AN EXPERIMENTAL INVESTIGATION INTO THE RHEOLOGY OF FINE POWDERS FOR MODELLING FLUIDIZED DENSE-PHASE PNEUMATIC CONVEYING

A
Thesis

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

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In
Thermal Engineering

Submitted by
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CERTIFICATION

I, Bheeni Chaudhry, declare that this thesis report entitled "***An Experimental Investigation into the Rheology of Fine Powders for Modelling Fluidized Dense-Phase Pneumatic Conveying***", submitted towards fulfillment of the requirements for the award of Master's Degree in Thermal Engineering, in Mechanical Engineering Department of Thapar University, Patiala, is entirely my own work. This document has not been submitted for any degree in any other institution.

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ABSTRACT

Fluidized dense-phase pneumatic conveying systems are being used in several industries to convey fine powders in an energy efficient and environment friendly manner. Modelling of the dense-phase turbulent flow of powders is not a trivial task due to the complex nature of the fluidized dunes. For accurate modelling of important flow parameters, such as minimum transport limits and the effects of particle size distribution on the transport capacity, it is of utmost importance to study the rheology of the powders. In this work, an experimental facility was developed in which yield stress and viscosity was measured under fluidized and unfluidized conditions. Tests were conducted with three different depths of immersions and three rotational speeds of the spindle. Yield stress has been measured for six different fine powders, such as fly ash and cement (d_{50}: 19-139 μm; ρ_s: 1950-2910 kg/m^3**;** ρ_{bl}: 660-1080 kg/m^3). Viscosity measurements were done on three different fly ash samples from different field ESP from a power plant. It was concluded from the experimental results that with fluidization, the yield stress and viscosity decreased considerably. It was also found that in unfluidized state, yield stress increases with an increase in the mean particle size of the powders. Yield stress and viscosity values also increased with the increase in depth of spindle immersion, but decreased with increase in rotational speed of the spindle. Froude numbers were calculated for minimum transport boundary points obtained from the pneumatic conveying characteristics for fly ash and cement conveyed in two pipelines (65 mm I.D x 254 m long, 80/100 I.D x 407 m long). These values were related to the yield stress values of these powders at a standard depth and rotational speed of the spindle. It was found out that as the yield stress of powders increased, the Froude number requirement for minimum transport also increased.

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A	Cross sectional Area, m^2
Ar	Archimedes number
C_D	Drag coefficient
D	Diameter of the MSFBR, m
d	Particle diameter, μm
d_0	Diameter of object, m
d_p	Median particle diameter, m
d_s	Diameter of metal sphere, m
Fr_{min}	Minimum Froude number at the inlet of the pipe, $Fr = V/(gD)^{0.5}$
g	Acceleration due to gravity, m/s^2
L	Total pipeline length, m
L_b	Length of bed, m
m^*	Solid loading ratio
	(m^* = Mass flow rate of solids, m_s / mass flow rate of air, m_a)
P	Gas pressure, Pa
P_f	Permeability constant, m^2 /bar sec
ΔP	Change in pressure, bar
Q	Volumetric flow rate, m^3/sec
Re_m	Modifed Reynolds number, $Re_m = d_0\ u_r\ \rho_{bf} / \mu$
r	Radius, m
s	metal sphere to bed density ratio
μ_p	Dynamic viscosity of powders, Ns/m^2

u_t	Terminal settling velocity of sphere, m/s
v	Velocity, m/sec
y	y direction
z	Depth in the msFBR, m
ρ_{bl}	Loose poured bulk density, kg/m^3
ρ_{bf}	Bulk density of fluidized bed, kg/ m^3
ρ_s	Particle density, kg/m^3
τ	Shear Stress, Pa
τ_o	Yield Stress, Pa
τ_w	Wall shear stress, Pa
μ	Viscosity, Pa.s
v_θ	Angular velocity of the inner rotating cylinder, radians/ sec
σ_z	Normal stress in the z direction, Pa
λ	Friction factor

Subscripts

bl	Bulk
bf	Bulk density of fluidized bed
min	Minimum
s	Particle
t	Terminal
w	Wall
z	z direction

Abbreviations

CFBR	Coutte Fluidized Bed Rheometer
ESP	Electro Static Precipitator
I.D	Internal diameter
MTB	Minimum Transport Boundary
MSFBR	Mechanically Stirred Fluidized Bed Rheometer
OFP	Optical Fiber Probe
PCC	Pneumatic Conveying Characteristics

CHAPTER 1: INTRODUCTION AND OBJECTIVES

1.1 Introduction

Pneumatic conveying is one of the fastest growing technologies in the bulk material handling techniques in almost all industries like chemical, food, agricultural, ceramic, cement, combustion of pulverized coal, dispersion of pollutants etc. Pneumatic conveying is designed to transport bulk materials like cement, fly ash, pulverized coal, grain, skimmed milk, food powders etc. through a constrained flow using a fluid like air (Wypych, 2006). The conveying medium is either used at negative pressure as a vacuum system or at positive pressure. The basic underlying principal of pneumatic conveying is the property of bulk solids to retain a certain amount of air (Setia, 2012).

Generally, there are two distinct gas-solids flow modes in a conveying zone; dilute phase and dense phase. The dilute phase flow is generally by suspending particles along the pipeline, whereas, the dense phase flow is a non-suspension flow. (Chen, 2013).

Fluidized dense-phase pneumatic conveying of fine powders is gaining popularity because of its numerous advantages over the conventional dilute phase transport systems. These benefits include higher achievable solids to air mass flow rate ratio (can go up to 100), lower conveying velocity requirements due to the non-suspension nature of conveying and hence reduced gas flow and size of air movers, reduced power requirements, smaller size of bag filters, reduced wear rate of pipelines, bends and product damage (Mallick, 2010). Fluidized dense-phase type of conveying is suitable for fine powders, typically Geldart type A powders (Mallick, 2010), such as fly ash, cement, pulverized coal etc that have good air retention capabilities (Klinzing et al.

2009). For the optimal design of a fluidized dense phase system, two important parameters that need to be accurately modelled and reliably scaled up are the total pipeline pressure drop due to solid-gas flows and optimum air flow rate requirement to sustain stable conveying. Over-prediction of pressure drop and air flow rate will cause wear of the pipelines, attrition of product and higher operating expenses. Under-prediction of pressure drop will result in reduced achievable material flow rates, whereas under estimation of air flow requirement will lead to unstable conveying and eventually pipeline blockage (Wypych, 1989). Considerable amount of success has been achieved in designing dilute-phase pneumatic conveying systems, where the suspension flow mechanics can be applied with degree of certainty (Mallick, 2010). Comparatively, modelling the flow mechanism of fluidized dense-phase systems has remained to be a significant challenge to the designers and researchers. This is due to the highly concentrated and turbulent nature of the flow (m^* is in the range of 30 - 100), which makes it difficult to fundamentally model important design parameters such as solids friction and minimum transport criteria or the minimum air flow rate requirement to sustain stable conveying without product build up in pipeline. The existing models to predict minimum transport boundary and solids friction factor are empirical in nature, based on power function formats, and they use non dimensional parameters, such as solids loading ratio, gas Froude number (based on pipe diameter), ratio of air to particle density and particle to pipe diameter etc (Mallick and Wypych, 2009), (Pan, 1992), (Weber, 1981), (Mills, 2004), (Martinussen, 1996), (Setia and Mallick, 2015), (Setia et al., 2015). These models have provided limited success towards accurately predicting minimum transport boundary and total pipeline pressure drop (especially, under scale up conditions of pipeline lengths and diameters) (Mallick, 2010), as these models (and dimensionless parameter groupings) do not fundamentally address the flow mechanism of fluidized dense-phase conveying of fine powders (dune type flow) as shown in Fig 1.1

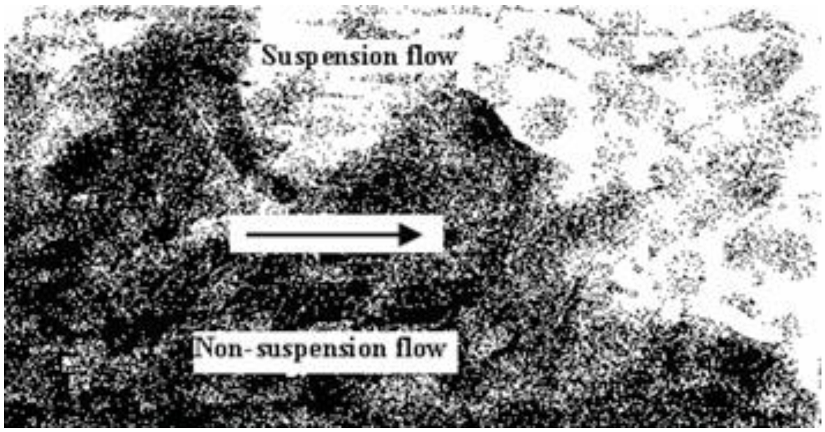

Figure 1.1: Two layer flow of fine powders in dense phase (Mallick, 2010)

Powder rheology is an important parameter for understanding the flow mechanism and modelling fluidized dense-phase type of conveying (Chen, 2013). Due to the natural ability of fine powders to retain air and form pseudo-fluids, fine powders (Geldart Group A) are able to exhibit liquid like fluid-like flow properties (in the form of moving dunes) (Mallick, 2010). Certain researchers have emphasized the role of rheology in the design of pneumatic conveying systems but none has attempted to correlate the particle and bulk properties or the rheological properties of bulk solids to model dense phase. However, for a two-phase flow, modelling of the rheological properties is complex. Not much work has been done in this area. Hence, the present study is necessary.

1.2 Objectives

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

i. To study the effect of aeration on the yield stress and viscosity of fine powders.
ii. To evaluate the effect of powder properties like particle size on the yield stress of powders under fluidized and unfluidized condition.
iii. To study the effect of depth of spindle immersion and rotational speed of the spindle on the yield stress and viscosity of powders.
iv. To predict the relation between yield stress and minimum Froude number requirement.

CHAPTER 2: LITERATURE REVIEW

This chapter presents the basic concepts and working of a pneumatic conveying system. It deals with various components and parts of a pneumatic conveying system. The later part of this chapter is aimed at throwing a light on work done by previous researchers in the field of rheology of fine powders.

2.1 Pneumatic conveying

Pneumatic conveying is one of the most widely used bulk material handling techniques in the process industry. The aim of pneumatic conveying is to transfer particulate material between storage locations, or to feed different kinds of reactors. Such a system is designed to transport bulk materials (e.g. cement, fly ash, pulverized coal or grain) through a confined flow channel (typically a pipeline) using either negative or positive pressure air as the moving medium. (Wypych, 2006). Other gases (hydrogen and nitrogen) are also considered as carrier fluids. It is well known that pneumatic conveying is an important technique used in significant number of industries like chemical, food, agricultural, ceramic, cement, combustion of pulverized coal, dispersion of pollutants etc.

Pneumatic conveying of powders is becoming increasingly popular in various industries due to the following advantages (Wypych, 2006):

- Reduced gas flow rate required for transportation, hence, lower is the power consumption. Also lower support/pipe required

- Less transport velocities required leading to less attrition of the product and less wear in the conveying pipeline
- Enclosed flow channel which provides safety to the material being transported and is hygienic and environment friendly
- Flexibility in routing of flow direction
- Multiple entries and multiple discharges possible
- Low manpower and maintenance cost

2.2 Components of a pneumatic conveying system

The pneumatic conveying system consists of four parts:

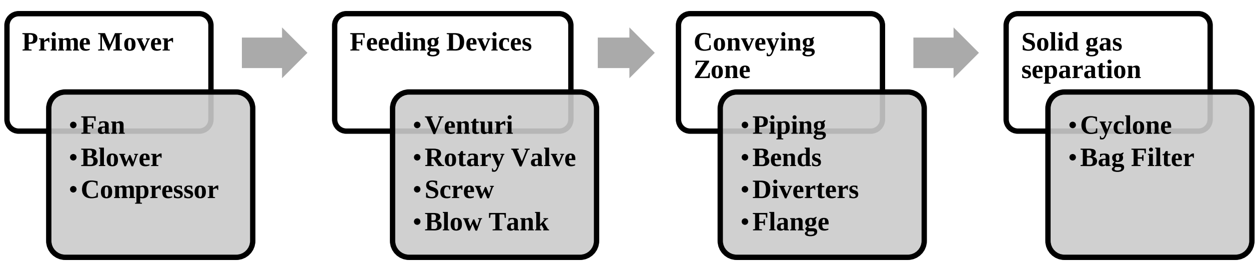

Figure 2.1: Basic components of a pneumatic conveying system

1. Prime Mover:

   The prime mover or the gas supply system is the prime component of a pneumatic conveying system. It is generally the most expensive part with respect to capital and running costs of the system (Chen, 2013). Depending upon the location where the air supply is placed, the system can be used as a positive or negative pressure system. The two most important parameters for a reliable and effective pneumatic conveying system are gas flow rate and the pressure supply from the air mover. For systems which use air as the conveying medium, the prime mover must be attached with a dryer and a filter to drive off the moisture from air before mixing with the powder. Mostly compressors, fans and blowers are used as prime movers.

2. Feeding Devices:

   The feeding section which ‘inserts’ the material into the conveying gas, is critical in a pneumatic conveying system. For a particular type of feeder, it can only be operated in a certain range of differential pressure between the feed hopper and the pipeline. Incompatibility of the parameters between the feeder and the prime mover often leads to conveying system problems. Venturi, rotary valve, screw feeder and blow tank are commonly used feeding devices in conveying applications.

3. Conveying Zone:

   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).

4. Solid Gas Separation:

   Cyclones, bag filters ate the usual devices used for solid gas separation. The material being conveyed is collected in a receiving storage whereas the air is generally vented out in the atmosphere.

2.3 Flow Modes

The flow modes in pneumatic conveying can be broadly classified into two main categories depending upon the velocity of air used in the conveying. The two flow modes (Klinzing, 2009):

1. Dilute phase conveying
2. Dense phase conveying

The flow mode is characterized by the ratio of the solids mass flow rate (ms) to the air mass flow rate (ma), which is referred to as the "solids loading ratio" ($m*$) (Wypych, 2006).

$$m^* = \frac{m_s}{m_a} \qquad (2.1)$$

A dilute phase system generally utilizes large volumes of gas at high velocities. The dense phase pneumatic conveying system uses gas at low velocity. Figure 2.2 and 2.3 show the dilute and dense phase flow of fly ash in pipelines conveyed at Thapar University.

Figure 2.2 Dilute phase (suspension) flow

Figure 2.3 Dense phase (non suspension) flow

2.4 Geldart's Classification Diagram

Geldart (1973) worked on material classification based on their fluidization characteristics. He segregated powders based on their fluidization characteristics. Classification was done on the basis of mean particle size and the difference in density between the particles and the fluidizing medium.

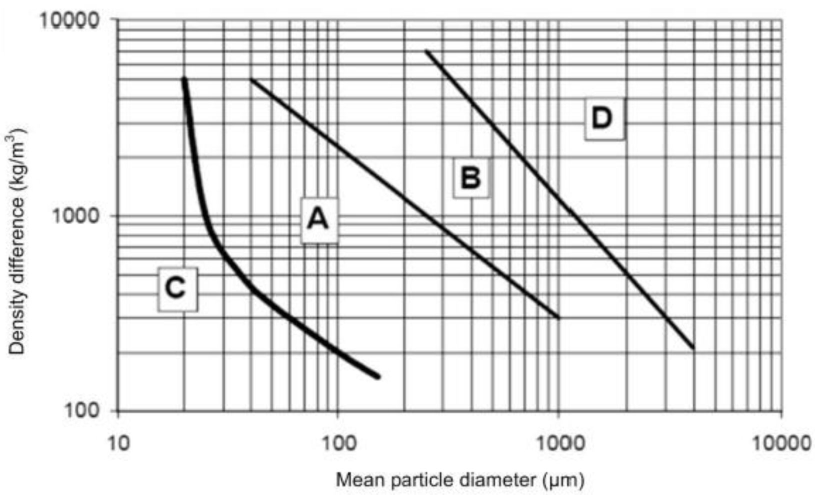

Figure 2.4: Fluidization Classification Diagram (Geldart, 1973)

He classified the materials into 4 groups based on their properties:

- Group A: These powders show minimum tendency to form bubbles and show considerable bed expansion between minimum fluidization velocity and minimum bubbling velocity. They retain aeration and the fluidized bed collapses slowly when the gas supply is switched off. Example: cement, flour

- Group B: These are the particles that fluidize readily and form bubbles. They show less bed expansion. The fluidized bed does not retain its aeration and collapses quickly when the gas supply is switched off. Example: limestone dust, sugar granules
- Group C: These powders are cohesive in nature and are of small particle size. These are difficult to fluidize. Fluidized bed forms solid plugs or stable channels of air flow. Example: fly ash, talcum powder
- Group D: These are large sized particles. In these particles, fluidization is similar to group B but higher gas velocities are required for fluidization. Example: wheat kernels, mustard seeds

2.5 Rheology

Rheology can be defined as the flow characteristics of a material. It is the study of flow and deformation of materials under applied stress. Rheology of powders is the study of the powder under conditions in which they no longer deform elastically on application of external stress but starts to deform plastically. Rheology comprises of a component called viscosity which is resistance to flow. Viscosity depends upon the type of fluid; Newtonian or non Newtonian. When the powders are fluidized, they are observed to exhibit fluid like behavior. Hence, an analogy exists between a fluid and the fluidized powders.

2.6 Yield stress

Yield stress is an important parameter for the study of rheology of powders. Powders have an inherent strength due to the molecular packing unlike liquids. A powder when fluidized will begin to flow only when the applied stress exceeds the yield stress of the material. The flow particles before fluidization exhibit a level of elasticity showing the transition from solid to fluid states. When the applied stress is below the yield stress, the powder will deform elastically. When the yield stress is reached, the powder starts flowing like a viscous fluid. Hence, yield stress is an important parameter in the rheology study of fluidized powders (Chen, 2013). Yield stress is an important parameter in the design of pneumatic conveying systems. By feeding air into the powders and fluidizing them, the yield stress is considerably decreased. So the minimum transport condition can be designed by studying the rheology of fluidized powders.

2.7 Viscosity

Viscosity can be defined as the measure of resistance of a fluid against deformation under applied shear stress. Viscosity can be described as an analogous term to fluid friction caused due to internal friction between different layers of the fluid. Issac Newton stated that for uniform and parallel fluid flow, the shear stress is proportional to the velocity gradient in the direction which is normal to the layers. It can be formulated as:

$$\tau = \mu \frac{dv}{dy} \tag{2.2}$$

Fluids displaying such behavior are called Newtonian fluids, example water. Viscosity of Newtonian fluids remains constant. It does not depend upon the shear rate. If stress is plotted against strain then the slop of the curves gives viscosity. The slope of the stress strain curve for a Newtonian fluid will be a straight line as shown in Figure 2.5.

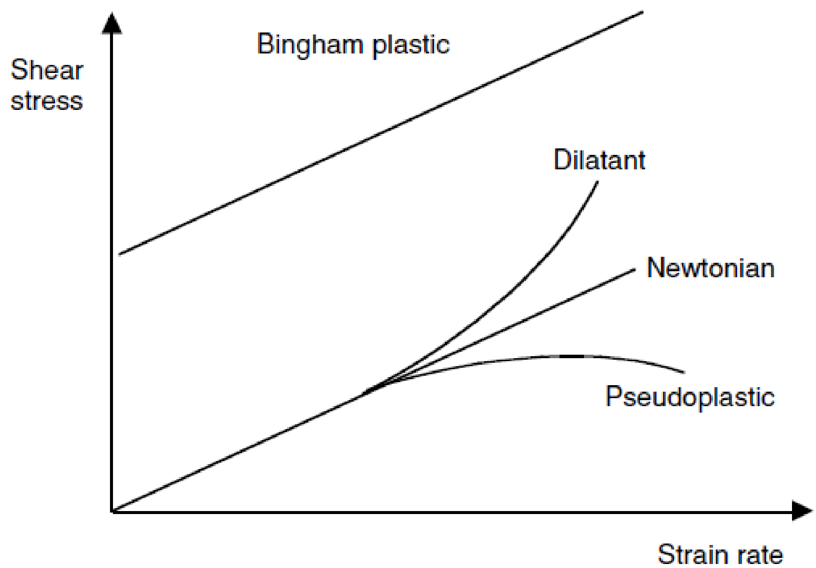

Figure 2.5: Stress versus strain curves for different materials (McGlinchey, 2004)

Non Newtonian fluids are the ones which do not have a direct proportional relation between stress and strain, example ketchup, and slurry. The viscosity for such fluids is called apparent viscosity (Chen, 2013).

Under Non Newtonian fluids are the Pseudoplastic or the shear thinning fluids. These fluids are characterized by decrease in apparent viscosity with increase in shear rate. Due to the reduced viscosity these fluids are called shear thinning fluids (McGlinchey, 2004).

For dilatant fluids, this apparent viscosity increases with increasing shear rate. This is shown by the Dilatant curve in Figure 2.5. These are also called as shear thickening fluids, example ethylene glycol.

Another class of material are called Bingham plastics. Such fluids behave like a solid when the apllied stress is below a threshold called yield stress. Once stress greater than yield stress has been applied, the fluid begins to flow with stress proportional to strain. The examples of such type of fluids are pastes and paints (Bruni, 2005).

2.8 Previous research work

Given below is the extensive literature review that has been done in order to study the rheology of fine powders under dense phase fluidized conditions.

Grace (1970) calculated apparent viscosities by using the spherical bubble method. He calculated the viscosities and then compared the values with previous researchers work. He stated that the apparent viscosities are much greater than those predicted theoretically. This shows the effect of particle interactions. Previous methods of calculating fluidized bed viscosities were studied. These included:

1) Experimental techniques that included resistance to rotating paddles, falling sphere method, dumbbells.
2) Indirect methods on the behavior of bubbles in fluidized beds.

It was concluded that by observing the shape of the bubble in the fluidized bed, viscosity can be estimated. Spherical cap bubbles in less viscous liquids have included angle of bubble around 100^{o} and higher included angle in more viscous liquids.

King et al. (1980) studied the effect of increasing pressure on viscosity. He calculated the dense phase viscosities of fluidized beds uptill a pressure of 20 bar. Glass powders with sizes 64, 101, 475 µm were taken and fluidized with CO_2 or N_2. Falling sphere technique was used. Terminal velocity of the sphere was measured by the setup and dynamic viscosity was calculated using the following formula:

$$C_{d}\left[\frac{\rho_b U_t\, d_s}{\mu_p}\right]^2 = \frac{4g(s-1)d_s^3\, \rho_{bl}^2}{3\mu_p^2} \qquad (2.3)$$

It has been found that increase in pressure leads to decrease in the kinematic viscosity, but when powder size is greater than 100 µm, there was no effect. However, no correlation was predicted for dynamic viscosity of powders.

Kai et al. (1990) evaluated the relation between apparent bed viscosity and the fluidization viscosity for fine powders. He used two velocities to fluidize the particles that is; minimum fluidizing velocity and bubbling velocity. Falling sphere method was used to measure the terminal velocity. It was found out that as the diameter of the sphere increased, the apparent viscosity also increased. Apparent viscosity in emulsion phase of bubbling fluidized bed was related with gas and particle properties with correlation of voidage.

Anjaneyulu and Khakhar (1994) experimentally studied the rheology of granular materials. The setup consisted of a fluidized bed in a cylindrical vessel. Glass beads were silvered to use them as tracers and photographs were taken to measure the thickness of the layer sheared. An experimental study was carried out on the rheology of glass beads (d50: 400-1000 µm) using a rotary viscometer and it was concluded that the yield stress decreases with an increase in the amount of aeration. The following relation was proposed relating the yield stress and viscosity of powders:

$$\tau = \tau_o - \mu r \frac{d}{dr}\left(\frac{v_\theta}{r}\right) \qquad (2.4)$$

The yield stress observed was in the range of 1 to 5 Pa. However, only granular products like beads were analyzed. No estimate was given about the prediction for fine powders.

Felice (1997) showed the applicability of pseudo fluid model. When foreign particles enter the solid fluid suspension, pseudo fluid model was tested. If the particle density and the density of the suspension particle are similar, this model is not applicable. Also, validity of this model has been shown with bed particle size of 0.8 mm, but it deviates at a particle size of 0.635 mm due to large spheres fluidizing in a non homogeneous manner.

Goossens (1998) stated that by knowing the particle diameter, a material can be placed on the classification diagram and its flow can be predicted. He stated that the behavior of fluidized particles is dominated by the relative importance of laminar and turbulent flow effects during interaction of solid particles and fluidizing particles. Archimedes Number was used to classify the particles and Geldart's classification diagram was further modified:

1) Class A- Turbulent flow effects are negligible at minimum fluidization Ar_1= 0.97
2) Class B- On onset of fluidization, turbulent effects start to increase Ar_2= 88.5
3) At equal laminar and turbulent flow, Ar_3= 176900
4) To break interparticle cohesive force, fluid behaves in turbulent manner, Ar_4= 9.8

Pan (1999) developed a classification diagram by using loose pored density in the Geldart's diagram. He discovered three flow modes during pneumatic conveying of bulk solids:

- PC1 – Dense flow, PC2- Slug formation and PC3- Dilute phase. The concept of loose poured density was used in place of particle density. After determining the classification, boundaries were also classified.
- The boundary between fine and course powders corresponds to the equation:

$$d_p\rho_{bl} = 0.1206 \quad (2.5)$$

- The boundary between slug flow and dilute flow correspond to:

$$\rho_{bl} = 1000 \quad (2.6)$$

It was concluded that there exists an inverse relation between the loose poured density and mean particle diameter.

Hirota et al. (2000) constructed an experimental setup with a progressive cavity pump as the feeder and an inclined pipe for conveying. He focused on the relation between pressure drop for pneumatic conveying in an inclined pipe and material properties. Pressure drop was expressed by friction coefficient of powder and the inclined angle of the pipe. Three kinds of powders were selected and tested such as silica, flyash and soft flour. Different inclined angles were used- 0, 20, 30, 45, 60 and 90^{o}. Pressure drop coefficient in an inclined pipe can be estimated by inclined angle and friction factor. It was also stated that the factor of $\lambda Fr/2$ reaches the peak at 30-45 degree in an inclined pipe.

Zhao and Wei (2000) studied the viscosity of fluidized beds with the help of solid settling experimentation. The experimental setup was used to measure the terminal velocity of a sphere using induction coils and a tracer. The terminal velocity was calculated for the falling sphere and it was used to measure the plastic viscosity and yield stress. It was found out that plastic viscosity and yield stress increased with increasing the size of the fluidized particle. Rheological characteristics were studied. Plastic viscosity and yield stress were calculated using regression analysis.

Wei and Chen (2001) experimentally determined the drag coefficient of spherical objects in fluidized granular bed using falling sphere technique. They assumed the fluidized powder to follow Bingham plastic model. Drag coefficients on the sphere were calculated experimentally and validated by the following model:

$$C_D = \frac{24}{Re_m} \left(1 + 0.15\, Re_m^{0.687}\right) \quad (2.7)$$

$$Re_m = \frac{d_0\, u_t\, \rho_{bf}}{\mu + \frac{\tau_0 d_0}{3u_t}} \quad (2.8)$$

Sanchez et al. (2003) studied the feasibility of conveying bulk solids in dense phase. It depends on the various particle properties like particle size, density and shape, permeability, deaeration, surface characteristics, elasticity, temperature sensitivity. Fluid test column was used to study the permeability and deaeration. The permeability factor is given by:

$$P_f = \frac{\Delta PA}{L_b Q} \quad (2.9)$$

Parameters like particle and bulk density, permeability factor and de-aeration factor, mean particle size, and minimum fluidization properties can indicate the flow mode of the material. It was observed that the data formed clusters according to Geldart classification. The plots show that some materials do not lie in the clusters in the Geldart chart. This is due to the secondary properties of materials such as cohesion, moisture, etc. which can affect the flow modes of the materials. The best correlation found in this study was obtained using the dimensionless numbers that are a function of permeability factor, de-aeration factor , and minimum fluidization velocity.

Bruni et al. (2005) set up an experiment with the msFBR- Mechanically stirred fluidized bed rheometer. The setup comprised of a fluidizing unit, an agitating system- shaft fitted with two flat bladed paddle, and materials- Alumina, Glass spherical ballotini. Torque measurements were done by agitating the fluidizing bed with the impeller. The parameters were impeller depth and impeller speed. Experiments were done on two conditions:

1) Just before minimum fluidization
2) At minimum fluidization

It was observed that below minimum fluidization, torque was independent of impeller depth. With increasing impeller depth, Torque curves resembled normal stress curves. At minimum fluidization, torque was dependent on impeller speed and increased linearly with impeller depth. However, explanation was not given about the choice and dimensions of the agitating unit being used in the experiment. Also the effect of shape of the agitating unit was not clearly underlined.

Barletta et al. (2007) developed a new shear (rotational) tester to study the effect of shearing. Two different powders belonging to group C were used in the study, magnesium carbonate and silica. Incipient and dynamic shear experiments were done. Both show the same result. It was found that aeration does not affect the unconfined yield strength and rheological properties, only the stress is changed.

Bruni et al. (2007) constructed a setup to measure the rheological characteristics of powders. The setup is shown below:

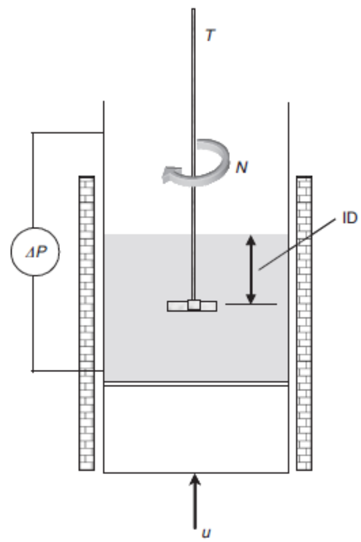

Figure 2.6: msFBR Unit (Bruni et al.,2007)

He used msFBR- Mechanically stirred fluidized bed rheometer to study the rheology of fine powders below minimum fluidization. The materials used to study the rheology were ballotini (d_{50}: 350 μm) and alumina (d_{50}: 75 μm. Torque measurements were carried out near minimum fluidization velocities at different impeller depths of immersions and rotational speeds of the impeller. A model was developed to study the state of stress at an impeller depth and also to evaluate the torque. It was also stated that change in aeration does not change the powder rheology but effects the stress distribution. However, there was no attempt to study the effect of different aeration level on the rheology of powders.

$$\frac{d\,\sigma_z}{dz} + \frac{4\tau_w}{D} + \frac{dP}{dz} = \rho_b\, g \tag{2.10}$$

Gibilaro et al. (2007) stated that pressure has no fluctuations on apparent viscosity in a gas fluidized system. He tried to predict an analogy between a spherical particle in a fluidizwd bed and the same particle suspended under terminal conditions surrounded by other particles. Upto particle concentrations for about 40%, the analogy holds true. At higher particle interactions, this analogy fails because of inter particle interactions.

Colafigli et al. (2008) developed a fluidized bed and the aeration was done using ambient nitrogen. CFBR (Coutte fluidized bed rheometer) was used for the experiment. The fluidized gas was contained between two vertical cylinders. The inner cylinder can rotate at different speed. The experiment was done to determine to what extent, the rotation of the inner cylinder affected basic fluidization characteristics of the bed. The results provided evidence of pseudo plastic behavior that is apparent viscosity decreased with increasing shearing. The torque measurements were done with the help of the rheometer, and then the viscosity was calculated.

Mallick and Wypych (2009) conveyed different powders such as fly ash, ESP dust and cement in different pipe lengths and diameters. They developed Froude number based criteria for predicting minimum transport boundary. They developed a model which could be scaled up reliably from the laboratory test rig to the industrial systems to predict blockage points in dense phase conveying of powders. Initially Froude Number = 6 was predicted by Mallick and Wypych for reliable and safe conveying of powders, but recently, **Setia and Mallick (2015)** and **Setia et al. (2015)** have developed improved models for solids friction and better scale up of dense phase conveying of powders.

Rabinovich and Kalman (2011) used vertical pneumatic conveying. They selected the criterion of Reynolds number and Archimedes number and constructed a flow regime diagram. An attempt was made to study the effect of pipe diameter, particle concentration and fluid properties on the flow modes in vertical pneumatic conveying systems. Experiments were carried out to calculate the transition velocities in a vertical pipe. It was found out that pipe diameter has no effect on the transition velocity. It was also found out that Reynolds number, Archimedes number and volume concentration of solids affect the transition velocities. An attempt was made to relate the flow diagram with Geldart's classification diagram.

Wei et al. (2011) used a negative pressure test rig. Two different sized powders were used. OFP (Optical Fibre Probe) was used to measure volumetric solid concentration and particle velocity. Also after measuring the particle the particle velocity, solid concentration was found out by the relation. The two values were found to be in good agreement. It was found out that particle velocities are different in upper and lower part of the horizontal pipe, difference generally not being more than 2 m/s. With increasing gas velocity and increasing mass flow rate, difference in velocity decreases. Solid friction factor was modified to obtain a new correlation for particle velocity which was in better agreement with the experiments.

Chen (2014) measured the yield stress of three different powders, alumina, cement and fly ash, at different aeration levels using the technique of double ended cone penetration. It was concluded that the yield stress decreases with an increase in air flow rates and the decreasing trend ceases at minimum fluidization velocity. An empirical model was developed to establish a relation between yield stress and bulk density. However, the effect of particle size on yield stress was not studied. He advocated that the values of yield stress are largely dependent on the type of measurement technique adopted, i.e the dimension of the spindle used and the quantity of aeration.

Leturia et al. (2014)

Seven materials were chosen to test the rheology and the flowability of powders. They ranged from nanoparticles to group B powders. The FT4 powder rheometer was used for the analysis. Various stress levels were used to study the rheology. These were compaction, free surface and aerated condition. It was concluded that the stress levels and the bed voidage has a direct impact on the flowability of powders.

CHAPTER 3: TEST FACILITY AND EXPERIMENTAL PROCEDURES

3.1 Introduction

In recent years, Mallick (2009) advocated that rheological properties of bulk solids must be considered for better fundamental and accurate modelling of the transport of dunes during fluidized dense-phase pneumatic conveying. He proposed two-layer dune flow model for solids friction, where the non-suspended highly turbulent layers of powders having fluid like properties were considered to be duning along the bottom of the pipeline and a relatively dilute suspension fine powders were considered to conveyed on top of these dunes. He attempted to incorporate a pseudo-viscosity term in solids friction factor model. However, the work was limited due to the lack of rheological data for fine powders. Chen (2013) measured the yield stress of three different powders at different aeration levels. These studies tend to emphasize the importance of rheological study for accurate modelling of fluidized dense phase. However, overall it can be stated that only limited attempts have been made so far to include rheological parameters of aerated dunes (which tend to behave like pseudo-fluids) in the modelling of important parameters of fluidized dense-phase conveying, such as solids friction or reliable transport limits. Also, limited work has been carried out to investigate into the effects of particle size on the rheological property of fluidized dunes. Considering the non-Newtonian nature of non suspension layer of the turbulent dune, yield stress of powders is considered to be an important parameter that would govern the limits of powder flow. In this research, yield stress of three different powders (fly ash from different fields Electro Static Precipitator) have been experimentally determined using different rotational speeds and depths of insertion of spindle to investigate into the effects of particle size, rotational speed and powder compaction on the yield stress values. Additionally, yield stress values obtained for two different fly ash and cement samples have been related to their experimentally observed transport boundary to examine the relationship between yield stress and reliable transport limits. Also, viscosity measurements have been done experimentally on three different powders at different spindle depth of immersion and rotational speeds under fluidized and unfluidized states.

The main objectives of this chapter are to provide the details of experimental setup, instrumentation, and operating procedures. Standard calibration and operational procedures were used to perform experiments.

3.2 Experimental setup

Conveying of powders was performed at the Laboratory for Particle and Bulk Solids Technologies of Thapar University, India. The experimental setup was able to fluidize the powder so that the effects of aeration on the yield stress of the powders could be studied. For fundamentally studying the flow mechanism of pneumatic conveying systems, it was important to determine the yield stress and viscosity at different depths of fluidized bed to investigate into the effects of powder compaction and bed height on yield stress and viscosity. Brookfield YR 1 Rheometer with different vane spindles (V-72 to V-75) were used to measure the yield stress values and Brookfield LV DVIII Ultra Rheometer with Spindle LV-5 (65) was used for viscosity measurements. The schematic of the setup is shown in Figure 3.1.

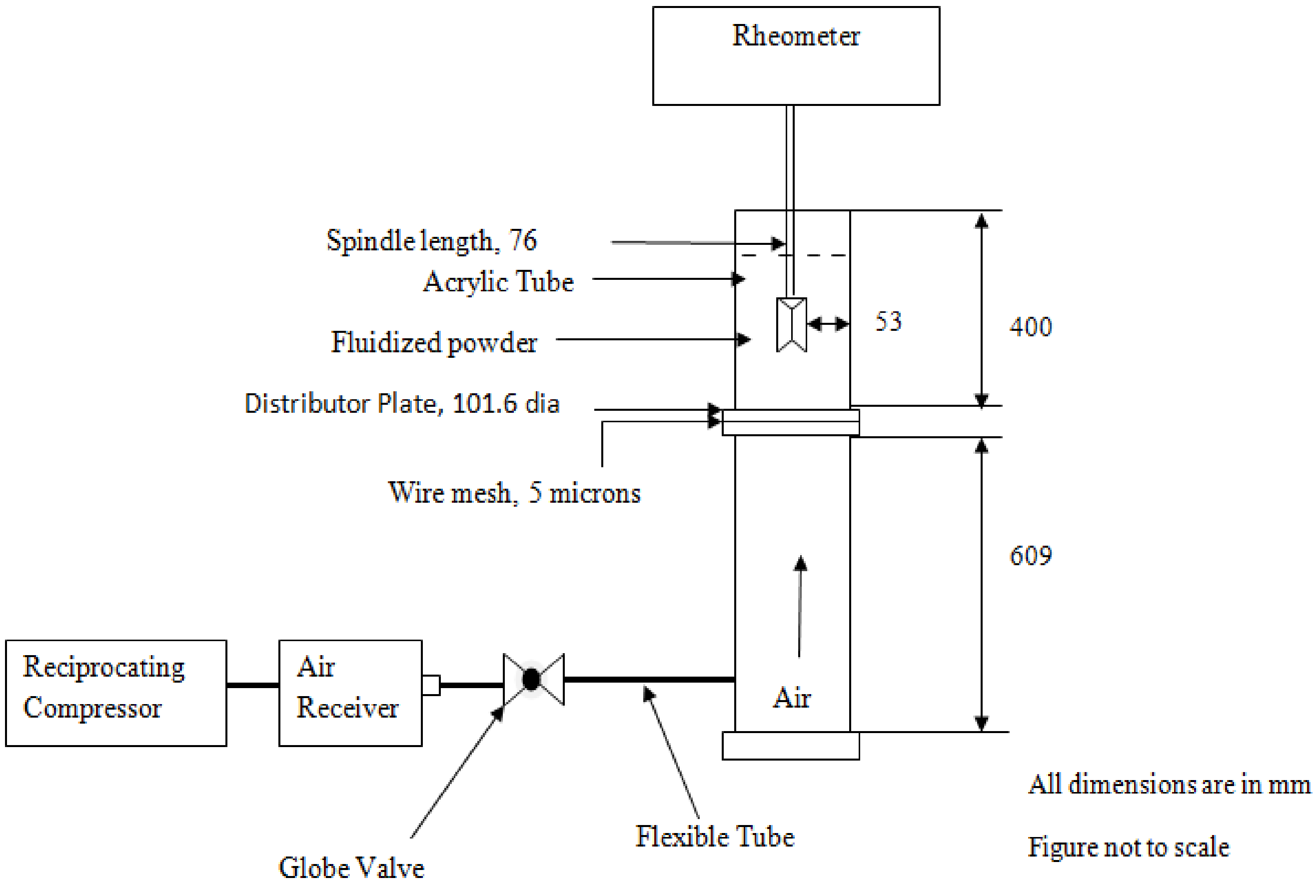

Figure 3.1 Schematic of the experimental setup

The setup consists of the following parts:

- Fluidizing chamber: This is a 400mm acrylic pipe with a flange which is attached to the distributor plate. The powder is poured into this chamber and the spindle is lowered to calculate the yield stress and viscosity.

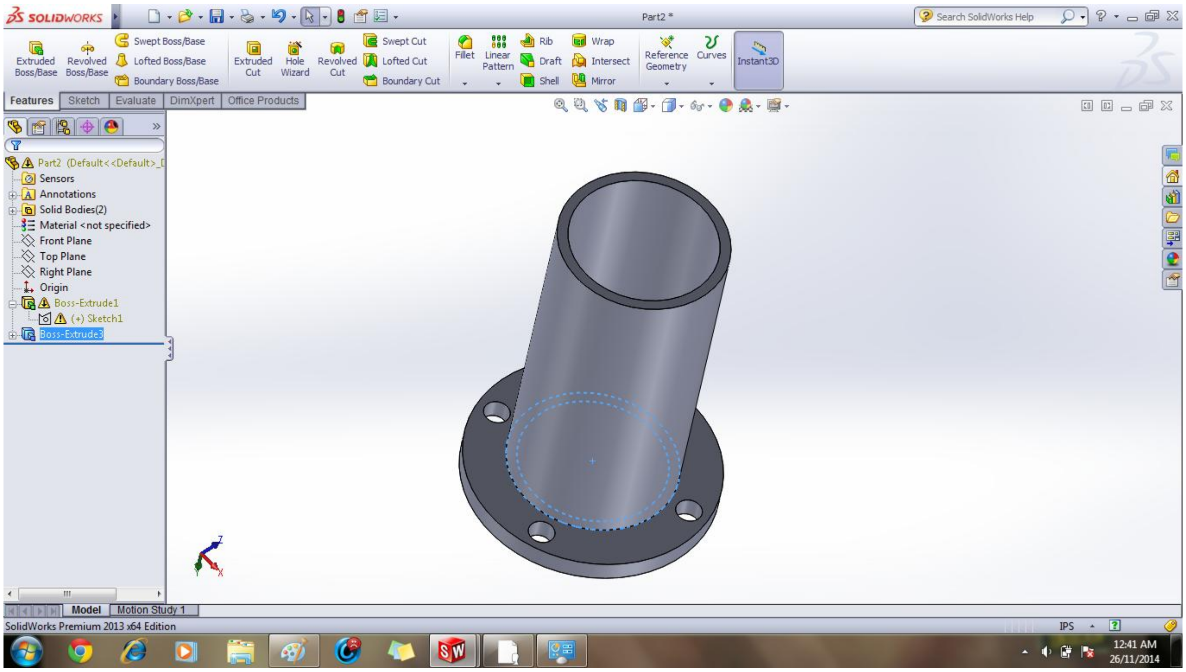

Figure 3.2: Fluidizing Chamber

- Distributor Plate: This is a plate which has holes of 6mm diameter drilled so that air from the compressor is uniformly fed to the fluidization chamber and there is proper fluidization of the powder.

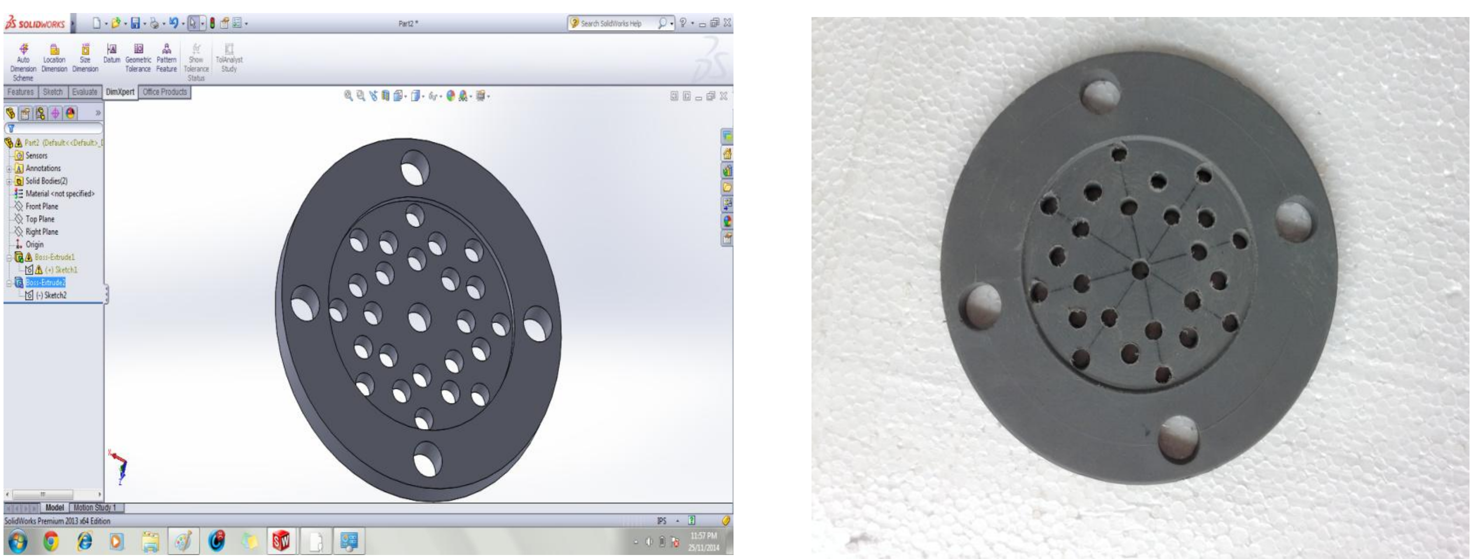

Figure 3.3: Distributor Plate

- Compressor: A 2 bar continuous supply reciprocating compressor was used for uninterrupted air supply for fluidizing the powder. A flexible tube was used to connect the outlet of the compressor to the lower fluidizing column. A globe valve was attached to control the supply of air.
- Mesh: A 5 μm pore-sized mesh was used above the distributor plate to separate the upper and lower fluidizing columns. The mesh prevented the powder from dropping into the lower fluidizing column from where the air was supplied.
- YR 1 Rheometer and vane spindles: Brookfield HV YR 1 Rheometer with EZ Yield software is used to calculate the yield stress and corresponding torque on the powders during unfluidized and fluidized states. Four spindles V-72, V-73, V-74 and V-75 have been used to measure the yield stress of different powders.
- LV DV III Ultra Rheometer and vane spindle: Brookfield LV DV III Ultra Rheometer along with LV-5 Spindle was used to calculate the viscosity at both unfluidized and fluidized states and at varying spindle depths and rotational speeds.

The actual picture of the experimental setup as taken in the laboratory during experiments is given in Figure 3.4.

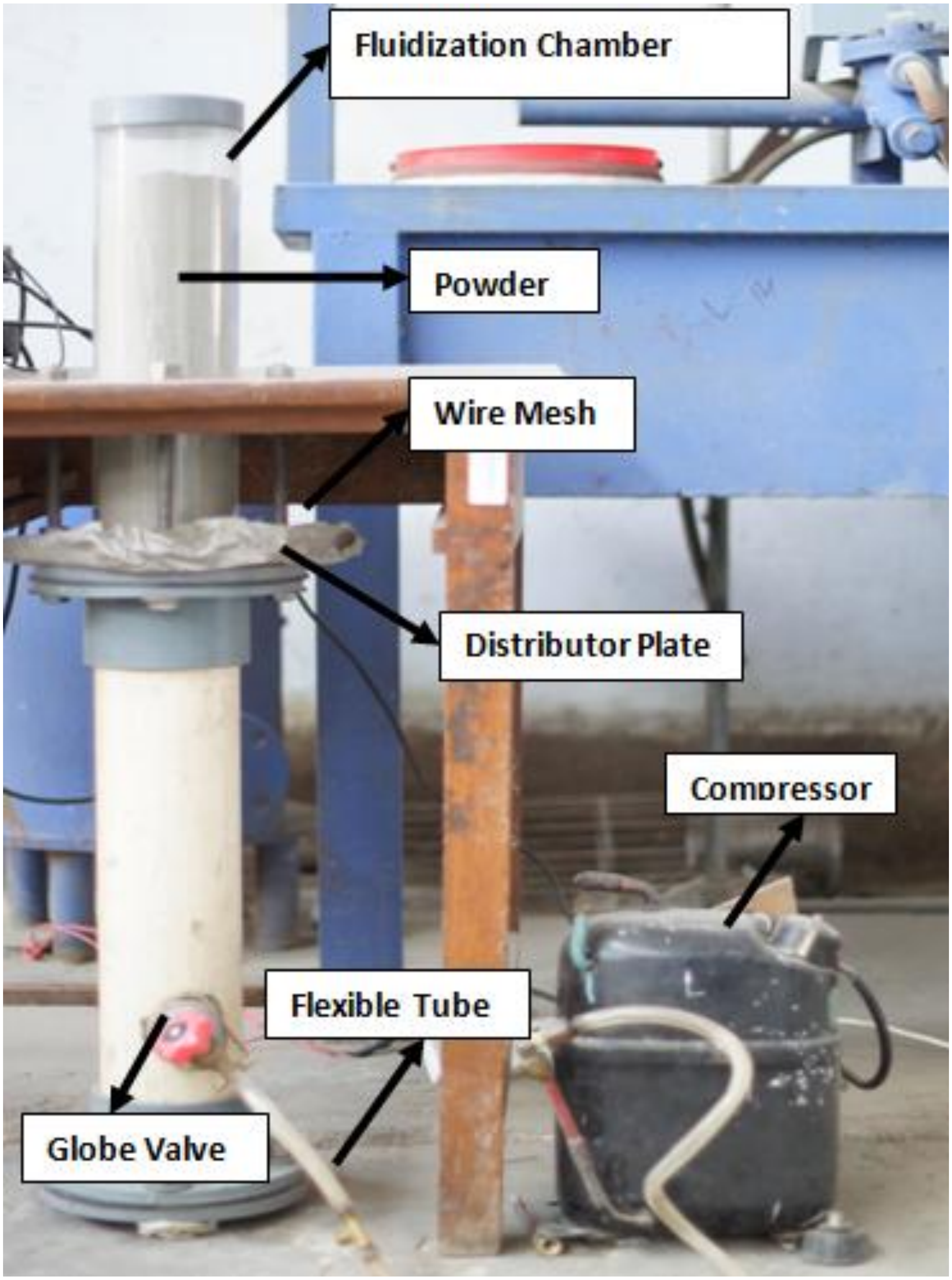

Figure 3.4: Setup

3.3 Test Powders

The yield stress testing was performed on powders with varying particle size. The particle sizes have been determined using laser diffraction technique. The physical properties of different powders are given in Table 1.

Table 3.1: Physical properties of powders

Powder No	Material	d_{10} (µm)	d_{50} (µm)	d_{90} (µm)	ρ_s (kg/m^3)	ρ_{bl} (kg/m^3)
1	Fly ash from power plant 1, ESP hopper 1	42	139	316	2015	848
2	Fly ash from power plant 1, ESP hopper 4	18	69	170	2025	818
3	Fly ash from power plant 1, ESP hopper 7	6	21	63	2025	759
4	Fly ash from power plant 2	3	19	140	1950	950
5	Fly ash from power plant 3	4	22	83	2370	660
6	Cement	3	19	75	2910	1080

The particle size of the powders was measured with the help of laser diffraction method. A graph has been plotted between volume density of the powders and the range of powders to find out the d_{10}, d_{50} and d_{90} values of the diameter. The graphs have been plotted for Powder number 1, 2 and 3 as shown by Figure 3.5, 3.6 and 3.7.

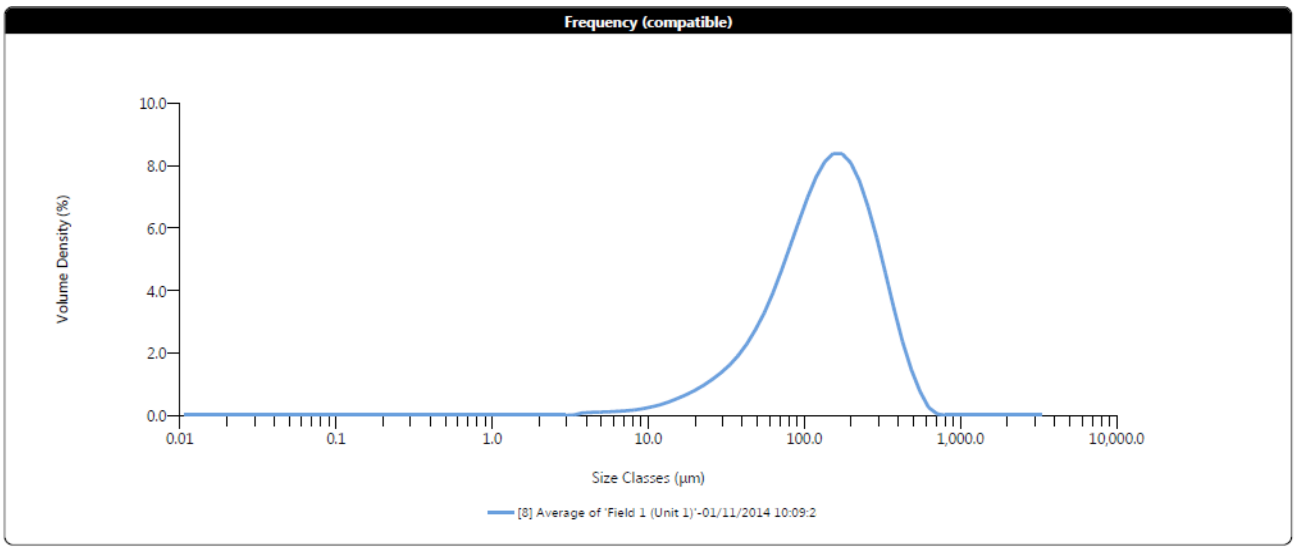

Figure 3.5: Volume Density versus size class for Powder number 1

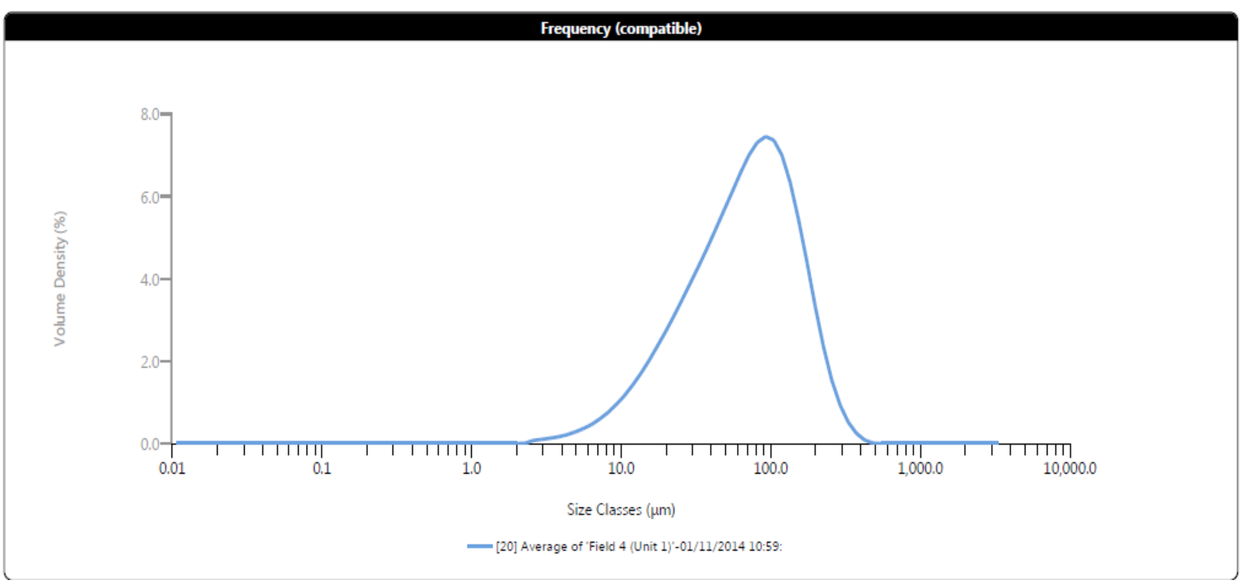

Figure 3.6: Volume Density versus size class for Powder number 2

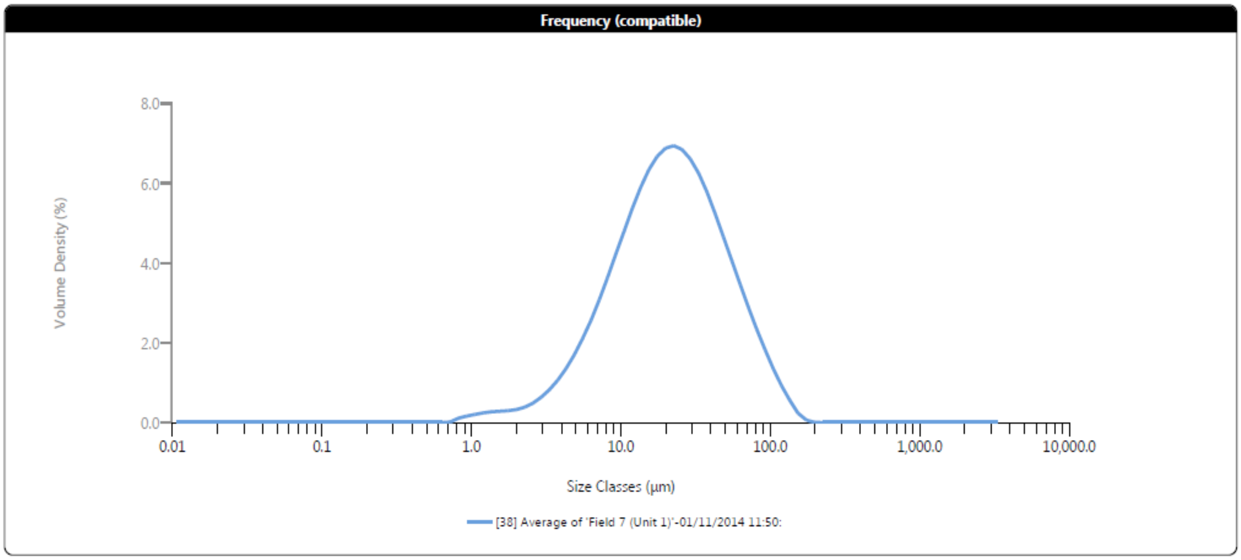

Figure 3.7: Volume Density versus size class for Powder number 3

Powder no. 1 to 3 were obtained from the different fields of Electro Static Precipitators (ESP) of the same power station (plant no.1), i.e. the measured yield stress values would indicate the effects of particle size on yield stress. Yield stress values obtained for fly ash and (powder no. 5) and cement (powder no. 6) were related to their minimum transport boundary limits. Yield stress was determined with different aeration rates and the values were compared with yield stress values of unfluidized states. Viscosity calculations were done on Powder No 1, 2 and 3 at different spindle depths and rotational speeds at both unfluidized and fluidized states. To achieve the unfluidized state, there was no air supply from the compressor. For fluidizing the powders, the compressor was turned on and air supply was controlled using the globe valve. At a particular air supply, when the powders were in a fluidized state, then the spindle was lowered slowly to measure the yield stress and viscosity.

3.4 Operating Procedure

The experiments were performed at an ambient room temperature of 25°C. Three different rotational speeds were used (1, 3 and 5 rpm). Three different depths of immersions (for the spindle) were selected as 1.6, 2.3 and 3.4 cm. Before measurement of the yield stress and viscosity, the powders were heated in an oven for 2 hours and at 90°C to drive off any moisture. This was done to prevent channeling of the powders and for achieve uniform fluidization. To check the repeatedly of the test results, all experiments were repeated three times.

The standard operating procedure used in the experiments is given below:

a) The powder was heated to drive off any moisture. After cooling of the powder, it was poured into the fluidization chamber under loose poured state.

b) The rheometer was switched on, leveled and auto-zeroed. The appropriate spindle was attached to the rheometer and was connected to the computer with the help of the software EZ- yield in case of yield stress measurements.

c) For experiments in the unfluidized states the powders remained in loose poured state. Selected rpm was set for the spindle rotation. The spindle of the rheometer was slowly immersed till the required depth and the reading was taken for yield stress and viscosity.

d) For fluidized state experiments, the compressor was switched on. The powder was aerated with the help of controlled air supply via the globe valve. When the powder was uniformly fluidized, the spindle was immersed and the readings were taken.

e) Yield stress and viscosity readings were taken at three different depths of spindle immersion to study the effect of powder compaction on yield stress and minimum transport points. Experiments were performed at three different rotational speeds of the spindle.

f) After generation of the required data, plots were constructed to study the effect of particle size and rotational speed on yield stress of the powders. Also, these were related to their minimum transport points and their corresponding Froude number lines to predict blockage points in conveying.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Measurement of Yield Stress with Brookfield YR 1 Rheometer

Yield stress was measured experimentally with the help of Brookfield YR 1 rheometer along with EZ Yield software and vane spindles. Brookfield YR 1 Rheometer was used because it can measure the yield stress of thin to highly viscous materials with stress range of .0125 Pa to 3200 Pa It can be used for a variety of products like yogurt, gels, ketchup, lotion, toothpaste, chocolate etc. Experiments were performed under both fluidized and unfluidized states to study the effect of aeration on the yield stress of powders.

Figure 4.1: Brookfield YR 1 Rheometer

Figure 4.2: Brookfield Vane spindles (V-72, V-73, V-74 and V-75)

The specifications of the spindles used were:

Table 4.1: Spindle Shear stress range

Spindle	Shear Stress Range (Pa)
V- 72	2 – 20
V- 73	10 – 100
V- 74	100 – 1000
V- 75	40 – 400

The EZ yield software is used with the YR 1 Rheometer. It provides the user with the options to create a program and download it to the rheometer. The program is created by pitting into the values of the spindle number, rotational speed of the spindle, zero time and the immersion mark selected on the spindle. The software displays a stress strain curve starting from the time the spindle starts rotating to the time the yield point is reached. It also displays the yield stress value of the material under specific rotational speed. The interface of the software is shown below:

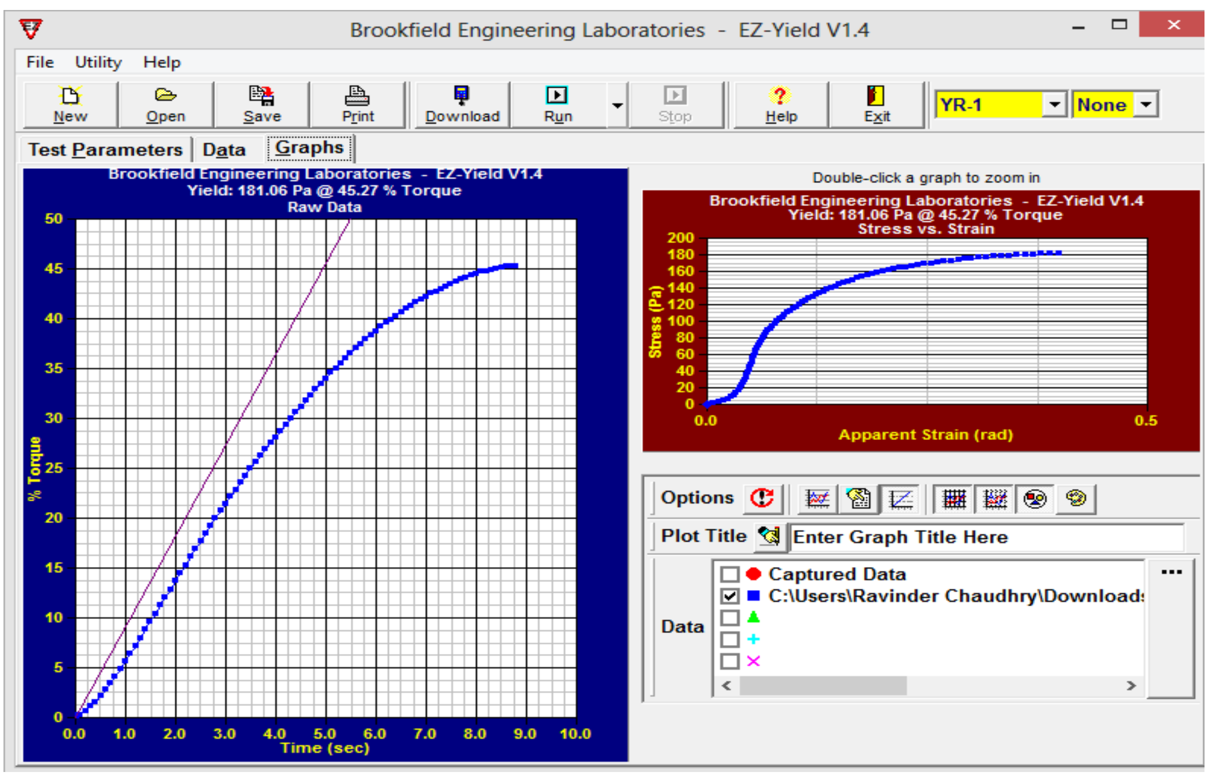

Figure 4.3: EZ Yield Software

4.1.1 Investigation into the effects of particle size on yield stress

The yield stress was measured for all the powders with three different depths of spindle immersion and three rotational speeds of the spindles in fluidized and unfluidized states of powders. The results are presented in Figures 4.4 to 4.9. Figure 4.4 to 4.7 provide yield stress values for three powders (powder number 1, 2 and 3) under fluidized and unfluidized states. In Figure 4.4 and 4.5, yield stress has been plotted against the depth of immersion for fluidized and unfluidized states. Results of three levels of depth of spindle immersion have been shown.

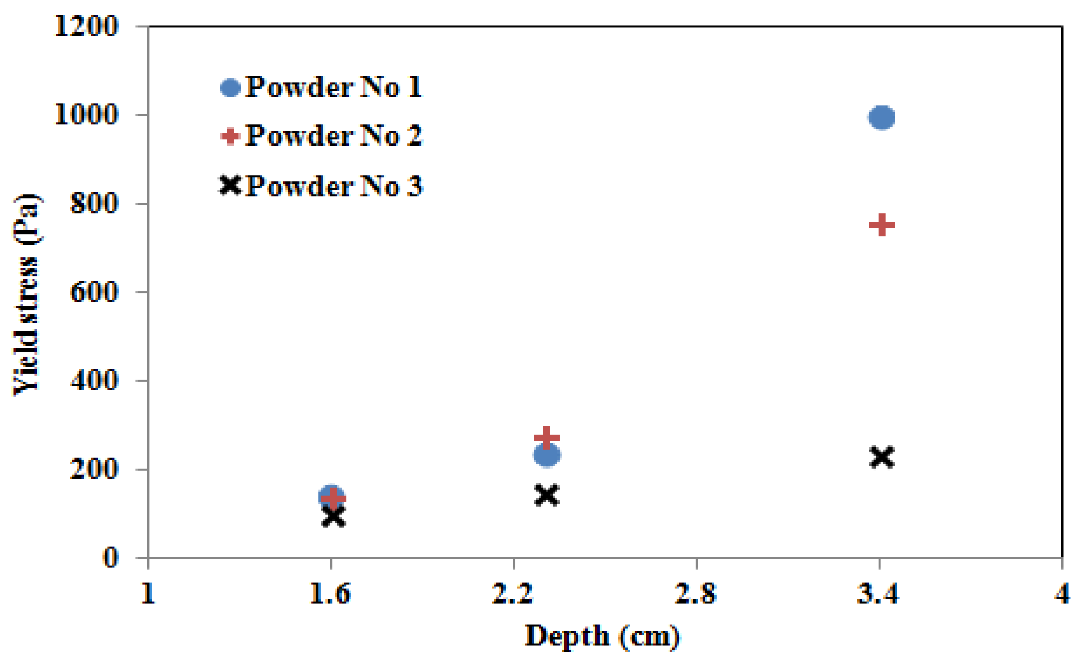

Figure 4.4: Yield stress versus depth of immersion of spindle for different particle sizes (powder no. 1, 2 and 3) under unfluidized condition

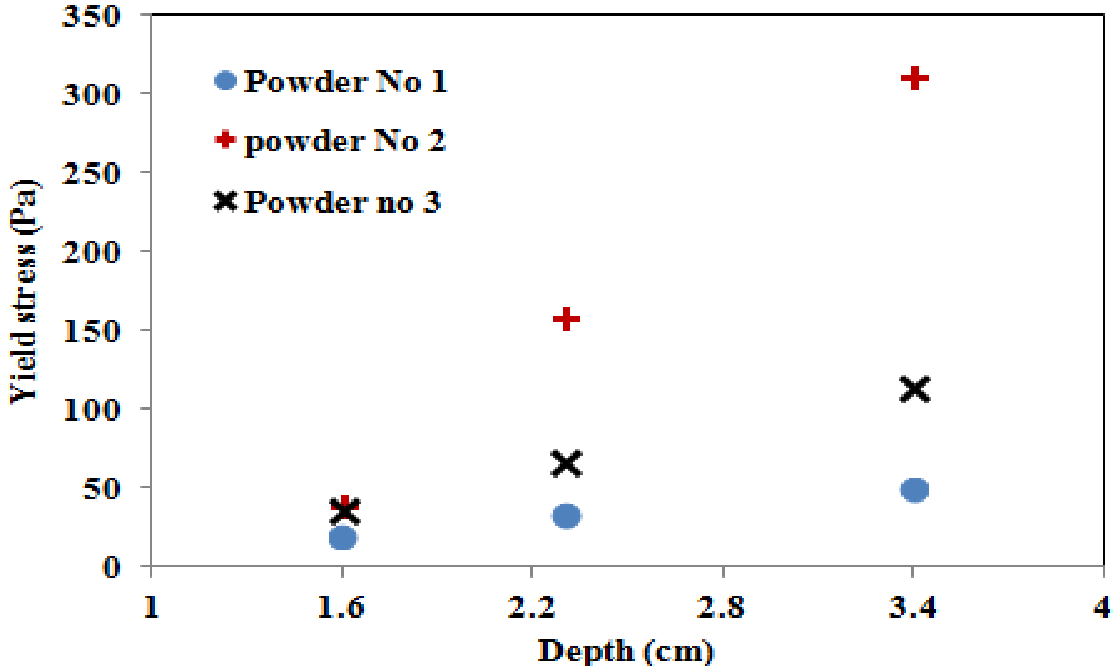

Figure 4.5: Yield stress versus depth of immersion of spindle for different particle sizes (Powder number 1, 2 and 3) under fluidized condition

Figure 4.4 and 4.5 show that the yield stress values increased with the depth of spindle immersion. This is due to more weight of powder is exerted upon the vanes of the spindle and on powders (contributing in powder compaction) and hence more will be the force required to make the powder flow. It is observed that the yield stress is maximum for powder no. 1 in unfluidized state, which has the largest median particle size amongst all the powders. Also, powder no. 3 (having the smallest particle size) has the least yield stress. Therefore, with an increase in particle size, yield stress also increased in unfluidized state. When the powders were fluidized, yield stress values have considerably decreased compared to those under unfluidized condition. This property of fine powders to retain the air is used in the fluidized dense-phase pneumatic conveying. When air is supplied into a bed of powders, the yield stress reduces considerably, which promotes powder flow. It can be seen that for powder 1, which has the highest yield stress values in unfluidized state, provides least yield stress when it is fluidized. This can be accounted for the larger particle size and higher loose poured bulk density. The air gets entrapped in the voids between larger particles of the powder (compared to the high packing density of the finer particles) and the yield stress significantly gets reduced. Fig 4.6 and 4.7 show the variation of yield stress with rotational speed of the spindle. The selected values of rotational speeds were low (1, 3 and 5 rpm) to prevent powders getting permanently displaced from its position due to the centrifugal force of rotation or by creating a groove, that would promote relatively unconstrained rotation of the spindle.

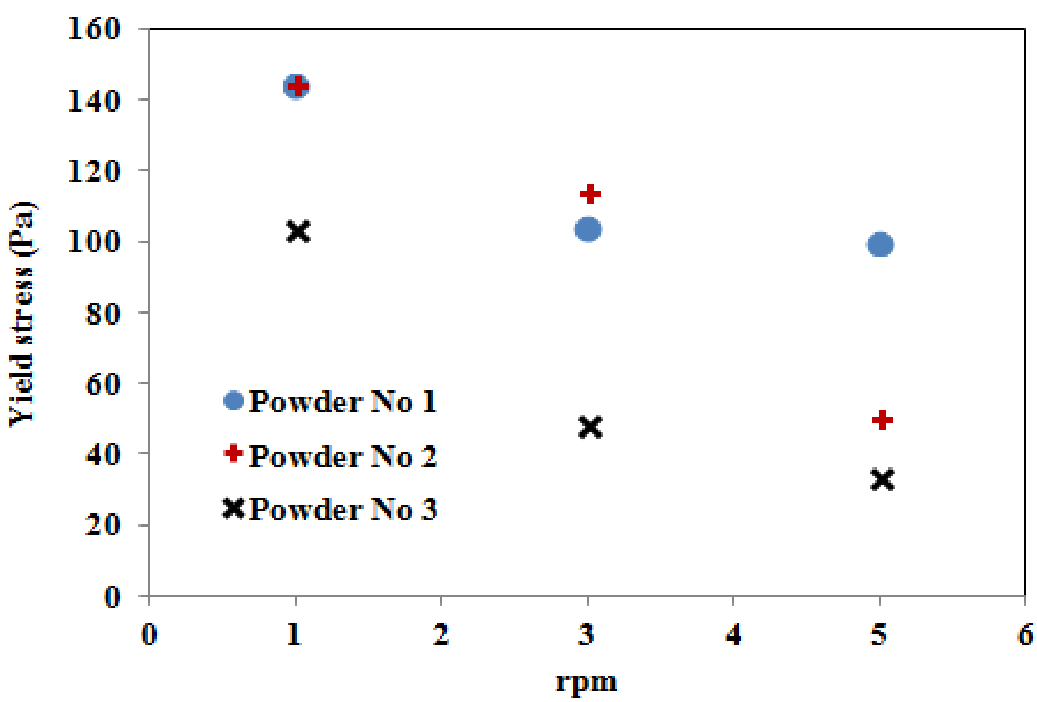

Figure 4.6: Yield stress versus rpm of spindle for different particle sizes (powder number 1, 2 and 3) under unfluidized condition

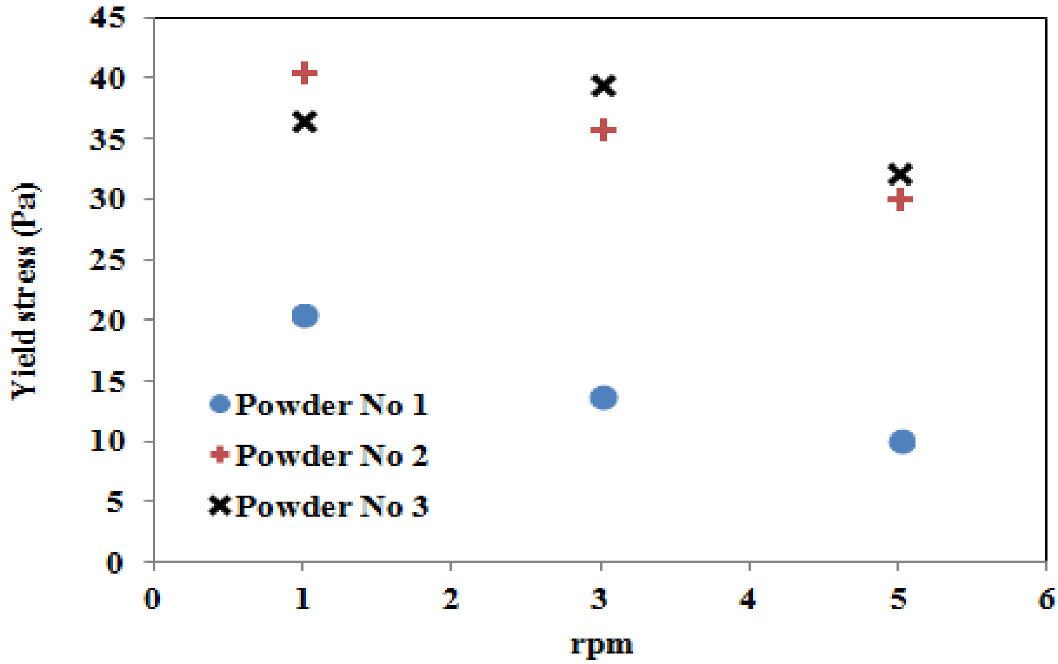

Figure 4.7: Yield stress versus rpm of spindle for different particle sizes (Powder number 1, 2 and 3) under fluidized condition

It was observed that an increase in the rotational speed has reduced the yield stress of the powders. A probable reason for this behavior could be associated with the property of powders. Fine powders tend to behave as a pseudo fluid, especially when aerated. They are not proper liquids that would return to their original position upon considerable disturbances. When the spindle rotates in the powders, practically it was observed that some of the powders got displaced due to the centrifugal force acting on them. Unlike liquids, these powders did not fully return to their original positions. Thus, air pockets were created and yield stress got reduced with increase in rotational speed of the spindle.

4.1.2 Effect of yield stress of powder on minimum transport limits

Figure 4.8 and 4.9 present the yield stress values for the other two fly ash samples (powder no. 4 and 5) and cement. The variations of yield stress values with depth of immersion and the rotational speed of the spindles show similar trends obtained for three fly ash samples of power plant 1 (refer to Figure 4.4 to 4.7).

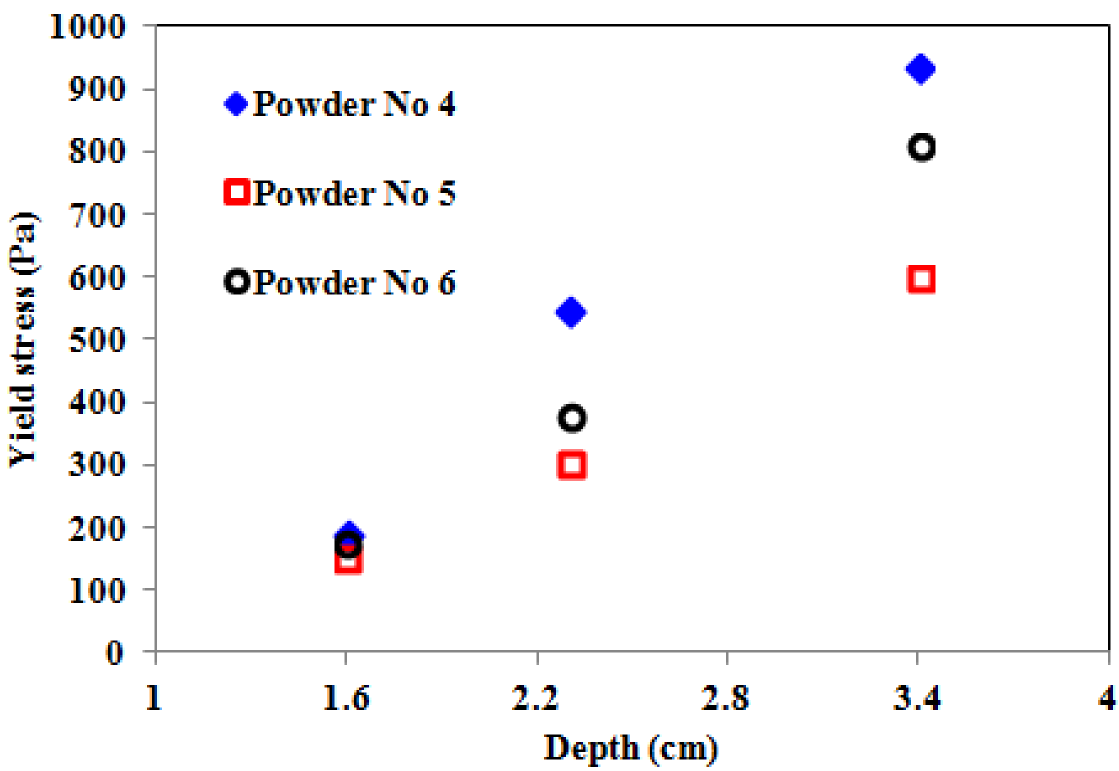

Figure 4.8: Yield stress versus depth of immersion of spindle for different powders (Powder number 4, 5 and 6) under unfluidized condition

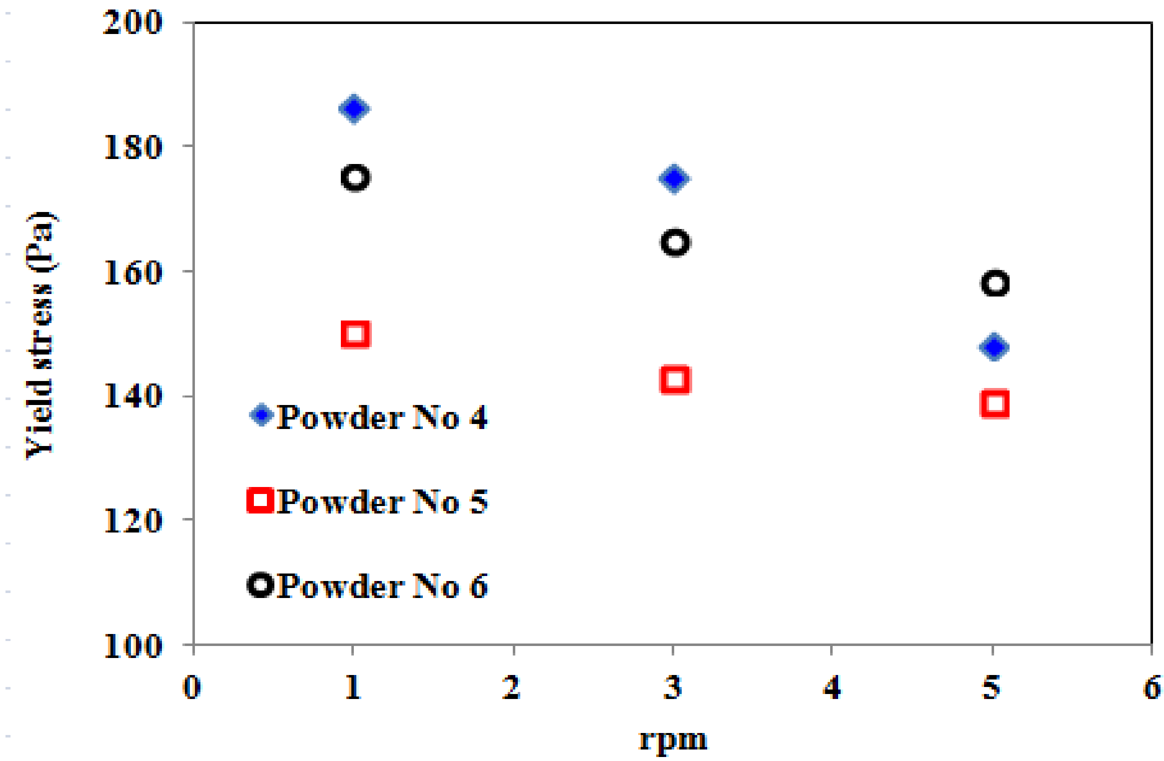

Figure 4.9: Yield stress versus rpm of spindle for different powders (powder number 4, 5 and 6) under unfluidized condition

Fly ash and (powder no. 5) and cement (powder no. 6) were conveyed in larger and longer pipelines (65 mm I.D x 254 m long, 80/100 mm I.D stepped diameter x 407 m long) (Setia et al., 2015). Detailed description of the test set up and experimental program are provided by Setia et al. (2015). Using the test data, they developed pneumatic conveying characteristics for different solids and air mass flow rates for these two pipelines and products (fly ash and cement). In this work, conveying characteristics of the two different products for the same pipeline have been superimposed and the extreme left points of the PCC have been designated as the minimum transport limits. These points (minimum transport limit) indicate the minimum air flow rates required to sustain stable conveying. Below this air flow rate, the conveying would become unstable with product deposition in the pipeline and is characterized by large pressure fluctuations. Further reduction of air flow rate would result pipeline blockage. Figure 4.10 and 4.11 show the superimposed pneumatic conveying characteristics for fly ash and cement for the 65 mm I.D x 254 m long and 80/100 mm I.D x 407 m long pipelines, respectively. Points A and B (for the 65 mm I.D x 254 m long pipeline) and points C and D (for the 80/100 mm I.D x 407 m long pipeline) indicate the minimum transport conditions. A, C and B, D correspond to the higher and lower material flow rates, respectively. Froude number values corresponding to these points have been calculated, as Froude number has been referred to be an important parameter to define the minimum transport boundary.

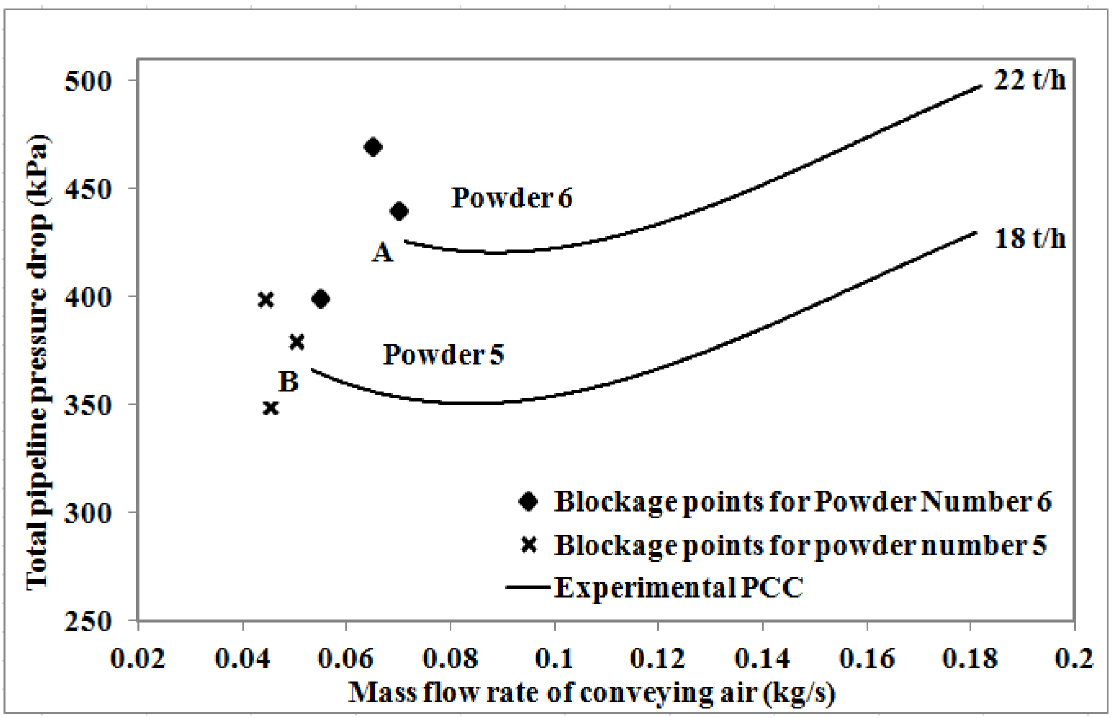

Figure 4.10: Pneumatic Conveying Characteristics and minimum transport limit for fly ash (powder no. 5) and cement (powder no. 6) conveyed through 65 mm I.D x 254 m long pipeline

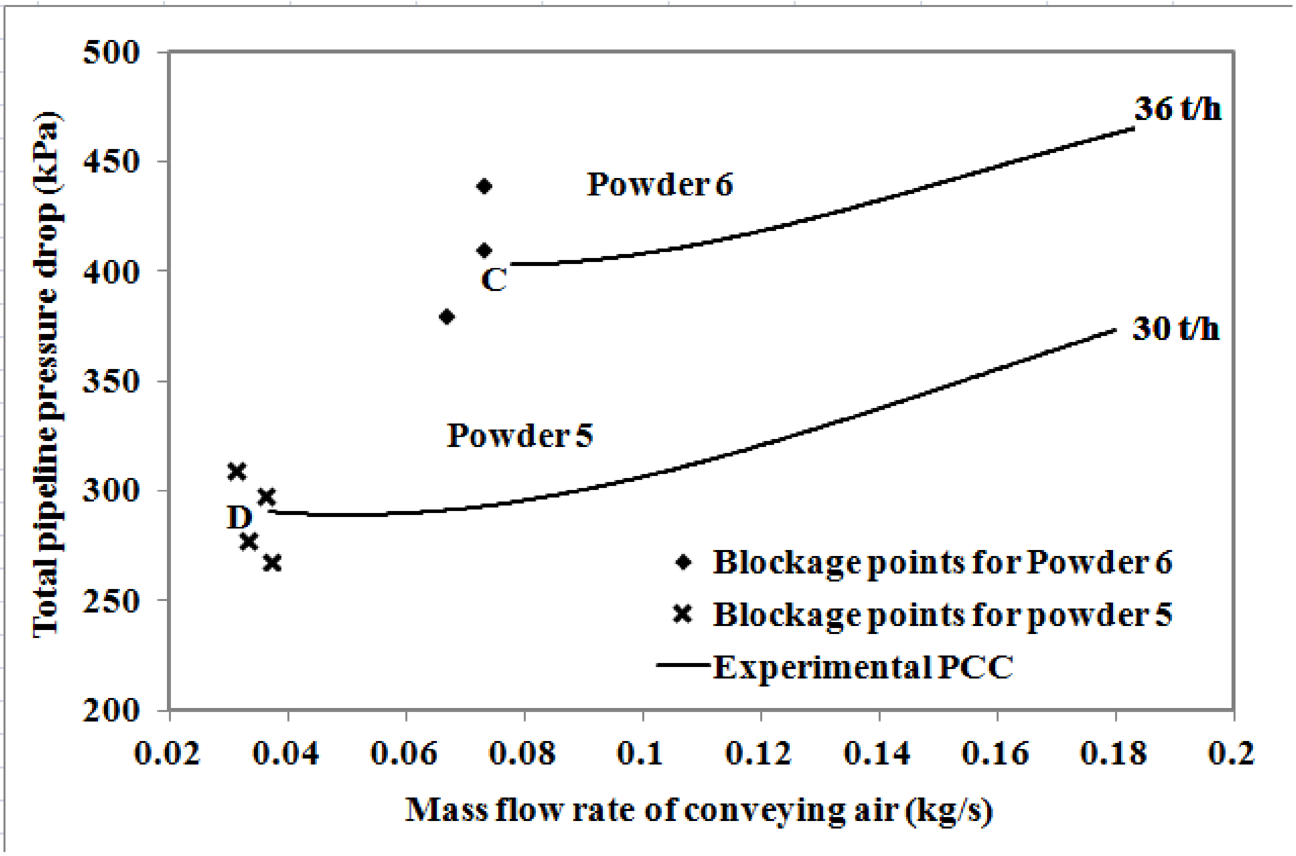

Figure 4.11: Pneumatic Conveying Characteristics and minimum transport limit for fly ash (powder no. 5) and cement (powder no. 6) conveyed through 80/100 mm I.D x 407 m long pipeline

Minimum transport condition can be considered as the limiting condition where the powders (dunes) are just on the verge of flow or undergoing yield phenomenon. Yield stress corresponds to a point where the material starts to deform plastically and begins to flow. In a similar way, it can be imagined that this is the same point corresponding to the point of minimum transport on the PCC, as it also depicts the onset of material flow in a pipeline. It can be seen from Table 4.3 that the material having less yield stress has a lesser Froude number. Table 4.3 shows the relation between yield stress and minimum transport limit. The yield stress values considered here are for unfluidized condition of powders, spindle rotation speed of 1 rpm and for 1.6 cm of depth of spindle immersion in the powdered bed.

Table 4.3 Yield stress and Froude number (at minimum transport limit) for different powders

Pipeline	Material	d_{50} (μm)	ρ_s (kg/m^3)	ρ_{bl} (kg/m^3)	Yield Stress (Pa)	Fr_{min}
65 mm I.D x 254 m long pipeline	Fly ash (powder no. 5)	22	2370	660	320	3.5
	Cement (powder no 6)	19	2910	1080	431	4.2
80/100 mm I.D x 407 m long pipeline	Fly ash (powder no. 5)	22	2370	660	320	1.7
	Cement (powder no 6)	19	2910	1080	431	2.9

Table 2 shows that for the same pipe, an increase in the value of yield stress has resulted in higher Froude number requirement. It can be considered that higher yield stress (caused by inadequate aeration of powders) would require larger amount of air flow to keep the dunes under flow condition. Higher yield stress could be related to the increased tendency of pipeline blockage and to compensate for this, appropriate amount of air flow must be provided.

4.2 Measurement of Viscosity with Brookfield LV DV III Ultra Rheometer

Brookfield LV DV III Ultra along with cylindrical spindle was used to measure viscosity of the powders under fluidized as well as unfluidized states. Brookfield LV DV III Ultra was used because it covered a wide range of viscosity ranging from 1 cP to 6 million cP. It can also take measurements for rpm ranging from 0.01 to 250. The same experimental setup was used for viscosity measurements. Only the rheometer was changed in the previous setup. In viscosity measurements, no software was required to develop the curves. The rheometer directly displayed the values of the viscosity on cP. In these experiments, viscosity was tested for three products (Powder 1, 2 and 3) in unfluidized and aerated states. Three rotational speeds of the spindle were selected (rpm 1, 3 and 5) and three depths of spindle immersion were used (1.6 cm, 2.3 cm and 3.4 cm). The aim of these experiments was to study the effect of powder compaction and rotational speed of the spindle on the viscosity of the powders. Also, the effect of fluidization on the viscosity of powders was studied.

Figure 4.12: Brookfield LV DV III Ultra Rheometer

The spindle used was LV- 65 (5) which had a viscosity measuring range of 2000 cP to 4 million cP. The standard procedure of experiment was same as for yield stress measurements. While making viscosity measurements, the values obtained cover a wide range due to the behavior of fluidized powder. Hence, the experiments have been repeated thrice to check the repeatability of the results. Given below are the viscosity values for three powders (Powder 1, 2 and 3) for fluidized and unfluidized states using three depths of spindle immersion and three rotational speeds of the spindle

Table 4.4 gives the viscosity values for powder 1 in fluidized as well as unfluidized states.

Table 4.4 Viscosity measurements for Powder 1

Rpm	Depth	Viscosity (cP) in unfluidized state	Viscosity (cP) in fluidized state
1	1	180000	79183
1	2	230000	NA
1	3	313000	NA
3	1	54300	23500
3	2	74000	NA
3	3	116000	NA
5	1	5500	2639
5	2	43221	NA
5	3	74135	NA

For powder 1, three rotational speeds have been considered, but measurements have not been taken for different depths of spindle immersion under fluidized condition. This is due to the fact that Powder 1 has the biggest median particle size. This caused bubbling of the powders under fluidized state as shown by Figure 4.13. The bed did not fluidize as a whole but bubbling took place due to which measurements could not be taken at different depths.

Figure 4.13: Bubbling bed for Powder 1

It can be observed from the experiments that the viscosity values drastically dropped after fluidization as compared to the unfluidized states. This property of air retention by fine powders is the basic principle employed in the transfer of bulk solids through pneumatic conveying. When air is fed into the powders, the viscosity reduces considerably and hence less power is used to transport the materials.

Table 4.5 given below gives the viscosity values of Powder 2 under fluidized and unfluidized states with three depths of spindle immersion and three different rotational speeds of the spindle.

Table 4.5 Viscosity measurements for Powder 2

Rpm	**Depth**	**Viscosity (cP) in unfluidized state**	**Viscosity (cP) in fluidized state**
1	1	360000	160000
1	2	650000	370000
1	3	840000	410000
3	1	131000	99000
3	2	202000	114000
3	3	277000	152000
5	1	71035	32153
5	2	129000	82000
5	3	223000	104000

It can be observed from Table 4.5 that as the depth of the spindle increases, the viscosity increases. This is due to the fact that as depth increases, more weight of powders is exerted and the powders get compacted. Thus compaction of powders increases the viscosity of powders.

Also it has been observed from the experimental results that as the rotational speed of the spindle increases, the viscosity values decrease. This is because fluidized powders are not pure liquids. They exist in an intermediate state between solids and liquids. When the spindle rotates in the powder, the powder gets displaced and unlike liquids they do not take back their original position. The powders get displaced due to the centrifugal force of the rotating spindle and a groove is created. The air enters the groove and takes place of the displaced powder. The friction between solid powder particles reduces and hence, the viscosity decreases.

Table 4.6 gives the viscosity values under fluidized and unfluidized states with three depths of spindle immersion and three different rotational speeds.

Table 4.6 Viscosity measurements for Powder 3

Rpm	Depth	Viscosity (cP) in unfluidized state	Viscosity (cP) in fluidized state
1	1	187000	15597
1	2	252000	71985
1	3	310000	157000
3	1	52980	7988
3	2	60125	32395
3	3	250000	93980
5	1	36000	5999
5	2	40000	17269
5	3	120000	40000

Powder 3 also shows the same trends as both the above powders. With depth the viscosity increases due to compaction of powders and with increasing rotational speed, the viscosity decreases due to displacement of powder by air.

Figure 4.14: Channeling for cohesive Powder 3

It has also been observed that for Powder 3, it possessed the smallest median particle size. Also, it was cohesive in nature and had the tendency to channelize as shown by figure 4.14. The bed could not be uniformly fluidized and the air had a tendency to form a channel and escape. This was due to the small particle size and the cohesive nature of the powder.

CHAPTER 5: CONCLUSION AND FUTURE SCOPE OF WORK

5.1 Conclusion

An experimental setup was designed and fabricated to fluidize the powders and rheology tests were performed on them. Yield stress measurements were done on six different powders (fly ash and cement) under fluidized and unfluidized states. It can be concluded from the experimental results that yield stress decreased significantly with fluidization. Yield stress was found to be dependent on the median particle size of the material. As the particle size increased, the yield stress values increased in the unfluidized state. It was that yield stress considerably increased with the depth of spindle immersion due to increased weight exerted by the powder depth. It was also found that yield stress decreased with increase in rotational speed. Froude numbers of the minimum transport boundary points obtained from the pneumatic conveying characteristics for fly ash and cement conveyed in two pipelines were related to the yield stress values of the powders. It was found out that as the yield stress of powders increased, the Froude number requirement for minimum transport also increased. Additionally experiments were used to measure the viscosity of three powders (fly ash from different fields ESP of a thermal power plant) in both fluidized and unfluidized states. It was observed from the results that the viscosity also decreased considerably after fluidization. It was also found out that viscosity follows the same trend as yield stress. It increases with increase in depth and decreases with increase in rotational speed of the spindle.

5.2 Future scope of work

Further scope of work will include:

(i) Future scope of research would include further validation of the findings of the present work for other powders and relating solids frictions to the rheological properties of powders.

(ii) An effort has been made to relate rheology with fluidization and minimum transport in this study, but, still there are many parameters such as wall friction angle, coefficient of sliding friction and relation of rheology parameters with material properties which need to be further studied and investigated.

(iii) Modelling fluidized dense phase of powders and including above parameters to create a reliable, safe and en efficient pneumatic conveying system, taking into the effects of rheology.

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