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An experimental investigation into modeling solids friction for fluidized dense-phase pneumatic transport of powders

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ABSTRACT

Results are presented of an ongoing investigation into modeling friction in fluidized dense-phase pneumatic transport of bulk solids. Many popular modeling methods of the solids friction use the dimensionless solids loading ratio and Froude number. When evaluated under proper scale-up conditions of pipe diameter and length, many of these models have resulted in significant inaccuracy. A technique for modeling solids friction has been developed using a new combination of dimensionless numbers, volumetric loading ratio and the ratio of particle free settling velocity to superficial conveying air velocity, to replace the solids loading ratio and Froude number. The models developed using the new formalism were evaluated for accuracy and stability under significant scale-up conditions for four different products conveyed through four different test rigs (subject to diameter and length scale-up conditions). The new model considerably improves predictions compared with those obtained using the existing model, especially in the dense-phase region. Whereas the latter yields absolute average relative errors varying between 10% and 86%, the former yielded results with errors from 4% to 20% for a wide range of scale-up conditions. This represents a more reliable and narrower range of prediction that is suitable for industrial scale-up requirements.

Introduction

The pneumatic transportation of bulk solids through pipelines has been adopted in several industrial applications and is playing a more vital and integral role in numerous bulk handling operations and processes. Some benefits of pneumatic conveying include: totally enclosed conveying, environment friendly and hygienic mode of conveying, enhanced workplace safety, relatively low capital and maintenance costs (for well-designed systems), flexibility in layout, ease of automation and installation, and increased security. The traditional flow mode of conveying is known as dilute-phase (or suspension) flow, where the velocity of the carrier gas is sufficiently high to entrain and suspend all the particles along the pipeline. Because of the dispersed and suspended nature of flow mechanism, researchers have enjoyed encouraging success in modeling the relevant particle interactions and flow phenomenon (e.g., friction, impact, drag, and slip velocity) and in developing several solids friction factor and pressure drop models (Klinzing, Rizk, Marcus, & Leung, 2010), as suspension flow mechanics can be applied to this type of flow. The high gas velocity requirement (to ensure suspension of particles) calls for large-sized compressors and high operating power usage. Also, high particle velocities would increase wear on pipelines and bends. For fragile products, impacts of solids with pipelines and solids with solids result in product attrition thereby losing quality control. Moreover, large gas flows require large-sized filtration equipment (e.g., bag filters), hence requiring additional capital and space. To prevail over these limitations in conventional suspension or dilute-phase flows, low-velocity dense-phase pneumatic conveying is acquiring popularity within the industry in recent years. In this mode of conveying, because of the lower operating gas and particle velocities, the volume of moving air is greatly reduced and hence reduces energy consumption during operations. Also, a low conveying velocity ensures reduced wear rates of pipes and bends and higher product quality control.

There are different types of dense-phase modes of flow depending on air retention capability and permeability of the bulk solids, such as fluidized dense-phase flow, and slug and plug flow (Pan, 1999). Fine powders such as fly ash, cement, and pulverized coal

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Symbols and abbreviations

B	bend loss factor
D	internal diameter of pipe (m)
d_{50}	median particle diameter (μm)
d_s	particle diameter (m)
$Fr = V/(gD)^{0.5}$	Froude number of flow
K	constant of power function
L	length of pipe or test section (m)
$m^* = m_s/m_f$	solids loading ratio
m_f	mass flow rate of air (kg/s)
m_s	mass flow rate of solids (kg/s)
N	number of bends
V	superficial air/gas velocity (m/s)
$VLR = (m_s/\rho_s)/(m_f/\rho_f)$	volumetric loading ratio
w_{fo}	free settling velocity of an isolated particle (m/s)
λ_f	air-only friction factor
λ_s	solids friction factor through straight pipe
ρ_f	density of air (kg/m^3)
ρ_{bl}	bulk density of particles (kg/m^3)
ρ_s	particle density (kg/m^3)
ΔP	pressure drop through a straight horizontal pipe or pipe section (Pa)
ΔP_b	pressure drop through a bend (Pa)

Subscripts

b	bend
f	fluid (air)
s	solids

Abbreviations

I.D.	internal diameter of pipe
NB	nominal bore
PCC	pneumatic conveying characteristics
PMC	pressure minimum curve
t/h	tonnes per hour

that have good air retention capability (typically Geldart Group A powders), can be transported in fluidized dense-phase mode. Through their air retention capability, these materials flow through the pipes as fluidized or non-suspension dunes. This mode of conveying can sustain much higher solids-to-gas mass ratio (even as high as 100), resulting in significant benefits of lower gas flow rates, pipe sizes, and product and pipeline damage. For reliable design of these fluidized dense-phase pneumatic conveying systems, the total pipeline pressure drop and the condition for pipe blockage need to be accurately estimated. Inaccurate predictions of the total pipeline pressure drop would result in reduced throughput (for under-designed systems) or excessive conveying velocities (in over-designed systems). Selection of a conveying gas velocity lower than minimum transport criteria would result in products unable to be conveyed, gradual build-up of powder in the line, and ultimately pipe blockage (Mallick, 2009). Total pipeline pressure loss includes pressure drops in horizontal straight sections, verticals, bends, and acceleration losses. For pipelines having relatively longer horizontal straight-pipe runs (e.g., fly ash conveying pipelines in coal fired power plants from intermediate surge hoppers to remote silos), an accurate prediction of pressure drop for the horizontal straight-pipe run is of paramount importance as the major contribution of the total drop comes from long length of horizontal section. The pressure loss for solids–gas flow through a straight horizontal section of pipe can be expressed as

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

Barth (1958) and Weber (1981) employed this model for coarse particles in dilute-phase type flows. However, various subsequent researchers (Jones & Williams, 2003; Mallick, 2009; Pan, 1992; Pan & Wypych, 1998; Rizk, 1982; Wypych, 1989) have applied this representation to determine pressure drops for the dense-phase conveying of fine powders, such as fly ash, pulverized coal, and electrostatic precipitator (ESP) dust, for horizontal straight pipes.

This model considers the pressure drop due to gas and solids separately and the total pressure drop for the straight-pipe section is a sum of individual frictional losses for the gas and solids. Whereas most parameters in Eq. (1) can be calculated rather easily, based on well-established gas-only friction factor formulae (Swamee & Jain, 1976), accurate modeling of the solids friction factor is a challenging task. The solids friction factor term is a combined representation of the energy loss through solids-to-solids, solids-to-gas, and solids-to-pipe wall interactions. Because of the highly turbulent and complex nature of the moving fluidized bed of particles under high solids-to-gas mass concentration ratio (in the form of dunes), only limited progress has been achieved so far towards fundamentally understanding the flow mechanisms and modeling friction in solids. Because of these difficulties, empirical power-function-type modeling has been generally preferred over the years by several investigators, such as Rizk (1982), Wypych (1989), Pan (1992), Pan and Wypych (1998), Jones and Williams (2003), Mallick (2009), to avoid the need to establish fundamental equations describing the relationship between solids friction factor and the particle and bulk properties of powders. One of the most popular forms of solids friction factor model relations (Jones & Williams, 2003; Keys & Chambers, 1995; Mallick, 2009; Pan, 1992; Wypych, 1989) is

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

This power law uses the mass flow rate ratio of solids to air and the Froude number for the gas as dimensionless numbers. This formula has been applied by various researchers (from Wypych (1989) to Jones and Williams (2003)) and can provide good accuracy when applied to researchers' own data. However, recent scale-up evaluations by Mallick (2009) and Setia, Mallick, and Wypych (2014) have shown that these existing choices of dimensionless terms can provide significant inaccuracy under meaningful scale-up conditions of pipeline length and diameter. Therefore, there is a need to develop improved models for solids friction factor using parameters that provide a better representation of the flow mechanism for fluidized dense-phase pneumatic conveying of fine powders. Having a validated reliable modeling and scale-up procedure would benefit the industry in the following ways: minimization of air flows; reduced-sized compressor and power consumption; optimal pipe sizing for a given product, capacity, and pipe layout – large capacity, long-distance conveying; accurate predictions of pressure drop reduction in establishing design safety margins; improved ability to troubleshoot existing systems; minimization of filtration equipment and workplace/environmental emissions; and increased acceptance of fluidized dense-phase mode of conveying within the industry.

Experimental data

Fly ash and cement were conveyed from fluidized dense- to dilute-phase at the pneumatic conveying test facilities of Fujian Longking Co., Ltd., China. Also, different samples of fly ash and ESP dust were conveyed at the Bulk Materials Handling Laboratory of the University of Wollongong, Australia. The crucial physical properties of the products and pipelines are their diameters, which have

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