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Energy loss at bends in the pneumatic conveying of fly ash

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ABSTRACT

An accurate estimation of the total pressure drop of a pipeline is important to the reliable design of a pneumatic conveying system. The present paper presents results from an investigation into the modelling of the pressure drop at a bend in the pneumatic conveying of fly ash. Seven existing bend models were used (in conjunction with solids friction models for horizontal and vertical straight pipes, and initial acceleration losses) to predict the total pipeline pressure drop in conveying fly ash (median particle diameter: 30 μm; particle density: 2300 kg/m^3; loose-poured bulk density: 700 kg/m^3) in three test rigs (pipelines with dimensions of 69 mm inner diameter (I.D.) × 168 m length; 105 mm I.D. × 168 m length; 69 mm I.D. × 554 m length). A comparison of the pneumatic conveying characteristics (PCC) predicted using the seven bend models and experimental results shows that the predicted total pipeline PCC and trends depend on the choice of bend model. While some models predict trends that agree with the experimental results, other models predicted greater bend pressure drops for the dense phase of fly ash than for the dilute phase. Models of Pan, R. (1992). Improving scale-up procedures for the design of pneumatic conveying systems. Doctoral dissertation, University of Wollongong, Australia, Pan, R., & Wypych, P.W. (1998). Dilute and dense phase pneumatic conveying of fly ash. In Proceedings of the sixth International Conference on Bulk Materials Storage and Transportation (pp. 183–189), Wollongong, NSW, Australia and Chambers, A.J., & Marcus, R.D. (1986). Pneumatic conveying calculations. In Proceedings of the second International Conference on Bulk Materials Storage and Transportation (pp. 49–52), Wollongong, Australia reliably predicted the bend losses for systems conveying fly ash over a large range of air flows.

Introduction

Pneumatic conveying is the process of transporting dry bulk materials through pipelines with the help of air or other non-reacting gases. This process is used in, for example, thermal power (to convey pulverised coal and fly ash), cement, chemical, food, and petrochemical plants. Such transport has the advantages in that the system is totally enclosed and thus easy to use, has a flexible layout, can be automated and easily controlled, and is dust free, hygienic and environmental friendly. The conventional mode of conveying is known as dilute-phase (suspension-flow) conveying, where the velocity of the gas is sufficiently high to suspend particles in the pipeline. However, to meet the increasing demands of industries requiring new products and processes and improved quality, several modes of dense-phase (non-suspension flow) conveying have been developed by taking advantage of particular product properties (e.g., aeration characteristics). An accurate estimation of the minimum transport boundary (i.e., the minimum requirement that ensures sufficient aeration of fluidised powders) and total pressure drop of the pipeline is important for the reliable design of pneumatic conveying systems. Under-prediction of the minimum transport boundary results in either reduced throughput or line blockage. The total pressure drop of a pipeline consists of losses due to horizontal straight pipes, bends, vertical straight pipes, and the initial acceleration of particles from rest. Accurate prediction of losses for horizontal pipes, vertical pipes, and bends is important as these account for a large share of the total pipeline loss. For straight-pipe losses, Barth (1958) proposed using Eq. (1) to determine the pressure drop (Δp) for solid–gas flow. This equation is believed to have been originally proposed for the dilute-phase transport of coarse particles. However, various researchers such as Stegmaier (1978), Weber (1981), Pan (1992), Pan and Wypych (1998), and Jones and Williams (2003) employed this expression to predict the pressure loss for the

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Nomenclature

B	bend loss factor
D	internal diameter of pipe (m)
d	particle diameter (μm)
$Fr = V/(gD)^{0.5}$	Froude number of flow
Fr_m	mean Froude number of flow
g	acceleration due to gravity (m/s^2)
K	constant of power function for straight pipe
K_b	constant of power function for bend
L	length of pipe (m)
m_f	mass flow rate of air (kg/s)
m_s	mass flow rate of solids (kg/s)
$m^* = m_s/m_f$	solid loading ratio
N	number of bends
Δp	pressure drop through straight horizontal pipe (Pa)
Δp_{bo}	pressure drop through bend (Pa)
Δp_{bf}	bend pressure drop due to air only (Pa)
Δp_{bs}	bend pressure drop due to solids only (Pa)
Δp_{zs}	pressure drop due to solids for an equivalent straight length of the bend (Pa)
r	internal radius of pipe (m)
R_B	radius of curvature of bend (m)
$Re = \rho VD/\mu$	Reynolds number
V	superficial air velocity for straight pipe (m/s)
V_o	superficial air velocity at bend outlet (m/s)

Greek symbols

β_a	bend angle, degrees
λ_{bs}	solids friction factor at bend
λ_f	air/gas-only friction factor
λ_s	solids friction factor
μ	fluid viscosity (Pa s)
ρ	density of air (kg/m^3)
ρ_o	density of air at bend outlet (kg/m^3)
ρ_{sus}	suspension density (kg/m^3)

Subscripts

b	bend
f	fluid (air)
o	outlet condition
p	particle
s	solids
sus	suspension
z	straight horizontal pipe

Abbreviations

BD	bottom discharge
I.D.	internal diameter of pipe
PCC	pneumatic conveying characteristics

dense-phase flow of fine powders (such as fly ash, cement, and pulverised coal) through straight pipes. The equation is

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

where Δp is the pressure drop through a straight horizontal pipe, λ_f is the air-alone friction factor, λ_s is the friction factor due to solids, m^* is the solid loading ratio, ρ is the density of air, L is the length of the pipe, V is the superficial air velocity for a straight pipe, and D is the internal diameter of the pipe.

More effort has been directed towards modelling the friction of solids passing through horizontal straight pipes rather than clarifying the flow phenomenon around bends. Models that have been developed for bends include those of Schuchart (1968), Singh and Wolfe (1972), Rossetti (1983), Chambers and Marcus (1986), Bradley and Mills (1988), Pan (1992), Pan and Wypych (1998), and Das and Meloy (2002). Most models on bend losses are related to the specific product and laboratory conditions; e.g., the location and orientation of the test bend and specific flow conditions. Schuchart (1968) was one of the first researchers to study gas–solid flow through pipe bends. Bradley and Mills (1988) proposed that the overall pressure loss can be more accurately predicted by predicting the pressure drops through the straight pipes and bends separately because, upon exit from a bend, solids decelerate and thus drop out of the gas stream and then re-accelerate to regain the flow. This re-acceleration of particles reduces the pressure of the gas. Bradley (1990a, 1990b) conducted experiments on the pressure drop at a bend with a test setup similar to that presented by Bradley (1989) using wheat flour and seven different types of bends. It was concluded that bends of different radius produce similar losses (i.e., the pressure drop is independent of the radius of curvature of the bend), but this result contradicts the findings of Mills and Mason (1985). Chaudhry, Bradley, Hyder, Reed, and Farnish (2001) conducted experiments on 10 materials using a setup based on that of Bradley (1989) and developed a model having 50% accuracy in predicting the pressure drop at a bend. All these existing models are empirical and have provided reliable results for the total pressure drop of a pipeline when used with the researchers own data, but their accuracy and reliability have not been adequately examined for different products and setup conditions. The aim of the present paper is to investigate the performance of different bend models in terms of the prediction of total-pipeline pneumatic conveying characteristics of different pipelines.

Experimental setup

Power plant fly ash was conveyed from a fluidised dense phase to a dilute phase through pipelines of different lengths and diameters (i.e., pipelines having dimensions of 69 mm inner diameter (I.D.) × 168 m length, 105 mm I.D. × 168 m length, and 69 mm I.D. × 554 m length). The physical properties of fly ash and the pipeline conditions are given in Table 1. Tests were conducted for different air and solid mass flow rates (air flow rates of 0.02–0.3 kg/s and solid flow rates of 2–8 kg/s).

A schematic of the 69 mm × 168 m pipeline is shown in Fig. 1 and schematics for larger and longer pipelines are shown separately in Figs. A1 and A2 of Appendix A. The setup included a 0.5-m^3 bottom-discharge (BD) blow tank feeding system. Single and twin blow tanks were used for pipes having lengths of 168 and 554 m, respectively. Straight pipes and bends used in the experiments were made of mild steel.

The 168-m pipeline consisted of five bends (two closely coupled) and a vertical lift of 7 m, while the 554-m pipeline had 17 bends (eight closely coupled) and a vertical lift of the same elevation. All bends had a radius of curvature of 1 m and a bend angle of 90°. Compressed air at maximum pressure of approximately 800 kPa was supplied by a diesel-powered screw compressor (P375-WP, Ingersoll Rand, USA) with free air delivery of 10.6 m^3/min. Five static pressure transducers (P8–P12) were used to measure static pressure in the horizontal straight pipes. These were installed in a way that they were unaffected by any bend effects. P8 was used to measure the total pressure drop of the pipeline while P9–P12 measured the static pressure along the pipeline. Output data from P9–P12 were used to model the solids friction factors of straight horizontal pipes. The static pressure transducers (Cerabar PMC133, Endress and Hauser, Germany)