Powder Technology 277 (2015) 244–251

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Modeling minimum transport boundary for fluidized dense-phase pneumatic conveying systems

G. Setia [a,*], S.S. Mallick [a], R. Pan [b], P.W. Wypych [c]

[a] Department of Mechanical Engineering, Thapar University, Patiala, Punjab 147004, India
[b] Fujian Longking Co., Ltd., No. 81, Lingyuan Road, Longyan City, Fujian, China
[c] Faculty of Engineering and Information Sciences, University of Wollongong, Wollongong, NSW 2500, Australia

ARTICLE INFO

Article history:
Received 6 November 2014
Received in revised form 12 January 2015
Accepted 25 February 2015
Available online 5 March 2015

Keywords:
Fluidized dense-phase
Pneumatic conveying
Blockage boundary
Minimum conveying velocity
Scale-up

ABSTRACT

For the reliable design of fluidized dense-phase pneumatic conveying systems, it is of paramount importance to accurately estimate blockage conditions or the minimum transport boundary. Existing empirical models for the fluidized dense-phase conveying of fine powders are either based on a limited number of products and pipelines or have not been tested for their accuracy and stability over a wide range of scale-up conditions. In this paper, based on the test results of 22 different powders conveyed through 38 pipelines, a unified model for the minimum transport boundary has been developed that represents gas Froude number as a function of solid loading ratio and particle Froude number. The model has been validated by predicting the minimum transport boundary for 3 different products, conveyed through 5 different pipelines. Various other existing models have also been validated for the same products and pipelines. Comparisons between experimental blockage boundary and predicted results have shown that the new particle Froude number and solid loading ratio based model provides more accurate and stable predictions compared to the other existing models, which can unexpectedly provide significant inaccuracies. The model incorporates both pipe diameter effect and some important physical properties of the particles. The model is believed to be useful in predicting minimum conveying velocities to avoid pipe blockage and to ensure optimum operating point for industrial pneumatic conveying systems.

1. Introduction

The pneumatic conveying of bulk solids is widely used in industry to convey a large number of products, such as fly ash, pulverized coal, cement, calcium carbonate, plastic pellets, chemical powders, and food products, to list a few. The reasons are: completely closed form of conveying; hygienic; possibility of flexible layout; ease of automation and control; and so on. The dilute-phase mode of conveying has been used for many years, where the gas flow velocity is maintained sufficiently high to keep the particles suspended in gas during the flow. Researchers and designers have enjoyed relatively higher success in modeling such types of flow due to the dispersed and suspended nature of bulk solids by applying the principles of suspension flow mechanics. However, such types of dilute-phase flow result in larger air flow and velocity requirements. The high gas velocity (necessary for the suspension of particles) results in the damage of products (for fragile particles) or abrasive/impact wear of the pipeline and bends. To address the above issues of product quality control, pipeline wear and energy optimization, the dense-phase pneumatic conveying of powders has emerged in more recent years as a promising technique for bulk solid transport. In this method, the gas velocity is kept lower than the saltation velocity of particles and the particles travel in non-suspension mode in the form of dunes, slugs and plugs (depending on the deaeration or permeability characteristics of the product [1]). Fine powders (such as fly ash, cement, etc) that have good air-retention properties are capable of being conveyed in the fluidized dense-phase mode. Amongst all the different types of dense-phase conveying, the fluidized dense-phase mode provides the highest solids to air mass ratio (in excess of 50) as compared to typical dilute-phase flows (having lower solid loading ratio values up to 15). Due to this higher solid concentration, larger solid throughputs are achieved with smaller sized pipes. The size requirement of the air-solid separation unit is also minimized. Other benefits include lower operating and maintenance costs. Due to these benefits, the fluidized dense-phase conveying of fine powders is considered to be a significantly better alternative compared to traditional dilute-phase systems. However, the reliable design of fluidized dense-phase conveying system is considered significantly more difficult than doing the same for dilute-phase systems. This is due to the highly concentrated and turbulent (and complex) nature of flow of the fluidized bed [1,2]. Two important design parameters are total pipeline pressure drop and the air flow rate required for stable conveying. For reliable estimations of the same, solid-air-wall friction and minimum transport criteria (or pipe blockage condition) should be accurately modeled and scaled-up.

* Corresponding author. Tel.: +91 175 2393370.
E-mail address: gautamsetia@yahoo.com (G. Setia).

http://dx.doi.org/10.1016/j.powtec.2015.02.050
0032-5910/

Over-estimation of the minimum transport boundary would cause unnecessarily high velocities, thus nullifying many of the advantages of low-velocity dense-phase conveying. Under-estimation of the minimum transport boundary would result in unstable conveying, product build-up in the line and/or pipe blockage. Therefore, it is essential that the blockage condition or the minimum air velocity requirement to sustain stable conveying be modeled and scaled-up reliably. The existing models [3–8] are mostly empirical and have not been adequately examined for their accuracy for different products and pipeline scale-up conditions. The aim of this paper is to test the reliability of the existing models and to validate a new unified model to predict the minimum transport boundary for the fluidized dense-phase pneumatic conveying of powders.

2. Experimental data

Conveying trails were performed using fly ash at the Laboratory for Bulk Solids and Particulate Technologies of Thapar University (India) and with fly ash and cement at the pneumatic conveying test set-up of Fujian Longking Co. Ltd. (China) with different pipeline configurations. Table 1 lists the physical properties of these products.

A schematic of the test rig used for fly ash conveying at Thapar University is shown in Fig. 1. Compressed air was supplied via a rotary screw compressor (Make/Model: Kirloskar/KES 18-7.5) having a maximum delivery pressure of 750 kPa and flow rate of 202 m^3/h (Free Air Delivery). An air flow control valve was installed in the compressed air line to obtain different air flows. A vortex flow meter was installed in the compressed air line to measure the air flow rates. A bottom discharge type blow-tank (having 0.2 m^3 empty volume) was used to feed the product into the pipeline. The blow tank was provided with solenoid operated dome-type material inlet, outlet and vent valves. A receiving bin of 0.70 m^3 capacity was installed on top of the blow tank and fitted with bag filters having a reverse pulse jet type cleaning mechanism. The receiving bin and blow tank were supported on shear beam type load cells to provide data for the mass flow rate of solids. Mild steel pipelines of different diameters and lengths, such as 43 mm I.D × 24 m long, 69 mm I.D × 24 m long and 54 mm I.D × 70 m long, were used for the test program. All pipelines included a 3 m vertical lift and had 4 × 90° bends of 1 m radius. Static pressure measurement point P1 was used to measure the total pipeline pressure drop. The transducer was Endress & Hauser, model: Cerabar PMC131, pressure range: 0–2 barg, maximum pressure: 3.5 bar (absolute). Calibration of the pressure transducer, load cells and flow meter were performed using a standardized calibration procedure [1]. A portable PC compatible data logger was used to convert and record the electrical output signals from the load cells, pressure transducers and flow meter. The data logger provided up to 16 different channels with 14 bit resolution. Every pipeline was installed with two sets of 300 mm long sight-glasses made of borosilicate glass for flow visualization (and to visualize the blockage phenomenon). Fly ash was conveyed for a range of solids and air flow rates. Sight glass observations revealed a significant amount of non-suspension flow, therefore confirming fluidized dense-phase conveying performance of the fly ash. Further reduction of air velocity provided pulse-type discontinuous dune structures. Even further reduction of air velocity provided unstable conveying, characterized by high pressure fluctuations and a gradual build-up of product in the pipeline. In the present study, this unstable-phase conveying is considered in the proximity of blockage. Repeated trials of conveying with a gradual product build-up condition would completely block the pipeline in few cycles of conveying. Because of the practical limitation of setting the air flow control valve exactly for the blockage condition, it was found that experimentally it was difficult to be very precise about the air flow rate corresponding to pipeline blockage. Therefore, the blockage boundaries drawn in this paper represent the reliable transport boundaries. These are the limits to which the product was conveyed without instability. To the left of the reliable transport or minimum transport boundary, unstable points are shown. Blockage points were obtained and are shown at even further lower air flow rates. A series of experiments were performed near to the blockage boundary to confirm a zone of air flow rates for which blockage would occur. Tests were performed multiple times to ensure repeatability of test data, especially near the blockage boundary.

Different samples of fly ash and cement were conveyed in fluidized dense-phase mode through larger and longer pipelines (65 mm I.D. × 254 m long and 80 and 100 mm I.D. × 407 m long stepped pipeline) in the Bulk Materials Handling Laboratory of Fujian Longking Co. Ltd. (China). Schematic of the 65 mm I.D. × 254 m long test rig is shown in Fig. 2. The test facility comprised: 0.75 m^3 bottom-discharge type blow tank feeding system; mild steel pipelines including bends with 1 m radius 90° bends, several pressure transducers to determine pipeline pressures; screw compressor with capacity of about 660 m^3/h of Free Air Delivery. The system also included other instrumentation, data acquisition system, bag filters, etc (Fig. 2).

3. Existing models for minimum transport criteria

Previous models to predict minimum transport boundary are provided here. Weber [3] provided the following expressions to predict blockage boundary.

$$\text{For,} \quad w_{fo} \leq 3\text{m/s}, \quad \text{Fr}_i = \left[7+(8/3)\ w_{fo}\right](\text{m}*)^{0.25}(d/D)^{0.1} \tag{1}$$

$$\text{For,} \quad w_{fo} \leq 3\text{m/s}, \quad \text{Fr}_i = 15(\text{m}*)^{0.25}(d/D)^{0.1} \tag{2}$$

Martinussen [4] conveyed products through a horizontal pipeline of 53 mm diameter and 15 m length. By applying a fluid analogy, he developed the following model to determine the minimum transport criteria:

$$V_i^2 = \text{K}\,\text{D}\,g(\rho_{bl}/\rho)[1-\text{m}*(\rho/\rho_{bl})]^3 \tag{3}$$

where, K (geometrical factor) = Π/4 at the filling level of D/2. Martinussen [4] mentioned that this model could provide better predictions for fine materials than for coarse ones.

Table 1
Physical properties of fly ash and cement conveyed and pipeline conditions.

No.	Powder	Laboratory	d_{50} (μm)	ρ (kg/m^3)	ρ_{bl} (kg/m^3)	Blow tank type	D (mm)	L (m)	$V_{i,\,min}$ (m/s)	L_h (m)	L_v (m)	L_v/L × 100%	No. of bends	% loss in L_v	% loss in bends
1	Fly ash	Thapar University, India	19	1950	950	BD	43	24	2.3	21	3	12.5	4	13.8	36.8
							54	70	3.6	67	3	4	4	6.7	17.9
							69	24	4.1	21	3	12.5	4	13.8	36.8
2	Fly ash	Longking Co., China	22	2370	660	BD	65	254	3.5	238	16	6	10	10.3	13
							80/100	407	2	391	16	4	14	6.7	11.7
3	Cement	Longking Co., China	19	2910	1080	BD	65	254	3.2	238	16	6	10	10.3	13
							80/100	407	2.7	391	16	4	14	6.7	11.7