Pneumatic conveying of Fly Ash: Bend Models investigation

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Abstract

This paper presents results of an ongoing investigation into the modelling of pressure losses through bends during pneumatic conveying of fly ash. For the reliable design of pneumatic conveying systems, an accurate prediction of bend pressure drop is of paramount importance as the same can significantly influence the total pipeline pressure loss. In the present study, seven existing bend models (Schuchart, Singh and Wolf, Rossetti, Westman, Bradley, Pan, Pan and Wypych, Das and Meloy models) were used to predict the total pipeline pressure drop for conveying fine fly ash through two test rigs: 63.5 mm I.D. x 24 m long and 54 mm I.D. x 70 m long. Comparisons between the predicted pneumatic conveying characteristics using the seven bend models and the experimental data have shown that the trends and values of the total pipeline pressure drops can significantly vary depending on the choice of bend model. While some models have provided increasing values of bend pressure drops with rise in air flows, some other models have produced reversed characteristics. It is concluded that the parameter grouping used in the existing bend models are not generally capable of predicting bend pressure drop reliably and therefore, further research is required to better understand the flow mechanisms of gas-solids flows across bends towards developing improved bend models. Copyright © 2017 VBRI Press.

Keywords: Pneumatic conveying, fly ash, bends, bend loss models, pneumatic conveying characteristics.

Introduction

Pneumatic conveying technique is widely used in a number of industries to transport pulverised coal, fly ash, cement, chemical and food products etc due to its inherent advantages, such as completely enclosed system – hence environment friendly, dust free and hygienic, ease of automation and control and layout flexibility. For the reliable design of pneumatic conveying systems, an accurate estimation of blockage boundary and total pipeline pressure drop are important requirements. Whereas, under-prediction of blockage boundary could lead to high pressure fluctuations (unstable conveying) and line blockage bringing about plant shutdown, erroneous estimation of the total pipeline pressure drop would result in either excessive gas flows causing higher energy cost of transportation, increased wearing of the pipeline and bends etc or reduced material throughput rate (in cases of over- or under-estimation of line pressure drop, respectively). Total pipeline pressure drop consists of energy losses in horizontal straight pipes, bends, verticals and due to the initial acceleration of particles. It is exceedingly important to accurately predict pressure drop for each of these elements to get reliable overall prediction. Out of these components, losses in the horizontal straight-pipes and bends are especially critical (and hence, demand for high degree of accuracy in modelling and predictions) as they form the significant share of total pipeline drops. Correlation for the pressure loss of solid-gas flow through straight pipe sections has given in equation (1) [1]. This equation is thought of originally proposed for dilute-phase conveying of coarse particles, but several investigators over the years have employed this model for the case of dense-phase flow of fine powders (such as fly ash, cement, pulverised coal etc) through straight pipes [2-6].

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

In order to estimate the pressure loss in bends during pneumatic conveying, several researchers provided bend loss models over the years [4, 5, 7-11]. These models are mostly empirical and are applicable to the test condition and product properties, e.g. location and orientation of the test bend (horizontal-to-horizontal or horizontal to vertical, dense- or dilute-phase flow etc). Schuchart was one of the first researchers to have modelled gas-solids flow through pipe bends [7]. More accurate estimation of the total pipeline pressure drop can obtain if pressure drop through the straight pipes and bends are modelled separately [12]. Velocities of the solid particles reduce significantly at the exit to the bends. As a result, these particles drop out of the flowing gas stream and would then need to be re-accelerated to be again in the flow stream. This phenomenon of re-acceleration of particles causes pressure drop of the gas. Extensive test program has carried out using wheat flour and with seven different types of bends and it was found that different radius bends contribute to similar magnitude of pressure drop [13], but this result was contradicted by the findings of Mills [14]. Ten different materials were conveyed using the setup of Bradley [13] and developed a model that can provide 50 % accuracy in estimating bend pressure drop [15]. In spite of the relatively large effort that has been directed over the years to study the pressure drop through isolated bends and to develop bend loss models from this, very little work has been carried out so far in evaluating the applicability and reliability of those models in scale-up situations of having pipeline systems with multiple bends. The aim of the present paper is to investigate into the effects of different bend models on the prediction of total pipeline pneumatic conveying characteristics for different pipelines.

Experimental

Indian fly ash from Bathinda Thermal Power Plant (Punjab) was conveyed through different pipelines at the pneumatic conveying laboratory of Thapar University, Patiala. The physical properties of the fly ash are provided in Table 1.

Table 1. Physical properties of the 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 shows a typical schematic of the test set facilities. A rotary screw compressor (Kirloskar made electric-powered Model KES 18-7.5) was used. The compressor could deliver air at a maximum delivery pressure of 750 kPa with the capacity of 3.37 m^3/min of free air delivery. To vary the conveying air flow rates, an air flow control valve was installed in the compressed air line in the upstream of the blow vessel. A vortex flow meter was used in the compressed air line for the measurement of air flow rates. Blow vessel with bottom discharge facility of material was used as the feeding device. The blow vessel was of 0.2 m^3 capacity (water fill volume). Solenoid operated dome type material inlet, outlet and vent valves were used in the blow vessel. The test rigs worked in closed loops having a receiver bin of 0.65 m^3 capacity installed above the blow vessel. Bag filters having sufficient capacity and pulse jet type cleaning mechanisms were mounted on top of the receiver bins. The blow vessel and the receiver bin were supported on shear beam type load cells. Test loops with mild steel pipelines were used having dimensions of 63.5 mm I.D x 24 m long and 54 mm I.D x 70 m long. Each loop included a 3 m vertical lift and 4 x 90^o bends. Each bend had 1 m radius of curvature. Different tapping points for static pressure measurement were installed along the pipeline (P6 to P9). Total pipeline pressure drop in the line was measured by the P4 transducer. The transducers were Endress & Hauser made, model Cerabar PMC131, pressure range of 0-2 bar, having current signal of 4-20 mA. The pressure transducers, load cells and flow meter were calibrated using a standardized calibration procedure [16]. A portable PC compatible data logger system used was used having 16 different channels with 14-bit resolution. Two sets of 300 mm long sight-glasses made of toughened borosilicate glass were installed in line for the flow visualization of solids-gas transport. Fly ash was conveyed for different solids and air flow rates (fluidized dense- to dilute-phase). Selected tests were repeated to ensure repeatability of test data.

Bend pressure drop models

Schuchart's work was based on a number of different bends using glass and plastic granules as the test materials [7]. The particles were of rather larger size, 1-2 mm in diameter for volumetric concentrations up to only 5% (dilute-phase). In spite of this, the model was tried for fine powders (in dense-phase) as the model seemed to be popular [17, 18] for dilute-phase flow. It was considered worthwhile to analyze its potential under dense-phase conveying conditions. The solids contribution of the pressure drop during solids-gas flow through the bends was given by the following formula:

$$\left(\frac{\Delta p_{bend}}{\Delta p_z}\right)_{solids} = 210\left(\frac{2R_B}{D}\right)^{-1.15} \qquad (2)$$

Here, $(\Delta p_{bend})_{solids}$ is the contribution of pressure drop by the solids flowing through the bend; $(\Delta p_z)_{solids}$ is the solids contribution to the pressure drop through a straight pipe of straight length equivalent to the bend. Finally, the total bend loss is obtained by calculating the pressure drop due to $(\Delta p_{bend})_{gas}$ (gas-only friction) using Ito's expression and then adding it to $(\Delta p_{bend})_{solids}$ [**18, 19**]. The Schuchart model includes a straight-pipe pressure drop term [**7**]. Therefore, the accuracy of this bend model would depend on the reliability of modelling solids friction through straight pipes [**7**]. Singh and Wolf carried out extensive test program with granular chopped forged. Conveying performed using three bends having radius of curvatures of 381, 762 and 1220 mm and pipe I.D of 150 mm. They developed the following parameter groupings using dimensionless approach of modelling [8]:

$$\frac{\Delta p_{bs}}{\rho_{fo} V_{fo}^2} = f\left(\frac{R}{D}, \frac{m_s}{\rho_{fo} V_{fo} D^2}, \beta_a\right) \qquad (3)$$

In equation (3), β_a is the bend angle. Considering generalized power function law would be valid, a relationship was developed between $\frac{\Delta p_{bs}}{\rho_{fo} V_{fo}^2}$ and $\frac{m_s}{\rho_{fo} V_{fo} D^2}$, which provided the following model for the pressure losses in bends:

$$\Delta p_{b0} = a_c + a_s \frac{m_s.V_o}{D^2} (\frac{R}{D})^{a_b} \tag{4}$$

where, a_c is the pressure due to air only. Using least square method and comprehensive set of experimental data, the following model was derived. For bend angles of 45° and 90°, the values of a_s were found to be 0.00334 and 0.00537, respectively.

$$\Delta p_{b0} = 0.13 + a_s \frac{m_s.V_o}{D^2} \left(\frac{R}{D}\right)^{-0.18} \tag{5}$$

Rossetti used different sets of bends with pipe diameter to bend diameter ratio of 2 to 8.4, conducted a test program by conveying coarse and fine particles, and proposed the following equation (6) for bend pressure loss [9]. The model uses condition at the outlet of bends. This appears to be a justified choice as re-acceleration of particles in the downstream of bends is believed to be the primary cause of energy drop in bends. Westman provided the models given by equations (7) and (8) to represent λ_f and λ_s [20].

$$\Delta p_{bo} = \left(\lambda_f + \lambda_s\right) \frac{\rho_o V_o^2}{2} \tag{6}$$

Westman conveyed four polymers with bulk densities ranging from 80 to 824 kg/m^3 of equivalent particle diameter from 3.40 to 3.51 mm using a vacuum system. They studied the bend pressure loss in dilute-phase flow through 90° bends of various geometries ($2R_b/D$ = 3, 10, 24) [**20**]. He concluded that total bend loss can be expressed as a sum of air and solids only pressure drop through the bend. The correlation is given as follows:

$$\lambda_f = 0.167 \left[1 + 17.062 \left(\frac{2R_B}{D}\right)^{-1.219}\right] Re^{-0.17} \left(\frac{2R_B}{D}\right)^{0.84} \tag{7}$$

$$\lambda_s = \frac{5.4\, {m^*}^{1.293}}{Fr_o^{0.84} \left(\frac{2R_B}{D}\right)^{0.39}} \tag{8}$$

The total pressure loss in bends (Δp_b) due to the flow of air and solids is provided by the equation (9) [10]. This model used to calculate total bend loss in pipeline using a back calculation method to derive an expression for the solids friction factor [**6, 22**]. Eq. (9) does not have any derivation details [10].

$$\Delta p_{bo} = NB(1 + m^*) \frac{\rho V^2}{2} \tag{9}$$

Bradley transported fly ash and wheat flour through test pipelines of 50, 75 and 100 mm I.D and used 7 types of bends of varying radius of curvature [13]. Data were taken for a wide range of conveying; solid loading ratio was up to 130 and flow velocity was varied from 4 to 45 m/s. He proposed the model format provided by equation (10) to represent losses in the bends. Bradley questioned the applicability of using a mass ratio term, as provided in equations (9) and (10). He proposed that volumetric occupancy of solids in pipeline is a better representation of the flow mechanism than the mass ratio (solids loading ratio). He represented K_b as a function of suspension density [13].

$$\Delta p_b = {}^1\!/_2\, K_b \rho_{sus} V^2 \tag{10}$$

Pan [4] conveyed fly ash (λ_s: 634 kg/m^3**;** ρ_b: 2197 kg/m^3**;** mean d_p: 15.5 µm) through four radius bends. Using dimensionless analysis, he proposed the following models (equations 11 and 12) for solids friction through the bends. Using the steady-state data through a series of pressure transducers placed after the bends and using the technique of minimising the sum of squared errors method, Pan proposed the values of Y_1, Y_2 and Y_3 as 0.0052, 0.49 and 1.1182, respectively [4]. Pan's use of velocity, density and Froude number corresponding to the bend outlet condition indicates that his approach of considering the phenomenon of reacceleration of particles at the bend exist majorly contributes to the bend losses.

$$\Delta p_{bo} = m^* \lambda_s \frac{\rho_o V_o^2}{2} \tag{11}$$

$$\lambda_s = Y_1 {m^*}^{Y_2} {Fr_o}^{Y_3} \tag{12}$$

Pan and Wypych conveyed four samples of fly ash (particle size: 3.5 to 58 µm; particle density: 2180 to 2540 kg/m^3; loose poured bulk density: 634 to 955 kg/m^3) from dense to fluidized dilute-phase (conveying velocity range of 3 to 25 m/s). They derived the following bend model (equation 13 and 14) to estimate pressure drops caused by solids only [5].

$$\Delta p_{bs} = 0.5 m^* \lambda_{bs} \rho_{bo} V_{bo}^2 \tag{13}$$

Where:

$$\lambda_{bs} = 0.0097 {m^*}^{0.5676} {Fr_o}^{0.9647} \rho_o^{-0.6232} \tag{14}$$

Das and Meloy pneumatically transported six different types of fly ash through a pipeline of 63.5 mm I.D. x 169.8 m length and compared the pressure drops across close-coupled to isolated 90° bends [11]. The following model format was proposed for single and close-coupled bends. X_1 and X_2 are constants whose values would depend on the particular ash type and bend geometry. The values of X_1 and X_2 were 0.3 x 10^{-7}and 3.4, respectively for single bends. For double (close-coupled) bends, the values of X_1 and X_2 were 2.2 x 10^{-7} and 3.0, respectively.

$$\frac{\Delta p_{solids}}{m^*} = X_1 {V_o}^{X_2} \tag{15}$$

Model for solid friction factor for horizontal straight pipe

To investigate the effect of choosing different bend models on the total pipeline pneumatic conveying characteristics, pressure drops across straight pipe sections are to be determined, which would then be added to the estimated bend losses (to be obtained using different bend models) to find out the total pipeline pressure drop values. To model solids friction factor for straight pipes, power function based model format, as given by equation (18), was used. This format was previously used by other researchers [5, 6, 22].

$$\lambda_s = K(m^*)^a (Fr)^b \tag{16}$$

Using static pressure data obtained from straight pipe points (P6-P7) of length 8 m of 50 mm I.D. x 70 m long pipeline for a wide range of conveying data from fluidized dense- to dilute-phase, the following model (equation 17) for solid friction factor has been derived using least square method. The high value of R^2 indicates that the solid friction factor model is a good fit with the experimental data.

$$\lambda_s = 1.431(m^*)^{-1.04523}(Fr_m)^{-0.4849} \; [R^2 = 0.954] \tag{17}$$

Evaluation of bend models

The effects of selection of different bend pressure drop models on the estimation of total pipeline pressure drop conveying characteristics were evaluated by predicting the total pipeline conveying characteristics for fly ash for different solids flow rates for the two test rigs (63.5 mm I.D. x 24 m long, 54 mm I.D. x 70 m long pipelines) by using seven bend models and comparing the predicted PCC against the experimental data. Straight-pipe model (equation 17) was used for all cases to estimate the pressure drop in straight pipe lengths [21]. Losses in vertical pipes and for initial material acceleration were estimate as per Marcus et al. [19]. Because the same set of models were used to predict pressure losses in horizontal pipes, vertical sections and for the initial acceleration, therefore any difference of the predicted total pipeline PCC must have been caused by the choice of different bend models. Results of evaluations are provided in **Fig. 2 to 5**. **Fig. 2 and 3** are for the larger diameter pipe (63.5 mm I.D x 24 m long) and **Fig. 4 and 5** are for the longer pipe (54 mm I.D x 70 m long) for different solids flow rates.

Fig. 2 to 5 show that the selection of different bend models provides significantly different predicted total pipeline PCC. In all the figures, the experimental PCC show a change in slope from low to high velocity; pressure drops decrease or almost remain constant at low air velocity range (dense-phase) and gradually increase with rise in air velocity in the high velocity range (dilute-phase). However, all the predicted PCC are almost linear and the estimated values of pressure drops monotonically increase with rise in air flow rates. In **Fig. 2 and 3**, the Schuchart model provides reasonably good predictions, whereas all the other models provide significant under-predictions, with Das and Meloy, Singh and Wolf providing the maximum degree of under-predictions [7, 8, 11].

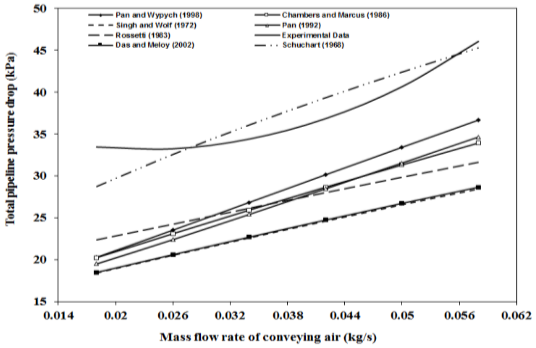

Fig. 2. Comparison of experimental versus predicted values of total pipeline pressure drop (fly ash, I.D = 63.5 mm, L = 24 m, m_s = 4.5 t/h).

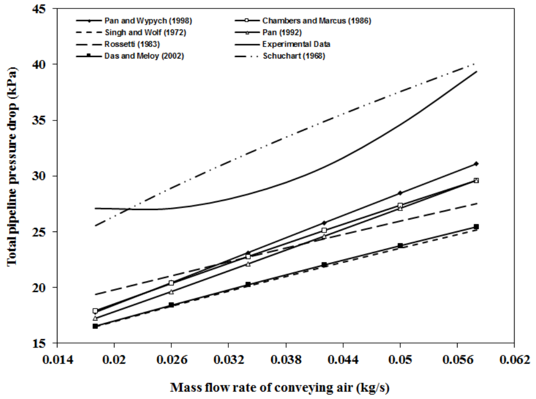

Fig. 3. Comparison of experimental versus predicted values of total pipeline pressure drop (fly ash, I.D = 63.5 mm, L = 24 m, m_s = 3.5 t/h).

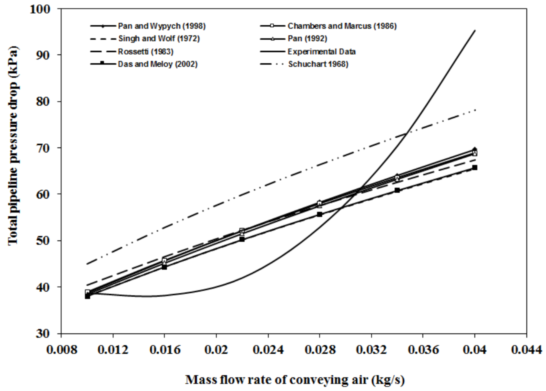

Fig. 4: Comparison of experimental versus predicted values of total pipeline pressure drop (fly ash, I.D = 54 mm, L = 70 m, m_s = 2.5 t/h).

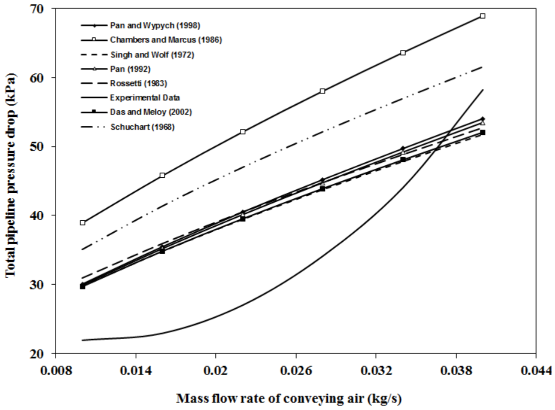

Fig. 5: Comparison of experimental versus predicted values of total pipeline pressure drop (fly ash, I.D = 54 mm, L = 70 m, m_s = 1.5 t/h).

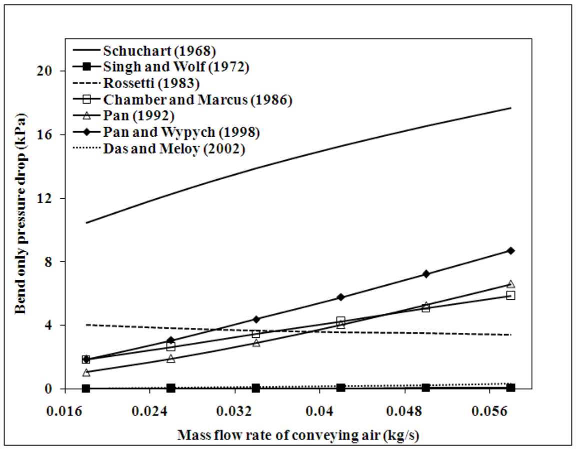

Fig. 6: Bend loss PCC based on different bend models in dense to dilute phase (fly ash, I.D = 63.5 mm, L = 24 m, m_s = 4.5 t/h).

For 70 m long pipe and higher ash flow rate (2.5 t/h), all the models provide over-predictions up to a certain airflow rate (about 0.03 kg/sec), with Schuchart model resulting in maximum amount of deviations from the experimental plots. Above this air flow rate, all the models provide under-predictions. A very different trend is observed for the lower solids flow rate (1.5 t/h) and 70 m long pipe, where all the models significantly provide over-predictions. The Chambers and Marcus model results in highest amounts of over-predictions, followed by the predictions of Schuchart. **Fig. 6** plots only the predicted bend losses (sum of all the bend pressure drops in the pipeline) using different bend loss models for the 63.5 mm I.D x 24 m long pipe.

Fig. 6 shows that different bend models have generated significantly different values of predicted total bend pressure drops in low and high velocity flows. Predictions of Schuchart, Chamber and Marcus, Pan and Pan and Wypych have provided higher-pressure loss in dilute-phase (high velocity) than that of to dense-phase regime (low velocity), which seems to be following the expected trend. However, the Schuchart model has resulted in considerably higher values of predictions over Chamber and Marcus, Pan and Pan and Wypych models. The Rossetti model has predicted that the bends pressure loss in dense-phase is more than that in dilute phase, i.e. it does not follow the expected trend. Pan, Singh and Wolf, Das and Meloy models are almost superimposing on each other and predicted unexpectedly very low values of bend loss.

Conclusion

The selection of bend model to predict the pressure losses occurring due to the flow of solids-gas flow through the bends have shown to have significant influence on the trends and values of the estimated total pipeline pneumatic conveying characteristics. A particular bend model that has provided under-predictions under certain pipeline and solids flow rate conditions, can provide over-predictions under different experimental conditions. Predictions of Schuchart, Chamber and Marcus, Pan, Pan and Wypych have resulted in increasing trend of bend losses with an increase in airflow rates, which seems to be following the expected trend. However, the Rossetti model has predicted that bend pressure loss in dense-phase is more than that of dilute phase. This prediction does not seem to follow the expected experimental data. Singh and Wolf, Das and Meloy models have resulted in unexpectedly low values of estimation of bend losses. It appears that the parameter groupings used in the existing models are generally not capable of predicting pressure drops accurately. Therefore, further research is required to predict the bend pressure loss more reliably.

List of Symbols

B	Bend loss factor
D	Internal diameter of pipe [m]
Fr = V/(gD)$^{0.5}$	Froud number of flow
G	Acceleration due to gravity [m/sec^2]
L	Length of pipe [m]
m_f	Mass flow rate of air [kg/sec]
m_s	Mass flow rate of solids [kg/sec]
m^* = ms/mf	Solid loading Ratio
K	Constant of power function
N	Number of bends
ΔP	Pressure drop through a straight horizontal pipe [Pa]
ΔP_{bo}	Pressure drop through bend [Pa]
$(\Delta P_z)_{solid}$	Pressure drop due to solids for an equivalent straight length of the bend [Pa]
R_B	Radius of curvature bend [m]
r	Radius of bend pipe [m]
Re = ρVD/μ	Reynolds number
V	Superficial air velocity [m/sec]
Vo	Velocity at bend outlet [m/sec]
ρ	Density of air [kg/m^3]
ρ_o	Density of air at bend outlet
λ_f	Air/gas only friction factor
λ_{bs}	Solid friction factor at bend
λ_s	Solid friction factor
μ	Fluid viscosity [Pa.sec]

Abbreviations

BD	Bottom Discharge
I.D.	Internal diameter of pipe
PCC	Pneumatic conveying characteristics

Author's contributions

All authors have equal contribution to prepare this manuscript and experiment.

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