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Keywords

modeling, pneumatic, phase, systems, dense, conveying, fluidized, boundary, transport, minimum

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Modelling Minimum Transport Boundary for Fluidized Dense-Phase Pneumatic Conveying Systems

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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 solids loading ratio and particle Froude number. The model has been validated by predicting the minimum transport boundary for 3 different products, conveyed through 6 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 solids 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.

Keywords*:* Fluidized dense-phase, pneumatic conveying, blockage boundary, minimum conveying velocity, scale-up

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, 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 modelling 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 solids 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 solids loading ratio values up to15). Due to this higher solids concentration, larger solids throughputs are achieved with smaller sized pipes. The size requirement of the air-solids separation unit is also minimised. 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 modelled and scaled-up. 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 modelled and scaled-up reliably. The existing models [3 to 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.

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

No.	**Powder**	**Laboratory**	**d_{50} (µm)**	**ρ_p (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 x 100%**	**No. of bends**	**% loss in L_v**	**% loss in bends**
1	Fly ash	Thapar University, India	19	1950	950	BD	43 54 69	24 70 24	2.3 3.6 4.1	21 67 21	3 3 3	12.5 4 12.5	4 4 4	13.8 6.7 13.8	36.8 17.9 36.8
2	Fly ash	Longking Co., China	22	2370	660	BD	65 80/100	254 407	3.5 2	238 391	16 16	6 4	10 14	10.3 6.7	13 11.7
3	Cement	Longking Co., China	19	2910	1080	BD	65 80/100	254 407	3.2 2.7	238 391	16 16	6 4	10 14	10.3 6.7	13 11.7

A schematic of the test rig used for fly ash conveying at Thapar University is shown in Figure 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/hr (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^3empty 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 diameter and length, such as 43 mm I.D x 24 m long, 54 mm I.D x 24 m long, 69 mm I.D x 24 m long and 54 mm I.D x 70 m long, were used for the test program. All pipelines included a 3 m vertical lift and had 4 x 90^o 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 bar-g, 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.

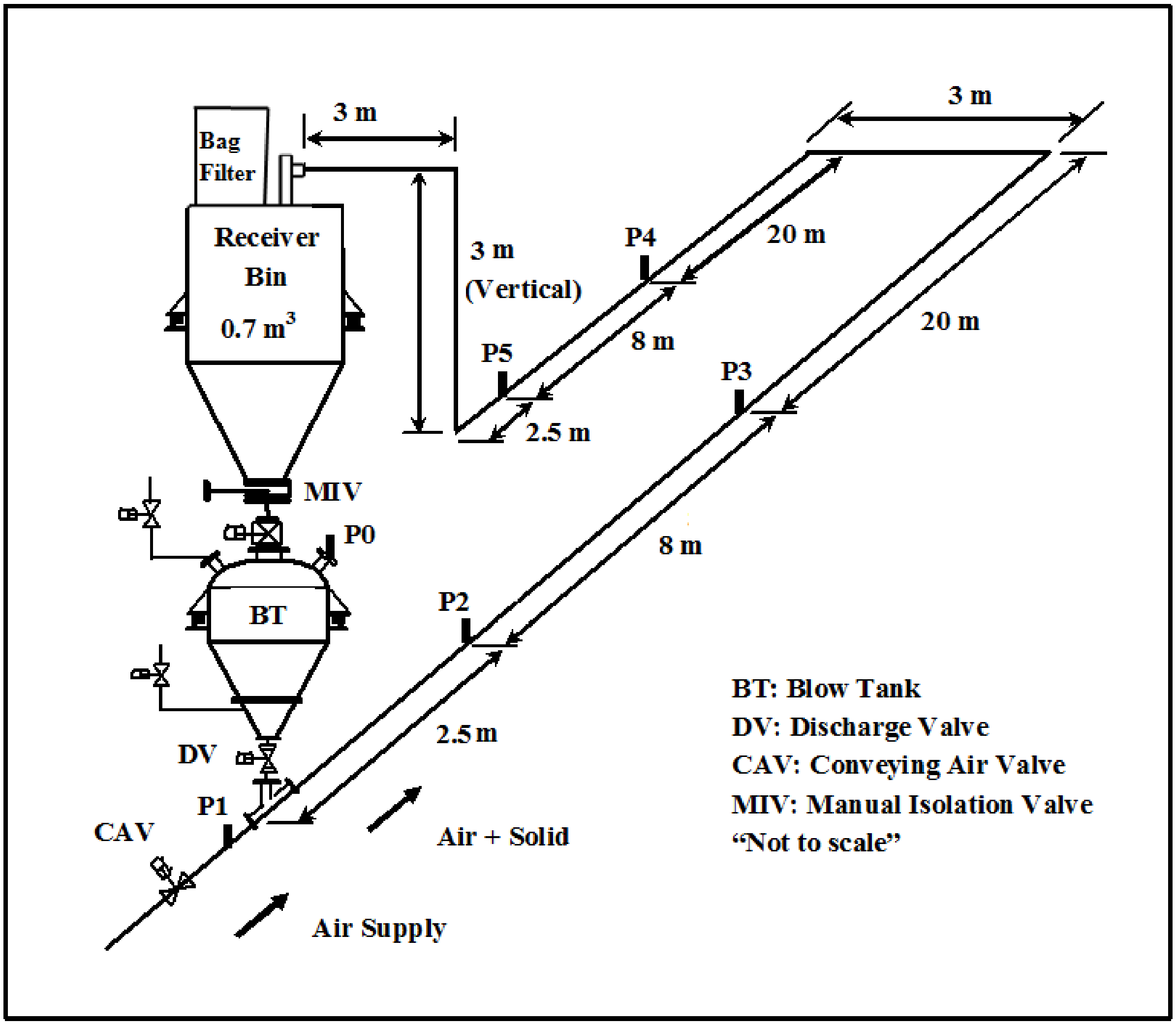

Figure 1. Schematic Layout of the 54 mm I.D. × 70 m test rig at Thapar University (India)

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). Schematics of the 65 mm I.D. × 254 m long test rig is shown in Figures. 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/hr of Free Air Delivery. The system also included other instrumentation, data acquisition system, bag filters, etc.

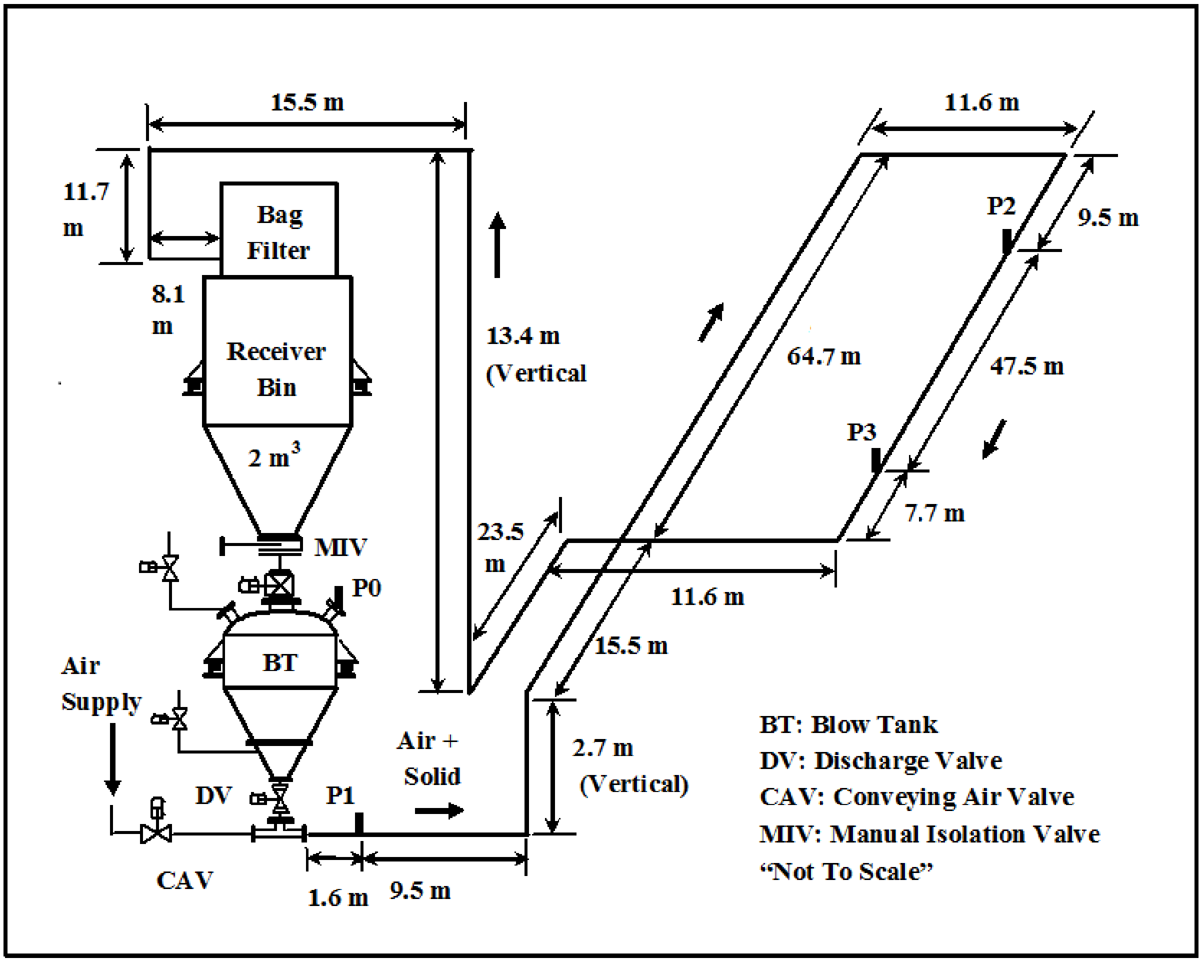

Figure 2. Layout of the 65 mm I.D. × 254 m test rig at Fujian Longking Co., Ltd. (China)

3. Existing models for minimum transport criteria

Previous models to predict minimum transport boundary are provided here in chronological order as much as possible. Weber [3] provided the following expressions to predict blockage boundary.

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

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

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

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

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

Mills [5] conveyed cement through 81 mm I.D. × 95 m test rig and provided dense-phase minimum transport boundary limit as 3 m/s. However, this model is applicable for one pipeline and product (cement). Also, the model does not include pipeline diameter and length scale-up effects. Mallick and Wypych [6] established a Froude number based criterion ($Fr_{min} = 6$) to represent the minimum transport criteria using different fly ash, ESP dust and cement data conveyed through pipelines of various pipe diameters and length. This Froude number based model (Fr_{min} = 6) did not consider particle parameters and the effect of solids loading ratio, which is a major limitation for its application for different powders and different loading ratio. More recently, Mallick et al. [7] indicated that a constant Froude number line to predict the blockage boundary may provide only limited accuracy over a wide range of scale-up conditions. It was believed that the solids loading ratio term would have some effect on predicting minimum conveying velocity requirement, as fluidized powders at higher concentrations seem to exhibit "self-pushing" or "self-cleaning" effects along the pipeline (thus promoting powder flow movements). Therefore, higher solids concentration could provide assistance towards flow initiation. Setia et al. [8] incorporated the above concept of self-pushing mechanism of powders at higher solids loading ratio and proposed the following model format, equation (4). This model showed some improvement but was far from being highly comprehensive and unified. The reason is the model format does not directly take into consideration important particle parameters, such as particle size and density effects. As a result, this format could not be used as a unified model and separate 'K' and 'a' are to be determined for each individual product based on pilot plant testing.

$$Fr_i = K\,(m^*)^{a} \qquad \text{Where, 'a'<0} \qquad (4)$$

Rizk [9] carried out experiments on minimum conveying velocity using pipelines of 50 to 400 mm diameter pipelines. Sryropor and polystrol were used as the test materials. The minimum pressure drop curve was considered as the boundary between safe steady flow and a region of stationary particles. The correlation of the minimum conveying velocity was presented as:

$$m^* = (1/10^{\delta})\, Fr_i^{\,\chi} \qquad (5)$$

Where, $\delta = 1.44\, d + 1.96$ and $\chi = 1.1\, d + 2.5$

Schade [10] investigated into minimum conveying velocity (the gas velocity at which the particles are unable to be transported) in a wide range of diameters (D = 50, 60, 80, 100, 120, and 150 mm) and the test materials used in the experiments were granule, sand, styropor, rubber, and polystyrol. Schade's correlation was:

$$V_i / (g\, D)^{0.5} = (m^*)^{0.11} (D/d)^{0.025} (\rho_p/\rho)^{0.34} \qquad (6)$$

Cabrejos and Klinzing [11] applied rules of dimensional analysis to find the relation for the pickup velocity of particles larger than 100 μm. The expression was given as:

$$V_i / (g\, d)^{0.5} = 0.0428\, (Re_p)^{0.175} (D/d)^{0.25} (\rho_p/\rho)^{0.75} \qquad (7)$$

Kalman et al. [12] presented the pickup velocity in terms of modified Reynolds number as a function of modified Archimedes number. The Reynolds number was modified to take into account the pipe diameter. They derived the three zone model, which is based on the particle size. The model is given as:

For $Ar > 16.5,$ $Re_p^* = 5\,Ar^{(3/7)}$ (8)

For $0.45 < Ar < 16.5,$ $Re_p^* = 16.7$ (9)

For $Ar < 0.45,$ $Re_p^* = 21.8\,Ar^{(1/3)}$ (10)

Where, Re_p^* is Reynolds number modified by pipe diameter.

The models given by researchers [5] to [10] are in the area of coarse and/or granular product conveying (and not for fine powders) and use the concept of saltation and pick-up velocities. Hence, the following models have not been evaluated in the present paper. The aim of this paper is to develop a validated and reliable unified model to predict the minimum transport boundary (or blockage condition) that can be applied to a variety of different powders. Such a tool would help the designer to effectively design a good dense-phase system, benefited by the high solids loading ratio (m*), yet preventing pipeline blockage.

4. New model development for minimum transport criteria

In this section, an attempt has been made to develop a unified model (and not particle specific model) for a wider range of applications and usability. In this approach, models in different formats have been developed by using a large number and variety of data points of 22 different powders conveyed through 38 pipelines (covering high to low solids flow rates).The various products and pipelines are summarised in Table 2. The first format (New model 1) is provided by equation (11); however, the ‘K’ and ‘a’ values are to be determined not for individual products, but by combining the large number of data sets (viz. 22 products and 38 pipelines). The gas

Froude number (Fr) term signifies that higher minimum conveying velocity is required for larger pipe diameters.

New model format 1: $Fr_i = K\,(m^*)^{a}$ (11)

In the second format, further improvement in modelling has been attempted by directly incorporating some particle parameters in the form of a particle Froude number. The format is given by equation (12). In this format, the gas velocity requirement to prevent pipeline blockage is a function of pipe diameter, particle Froude number (based on free settling velocity of particles and averaged diameter of particle) and solid loading ratio (representing the "self-cleaning" effect). Therefore, this model incorporates the effect of particle properties (particle size and density). Hence, this format can be used for different powders. The 'K', 'a' and 'b' values are to be determined from the large number of data sets (viz. 22 products and 38 pipelines). The new model includes important parameters such as the solids loading ratio and particle properties in addition to the pipe diameter effect. Thus, the new model is significantly more capable than the existing model ($Fr_{min} = 6$). It has been experimentally seen that at higher solids loading ratios, the products seem to be self-pushing and needing relatively low velocities for reliable transport. Therefore the effect of m* should not be ignored. Additionally, the aim of the new model was to incorporate the particle parameters in the model, so that the model can be applied reliably for different products. With this view, a particle Froude number term has been incorporated that aims to include the effects of particle diameter and density.

New model format 2: $Fr_i = K\,(m^*)^{a}\,(Fr_p)^{b}$ (12)

Where, Fr_p is particle Froude number defined as $Fr_p = w_{fo} / (g\ d)^{0.5}$

Table 2: Summary of 22 products conveyed and 38 pipeline configurations

No.	**Powders**	**d_{50} (μm)**	**ρ_p (kg/m^3)**	**ρ_{bl} (kg/m^3)**	**Blow tank type**	**D (mm)**	**L (m)**	**L_h (m)**	**L_v (m)**	**L_v/L x 100%**	**No. of bends**	**Percentage loss in verticals**	**Percentage loss in bends**
1	White powder [1]	55	1600	620	BD	69	148	142	6	4	6	6.7	14
2	ESP dust [1]	7	3637	610	BD	69 69 105	168 554 168	161 547 161	7 7 7	4 1 4	5 17 5	7.2 2.2 7.2	10 11 10
3	Fly ash [1]	30	2300	700	BD	69 69 105	168 554 168	161 547 161	7 7 7	4 1 4	5 17 5	7.2 2.2 7.2	10 11 10
4	Barytes [2]	12	4200	*	TD	75 75 100	72 66 66	64 66 66	8 0 0	11 0 0	5 4 4	16 0 0	20 20 20

						125	68	68	0	0	4	0	19
5	Cement [2]	15.5	3100	*	TD	75	72	64	8	11	5	16	20
						75	66	66	0	0	4	0	20
						100	66	66	0	0	4	0	20
						125	68	68	0	0	4	0	19
6	Ilmenite [2]	9.5	4600	*	TD	75	66	66	0	0	4	0	20
						100	66	66	0	0	4	0	20
						125	68	68	0	0	4	0	19
7	Bentonite [2]	25	2800	*	TD	75	72	64	8	11	5	16	20
8	Alumina 1 [2]	59.2	2800	*	TD	75	138	130	8	6	9	8.8	20
9	Alumina 2 [2]	72	2800	*	TD	75	138	130	8	6	9	8.8	20
10	Alumina 3 [2]	79.3	2800	*	TD	75	138	130	8	6	9	8.8	20

11	Alumina 4 [2]	86.7	2800	*	TD	75	138	130	8	6	9	8.8	20
12	Alumina 5 [2]	90.5	2800	*	TD	75	138	130	8	6	9	8.8	20
13	Cement [7]	14	3060	1070	TD	81 53	95 101	95 101	0 0	0 0	9 17	0 0	28 40
14	Fly ash [13]	15.5	2197	634	BD	52.5 52.5 69 69	102 135 172 553	96 129 165 547	6 6 7 6	6 4 4 1	4 4 5 17	9.6 7.6 7 2	13 10 10 11
15	Tallawarra fly ash [14]	20	2350	500	BD	52	71	67.4	3.6	5	11	6	37
16	Eraring fly ash [14]	27	2160	880	BD	52	71	67.4	3.6	5	11	6	37
17	Munmorah fly ash [14]	25	2100	650	BD	52	71	67.4	3.6	5	11	6	37

18	Vales Point fly ash [14]	19	2130	700	BD	52	71	67.4	3.6	5	11	6	37
19	Gladstone fly ash [14]	18	2250	1030	BD	52	71	67.4	3.6	5	11	6	37
20	Wallerawang fly ash [14]	12	2195	455	BD	52	71	67.4	3.6	5	11	6	37
21	Liddell fly ash [14]	13	2415	640	BD	52	71	67.4	3.6	5	11	6	37
22	Cement [15]	20	3100	950	BD	69	168	161	7	4	5	7.2	10

* Not provided in source reference

The losses in bends and verticals in Table 1 and 2 have been calculated using the models of Mills [5]. Using the minimum transport boundary data provided in Table 2, the values of ‘K’, ‘a’ and ‘b’ have been calculated. The new models and the correlation coefficient values are provided by equations (13) and (14), as follows:

New model 1: $Fr_{min} = 40(m^*)^{-0.48}$ $[R^2 = 0.87]$ (13)

New model 2: $Fr_{min} = 23.5\,(m^*)^{-0.396}\,(Fr_p)^{0.131}$ $[R^2 = 0.89]$ (14)

5. Validation of models of minimum transport criteria

The above models (existing and new models) have been validated for their reliability by using them to predict the blockage boundary for two fly ash and cement samples conveyed through different pipelines in dense-phase. The product properties and pipeline details are provided in Table 1. The new models 1 and 2 were not developed from the data of these products and pipelines for “better” validation. Figure 3 shows the predictions of different models for cement conveyed through 65 mm I.D. and 254 m long pipe**.**

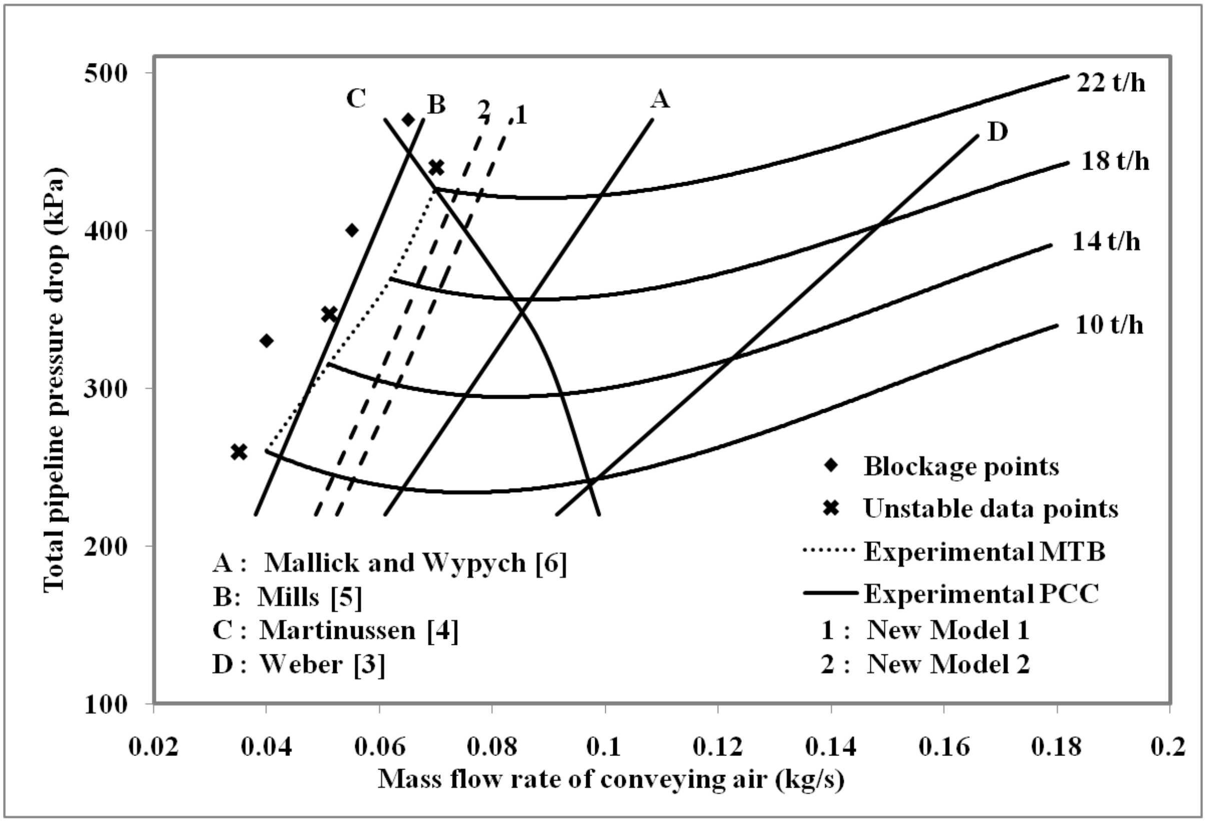

Figure 3. Validation of models of minimum transport boundary for cement, 65 mm I.D. × 254 m long pipe

It can be seen that the Mallick and Wypych [6] and Weber [3] models provide over-predictions; in fact, the Weber [3] model predicts significantly higher air flow rate requirements. This could be due to the positive exponents of solids loading ratio in the expression of the Weber [3] model. As a result, it has predicted higher velocities for larger tonnages. The Mills [5] model has provided some under-predictions; hence use of this model for this product and pipeline could result in unstable flow and pipe blockage. The new models 1 and 2 provided reasonably good predictions (with trivial amounts of over-predictions), with model 2 providing the best results. The Martinussen [4] model predicted trends of minimum transport boundary that contradicted the slopes of the experimental blockage boundary. The Martinussen [4] model provided significantly lower air flow rate requirements at higher solids flow rates; i.e. the model would predict unnecessarily high amount of air flows in lower tonnages, but would result in unstable conveying or pipe blockage at higher air flows. This could be because the minimum conveying velocity requirement decreases with an effective exponent of 1.5 to m* as per this model, i.e. the minimum predicted velocity according to this model would rapidly decrease with an increase in m*. As a result, the model predicts significantly lower transport limits at higher solids flow rates (due to rise in m*). As a result, it has been decided not to further evaluate the model in subsequent figures. Figure 4 shows the predictions of different models for cement conveyed through 80/100 mm I.D. and 407 m long stepped-diameter pipeline**.**

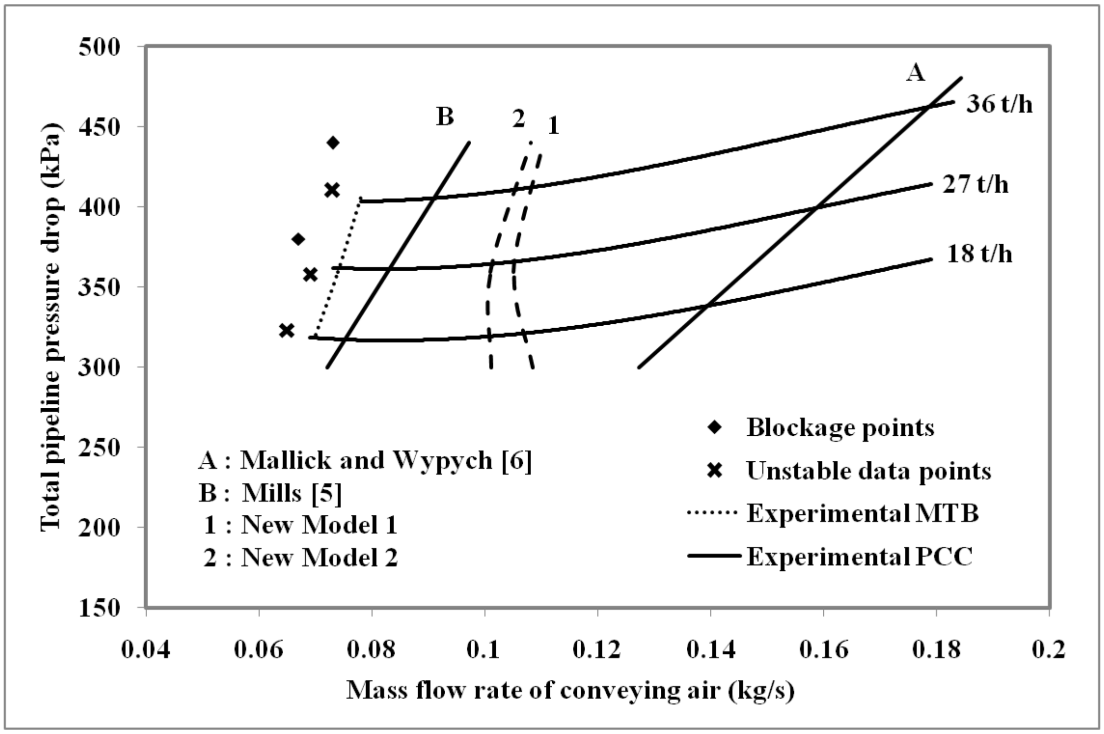

Figure 4. Validation of models of minimum transport boundary for cement, 80/100 mm I.D. × 407 m long pipe

It can be seen from Figure 5 that for longer pipe (407 m length) and higher mass flow rate of solids, conveying was possible with relatively lower velocities (compared to Figure 4). As a result, the Mills [5] model provided good predictions in this case. The Mallick and Wypych [6] model provided large over-predictions. The new models 1 and 2 provided similar results, with the new model 2 providing predictions that are closer to the experimental blockage boundary. The Martinussen [4] model provided similar trends as shown in Figure 4. Also, the Weber [3] model predicted excessively high air flows (beyond the range of Figure 5). Hence prediction with the Weber [3] model has not been included in Figure 4. Figure 5 and 6 show the predictions of different models for fly ash conveyed through the 65 mm I.D. and 254 m long and 80/100 mm I.D. and 407 m long pipes.

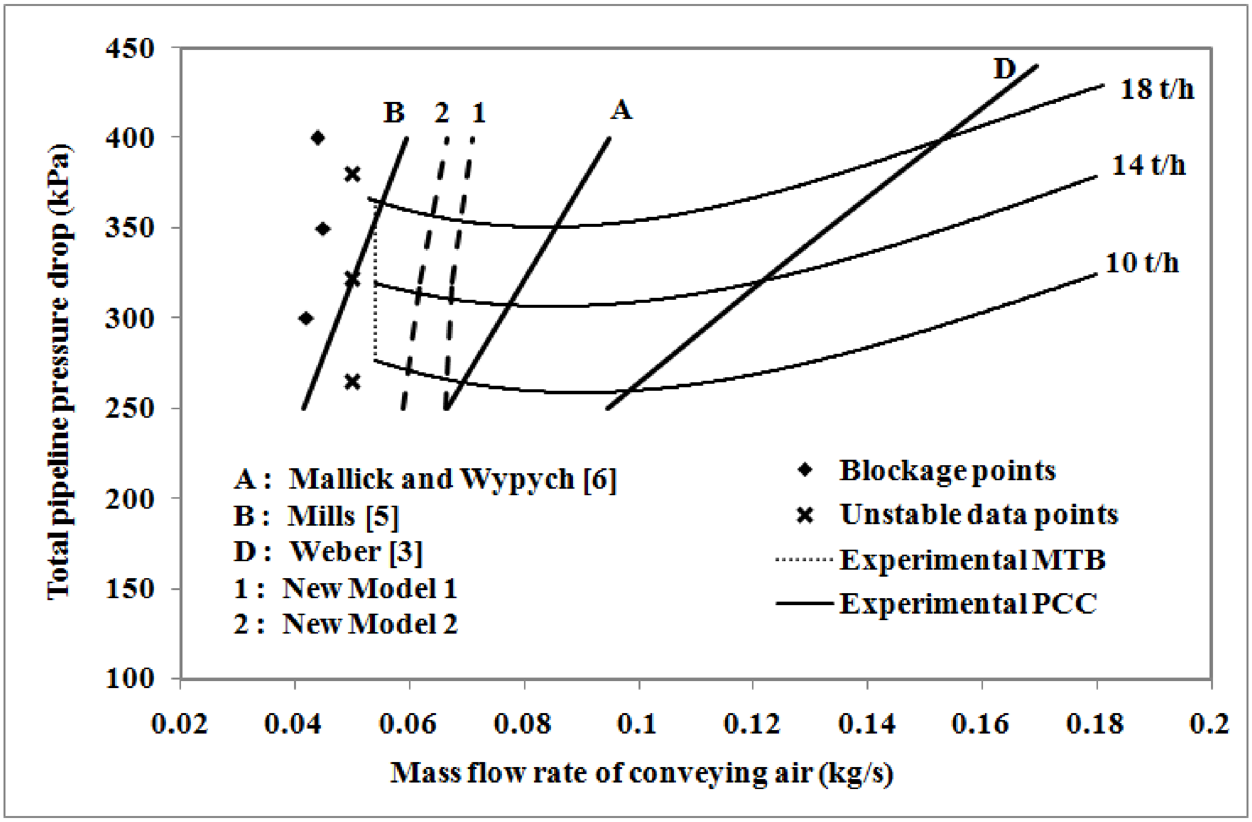

Figure 5. Validation of models of minimum transport boundary for fly ash, 65 mm I.D. × 254 m long pipe

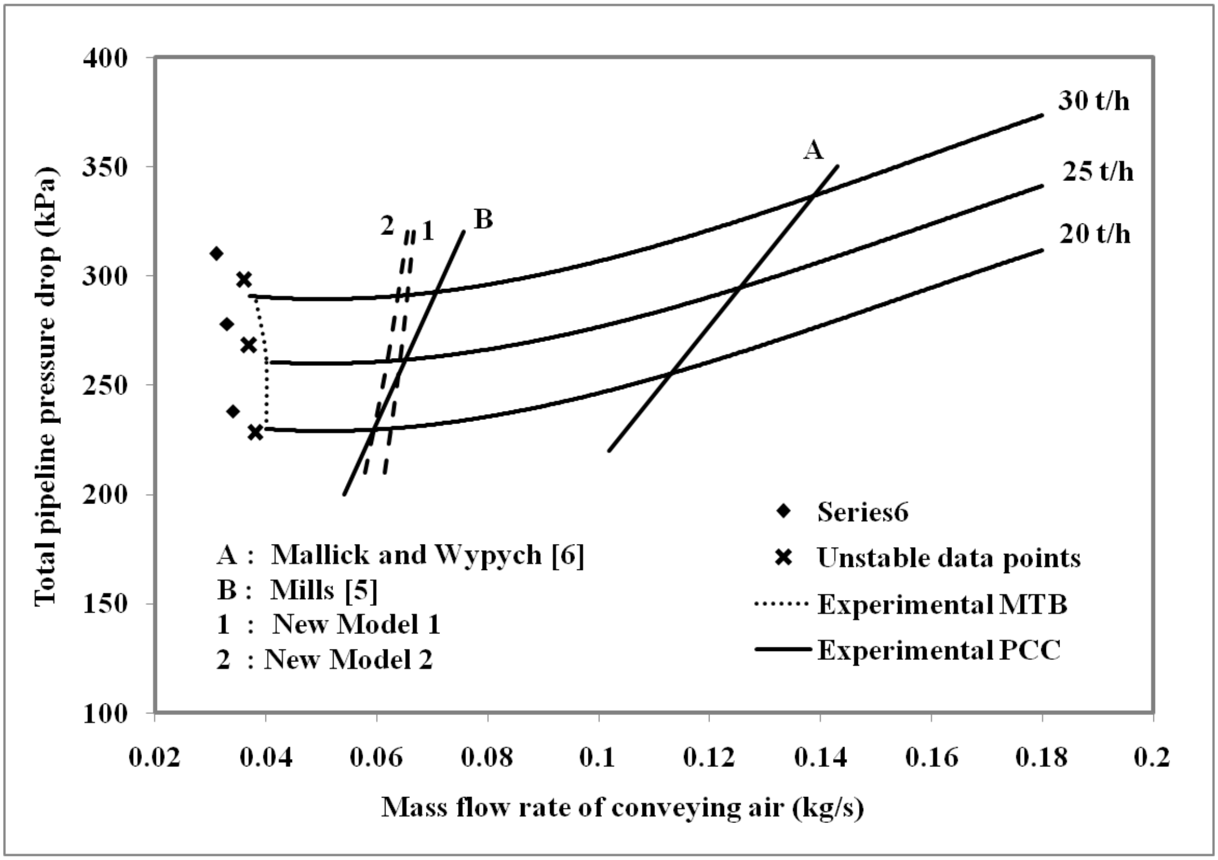

Figure 6. Validation of models of minimum transport boundary for fly ash, 80/100 mm I.D. × 407 m long stepped-diameter pipeline

Figures 5 and 6 show that the trends of predictions with the models for fly ash are similar to that of cement. Figure 6 shows that the model of Mills [5] shows under-predictions. The Weber [3] and Mallick and Wypych [6] models provided significant over-predictions. Hence, these models would result in unnecessarily higher air flows than what would be sufficient to achieve stable conveying, thus affecting system optimization and increasing the operating and maintenance costs of the system. The new models have provided stable-predictions, of which the new model 2 has resulted in most optimized predictions (i.e. the minimum transport boundary predicted by new model 2 is closest to the experimental blockage boundary and does not predict operating conditions to the “left “of the experimental blockage boundary). It is again found (similar to cement) that for higher tonnages, transport is possible with lower air velocity. This is perhaps due to the “self-pushing” effect of the products. Figures 7 to 9 show the predictions of different models for fly ash conveyed at Thapar University. In Figures 7 and 8, the pipe length was kept at 24 m for both cases and only the internal diameters were different – ranging from 43 and 69 mm. Therefore, Figures 7 and 8 are intended to represent the effect of increase in pipe diameter on the experimental minimum transport boundary and prediction of the same using different models. Figure 9 shows results from the model evaluations for the 54 mm I.D and 70 m long pipeline.

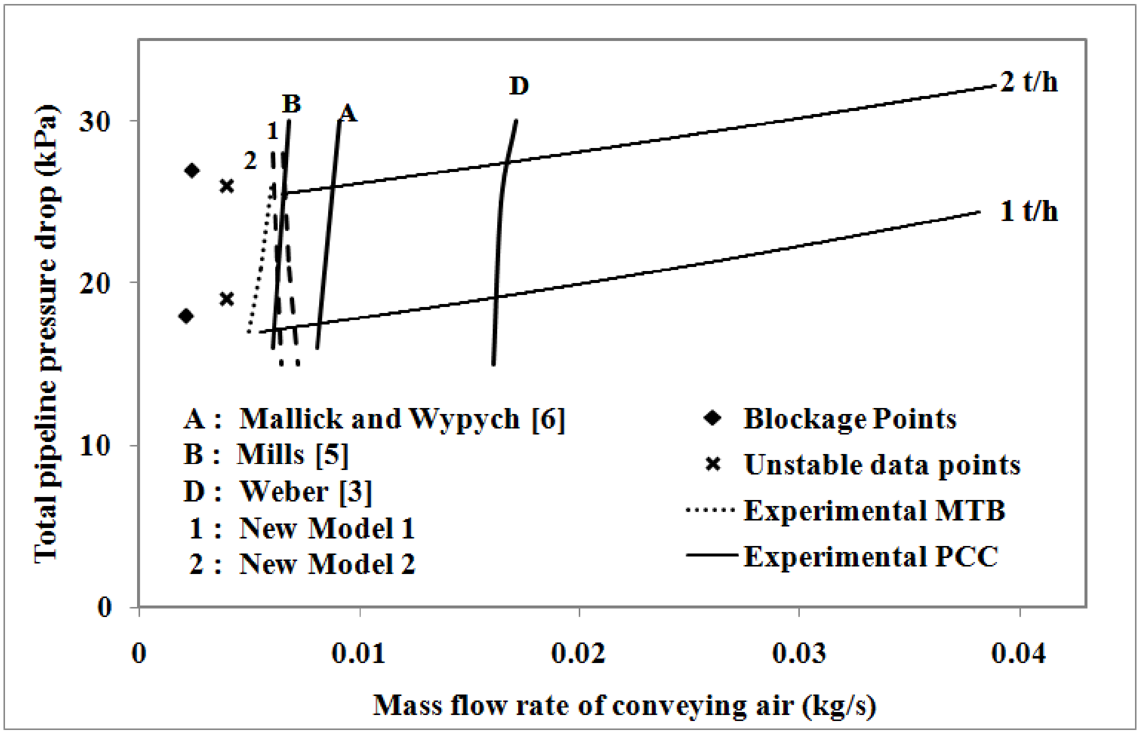

Figure 7. Validation of models of minimum transport boundary for fly ash (Thapar University), 43 mm I.D. × 24 m long pipe

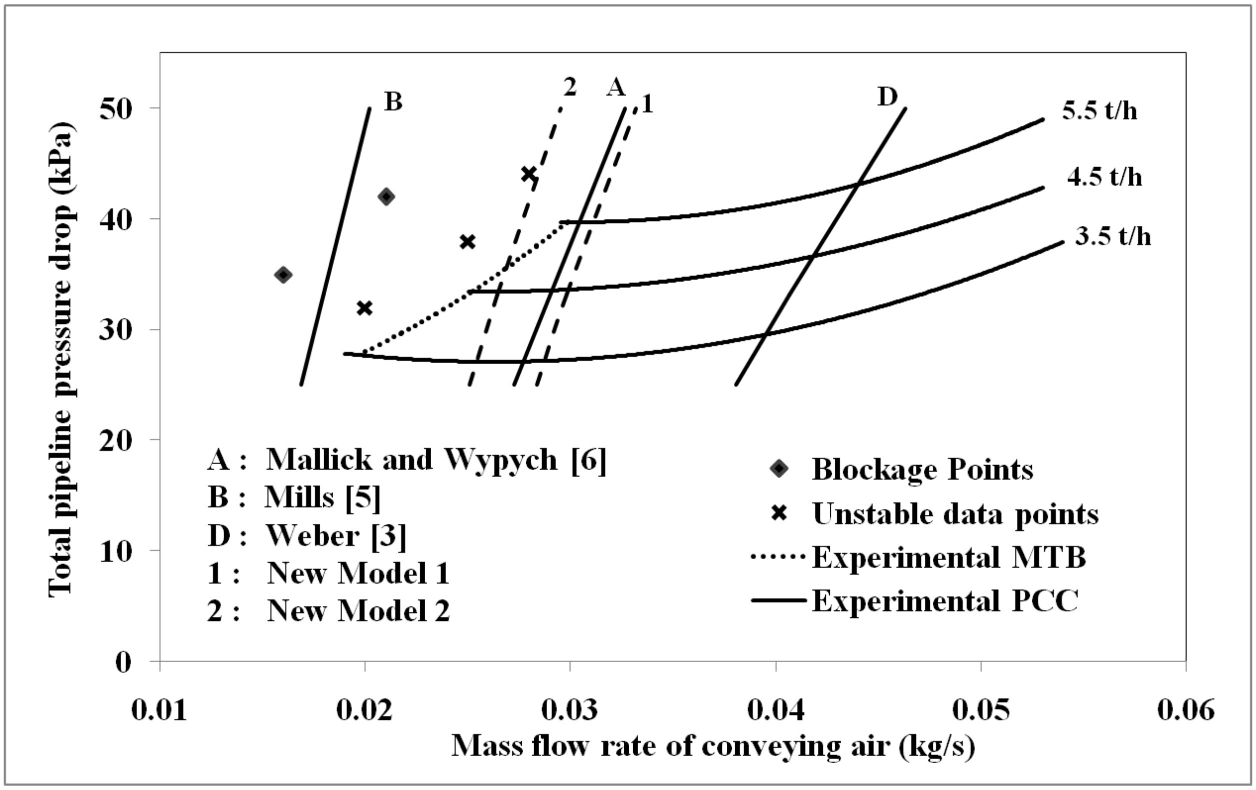

Figure 8. Validation of models of minimum transport boundary for fly ash (Thapar University), 69 mm I.D. × 24 m long pipe

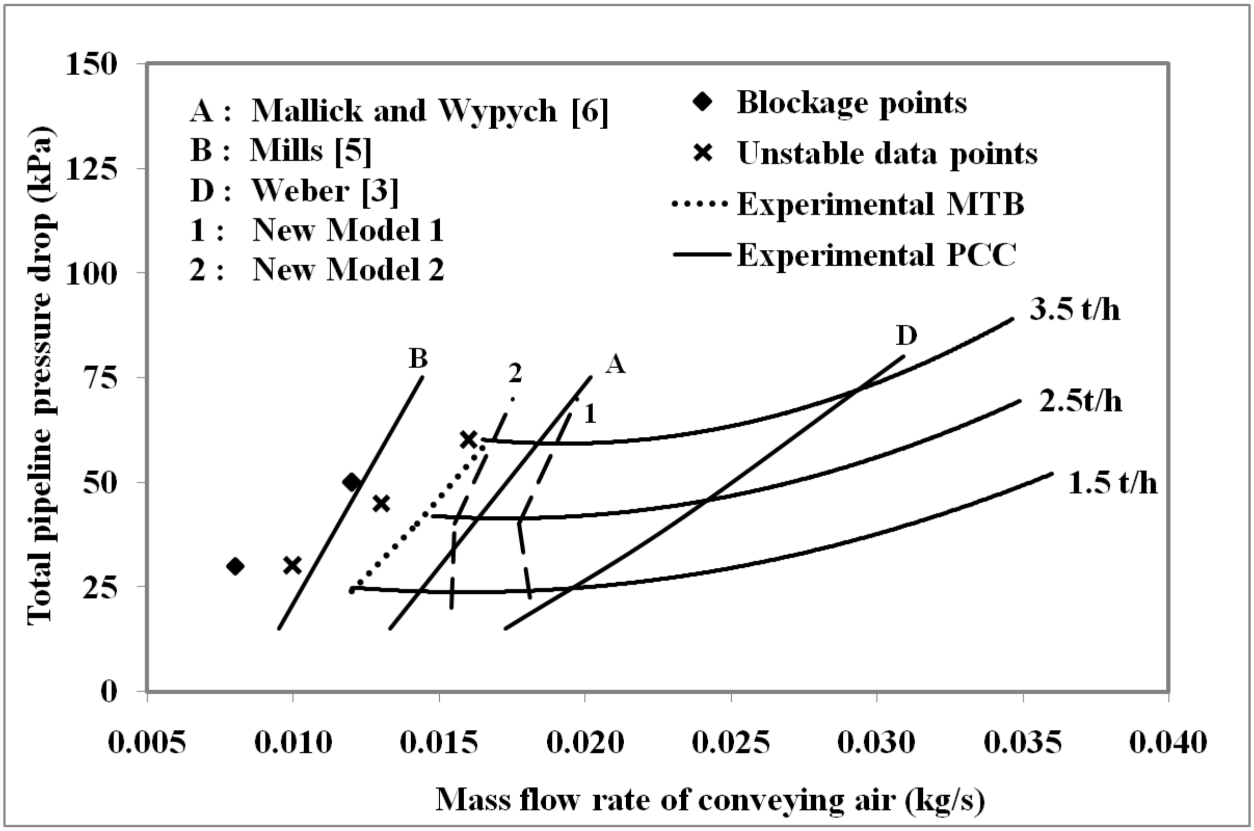

Figure 9. Validation of models of minimum transport boundary for fly ash (Thapar University), 54 mm I.D. × 70 m long pipe

Figures 7 and 8 show that the Weber [3] model consistently provided large amounts of over-prediction. The Mills [5] model provided good predictions for smaller pipelines. However, this model resulted in under-predictions (i.e. predicting possible transport within the blockage zone) when the diameter was scaled-up from 54 to 69 mm. This demonstrates that a constant velocity based model is not adequate and the effect of pipe diameter must be incorporated in selecting minimum transport criteria. The Mallick and Wypych [6] model provided some over-predictions in each case. New models 1 and 2 resulted in predictions that are very close to the actual blockage boundary. However, they tend to show some under-predictions partially for Figure 9. It seems that the new models are better for larger tonnages.

6. Conclusions

Based on the test results of 22 powders conveyed through 38 pipelines, unified models for minimum transport boundaries have been developed using 2 formats, which are: gas Froude number represented as a power function of only solids loading ratio; and as a power function of solids loading ratio and particle Froude number. The models were evaluated by predicting the blockage boundary for three different products, conveyed through six different pipelines by comparing the predicted versus experimental blockage boundaries. Seven other models were also evaluated against the same set of test results. Results showed that the existing models provided considerable over- or under-predictions and could become unexpectedly unreliable causing either unnecessarily high air flow rates or pipe blockage. The new model developed and presented in this paper that is based on gas Froude number as a power function of solids loading ratio and particle Froude number appears to provide the relatively better accurate and stable predictions. The model has the potential to serve the purpose for minimum transport criteria for wide range of products, as the model incorporates a particle settling velocity term, which in turn depends on particle density and size. In this paper, the variation in pipe diameter is from 52 to 125 mm (about a factor of 2.5). Future work will include validation of the model in large industrial set-ups.

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List of symbols

A	Cross sectional area, m^2
Ar	Archimedes number ($Ar = [g\ \rho\ (\rho_p - \rho) d^3]/(\mu)^2$)
D	Internal diameter of pipe, m
d_{50}	Median particle diameter, µm
d	Particle diameter, µm
Fr	Froude number ($Fr = V/(gD)^{0.5}$)
Fr_{min}	Minimum Froude number at the inlet to the pipe ($Fr_{min} = V_{min}/(gD)^{0.5}$)
Fr_p	Particle Froude number ($Fr_p = w_{fo}/(g\ d)^{0.5}$)
g	Acceleration due to gravity, m/s
K	Constant of power function
L	Total pipeline length, m
L_h	Horizontal pipeline length, m
L_v	Vertical pipeline length, m
m_f	Mass flow rate of air, kg/s
m_s	Mass flow rate of solids, kg/s
$m^* = m_s/m_f$	Solids loading ratio
Re_p	Particle Reynolds number ($Re_p = (d\ V_i\ \rho) / \mu$)

Re_p^*	Reynolds number modified by pipe diameter ($Re_p^* = Re_p / (1.4 - 0.8 e^{-((d/d_{50})/1.5)})$)
V	Superficial air/gas velocity, m/s
V_i	Velocity of air at pipe inlet, m/s
V_{min}	Minimum value of V, m/s
w_{fo}	Free settling velocity of an isolated particle, m/s
ρ	Air density, kg/m^3
ρ_p	Particle density, kg/m^3
ρ_{bl}	Loose poured bulk density, kg/m^3
μ_f	Fluid viscosity, kg/m.s
Subscripts	
bl	bulk
p	particle
i	inlet condition
min	minimum
Abbreviations	
BD	Bottom Discharge
I.D.	Internal Diameter
MTB	Minimum Transport Boundary
PCC	Pneumatic Conveying Characteristics
TD	Top Discharge

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