DEVELOPMENT OF IMPROVED DESIGN FOR LONG DISTANCE PNEUMATIC CONVEYING OF FLY ASH

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ABSTRACT

An accurate estimation of total pipeline pressure drop is of paramount importance for the reliable design of a pneumatic conveying system. In the present study, a two-layer based model has been developed by separately considering the solids friction contributions of the non-suspension (dense) bed of powders flowing along the bottom of pipe and the suspension (dilute-phase flow) of particles occurring on top of the non-suspension layer. Volumetric loading ratio and dimensionless velocity have been used to model the non-suspension dune flow layer. A solids impact and friction term and dimensionless velocity term have been employed to model the dilute-phase flow due their established reliability. The developed model for solids friction were validated for their scale-up accuracy by using them to predict the pressure drops in larger and longer pipelines. The two-layer model provided improved accuracy compared to the existing models.

1. INTRODUCTION

Low velocity fluidized dense-phase pneumatic conveying is acquiring popularity within industries in recent years. In this mode of conveying, due to the lower operating gas and particle velocities, the size of the air mover is considerably reduced (so, lower energy consumption). However, reliable design of such system is still a challenge. Design requirements for fluidized dense-phase pneumatic conveying of powders consist of accurate prediction of the total pipeline pressure drop. Inaccurate prediction of pressure drop, such as under-prediction would result in reduced throughput, whereas over-estimation of pressure drop would lead to use oversized air movers resulting in increased initial and operating costs. Total pipeline pressure loss includes pressure drops in horizontal straight sections, verticals, bends and acceleration losses. For pipelines having relatively longer horizontal straight pipe run (e.g. fly ash conveying pipelines in coal fired thermal power plants from intermediate surge hopper to remote silo that may have pipe length up to 1 km), accurate prediction of pressure drop for the horizontal straight pipe run is of paramount importance as the major contribution of the total pressure drop comes from the relatively long length of horizontal section. The pressure loss for solids-gas flow through a straight horizontal section of pipe can be expressed using equation 1, as given by Barth [1].

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

This above representation considers the pressure drop due to the gas and solids separately. In this model, while all other parameters can be calculated relatively easily based on well established gas only friction factor formula [2, 3], accurate modelling of solids friction factor is a challenging task due to the limited fundamental understanding of the flow mechanisms of powdered bed [2, 3]. Due to the highly turbulent and complex nature of the moving fluidized bed of particles under high solids to gas mass ratio (in the form of dunes), it is very difficult to link the particle and bulk properties and the above interactions to the actual operating conditions and modelling the design parameters. One of the most popular forms of solids friction factor model is provided in equation (2):

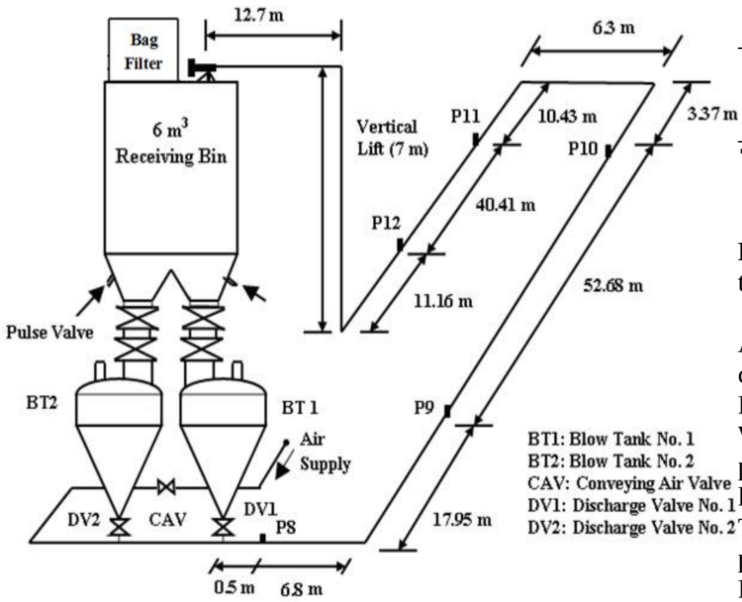
$$\lambda_s = K\ (m^*)^a\ (Fr)^b \tag{2}$$

This format has been applied by various researchers [2, 3] and can provide good accuracy when applied to researchers' own data, but previous investigations by the authors [3] have shown that the above formats of modelling provide gross inaccuracy under significant scale-up conditions of pipeline length and diameter. Very recently, the authors have provided a new model format by using volumetric loading ratio [4] and dimensionless velocity [3] as the flow defining parameters.

$$\lambda_s = K\ (VLR)^a\ (w_{fo}/V)^b \tag{3}$$

The predicted PCC (pneumatic conveying characteristics) did not provide adequate 'U' shaped characteristics [3], i.e. it could not follow the gradual change in flow mechanism from fluidized dense- to dilute-phase pneumatic conveying (i.e. non suspension to suspension flow mechanism). Hence, further studies are required to accurately model solids friction factor to address the changes in flow mechanism for the pneumatic conveying of fine powders and to provide pressure drop prediction characteristics that closely follow experimental plots both in values and trends.

2. EXPERIMENTAL DATA



d_{50} µm	ρ_s kg/m^3	ρ_{bl} kg/m^3	D mm	L m
30	2300	700	69	168
			105	168
			69	554

Table 1: Physical properties of products and pipeline configurations

Figure 1. Layout of 69 mm I.D. × 168 m test rig at University of Wollongong

Australian power station fly ash were conveyed at the Bulk Materials Handling Laboratory of the University of Wollongong, Australia. The physical properties of the products and pipeline lengths and diameters are provided in Table 1. Typical schematic (for one pipeline) of the test set up is shown in Figure 1.

The 69 mm I.D. × 168 m long pipeline included one 7 m vertical, five 90° bends having 1 m radius of curvature and a 150 mm N.B. tee-bend connecting the end of the pipeline to the receiver bin. For fly ash, static pressure measurement tapping points, P8, P9, P10, P11 and P12, were employed along the length of all the pipes. The P8 tapping location was used to measure total pipeline pressure drop. P11-P12 tapping points were used to obtain differential pressure loss, from where models for solids friction have been generated in this paper. All other necessary instrumentation for data recording and analysis were provided using a portable PC-compatible data acquisition system.

3. MODELING SOLIDS FRICTION USING TWO-LAYER FLOW THEORY

Figure 2a shows that the non-suspension layer is having a wavy/liquid type appearance with a turbulent top surface, where a rapid mass exchange of solids with the upper dilute-phase layer takes place. However, the interface between the non-suspension and suspension layers was not very distinct. With an increase in conveying air flow rate, the thickness of the non-suspension layer decreased (with more and more product getting into the suspension flow), ultimately resulting in the disappearance of the non-suspension layer and suspension flow (dilute-phase) occurring through the whole cross section of the pipe.

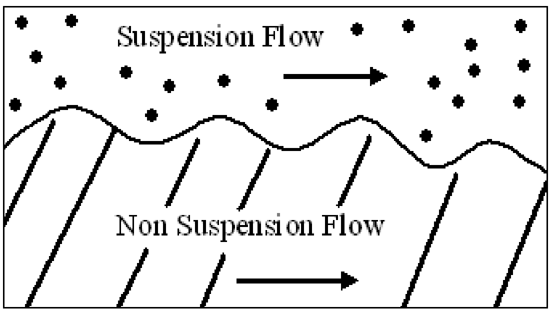


Figure 2a. Two-layer dune flow of fine powders in dense-phase under actual flow condition

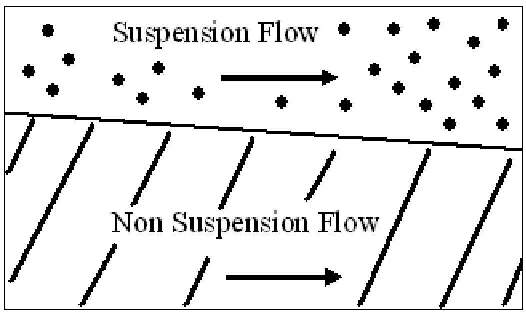


Figure 2b. Simplified representation of two-layer flow of fine powders in dense-phase

Figure 2a shows that the non-suspension layer is having a wavy/liquid type appearance with a turbulent top surface, where a rapid mass exchange of solids with the upper dilute-phase layer takes place. However, the interface between the non-suspension and suspension layers was not very distinct. With an increase in conveying air flow rate, the thickness of the non-suspension layer decreased (with more and more product getting into the

suspension flow), ultimately resulting in the disappearance of the non-suspension layer and suspension flow (dilute-phase) occurring through the whole cross section of the pipe. Figure 2b is a simplistic view of the complex flow phenomenon. The two layer modeling format is expressed as:

$$\lambda_s = \tau_1 \, (K \, (VLR)^a \, (w_{fo}/V)^b) \; + \; \tau_2 \, (\lambda_s^* \, C/V + 2\beta_0/[(C/V) \, Fr^2]) \qquad (4)$$

Where, K, a, b are constant and exponents of power function format and τ_1 and τ_2 represent the relative contributions of non-suspension and suspension layers, respectively, based on the Froude number criteria. The first term in equation 6, $\tau_1 (K (VLR)^a (w_{fo}/V)^b)$, represents the solids friction contribution of the non-suspension flow, where as the second term, $\tau_2 (\lambda_s^* C/V + 2\beta_0/[(C/V) Fr^2])$, represents the suspension flow contribution. It is considered that with an increase in gas Froude number (i.e. air velocity for a particular pipe diameter), the flow mechanism shifts from non-suspension to suspension mode. τ_1 and τ_2 are represented as:

$$\tau_1 = \{1-(Fr - Fr_{min})/(Fr_{max} - Fr_{min})\} \qquad (5)$$
$$\tau_2 = (Fr - Fr_{min})/(Fr_{max} - Fr_{min}) \qquad (6)$$

Where, Fr_{min} corresponds to the minimum gas Froude number, below which unstable flow and pipeline blockage was found to occur. This was found to happen in the range of Fr = 3 to 4. Fr_{max} corresponds to high velocity (suspension flows). This was considered to be Fr = 50 as the extreme limit considering all the products and pipeline conditions. Froude number (Fr) refers to the value of Froude number at a section of straight pipe (i.e. average value of Froude number across the pipe section). The developed models are provided in Table 2 and 3.

Table 2: Models developed using uniform flow modelling format

Format given by equation 4				R^2
K	**a**	**b**	**w_{fo} (m/s)**	
7.94	-0.26	1.51	0.06	0.98

Table 3: Models developed using new two-layer modelling format

Format given by equation 6					R^2
K	**a**	**b**	**w_{fo} (m/s)**	**λ_s^***	
8.04	-0.22	1.48	0.06	0.0043	0.98

4. SCALE-UP VALIDATION OF MODEL

Solids friction factor models developed as per the newly developed two-layer modeling formats (shown in Table 3) have been evaluated and compared for their accuracy and stability to predict the total pipeline drop for four products and five pipeline combinations. Predictions as per the uniform modelling format (models shown in Table 2) have been superimposed on the above predicted pneumatic conveying characteristics to demonstrate the possible improvements of pressure drop prediction capability of the new two-layer modelling format. The results are provided in Figures 3 and 4.

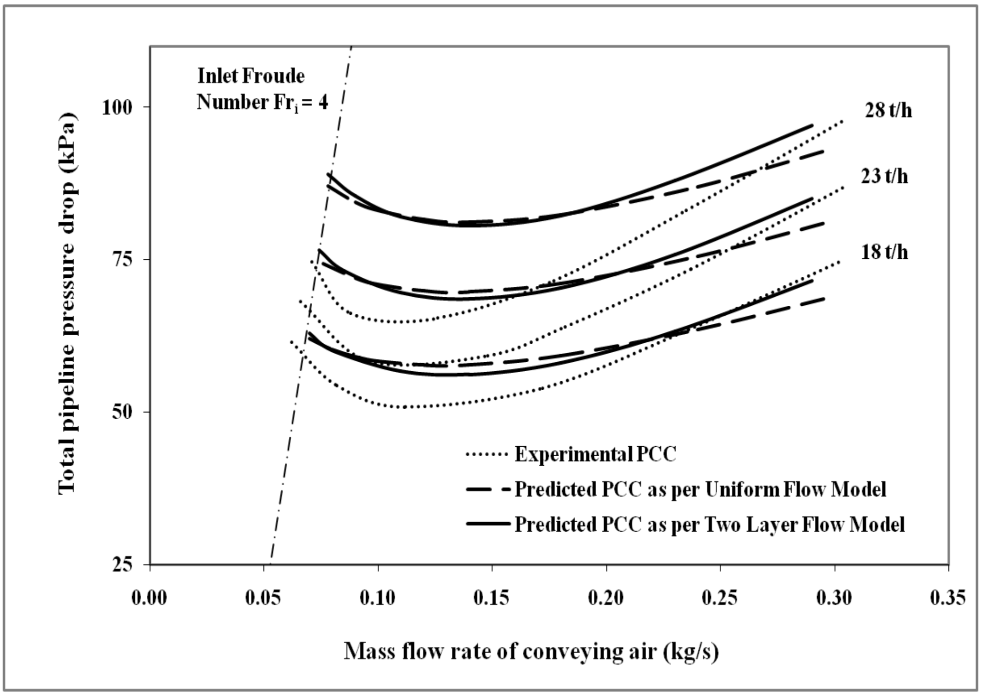


Figure 3. Experimental versus predicted PCC for fly ash through 105 mm I.D. × 168 m long pipe

Predictions using two layer model are better compared to that provided by the uniform flow mode, with the predicted PCC showing relatively more pronounced change in slopes in higher air flow rate for two-layer model.

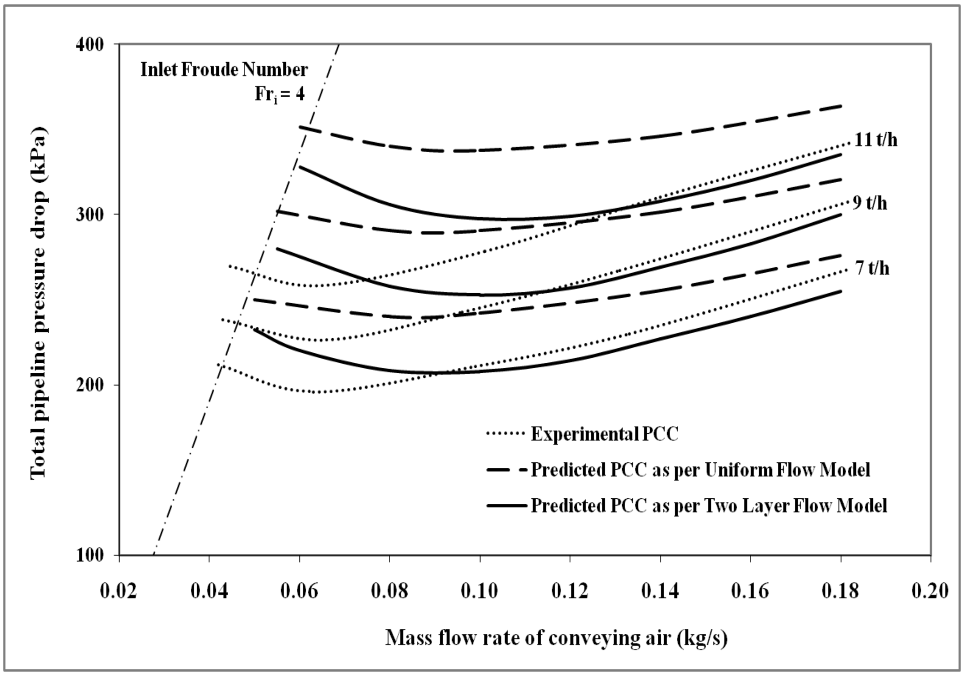


Figure 4. Experimental versus predicted PCC for fly ash through 69 mm I.D. × 554 m long pipe

For the length scale up for fly ash, the two-layer model provided far better predictions compared to the uniform flow model both in terms of reduced range of over-predictions and in terms of trends of predictions following experimental PCC.

5. CONCLUSION

A two-layer based model for solids friction has been developed by separately considering the solids friction contributions of the non-suspension and suspension layer of particles and suitably combining them using a Froude number based criteria. Model developed for fly ash, when tested under scale-up conditions by using them to predict the pressure drops for larger and longer pipelines and by comparing the experimental and predicted pneumatic conveying characteristics, have resulted in better reliable predictions compared to the existing models.

LIST OF SYMBOLS AND ABBREVIATIONS

a, b, c	Exponents of power function	m_f	Mass flow rate of air [kg/s]
C	Particle velocity [m/s]	m_s	Mass flow rate of solids [kg/s]
D	Internal diameter of pipe [m]	m*	Solids loading ratio = m_s / m_f
d_{50}	Median particle diameter [µm]	ΔP	Pressure drop through a straight horizontal pipe or pipe section [Pa]
Fr = $V/(gD)^{0.5}$	Froude number of flow	V	Superficial air/gas velocity [m/s]
Fr_i = $V_i/(gD)^{0.5}$	Froude number of flow at the beginning of pipe	VLR =	Volumetric loading ratio, $\{(m_s/\rho_s)/(m_f/\rho)\}$
Fr_{min} = $V_{min}/(gD)^{0.5}$	Froude number of flow corresponding to minimum transport	w_{f0}	Free settling velocity of an isolated particle [m/s]
g	Acceleration due to gravity [m/s^2]	ρ	Density of air [kg/m^3]
K	Constant of power function	ρ_s	Particle density [kg/m^3]
L	Length of horizontal pipe [m]	ρ_{bl}	Loose-poured bulk density [kg/m^3]
Abbreviations		λ_f	Air/gas only friction factor
I.D.	Internal diameter of pipe	λ_s	Solids friction factor through straight pipe
PCC	Pneumatic conveying characteristics	λ_s*	Impact and friction factor

REFERENCES

[1] W. Barth, Strömungsvorgänge beim transport von festteilchen und flüssigkeitsteilchen in gasen, Chemie – Ing. – Techn, 30 (3) (1958) 171-180.
[2] P.W. Wypych, PhD Dissertation, Pneumatic conveying of bulk solids, University of Wollongong, 1989.
[3] S.S. Mallick, PhD Dissertation, Modelling dense-phase pneumatic conveying of powders, University of Wollongong, 2009.
[4] Setia, G., Mallick, S.S., Pan, R., Wypych, P.W., An experimental investigation into modeling solids friction for fluidized dense-phase pneumatic transport of powders, Particuology, 30 (2017), 83-91.