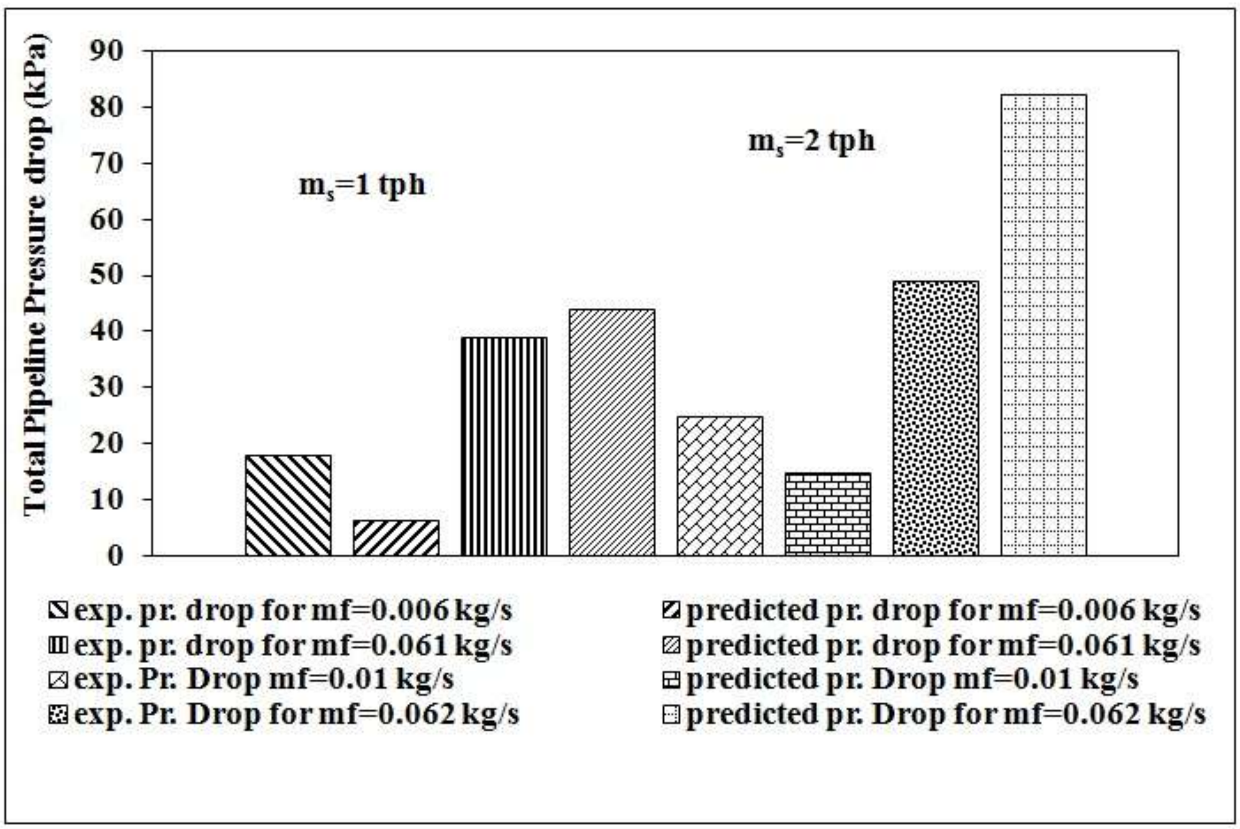

Figure 5.7 Experimental v/s Predicted PCC for Total Pipeline Pressure Drop for Fly Ash and 38.1 mm I.D x 24 m Pipe

The prediction from the model developed is done on this configuration and found that in dilute phase it is showing good results with minimum error, but as we go for dense phase it deviates with very large values from the experimental values and follows almost a linear trend line. Hence from here we can only say that the model is giving good results with only dilute phase.

In the next configuration of pipeline of 50.8 mm I.D x 24 m length the predictions for pressure drop shows different results as shown in Figure 5.8. The model is validated for two different mass flow rates of solid (3.5 tph and 5 tph) and showing good results.

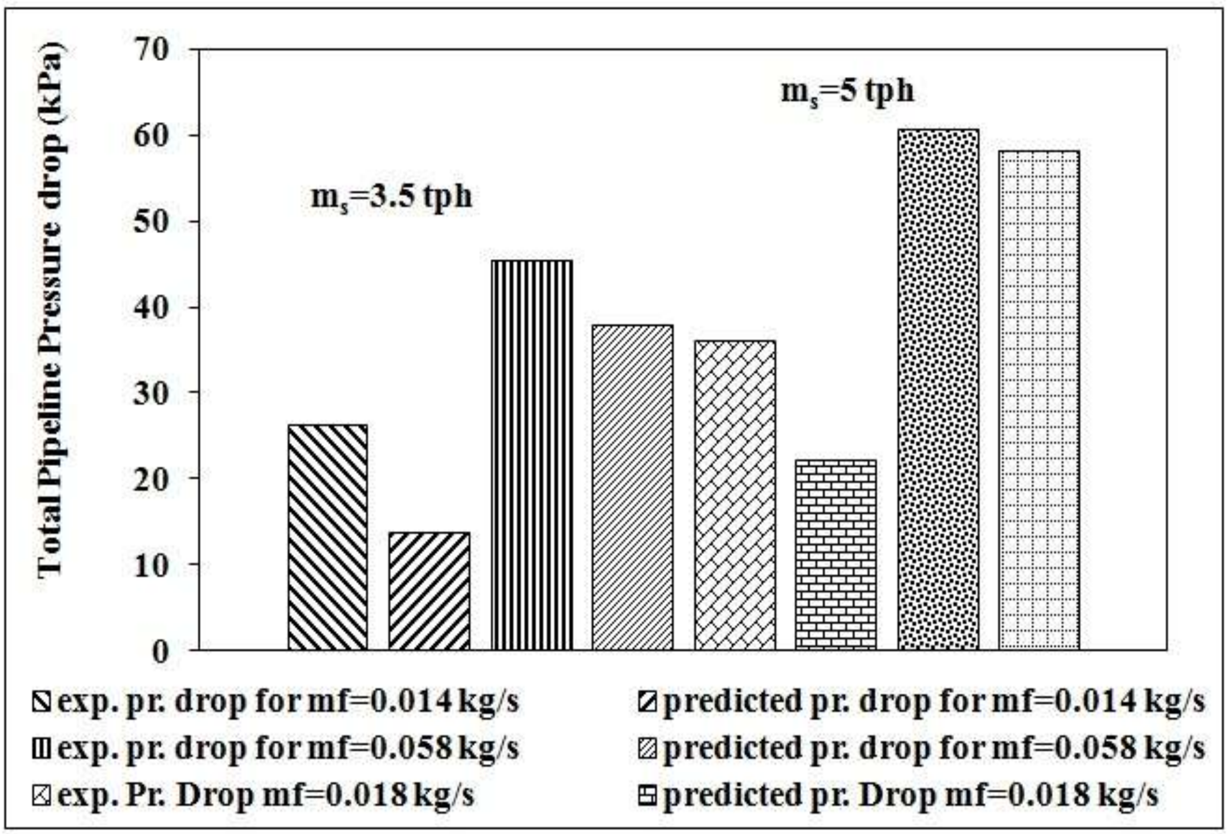

Figure 5.8 Experimental v/s Predicted PCC for Total Pipeline Pressure Drop for Fly Ash and 50.8 mm I.D x 24 m Pipe

In this configuration the predictions are almost the same as that of experimental values, showing that the model has effectively worked over the entire range of air mass flow rate. For the solid mass flow rate of 5 tph and the air mass flow rate of 0.018 kg/sec the model has worked very accurately. Thus it can be concluded form the Figure that for designing this configuration modelso developed gives good results.

The Figure 5.9 shows the pressure drop prediction in 63.5 mm I.D x 24 m pipeline length. The validation of model is done on two mass flow rates of solid (3.5 tph and 4.5 tph).

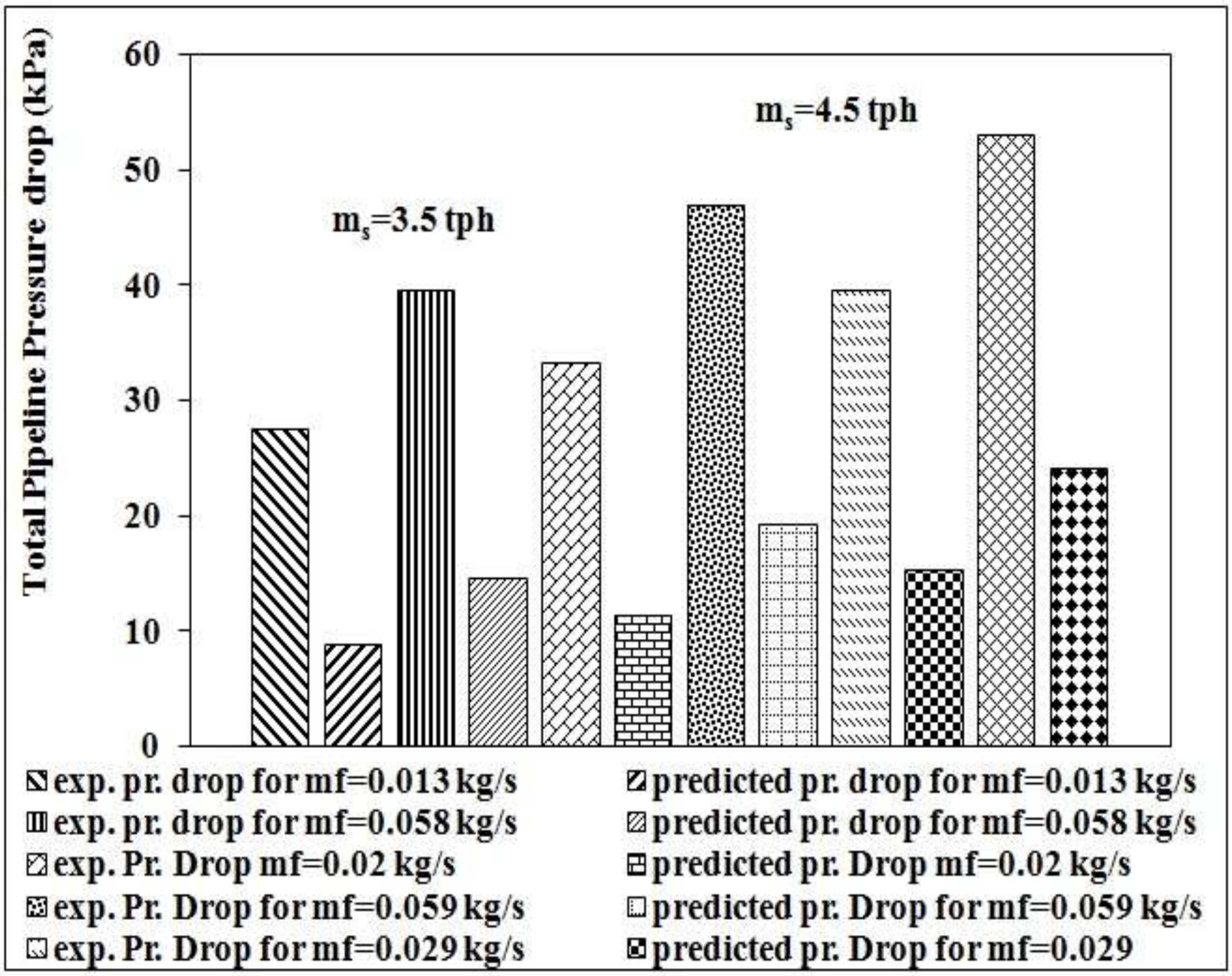

Figure 5.9 Experimental v/s Predicted PCC for Total Pipeline Pressure Drop for Fly Ash and 63.5 mm I.D x 24 m Pipe

The model gives very alarming results as can be seen from the Figure. The predicted values are far below the experimental values; this may be due to the increased pipe dia which shows a significant effect on the prediction of the pressure drop by using this model. The model for this configuration of pipeline is not suitable (in both dilute and dense phase) to be used for designing purpose. The predictions would be good if the model is used on bigger lengths of pipeline with this dia.

The Figure 5.10 shows the pressure drop prediction in 50.8 mm I.D x 72 m pipeline length. The validation of model is done on two mass flow rates of solid (3.5 tph and 4.5 tph).

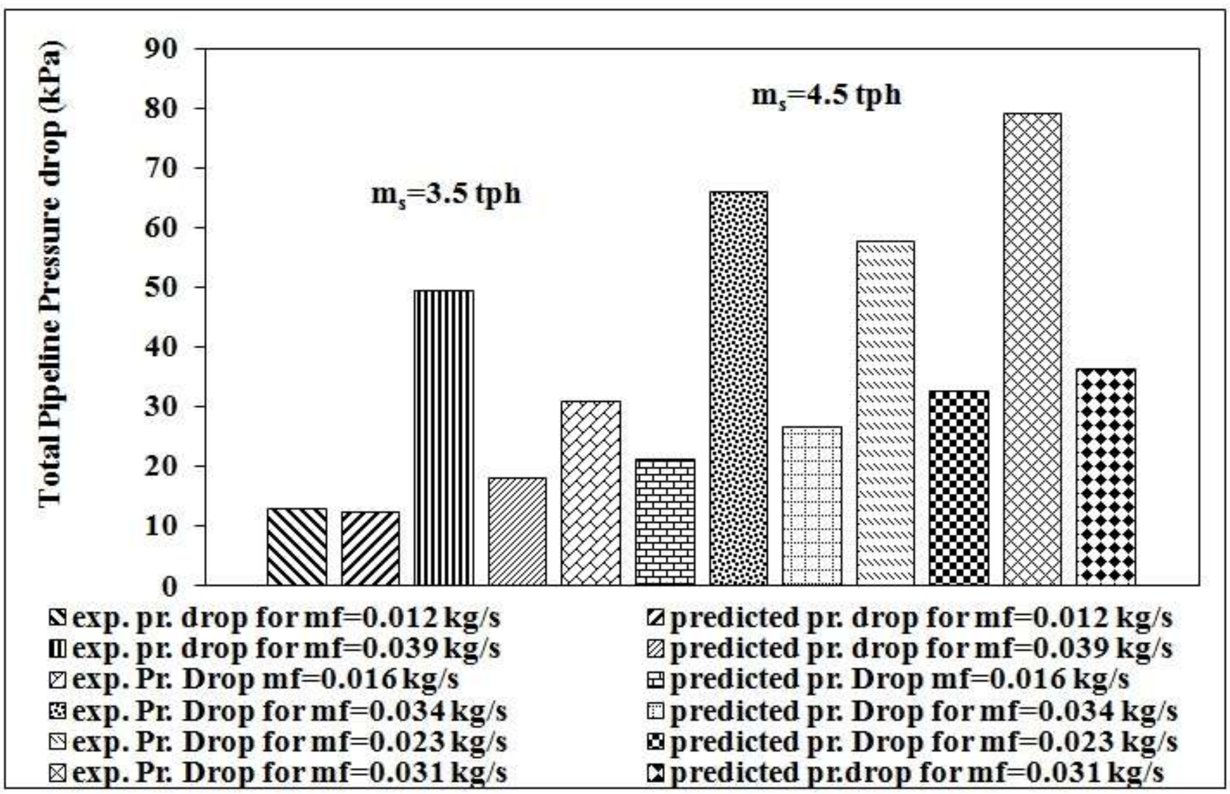

Figure 5.10 Experimental v/s Predicted PCC for Total Pipeline Pressure Drop for Fly Ash and 50.8 mm I.D x 72 m Pipe

In the Figure shown above the prediction of total pipeline pressure drop using the developed model is under predicting the drop. In both dilute and dense phase the predictions are very low as compared to the experimental values. For mass flow rate of solid 0.012 kg/sec and mass flow rate of solid 3.5 tph the predicted and the experimental values are almost same. This shows that the model is giving good result in dense phase when the solid transfer rate is in lower range.

5.2 Average Percentage Error

The percentage error is calculated and is tabulated under in Table 5.1. The negative Percentage error indicates that the model is over predicting the results and the positive error indicates that the model so developed used for prediction of pressure drop on total pipeline is under predicting the results.

Table 5.1 Average Percentage Error between the Experimental and Predicted Total pipeline Pressure drop compared from Pan (1992) and Thapar University

Bulk Material	Density (kg/m^3)	Bulk Density (kg/m3)	Pipeline Length (m)	Pipe I.D (mm)	Mass Flow Rate of Air (kg/sec)	Average Absolute Percentage Error (%)
Fly Ash (Pan)	2197	634	107	52.5	0.024	29.9
					0.036	35
					0.049	3.9
Fly Ash (Pan)	2197	634	135	52.5	0.016	36.3
					0.029	14.9
					0.044	0.76
Fly Ash (Pan)	2197	634	137	80.5	0.076	26.5

					0.102	19.2
					0.13	14.6
Fly Ash (Pan)	2197	634	172	69	0.121	24.6
					0.28	4
Fly Ash (Pan)	2197	634	553	69	0.095	19.1
					0.22	14.5
Pulverized Brown Coal (Pan)	1488	584	172	69	0.11	19.8
					0.24	-54.8
Fly Ash (TU)	1950	950	24	38.1	0.01	50.4
					0.04	-26.2
Fly Ash (TU)	1950	950	24	50.8	0.02	35.2
					0.05	9.07
Fly Ash (TU)	1950	950	72	50.8	0.024	38.7
					0.029	49.1

Table 5.1 shows that there is a lot of difference in the predicted values as compared to that of the experimental values. The error shown is so large so that while designing the particular system the predictions of pressure drop has to be multiplied with suitable constant accordingly by seeing the error associated with the pipeline configuration. At some places the error is very less and the model can be directly used for designing the system.

Chapter 6: Conclusion and Further Scope of Work

6.1 Conclusion

From the above results the conclusion is made that the developed model is showing good results when the flow is in dilute phase, also it gives good predictions when the flow is between the dilute and the dense phase but for dense phase it shows alarming results or predictions for pressure drop in total pipeline. It is due to the fact that there are many parameters on which the solid friction factor model depends. As the particle size increases or decreases there is a change in the d/D ratio which results in the prediction of pressure drop as the larger particles will offer more friction due to the more surface contact with the walls of pipe. Similarly as the pipe length increases the predictions are amazing, they are far above the experimental values, the model predicted the pressure drop effectively in somewhat dense phase but fails to predict the pressure drop in extremely dilute and dense phase. The model effectively works on moderate pipe lengths and diameters. With heavier particles the model is predicting the pressure drop in good range with less error as one of the dependent parameter is ρ/ρ_s,as the particle density increases this factor will have a direct effect on the solid friction factor model.The model so developed is giving good results at lower air mass flow rate with less error.

6.2 Further scope of work

The model for solid friction factor is developed by considering the various particle data on different configurations of pipe (size and lengths) and also with different bend radii.

The straight pipe pressure drop is calculated by subtracting the losses offered by bends and loss due to re-acceleration of the particles.

- The straight pipe solid friction factor depends upon number of variables, so it can be further modified by grouping other variables like loading ratio, ratio of particle density to air density, ratio of pipeline dia to particle dia, Froude number etc.
- The model can be further validated with other experimental data for different pipeline configurations and for different products with variation in operating conditions.

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APPENDIX A

Schematic layout of Pipelines

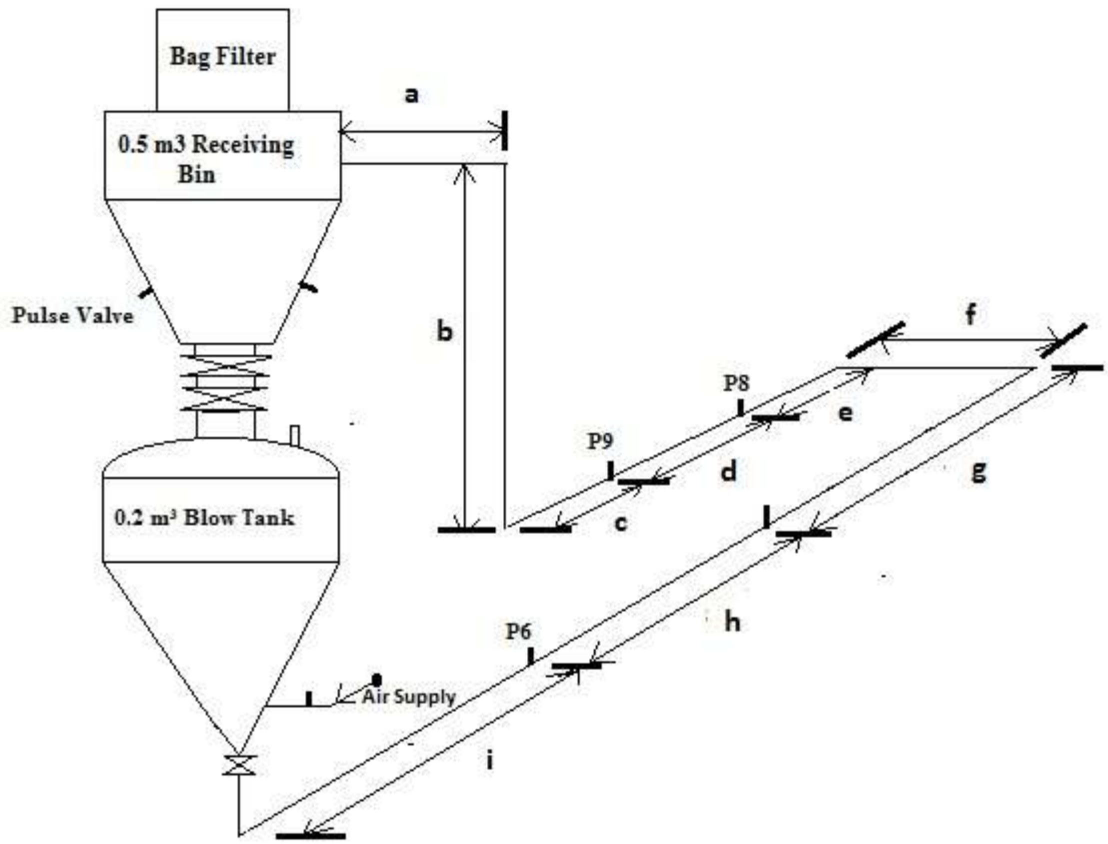

Figure A.1: Layout of Pipeline at Thapar University Laboratory

Table A.1: Thapar University Laboratory Pipeline Details

	Effective length of section (m)									
Pipeline	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**D (m)**
I	3	2	2	4	2	3	1	4	3	0.0381
II	3	2	2	4	2	3	1	4	3	0.0508
III	3	2	2	8	21	3	20	8	3	0.0508

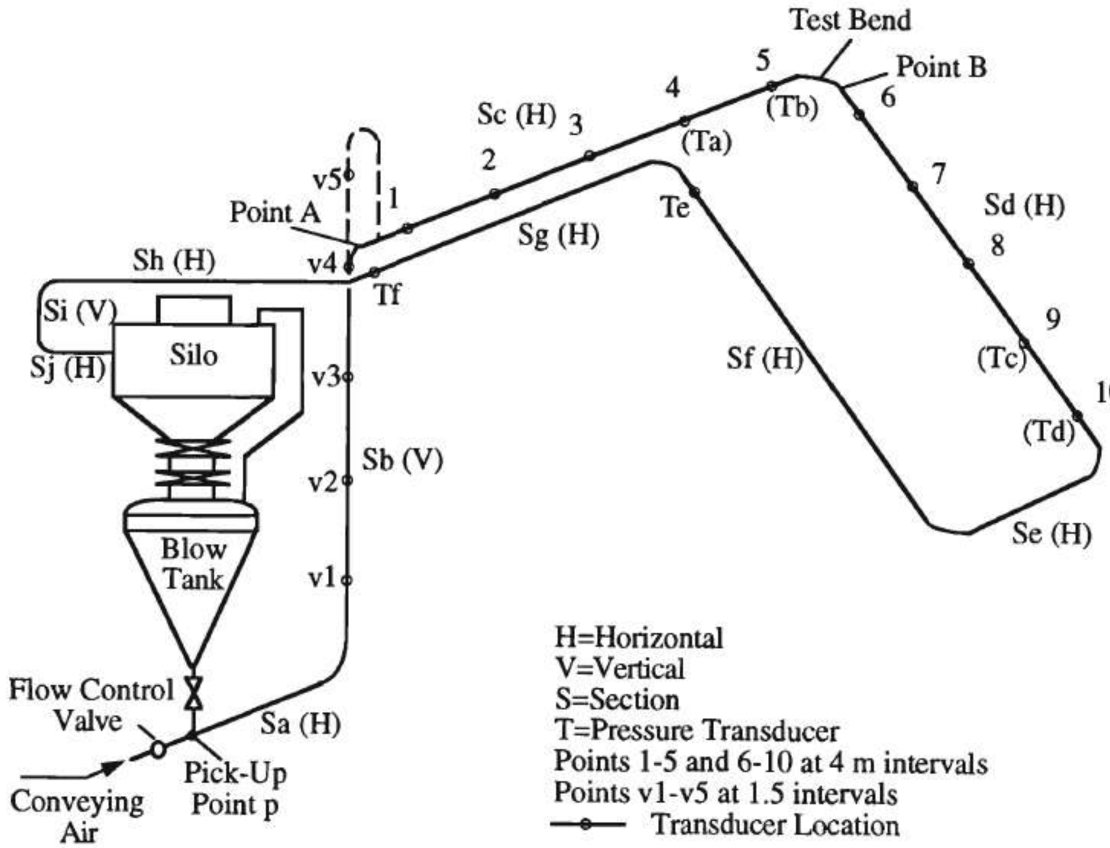

Figure A.2:Schematic Layout of Pipeline, Pan (1992)

Table A.2: Pan's Pipeline Details

	Effective length of section (m)										
Pipeline	**Sa**	**Sb**	**Sc**	**Sd**	**Se**	**Sf**	**Sg**	**Sh**	**Si**	**Sj**	**D (m)**
I	1.9	5.9	21.3	21.1	6.5	20.7	17	3	2.5	2	0.0525
II	1.9	5.9	21.3	37.6	6.5	37.2	17	3	2.5	2	0.0525
III	2.1	5.9	21.9	37.7	7.4	36.5	17.3	3.4	2.5	2.6	0.0805

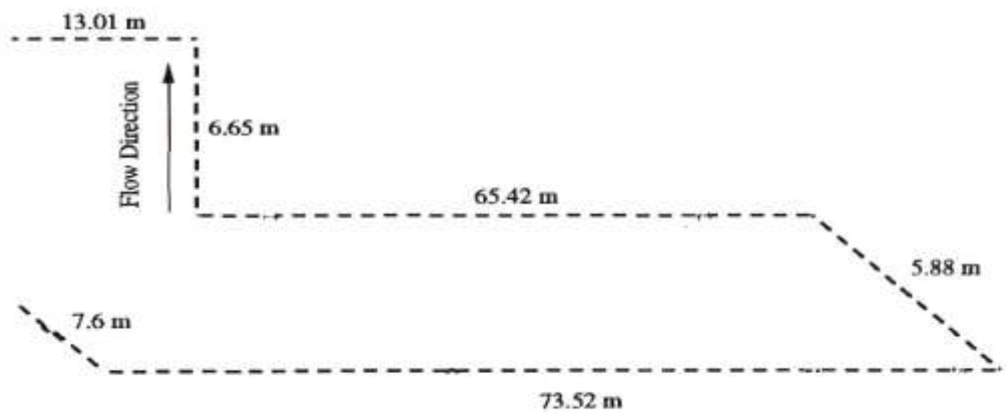

Figure A.3 Schematic Layout of Pipeline A1 (L=172m, D=69mm), Pan (1992)

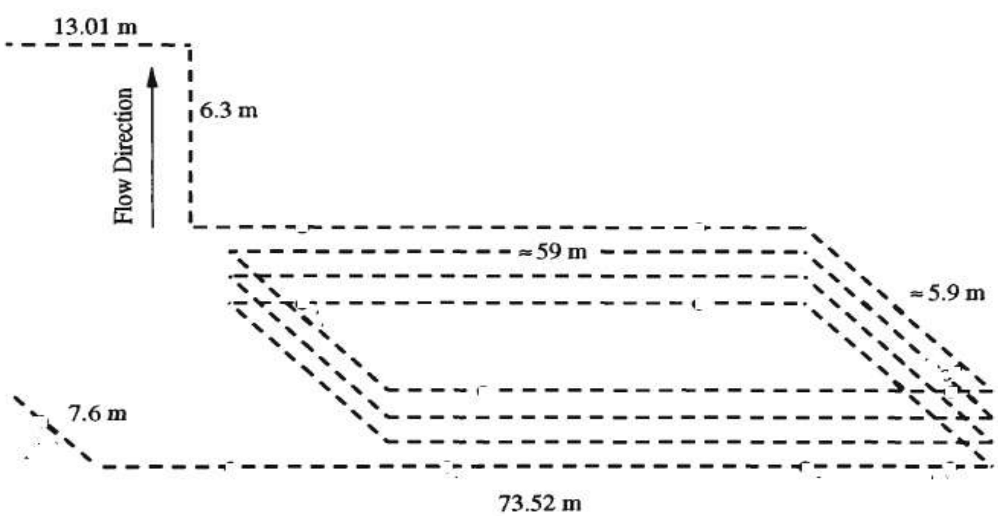

Figure A.4 Schematic Layout of Pipeline A2 (L=553 m, D=69 mm), Pan (1992)

APPENDIXB

Particles free settling velocity (W_{fo})

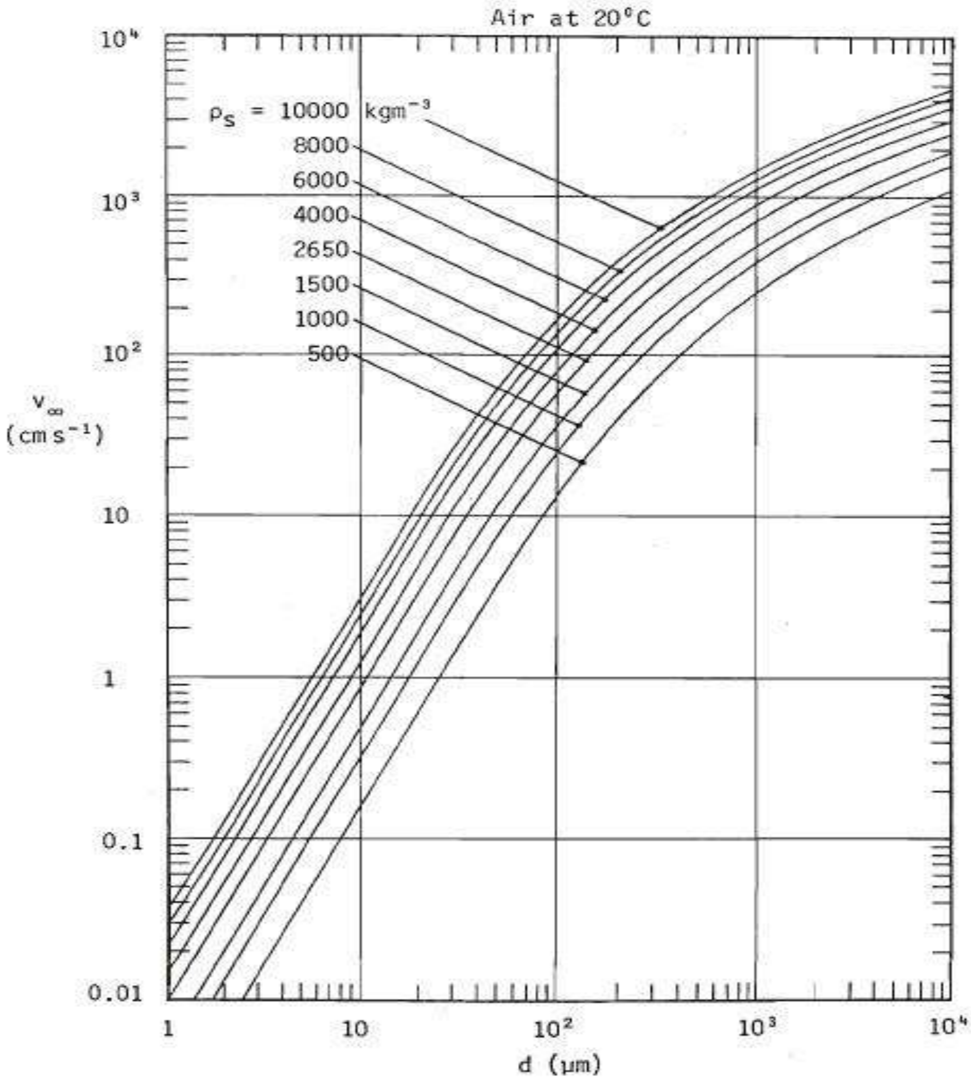

Figure B-1 Variation of particle free settling velocity based on the Clitt et al. (1978) drag correlations.

APPENDIX C

Summary of Solid Friction Factor Calculation for Different Materials in Different Pipe Configurations

Table C.1 Solid friction factor modeling

mf	ms	ΔP	Total Bend loss (kPa)	Elevation loss (kPa)	Accelartion loss (kPa)	Only Straight pipe loss (kPa)	λf	λs	Log(λs)	Log(V*)	Log(d/D)	Log(ρ/ρs)	log(wfo/v)
kg/s	kg/s	kPa											
0.005	2.5	83.504	2.04232	30.0132	1.26176159	50.18671	0.0346	0.14951	-0.8253	-0.2748	-3.23888	-2.97375	-1.48829
0.005	2.5	82.21	2.0516	29.87746	1.27065876	49.01028	0.0346	0.14534	-0.8376	-0.2767	-3.23888	-2.97572	-1.49026
0.005	2.5	81.132	2.05939	29.76437	1.27816715	48.03007	0.0346	0.14189	-0.848	-0.2784	-3.23888	-2.97736	-1.49191
0.005	2.5	80.269	2.06568	29.67384	1.2842423	47.24524	0.0346	0.13915	-0.8565	-0.2797	-3.23888	-2.97869	-1.49323
0.006	2.5	76.819	2.51042	24.42661	1.57094026	48.31103	0.0329	0.11711	-0.9314	-0.3642	-3.23888	-2.98402	-1.57774
0.011	0.5	33.18	2.89168	2.248551	0.76292816	27.27684	0.0279	0.04773	-1.3212	-1.4002	-3.27825	-3.05777	-1.96588
0.012	0.5	31.797	3.17938	2.049081	0.84093348	25.7276	0.0272	0.0409	-1.3883	-1.4405	-3.27825	-3.06032	-2.00623
0.015	0.5	30.876	4.01328	1.632824	1.05849136	24.1714	0.0257	0.03034	-1.518	-1.5392	-3.27825	-3.06203	-2.10485
0.02	0.5	29.493	5.43519	1.217364	1.42624507	21.4142	0.024	0.01959	-1.708	-1.6667	-3.27825	-3.06461	-2.23236
0.025	0.5	30.415	6.83217	0.97776	1.77032676	20.83474	0.0227	0.01492	-1.8262	-1.7619	-3.27825	-3.06289	-2.32755
0.029	0.5	31.797	7.93862	0.847896	2.0322559	20.97823	0.022	0.01275	-1.8946	-1.8237	-3.27825	-3.06032	-2.38944
0.033	0.5	35.023	8.97834	0.755376	2.25784158	23.03144	0.0213	0.01231	-1.9099	-1.8739	-3.27825	-3.05438	-2.43962
0.037	0.5	37.788	10.0255	0.681553	2.48119401	24.59974	0.0208	0.01168	-1.9326	-1.9186	-3.27825	-3.04936	-2.48429
0.041	0.5	42.396	10.9816	0.62685	2.66126327	28.12629	0.0203	0.01223	-1.9125	-1.9549	-3.27825	-3.04111	-2.52062
0.046	0.5	48.387	12.1379	0.572377	2.86630505	32.81045	0.0198	0.01298	-1.8866	-1.9944	-3.27825	-3.03062	-2.5601
0.05	0.5	54.378	12.9802	0.539156	2.99565243	37.86303	0.0194	0.01415	-1.8493	-2.0204	-3.27825	-3.02038	-2.58607
0.052	0.5	58.525	13.3333	0.526785	3.0346408	41.63029	0.0193	0.01528	-1.8158	-2.0305	-3.27825	-3.01342	-2.59615
0.056	0.5	64.055	14.163	0.499517	3.15877984	46.23367	0.019	0.01608	-1.7937	-2.0535	-3.27825	-3.00432	-2.61923
0.016	0.5	40.549	4.11851	1.594193	1.0520645	33.78423	0.0253	0.04164	-1.3805	-1.7165	-3.42375	-3.21135	-2.27015
0.02	0.5	39.231	5.21633	1.268441	1.32741439	31.41882	0.024	0.03045	-1.5164	-1.8158	-3.42375	-3.21371	-2.36942

0.025	0.5	38.855	6.59335	1.013175	1.66371938	29.58475	0.0227	0.02249	-1.648	-1.9134	-3.42375	-3.21438	-2.467
0.03	0.5	39.402	7.96932	0.846226	1.98870171	28.59775	0.0218	0.01777	-1.7504	-1.9916	-3.42375	-3.2134	-2.5452
0.034	0.5	39.942	9.07981	0.748336	2.24524491	27.86861	0.0212	0.015	-1.8239	-2.0449	-3.42375	-3.21243	-2.59859
0.039	0.5	42.799	10.3902	0.66008	2.52436589	29.22435	0.0205	0.0136	-1.8663	-2.0994	-3.42375	-3.20735	-2.65309
0.043	0.5	45.655	11.4081	0.605645	2.72918359	30.91206	0.0201	0.01303	-1.8851	-2.1368	-3.42375	-3.20232	-2.69047
0.047	0.5	48.494	12.4192	0.560437	2.92652408	32.58788	0.0197	0.01254	-1.9015	-2.1705	-3.42375	-3.19738	-2.72416
0.05	0.5	51.325	13.1362	0.532751	3.05557529	34.60045	0.0194	0.01259	-1.9001	-2.1925	-3.42375	-3.19252	-2.74616
0.016	1	66.013	7.34057	3.522293	1.78389363	53.36624	0.0253	0.03664	-1.4361	-1.3722	-3.42375	-3.16809	-2.22689
0.018	1	66.061	8.27292	3.131486	2.00630475	52.65029	0.0246	0.03205	-1.4942	-1.4233	-3.42375	-3.16802	-2.27797
0.005	0.5	43.395	1.24503	5.161129	0.32230359	36.66654	0.0347	0.14882	-0.8273	-1.1574	-3.31117	-3.15745	-1.6508
0.008	0.5	39.653	2.03483	3.176637	0.52937609	33.91216	0.0304	0.08443	-1.0735	-1.3682	-3.31117	-3.1641	-1.86157
0.011	0.5	37.239	2.84274	2.28726	0.74057543	31.36842	0.0279	0.05594	-1.2523	-1.5109	-3.31117	-3.16845	-2.00423
0.016	0.5	35.31	4.20921	1.559844	1.09241122	28.44854	0.0254	0.03417	-1.4664	-1.6771	-3.31117	-3.17196	-2.17046
0.021	0.5	33.895	5.61149	1.181384	1.4487963	25.65333	0.0238	0.02289	-1.6404	-1.7978	-3.31117	-3.17455	-2.29115
0.026	0.5	34.695	6.99059	0.957423	1.78319595	24.96379	0.0226	0.01766	-1.7529	-1.8891	-3.31117	-3.17308	-2.38244
0.031	0.5	36.739	8.3423	0.809916	2.09463594	25.49214	0.0217	0.01493	-1.826	-1.9618	-3.31117	-3.16936	-2.4551
0.035	0.5	40.121	9.35746	0.727491	2.30835608	27.7277	0.0211	0.01442	-1.841	-2.0084	-3.31117	-3.16327	-2.50171
0.04	0.5	43.502	10.6459	0.645422	2.57652341	29.63417	0.0205	0.01343	-1.8718	-2.0603	-3.31117	-3.15726	-2.5537
0.044	0.5	47.734	11.5978	0.596837	2.75369592	32.78568	0.0201	0.01366	-1.8647	-2.0943	-3.31117	-3.14985	-2.58769
0.048	0.5	51.938	12.5347	0.556288	2.92161795	35.92544	0.0197	0.01386	-1.8583	-2.1249	-3.31117	-3.14262	-2.61824
0.008	0.5	47.29	1.97264	3.27678	0.50216804	41.53841	0.0318	0.10678	-0.9715	-1.3609	-3.44185	-3.15678	-2.14913
0.011	0.5	44.709	2.75687	2.358499	0.70268668	38.89094	0.0292	0.07166	-1.1447	-1.5037	-3.44185	-3.16129	-2.29194
0.012	1	79.829	5.2155	4.937947	1.23586751	68.43969	0.0285	0.06625	-1.1788	-1.1828	-3.44185	-3.10362	-2.27206
0.017	1	74.588	7.56552	3.420928	1.80298191	61.79857	0.026	0.04122	-1.3849	-1.3422	-3.44185	-3.11176	-2.43146
0.016	1.5	110.519	9.39622	6.158843	2.11361064	92.85033	0.0264	0.0498	-1.3028	-1.0869	-3.44185	-3.05882	-2.35219
0.021	1.5	104.374	12.6209	4.600362	2.85699722	84.29574	0.0247	0.03362	-1.4734	-1.2136	-3.44185	-3.06743	-2.4789
0.018	2	136.141	13.0068	7.896664	2.82829982	112.4093	0.0257	0.0435	-1.3615	-0.9789	-3.44185	-3.02466	-2.36919
0.023	2	131.778	16.8783	6.1004	3.68158818	105.1177	0.0242	0.03131	-1.5043	-1.091	-3.44185	-3.03029	-2.48127
0.028	2	126.992	20.8974	4.939319	4.57589439	96.57937	0.0231	0.02318	-1.6349	-1.1827	-3.44185	-3.03656	-2.57297
0.021	2.5	161.783	17.6229	9.10117	3.72258974	131.3363	0.0247	0.03748	-1.4262	-0.9173	-3.44185	-2.99297	-2.40445
0.025	2.5	155.578	21.377	7.514798	4.53870299	122.1475	0.0237	0.0287	-1.5421	-1.0004	-3.44185	-3.00043	-2.48763
0.011	0.5	47.126	2.73019	2.381549	0.69124398	41.32302	0.0292	0.07693	-1.1139	-1.5233	-3.47049	-3.18087	-2.28771
0.015	1	73.562	6.68708	3.862701	1.60020077	61.41202	0.0269	0.04634	-1.334	-1.3133	-3.47049	-3.13717	-2.37871
0.02	1	72.413	8.99747	2.884972	2.14771343	58.38285	0.025	0.03269	-1.4856	-1.44	-3.47049	-3.13898	-2.50546
0.017	1.5	96.55	10.4566	5.537959	2.40426749	78.15121	0.026	0.03761	-1.4247	-1.1568	-3.47049	-3.10245	-2.39834

0.023	1.5	93.102	14.3687	4.046095	3.31052616	71.3767	0.0242	0.02492	-1.6034	-1.2931	-3.47049	-3.10748	-2.53466
0.019	2	120.113	14.4184	7.127074	3.20154152	95.36599	0.0253	0.03324	-1.4783	-1.0472	-3.47049	-3.06952	-2.41372
0.025	2	117.239	19.1989	5.368338	4.26795381	88.40378	0.0237	0.02308	-1.6367	-1.1703	-3.47049	-3.0734	-2.53679
0.008	0.5	45.237	1.98898	3.249859	0.50920347	39.48895	0.0318	0.10065	-0.9972	-1.3775	-3.65531	-3.17342	-2.50489
0.013	0.5	44.223	3.27732	1.991731	0.83322132	38.12073	0.0279	0.05912	-1.2282	-1.5902	-3.65531	-3.1752	-2.71752
0.025	0.5	43.902	6.45836	1.034353	1.60589103	34.8034	0.0237	0.02719	-1.5656	-1.8747	-3.65531	-3.17577	-3.00209
0.03	0.5	45.702	7.76712	0.868255	1.90347279	35.16315	0.0227	0.0227	-1.6439	-1.9508	-3.65531	-3.17261	-3.07811
0.035	0.5	46.938	9.10182	0.747923	2.20220204	34.88605	0.0219	0.01904	-1.7204	-2.0155	-3.65531	-3.17045	-3.1429
0.042	0.5	50.462	10.911	0.632071	2.58127878	36.33764	0.021	0.01634	-1.7867	-2.0886	-3.65531	-3.16436	-3.21599
0.047	0.5	54.518	12.1282	0.573883	2.81338323	39.00254	0.0205	0.01572	-1.8036	-2.1306	-3.65531	-3.15746	-3.25793
0.053	0.5	58.579	13.6115	0.516953	3.0919546	41.35859	0.0199	0.01474	-1.8315	-2.176	-3.65531	-3.15065	-3.3033
0.058	0.5	62.624	14.8011	0.479704	3.30015329	44.04309	0.0195	0.01439	-1.842	-2.2084	-3.65531	-3.14397	-3.33578
0.063	0.5	68.379	15.8766	0.451215	3.46306877	48.58815	0.0192	0.01486	-1.8279	-2.235	-3.65531	-3.13465	-3.36237
0.015	0.5	53.713	3.65571	1.792536	0.9025511	47.36221	0.0269	0.06611	-1.1797	-1.6774	-3.59215	-3.2003	-2.43593
0.021	0.5	50.856	5.23598	1.266111	1.28729735	43.06661	0.0247	0.04194	-1.3773	-1.8284	-3.59215	-3.20517	-2.58692
0.027	0.5	49.713	6.84035	0.980312	1.66762383	40.22472	0.0233	0.02983	-1.5254	-1.9395	-3.59215	-3.20713	-2.69803
0.033	0.5	49.713	8.45561	0.802073	2.0382069	38.41711	0.0222	0.02282	-1.6416	-2.0267	-3.59215	-3.20713	-2.78518
0.04	0.5	50.856	10.337	0.664708	2.45199495	37.4023	0.0212	0.0179	-1.7472	-2.1083	-3.59215	-3.20517	-2.86677
0.046	0.5	52.571	11.9388	0.581918	2.78836561	37.26187	0.0206	0.0152	-1.8181	-2.166	-3.59215	-3.20224	-2.92453
0.052	0.5	57.713	13.3749	0.525147	3.0501372	40.76284	0.02	0.01479	-1.8299	-2.2106	-3.59215	-3.19357	-2.96912
0.058	0.5	63.428	14.7563	0.481158	3.28404599	44.90647	0.0195	0.01477	-1.8307	-2.2486	-3.59215	-3.18414	-3.00711
0.063	0.5	69.713	15.7988	0.453436	3.43605484	50.02472	0.0192	0.01546	-1.8107	-2.2744	-3.59215	-3.174	-3.03288
0.068	0.5	76.57	16.7815	0.430674	3.56578267	55.792	0.0189	0.01637	-1.7858	-2.2967	-3.59215	-3.1632	-3.05525
0.018	1	78.856	7.89684	3.280624	1.86381341	65.81473	0.0257	0.04209	-1.3759	-1.4149	-3.59215	-3.15966	-2.47447
0.022	1	78.284	9.70934	2.678692	2.2852499	63.61071	0.0244	0.03304	-1.481	-1.503	-3.59215	-3.16054	-2.5625
0.028	1	78.284	12.4299	2.104686	2.90849987	60.84092	0.0231	0.02459	-1.6093	-1.6077	-3.59215	-3.16054	-2.66724
0.035	1	77.713	15.675	1.680326	3.64722143	56.71042	0.0219	0.01801	-1.7444	-1.7055	-3.59215	-3.16143	-2.76503
0.069	2.5	185.711	55.3703	2.951814	11.2116418	116.1773	0.0188	0.01029	-1.9874	-1.4608	-3.59215	-3.01989	-2.91828
0.03	0.2	33.242	3.54872	0.329874	0.83190173	28.53151	0.0227	0.04297	-1.3669	-2.1758	-2.53387	-2.99966	-1.2327
0.036	0.2	28.337	4.46236	0.269178	1.0360535	22.56941	0.0217	0.02602	-1.5847	-2.2641	-2.53387	-3.00879	-1.32101
0.043	0.2	27.248	5.51413	0.224296	1.24799195	20.26158	0.0209	0.0179	-1.7471	-2.3433	-2.53387	-3.01084	-1.40023
0.05	0.2	28.882	6.54992	0.194265	1.43293905	20.70487	0.0202	0.01477	-1.8306	-2.4057	-2.53387	-3.00776	-1.46266
0.058	0.2	32.697	7.71391	0.17023	1.61488489	23.19797	0.0195	0.01379	-1.8604	-2.4631	-2.53387	-3.00066	-1.52002
0.065	0.2	35.967	8.75774	0.154009	1.76667176	25.28858	0.0191	0.013	-1.8862	-2.5066	-2.53387	-2.99467	-1.56351
0.072	0.2	40.326	9.77847	0.141576	1.89669789	28.50926	0.0186	0.01317	-1.8803	-2.5431	-2.53387	-2.98681	-1.60006

0.078	0.2	44.141	10.6596	0.132738	2.00085863	31.34779	0.0183	0.01335	-1.8744	-2.5711	-2.53387	-2.98004	-1.62806
0.084	0.2	49.046	11.4988	0.125707	2.08447198	35.33706	0.018	0.01431	-1.8444	-2.5947	-2.53387	-2.97149	-1.65169
0.09	0.2	55.585	12.2618	0.120375	2.1402758	41.06259	0.0178	0.01635	-1.7865	-2.6136	-2.53387	-2.96035	-1.67052
0.097	0.2	61.035	13.2547	0.114046	2.22929849	45.437	0.0175	0.01704	-1.7686	-2.637	-2.53387	-2.95128	-1.69397
0.103	0.2	67.029	14.0397	0.109844	2.28290025	50.5966	0.0173	0.01848	-1.7334	-2.6533	-2.53387	-2.94151	-1.71028
0.041	0.4	56.675	8.45873	0.530707	1.9365742	45.74899	0.0211	0.02774	-1.5569	-1.9692	-2.53387	-2.95852	-1.32723
0.046	0.4	55.04	9.65879	0.470039	2.19546427	42.71571	0.0206	0.02236	-1.6504	-2.022	-2.53387	-2.96127	-1.37995
0.024	0.2	13.815	1.15889	0.378377	0.77783589	11.4999	0.0239	0.06464	-1.1895	-2.2578	-1.99197	-3.17867	-0.38768
0.026	0.2	12.263	1.27582	0.346766	0.85417163	9.78624	0.0235	0.0496	-1.3045	-2.2957	-1.99197	-3.18179	-0.42557
0.028	0.2	10.709	1.39622	0.319668	0.93263941	8.060473	0.0231	0.03675	-1.4347	-2.3311	-1.99197	-3.18495	-0.4609
0.03	0.2	9.376	1.51856	0.296493	1.01129173	6.549654	0.0227	0.02673	-1.573	-2.3638	-1.99197	-3.18767	-0.49359
0.032	0.2	8.261	1.64252	0.2765	1.08968919	5.252287	0.0223	0.01896	-1.7222	-2.3941	-1.99197	-3.18996	-0.52391
0.035	0.2	7.365	1.82751	0.251726	1.20167497	4.084093	0.0219	0.01212	-1.9164	-2.4348	-1.99197	-3.19181	-0.56468
0.037	0.2	6.252	1.95876	0.236857	1.28348822	2.772895	0.0216	0.0062	-2.208	-2.4613	-1.99197	-3.19412	-0.59112
0.039	0.2	6.017	2.08441	0.224457	1.35582843	2.352306	0.0213	0.00403	-2.3946	-2.4846	-1.99197	-3.19461	-0.61447
0.04	0.2	5.786	2.14918	0.218603	1.39359297	2.024624	0.0212	0.00262	-2.581	-2.4961	-1.99197	-3.19509	-0.62595
0.028	0.4	24.553	2.46124	0.68083	1.66009564	19.75084	0.0231	0.05055	-1.2963	-2.0027	-1.99197	-3.15764	-0.43359
0.03	0.4	23.002	2.66758	0.631103	1.80086761	17.90245	0.0227	0.04213	-1.3755	-2.0357	-1.99197	-3.16061	-0.46653
0.032	0.4	20.789	2.88697	0.585855	1.95574438	15.36043	0.0223	0.03312	-1.4799	-2.068	-1.99197	-3.16489	-0.49884
0.034	0.4	19.238	3.10315	0.547565	2.1047164	13.48257	0.022	0.02677	-1.5724	-2.0973	-1.99197	-3.16792	-0.5282
0.035	2	108.721	6.02147	4.561829	3.50769924	94.63	0.0226	0.01482	-1.829	-1.3935	-3.48812	-3.15042	-2.18217
0.045	2	106.492	7.83604	3.522685	4.55827704	90.575	0.0213	0.01077	-1.9678	-1.5057	-3.48812	-3.15354	-2.29443
0.058	2	106.13	10.1759	2.729917	5.88536569	87.33882	0.0202	0.00782	-2.1067	-1.6164	-3.48812	-3.15405	-2.40516
0.07	2	105.742	12.3684	2.259088	7.11633874	83.99816	0.0193	0.00601	-2.2209	-1.6987	-3.48812	-3.15459	-2.48737
0.082	2	107.936	14.4697	1.942212	8.2488702	83.27517	0.0187	0.00494	-2.3066	-1.7643	-3.48812	-3.15151	-2.55301
0.095	2	110.171	16.7479	1.688502	9.4556157	82.27902	0.0181	0.00404	-2.3939	-1.8251	-3.48812	-3.1484	-2.61381
0.107	2	115.856	18.6328	1.526386	10.3711991	85.32565	0.0177	0.00365	-2.4381	-1.8689	-3.48812	-3.14058	-2.65764
0.123	2	123.408	21.0817	1.35932	11.5213562	89.44565	0.0172	0.00323	-2.4907	-1.9193	-3.48812	-3.1304	-2.70798
0.141	2	133.625	23.6311	1.222952	12.6330119	96.13793	0.0167	0.00297	-2.5276	-1.9652	-3.48812	-3.11699	-2.7539
0.157	2	145.479	25.6065	1.137043	13.3908603	105.3446	0.0163	0.00294	-2.5316	-1.9968	-3.48812	-3.10195	-2.78553
0.165	2	152.731	26.4598	1.104454	13.6714398	111.4953	0.0162	0.00301	-2.5219	-2.0094	-3.48812	-3.09299	-2.79816
0.024	0.1	22.782	1.60161	0.197027	0.36081212	20.62255	0.0239	0.07433	-1.1289	-2.5412	-2.04391	-3.16104	-0.54614
0.026	0.1	20.695	1.77954	0.180187	0.39756668	18.3377	0.0235	0.05901	-1.2291	-2.58	-2.04391	-3.16508	-0.58494
0.028	0.1	18.956	1.96213	0.166014	0.43434011	16.39352	0.0231	0.04717	-1.3264	-2.6156	-2.04391	-3.16847	-0.62052
0.03	0.1	17.391	2.15032	0.153852	0.47150046	14.61533	0.0227	0.03749	-1.426	-2.6487	-2.04391	-3.17155	-0.65356

0.033	0.1	15.999	2.43535	0.13898	0.52480539	12.89987	0.0222	0.02799	-1.5529	-2.6928	-2.04391	-3.17431	-0.69771
0.035	0.1	15.13	2.63225	0.130517	0.56076617	11.80647	0.0219	0.02269	-1.6442	-2.7201	-2.04391	-3.17604	-0.725
0.037	0.1	14.26	2.83522	0.122969	0.59727295	10.70454	0.0217	0.01792	-1.7466	-2.746	-2.04391	-3.17778	-0.75087
0.039	0.1	13.565	3.04185	0.116289	0.63336717	9.773497	0.0214	0.01405	-1.8525	-2.7702	-2.04391	-3.17917	-0.77512
0.042	0.1	13.565	3.34654	0.107983	0.68208772	9.428393	0.0211	0.01122	-1.9502	-2.8024	-2.04391	-3.17917	-0.80731
0.029	0.2	40.172	3.31801	0.351276	0.76477936	35.73793	0.023	0.05852	-1.2327	-2.2901	-2.04391	-3.12876	-0.59604
0.03	0.2	37.912	3.47981	0.336406	0.80399479	33.29179	0.0228	0.05176	-1.286	-2.3089	-2.04391	-3.13282	-0.61483
0.032	0.2	35.825	3.77685	0.312644	0.87064677	30.86486	0.0225	0.04395	-1.3571	-2.3407	-2.04391	-3.1366	-0.64664
0.214	2	61.266	5.03888	0.646738	2.95426116	52.62612	0.0174	0.0174	-1.7594	-1.9803	-2.89086	-2.9509	-1.5445
0.248	2	64.425	5.85898	0.564753	3.35836956	54.64289	0.0169	0.01537	-1.8132	-2.0392	-2.89086	-2.94573	-1.60337
0.283	2	68.336	6.69194	0.502156	3.74397762	57.39793	0.0165	0.01399	-1.8543	-2.0902	-2.89086	-2.93941	-1.65439
0.322	2	73.757	7.59231	0.450166	4.12801458	61.58651	0.0161	0.01311	-1.8823	-2.1376	-2.89086	-2.93081	-1.70186
0.356	2	79.879	8.33231	0.416193	4.40967895	66.72082	0.0157	0.01292	-1.8887	-2.1717	-2.89086	-2.92129	-1.73594
0.386	2	85.243	8.979	0.391135	4.6437965	71.22906	0.0155	0.01278	-1.8933	-2.1987	-2.89086	-2.91313	-1.7629
0.4	2	89.031	9.2377	0.382413	4.71645064	74.69444	0.0154	0.0131	-1.8829	-2.2085	-2.89086	-2.90745	-1.7727
0.254	4	108.907	9.73396	1.286538	5.42352155	92.46298	0.0168	0.01577	-1.8022	-1.6816	-2.89086	-2.87881	-1.54684
0.278	4	112.01	10.6081	1.187179	5.84963015	94.36505	0.0165	0.01471	-1.8325	-1.7165	-2.89086	-2.87451	-1.58174
0.31	4	115.164	11.7994	1.075304	6.42792561	95.86136	0.0162	0.01334	-1.875	-1.7595	-2.89086	-2.87018	-1.62473
0.344	4	121.286	12.9474	0.987693	6.93674013	100.4142	0.0158	0.01268	-1.897	-1.7964	-2.89086	-2.86189	-1.66164
0.375	4	127.397	13.9516	0.923139	7.35979347	105.1624	0.0156	0.01228	-1.9108	-1.8257	-2.89086	-2.85377	-1.69099
0.399	4	133.468	14.6564	0.883574	7.6283186	110.2998	0.0154	0.01226	-1.9115	-1.8448	-2.89086	-2.84585	-1.71002
0.278	6	153.49	13.7541	2.015555	7.34595906	130.3744	0.0165	0.01576	-1.8023	-1.4866	-2.89086	-2.82072	-1.52796
0.5259	16.3	350	172.817	7.995469	81.97205	87.21594	0.0137	0.00108	-2.9649	-1.3899	-3.47712	-2.88168	-2.95735
0.6035	16.4	350	200.083	6.997516	94.4846516	48.43492	0.0134	0.00024	-3.6151	-1.4478	-3.47712	-2.88168	-3.01715
0.4285	17.7	400	138.807	11.59207	65.1404596	184.4606	0.0143	0.00364	-2.4388	-1.2285	-3.47712	-2.84406	-2.83079
0.5092	18.3	400	171.55	10.11058	80.2282559	138.1111	0.0138	0.00204	-2.6905	-1.2879	-3.47712	-2.84406	-2.90572
0.6093	18.8	400	211.852	8.679629	98.6362712	80.83256	0.0134	0.00072	-3.1426	-1.3542	-3.47712	-2.84406	-2.98371
0.4866	20.5	450	169.05	12.84384	78.1656418	189.94	0.014	0.00304	-2.5174	-1.184	-3.47712	-2.80945	-2.85144
0.5693	21.2	450	204.593	11.3238	94.3068308	139.7764	0.0136	0.00169	-2.7722	-1.2387	-3.47712	-2.80945	-2.91956
0.658	21.5	450	241.347	9.961879	110.852069	87.83892	0.0133	0.00069	-3.1587	-1.2944	-3.47712	-2.80945	-2.98248
0.1805	10.6	300	33.4906	0	20.6148681	245.8945	0.0171	0.01668	-1.7778	-1.3783	-3.79588	-3.14818	-2.81409
0.2553	9.89	300	44.4531	0	27.1276105	228.4193	0.0159	0.01157	-1.9367	-1.5598	-3.79588	-3.14818	-2.96448
0.3466	9.29	300	57.3364	0	34.6021872	208.0614	0.015	0.00799	-2.0972	-1.7197	-3.79588	-3.14818	-3.09729
0.4524	8.76	300	71.5536	0	42.5937739	185.8526	0.0143	0.00547	-2.262	-1.861	-3.79588	-3.14818	-3.21303
0.5499	8.44	300	84.8076	0	49.8405044	165.3519	0.0138	0.00382	-2.4177	-1.9623	-3.79588	-3.14818	-3.29782

0.6454	8.11	300	96.9498	0	56.2157516	146.8344	0.0134	0.00265	-2.5765	-2.0491	-3.79588	-3.14818	-3.36733
0.7637	7.85	300	112.887	0	64.4019389	122.711	0.013	0.00145	-2.8392	-2.1362	-3.79588	-3.14818	-3.44042
0.9027	7.53	300	130.576	0	72.9865241	96.43701	0.0126	0.00037	-3.4336	-2.2271	-3.79588	-3.14818	-3.51306
0.2208	24.6	250	33.0159	0	21.0715121	195.9126	0.0174	0.01799	-1.745	-1.0151	-3.80967	-3.0618	-2.67687
0.2987	22.6	250	41.3073	0	26.2536419	182.439	0.0164	0.01334	-1.8747	-1.1822	-3.80967	-3.0618	-2.80815
0.3989	21.1	250	51.7287	0	32.6932432	165.578	0.0155	0.00959	-2.0181	-1.3381	-3.80967	-3.0618	-2.93376
0.525	19.6	250	63.6526	0	39.9191723	146.4282	0.0147	0.00676	-2.1697	-1.4901	-3.80967	-3.0618	-3.05311
0.6234	18.6	250	72.2891	0	45.0422652	132.6686	0.0142	0.00527	-2.278	-1.5868	-3.80967	-3.0618	-3.12766
0.7217	17.9	250	81.098	0	50.2012898	118.7008	0.0138	0.00406	-2.3917	-1.6669	-3.80967	-3.0618	-3.19127
0.8274	17.2	250	90.0444	0	55.3263749	104.6292	0.0135	0.00304	-2.5167	-1.7434	-3.80967	-3.0618	-3.25066
0.9276	16.8	250	99.1766	0	60.524476	90.29891	0.0132	0.00218	-2.661	-1.8037	-3.80967	-3.0618	-3.30029
1.0055	16.5	250	106.296	0	64.5241178	79.18004	0.013	0.0016	-2.795	-1.846	-3.80967	-3.0618	-3.33532
1.0686	16.3	250	111.581	0	67.4192548	71.00023	0.0129	0.00121	-2.9176	-1.8798	-3.80967	-3.0618	-3.36174
0.1343	29.2	150	12.4823	0	8.7137842	128.804	0.0203	0.03802	-1.42	-1.0047	-4.11919	-3.34163	-2.54204
0.1504	28.4	150	13.5956	0	9.48442232	126.92	0.0198	0.0344	-1.4635	-1.0661	-4.11919	-3.34163	-2.59114
0.1939	25.6	150	15.8521	0	11.0335802	123.1143	0.0187	0.02863	-1.5432	-1.2211	-4.11919	-3.34163	-2.7015
0.2327	26.9	150	20.0131	0	13.9149758	116.0719	0.018	0.02135	-1.6706	-1.2787	-4.11919	-3.34163	-2.78068
0.2497	24.9	150	19.9425	0	13.8471699	116.2103	0.0178	0.02146	-1.6684	-1.3422	-4.11919	-3.34163	-2.81135
0.297	24.9	150	23.764	0	16.4697425	109.7662	0.0171	0.01698	-1.7701	-1.4175	-4.11919	-3.34163	-2.88668
0.332	24.1	150	25.743	0	17.8086394	106.4484	0.0167	0.01518	-1.8187	-1.4803	-4.11919	-3.34163	-2.93505
0.4143	22.5	150	30.0909	0	20.7213364	99.18775	0.016	0.01205	-1.9191	-1.6069	-4.11919	-3.34163	-3.03122
0.4796	20.9	150	32.452	0	22.2474417	95.3006	0.0156	0.01069	-1.9711	-1.7031	-4.11919	-3.34163	-3.09475
0.1779	39.3	175	20.7862	0	14.134571	140.0792	0.0191	0.0248	-1.6055	-0.9679	-4.11919	-3.31188	-2.63439
0.1998	38.1	175	22.6769	0	15.4093617	136.9137	0.0186	0.02222	-1.6533	-1.031	-4.11919	-3.31188	-2.68469
0.7497	3.63	300	126.863	1.135538	29.2582756	142.7428	0.013	0.00084	-3.0778	-2.2867	-2.93704	-2.97209	-2.21055
0.7917	3.24	300	123.329	0.959891	27.5799221	148.1308	0.0129	0.00073	-3.137	-2.3597	-2.93704	-2.97209	-2.23421
0.9064	4.39	350	168.659	1.24855	38.0290975	142.0637	0.0126	3.2E-05	-4.4951	-2.2455	-2.93704	-2.9309	-2.25178
0.061	5	61.569	3.27952	5.67872	2.1013396	50.50942	0.0237	0.02569	-1.5902	-1.2524	-3.54407	-3.166	-1.87398
0.066	5	57.451	3.60808	5.166697	2.33255722	46.34366	0.0233	0.02138	-1.6699	-1.2934	-3.54407	-3.17282	-1.91502
0.078	5	54.248	4.3275	4.317974	2.81342286	42.7891	0.0224	0.01639	-1.7855	-1.3713	-3.54407	-3.1782	-1.99295
0.092	5	52.647	5.15041	3.638072	3.35290646	40.50561	0.0215	0.01295	-1.8876	-1.4457	-3.54407	-3.18092	-2.06736
0.103	5	51.046	5.81515	3.229158	3.79324601	38.20845	0.021	0.01074	-1.9688	-1.4975	-3.54407	-3.18365	-2.11914
0.04	1.94	209.748	9.8492	5.140058	1.50460946	193.2541	0.0237	0.02092	-1.6794	-1.2859	-3.36173	-2.97262	-1.86201
0.05	1.94	197.799	12.7428	3.992888	1.95589822	179.1074	0.0225	0.01483	-1.8287	-1.3956	-3.36173	-2.98539	-1.97169
0.059	1.94	193.396	15.2723	3.346593	2.34244272	172.4347	0.0216	0.01178	-1.9288	-1.4722	-3.36173	-2.99019	-2.04837

0.067	1.94	195.912	17.3024	2.965724	2.63754374	173.0063	0.021	0.01033	-1.9857	-1.5247	-3.36173	-2.98744	-2.10085
0.076	1.94	197.17	19.6524	2.622773	2.97923057	171.9156	0.0204	0.00892	-2.0497	-1.5781	-3.36173	-2.98607	-2.15422
0.088	1.94	204.717	22.4665	2.307884	3.36456039	176.5781	0.0198	0.00789	-2.103	-1.6336	-3.36173	-2.97795	-2.20976
0.099	1.94	210.377	25.0633	2.079959	3.71639313	179.5174	0.0193	0.00707	-2.1508	-1.6788	-3.36173	-2.97196	-2.25492
0.11	1.94	217.296	27.5367	1.903326	4.03964848	183.8164	0.0188	0.00647	-2.1888	-1.7173	-3.36173	-2.96474	-2.29346
0.122	1.94	224.843	30.1767	1.746958	4.37666169	188.5427	0.0184	0.00594	-2.226	-1.7546	-3.36173	-2.957	-2.3307
0.133	1.94	233.019	32.4519	1.633125	4.65459384	194.2794	0.0181	0.0056	-2.2518	-1.7838	-3.36173	-2.94877	-2.35996
0.145	1.94	242.453	34.83	1.53041	4.93529042	201.1573	0.0178	0.00531	-2.2749	-1.812	-3.36173	-2.93947	-2.38817
0.156	1.94	249.371	37.0929	1.444608	5.20494273	205.6285	0.0175	0.005	-2.3012	-1.8371	-3.36173	-2.93277	-2.41323
0.167	1.94	256.918	39.2608	1.371988	5.45456693	210.8306	0.0173	0.00475	-2.3231	-1.8595	-3.36173	-2.92558	-2.43563
0.026	2.5	688.746	0	0	0.49505864	688.2509	0.0264	2.05342	0.31248	-0.6549	-3.36173	-2.63783	-1.34014
0.029	2.5	652.733	0	0	0.57855323	652.1544	0.0257	1.67389	0.22373	-0.7202	-3.36173	-2.65575	-1.40548
0.033	2.5	601.286	0	0	0.70656176	600.5794	0.0248	1.27308	0.10486	-0.8033	-3.36173	-2.68269	-1.48853
0.037	2.5	567.846	0	0	0.8317954	567.0142	0.0242	1.02731	0.0117	-0.8714	-3.36173	-2.70114	-1.55667
0.04	2.5	534.405	0	0	0.94654233	533.4585	0.0237	0.85514	-0.068	-0.9245	-3.36173	-2.72041	-1.6098
0.046	2.5	516.399	0	0	1.12025428	515.2787	0.0229	0.7006	-0.1545	-0.996	-3.36173	-2.73115	-1.68124
0.052	2.5	503.537	0	0	1.29330415	502.2437	0.0223	0.59317	-0.2268	-1.0571	-3.36173	-2.73899	-1.74233
0.06	2.5	493.248	0	0	1.51809869	491.7299	0.0216	0.49585	-0.3046	-1.1256	-3.36173	-2.74537	-1.81085
0.068	2.5	490.675	0	0	1.72799	488.947	0.0209	0.43332	-0.3632	-1.1815	-3.36173	-2.74698	-1.86682
0.074	2.5	485.531	0	0	1.8969433	483.6341	0.0206	0.39084	-0.408	-1.2215	-3.36173	-2.75021	-1.90677
0.02	2.5	516.564	0	0	0.48693701	516.0771	0.0282	2.10542	0.32334	-0.6341	-3.36173	-2.73105	-1.31942
0.027	2.5	496.933	0	0	0.67893637	496.2541	0.0261	1.45861	0.16394	-0.7765	-3.36173	-2.74307	-1.46177
0.033	2.5	477.301	0	0	0.85796671	476.443	0.0248	1.11349	0.04669	-0.876	-3.36173	-2.75544	-1.56128
0.04	2.5	465.031	0	0	1.06249118	463.9685	0.0237	0.87832	-0.0563	-0.9675	-3.36173	-2.76334	-1.65274
0.049	2.5	442.945	0	0	1.35436995	441.5906	0.0226	0.65968	-0.1807	-1.0702	-3.36173	-2.77795	-1.75548
0.059	2.5	430.675	0	0	1.66838573	429.0066	0.0216	0.52198	-0.2823	-1.1592	-3.36173	-2.78629	-1.84447
0.068	2.5	420.859	0	0	1.95903332	418.9	0.0209	0.43523	-0.3613	-1.2276	-3.36173	-2.79307	-1.91291
0.078	2.5	411.043	0	0	2.29017924	408.7528	0.0203	0.36425	-0.4386	-1.2941	-3.36173	-2.79997	-1.97939
0.087	2.5	401.227	0	0	2.6043271	398.6227	0.0198	0.31324	-0.5041	-1.3485	-3.36173	-2.80697	-2.03382
0.071	5	268.75	0	0	1.07647211	267.6735	0.0229	0.82872	-0.0816	-1.0668	-3.54407	-2.91454	-1.68845
0.084	5	258.333	0	0	1.31046248	257.0225	0.022	0.65762	-0.182	-1.1496	-3.54407	-2.92424	-1.77117
0.1	5	245.833	0	0	1.61625149	244.2167	0.0211	0.51051	-0.292	-1.2372	-3.54407	-2.93618	-1.85884
0.115	5	239.583	0	0	1.89276779	237.6902	0.0205	0.42592	-0.3707	-1.304	-3.54407	-2.94228	-1.92563
0.131	5	236.806	0	0	2.17381839	234.6322	0.0199	0.36665	-0.4357	-1.3633	-3.54407	-2.94501	-1.98494
0.156	5	236.111	0	0	2.59400137	233.517	0.0191	0.30578	-0.5146	-1.4399	-3.54407	-2.9457	-2.06148

0.183	5	234.722	0	0	3.05554172	231.6665	0.0185	0.25761	-0.589	-1.5106	-3.54407	-2.94708	-2.13218
0.213	5	232.639	0	0	3.57863415	229.0604	0.0179	0.2176	-0.6623	-1.5786	-3.54407	-2.94915	-2.20019
0.24	5	231.944	0	0	4.04067335	227.9033	0.0175	0.19168	-0.7174	-1.6311	-3.54407	-2.94985	-2.25271
0.04	1.94	525.641	0	0	0.74649092	524.8945	0.0237	2.09305	0.32078	-1.0389	-3.36173	-2.72561	-1.615
0.047	1.94	494.872	0	0	0.92239617	493.9496	0.0228	1.6053	0.20556	-1.1277	-3.36173	-2.74435	-1.70378
0.054	1.94	476.923	0	0	1.09267148	475.8303	0.0221	1.31115	0.11765	-1.1993	-3.36173	-2.75568	-1.7754
0.063	1.94	467.949	0	0	1.29487988	466.6541	0.0213	1.08743	0.0364	-1.272	-3.36173	-2.76145	-1.84812
0.074	1.94	466.667	0	0	1.52440311	465.1426	0.0206	0.92083	-0.0358	-1.3427	-3.36173	-2.76228	-1.91885
0.081	1.94	465.385	0	0	1.67237825	463.7126	0.0201	0.83693	-0.0773	-1.3828	-3.36173	-2.76311	-1.95893
0.092	1.94	460.256	0	0	1.91684044	458.3392	0.0196	0.72253	-0.1411	-1.4415	-3.36173	-2.76646	-2.01758
0.101	1.94	461.538	0	0	2.09956426	459.4384	0.0192	0.66085	-0.1799	-1.4811	-3.36173	-2.76562	-2.05728
0.112	1.94	462.821	0	0	2.3229345	460.4981	0.0188	0.59829	-0.2231	-1.5252	-3.36173	-2.76478	-2.10134
0.024	2.5	50.233	1.44216	0	2.38253725	46.4083	0.0269	0.03054	-1.5151	-1.1673	-3.36173	-3.18505	-1.85259
0.03	2.5	45.891	1.83856	0	3.0660249	40.98641	0.0254	0.02108	-1.6761	-1.2718	-3.36173	-3.19257	-1.95702
0.037	2.5	42.171	2.30839	0	3.87947785	35.98313	0.0242	0.01464	-1.8345	-1.3694	-3.36173	-3.19912	-2.05466
0.045	2.5	39.69	2.84519	0	4.80131148	32.0435	0.023	0.01045	-1.9807	-1.4588	-3.36173	-3.20355	-2.14409
0.054	2.5	37.829	3.45283	0	5.83864102	28.53753	0.0221	0.00753	-2.1233	-1.5413	-3.36173	-3.20689	-2.22662
0.062	2.5	36.899	3.99222	0	6.74873643	26.15805	0.0214	0.00584	-2.2339	-1.603	-3.36173	-3.20858	-2.2883
0.072	2.5	36.589	4.66025	0	7.85486188	24.07389	0.0207	0.00444	-2.3523	-1.6685	-3.36173	-3.20914	-2.35381
0.081	2.5	36.124	5.27137	0	8.86662032	21.986	0.0201	0.00343	-2.4647	-1.7205	-3.36173	-3.20998	-2.4058
0.028	2.5	53.117	1.66618	9.314414	2.72771253	39.40869	0.0259	0.02287	-1.6408	-1.2293	-3.36173	-3.18012	-1.91461
0.034	2.5	48.052	2.069	7.51876	3.42455032	35.03969	0.0247	0.01628	-1.7882	-1.3223	-3.36173	-3.18881	-2.00762
0.038	2.5	44.156	2.35263	6.622746	3.92995552	31.25066	0.024	0.01269	-1.8965	-1.3775	-3.36173	-3.19561	-2.06273
0.043	2.5	41.039	2.70156	5.778729	4.54443843	28.01427	0.0233	0.00981	-2.0083	-1.4367	-3.36173	-3.20113	-2.12194
0.053	2.5	42.208	3.32696	4.710898	5.55565714	28.61448	0.0222	0.00803	-2.0951	-1.5254	-3.36173	-3.19906	-2.21066
0.064	2.5	45.714	3.97781	3.957083	6.54872808	31.23038	0.0212	0.00725	-2.1395	-1.6011	-3.36173	-3.19288	-2.28639
0.071	2.5	48.442	4.37684	3.606135	7.13264152	33.32638	0.0207	0.00699	-2.1554	-1.6415	-3.36173	-3.18813	-2.32673
0.078	2.5	51.169	4.76964	3.318165	7.69571063	35.38548	0.0203	0.00677	-2.1692	-1.6776	-3.36173	-3.18344	-2.36287
0.024	2.5	28.025	1.58103	9.80052	2.79167227	13.85177	0.0269	0.01952	-1.7095	-1.2072	-3.36173	-3.22497	-1.89252
0.031	2.5	26.115	2.06493	7.524661	3.659964	12.86544	0.0252	0.01379	-1.8604	-1.322	-3.36173	-3.22859	-2.00728
0.039	2.5	24.204	2.62799	5.931166	4.6745813	10.97026	0.0239	0.00911	-2.0406	-1.4254	-3.36173	-3.23223	-2.11063
0.044	2.5	24.204	2.97075	5.25717	5.2738866	10.70219	0.0232	0.00779	-2.1085	-1.4777	-3.36173	-3.23223	-2.16302
0.053	2.5	24.204	3.59106	4.364443	6.35263613	9.895859	0.0222	0.00582	-2.2349	-1.5586	-3.36173	-3.23223	-2.24384
0.064	2.5	26.752	4.30668	3.654909	7.5184668	11.27195	0.0212	0.00546	-2.2629	-1.6356	-3.36173	-3.22738	-2.32089
0.071	2.5	29.299	4.73815	3.331152	8.17813312	13.05157	0.0207	0.00574	-2.2407	-1.6759	-3.36173	-3.22258	-2.36117

0.08	2.5	33.121	5.27058	3.005123	8.952793	15.8925	0.0202	0.00631	-2.1999	-1.7206	-3.36173	-3.21548	-2.40591
0.091	2.5	37.261	5.91693	2.688266	9.87952493	18.77628	0.0196	0.00664	-2.1779	-1.769	-3.36173	-3.20792	-2.4543
0.099	2.5	41.72	6.33913	2.516969	10.4129576	22.45095	0.0193	0.00747	-2.1267	-1.7976	-3.36173	-3.19992	-2.48289
0.14	5.28	91.083	15.546	4.516644	23.1104346	47.90997	0.0179	0.0066	-2.1805	-1.5437	-3.36173	-3.12	-2.55346
0.037	1.94	158.632	3.05411	5.531793	1.66545608	148.3806	0.0242	0.05489	-1.2605	-1.5085	-2.95462	-3.22911	-1.02033
0.04	1.94	147.883	3.40815	4.964648	1.87816088	137.632	0.0237	0.04559	-1.3412	-1.5555	-2.95462	-3.24223	-1.06731
0.045	1.94	138.599	3.94842	4.296123	2.19470061	128.1598	0.023	0.03659	-1.4366	-1.6183	-2.95462	-3.25389	-1.13012
0.051	1.94	129.805	4.60712	3.692996	2.58197506	118.9229	0.0224	0.02903	-1.5372	-1.684	-2.95462	-3.26523	-1.19581
0.059	1.94	123.453	5.45542	3.131249	3.0714095	111.7949	0.0216	0.02295	-1.6393	-1.7557	-2.95462	-3.27361	-1.26748
0.069	1.94	121.01	6.46032	2.657384	3.6314603	108.2608	0.0209	0.01866	-1.7291	-1.8269	-2.95462	-3.27687	-1.33874
0.081	1.94	121.01	7.62905	2.263697	4.26301861	106.8542	0.0201	0.01547	-1.8105	-1.8966	-2.95462	-3.27687	-1.40838
0.093	1.94	124.43	8.71903	1.992444	4.82041996	108.8981	0.0195	0.0137	-1.8634	-1.952	-2.95462	-3.27231	-1.46381
0.105	1.94	125.896	9.85785	1.772647	5.40729205	108.8582	0.019	0.01198	-1.9214	-2.0028	-2.95462	-3.27037	-1.51457
0.117	1.94	129.805	10.9189	1.609767	5.92335455	111.353	0.0186	0.01097	-1.9599	-2.0446	-2.95462	-3.26523	-1.55643
0.073	2.78	76.234	2.09443	3.029928	1.28166244	69.82798	0.0227	0.0578	-1.2381	-1.7612	-3.13696	-3.34155	-1.06321
0.086	2.78	68.052	2.5536	2.496447	1.58285254	61.4191	0.0219	0.04165	-1.3804	-1.8453	-3.13696	-3.35449	-1.14732
0.104	2.78	62.987	3.16675	2.025737	1.97316079	55.82136	0.0209	0.03043	-1.5167	-1.936	-3.13696	-3.36269	-1.23806
0.126	2.78	60.26	3.90603	1.654868	2.43091087	52.26819	0.02	0.02297	-1.6389	-2.0238	-3.13696	-3.36717	-1.32588
0.147	2.78	60.649	4.58321	1.420558	2.82925049	51.81598	0.0194	0.01929	-1.7146	-2.0901	-3.13696	-3.36653	-1.39218
0.171	2.78	61.429	5.35936	1.2248	3.27539356	51.56945	0.0188	0.01628	-1.7884	-2.1545	-3.13696	-3.36524	-1.45658
0.199	2.78	63.377	6.25002	1.060231	3.7666257	52.30012	0.0182	0.014	-1.8537	-2.2172	-3.13696	-3.36205	-1.51924
0.221	2.78	64.935	6.95156	0.96028	4.14383201	52.87933	0.0178	0.0126	-1.8995	-2.2602	-3.13696	-3.35952	-1.56224
0.241	2.78	66.104	7.59802	0.884436	4.4872839	53.13426	0.0174	0.01146	-1.9409	-2.2959	-3.13696	-3.35762	-1.59797
0.044	1.11	295.806	5.21746	3.227429	0.74079729	286.6203	0.0232	0.06014	-1.2209	-1.687	-2.95462	-3.08931	-0.95578
0.052	1.11	263.548	6.63845	2.554151	0.95289387	253.4025	0.0223	0.04168	-1.3801	-1.7886	-2.95462	-3.11837	-1.05739
0.062	1.11	235.161	8.5008	2.011738	1.23199833	223.4165	0.0214	0.02847	-1.5456	-1.8923	-2.95462	-3.14566	-1.16107
0.073	1.11	219.677	10.4733	1.648165	1.52055491	206.035	0.0206	0.02106	-1.6766	-1.9789	-2.95462	-3.1613	-1.24764
0.083	1.11	209.355	12.3095	1.414157	1.78629386	193.8451	0.02	0.0166	-1.78	-2.0454	-2.95462	-3.17205	-1.31414
0.095	1.11	210.645	14.1863	1.239396	2.03609828	193.1832	0.0194	0.01414	-1.8495	-2.1027	-2.95462	-3.17069	-1.37143
0.061	1.67	887.417	0	0	0.61873154	886.7983	0.0215	4.04933	0.60738	-1.3129	-2.95462	-2.74946	-0.75781
0.07	1.67	819.868	0	0	0.76208536	819.1059	0.0208	3.05708	0.48531	-1.4005	-2.95462	-2.77725	-0.84536
0.078	1.67	752.318	0	0	0.91637969	751.4016	0.0203	2.35022	0.37111	-1.4772	-2.95462	-2.80693	-0.92204
0.09	1.67	684.768	0	0	1.14822451	683.6198	0.0197	1.72166	0.23595	-1.5712	-2.95462	-2.83879	-1.01605
0.1	1.67	629.139	0	0	1.37296816	627.766	0.0192	1.33336	0.12495	-1.6451	-2.95462	-2.86691	-1.08993
0.113	1.67	573.51	0	0	1.67935052	571.8306	0.0187	1.00254	0.0011	-1.7282	-2.95462	-2.89697	-1.17307

0.125	1.67	549.669	0	0	1.92572436	547.7433	0.0183	0.84114	-0.0751	-1.7856	-2.95462	-2.91052	-1.23045
0.138	1.67	537.748	0	0	2.16565876	535.5823	0.018	0.7329	-0.135	-1.8355	-2.95462	-2.91746	-1.28036
0.148	1.67	533.775	0	0	2.33712057	531.4379	0.0177	0.67425	-0.1712	-1.8682	-2.95462	-2.9198	-1.31308
0.037	1.67	186.393	2.92626	5.054869	1.28978359	177.1221	0.0242	0.09057	-1.043	-1.1867	-3.09849	-2.84033	-1.45553
0.044	1.67	159.508	3.7536	3.956902	1.69190583	150.1056	0.0232	0.05983	-1.2231	-1.293	-3.09849	-2.87143	-1.56189
0.053	1.67	145.738	4.72484	3.160057	2.15157518	135.7015	0.0222	0.04293	-1.3672	-1.3907	-3.09849	-2.88827	-1.65955
0.064	1.67	133.934	5.94337	2.528243	2.72850215	122.7339	0.0212	0.03076	-1.512	-1.4876	-3.09849	-2.90324	-1.75642
0.079	1.67	126.066	7.57708	2.000311	3.48454429	113.0041	0.0203	0.02204	-1.6568	-1.5893	-3.09849	-2.91352	-1.85815
0.091	1.67	124.754	8.82325	1.729602	4.03713819	110.164	0.0196	0.01832	-1.7372	-1.6524	-3.09849	-2.91526	-1.9213
0.104	1.67	124.098	10.1787	1.510369	4.62730046	107.7816	0.0191	0.01537	-1.8132	-1.7113	-3.09849	-2.91613	-1.98016
0.117	1.67	124.098	11.5351	1.34255	5.20571302	106.0146	0.0186	0.01318	-1.8802	-1.7625	-3.09849	-2.91613	-2.03131
0.036	1.67	1308.7	0	0	0.25605251	1308.44	0.0243	7.17095	0.85558	-0.5854	-3.09849	-2.25092	-0.85423
0.043	1.67	1156.52	0	0	0.34284174	1156.179	0.0233	4.77055	0.67857	-0.7086	-3.09849	-2.29701	-0.97748
0.048	1.67	1047.83	0	0	0.41890737	1047.407	0.0227	3.56172	0.55166	-0.7926	-3.09849	-2.33322	-1.06146
0.056	1.67	943.478	0	0	0.53753708	942.9405	0.0219	2.51879	0.40119	-0.8974	-3.09849	-2.37106	-1.16625
0.064	1.67	821.739	0	0	0.69535141	821.0436	0.0212	1.71487	0.23423	-1.0042	-3.09849	-2.41983	-1.27301
0.073	1.67	704.348	0	0	0.90870297	703.4393	0.0206	1.14012	0.05695	-1.1142	-3.09849	-2.47269	-1.38301
0.081	1.67	634.783	0	0	1.10357702	633.6794	0.0201	0.85432	-0.0684	-1.194	-3.09849	-2.50735	-1.46283
0.093	1.67	530.435	0	0	1.47636054	528.9586	0.0195	0.54325	-0.265	-1.3118	-3.09849	-2.56515	-1.58063
0.105	1.67	473.913	0	0	1.83064876	472.0824	0.019	0.39591	-0.4024	-1.3993	-3.09849	-2.6	-1.66819

SUMMARY OUTPUT OF TABLE C.1

Regression Statistics	
Multiple R	0.83847444
R Square	0.703039386
Adjusted R Square	0.70210038
Standard Error	0.422672266
Observations	1270

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	535.0308603	133.7577	748.706	0
Residual	1265	225.9945831	0.178652		
Total	1269	761.0254434			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95.0%*
Intercept	1.61432	0.2337002	6.907655	7.78E-12	1.15583	2.0728
X Variable 1	-0.032269	0.034601	-0.93262	0.3511	-0.10015	0.0356122
X Variable 2	-1.460893	0.065144	-22.4256	4.76E-94	-1.58869	-1.33309
X Variable 3	1.80665	0.0689	26.21449	2.47E-121	1.67145	1.94186
X Variable 4	1.268754	0.037871	33.50139	1.14E-176	1.19445	1.34305

LIST OF PUBLICATIONS

Referred Journals (Under Communication) – 1 No.

Tripathi, N.M.,**Kumar, D.,** Mehta, E., Setia, G., and Mallick, S.S. An Investigation into pressure drop across bends for fluidised dense phase pneumatic conveying systems. **Powder Technology, Elsevier***(Under Communication)*.