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Modelling fluidized dense-phase pneumatic conveying of fly ash

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ABSTRACT

This paper presents the results of an ongoing investigation into modelling important design criteria, such as minimum transport condition, straight-pipe pressure drop and solid friction factor for fluidized dense-phase pneumatic conveying of powders. Fly ash (median particle diameter: 19 μm; particle density: 1950 kg/m^3; loose-poured bulk density: 950 kg/m^3) was conveyed over a wide range of flow conditions (from fluidized dense- to dilute-phase) under different conditions of pipeline diameters and lengths (viz. 43 mm I.D × 24 m length, 54 mm I.D × 24 m length, 69 mm I.D × 24 m length and 69 mm I.D × 70 m length). To define the safe minimum transport boundary, a Froude number based criteria at the pipe inlet has been used ($Fr_i = 7$). The Froude number based criterion is aimed to address the requirement of different conveying velocities for different pipe diameters. Straight-pipe pneumatic conveying characteristics obtained from two sets of pressure tapings installed at different locations of pipeline have shown that the trends and relative magnitudes of the pressure drops can be significantly different depending on the location of pressure tapping points, thus indicating a change in flow mechanism along the direction of flow. A new approach of modelling solid friction factor using a volumetric loading ratio term has provided better scale-up accuracy when the model predictions were compared with experimental data. This method of modelling solid friction is aimed to address the partial filling of pipe's cross section by the dune of solids, which appears to be a better representation of the flow conditions, especially for the dense-phase pneumatic conveying of fine powders.

1. Introduction

Pneumatic conveying of fly ash is widely used in pulverized coal fired thermal power plants all over the world. Such dry handling and conveying technology make it possible for the fly ash to be subsequently used for other purposes, such as fly ash in dry form can be mixed with cement. Other reasons include: pneumatic conveying is totally enclosed, environmentally friendly, provides increased workplace safety; relatively low capital/maintenance costs (for a well-designed system); layout flexibility; and ease of automation and installation. For countries such as India, where about 60% of total installed capacity of electricity generation is through coal fired power generation route using coals having ash content of as high as 40–50% (for worst coals), a large amount of fly ash has to be pneumatically conveyed everyday from Electro Static Precipitator (ESP) hoppers to remote silos with a total pipeline length of even up to 1 km (depending on the plant layout). This is achieved by either using a combination of negative and positive pressure systems (i.e. by evacuating the ash from individual ESP hoppers to a local surge hopper using a vacuum conveying system and then using a positive pressure conveying system to transport fly ash from the surge hopper to remote silos) or by positive pressure systems only (where blow tanks are placed under each ESP hopper, which directly transfer the fly ash to remote silo using compressed air as the transport medium). The positive pressure systems can be of two types: dilute-phase (or suspension flow) and dense-phase (or non-suspension flow). In dilute-phase conveying, the carrier gas velocity is sufficiently high to suspend all the particles for conveying. Due to the dispersed and suspended nature of the dilute-phase conveying, the designers and researchers have achieved relatively good success in modelling the relevant particle interactions and mechanisms to develop numerous friction factor and pressure drop models [1]. However, this mode of conveying results in higher gas flows (and reduced solid loading ratio), larger sized compressor (i.e. higher energy consumption), larger pipe, fitting and support dimensions, increased chance of wear of pipe and bends (i.e. increased maintenance requirement) and larger sizing of bag filters. Due to these disadvantages of dilute-phase systems, the plant owners and designers are showing increasing interest in recent times to employ dense-phase pneumatic conveying systems (instead of the conventional dilute-phase mode) to take advantage of the fluidized dune flow capabilities of fly ash under aerated condition. For about 800–1000 m long pipe (e.g. from intermediate surge hopper to remote silo in a power plant), a well designed fly ash dense-phase pneumatic conveying system would typically operate with a solid loading ratio of 30 (instead of 10–15 for a dilute-phase system) and with an initial conveying velocity 5–7 m/s (instead of about 15 m/s for dilute-phase). This would result in a substantial amount of savings in energy and initial capital costs in terms of smaller compressor and pipe sizes and maintenance

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(reduced frequency of wearing of bends). In spite of such merits and potential to be a better alternative of fly ash conveying, wide spread installation of such system is still limited as designing a reliable fluidized dense-phase system is a difficult task due to the highly turbulent and complex nature of the concentrated dune flow [1,2]. For a reliable design of industrial scale pneumatic conveying systems, the two most important parameters that are to be accurately estimated are: (i) total pipeline pressure drop and (ii) minimum transport criteria. Over-estimation of total pipeline pressure drop would result in unnecessarily higher supply of air flow, energy cost and wearing of pipeline due to excessive conveying velocity. Under-prediction of total pipeline pressure drop would cause reduced material throughput rate. Incorrect estimation of minimum transport condition will result in particle deposition in pipes, leading to pipe blockage [1,3]. In fact, a majority of the practical installations facing unreliable operations and requiring troubleshooting suffer from problems arising out of the above two reasons. Hence, these design parameters (pipeline pressure drop and blockage criteria) must be accurately modelled and scaled-up with high reliability. The pressure drop for the flow of solid and gas flow through a straight horizontal pipe section can be represented using Eq. (1). This equation was originally presented by Barth [4] and believed to be for coarse particles in dilute-phase flow. However, various other researchers, such as Pan and Wypych [2], Stegmaier [5], Weber [6], Rizk [7], Pan and Wypych [8] and Jones and Williams [9] have subsequently used this equation to predict the pressure loss for the fluidized dense-phase pneumatic transport of powders, such as fly ash, for horizontal straight pipes.

$$\Delta P = \left(\lambda_f + m^* \lambda_s\right)(L/D)\rho\left(V^2/2\right) \tag{1}$$

The main task in Eq. (1) is to model the solid friction factor accurately. Whereas more fundamental modelling and scale-up procedures based on powder mechanics have been established for low-velocity dense-phase slug-flow of granular materials, modelling solid friction for fluidized dense-phase conveying of fine powders has remained a relatively more difficult challenge due to the complex and turbulent nature of the moving bed [1], where it is very difficult to link the particle and bulk properties to the flow mechanisms during actual conveying conditions. Due to these difficulties in modelling, empirical power function based models have been employed by various previous researchers [4–11] over the years to avoid the need of developing fundamental relationships between solid friction factor and the relevant particle and bulk properties. These models have used different dimensionless parameters and have shown only limited success under scale-up evaluation [1]. Hence, there is a requirement to conduct further studies on important design parameters such as straight pipe pressure drop models for solid friction and minimum transport criteria with an aim to provide the industry a reliable scale-up procedures for dense-phase pneumatic conveying of fly ash.

2. Experimental data

Conveying trails were performed using the Indian fly ash with different pipeline configurations. Table 1 lists the physical properties of the fly ash.

A typical schematic of the test set up used for fly ash conveying is shown in Fig. 1. Kirloskar made electric-powered Model KES 18-7.5 rotary screw compressor was used having the capacity of 3.37 m^3/min

Table 1
Physical properties of fly ash conveyed.

Powder	Median particle diameter, d_{50} (μm)	Particle density, ρ_s (kg/m^3)	Bulk density, ρ_{bl} (kg/m^3)
Fly ash	19	1950	950

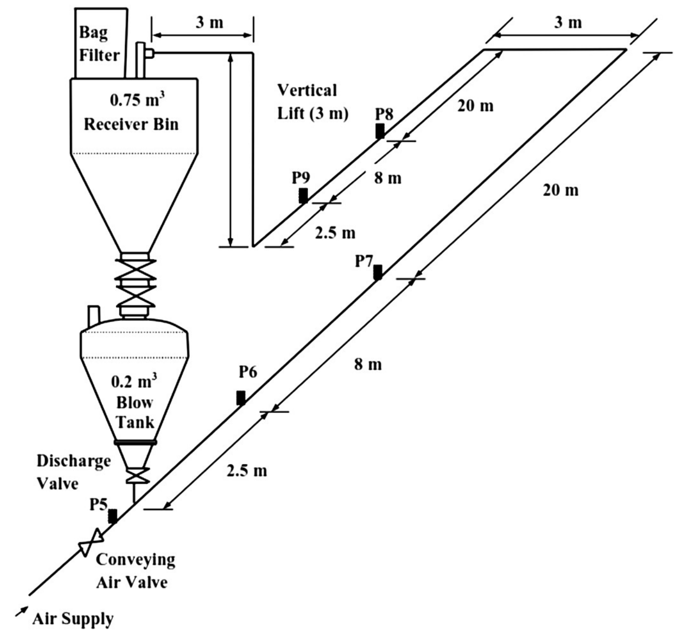

Fig. 1. Layout of the 54 mm I.D. × 70 m test rig.

of free air delivery and maximum delivery pressure of 750 kPa. Air flow control valve was installed in the compressed air line upstream of the blow tank to vary the conveying air flow rates over a wide range of air flows. For the measurement of air flow rates, a vortex flow metre was installed in the compressed air line. Bottom discharge type blow-tank was used as feeder having 0.2 m^3 capacity of water fill volume. It was mounted with solenoid operated dome type material inlet, outlet and vent valves. The blow tank was provided with air supply system with the help of orifice plate at the air inlet to blow tank. A receiver bin of 0.65 m^3 capacity was installed on top of blow tank. The receiver bin was fitted with bag filters having pulse jet type cleaning mechanism. The blow tank and receiver bin were supported by shear beam type load cells. Different mild steel pipelines of 43 mm I.D × 24 m length, 54 mm I.D × 24 m length, 69 mm I.D × 24 m length and 69 mm I.D × 70 m length were used as the test rigs. The test loops included a 3 m vertical lift and 4 × 90° bends having 1 m radius of curvature. Various static pressure measurement points were installed along the pipeline and bends, where P5 was used to measure the total pipeline pressure drop and all other transducers (i.e. P6 to P9) were installed to measure static pressures at the respective points, which were used to model solid friction factor of straight horizontal pipe. P6 and P7 were to measure static pressure in the initial part of the test loop, whereas P8 and P9 were used to measure static pressure for the later part of pipeline. All the static pressure transducers in the solid–gas flow line were strategically placed sufficient distance away from the influence of any change in flow pattern caused by the bends. Specification of static pressure transducers: manufacturer: Endress & Hauser, model: Cerabar PMC131, pressure range: 0–2 bar, maximum pressure: 3.5 bar (absolute), current signal: 4–20 mA. All other required instruments such as PRV (pressure reducing valve), flow metre, NRV (non-return valve), blow valve, pressure gauge and load cells (shear beam type) were suitably placed. Calibration of the pressure transducer, load cells and flow metre was performed using a standardized calibration procedure [1]. To record the electrical output signals from the load cells, pressure transducers and flow metre, a portable PC compatible data logger was used. The data logger had 16 different channels with 14 bit resolution. Every pipeline was installed with two sets of 300 mm long sight-glasses made of borosilicate materials for flow visualization (using high speed digital camera).