MODELLING MINIMUM TRANSPORT BOUNDARY FOR DENSE-PHASE PNEUMATIC CONVEYING OF FINE POWDERS

A

THESIS

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

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Submitted by

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THESIS CERTIFICATION

I hereby certify that this seminar report entitled, "**Modelling Minimum Transport Boundary for Dense Phase Pneumatic Conveying of Fine Powders**" in partial fulfillment of the requirements for the award of degree of Master of Engineering in Thermal Engineering submitted to Mechanical Engineering Department, Thapar University, Patiala, is an authentic record of my own work and has not been submitted for any other degree to any this or any other Institute.

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ABSTRACT

This thesis present results of an ongoing investigation into modelling fluidized dense-phase pneumatic conveying of powders. For the reliable design of dense-phase pneumatic conveying systems, an accurate estimation of the minimum transport boundary condition or the minimum transport velocity requirement is of significant importance. The existing empirical models for fine powder conveying in fluidized dense-phase mode are either based on only a particular pipeline and product or have not been tested for their accuracy under a wide range of scale-up conditions. In this thesis, a validated test design procedure has been developed to accurately scale-up the minimum transport boundary with the help of a modelling format that employs solids loading ratio and Froude number at pipe inlet conditions using conveying data of two different samples of fly ash, ESP dust and cement (particle densities: 2197-3637 kg/m^3; loose poured bulk densities: 634-1070 kg/m^3; median size: 7-30 μm). The developed models (in power function format) have been used to predict the minimum transport boundary for larger diameter and longer pipelines (e.g. models based on 69 mm I.D. × 168 m long pipe have been scaled up to 105 mm I.D. and 554 m length). The predicted minimum transport boundaries for the scale-up conditions were found to provide better accuracy compared to the existing models. A unified model was developed using data for a variety of powders and pipelines and the same has been evaluated under different scale-up conditions.

Keywords: Fluidized dense-phase, pneumatic conveying, minimum transport boundary, minimum conveying velocity, scale up

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Cross sectional area, m^2
D	Internal diameter of pipe, m
d_{50}	Median particle diameter, μm
d_p	Particle diameter, μm
g	Acceleration due to gravity, m/s
G_s	Product mass flow rate per unit area ($G_s = m_s/A$), kg/s.m^2
L	Pipeline length, m
m_f	Mass flow rate of air, kg/s
m_s	Mass flow rate of solids, kg/s
$m^* = m_s/m_f$	Solids loading ratio
P	Pressure, N/m^2
V_f	Superficial air/gas velocity, m/s
U_t	Single particle terminal velocity, m/s
U_{mf}	Minimum fluidisation velocity, m/s
V_i	Velocity of air at pipe inlet, m/s
V_{si}	safe initial velocity at pipe inlet, m/s
V_c	Critical velocity, m/s
V_{min}	Minimum conveying velocity, m/s
ρ_f	Air density, kg/m^3
ρ_p	Particle density, kg/m^3
ρ_b	Loose poured bulk density, kg/m^3

Fr_i	Froude number at the inlet to the pipe ($Fr_i = \frac{V_i}{\sqrt{gD}}$)
Fr_{si}	Safe initial Froude number at pipe inlet ($F_{r_{si}} = \frac{V_{si}}{\sqrt{gD}}$)
μ_f	Fluid viscosity, kg/m.s

Subscripts

b	Bulk
exp	Experimental
f	fluid (air)
i	inlet condition
min	Minimum
pr	Predicted
p	Particle

Abbreviations

BD	Bottom Discharge
I.D.	Internal Diameter
MTB	Minimum Transport Boundary
PCC	Pneumatic Conveying Characteristics
TD	Top Discharge

CHAPTER 1: Introduction and Objectives

1.1 Introduction

Fluidised dense-phase pneumatic conveying of powders is becoming increasingly popular in various industries to transport fine bulk solids such as cement, fly ash, pulverized coal, soap powder, skim milk powder, lead dust, powdered limestone, flour, to mention a few. This mode of pneumatic transport takes advantage of the air retention properties of the bulk material. FDP offers the following advantages over the conventional dilute-phase flow:

a) Reduced gas flow rate requirement (hence, less compressor power consumption), which results in more efficient conveying system and therefore, less environmental emissions;
b) lower transport velocities and hence, reduced pipeline wear and product degradation;
c) Smaller sizes of pipe, filtration equipment, fitting and support sizes/structures for same conveying capacities;
d) Increased workplace safety as it offers a "natural" explosion barrier due to the higher concentrations of product along the pipeline, preventing propagation of dust explosions, as well as avoiding the risk of explosion detonation. Such potentially dangerous incidents are possible in dilute-phase pneumatic conveying (Mallick, 2010);
e) Improving the ability to troubleshoot pneumatic conveying systems (Mallick, 2010);

For FDP conveying the conveying velocities should be less than the saltation velocities of the bulk powders, so that the non-suspension mode of conveying (or dense-phase flow) is achieved. However, an inadequate air flow, i.e. reduction in gas flow rate beyond the good "steady state" dense-phase region, would form unsteady dunes, characterized by enhanced pressure fluctuations. Further reductions in gas velocity would cause build-up of powder in the pipeline in the form of deposits, resulting in an inability of the system to attain a consistent steady-state conveying condition (i.e. the pressure signal would continue to gradually increase with time), as represented by the “Unstable points” shown in Figure 1.1. Mallick and Wypych (2009) considered this state as minimum transport boundary (unstable boundary) in their study. A further reduction in gas flow rate would cause a flow blockage, indicated by a rapid increase in pressure.

The lowest possible inlet air velocity conditions for a FDP pneumatic conveying system at which a consistent steady-state conveying condition can be attained, is considered as the minimum transport boundary in the present work. This can be represented graphically in typical Pneumatic Conveying Characteristics (PCC) as shown in Figure 1.1.

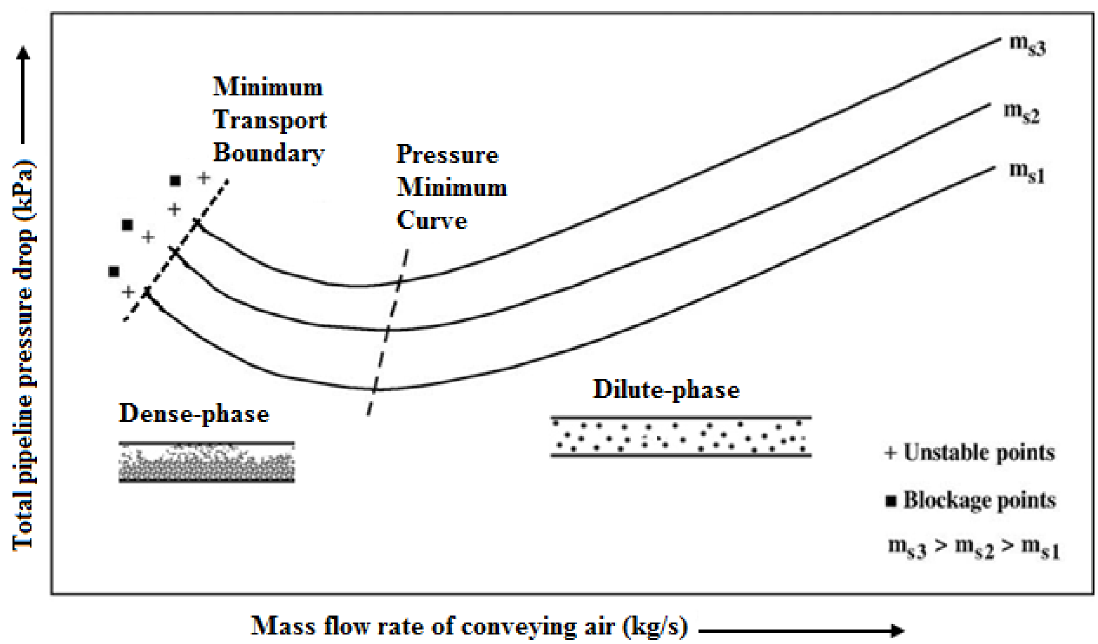

Figure 1.1: Typical pneumatic conveying characteristics (PCC) of fluidised dense-phase conveying showing Minimum Transport Boundary (MTB). (Mallick, 2010)

It is apparent that for reliably designing a good dense-phase pneumatic conveying system, the accurate prediction of the minimum transport condition through a given pipeline system is of significant importance. Such information affects the determination of maximum solids loading and the proper sizing of the conveying pipelines. Whereas, some fundamental the minimum transport or blockage prediction models based on powder mechanics have been developed for the low-velocity slug-flow of granular products (Wypych and Yi, 2003), relatively less progress has been made so far towards developing a validated scale-up procedure for reliably predicting the minimum transport boundary for fluidised dense-phase pneumatic conveying of powders due to the complex interaction between the particles, carrier gas and pipe/bend walls.

The existing models are largely empirical, such as Mills et al. 1982, Mills 2004 and 2004a, provided a plot of V_i versus m*. Mills (2004, 2004a) seemed to indicate V_i = 3 m/s to represent the minimum conveying condition. This model, however, does not appear to address scale-up reliability issues (i.e. prediction of minimum conveying velocities for larger and longer industrial scale pipelines). Mallick and Wypych (2009) developed a Froude number based criterion (Fr_i = 6) to represent the minimum transport criteria using different fly ash, ESP dust and cement data conveyed through pipelines of various diameters and lengths. However, more recently, Mallick (2010) and Mallick et al. (2011) indicated that a constant Froude number line to predict the minimum transport boundary may provide only limited accuracy over a wide range of scale-up conditions and recommended further studies towards developing a more accurate test design procedure. Therefore, the aim of this thesis is to develop a validated modelling and scale-up procedure for minimum transport boundary (or blockage condition), so that the minimum boundary information obtained by conveying fine powder through a laboratory based test rig can be reliably scaled-up to industrial sized plants (i.e. under significant length and/or diameter scale-up conditions). Such a tool will help the designer to effectively design a good dense-phase system – benefited by the high solids loading ratio (m*) and also avoiding pipeline blockages.

1.2 Objectives

Specific objectives include:

i. Evaluating the existing techniques for predicting minimum transport boundary;

ii. To develop a suitable model to predict the minimum transport boundary and validation of the same for scale-up accuracy and stability in terms of changing pipe diameter and pipe length;

iii. To develop a Unified model to predict the minimum transport boundary for different powders.

CHAPTER 2: Literature Review

This chapter reviews published literature to present the current state knowledge on dense phase pneumatic conveying. Initial studies conducted during the thesis work were related to the general concepts, material classification, modes of pneumatic conveying system, pneumatic conveying characteristics, and design considerations of pneumatic conveying systems. Here, conscious efforts have been made to present the review more confined to minimum transport boundary in FDP pneumatic conveying.

2.1 Pneumatic conveying systems

The pneumatic conveying of powders and granular bulk materials has been in existence for over 200 years. A pneumatic conveying system may be defined as the process by which bulk materials of almost any type are transferred using either positive or negative pressure of air or other gases as the conveying medium from one or more sources to one or more destinations (Wypych, 2006). In thermal power stations, nuclear plants, and chemical and industrial plants, different types of particulate bulk materials are used. The materials exist in different forms including lump, powder, granules, chips, and pallets. Some typical examples are pulverized coal, fly ash, chocolate powder, flour, cement, nylon chips, and alumina. These also include and granular materials (e.g. crushed coal, grain, Sugar etc.).These bulk materials, in their different forms, require efficient and reliable material handling systems. Most of these particulate bulk materials can be conveyed pneumatically. A well designed pneumatic conveying system is often a more practical and attractive method of transporting materials from one point to another than alternative mechanical systems such as belt, screw, vibrating, drag conveyors and other methodologies because of following key reasons:

- Totally enclosed transportation: Specific materials may require conveying in an enclosed form. Hence, these are relatively clean, more secured, more environmentally acceptable and simple to maintain (e.g. Zircon, zirconium hydro-oxide are found in nuclear power plants) (Yi, 2001).
- Flexibility of layout (flexible in terms of rerouting and expansion): Changes in flow direction are possible by addition of bends. So, with layout constraints, it is preferred to convey materials in pipes using pneumatic systems (Yi, 2001).
- Multiple entries and multiple discharges: These systems have ability to convey product from one or more sources to one or more destinations (Wypych, 2006).
- Ease of control and automation (Yi, 2001).
- Low installation, maintenance and manpower cost
- Greater Capacity: Solid particles such as pulverized coal, cement, and corn can be transported efficiently at large conveying rates (e.g. 100 - 400 t/h) (Yi, 2001).

Disadvantages: Some of the disadvantages of pneumatic conveying are listed below:

- High power consumption, wear and abrasion of equipment (Wypych, 2006).
- Limited conveying distance where with the aid of stepped pipeline design 5000 m may be considered the upper limit of pipe length for pneumatic conveying of fine powders, such as fly ash and cement. However, most systems require conveying distances from only a few meters to about 500 m (Wypych, 2006).
- Damage to the product (Yi, 2001).
- High level of skills to design, operate and maintain a system (Yi, 2001).

2.2 Basic components of pneumatic conveying systems

The Basic of components pneumatic conveying systems consist of four main groups as shown in Figure 2.2. Different components need to be matched carefully to obtain successful conveying system. The groups are:

a) Prime movers: A wide range of compressors, blowers and fans is available to provide the conveying gas. The prime mover is usually the most expensive single item in terms of capital and running costs of a pneumatic conveying system (Wypych, 2006).

b) Pipeline feeding devices: The method of feeding the product to the conveying gas is critical. This is the zone where the majority of pneumatic conveying system problems occur due to mismatch of feeder characteristics to the prime mover as feeding device has to cater usually for a pressure differential between pipeline and storage hopper (Wypych, 2006).

   Commonly used feeding devices with their relevant pressure ranges can be listed as below;

   1. Rotary valves – low pressure (maximum 100 kPa)
   2. Screw feeders – medium pressure (maximum 300 kPa)
   3. Venturi feeder – low pressure (operate upto 20 kPa)
   4. Vacuum nozzle – negative pressure
   5. Blow tanks – high pressure (maximum 1000 kPa)

Blow tanks are very often used in pneumatic conveying systems, as they offer a wide range of conveying conditions, both in terms of pressure and flow rates.

Where it is required to convey a product over long distances and/or in dense-phase, a high pressure system is used and feeding into high-pressure systems almost always involves the use of blow tanks, which usually are capable of working pressures up to 7 ~ 10 bars.

Blow tanks are typically available in two different structures; top discharge and bottom discharge, which generally refer only to the direction, in which the contents of the vessel are, discharged (Wypych, 2006).

c) Conveying line: This includes piping, bends, expansions, diverters, couplings or flanges etc. The selection of the piping material will depend upon the factors such as the pressure requirement, product abrasiveness and product physical properties. Bends provide a change in flow direction (Wypych, 2006).

d) Gas–solids separation devices: Cyclones and bag-filters are devices used commonly to separate the gas and product at the end of a pipeline.hey are mounted on the top of the receiver bin and are capable of continuous operation (Wypych, 2006).

2.3 Product (bulk solid) properties

Dense-phase pneumatic conveying is recognized by high concentration product flow. Particle and the bulk properties are regarded as crucial parameters to assess whether materials will be conveyed in higher solid concentrations. As indicated in their names, the properties related to individual particle are known as particle properties (for example; particle size, shape, density, elasticity, free settling velocity etc.) and the properties which are more appropriately attributed to mixture (bulk solid) as a whole are regarded as bulk properties (for example; particle size distribution, bulk density, wall friction, angle of repose, fluidastion and deaeration etc.).

Some of these important properties are their different measurement techniques are briefly given below:

1. Particle size / size distribution / shape: To predict the dense-phase convey ability and conveying design parameters of a powder or granular material the particle size is of very significance. An irregularly shaped particle will present different dimension depending on the orientation that it is observed from, which makes the determination of particle size difficult. That is why results obtained by different methods of size measurement vary generally. Particle shape is an important characteristics as it influences flow ability, packing, interaction with fluids and hence suitability for pneumatic conveying. However, the understanding of this influence is still limited. Table 2.1 lists a number of common methods of measuring the size of particles (Wypych, 1989).

Table 2.1: Common methods of size analysis (Wypych, 2006)

Methods Of Size Analysis	Approximate Size Range
Mechanical Sieving	125 mm – 38 µm
Sedimentation	100 µm – 2 µm
Microscope	100 µm – 1 µm
Electron microscope	5 µm – .001 µm
Scanning Electron Microscope	100 µm – 0.1 µm
Classification	50 µm – 2 µm
Laser Diffraction	1.8 mm – 1 µm

From the above listed methods, mechanical sieving is perhaps the most widespread. It is a straight forward method. Sieves are manufactured in a range of standard apertures (6.7 µm – 125 mm), and to carry out the analysis a set of sieves is arranged in a stack (in order of decreasing aperture from top to bottom), with a pan enclosing the bottom and a lid at the top. A sample is placed on the top sieve and the assembly is shaken (usually mechanically) for a set of period of time. The mass retained on each sieve is then recorded, allowing a particle size distribution for the sample to be determined. At small particle sizes, and particularly for low density substances, normal dry sieving becomes ineffective. Below 75 µm, wet sieving is recommended to improve the reliability and repeatability of the results (Wypych, 1989).

Laser diffraction particle size analysis is becoming an increasingly popular technique. It offers ease of use, rapid test and apparently good accuracy. With laser diffraction methods, account is made of the number of particles in each size range is made. Irregularly shaped particles are likely to present the laser beam in random fashion and the results are presented in terms of a volume distribution. The equivalence of a volume based size distribution and a mass based distribution is reliant on the density of particles being effectively constant throughout (Wypych, 2006). As noted above particle size analysis normally results in a particle size distribution which is an important parameter, and is significant contributor to many other bulk properties (e.g. fluidization, deareation, permeability etc.). A characteristic value commonly assigned to this information is the "median" size. 50% of the sample by mass or volume, depending upon measuring technique) is above or below this value. Use of this value alone may be misleading as products with different particle size distribution may have the same valve of median size. It should be noted that the mean particle size is not necessarily the same as the median size. A skewed size distribution will result in a difference between these values. It may be noted that there are also likely to be differences between volume and mass based particle size distributions, and their corresponding characteristics values (d_{50}) (Wypych, 1989).

2. Particle density: This term represents the actual density of a solid. It is of significance in pneumatic conveying systems because of its effect on minimum transport velocities and air pressure requirements. The particle density can be determined from a specific gravity bottle (respect to water) or by using an air-comparison pycnometer to determine the true volume of a known mass of particles (Wypych, 2006).

3. Bulk density: Solid density denotes the actual density of the constituents of bulk solid. The bulk density of the material is a measure of the average density of the material. This is a function of not only the particle density of the constituents but also the particle size (and size distribution) and shape, the packing arrangement adopted by the particles (the amount of voids between the particles), the degree to which the particle is compacted (or aerated), the moisture content etc. In terms of storage capacity (silos, hoppers etc.) and through-put capacity (rotary valves, pressure vessels, pipelines etc.) the bulk density is a critical parameter. Since bulk solids are generally a random arrangement of arrange of particle sizes and shapes, it is usually possibly to obtain a number of bulk densities depending on the consolidation that has been experienced by the sample. Vibration, agitation, compressive stresses and settling over time can be lead to rearrangement of the packing of particles and proportion of voids, therefore the bulk density with in a silo would vary at different locations over time (Wypych, 2006).

4. Fluidisation: Fluidisation refers to the action of a bulk solid being mixed with a gas (usually air) to make it behave like fluid. The minimum superficial velocity of gas (V_f) required to fluidise a given product is referred to as the minimum fluidisation velocity (U_{mf}), determined at atmospheric conditions. Minimum fluidisation velocity is obtained from a fluidisation curve which represents the variation of pressure gradient across a section of fluidised bed (viz. bed pressure drop per unit bed height) with respect to superficial velocity (Wypych, 2006).

An ideal fluidisation curve is presented in Figure 2.2, which also shows schematically a typical fluidisation test chamber (with relevant variables h, Δp and V_f). However, due to variation of pressure in fluidised bed may be quite different to that shown in Figure 2.2. The method of determining U_{mf} (i.e. using "Air-decrease" test) is also demonstrated in Figure 2.2.

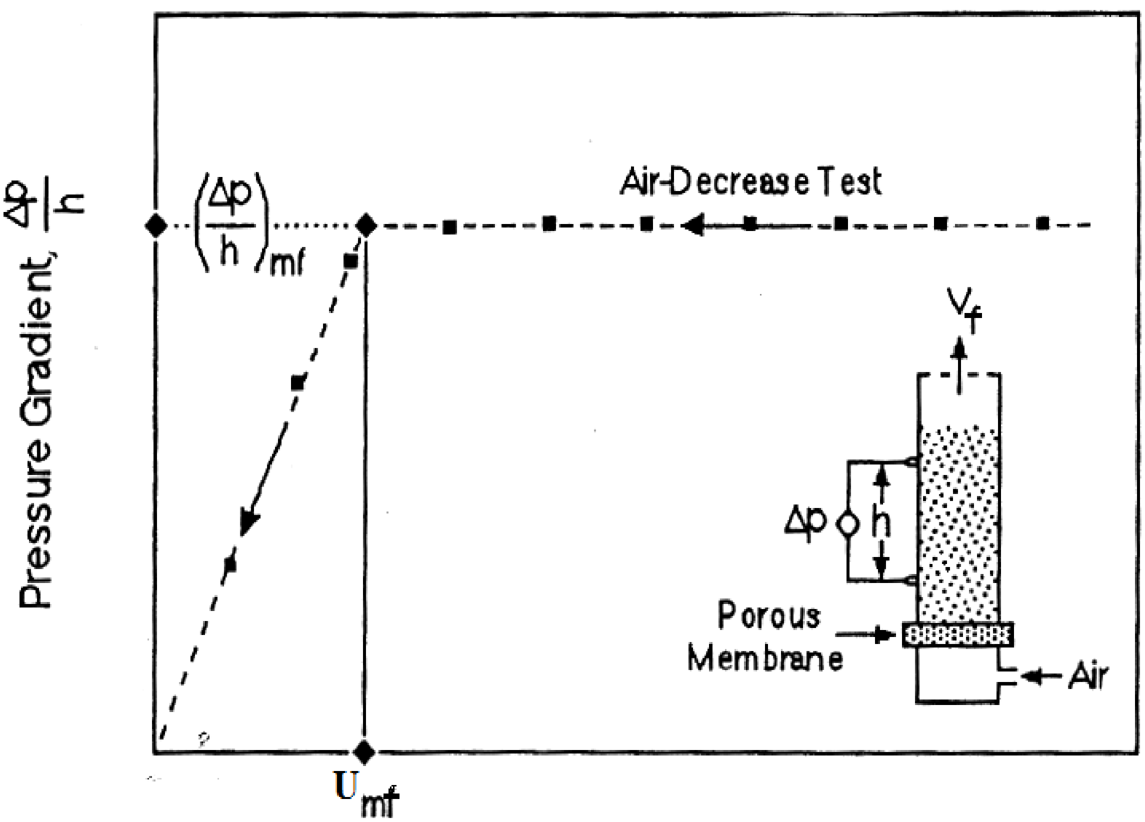

Figure 2.1: An ideal fluidisation curve showing a typical test chamber and parameters h, Δp, V_f and U_{mf} (Wypych, 2006).

5. Permeability: In many cases a linear relationship is observed between the pressure gradient across the bed and the superficial air velocity, as is noted at the low velocity end of the fluidisation curve as shown in Figure 2.1.

The slope of the curve is commonly known as the permeability factor. Where the fluidisation curve flattens out and little change to the pressure gradient across the bed occurs with increasing superficial air velocity, It is generally found that the pressure gradient is sufficient to support the mass of bulk solids within the fluidising column (Wypych, 2006).

6. Deaeration: Deaeration refers to the action of gas leaving a fluised bed after the gas supply has been turned off. It may be measured by either observing the collapse in bed height as the gas escapes, or more conveniently by recording the drop in pressure gradient over the same process. The behavior provides a useful measure of the materials ability to retain air, which is a complex function of factors such as particle shape, density, porosity, packing, drag etc. Many materials show an exponatial rate of decay in this pressure gradient. This in turn allows a characteristic time constant to be determined for each material (Wypych, 2006).

2.4 Material classification

Geldart (1973) was one of the first who worked on material classification of particulate materials based on their fluidization characteristics. This classification is in terms of the mean particle size, and the difference in density between the particles and the fluidizing medium as presented in Figure 2.2. In this representation, particle density rather than density difference is employed. This is because in fluidizing with air, the density of the air can be disregarded as it is negligible compared with almost any particle.

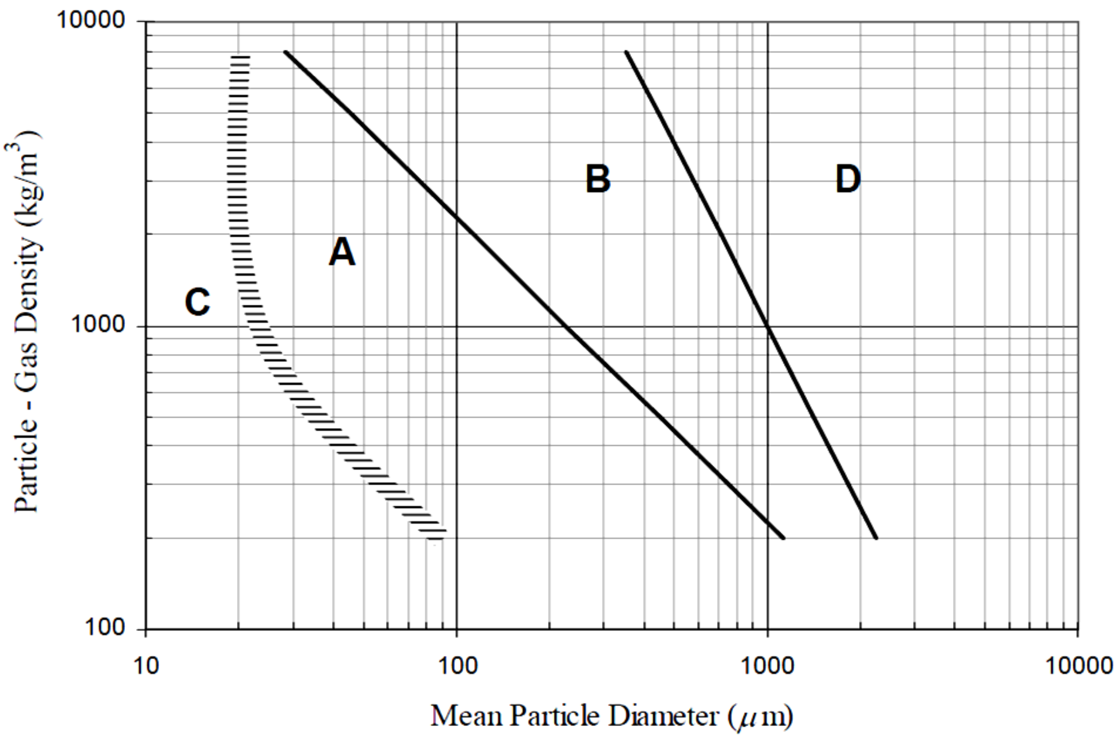

Figure 2.2: Geldart's fluidization Diagram

Four different groups of material are identified according to their fluidization behavior. The description of the characteristics of these four groups can be given as;

- *Group A:* This includes the powders having a limited tendency to form bubbles and generally exhibit considerable bed expansion between the minimum fluidization velocity and the minimum bubbling velocity. When the gas is turned off these powders retain aeration and the fluidised bed collapse very slowly.
- *Group B:* Materials belonging to this group fluidize readily and tend to form bubbles, which grow rapidly by coalescence. However, bed expansion is small. The minimum bubbling velocity is approximately equal to (or only slighter greater than) the minimum fluidizing velocity. The fluidised bed does not retain its aeration and collapses quickly when the gas supply is turned off.

- *Group C:* This group contains powders, which are of small particle size and cohesive in nature. As a result normal fluidization is very difficult. The powder lifts as a plug in small diameter tubes.
- *Group D:* This group contains large and/or high-density particles. It is believed that the bubble sizes may be similar to those in Group B, although higher gas velocities are required for fluidization.

It is generally accepted that fluidization and deaeration characteristics are significant in assessing the suitability of bulk solid for pneumatic conveying. Hence, Geldart's classification, though not developed to classify the pneumatic conveying performance of materials, has been used as a useful guide to dense-phase suitability of powders and granular materials.

Marcus (1983), for example, suggested the following.

- Group A materials are the Air Retentive materials and hence potentially suited for fluidised dense-phase, FDP conveying.
- Group B deaerate readily and hence troublesome in dense-phase. These materials generally require higher superficial air velocities.
- Group C includes cohesive materials that are difficult to fluidize satisfactorily and consequently generally unsuited to dense phase conveying .(The dividing line between groups C and A is very indistinct and the only way of properly assessing the suitability of doubtful materials for air-assisted gravity conveying is by practical experiment in a small scale test rig)

- Group D covers materials of larger particle size and high density granular materials. Depending on size, shape and solid density, some of these materials readily form plugs and perform well in dense phase systems. (e.g. plastic pellets, grains)

In later investigations, Dixon (1979) revealed that the convey ability of a product in dense-phase is significant depends to the fluidization properties of that product. His theoretical description enabled boundaries between expected flow conditions to be drawn on the same axes as Geldart's classification. It can be seen that the boundaries between strong axisymmetric slugging, weak asymmetric slugging and no slugging relate well to Geldart's boundaries between groups D, B and A. Dixon concludes that group A products are the best candidates for dense phase conveying. Group D products are also good candidates because of their strong natural slugging behavior. Group B products can cause problems if high solids loading ratios are used and group C products are possibly the least suitable materials for conveying in a dense phase mode.

Pan (1999) developed a flow mode diagram characterised by loose-poured bulk density and mean particle diameter. The flow mode diagram classifies the bulk solid materials into three groups;

- Materials which can be transported smoothly and gently from dilute to fluidised dense-phase (e.g. cement, fly ash, pulverized coal, soap powder, skim milk powder, lead dust, powdered limestone, flour)
- Materials that can be conveyed in dilute phase or slug flow
- Bulk solids which can be conveyed only in dilute phase.

2.5 Modes of pneumatic conveying systems

Different modes of dense-phase have been developed recently to take advantage of the different behavioral properties of bulk materials and also to meet the increasingly demanding requirements of industry in the areas of system reliability, product quality control and energy efficiency. It may be a daunting task to determine which mode is best for a particular product and application. Some information in the literature, such as the Geldart's fluidization Diagram shown in Figure 2.2, may prove useful in short listing some of the options or possibilities. Hence this diagram can be regarded as dense-phase classification diagram as this classification was developed mainly for the powders and granules handled and conveyed in the (plastics) chemical industry, care should be taken in using such generalized diagrams. For example, most of the other bulk materials found in industry tend to have a relatively wide particle size distribution (that could span at least 2 of the dense-phase categories or zones shown in Figure 2.2).

Following details summarize and describe each popular mode of pneumatic conveying and clarify the link between bulk material properties and pneumatic conveying performance, as indicated in Figure 2.2.

Pneumatic transport systems can be classified based on the modes of transportation, which depends on air velocity and at the pipeline inlet. According to this aspect, they seem to fall into two main categories: dilute phase and dense phase.

2.5.1 Dilute-Phase (Suspension Flow)

Traditional pneumatic conveying is based on the simple concept of providing sufficient air to entrain, suspend and transport particles along the pipeline, as indicated in Figure 2.3. Several terms are employed to describe this mode of flow, such as dilute-phase, lean-phase or suspension-flow. Dilute phase conveying is the most common used method of transporting materials.

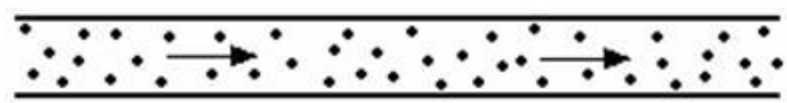

Figure 2.3: Dilute-phase (suspension flow) (Yi, 2003).

Many different feeders can be employed for dilute-phase pneumatic conveying systems, such as venturis, rotary valves, screw pumps and blow tanks. There is virtually no limit to the range of materials that can be conveyed with dilute-phase system.

Products commonly conveyed in dilute phase systems include flour, resins, specialty chemicals, ground feeds, and granular and palletized products. Of the various types of pneumatic systems, a dilute phase system will generally be lowest in capital cost.

Limitations

This process uses a relatively large amount of air to convey a relatively small amount of material and at lower pressures than dense phase systems. So power requirements are also high. Higher air velocities will have the following other disadvantages:

- The wear caused by the product on the pipe is considerably higher therefore this process is not suitable for materials which are susceptible to degradation and/or are abrasive in nature.
- The products can get deformed or crushed therefore this process is not recommended for friable products.

2.5.2 Dense-Phase Conveying (Non Suspension Flow)

The different modes of dense-phase conveying, also referred to as non-suspension flow, have been developed mainly to eliminate/minimise the problems generally occurs in dilute-phase systems (previously discussed) and hence, expand the future potential of pneumatic conveying. Due to the product being the dominant phase in dense-phase conveying, test work and experience usually are necessary to confirm dense-phase suitability, accurate operating conditions and product quality. The dense-phase classification diagram is useful in providing an initial indicator of dense-phase suitability.

In a dilute phase conveying system, the product is transported in suspension mode in the air stream. As the velocity is subsequently reduced, the larger particles cannot sustain this lift and they begin to fall from suspension to the bottom of the pipe. The technical term used in the industry that describes the velocity at which particles fall from suspension from the air stream is "saltation velocity". Unlike dilute phase conveying systems that typically use larger amounts of air to move relatively small amounts of material at high velocities in suspension, dense phase offers the enormous advantage of efficiently "pushing" a much denser concentration of bulk solids at relatively low velocities through a conveying line. The best, single description for identifying if a system is dense phase is whether the product velocities in the pipe are designed to be operating below the saltation velocity. (Wypych and Hauser, 1990) The dense phase pneumatic conveying systems uses low volume, medium pressure air stream and relies on a continuously expanding volume of air pushing cohesive slugs of material along the pipe. This system uses a transfer vessel/pump tank to feed the material into the conveying line.

Types of Dense Phase Systems: The following different modes of dense-phase conveying are in use.

i. Fluidised dense phase
ii. Low velocity slug flow
iii. Low velocity plug flow
iv. Bypass conveying
v. Single slug conveying
vi. Air assisted gravity conveying

i. Fluidised dense-phase

Fluidised dense-phase, Figure 2.4, is considered often as the most reliable and efficient method of conveying certain powders or fine granular bulk solids over distances ranging from only a few meters up to 1 km. It takes advantage of the fluidisation and air retention properties of the bulk material (Mainwaring and Reed, 1987). Group A materials, as shown in Figure 2.2, are generally the best candidates for this mode of conveying (e.g. cement, fly ash, pulverized coal, soap powder, skim milk powder, lead dust, powdered limestone, flour). The suitability of a given material to this mode of conveying and the best types of feeder for these systems (e.g. blow tank), including optimal operating conditions and the method of air injection, usually are determined by test work and experience (Wypych and Hauser,1990). Fluidization describes the state some bulk materials achieve when a gas has been entrained into the void spaces between the particles of the material. Material in a highly fluidised state tends to behave more like a fluid (as the term implies) than a solid bulk material. The system is characterized by high velocities, although not as high as for dilute phase systems. Product degradation and pipe wear may be lower.

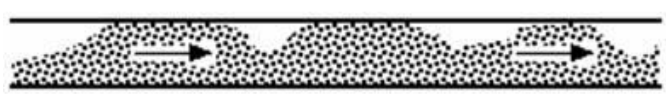

Figure 2.4: Fluidised dense-phase (FDP) (Wypych and Hauser, 1990).

ii. Low-velocity slug-flow (LVSF)

This mode of dense-phase pneumatic conveying, see Figure 2.5, has been developed to allow friable and/or granular products to be conveyed with extremely low levels of particle damage (e.g. sugar, wheat, barley, skim milk powder, poly pellets, peanuts, milled grain, semolina, muesli, powdered and granulated coffee, sand grinding media) and also system damage (e.g. bend wear). These bulk materials are usually located in the Group D category shown in Figure 2.2. However, it should be noted many other Group D materials, especially those with a wide particle size range such as crushed coal and iron ore, cannot be conveyed under LVSF conditions.

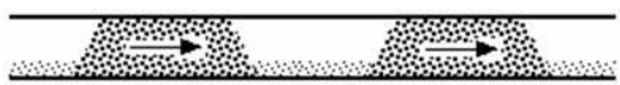

Figure 2.5: Low velocity slug flow (LVSF) (Pan et al., 1994).

iii. Low-velocity plug-flow

The low velocity conveying systems typically transport the product as a series of discrete plugs. At first glance, as indicated in Figure 2.6, this mode of flow appears similar to LVSF. However, the main differences are that LVPF does not produce a stationary layer of material. It is most suited to cohesive or sticky powders, such as full-cream milk powder, drinking chocolate and cocoa powder. Usually, a plug-forming method or device is employed at the feeder (e.g. blow tank, rotary valve) to ensure stable plugs are generated along the pipeline (Wypych and Hauser, 1990).

Figure 2.6: Low velocity plug flow (LVPF) (Wypych and Hauser,1990)

iv. Bypass conveying

A relatively unique range of gritty bulk materials (e.g. alumina, poly powder, fine sand, coarse fly ash) are troublesome in any of the previously discussed modes of dense-phase and can cause severe plugging, pipe vibrations and/or pressure surges in conventional pipeline systems. These bulk materials usually are found in the Group B shown in Figure 2.2. Although these materials usually display good fluidisation behavior, they also deaerate quite quickly (especially compared with the powders suited to FDP). Hence, it becomes necessary to employ dilute-phase for such materials. However, by employing specially designed bypass technology, it is possible to convey such materials in dense-phase. Various types of bypass technology are available (J. Klintworth and R.D. Marcus, 1985), such as multipoint injection, external bypass and internal bypass, as shown in Figure 2.7.

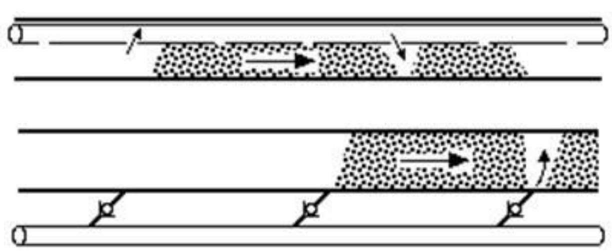

Figure 2.7: (At top) internal bypass and (below) external bypass.

(J. Klintworth and R.D. Marcus, 1985)

The main concepts involved with this technology are controlling the length of material build-up along the pipeline and preventing the conveying air from being forced through this material. Blow tanks are usually employed for such bypass conveying systems.

v. Single-slug conveying

This dense-phase mode involves the transportation of a limited batch of material per conveying cycle, Figure 2.8.

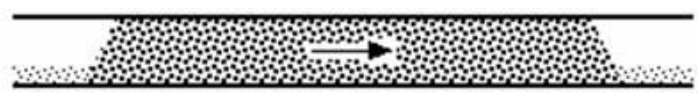

Figure 2.8: Single-slug conveying. Wypych and Arnold (1989)

A detailed description of this method of transport together with typical performance results has been presented by Wypych and Arnold (1989). It can be used to transport granular materials (e.g. crushed coal, sand, grains, diamond ore aggregate, petroleum coke, food products, bone char) over relatively short distances (e.g. up to 200 m). The materials suited to LVSF also can be conveyed successfully in single-slug mode, but this would result in inefficient conveying performance.

vi. Air-assisted gravity conveying

It is actually one of the most efficient modes of dense-phase due to its relatively high solids loadings, low conveying velocities and low specific air power requirements. For example, a Roots-type blower or even a centrifugal fan is only required, as opposed to a compressor that quite often is selected for the other modes of dense-phase (Ashenden et al., 1995). The coarse end of Group A and the fine end of Group B materials should be good candidates for this mode of pneumatic conveying. Almost any bulk particulate material having good fluidizing characteristics will, when suitably aerated, flow easily down an inclined surface. Such materials can, therefore, be transported satisfactorily in an air-assisted gravity conveyor. Many materials that are slightly cohesive can also be conveyed. However, very cohesive materials are generally unsuitable for air-assisted gravity conveying.

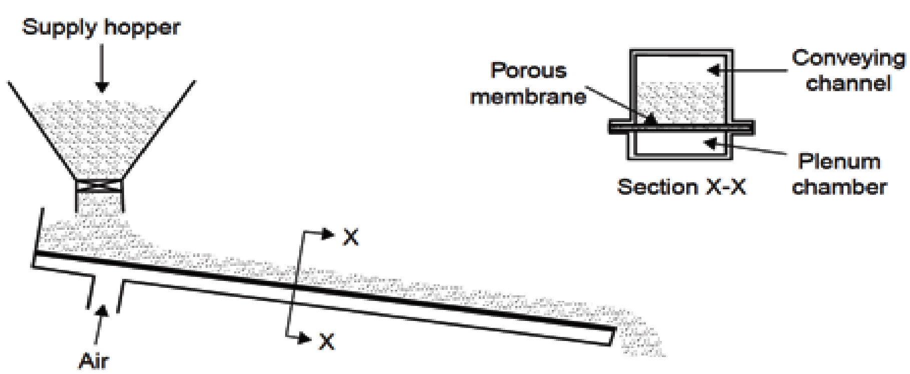

Figure 2.9: Air-assisted gravity conveying (Mills 2004)

2.6 Pneumatic conveying characteristics

Pneumatic conveying characteristics is probably the best way to describe the solid-gas transportation process PCC provide a quantitative representation of a given product being conveyed through a particular pipe and may be considered as “performance curves” similar to pumps, fans and blowers (i.e. variation of pressure drop for a given air flow rate and operating speed). If a pneumatic conveying system is to be designed to ensure satisfactory operation, and to achieve maximum efficiency, it is necessary to know the conveying characteristics of the material to be handled. The conveying characteristics will tell a designer what the minimum conveying velocity is for the material, whether there is an optimum velocity at which the material can be conveyed, and what pipeline diameter and air mover rating will be required for a given material flow rate and conveying distance (Mills, 2004).

For fluidised dense-phase conveying, the transition from the dilute phase (suspension) to dense-phase (non-suspension) mode is gradual i.e. without any sudden changes in flow mechanism causing instability (Wypych and Yi, 2003).

The typical format for PCC for a fluidized dense-phase is already shown in chapter 1 (see Figure 1.1). For forming the PCC's, the discrete steady state conveying data were obtained from the experiments. Then, by using the obtained data point plots of pressure drop (y-axis) versus mass flow rate of conveying air (x-axis) were drawn. In these plots, different constant lines for mass flow rate of solid (m_s) were drawn, by using the plotted data points with the help of interpolation technique.

2.7 Design Consideration of FDP pneumatic conveying

Fluidized dense-phase conveying system is widely used in industries. For Fluidised dense-phase, the lack of simple procedure for selection of an optimal system is a major problem in pneumatic transport system design. The predictions based on existing mathematical models for gas-solids flow change drastically with different conveying conditions and types of conveying materials. The key reason for this is the inherent unpredictability of multiphase flow. So there is a challenging job for accurately understanding and modelling the flow phenomena of gas-particle transport (research is under the developing stage) and hence requires further studies.

Two parameters “pressure drop along the line” and “minimum transport boundary” (minimum conveying velocity) are the key parameters in the design of a reliable pneumatic conveying system. Since there are numerous influential parameters (e.g. particle size and size distribution, particle density, particle shape, etc.), empiricism has been used extensively using some of the above parameters, to establish the mathematical models for “pressure drop along the line” and “minimum transport boundary”. Also, the applicability of these models to industry is very limited, and is reduced further for materials possessing small particle size, relatively wide particle distributions, and complex physical properties. Existing literature suggests only empirical methods (that involve testing a sample of the product to be conveyed in the final system in a pilot scale rig over a wide range of operating conditions) to predict the pressure drop and minimum transport boundary for dilute-phase as well as FDP. It gives a higher reliability level about the effects of product type.

Pilot plant test is very important because it provides useful information on the convey ability of product and determination of minimum conveying limits as well. However, it is not always feasible to use a pilot plant, which is of identical geometry (length, bore, number of bends, types of bends, etc.) to that of the required industrial installation. Therefore, it is required to scale-up the conveying characteristics that are based on the pilot plant data, to predict the behavior of the proposed industrial (full scale) plant, using some experimentally determined factors. Scaling up in terms of pipe line geometry needs to be carried out with respect to conveying distance, pipeline bore, the air supply pressure available, etc. Pipeline material, bend geometry and stepped pipelines are other important parameters that are also needed to be considered. The scaling up of pilot plant data provides the required link between laboratory pilot plant test results and the full-scale industrial installation. Hence, accuracy and reliability of scaling methodology are vital. A considerable number of researches have been carried out to establish the mathematical models and relevant conditions of scaling up procedure.

2.7.1 Pressure drop

The total pressure drop is utilized to overcome the friction between the pipeline wall and the gas-solids mixture, which can be considered as one of the flow properties of the conveyed material. Weber (1981) referred that for coarse particles in dilute phase flow; Barth (1958) calculated the Pressure loss for a straight horizontal section of pipe for the gas-solid mixture by using following equation.

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

This is the most popular form for representing pressure drop for a solids-gas mixture flowing through a straight horizontal section of pipe. In this equation the main challenge to find the value of the solids friction factor accurately**.** Barth purposes this equation only for coarse particles in dilute phase flow, but as the fundamental modelling of dense-phase conveying of powders is much difficult problem to solve, so many researchers (Stegmaier, 1978; Pan, 1992; Pan and Wypych, 1998; Wypych, 1989; Jones and Williams, 2003) showed confidence on this equation to have potential to be used in cases of finer particles. As this thesis is not related to the pressure drop issues, so the details of are not presented here.

2.7.2 Minimum transport boundary

An unnecessarily high conveying velocity will result in higher energy costs due to an increased pressure drop in the system, solids degradation, and pipe erosion that can result in an economically unattractive operation. On the other hand, systems designed with extremely low conveying velocities or extremely high solid flow rates are subject to erratic operation due to solids disposition or they may be completely inoperable because of blocking.

Literature review mentioning the studies and existing correlations for minimum transport boundary for FDP dense-phase conveying which is included in Chapter 3.

CHAPTER 3: Evaluation of Existing Models for Minimum Transport Boundary

Most models to date have been largely empirical (Mills et al., 1982; Martinussen, 1996; Mills, 2004a, etc.). Preliminary investigation has shown that such models have been based on certain products and pipeline conditions, and have not been tested properly under important criterion, such as scale-up accuracy. So there is a need to conduct proper investigation for scale-up accuracy for the existing models for the Minimum Transport boundary.

For this, the experimental data (and conveying characteristics) from the test rigs of different sizes and lengths are required for derivation of models for minimum transport boundaries and their scale-up evaluations. Hence a series of pilot-plant test with different pipeline configurations are necessary. The conveying characteristics (minimum transport boundary behavior) obtained from the testing of products in small test rigs, can be directly used to predict the minimum transport boundaries in larger and/or longer pipelines using suitable scale-up techniques. Since this facility is not available, so it was decided that extensive test data of previous experimental programs carried out by other researchers with various powders conveyed in different pipelines would be used in this thesis.

With this background, the objectives of this chapter are to collect the extensive test data of previous experimental programs carried out by other researchers with various powders conveyed in different pipeline and evaluate the existing techniques for predicting minimum transport boundary by using above data.

3.1 Determination of minimum transport boundary

For this thesis, the investigations were done with the help of product and pipeline data obtained from the previous work of other researchers. The fluidized dense phase flow PCC of fly ash and ESP dust based on experimental data of Wypych et al., 2005 (also shown by Mallick, 2010) are again used for further evaluations and investigations. These are tested in test rig having different diameters and lengths of pipes (69 mm I.D. ×168 m, 105 mm I.D. × 168 m and 69 mm I.D. × 554 m long). Schematic of these test set-ups are shown in Figures A1.1, A1.2 and A1.3 respectively of Appendix A. The conveying data related to cement shown by Mills, 2004a; is also used. Some PCC of Pan (1992) were found to be well suited for the present investigation as the particle diameter and density of conveyed materials (see Table 3.1) would suggest a possible FDP mode of conveying.

Table 3.1 shows the various materials for different pipeline configurations with their physical properties included in this study.

Table 3.1: Properties of products and pipeline conditions

S No.	Powder	d_{50} (μm)	ρ_p (kg/m^3)	ρ_b (kg/m^3)	Blow Tank	D (mm)	L (m)	No. of bends
1	Fly Ash (Wypych et al., 2005)	30	2300	700	BD	69 69 105	168 554 168	5 17 5
2	ESP Dust (Wypych et al., 2005)	7	3637	610	BD	69 69 105	168 554 168	5 17 5
3	Cement (Mills, 2004a)	14	3060	1070	TD	52.5 81	101 95	17 9
4	Fly ash (Pan, 1992)	15.5	2197	634	BD	52.5 52.5 69 69	102 135 172 554	5 5 5 17

BD: Bottom Discharge

TD: Top Discharge

As listed above, all the selected test data for different test materials in different pipeline configurations were re-plotted and two lines corresponding to constant velocity at pipeline inlet (V_i and V_{si}) were superimposed on them. Here, V_i lines corresponds to the left most solid flow points on solid flow lines, whereas V_{si} lines represent the right most constant velocity line covering all the solid flow lines. With each velocity line corresponding inlet Froude number (represented by Fr_i and Fr_{si}) are also given. As Mallick (2010) used V_i and Fr_i , so these terms were used for initial investigation. Here, V_{si} and Fr_{si} were considered as they are safe and more relevant boundary from designer point of view. These values ensure that conveying is possible for all the mass flow rates of solid within the experimental boundary. For evaluation of exiting model and to develop the new validated modelling procedure, the actual minimum transport boundary for each PCC was also shown. These are shown in Figures 3.1 to 3.12.

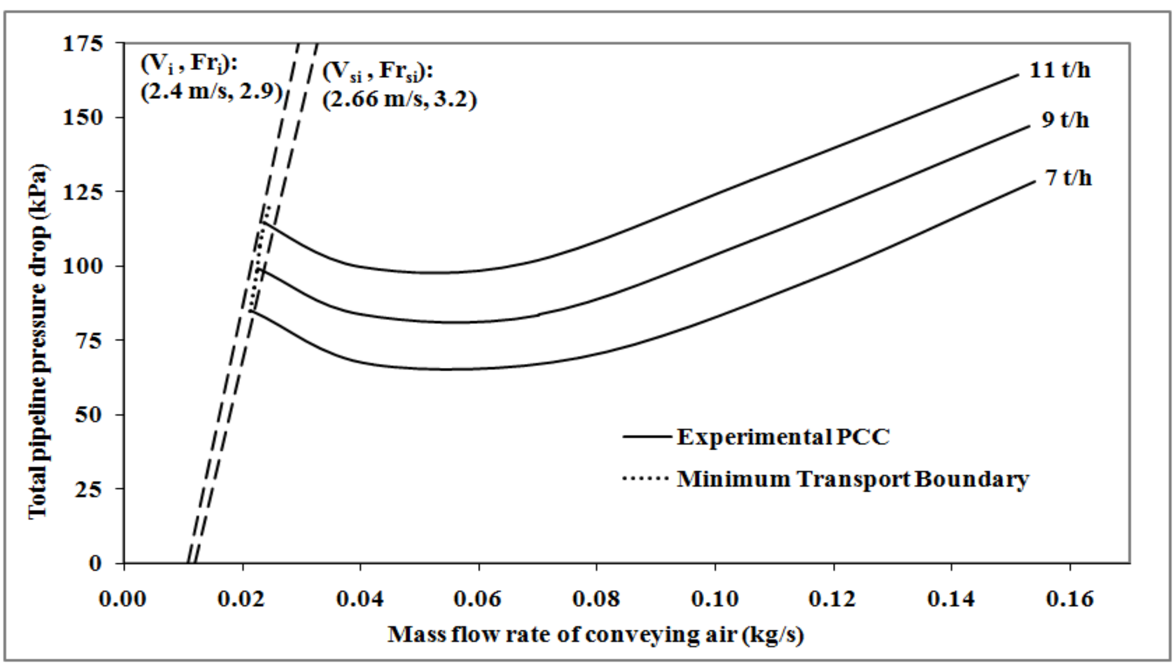

Figure 3.1: Minimum transport boundary for fly ash (Wypych et al., 2005) for 69 mm I.D. × 168 m long pipe

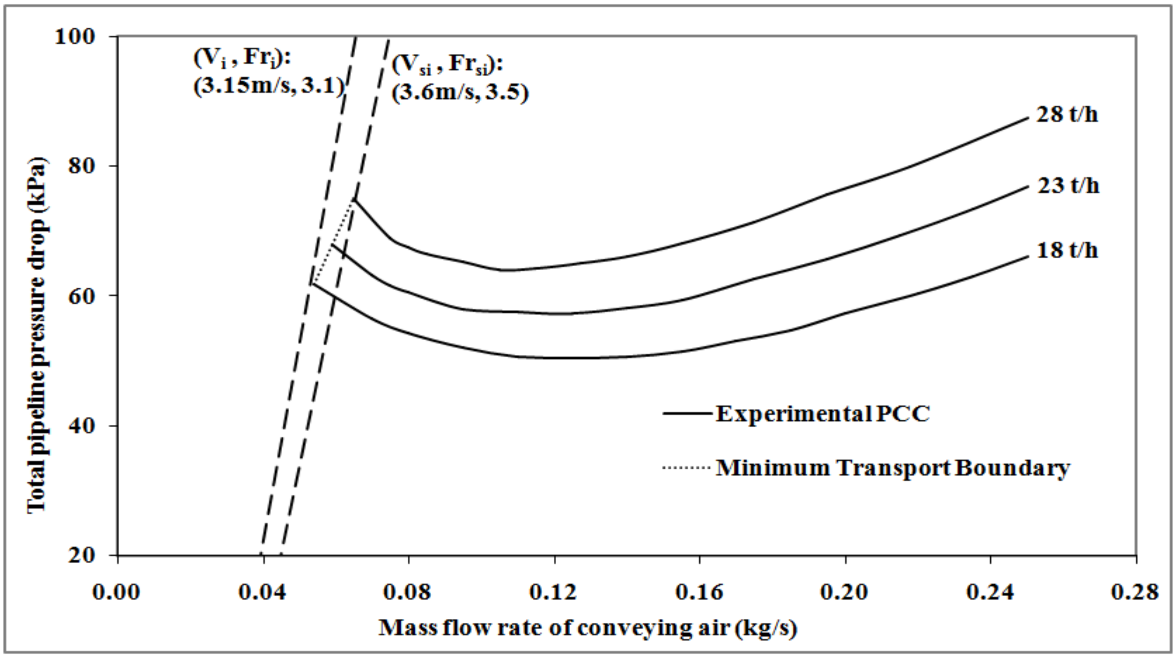

Figure 3.2: Minimum transport boundary for fly ash (Wypych et al., 2005)

for 105 mm I.D. × 168 m long pipe

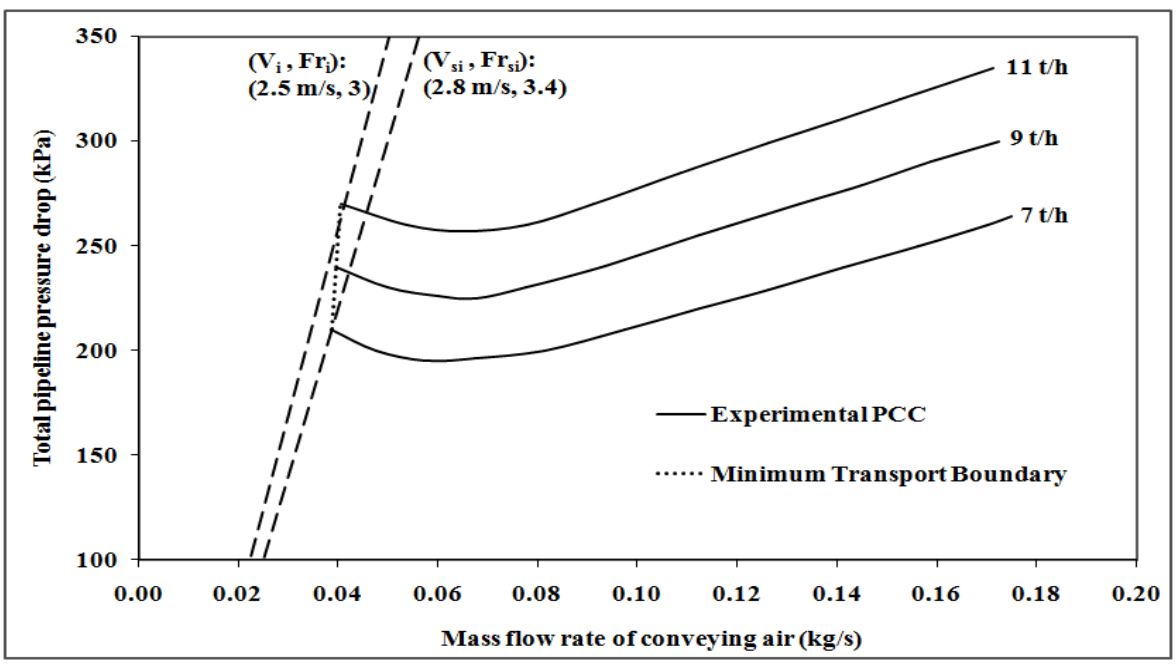

Figure 3.3: Minimum transport boundary for fly ash (Wypych et al., 2005)

for 69 mm I.D. × 554 m long pipe

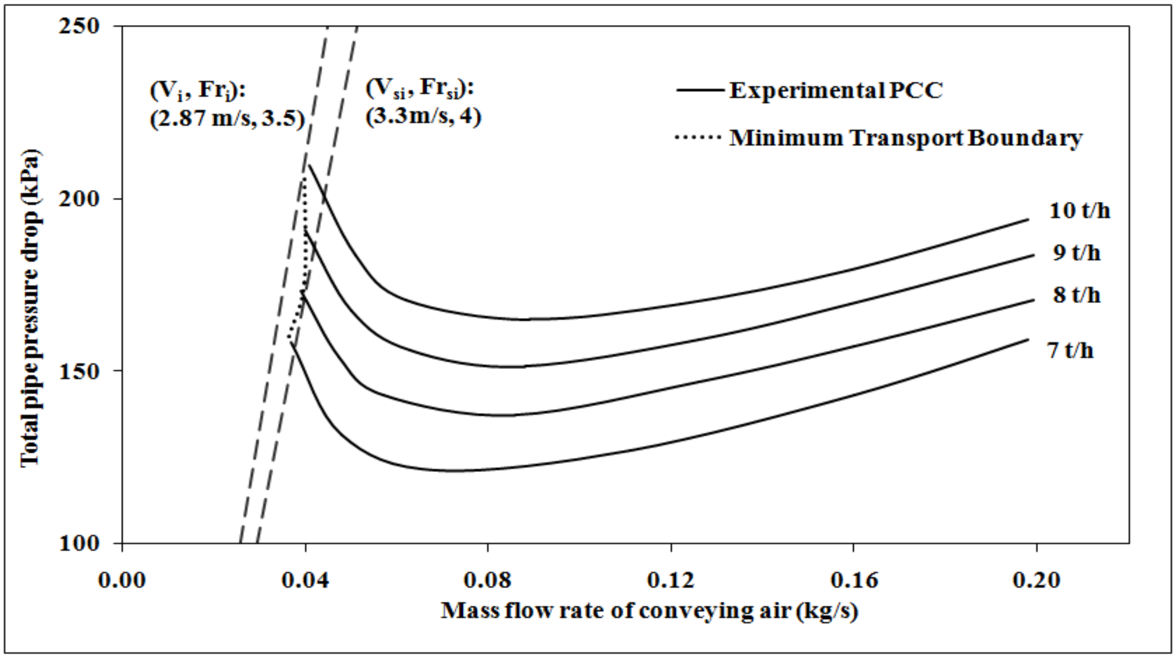

Figure 3.4: Minimum transport boundary for ESP dust (Wypych et al., 2005)

for 69 mm I.D. × 168 m long pipe

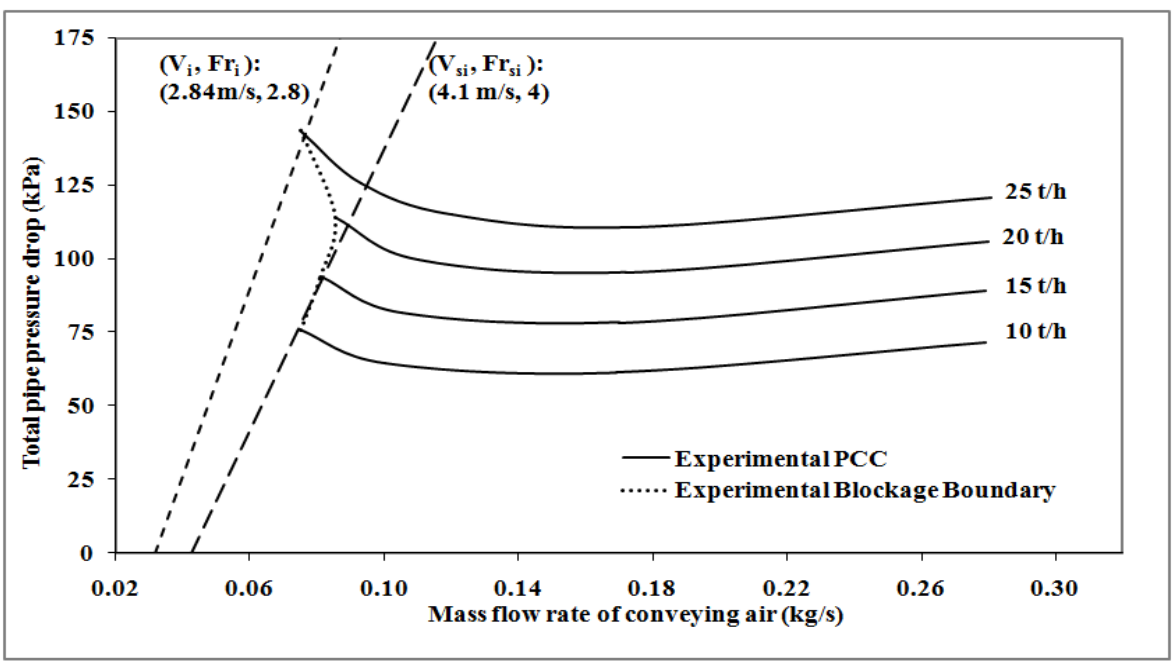

Figure 3.5: Minimum transport boundary for ESP dust (Wypych et al., 2005)

for 105 mm I.D. × 168 long m pipe

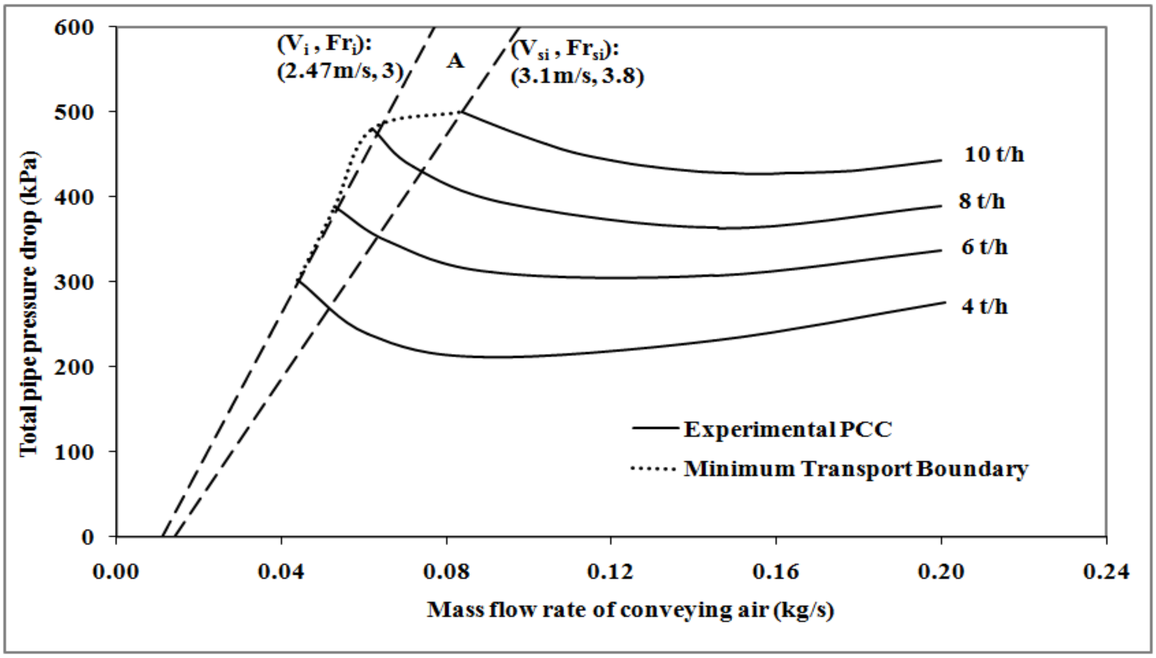

Figure 3.6: Minimum transport boundary for ESP dust (Wypych et al., 2005)

for 69 mm I.D. × 554 m long pipe

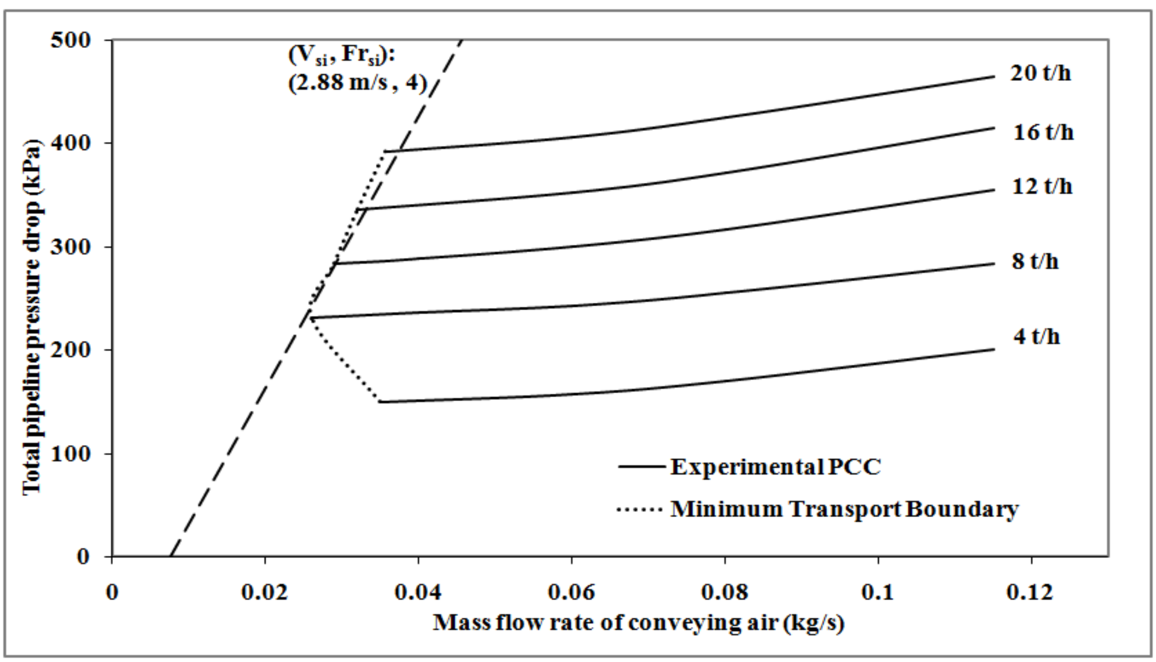

Figure 3.7: Minimum transport boundary for cement (Mills, 2004a)

for 52.5 mm I.D. × 101 m long pipe

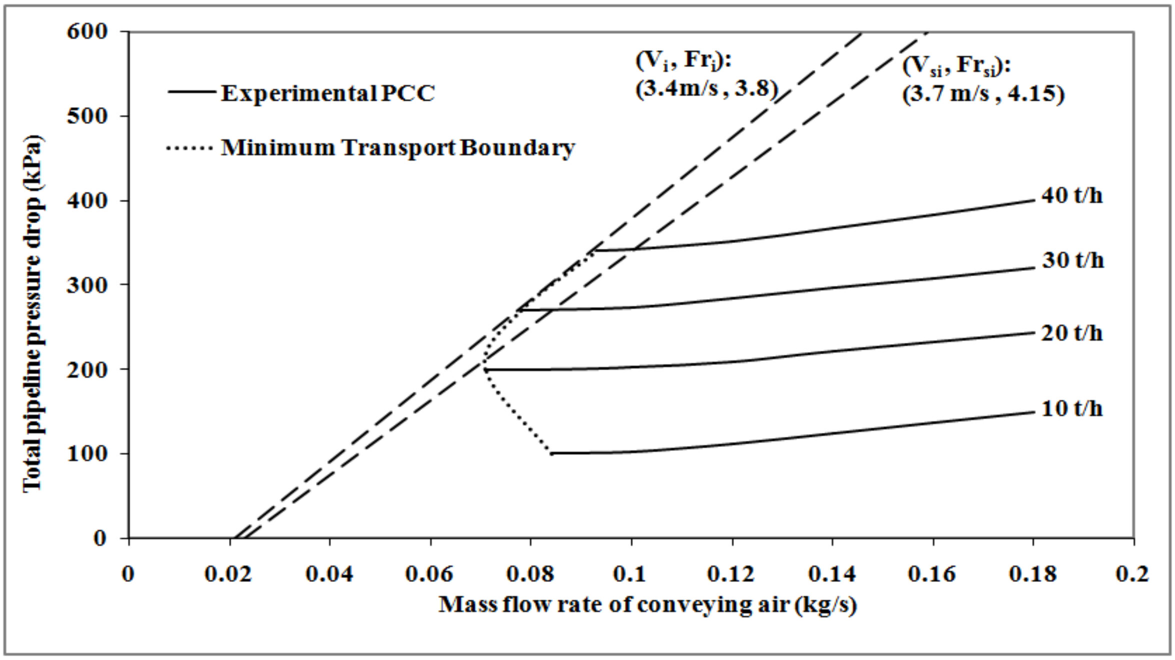

Figure 3.8: Minimum transport boundary for cement (Mills, 2004)

for 81 mm I.D. × 95 m long pipe

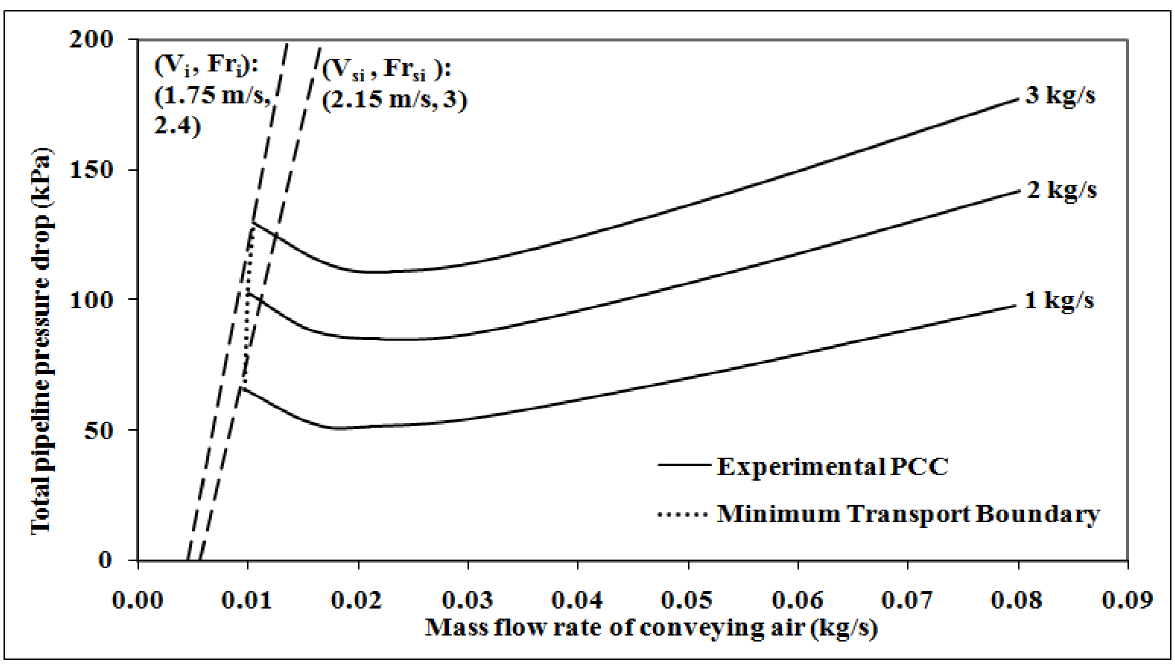

Figure 3.9: Minimum transport boundary for fly ash (Pan, 1992)

for 52.5 mm I.D. × 102 m long pipe

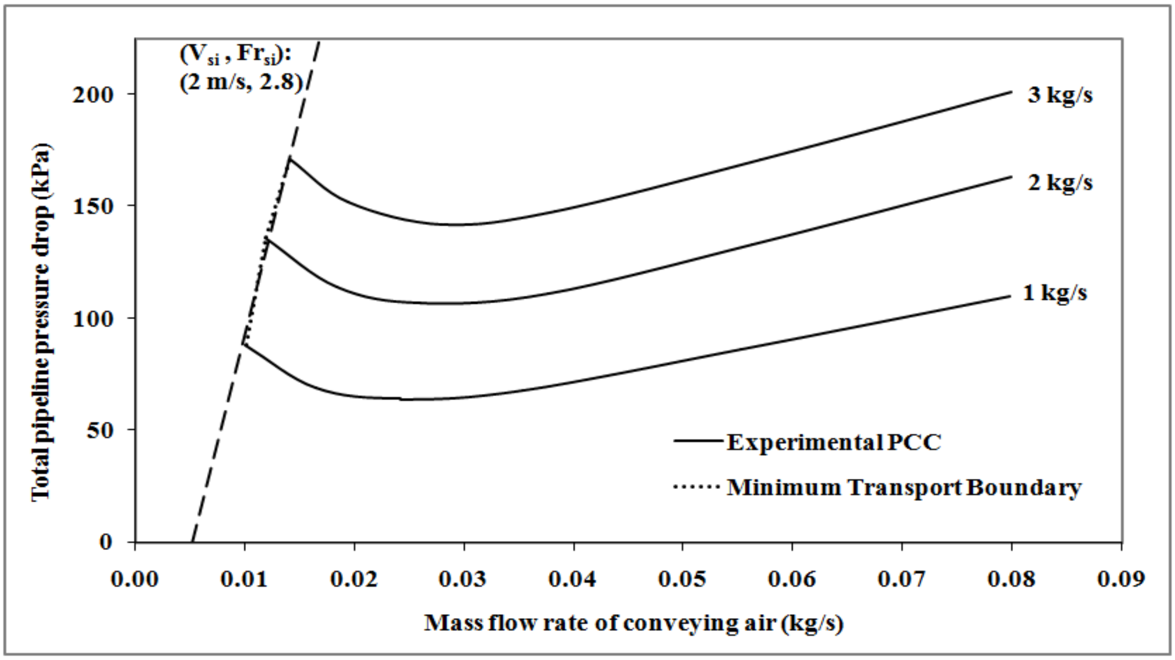

Figure 3.10: Minimum transport boundary for fly ash (Pan, 1992)

for 52.5 mm I.D. × 135 m long pipe

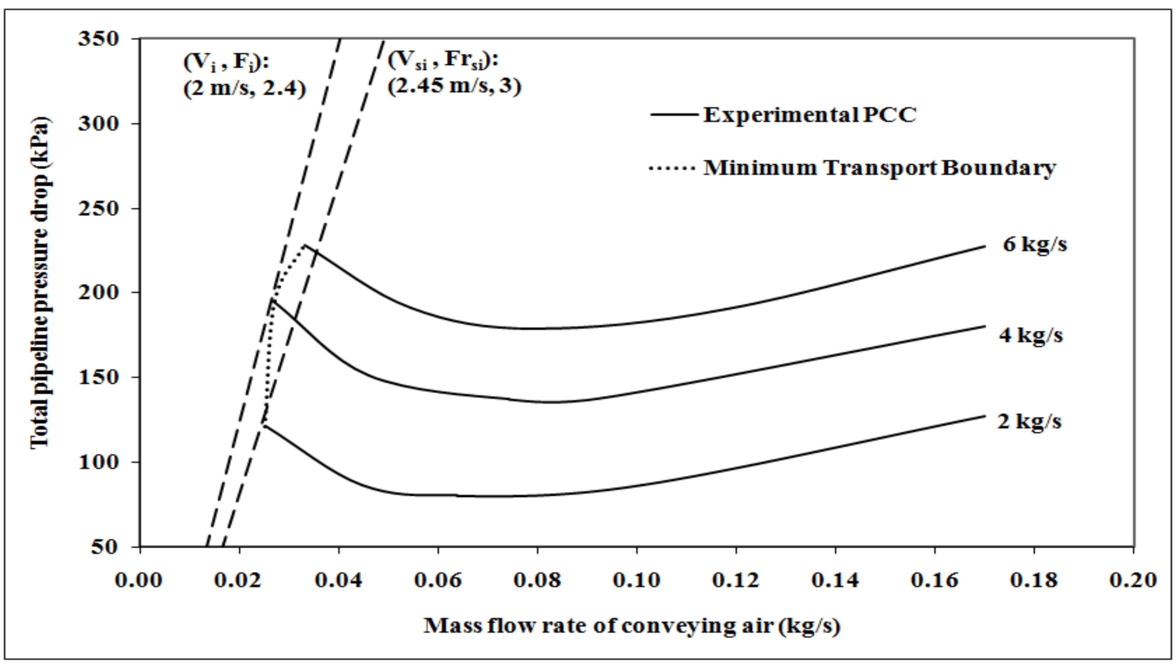

Figure 3.11: Minimum transport boundary for fly ash (Pan, 1992)

for 69 mm I.D. × 172 m long pipe

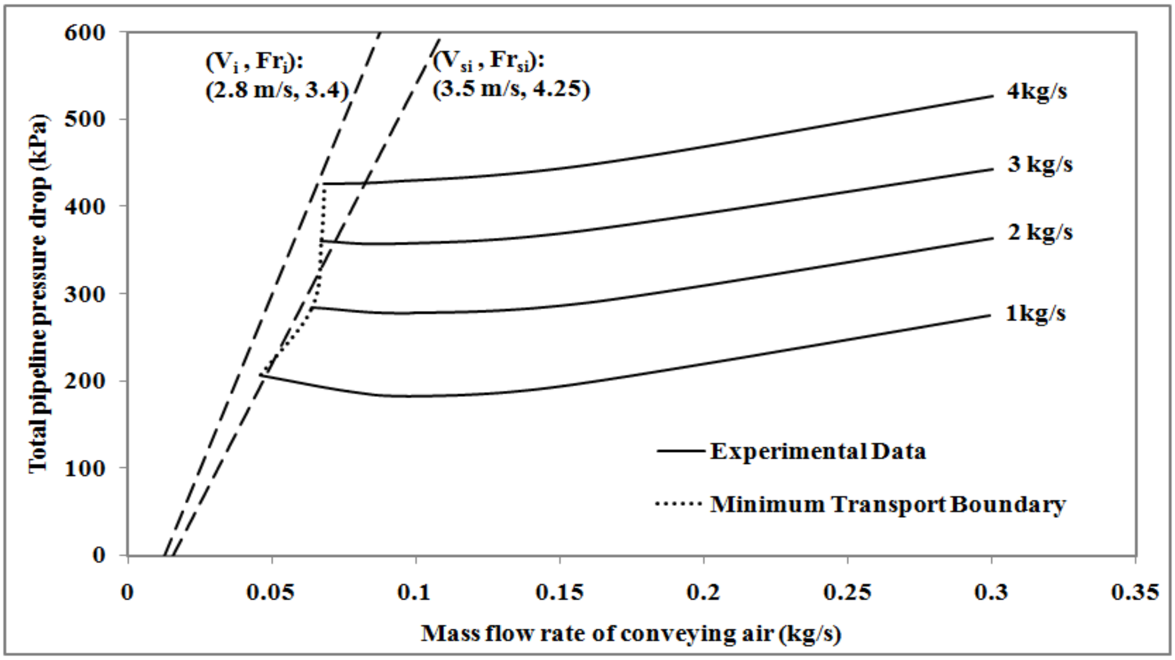

Figure 3.12: Minimum transport boundary for fly ash (Pan, 1992)

for 69 mm I.D. × 554 m long pipe

Based on the experimental data of four different powders (shown from Figures 3.1 to 3.12) conveyed over a range of pipe lengths and diameters, it is found that the products do not have its unique minimum velocity values (i.e. even for the same product, the minimum conveying velocity requirement is dependent on pipe diameter and length). The minimum conveying air velocity increases quite considerable with increase in pipe diameter. At higher values of m*, the minimum conveying requirement decreases. Comparatively, the change in the corresponding values of Froude number with diameter scale-up (for the same product) is less.

The values of V_i and V_{si} with corresponding Froude numbers i.e. Fr_i and Fr_{si} for above PCC are provided in Table 3.2.

Table 3.2 Summary of V_i , V_{si} , Fr_i ,and Fr_{si} values for above PCCs in sequence of Table 3.1.

S No.	Powder	V_i (m/s)	Fr_i	V_{si} (m/s)	Fr_{si}
1	Fly ash (Sample1) (Wypych et al., 2005)	2.4 3.15 2.5	2.9 3.1 3	2.6 3.6 2.8	3.2 3.5 3.4
2	ESP Dust (Wypych et al., 2005)	2.87 2.84 2.47	3.5 2.8 3	3.3 4.1 2.6	4 4 3.8
3	Cement (Mills, 2004)	2.88 3.4	4 3.8	2.9 3.7	4 4.15
4	Fly ash (Pan, 1992)	1.75 2 2 2.8	2.4 2.8 2.4 3.4	2.15 2 2.45 3.5	3 2.8 3 4.25

3.2 Existing models for predicting minimum transport boundary

Reports on the previous studies have been presented here according to chronological orders as far as possible. The following contains a list of existing models of minimum transport boundary (as mentioned in Matsumoto et al., 1974 to Mallick et al., 2011). Some of these models are originally developed for dilute-phase flow of coarser particles, but the same has been included here to investigate as they can be applicable for fine powders as both the flow modes contain particle wall and particle-particle interactions (although in varying degrees for different flow modes). This is also supported by Mallick (2010).

Rizk (1976) carried out investigation on horizontal pipelines of 50 mm, 100 mm, 200 mm and 400 mm diameter. Sryropor and polystrol were used as the test materials. The minimum pressure drop curve was considered as the boundary between safe steady flow and a region of stationary particles. According to him minimum conveying velocity depends upon the solids loading ratio the following relationship.

$$m^* = \left(\frac{1}{10^{\delta}}\right) \cdot \mathrm{Fr_{min}}^{\chi} \qquad (3.1)$$

where, $\delta = 1.44\ d_p + 1.96$

and $\chi = 1.1\ d_p + 2.5$

and d_p is the particle diameter in mm.

Weber (1981) provided correlation for minimum conveying velocity as provided in equation 3.2 and 3.3. Weber (1981), however, did not clearly indicate whether the models are applicable for both fine and coarse particles.

For $U_t \leq 3\, m/s$ $\quad$ $Fr_{min} = \left[\frac{8}{3} U_t + 7\right] m^{*0.25} \left(\frac{d_p}{D}\right)^{0.1}$

(3.2)

For $U_t \leq 3\, m/s$ $\quad$ $Fr_{min} = 15 m^{*0.25} \left(\frac{d_p}{D}\right)^{0.1}$ (3.3)

Hilgraf (1987) proposed that the minimum conveying velocity depends on the absolute conveying pressure and the pipeline diameter which can be formulated as:

$$V_{min} = K \frac{D^{\alpha}}{P^{l}} \quad (3.4)$$

Where, K, α and l are defined as material dependent numerical constants that can be found by using least square method.

Schade (1987) invested minimum conveying velocity in a wide range of diameters (D= 50, 60, 80, 100, 120, and 150 mm) and the test materials used in the experiments were granule, sand, styropor, rubber, and polystyrol. Capacitive plates built into the wall of the pipes were used to measure the deposition of material at the bottom of the pipeline. The definition of the minimum conveying velocity in Schade’s work was the gas velocity at which the particle velocity became zero. Hence, the value of Schade’s critical velocity is lower than a particle minimum conveying velocity (i.e. if particle deposition is to be avoided).

Schade's correlation was:

$$\frac{V_c}{\sqrt{g \cdot D}} = (m^*)^{0.11} \cdot \left(\frac{D}{d_p}\right)^{0.025} \cdot \left(\frac{\rho_p}{\rho_f}\right)^{0.34} \tag{3.5}$$

Wypych and Reed (1990) used an empirical method to find out the minimum transport velocity for designing stepped pipelines. For the purpose of scaling up, they proposed the following equation for the minimum conveying velocity at the entry of pipe section for a given product by using dimensional analysis.

$$V_{min} = x_1\,(m^*)^{x_2}\,(\rho_f)^{X_3}\,(D)^{X_4}\,\cdot \tag{3.6}$$

Where, x_i is the coefficients to be determined by minimizing sum of square error method.

Geldart and Ling (1992) conducted experiments on minimum conveying velocity with high pressures (upto 82.5 bar) through pipelines having 9.19 mm and 12.52 mm diameters.The test material was fine coal with average particle sizes of 8, 18, and 26 μm.They proposed the following models:

For $\frac{G_s}{D} > 47000$ $\quad V_{min} = 1.5 \cdot {G_s}^{0.4605} \cdot D^{-0.01} \cdot {\mu_f}^{0.55} \cdot {\rho_f}^{-0.42}$ (3.7)

For $\frac{G_s}{D} < 47000$ $\quad V_{min} = 8.7 \cdot {G_s}^{0.302} \cdot D^{0.153} \cdot {\mu_f}^{0.55} \cdot {\rho_f}^{-0.42}$ (3.8)

Martinussen (1996) used experimental set-up of horizontal pipeline of 53 mm diameter and 15m length. By applying the fluid analogy he developed the model to determine the minimum conveying velocity which was given in equation 3.9.

$$V_{min}^{2} = KDg\frac{\rho_b}{\rho_a}\left[1 - m^{*}\frac{\rho_a}{\rho_b}\right]^{3} \tag{3.9}$$

Where, K (geometrical factor) = Π/4 at the filling level of D/2. According to Martinussen (1996), this model gives better predictions for fine materials than for coarse ones.

Mill (2004) conveyed cement through an 81 mm I.D. × 95 m test rig (Figure 3.13a). From this conveying data, he presented a graph of V_i versus m^*(Figure 3.13b) to represent the minimum conveying conditions for given material.

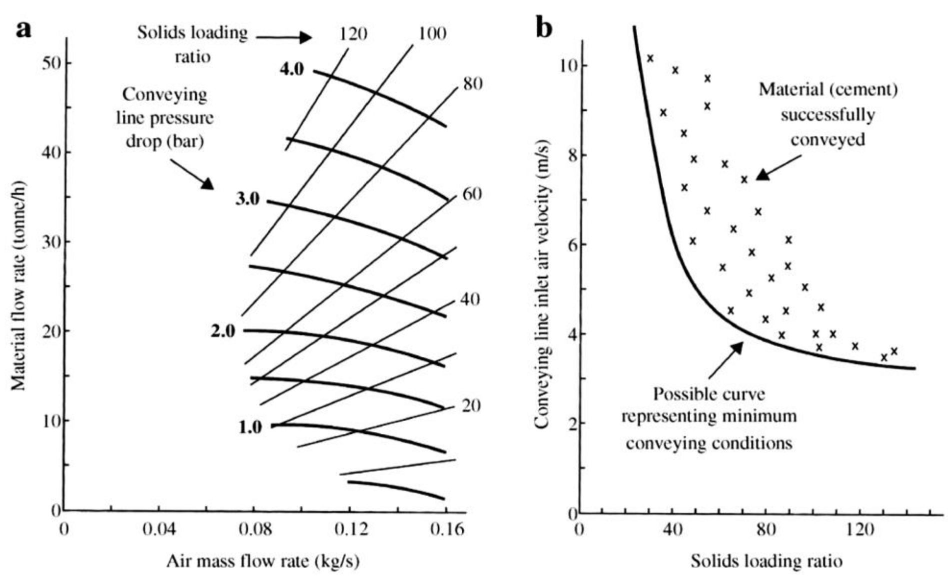

Figure 3.13: Design data for pneumatic conveying of cement:

a) PCC for 81 mm I.D. × 95 m test rig; b) minimum velocity relationship (Mills, 2004)

In the same reference (Mills, 2004), Mills has provided another example of representing the minimum conveying boundary by conveying cement through a different test rig (53 mm I.D. × 101 m; 17 × 90 degree bends; top discharge blow tank). It appears that the same work has also been presented in (Mills, 2004a). He also proposed a relationship between V_i and m* for this material as shown in Figure 3.14 and seemed to indicate a constant velocity based criterion (V_i = 3) to represent the minimum conveying condition (lower dense-phase conveying boundary) as dense-phase minimum transport boundary limit is defined at 3 m/s. This model, however, is applicable for one pipeline and product (cement) only and does not appear to seem to address scale-up reliability issues (i.e. prediction of minimum conveying velocities for industrial scale larger and longer pipelines). However, the finding of Mills (2004) on MTB is only based on certain product (cement) and pipeline geometry and does not include pipeline diameter and length scale-up effect.

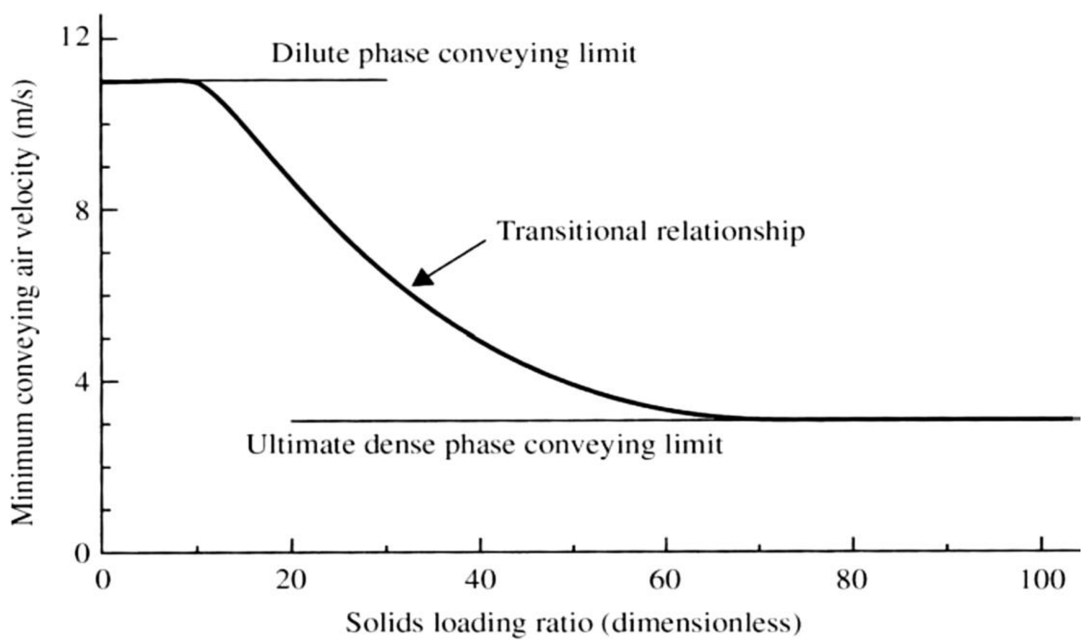

Figure 3.14: Minimum velocity relationship (Mills, 2004, 2004a)

Mallick and Wypych (2009) developed a Froude number based criteria ($Fr_i = 6$) to represent the minimum transport criteria using different fly ash, ESP dust and cement data conveyed through pipelines of various diameters and length. However, more recently, Mallick (2010) and Mallick et al. (2011) indicated that a constant Froude number line to predict the blockage boundary may provide only limited accuracy under a wide range of scale-up conditions and further studies were recommended towards developing a more accurate test design procedure. Therefore, the aim of this paper is to develop a validated modelling and scale-up procedure for minimum transport boundary (or blockage condition), so that the minimum transport boundary information obtained by conveying fine powder through a laboratory based test rig can be reliably scaled-up to industrial sized plants (i.e. under significant length and diameter scale-up condition). Such a tool would help the designer to effectively design a good dense-phase system – benefited by the high solids loading ratio (m*), yet preventing blockage to occur in pipelines.

It may be noted that some researchers (Wypych and Reed, 1990; Martinussen 1996 etc.) have attempted to include air density but they have also included m* in the expression for MTB. Both the parameters seem to be interrelated (effect of density and velocity terms already comes in m* parameter). Hence, these modelling might have included some redundancy.

3.3 Evaluation of Existing models

The above models (Rizk, 1976 to Mallick et al. 2011) have been evaluated for their diameter scale-up accuracy by using them to predict the minimum transport boundary for 105 mm I.D. × 168 m pipe for fly ash and ESP dust. The results are shown in Figures 3.14 and 3.15. However, for the length scale-up accuracy the predictions are superimposed on the PCC for 69 mm I.D. × 554 m pipe for fly ash and ESP dust which are shown in Figures 3.16 and 3.17.

It should be noted that to evaluate corelatons of Hilgraf (1987) and Wypych and Reed (1991) the specific models are generated using the minimum transport boundary data 69 mm I.D. × 168 m long test rig and then both the models scaled up for 105 mm I.D. × 168 m long pipeline (larger test rig) and 105 mm I.D. × 168 m long pipeline (longer test rig).

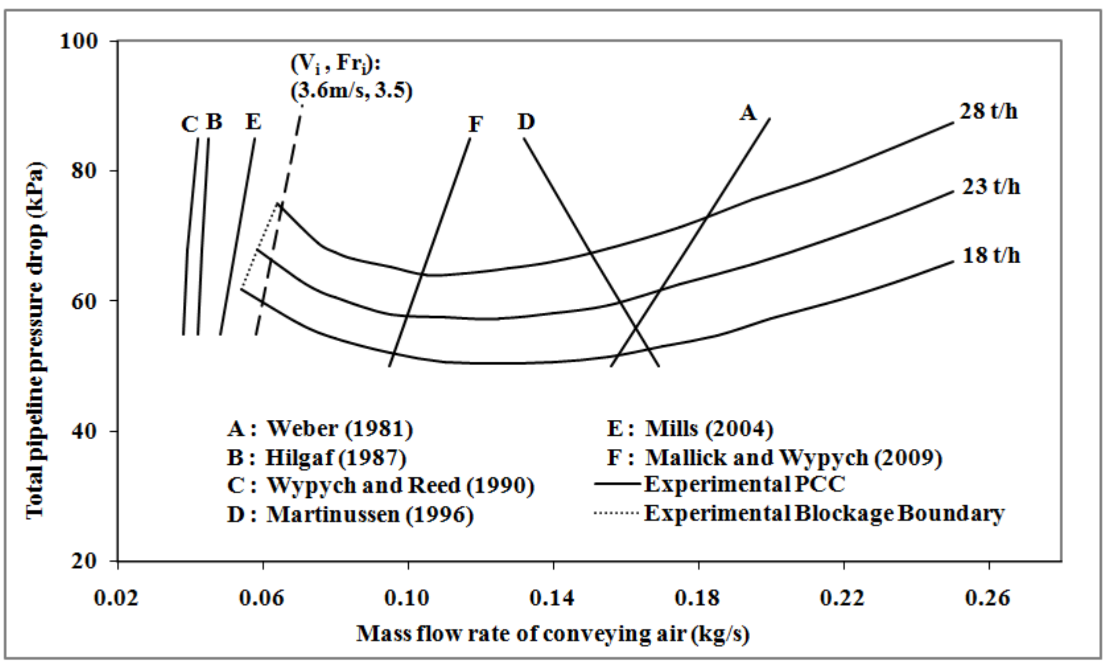

Figure 3.15: Evaluation of existing models, fly ash, 105 mm I.D. × 168 m long pipe

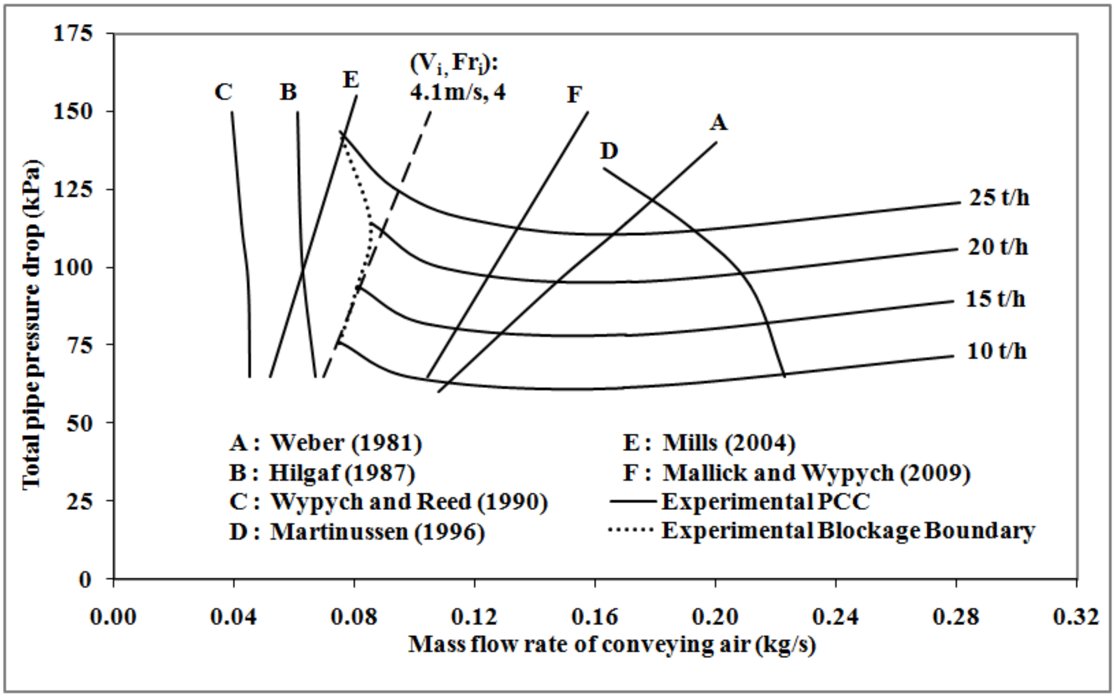

Figure 3.16: Evaluation of existing models, ESP dust, 105 mm I.D. × 168 m long pipe

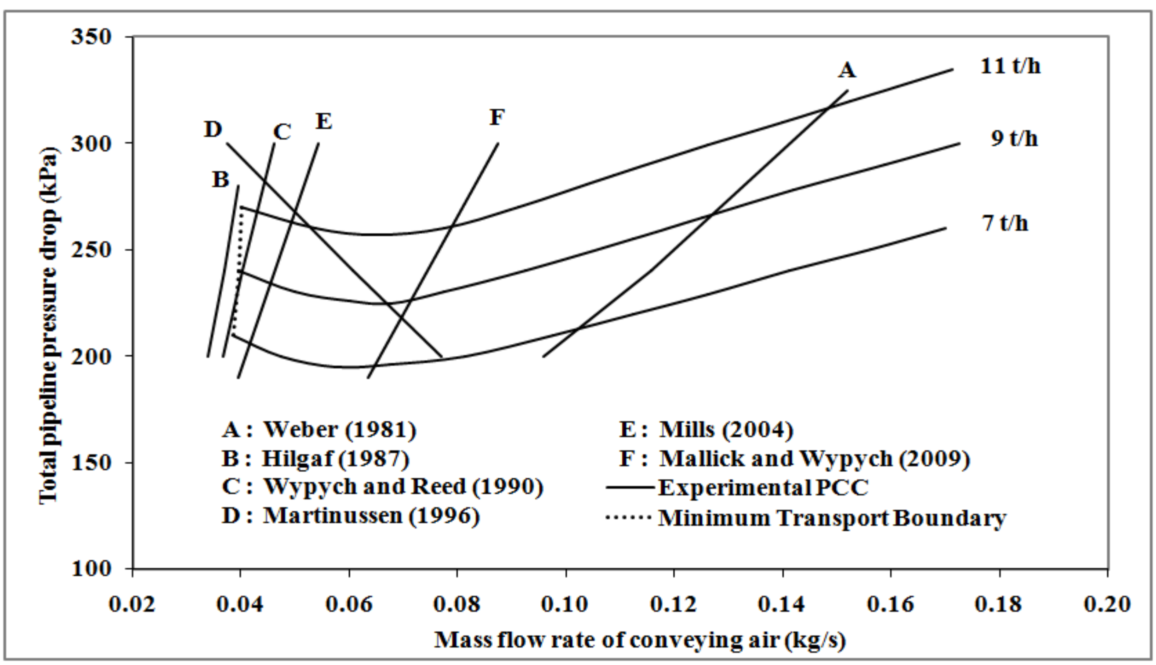

Figure 3.17: Evaluation of existing models, fly ash, 69 mm I.D. × 554 m long pipe

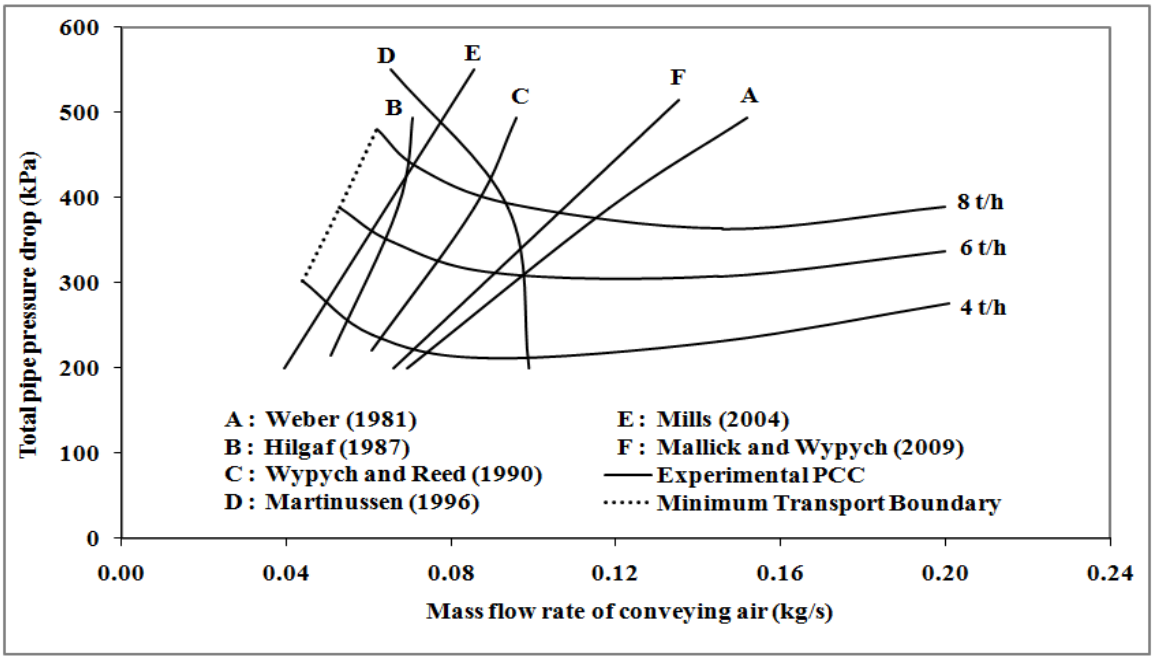

Figure 3.18: Evaluation of existing models, ESP dust, 69 mm I.D. × 554 m long pipe

Results show that in case of diameter scale-up for both fly ash and ESP dust, the models of Wypych and Reed (1990), Hilgraf (1987) and Mills (2004) showed under-predictions, with maximum under-prediction obtained from Wypych and Reed (1990) model (see Figure 3.15 and 3.16). For longer pipeline Hilgraf (1987) gives under-predictions in case of fly ash (Figure 3.17) and over predictions in case of ESP dust (Figure 3.1). While, Wypych and Reed (1990) gives good predictions in case of fly ash (Figure 3.17) and large over predictions in case of ESP dust (Figure 3.18). Mills (2004) gives slight over –predictions for both the products in length scale-up.

The Martinussen (1996), Weber (1981) and Mallick & Wypych (2009) models provide considerable over-predictions, with Weber (1987) model providing the largest over-predictions (Figures 3.15, 3.16, 3.17 and 3.18). Martinussen (1996) model seemed to provide the gross over-predictions for both the products. The slope of predicted boundaries of

Martinussen (1996) model is quite different from the experimental minimum transport boundaries.

The Geldart and Ling (1992) model provided significant under-predictions, whereas Schade (1987) and Rizk's model (1976) gave significant over-predictions; hence these three models have not been included in Figures 3.15, 3.16, 3.17 and 3.18. Over-predictions are expected from Rizk (1976) model as this model was originally derived for pressure minimum curve in horizontal straight pipe lines. Under predictions from the Geldart and Ling (1992) model are perhaps understandable as this model was derived from very high pressure (upto 82.5 bar) conveying data, where evaluation is on 1-5 bar conveying data.

From the results, it is apparent that the existing models are unable to accurately predict the minimum transport boundary for dense-phase pneumatic conveying of powders.

CHAPTER 4: Development of Validated Models for Minimum Transport Boundary

Previous investigations (Chapter 3) to examine the scale-up accuracy and stability of the different "existing" models for minimum transport boundary (Rizk, 1976 - Mallick et al. 2011) by comparing the predicted and experimental minimum conveying velocities for two samples of fly ash (Wypych et al., 2005), and ESP dust (Wypych et al., 2005) have shown that the models generally can provide significant inaccuracy under significant scale-up conditions of diameter and/or length. Hence, there is a need for studies to be carried out towards developing accurate modelling and scaling up of minimum transport boundary.

4.1 Modelling minimum transport boundary

Based on the previous investigations (Chapter 3) we can conclude:

(i) The minimum conveying requirement increases with an increase in pipe-diameter;

(ii) At higher values of m*, the minimum conveying requirement decreases.

To take into account the effect of pipe diameter and m*, minimum transport boundary is represented as: $f\left(Fr_{min} = \frac{V_{min}}{\sqrt{gD}}, m^*\right) = 0$ (4.1)

Traditionally, the Froude Number is a dimensionless parameter representing the ratio of the inertia force on an element of fluid to the weight of the fluid element (i.e. the inertial force divided by gravitational force), and has been used in open channel flow and wave and surface behavior calculations in particular.

In the context of minimum transport boundary, the Froude number for a given powder can be considered to represent the inertial (driving) forces needed for a certain gravitational force (or “mixture” weight or solids loading). Equation 4.1 can be written as:

$$Fr_{min} = K(m^*)^{\alpha} \tag{4.2}$$

The values of ‘K’ and ‘α’ were determined using test data of minimum transport boundary of the shorter and/or smaller pipeline, such as 69 mm I.D. × 168 m test rig; see the PCC for fly ash (Wypych et al., 2005) (see Figure 4.1 as a typical example). PCC for ESP dust (Wypych et al., 2005) for the 69 mm I.D. × 168 m test rig is already shown in Figure 3.4. Similarly PCC for cement (Mills, 2004a) conveyed through 53 mm I.D. × 101 m long pipe and for fly ash (Pan, 1992) conveyed through 52.5 mm I.D. × 102 m long pipe, can be found in Chapter 3 (see Figure 3.7 and Figure 3.9).

Table 1 lists the different values of ‘K’, ‘α’ obtained using least square methods and the corresponding R^2 values. The high values of R^2 indicate good fit. Figure 4 shows a typical plot of the m* versus Fr_i for fly ash (Wypych et al., 2005). Similar plots have been seen for ESP Dust (Wypych et al., 2005), Cement (Mills, 2004) and Fly ash (Pan, 1992) which are shown in Figure A1.4, A1.5 and A1.6 respectively of Appendix.

Table 4.1: Minimum transport boundary models for different powders

Product	**K**	**α**	$\mathbf{R^2}$
Fly ash (Wypych et al., 2005),	5.41	-0.11	0.99
ESP Dust (Wypych et al., 2005),	17.49	-0.37	0.95
Cement (Mills, 2004)	7.66	-0.13	0.99
Fly ash (Pan, 1992)	8.63	-0.22	0.99

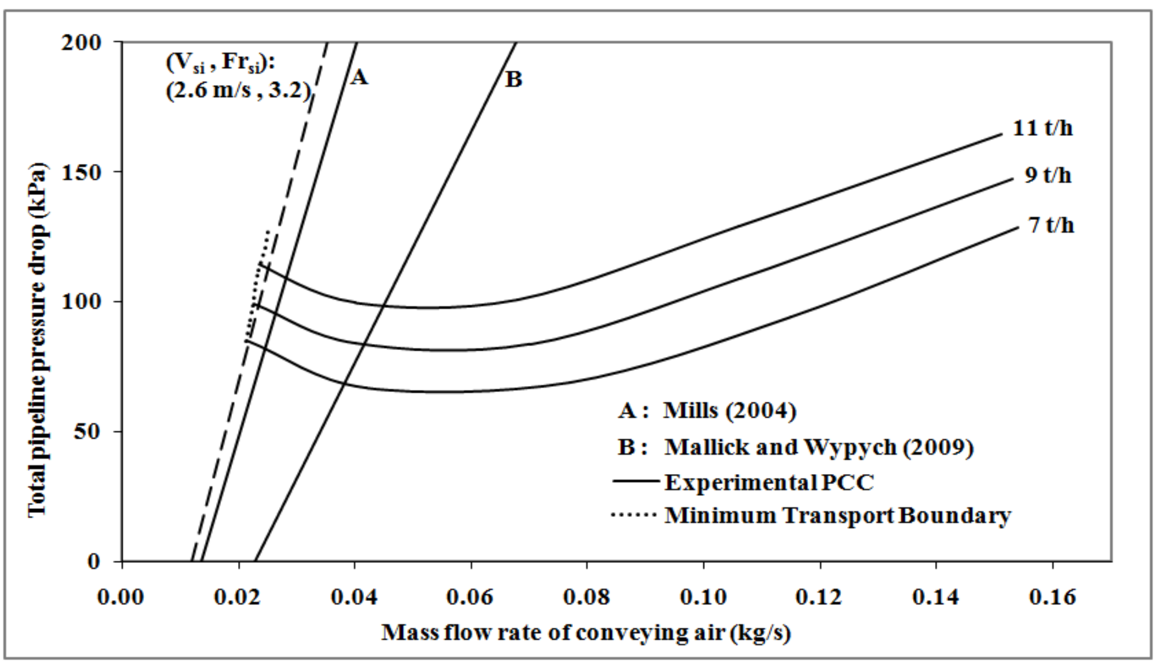

Figure 4.1: Experimental minimum transport boundary, fly ash (Wypych et al., 2005),

69 mm I.D. × 168 m long pipe

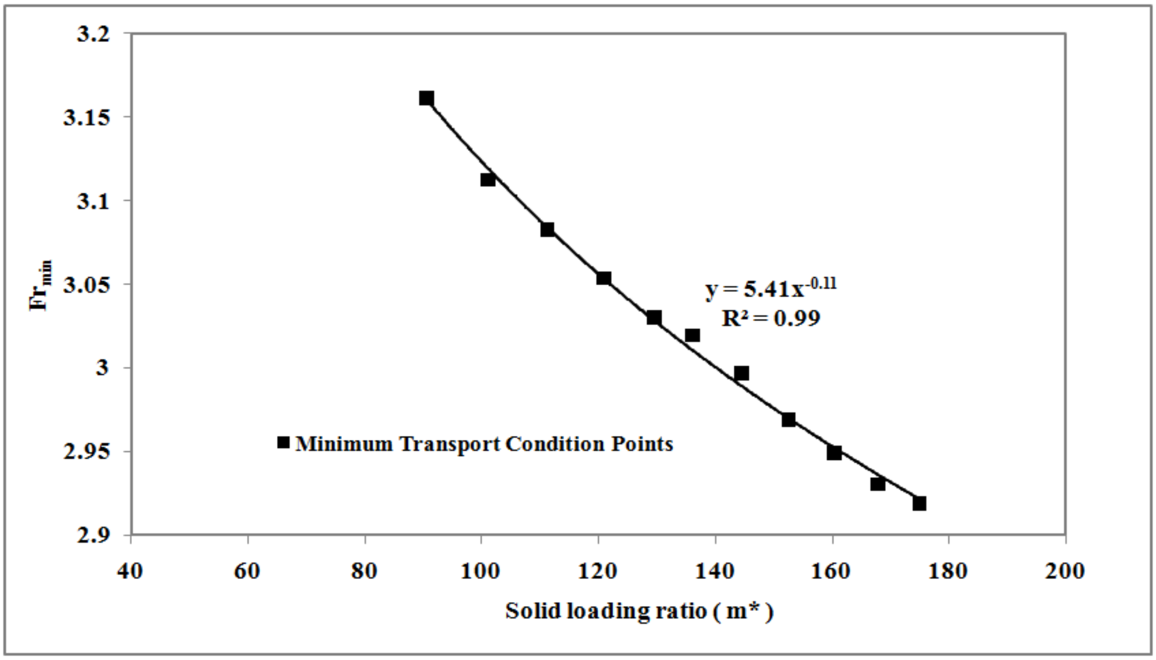

Figure 4.2: Fr_{min} versus m* for experimental minimum transport boundary, fly ash (Wypych et al., 2005), 69 mm I.D. × 168 m long pipe

4.2 Scale-up validation of models

The above models (Table 4.1) have been validated for their scale-up accuracy by using them to predict the minimum transport boundary for larger and longer diameter pipes. Figure 4.3 and 4.4 shows the predictions for fly ash; model generated using the minimum transport boundary data of 69 mm I.D. × 168 m long test rig [$Fr_i = 5.41(m*)^{-0.11}$] has been scaled up for 105 mm I.D. × 168 m and 69 mm I.D. × 554 m long test rigs. Lines corresponding to V_i = 3 and Fr_i = 6 have been superimposed on the PCC. Dotted points are the experimental minimum transport boundaries and the dashed lines indicate the right-most points of the experimental minimum transport boundaries (in all Figures from 4.1 to 4.9).

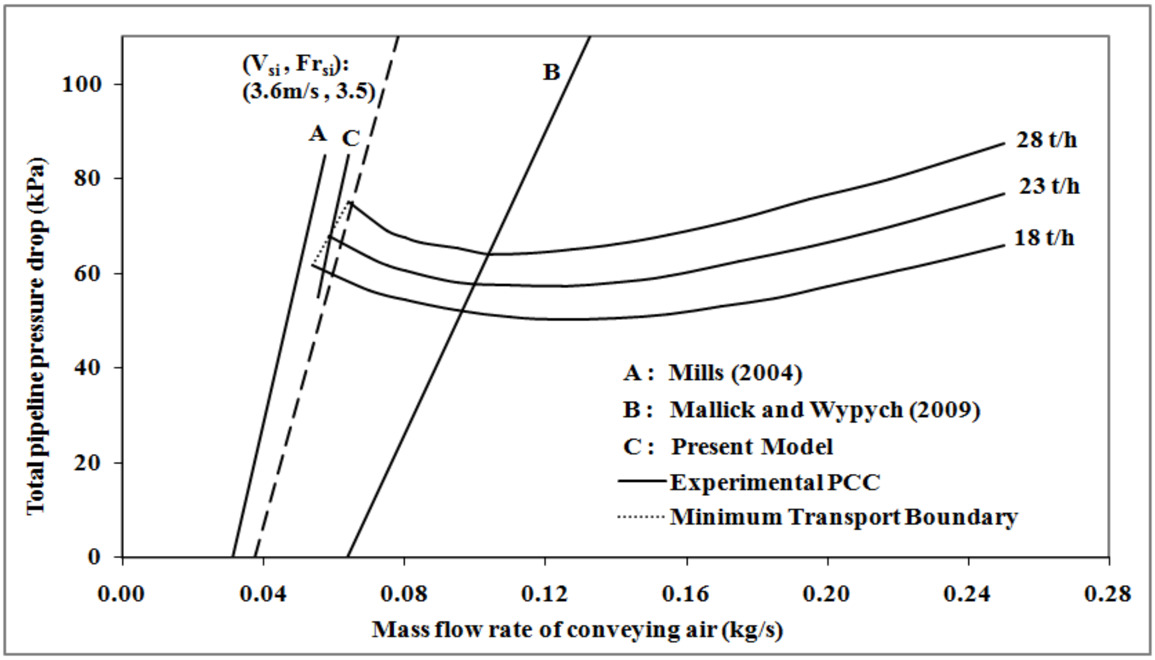

Figure 4.3: Experimental versus predicted minimum transport boundary, fly ash (Wypych et al., 2005), 105 mm I.D. × 168 m long pipe

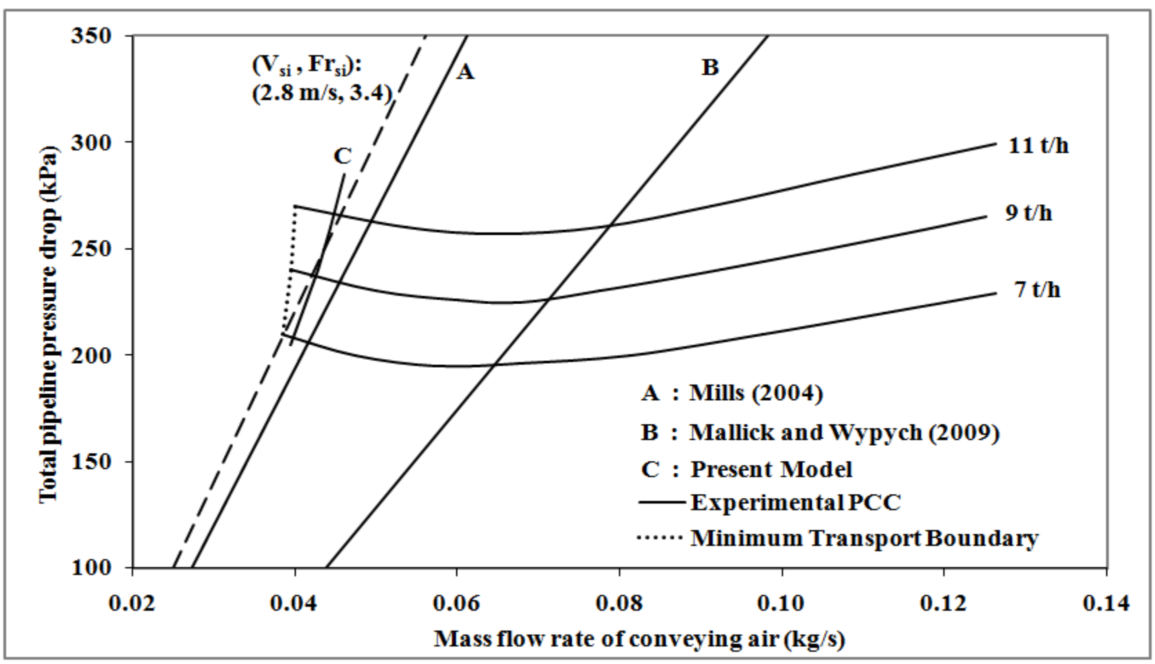

Figure 4.4: Experimental versus predicted minimum transport boundary, fly ash (Wypych et al., 2005), 69 mm I.D. × 554 m long pipe

Results (Figure 4.3 and 4.4) show that for both diameter and lenth scale-up, the present model predicts the experimental minimum transport boundary accurately, whereas $Fr_i = 6$ line shows considerable overpredictions (i.e. higher conveying velocity, that would result in lager gas flows and energy consumption). Figure 4.5 and 4.6 shows the predictions for ESP dust; model generated using the minimum transport boundary data 69 mm I.D. × 168 m long test rig [$Fr_i = 17.49(m*)^{-0.37}$] has been scaled up for 105 mm I.D. × 168 m and 69 mm I.D. × 554 m long test rigs.

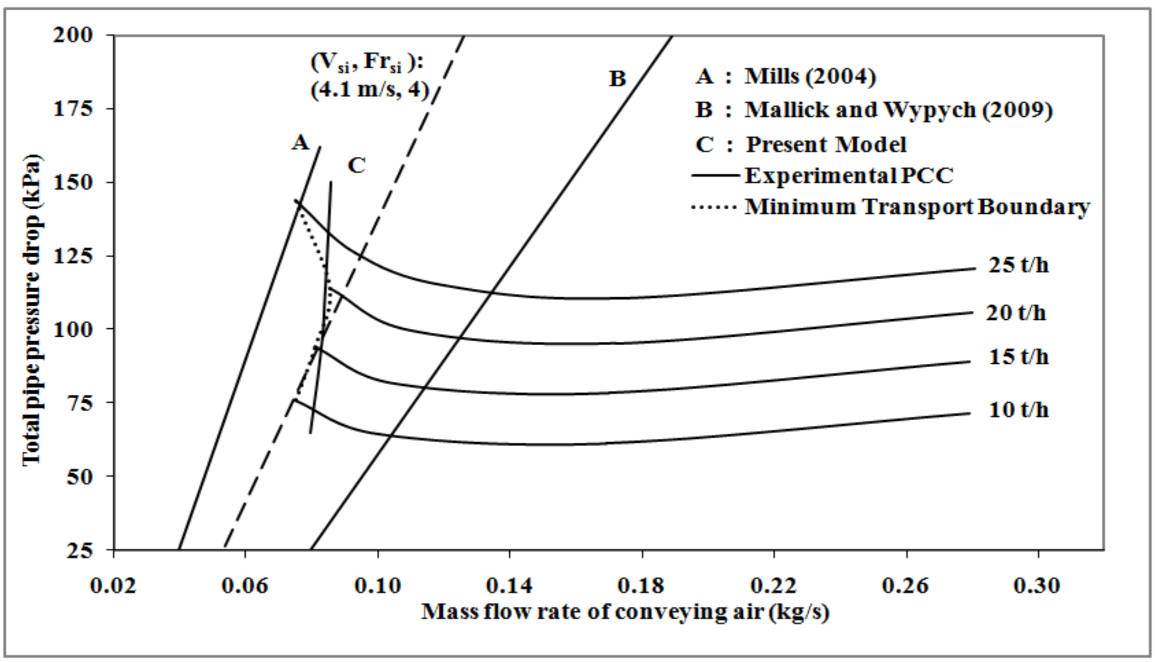

Figure 4.5: Experimental versus predicted minimum transport boundary,

ESP dust (Wypych et al., 2005) 105 mm I.D. × 168 m long pipe

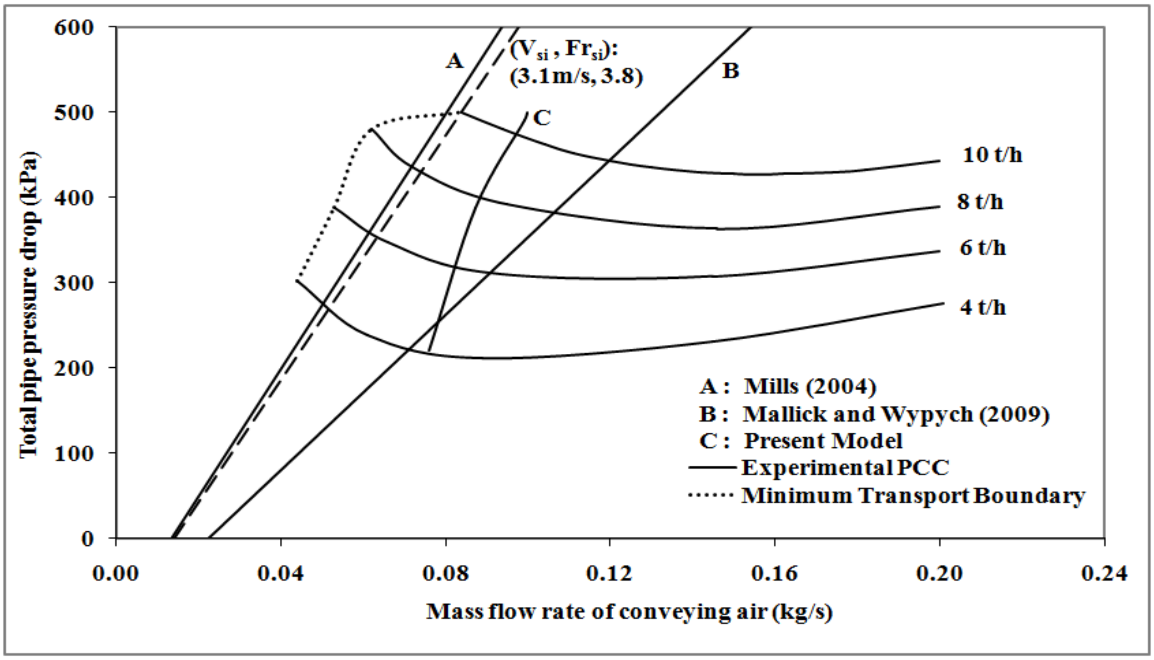

Figure 4.6: Experimental versus predicted minimum transport boundary, ESP dust (Wypych et al., 2005), 69 mm I.D. × 554 m long pipe

Results (Figure 4.5 and 4.6) show that the present model predicts the experimental minimum transport boundary quite well for diameter scale-up (105 mm I.D. × 168 m long pipe), whereas, $Fr_i = 6$ line again shows considerable over-predictions. The model, however, shows some over-predictions for the length scale-up, though the amount of over-prediction is lower compared to the $Fr_i = 6$ line, thus showing improvement over the existing method.

Figure 4.7 shows the predictions for cement (Mills, 2004); model generated using the minimum transport boundary data 53 mm I.D. × 101 m long test rig (Figure 3.7) [$Fr_i = 7.66(m^*)^{-0.13}$] has been scaled up for 81 mm I.D. × 95 m long test rigs.

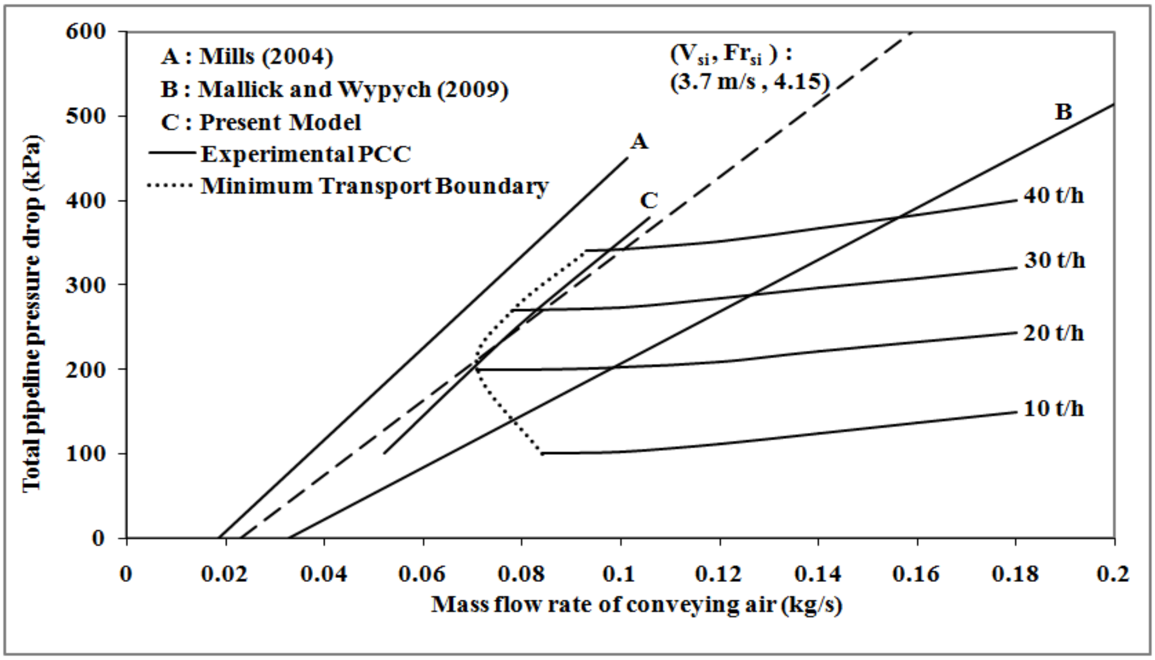

Figure 4.7: Experimental versus predicted minimum transport boundary, cement (Mills, 2004), 81 mm I.D. × 95 m long pipe

Results (Figure 4.7) show that the present model predicts the experimental minimum transport boundary quite well for diameter scale-up (81 mm I.D. × 95 m long pipe) for 20 to 40 t/h. The experimental minimum transport point is shifted to the right (towards higher air flow rate); this may be due to the use of top discharge blow tank by Mills (2004). Again, Fr_i = 6 line shows considerable over-predictions. Figure 4.8, 4.9 and 4.10 shows the predictions for fly ash (Pan, 1992); model generated using the minimum transport boundary data 52.5 mm I.D. × 102 m long test rig [$Fr_i = 8.63(m*)^{-0.22}$] has been scaled up for length scale-up (52.5 mm I.D. × 135 m long test rig) and for simultaneous diameter and length scale-up (69 mm I.D. × 172 m long test rig) and (69 mm I.D. × 554 m long test rig).

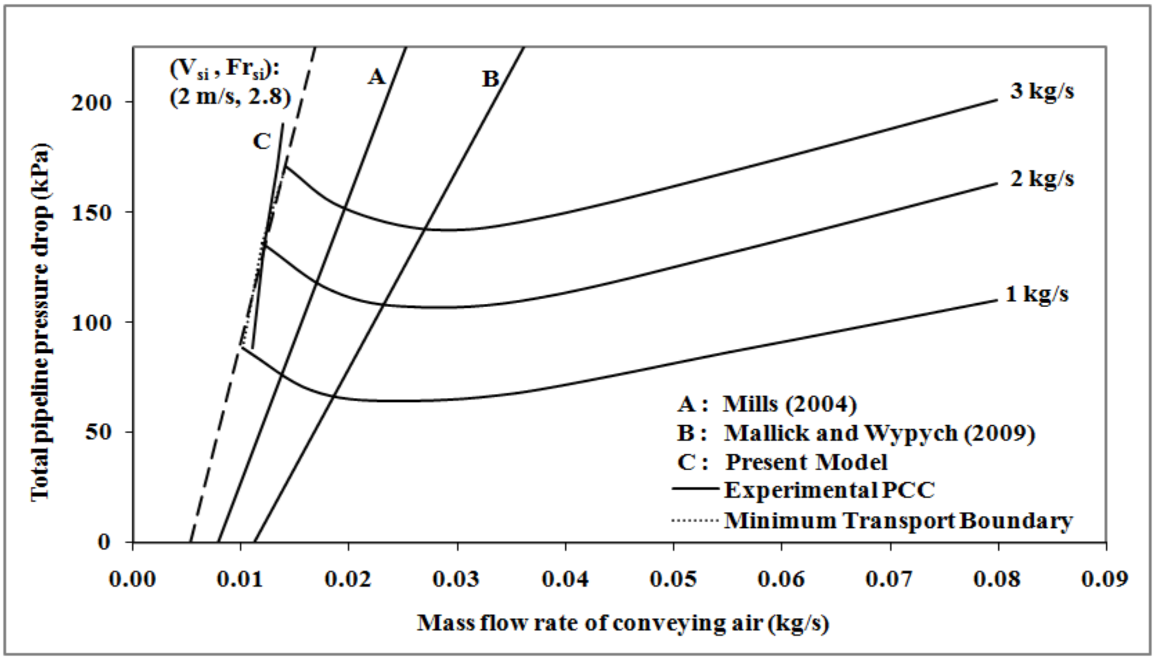

Figure 4.8: Experimental versus predicted minimum transport boundary,

fly ash (Pan,1992), 52.5 mm I.D. × 135 m long pipe

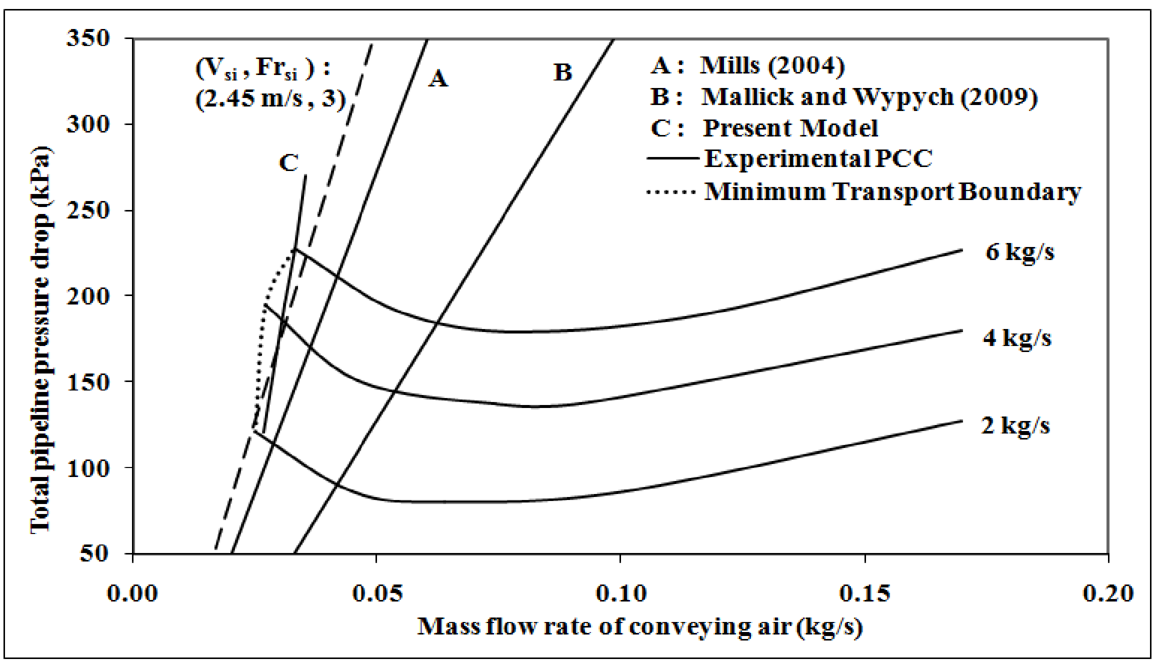

Figure 4.9: Experimental versus predicted minimum transport boundary,

fly ash (Pan,1992), 69 mm I.D. × 172 m long pipe

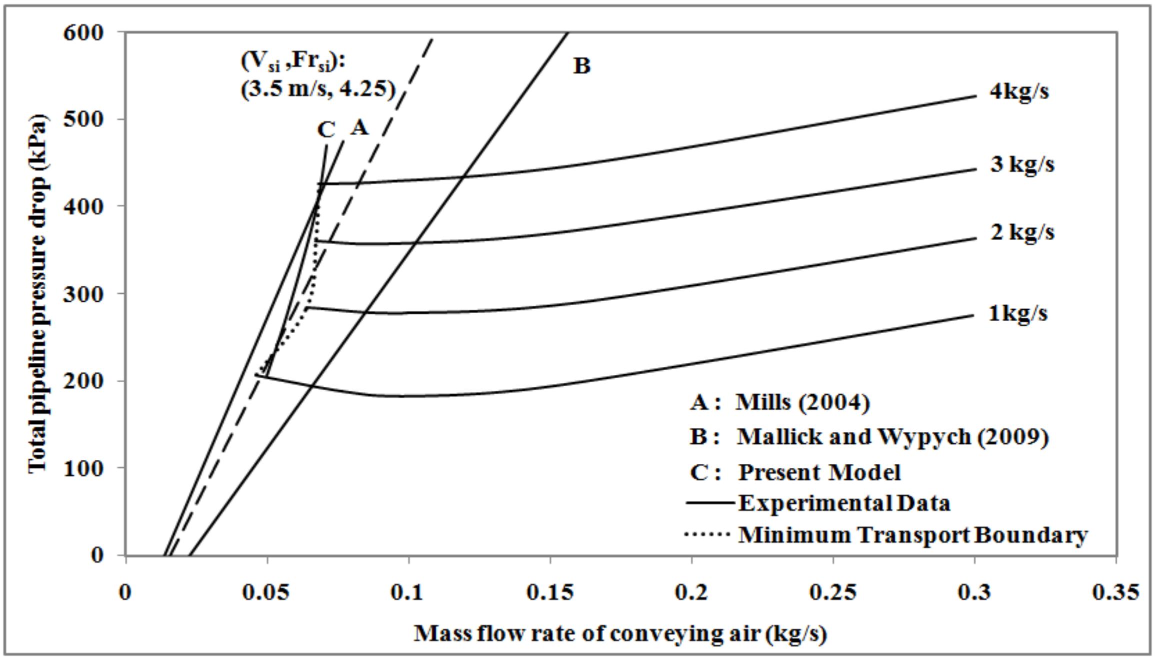

Figure 4.10: Experimental versus predicted minimum transport boundary,

fly ash (Pan,1992), 69 mm I.D. × 554 m long pipe

Results (Figures 4.8, 4.9 and 4.10) show that the present model predicts the experimental minimum transport boundary quite well for both diameter scale-up (52.5 mm I.D. × 135 m long pipe) and for diameter and length scale-up (69 mm I.D. × 172 m long test rig). Once again, the Fr_i = 6 line shows considerable over-predictions. Table 4.2 provides error analysis (relative error) of the models. It can be seen that the model is within 6.85% accuracy level, expect for the 69 mm I.D. × 554 m long pipe with ESP dust. However, over-prediction is a relatively less dangerous situation than under-prediction, which would lead to potential minimum transport.

Table 4.2: Relative errors in model predictions

Product	**D** (mm)	**L** (m)	$V_{i, exp}$ (m/s)	$V_{i, pr}$ (m/s)	$\frac{V_{i,pr} - V_{i,\exp}}{V_{i,\exp}} \times 100\%$
Fly ash (Wypych et al., 2005)	105 69	168 554	3.65 2.8	3.4 2.82	+ 6.85% -0.7%
ESP Dust (Wypych et al.,2005)	105 69	168 554	4.1 3.1	4.1 4	+0% + 29%
Cement (Mills, 2004)	81	95	3.7	3.72	+0.54%
Fly ash (Pan, 1992)	52.5 69	135 172	2 2.45	2 2.45	+0% +0%
'+' stands for over-prediction '-' stands for under-prediction					

4.3 Discussion

A test design procedure has been developed using dimensionless solids loading ratio and Froude number at pipe inlet terms for accurately scale-up minimum transport boundary. The Froude number term is intended to accommodate for the pipe diameter effect (as larger diameter pipes tends to have higher minimum conveying velocity requirements) and the higher value of solids loading ratio is intended to address the effect of pipe length. The developed model (in power function format) has generally provided good predictions under different diameter and length scale-up conditions (for various products).

CHAPTER 5: Development of a new unified criterion for minimum transport boundary and its validation

It may be not possible every time to perform a pilot plant test for prediction of minimum transport boundary as pilot plant tests require a great infrastructure, large time and huge costs. Efforts have been done to establish unified criteria to represent minimum transport condition for a wide range of products and pipelines, are included in this chapter.

5.1 Modelling new unified criterion for minimum transport boundary

It was found that for the cumulative experimental minimum conveying data point of fly ash (Wypych et al. 2005), ESP dust (Wypych et al. 2005) and fly ash (Pan, 1992), minimum Froude number and corresponding solids loadings m* in a power function format strong relationship. This could be clearly seen in the Figure 5.1which is given below:

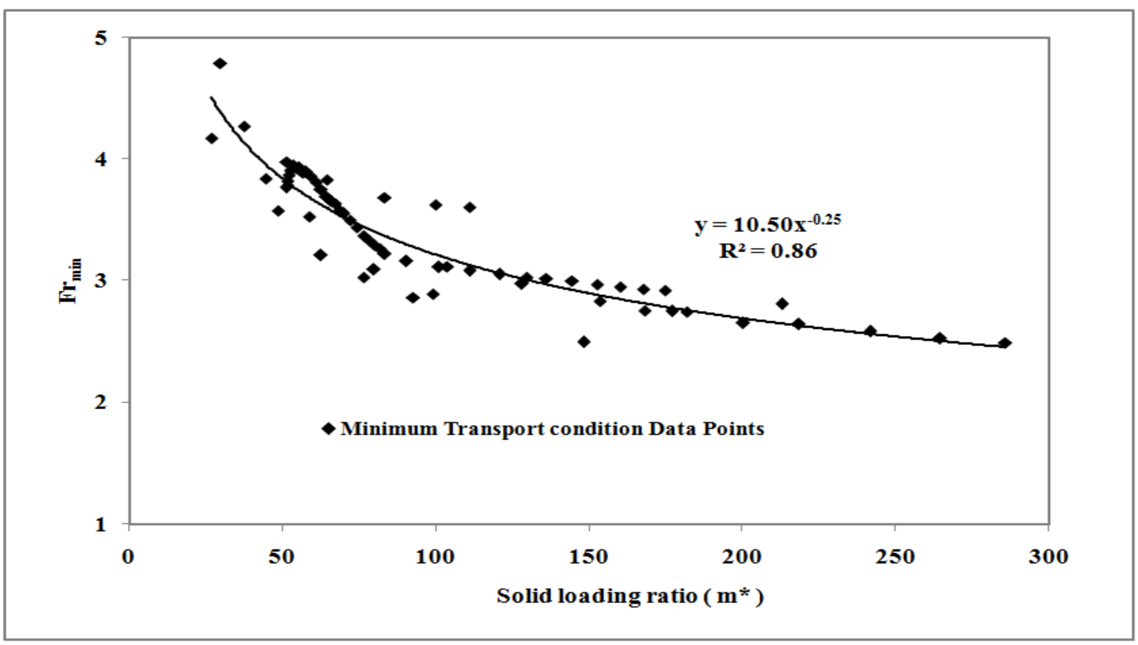

Figure 5.1: Fr_{min} versus m* for cumulative experimental minimum transport boundary, fly ash (Wypych et al. 2005), ESP dust (Wypych et al. 2005) and fly ash (Pan, 1992) for all pipeline configurations

The fitted power curves for this relationship is given by equation (5.1) showed high degrees of fitting (R^2=0.86). Hence following relation is introduced

$$Fr_{min} = 10.50 \cdot m^{*-0.25} \quad (5.1)$$

5.2 Validation of new unified criterion

For the purpose of verifying the present unified model (shown by equation 5.1), the various test data from which this model is evolved are used. The results are shown from Figure 5.2 to 5.11 and Table 5.1.

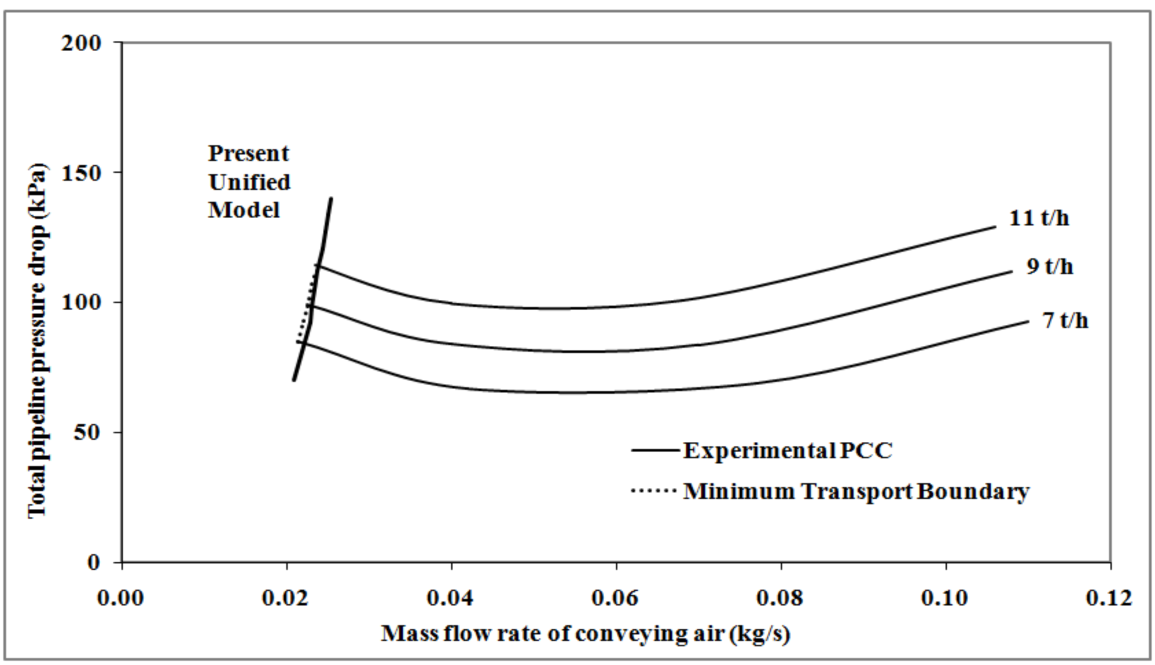

Figure 5.1: Experimental versus predicted MTB for fly ash (Wypych et al. 2005)

for 69 mm I.D. × 168 m long pipe

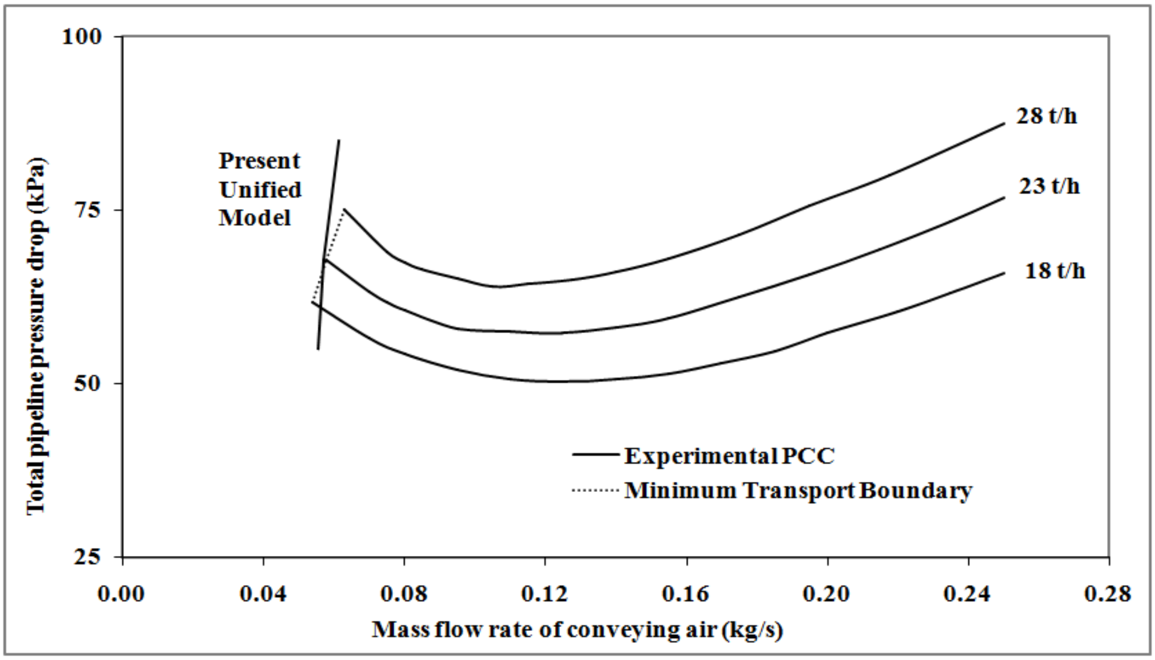

Figure 5.2: Experimental versus predicted MTB for fly ash (Wypych et al. 2005)

for 105 mm I.D. × 168 m long pipe

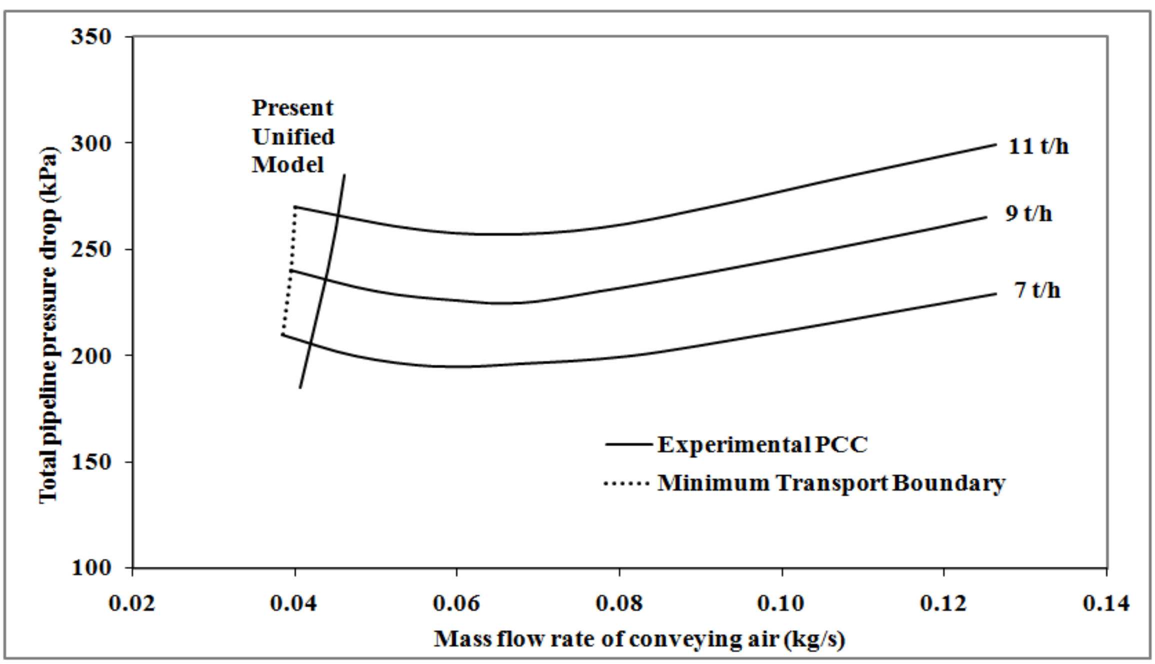

Figure 5.3: Experimental versus predicted MTB for fly ash (Wypych et al. 2005)

for 69 mm I.D. × 554 m long pipe

For fly ash (Wypych et al. 2005), the results show that for 69 mm I.D. × 168 m long pipe (see Figure 5.1), the predicted minimum transport boundary is same as that of experimentally observed boundary. Whereas in case of 105mm I.D. × 168 m long pipe the predictions are good but the predicted slope is relatively higher than the actual slope of MTB. Exact prediction is seen for m_s = 23 t/h (Figure 5.2). However for longer pipeline (69 mm I.D. × 554 m long), shown in Figure 5.3, there is slight over prediction which is acceptable as it ensures the safe optimal conveying. This over prediction may be due relatively high initial air density.

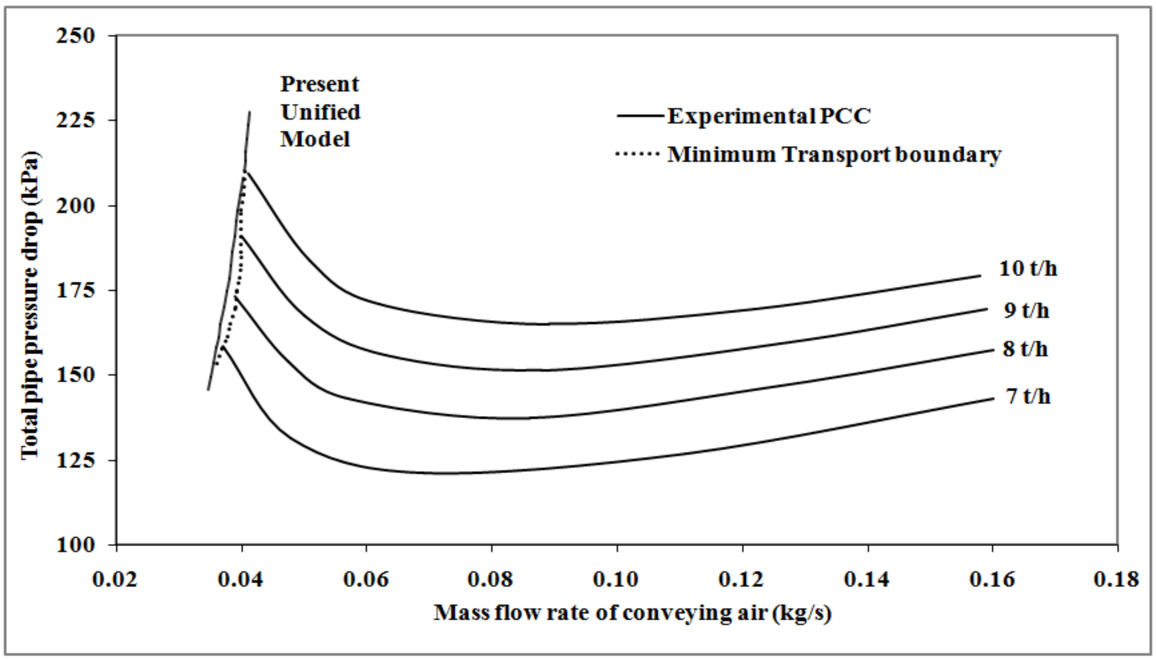

Figure 5.4: Experimental versus predicted MTB for ESP dust (Wypych et al. 2005) for 69 mm I.D. × 168 m long pipe

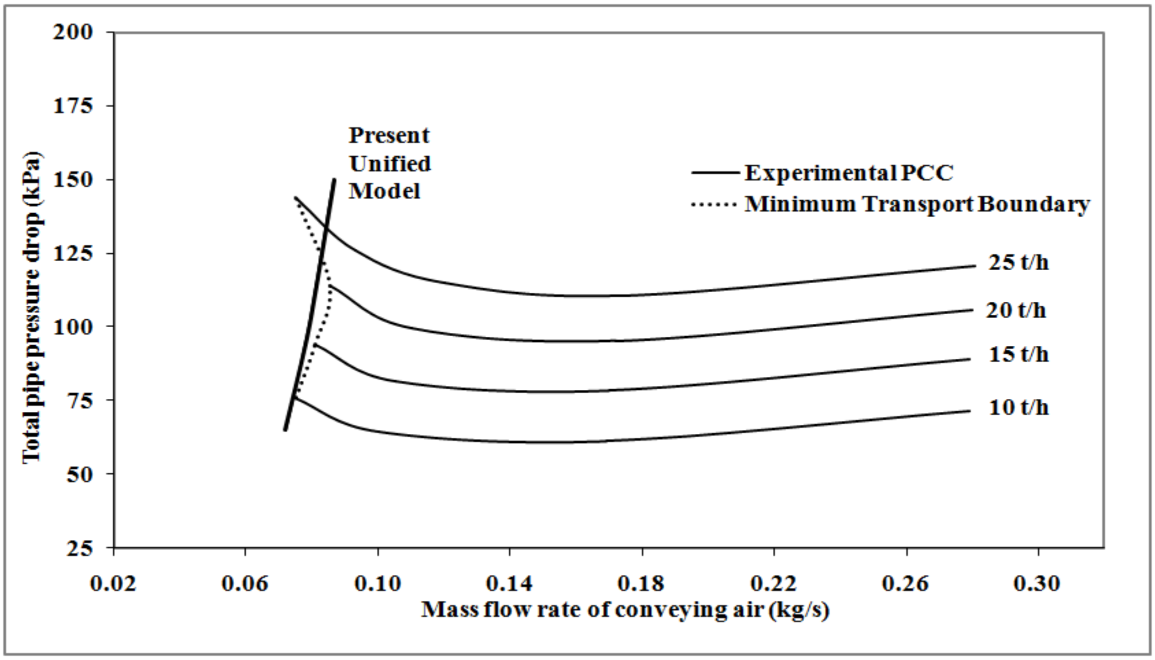

Figure 5.5: Experimental versus predicted MTB for ESP dust (Wypych et al. 2005) for 105 mm I.D. × 168 m long pipe

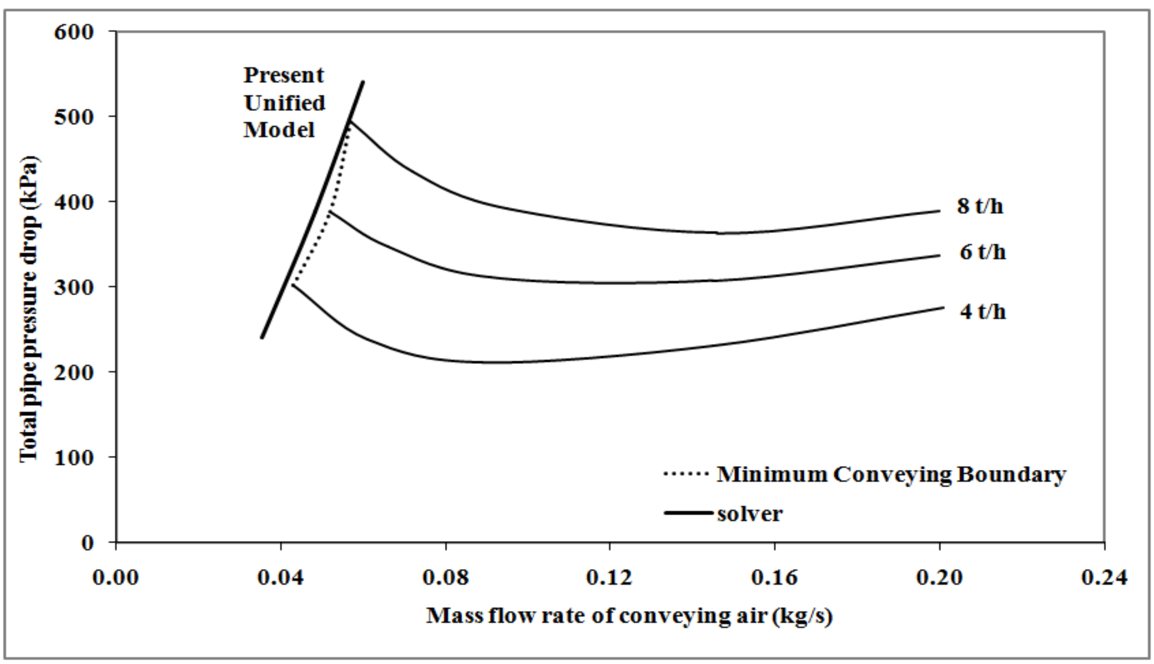

Figure 5.6: Experimental versus predicted MTB for ESP dust (Wypych et al. 2005) for 69 mm I.D. × 554 m long pipe

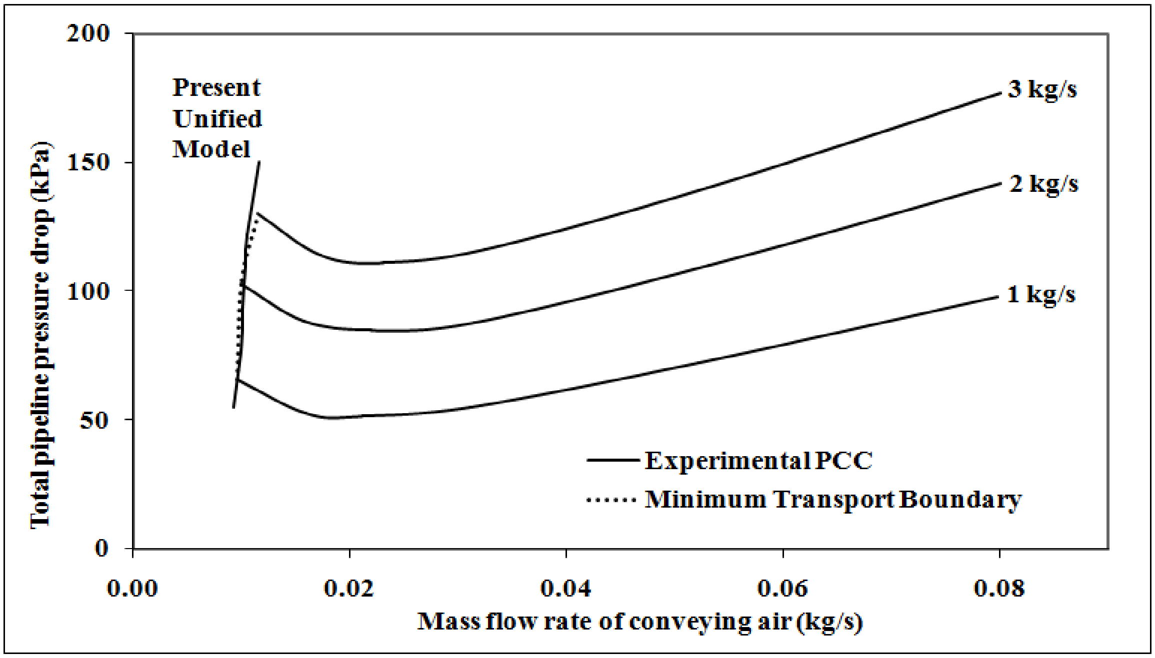

Figure 5.7: Experimental versus predicted MTB for fly ash (Pan, 1992)

for 52.5 mm I.D. × 102 m long pipe

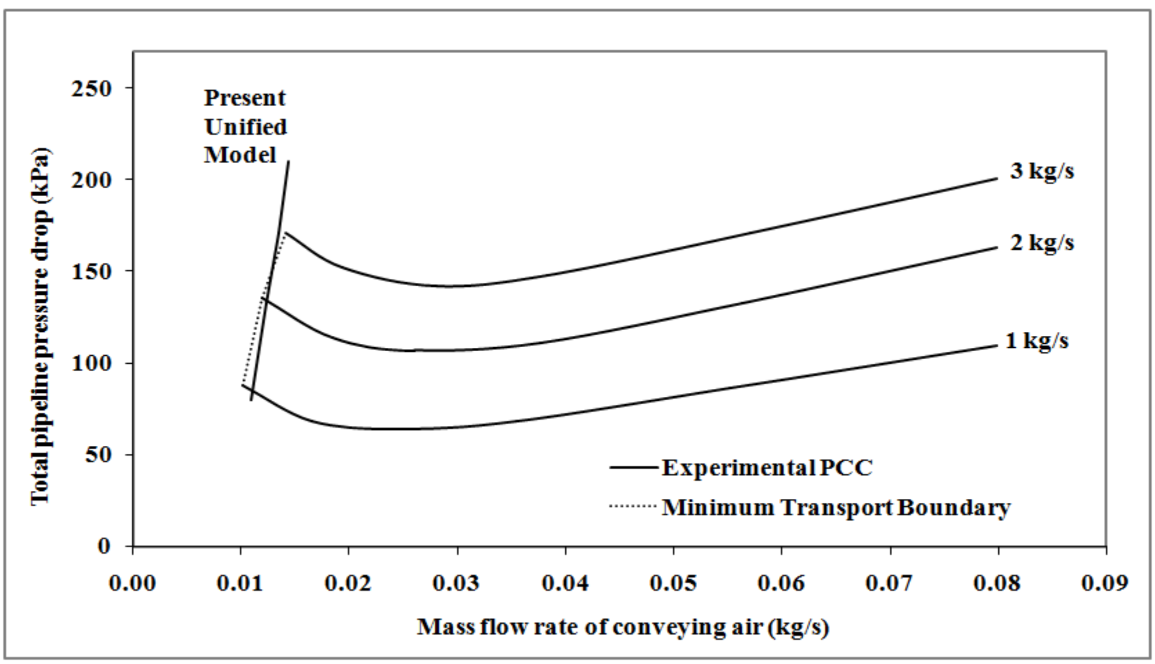

Figure 5.8: Experimental versus predicted MTB for fly ash (Pan, 1992)

for 52.5 mm I.D. × 135 m long pipe

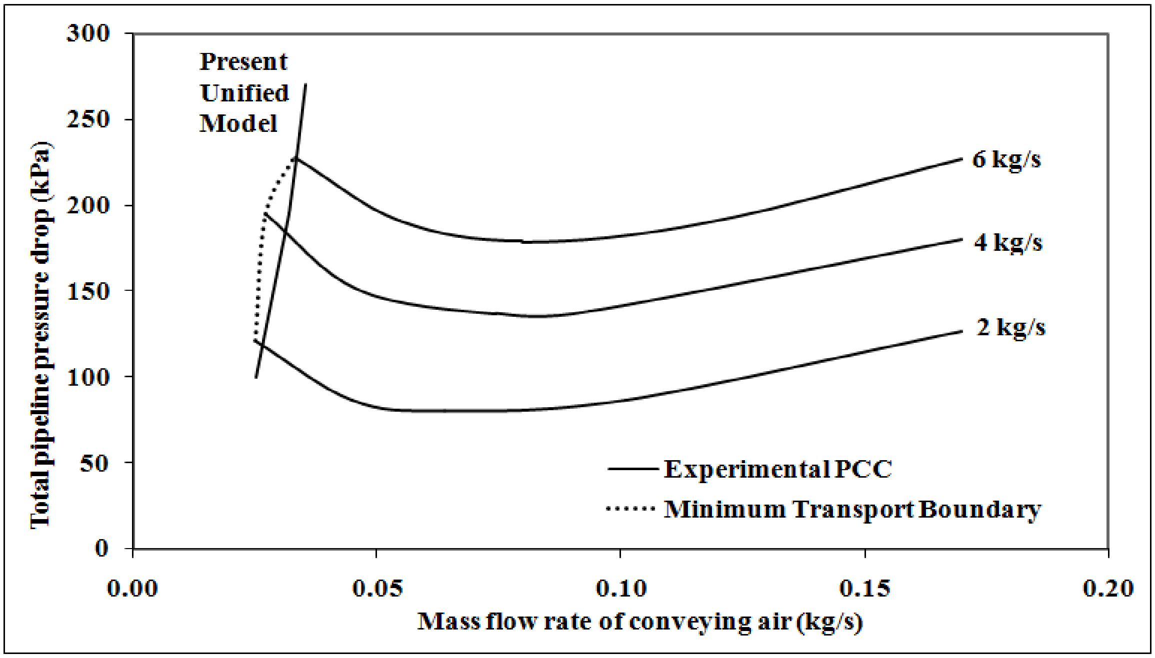

Figure 5.9: Experimental versus predicted MTB for fly ash (Pan, 1992)

for 69 mm I.D. × 168 m long pipe

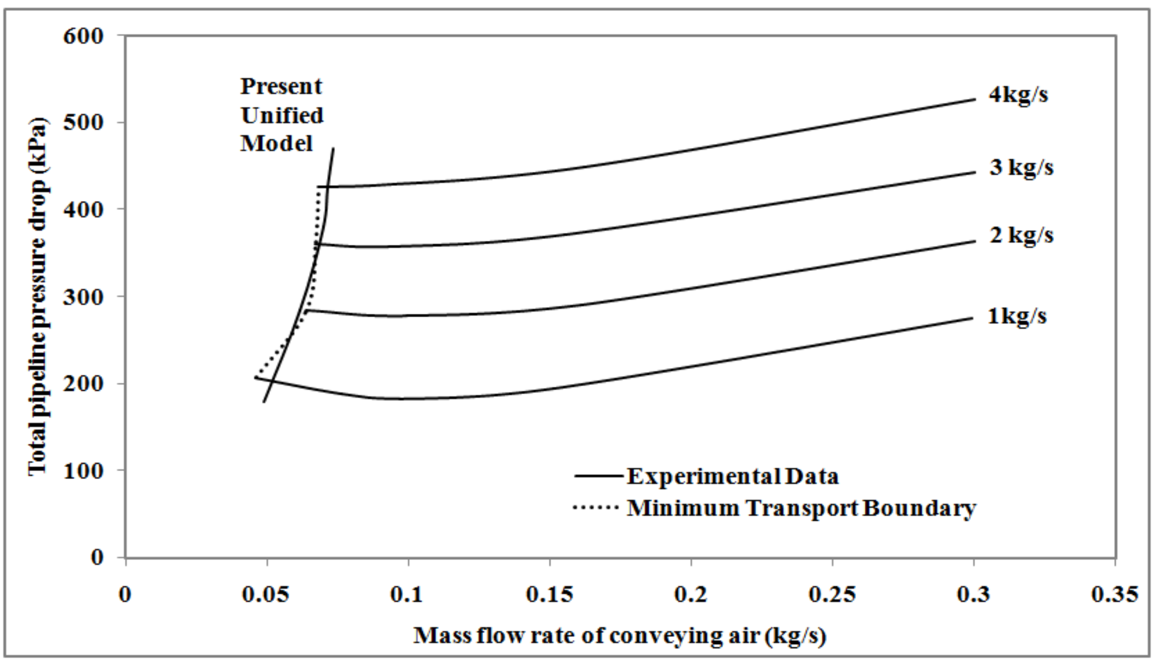

Figure 5.11: Experimental versus predicted MTB for fly ash (Pan, 1992)

for 69 mm I.D. × 554 m long pipe

Results (Figure 5.2 to 5.11) show that present unified model gives quite well predictions for all the experimental test data for ESP dust (Wypych et al. 2005) as well as fly ash (Pan, 1992).

5.3 Verification on other experimental data

To verify the reliability of present unified model, it is very important to further check its accuracy for other experimentation data. So, the work is extended with the help of various other product and pipeline data obtained from the previous work of other researchers.

Test data (PCC) from the following products has been used for this analysis.

- Cement (Mills 2004)
- White powder (Mallick, 2010)
- Fly ash Different samples (Pan and Wypych, 1998)
- Different power plant fly ash (Wypych, 1989)
- Pulverised coal (Wypych, 1989)
- Cement (Wypych and Arnold 1984)

Some product properties, pipeline lengths and diameters of above said data are provided in Table 5.1. These PCC were re-plotted, with line corresponding to minimum Froude number at pipeline inlet superimposed on PCC. These are shown in Figures 5.12 to 5.30. It is to be noted that the left most points on the solids flow lines in the original source of these PCC are considered to represent the experimental minimum transport condition line for the purpose of this work.

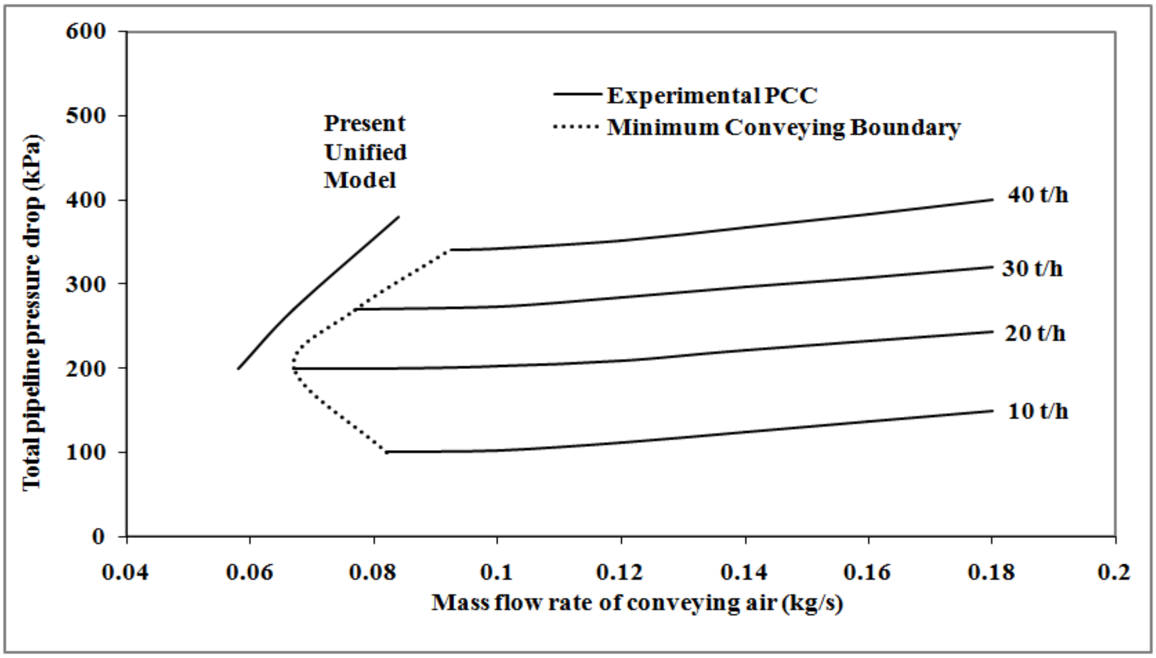

Figure 5.12: Experimental versus predicted MTB for cement (Mills, 2004a)

for 81 mm I.D. × 95 m long pipe

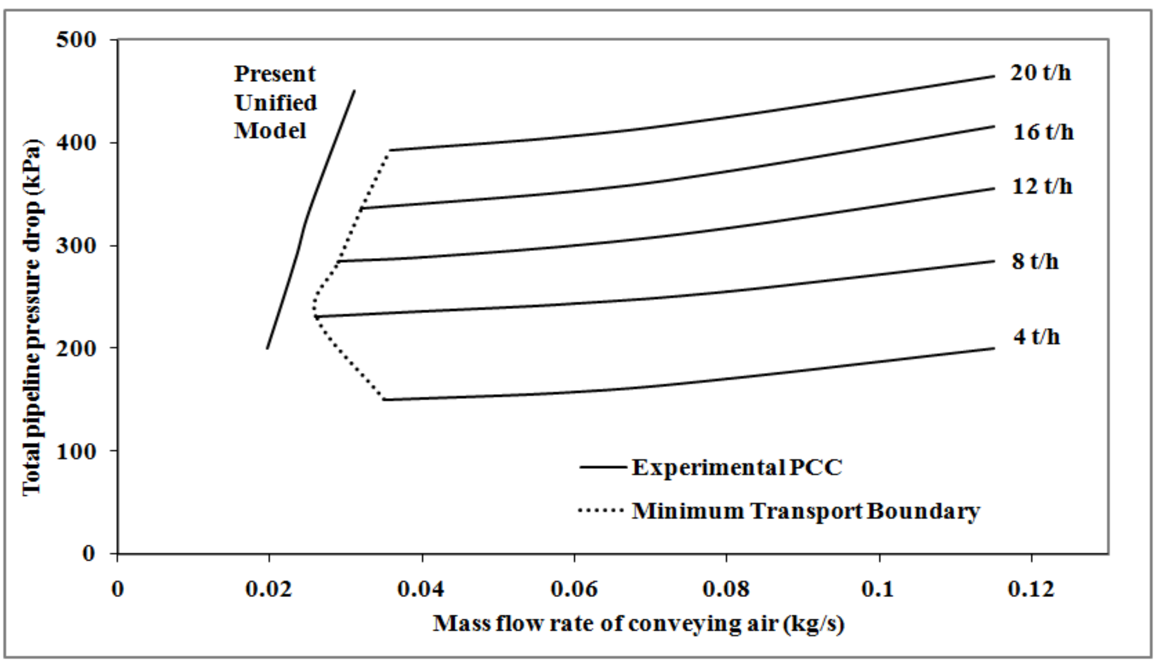

Figure 5.13: Experimental versus predicted MTB for cement (Mills, 2004a)

for 53 mm I.D. × 101 m long pipe

Minimum transport criterion is further investigated on cement (Mills, 2004; Mills 2004a). The present model (equation 5.1) is giving some under predictions in this data (Figures 5.12 and 5.13). This may be because the unified model is an average model whereas cement is a heavy product with high particle and bulk density. These data has shown the dramatically changing slope of MTB for lower mass flow rates of cement. One possible reason for this may be the top discharge blow tank. As shown in Figure 5.12, from 20 to 40 t/h, the newly developed model and the actual minimum transport boundary has the same slope. Similarly in Figure 5.13 the slope is nearly same from 8 to 16 t/h. Although the present unified model under predicts the actual boundary.

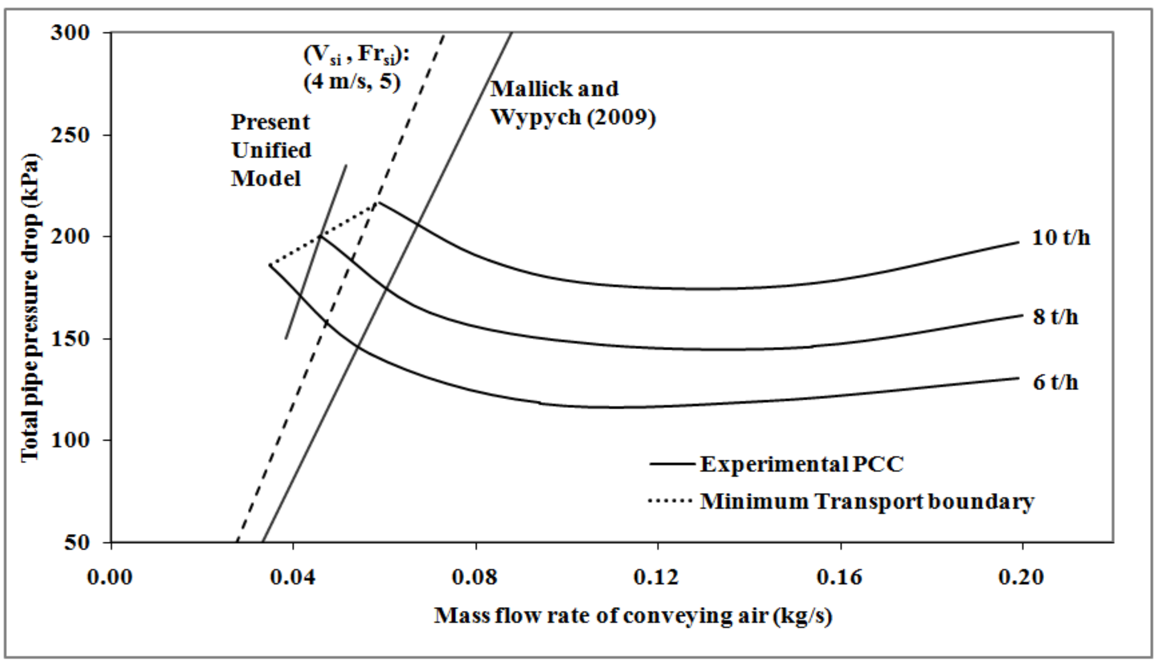

Figure 5.14: Experimental versus predicted MTB for white powder (Mallick, 2010) for 69 mm I.D. × 148 m long pipe

As shown in Figure 5.14, the present model predictions are very good and slope of predicted boundary line is slightly higher. The prediction is exact at m_s = 8 t/h.

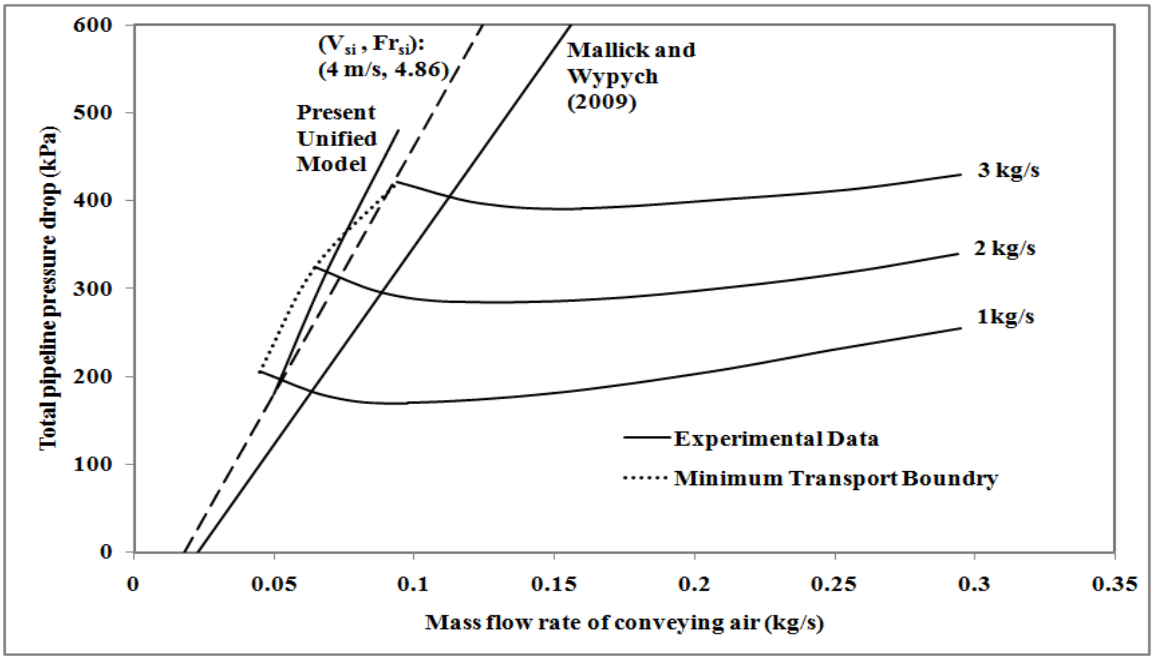

Figure 5.15: Experimental versus predicted MTB for fly ash (sample 1)

(Pan and Wypych, 1998) for 69 mm I.D. × 554 m long pipe

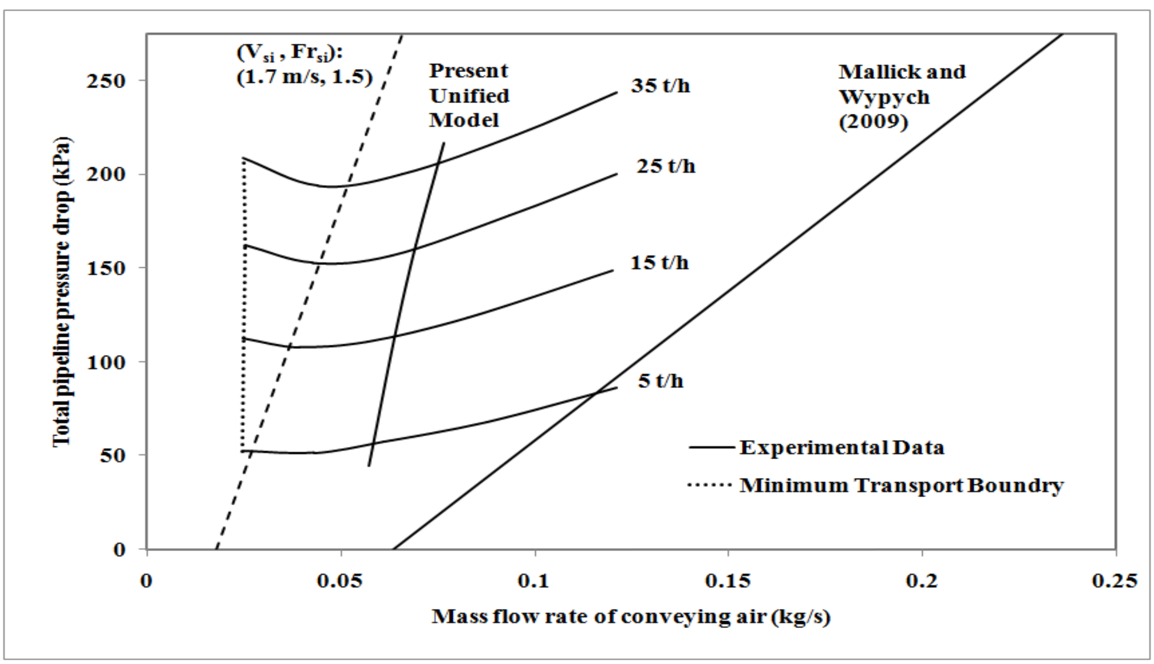

Figure 5.16: Experimental versus predicted MTB for fly ash (sample 2)

(Pan and Wypych, 1998) for 105 mm I.D. × 168 m long pipe

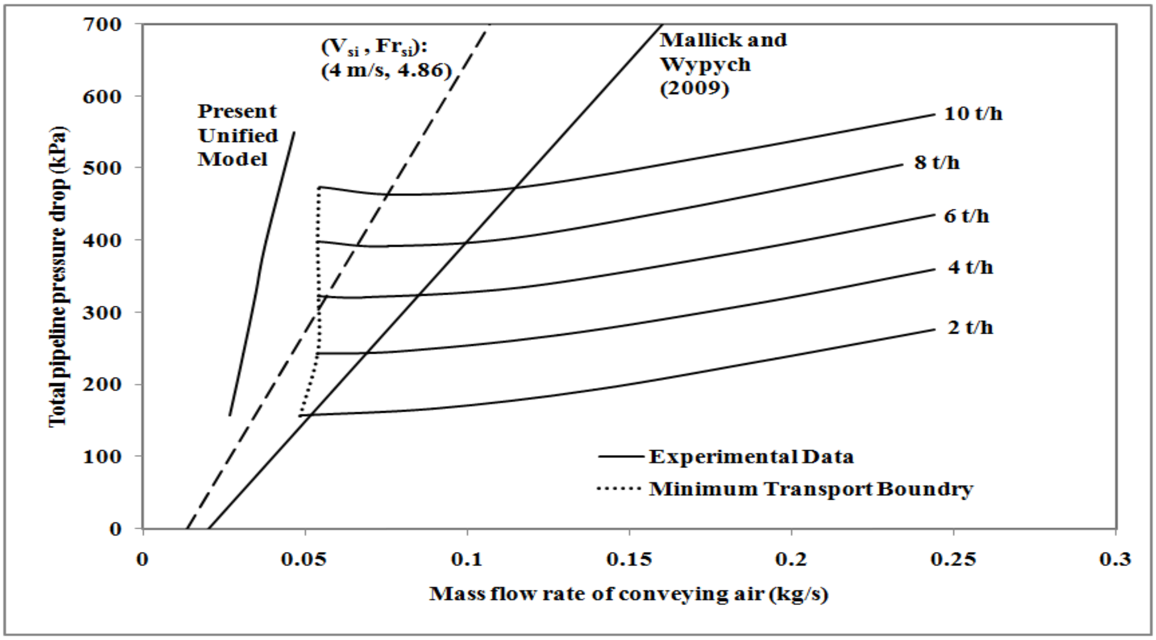

Figure 5.17: Experimental versus predicted MTB for fly ash (sample 3)

(Pan and Wypych, 1998) for 69/81 mm I.D. × 945 m long step-up pipe

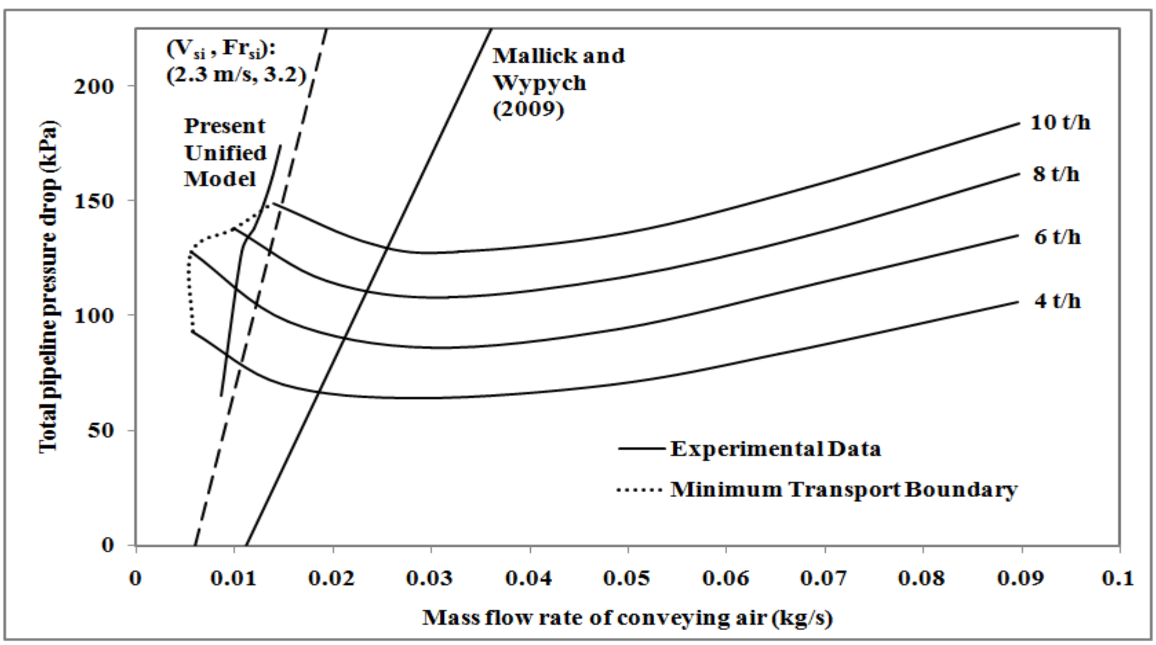

Figure 5.18: Experimental versus predicted MTB for fly ash (sample 4)

(Pan and Wypych, 1998) for 52.5 mm I.D. × 70 m long pipe

The predictions given by present unified model on different samples of fly ash (Pan and Wypych, 1998) are shown from Figure 5.15 to 5.18, are very close to the experiment minimum transport boundary. Over-predictions are seen in case of fly ash (sample 2) for 105 mm I.D. × 168 m long-pipe (Figure 5.16). Small under-predictions are seen in case of fly ash (sample 3) for 69/81 mm I.D. × 945 m long step-up pipe (Figure 5.17).

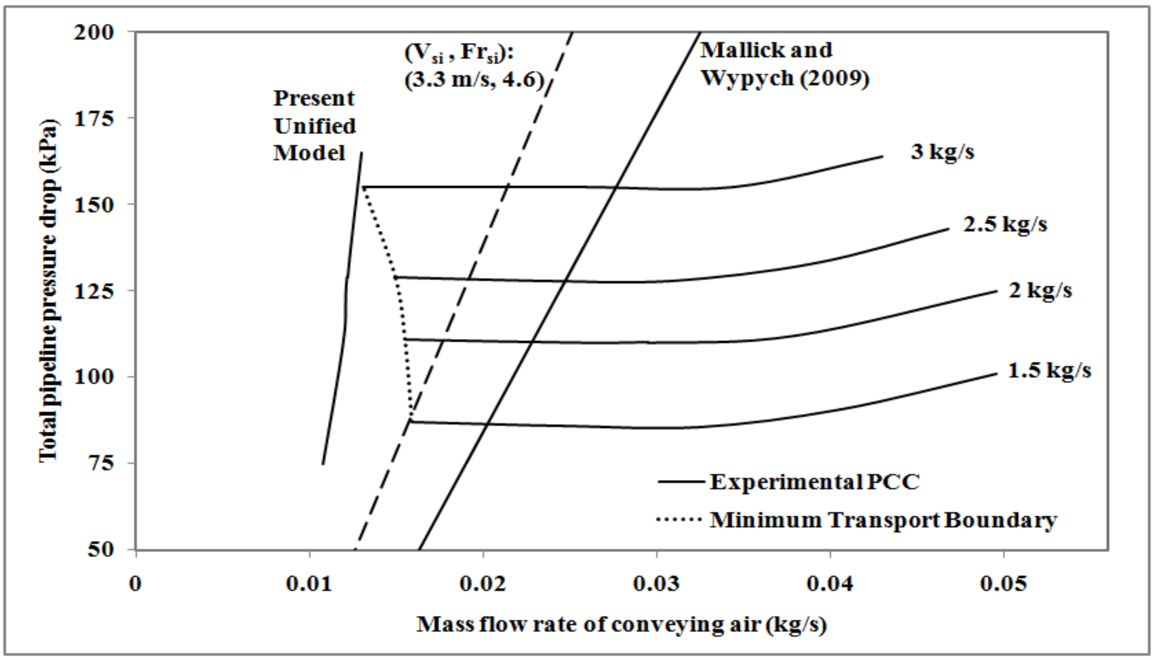

Figure 5.19: Experimental versus predicted MTB for Tallawarra fly ash (Wypych, 1989) for 52 mm I.D. × 71 m long pipe

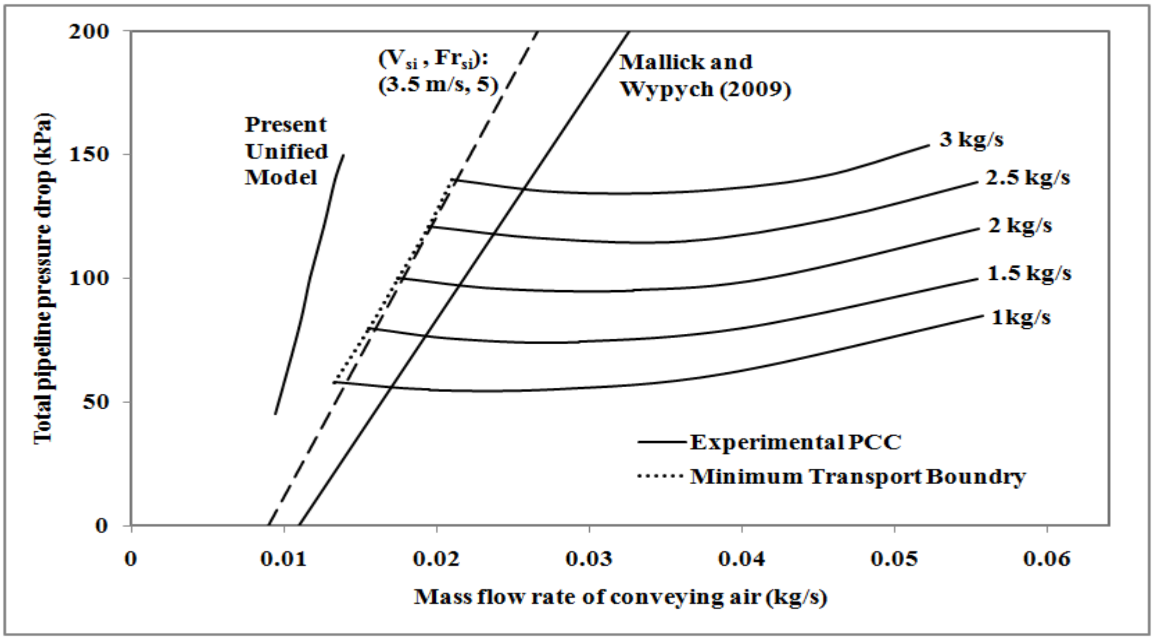

Figure 5.20: Experimental versus predicted MTB for Eraring fly ash (Wypych, 1989)

for 52 mm I.D. × 71 m long pipe

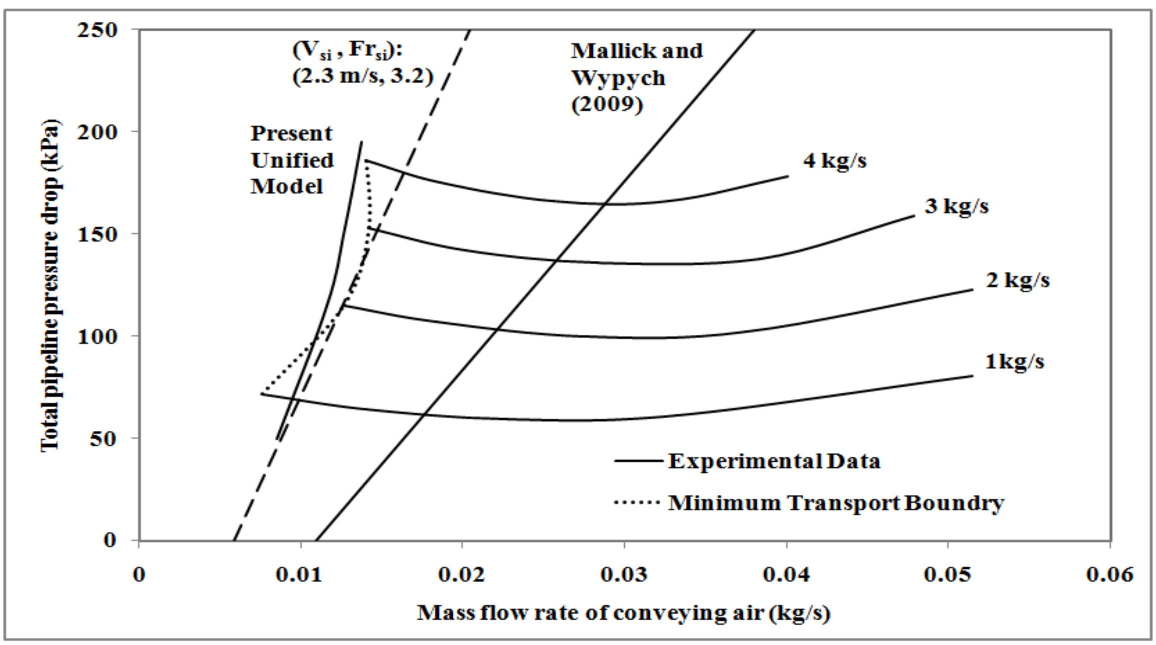

Figure 5.21: Experimental versus predicted MTB for Munmorah fly ash (Wypych, 1989)

for 52 mm I.D. × 71 m long pipe

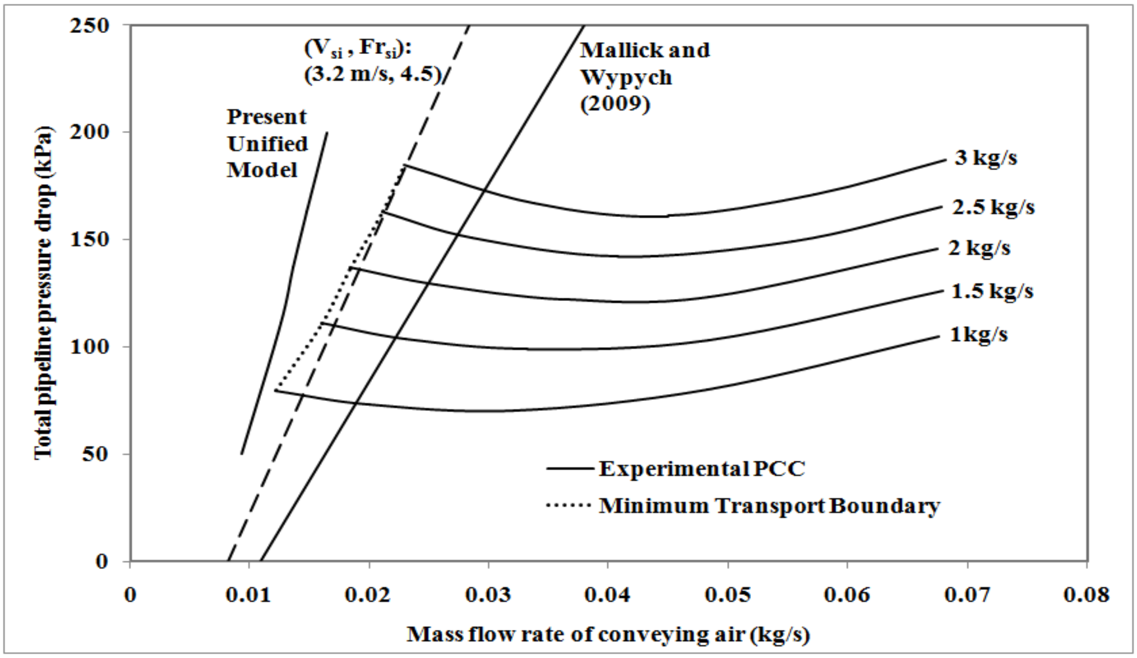

Figure 5.22: Experimental versus predicted MTB for Vales Point fly ash (Wypych, 1989) for 52 mm I.D. × 71 m long pipe

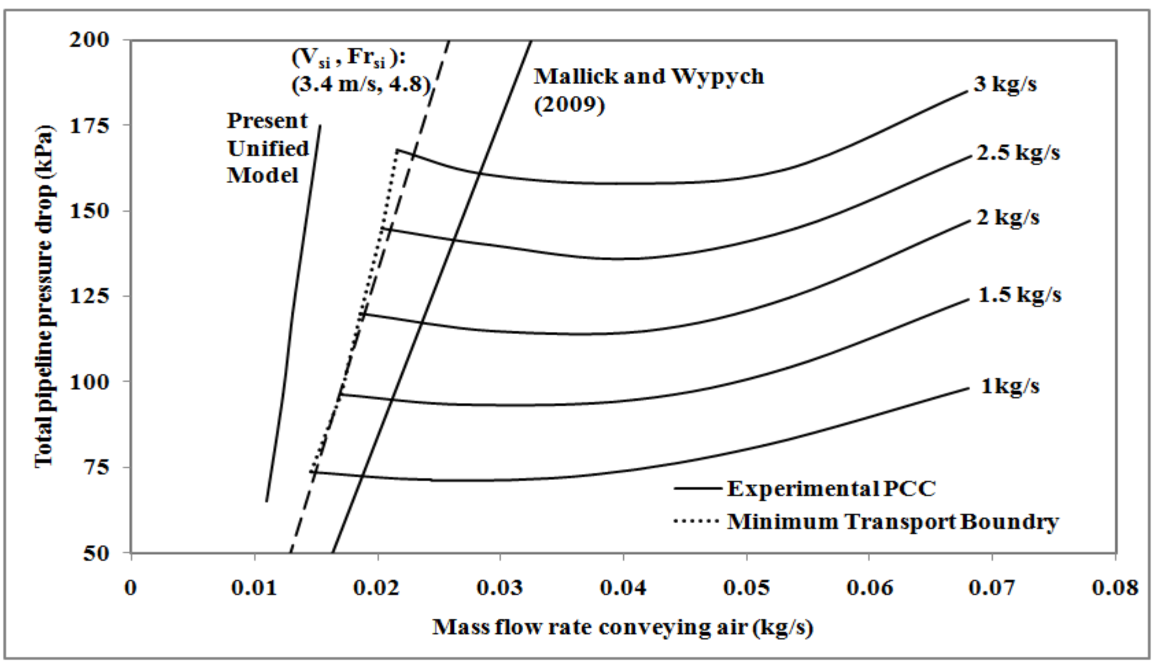

Figure 5.23: Experimental versus predicted MTB for Gladstone fly ash (Wypych, 1989) for 52 mm I.D. × 71 m long pipe

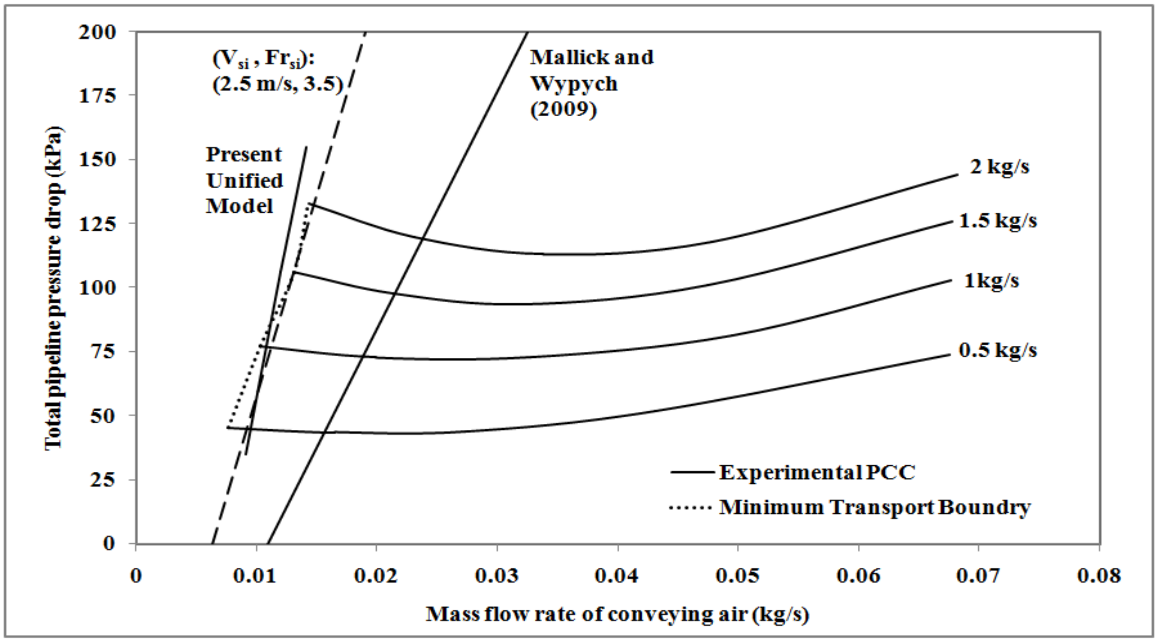

Figure 5.24: Experimental versus predicted MTB for Wallerawang fly ash (Wypych, 1989) for 52 mm I.D. × 71 m long pipe

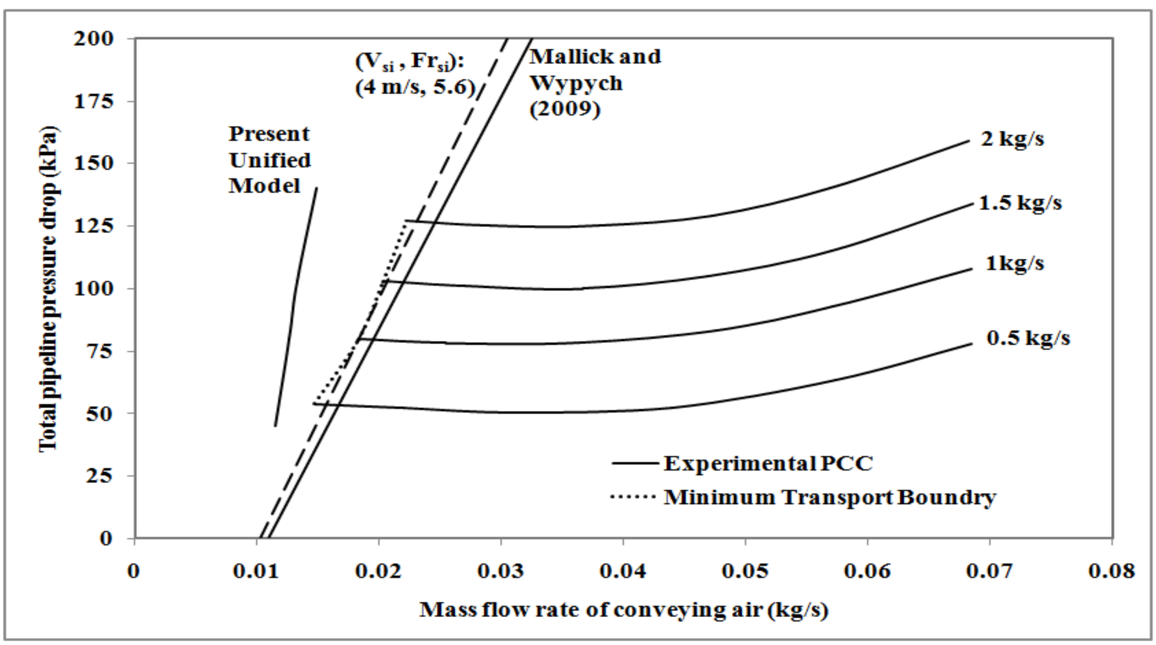

Figure 5.25: Experimental versus predicted MTB for Liddell fly ash (Wypych, 1989) for 52 mm I.D. × 71 m long pipe

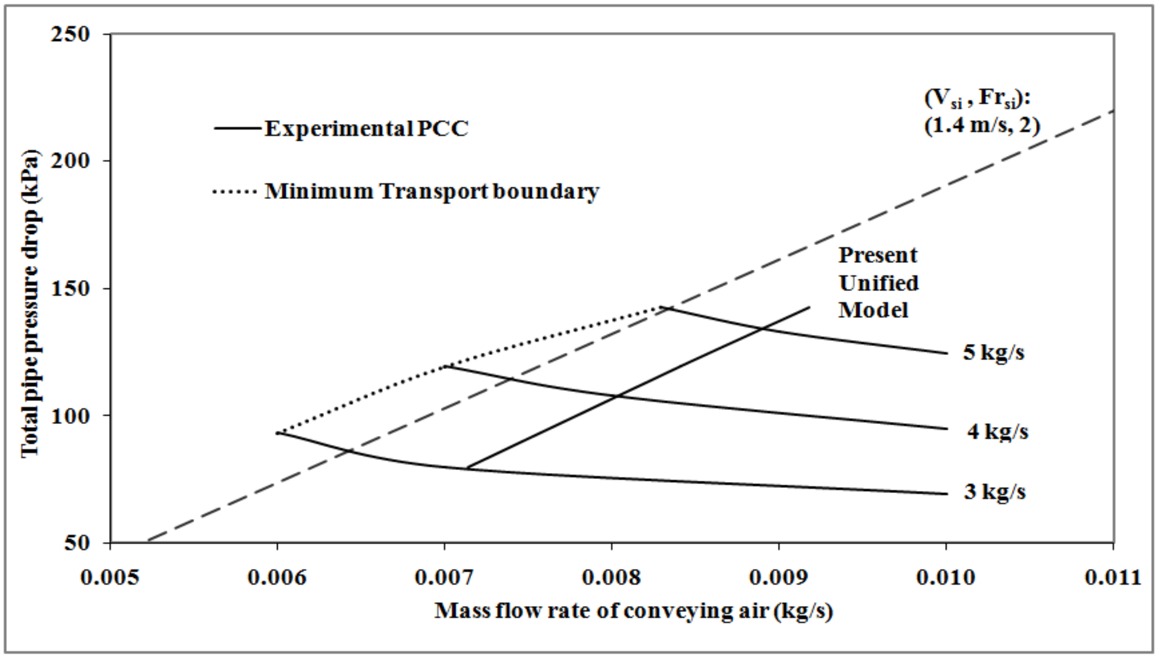

Figure 5.26: Experimental versus predicted MTB for pulverised coal (Wypych, 1989)

for 52 mm I.D. × 25 m long pipe

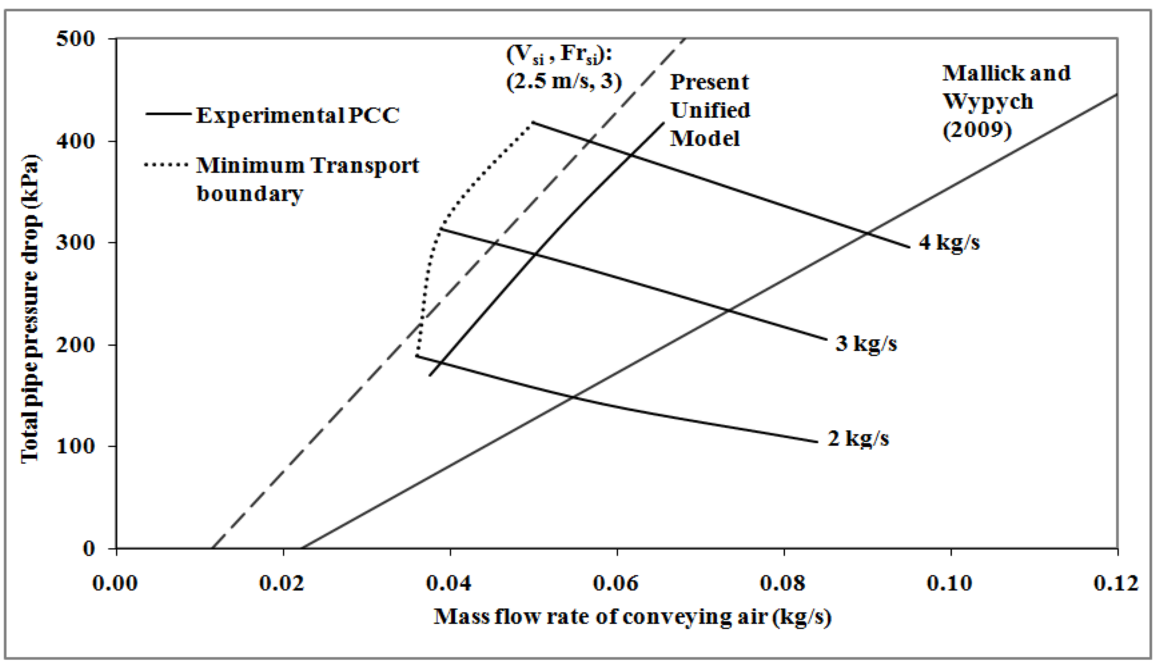

Figure 5.27: Experimental versus predicted MTB for cement (Wypych and Arnold, 1984)

for 69 mm I.D. × 168 m long pipe

For different power plants fly ash (Wypych, 1989), generally small under-predictions are seen (Figure 5.19 to 5.25), however in case of Munmorah fly ash (Figure 5.21) and Wallerawang fly ash (Figure 5.24), the predictions as well as the slope of minimum transport boundary line are very accurate.

A comparison between experimental versus predicted minimum transport boundaries on pulverized coal (Wypych, 1989) and cement (Wypych and Arnold, 1984), (Figure 5.26 and 5.27) has shown the good accuracy of the present unified model.

Table 5.1: Product properties, pipeline lengths and diameters and relative errors in unified model predictions

Powder	**d_{50} (μm)**	**ρ_p (kg/m^3)**	**ρ_b (kg/m^3)**	**D (mm)**	**L (m)**	**$V_{i,exp}$ (m/s)**	**$V_{i,pr}$ Unified (m/s)**	**Relative Error**
Cement (Mills, 2004)	14	3060	1070	81	95	3.7	3.2	-13.5%
Cement (Mills, 2004a)	14	3060	1070	53	101	2.8	2.35	-16.1%
White powder (Mallick, 2010)	55	1600	620	69	148	4	4	0%
Fly ash 1st sample (Pan and Wypych, 1998)	16	2197	634	69	554	4	3.9	-2.5%
Fly ash 2nd sample (Pan and Wypych, 1998)	12	2215	955	105	168	1.7	2.6	+53%

Table 5.1(contd.): Product properties, pipeline lengths and diameters and relative errors in unified model predictions

Powder	**d_{50} (μm)**	**ρ_p (kg/m^3)**	**ρ_b (kg/m^3)**	**D (mm)**	**L (m)**	**$V_{i,exp}$ (m/s)**	**$V_{i,pr}$ Unified (m/s)**	**Relative Error**
Fly ash 3rd sample (Pan and Wypych, 1998)	3.5	2540	670	69/81	945	4	3.5	-12.5%
Fly ash 4th sample (Pan and Wypych, 1998)	58	2180	730	52.5	70	2.3	2	-13.04%
Tallawarra fly ash (Wypych, 1989)	20	2350	500	52	71	3	2.2	-26.7%
Eraring fly ash (Wypych, 1989)	27	2160	880	52	71	3.4	2.4	-29.4%
Munmorah fly ash (Wypych, 1989)	25	2100	650	52	71	2.3	2	-13%
Vales Point fly ash (Wypych, 1989)	19	2130	700	52	71	3.2	2.4	-25%
Gladstone fly ash (Wypych, 1989)	18	2250	1030	52	71	3.4	2.5	-26.5%
Wallerawang fly ash (Wypych, 1989)	12	2195	455	52	71	2.5	2.45	-2.0%
Liddell fly ash (Wypych, 1989)	13	2415	640	52	71	4	2.8	-30%
Pulverised coal (Wypych, 1989)	30	1600	760	52	25	1.4	1.5	7.14%
Cement (Wypych and Arnold 1984)	20	3100	950	69	168	2.5	2.9	+16%

Results (Based on Table 5.1) show that the present unified model gives reasonable predictions for various products, small under-predictions are found in some cases. Hence some caution should be adopted while designing industrial plants. For example some safety factor (with 30% margin) could be employed to ensure the reliable design. The modified version of present unified model is given as under:

$$\mathrm{Fr_{min}} = 13.65\,\left(\mathrm{m}^{*-0.25}\right) \tag{5.2}$$

The above relation seems to have good promise in predicting the minimum transport boundary.

CHAPTER 6: Conclusions and Future Scope of Work

6.1 Conclusions

Based on the investigation and finding of this thesis, the following conclusions can be made:

- The experimental data of various other researchers for several products and pipeline configurations showed that with increase in diameter minimum velocity increases.
- It was found that the available models did not give reliable predictions, especially for fine powders.
- From the existing literature and test results, solid loading ratio (m*) and minimum Froude number (Fr_{min}) are found as two main influencing parameters for minimum transport boundary. For example, Mills (2004, 2004a) suggested minimum transport criterion greatly influenced by m* and Mallick and Wypych (2009) had shown that Fr_{min} represents the minimum transport boundary well.
- Using solid loading ratio (m*) and minimum Froude number (F_{rmin}) product and pipeline specific power function based models were developed. The validation and comparison analysis showed a good agreement between the predictions of newly developed model and experimentally observed minimum conveying conditions.
- Some efforts are made to develop a unified model (suitable for different powders).Present unified model predicts well generally but in some cases it showed some under predictions. However the model with 30% margin seemed to be quite reliable to be used for industrial applications.

6.2 Future Scope of Work

Although the results obtained in this thesis have contributed significantly to predicting and understanding the pneumatic transportation of fine powders, the following areas of investigation still require further attention:

- The work should be done to be by investigating the effect of the particle properties and its fluidization characteristics (deareation, permeability) and different dimensionless numbers, which represent the minimum fluidization conditions.
- Attempt should be made to incorporate the effects of particle side distribution in the proposed models.
- Further work is required for better understanding of pressure fluctuation and associated instability of flow at vicinity of minimum transport boundary.
- Flow visualization at blockage condition is very important. One should have some transparent pipes to see it.
- It is important to see the effect of blow tank mode and blow tank design on minimum transport boundary for example adjusting the top air and fluidizing air quantities.
- More efforts are required to develop a reliable scale-up procedure for stepping pipelines and its validation under a wider range of powders and scale-up situations.

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Appendix A

Products and test rig

A typical schematic of the test set up used for fly ash conveying is shown in Figure A1.1. The test facility comprised:

- Tandem 0.9 m^3 bottom-discharge blow tank feeding system;
- 69 mm I.D. × 168 m long mild steel pipeline, including 6.5 m vertical lift, five 1 m radius 90° bends and 150 mm N.B. tee-bend connecting the end of the pipeline to the feed bin;
- Various static pressure measurement tappings along the pipe (P8-P12), where P8 was used to measure the total pipeline pressure drop. The other tapping points were used to provide information regarding the local flow condition along the pipe;
- 6 m^3 receiving bin with insertable pulse-jet dust filter;
- All necessary instrumentation (e.g. pressure transmitters, load cells on feed bin and receiving bin, annubar with DP meter);
- Data acquisition unit for data recording and analysis.

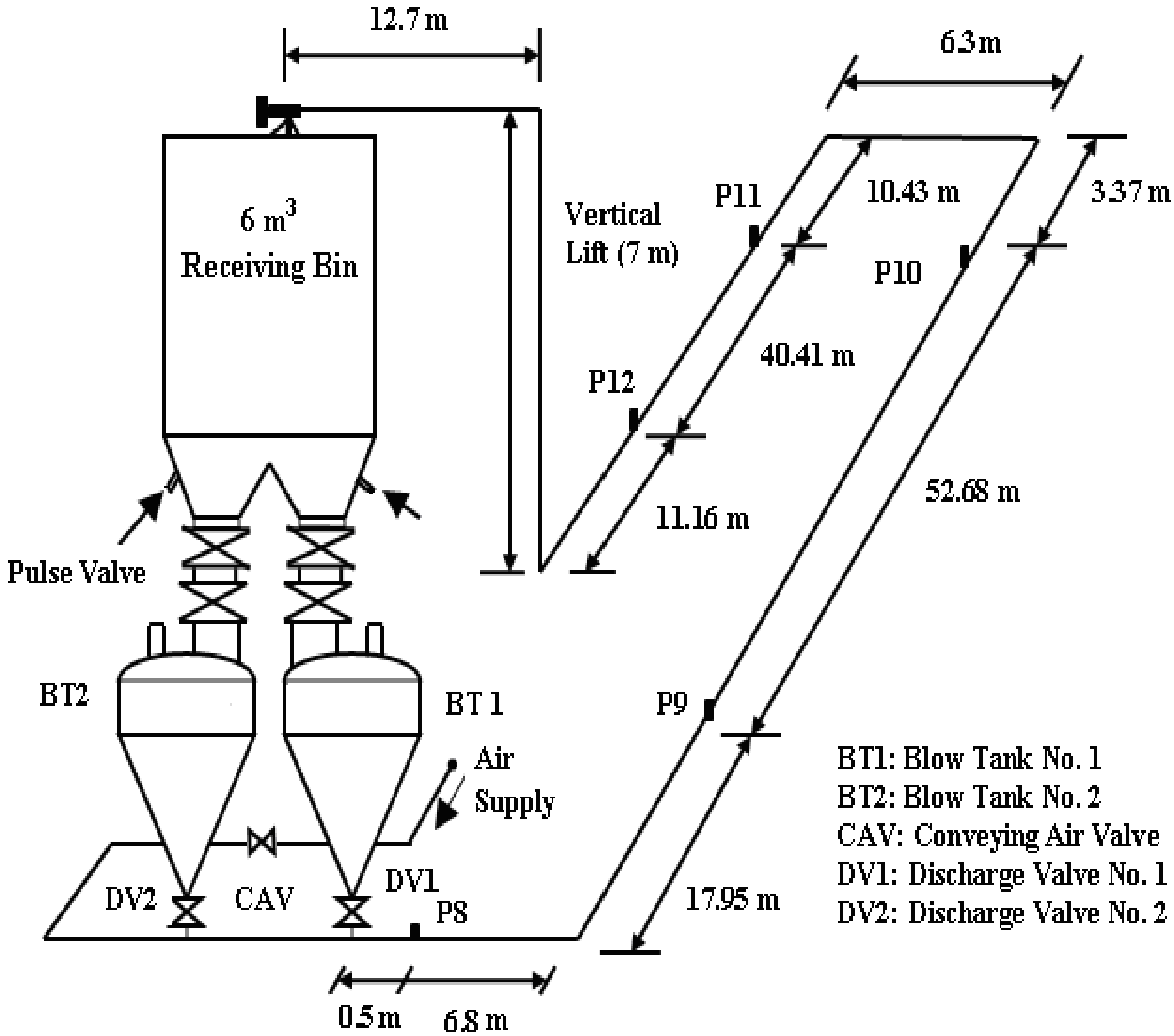

Figure A1.1: Layout of the 69 mm I.D. × 168 m long test rig (for fly Ash and ESP dust)

(Wypych et al., 2005)

To investigate effect of pipe diameter on FDP boundaries, same powder is tested in 105 mm ID × 168 m long mild steel pipeline, which has the same layout as shown in Figure A1.2.

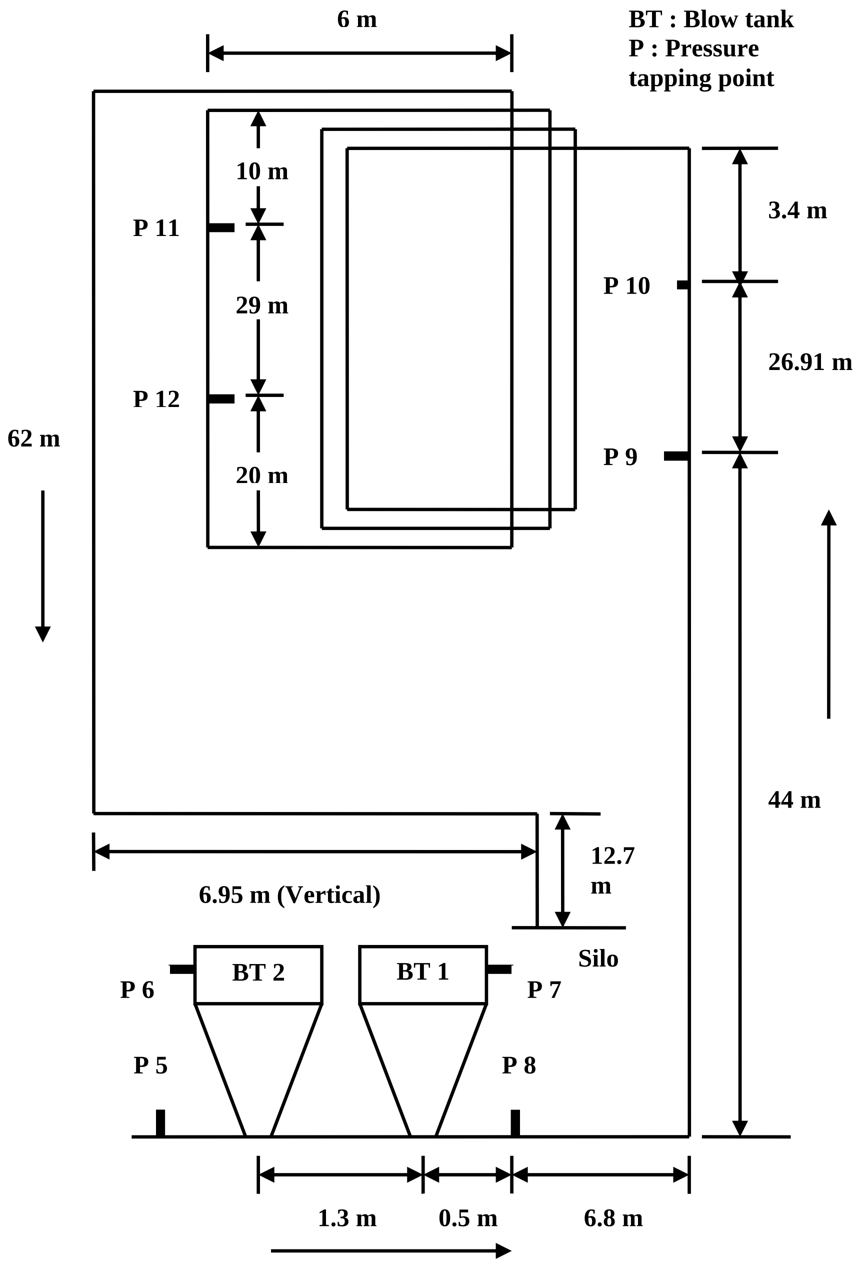

Figure A1.2: Schematic of the 105 mm I.D. × 168 m long test rig (for fly Ash and ESP dust) (Wypych et al., 2005)

To investigate effect of pipe length on FDP boundaries, tests are carried on in a 69 mm ID × 554 m mild steel pipeline with 17 bends test rig whose layout is given in Figure A1.3.

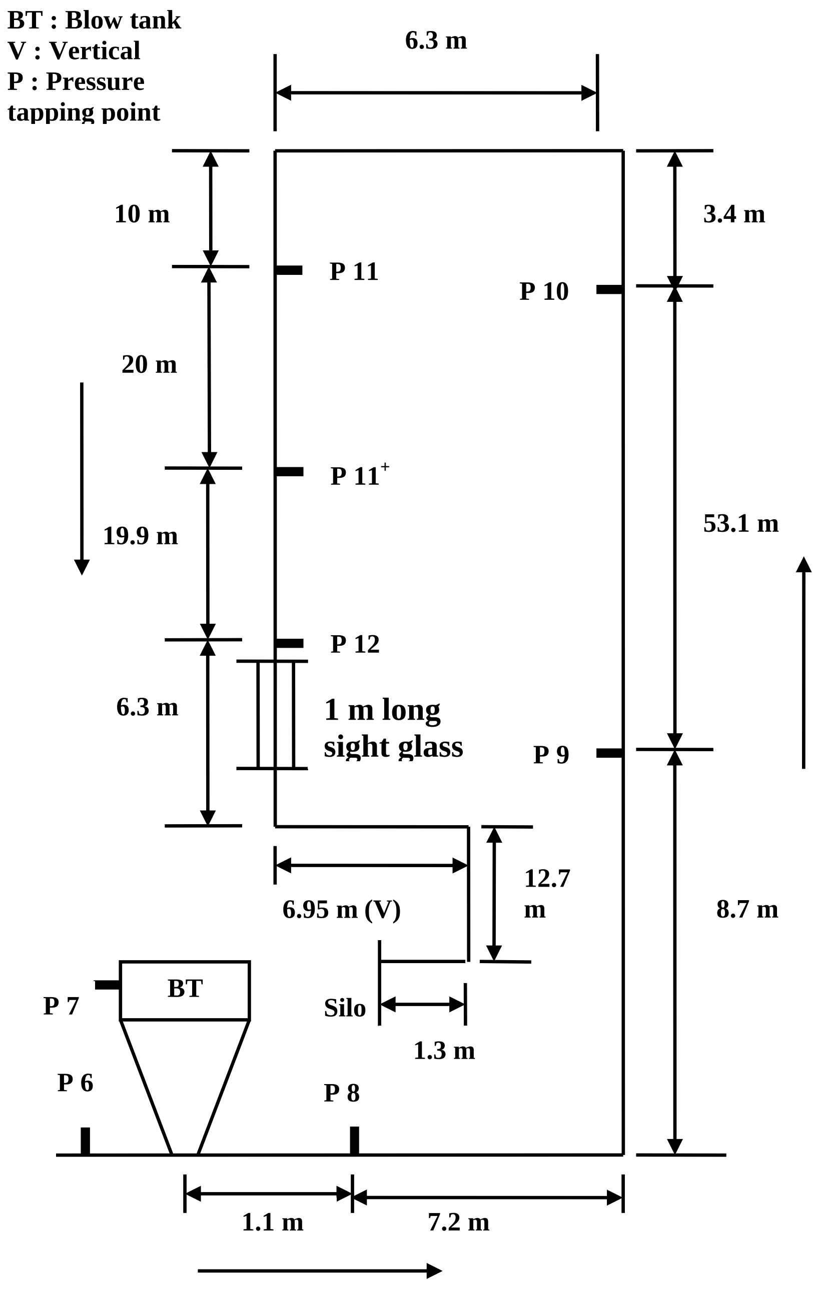

Figure A1.3: Schematic of the 69 mm I.D. × 554 m long test rig (for fly ash and ESP dust) (Wypych et al., 2005)

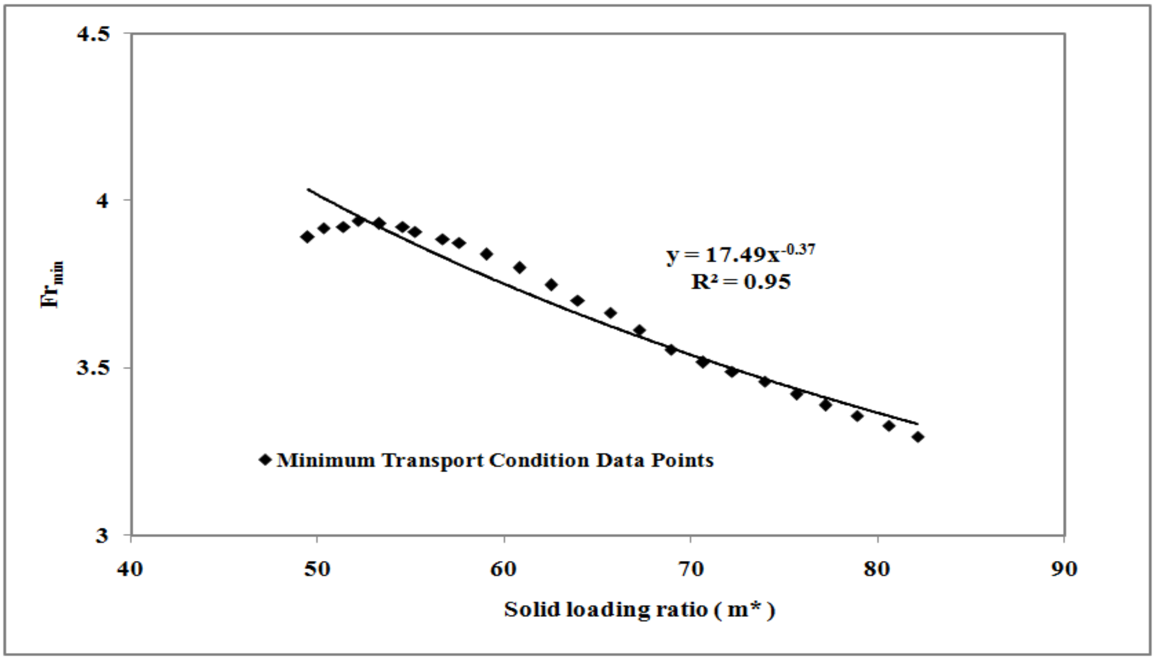

Figure A1.4: Fr_{min} versus m* for experimental minimum transport boundary, ESP dust (Wypych et al., 2005), 69 mm I.D. × 168 m long pipe

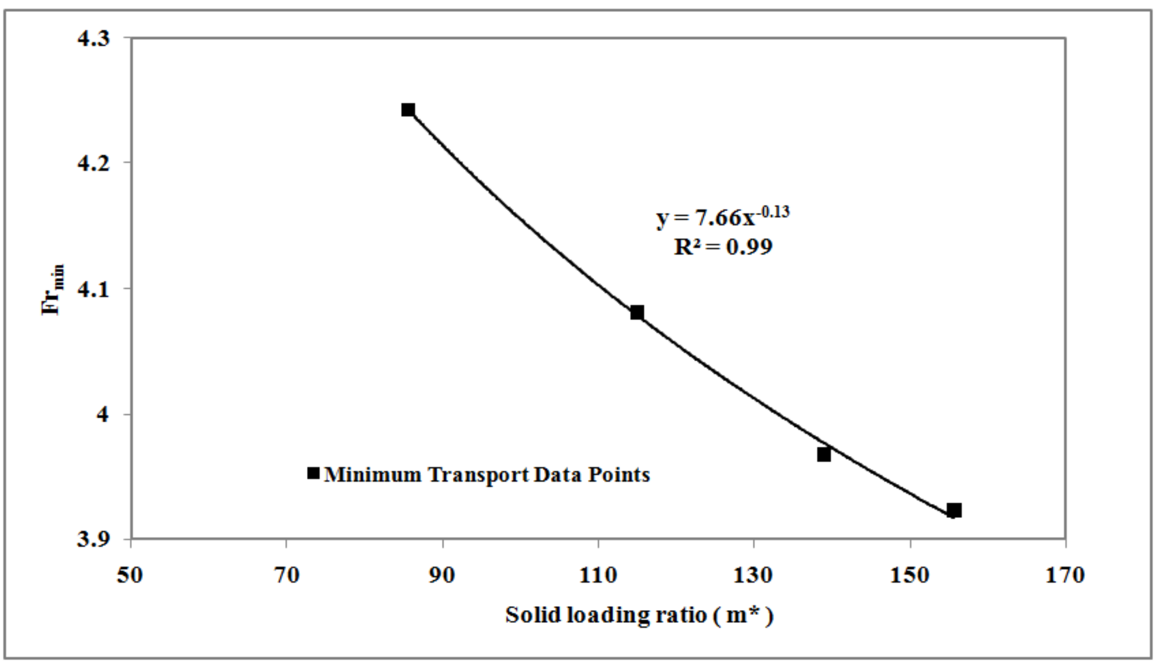

Figure A1.5: Fr_{min} versus m* for experimental minimum transport boundary, cement (Mills, 2004a), 53 mm I.D. × 101 m long pipe

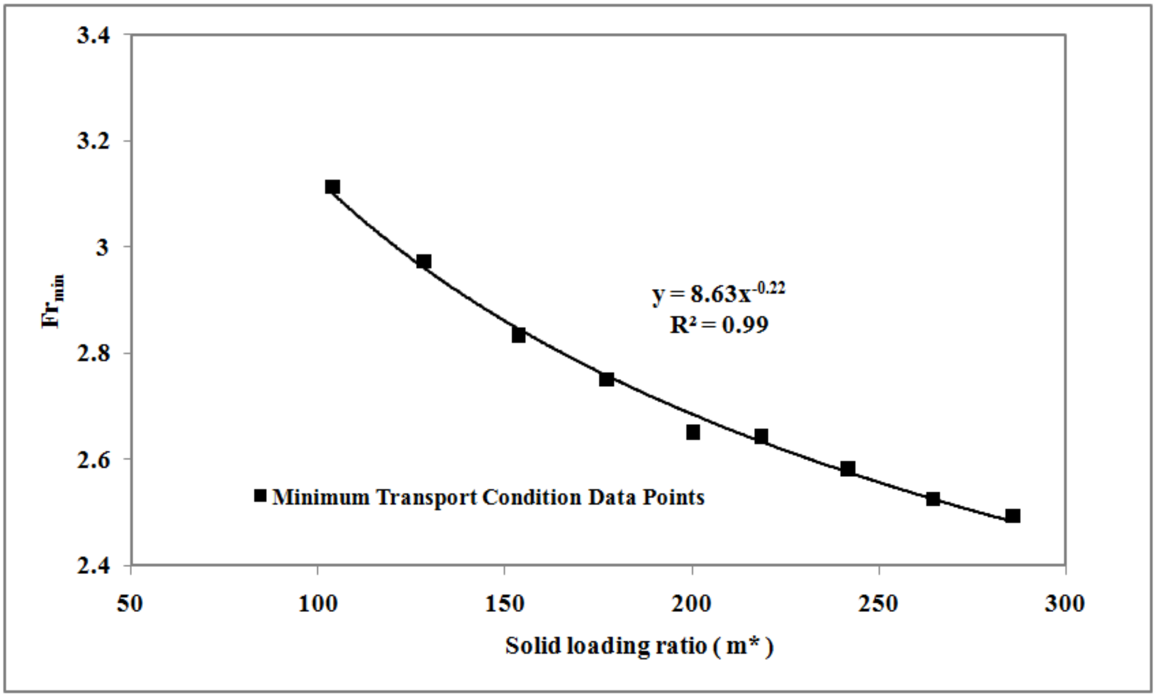

Figure A1.6: Fr_{min} versus m* for experimental minimum transport boundary, fly ash (Pan,1992), 52.5 mm I.D. × 102 m long pipe

LIST OF PUBLICATIONS

Referred Journals (Under Review) – 1 No.

Setia, G., Mallick S.S., Wypych P.W. and Pan R. Validated Scale-up Procedure to Predict Blockage Condition for Fluidised Dense-Phase Pneumatic Conveying Systems. **Particulogy.**

Conferences (Published/Accepted) – 2 Nos.

Setia, G., Bansal, A. and Mallick, S.S. Investigating Straight-Pipe Pneumatic Conveying Characteristics and Minimum Transport Boundaries for Fluidised Dense-Phase Pneumatic **Conveying of Fine Powders. 7th International Conference for Conveying and Handling of Particulate Solids - CHoPS 2012, 10 to 13 September 2012, Friedrichshafen, Germany (Accepted for oral presentaion).**

Bansal, A., **Setia G.** and Mallick, S.S. Investigating pneumatic conveying characteristics and minimum transport velocity for fluidised dense-phase transport of fine powders. **Technological Advancements in Chemical and Environmental Engineering 2012 (TACEE-2012), 23 to 24 March 2012, BITS Pilani.**