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On improving solid friction factor modeling for fluidized dense-phase pneumatic conveying systems

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ABSTRACT

This paper presents results from an ongoing investigation into the modeling of solid friction factor for fluidized dense-phase pneumatic transport of powders. In spite of having the potential of being an energy economic and a better maintenance free mode of pneumatic transport, reliable design of fluidized dense-phase pneumatic conveying systems is still a difficult task due to the highly turbulent and complex nature of the flow of fine powders under high concentrations, where is it difficult to model particle–wall–air interactions. Several popular/applicable models (developed by other researchers, including one of the co-author of this paper) were evaluated to predict the total pipeline pressure loss for the dense-phase pneumatic conveying of fly ash (median particle diameter: 30 μm; particle density: 2300 kg/m^3; loose-poured bulk density: 700 kg/m^3) and ESP dust (median particle diameter: 7 μm; particle density: 3637 kg/m^3, loose-poured bulk density: 610 kg/m^3) under different diameter and length scale-up conditions (viz. 69 mm I.D. × 168 m; 105 mm I.D. × 168 m and 69 mm I.D. × 554 m pipes). These models are based on solids loading ratio and Froude number). A comparison between the predicted pneumatic conveying characteristics (PCC) and the experimental results showed that the models resulted in significant inaccuracy, especially under scale-up conditions of a new modeling technique has been developed using air velocity and a volumetric loading ratio term by replacing solid loading ratio and Froude number. The volumetric loading ratio term intends to address the product volume occupancy inside the pipeline, which is believed to be a better representation of flow conditions compared to mass ratio. The derived models were examined for scale-up accuracy by predicting pressure drop for different diameter/lengths of pipelines. It is found that the models have generally provided improved predictions in the dense-phase region. Whereas the existing models predicted with relative errors varying between 10 and 127% (depending on product and pipeline conditions), the new developed model resulted in predictions within 24% accuracy for a wide range of scale-up conditions, which provides better reliability and a narrower range of predictions, more suitable for industrial scale up requirements. Future work would require a more fundamental approach to understand the solid friction phenomenon for further accurate modeling.

1. Introduction

The pneumatic transportation of particulates through pipelines is being selected for an increasing number of industrial applications and products and is playing a more vital and integral role in numerous bulk handling operations and processes. Some reasons include: totally enclosed, hygienic and environmentally friendly; increased workplace safety; relatively low capital/maintenance costs (for a well-designed system); layout flexibility; ease of automation and installation; increased security. The traditional mode of conveying is referred to as "dilute-phase" (or "suspension flow"), where the carrier gas velocity is sufficiently high to entrain and suspend all the particles along the pipeline, and has been in existence for over 100 years. Due to the dispersed and suspended nature of flow, researchers have enjoyed good success in modeling the relevant particle interactions and mechanisms (e.g. friction, impact, drag, slip velocity, etc) and developing numerous friction factor and pressure drop models [1]. However, to meet the increasingly demanding requirements of industry (e.g. new products/processes, improved product quality, minimal power), several modes of "dense-phase" pipeline conveying (or non-suspension flow) have been developed over the past few decades to take advantage of particular product characteristics [2]. Accurate prediction of total pipeline pressure drop and minimum transport boundary are important parameters for reliable design of industrial systems. Total pipeline pressure drop mainly consists of losses in horizontal straight sections, verticals and around bends. For pipelines having relatively longer horizontal straight pipe run (e.g. fly ash conveying pipelines in coal fired power plants that run from buffer hopper and/or electrostatic precipitator hoppers to remote silo), accurate prediction of pressure drop is of paramount importance. Over designed systems with too high conveying velocity would cause higher operating cost, wear of pipelines and bends. On the

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contrary, under-prediction of total pipeline pressure drop and inaccurate estimation of minimum transport boundary (i.e. minimum conveying air requirement to avoid lack of aeration of the fluidized powders and especially for fine cohesive powders) would result in either reduced throughput and/or line blockage [3,4].

The pressure loss for solids-gas flow through a straight horizontal section of pipe can be expressed using Eq. (1), as given by Barth [5]. This equation was developed for coarse particles in dilute-phase flow. However, various researchers such as Stegmaier [6], Weber [7], Rizk [8], Pan and Wypych [9], Pan and Wypych [10] and Jones and Williams [11] to have subsequently employed this expression to predict the pressure loss for the dense-phase pneumatic transport of fine powders, such as fly ash, for horizontal straight pipes.

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

The key task in Eq. (1) is to determine the solids friction factor accurately. While more fundamental modeling techniques based on powder mechanics have been developed for dense-phase low-velocity slug-flow of granular products, the modeling of fluidized dense-phase conveying of fine powders has remained a relatively more difficult problem to solve at a similar depth of detail. Despite the widespread use and popularity of FDP, very little fundamental work has been done in trying to predict the total pipeline pressure drop (Δp_t) for the FDP conveying of powders. The main reasons are [11,12]: the nature of flow is quite complex (viz. moving turbulent fluidized bed of powder); it is extremely difficult to model the relevant particle and wall interactions and mechanisms; hence, it is very difficult to link particle/bulk properties and the above interactions/mechanisms to actual conveying parameters or operating conditions.

As a result of the above difficulties in modeling, empirical power function type models have been used for years by various investigators [6 to17] to avoid the necessity of developing fundamental relationships between solids friction factor and the relevant particle and bulk characteristics. These models have used different dimensionless parameters and have shown reliable results when applied to the researchers' own data, but have not been adequately examined for their scale-up accuracy. Hence, there is a requirement to examine the accuracy of the models under different scale-up conditions of conveying pipeline diameter and/or length and to develop more accurate modeling and scale-up procedures.

2. Experimental data

For the purposes of this study, pneumatic conveying data of transporting power station fly ash and ESP dust in fluidized dense-phase mode through pipelines of various diameter and length (viz. D = 69 and 105 mm I.D.; L = 168 and 554 m) have been used. The physical properties of the various powders and pipeline conditions are listed in Table 1. Tests were conducted for different solids and air mass flow rates. These powders are typical Geldart Group-A type powders capable of air retention and fluidized dense-phase type flows [12], hence these powders have been selected as the conveying products in the present study.

Table 1
Physical properties of products and pipelines.

Product	d_{10} (μm)	d_{50} (μm)	d_{90} (μm)	ρ_s (kg/m^3)	ρ_{bl} (kg/m^3)	Blow Tank	D (mm)	L (m)
Fly ash	2	30	110	2300	700	BD	69	168
							105	168
							69	554
ESP Dust	3	7	25	3637	610	BD	69	168
							105	168
							69	554

A typical schematic of the test set up used for fly ash conveying is shown in Fig. 1. 0.425 m3 capacity bottom-discharge type blow vessel feeder was used as feeder. A single blow tank was used for 168 m long pipes; twin blow tank system was used for 554 m long pipes. Three pipelines of different diameters and lengths (69 mm I.D. × 168 m long, 105 mm I.D. × 168 m long and 69 mm I.D. × 554 m long mild steel pipelines) were used. Schematics for the 105 mm I.D. × 168 m long and 69 mm I.D. × 554 m long mild steel pipelines are shown in Annexure — Figs. A1 and A2, respectively. 168 m and 554 m long pipes had 5 and 17 bends, respectively. All these pipes were used also for the conveying of ESP dust. All bends were of 1 m radius of curvature and 90°. There is a 150 mm N.B. tee-bend connecting the end of the pipeline to the receiver. Spigotted flanges were employed to ensure smooth internal surfaces at each pipe–pipe and pipe–bend connections. Various static pressure measurement points (P8–P12) were installed along the pipe, where P8 was used to measure the total pipeline pressure drop and transducers at other points measured local static pressure. The static pressure transducers were of the specification: manufacture: Endress and Hauser, model: Cerabar PMC133, pressure range: 0–6 and 0–2 bar, maximum pressure: 40 bar (absolute), signal: 4–20 mA. A 6 m3 receiving bin with insertable pulse-jet dust filter was placed on the receiver bin. All necessary instrumentation (e.g. pressure transmitters, load cells on feed bin and receiving bin, annubar with DP meter) were suitably placed. Calibrations of the above were performed using the standardized calibration procedure of the Bulk Material Handling Laboratory (University of Wollongong), as described in Pan [13]. In order to record the electrical output signals from the load cells, pressure transducers (static tapping points), a portable PC compatible data acquisition system (Datataker 800 or DT800 of Data Electronics) was used. DT800 is a high speed unit featuring 16 bit resolution. This has 42 analog inputs, giving 42 separate single ended channels or 24 differential channels. The sampling speed varies with input type, mode and number of channels. Data logging was done at 1 scan per second. For fly ash, P9–P10 straight pipe pressure drop data of 69 mm I.D. × 168 m long pipe was used. As, the P9–P10 (about 52.68 m) data for ESP dust on 69 mm I.D. × 168 m pipe showed too much scatter (difficult to draw straight-pipe PCC, thus somewhat unsuitable for modeling), hence P9–P10 (26.91 m) data for ESP dust was taken from 69 mm I.D. × 554 m long pipe. The length of test section (straight pipe length between horizontal pressure tapping points) would not affect λ_s modeling as pressure drop is expressed in the form of per unit length in the expression of λ_s. Compressed air at maximum available pressure of approximately 800 kPag was supplied from Ingersoll Rand diesel-powdered Model P375-WP, 10.6 m^3/min free air delivery rotary screw compressor. This compressor was used for all the pipes. Following standardized test procedure, initial tests were carried out with a medium range of air flow for a certain solid flow rate and then the air flow rate was gradually reduced to highly dense non-suspension flow to large pressure fluctuation region (indicating unstable flow conditions) and eventually pipe blockage. Tests near to the blockage boundary were repeated and carefully monitored due to the large pressure fluctuations, thus to ensure sufficient amount steady state data is recorded and for clearly delineating the blockage boundary. After this, the air flow was increased to high velocity zone (dilute-phase region) for obtaining pneumatic conveying characteristics from fluidized dense-to-dilute-phase region. At the end of a conveying program, certain tests were repeated to confirm there is no appreciable change in product characteristics.

3. Existing modeling and scale-up procedures for solids friction factor

In this section, various modeling and scale-up procedure for the solids friction factor, developed by the researchers over the years, are presented.

While more fundamental modeling techniques based on powder mechanics have been developed for dense-phase low-velocity slug-flow of granular products, the modeling of fluidized dense-phase conveying