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Transportation Boundaries of Slug-flow in a Horizontal Pipeline

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SYNOPSIS

An experimental program was established to investigate boundaries in low-velocity slug-flow pneumatic conveying. A straight horizontal pipeline of L=21m and D=60.3mm ID was set up for actual conveying trials and a simple rig was designed and built specifically to simulate the boundaries of slug-flow. After running several tests in the simulation rig with a sample of the product, the slug-flow were able to be determined with good accuracy. Combined with the theoretical correlations developed to determine pressure drop in slug-flow, reliable operating conditions can be predicted. Good agreement was achieved after the predicted results were compared with the experimental results from the large-scale pipeline.

1. NOMENCLATURE

A	Internal pipeline area, m^2
a, b	Packed-bed model constants
d_p	Particle diameter, m
m_f	Air mass flowrate, kg s^{-1}
m_s	Product mass flow rate, kg s^{-1}
P	Upstream pressure, Pag
$P1$	Pressure at top of material bed, Pag
Q_a	Volumetric flow rate of air, m^3 s^{-1}
R	Universal gas constant, Nm kg^{-1} K^{-1}
T	Absolute temperature, K
U_a	Superficial air velocity, m s^{-1}
$U_{a,min}$	Minimum superficial air velocity, m s^{-1}
U_p	Slug velocity, m s^{-1}
U_{sp}	Superficial slip velocity, m s^{-1}
ΔP	Pressure drop across material bed, Pa
δp	Pressure gradient in the slug, Pa m^{-1}
ϕ_w	Wall friction angle, degree
ρ_b	Loose-poured bulk density, kg m^{-3}
ρ_f	Air density, kg m^{-3}
ρ_s	Particle density, kg m^{-3}

Subscript

m	Mean conditions (based on air density)

2. INTRODUCTION

The pneumatic conveying of bulk solid materials through pipelines has been used for over one hundred years. Suspension flow, or dilute-phase, is used widely in industry due to its simplicity in design and operation. However, since a high air velocity (eg. 20 to 40 m/s) has to be used in suspension flow, there are often problems such as high power consumption, product degradation and pipeline wear. To overcome these problems, low-velocity slug-flow pneumatic conveying has received considerable attention over the past decade from both researchers and commercial suppliers of equipment. In slug-flow, bulk solids are transported in slugs and there is no relative motion between the particles within the slug. Power consumption, product degradation and pipeline wear are reduced dramatically during low-velocity slug-flow.

However, to achieve good and reliable low-velocity slug-flow, the air velocity along the pipeline should be controlled. As conveying air flows through the pipeline, the pressure reduces and the air velocity increases towards the end of the pipeline. If the air velocity is over a certain value at which the particles can be picked up or suspended from the stationary bed between the slugs, long slugs are formed and/or dilute-phase conveying is achieved in the pipeline. If the air velocity is below a certain value, the slug cannot be carried along the pipeline, thus the pipeline becomes blocked. Therefore, it is very important that the air velocity range required for achieving low-velocity slug-flow can be determined accurately.

This paper will explain how an experimental program was established to determine the boundaries in low-velocity slug-flow pneumatic conveying. A simple and specific rig was used to simulate the boundaries in slug-flow. Combined with theoretical correlations, the results from the simulation rig were used to predict pressure drop and locate the boundaries in slug-flow. The predicted results were then compared directly to the experimental results obtained from the large-scale test program. Good agreement was achieved.

3. TEST PROGRAM

3.1 Full-scale test rig

The full-scale test rig has a compressed air supply entering a bank of sonic nozzles allowing various air mass flowrates to be achieved. A 2m^3 feed bin is located over a 250mm diameter drop-through rotary valve to feed product into the conveying line. This rotary valve is connected to a variable speed drive to allow different product mass flow rates to be achieved. A straight horizontal pipeline of L=21m constructed of 60.3mm ID stainless steel pipe is used, containing two sight-glasses along the pipeline. The sight-glasses are installed for the purpose of visualising the flow of particles through the pipeline.

A 1m^3 receiving bin is used to collect product before being fed through a 200mm diameter drop-through rotary valve into a 78mm ID mild steel return line and back to the feeding bin. Pressure transmitters and load cells are used to record pipeline pressures and feed rates, respectively. These readings are collected and analysed using a data acquisition unit.

The layout of full-scale test rig is shown in Figure 1.

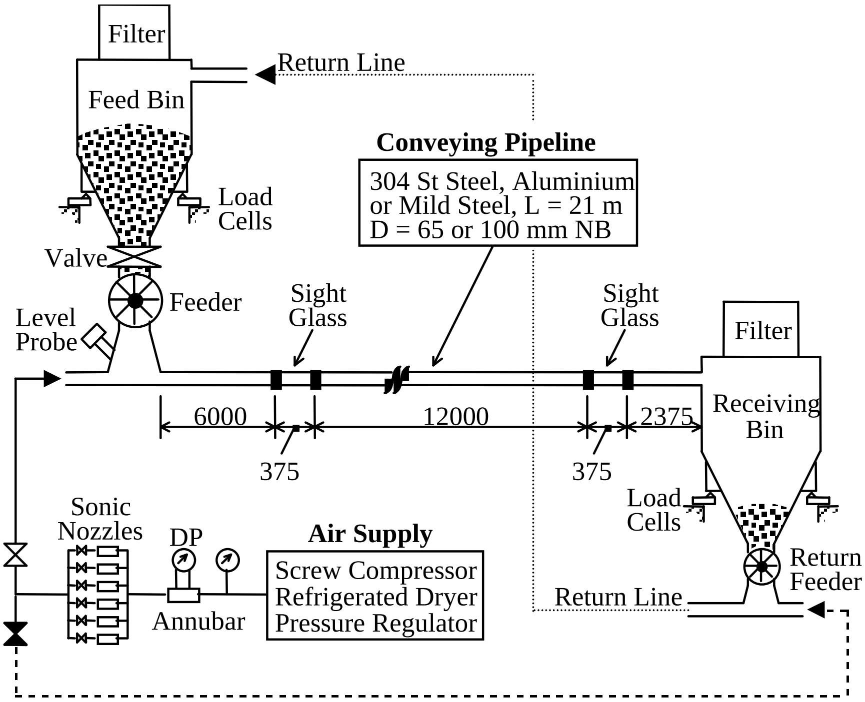

Figure 1 Full-scale test rig layout

3.2 Simulation rigs

3.2.1 Vertical test chamber

To predict total pipeline pressure, the following packed bed model is used [1, 2].

$$\delta p_m = aU_a + b\rho_f U_a^2$$

It is clear that constants a and b should be determined in advance. It has been observed that there is no relative motion between particles within the slug. A vertical test chamber, see Figure 2, was devised to determine the parameters 'a' and 'b' in the packed bed model by plotting the relationship between $\delta p_m/U_a$ and m_f/A [1, 2].

Air supplied to the test chamber passes through a rotameter to provide a direct measurement of the volumetric flow rate of air running through it. The differential pressure across the material bed is measured using a manometer and the mean air velocity in the test chamber is calculated using a pressure transducer to record the air pressure in the material bed.

The actual tests involve filling the test chamber to within a few millimetres of the top and fixing a porous plate in place. Air is then allowed to enter the test chamber until the material bed aerates and rises up against the porous plate. This is referred to as the critical point. At this time the air mass flow rate and rotameter readings are recorded. Once this critical point is located, several tests are performed on both the low and high sides. Only tests on the high side of the critical point are used to determine the values for a and b as this is the region where the material is transported in slugs. Below the critical point the material bed is static.

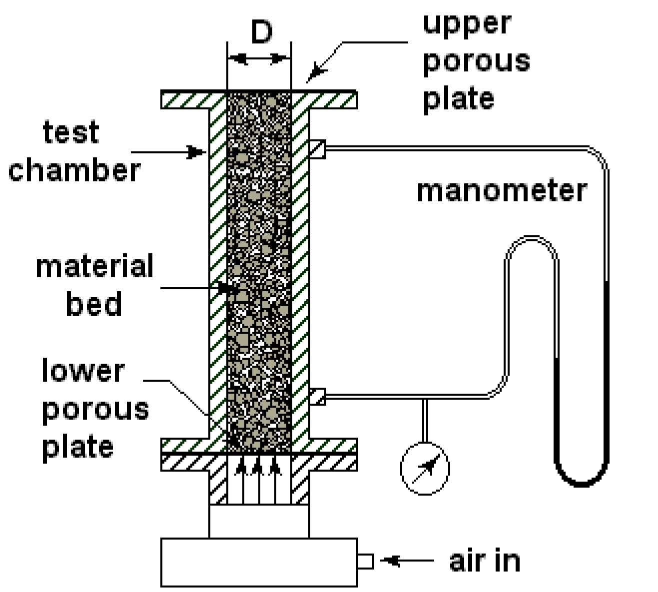

Figure 2 Vertical test chamber for determining a and b [1, 2]

3.2.2 Boundary simulation rig

Based on the mechanisms involved at the boundaries, the simple test rig shown in Figure 3 was designed and built [3]. The internal pipe diameter was 78 mm. The steel pipes were used to simulate the actual conveying pipelines where the bulk solids are transported in slugs. The glass section of pipe was for determining the pickup velocity of particles from the stationary bed and also observing whether the slug in the mild steel pipe was moving.

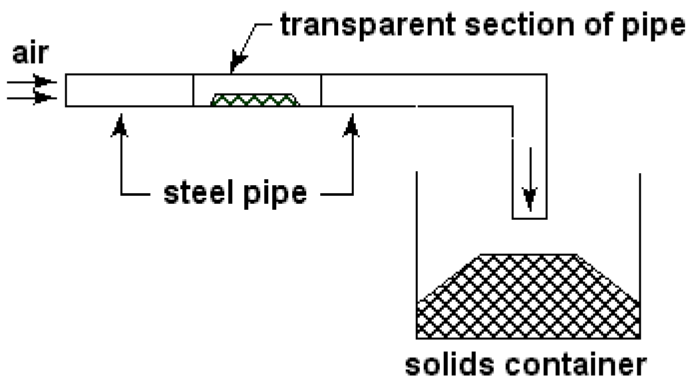

Figure 3 Test rig for determining boundaries [3]

To locate the lower dense phase boundary, a single slug was produced in the steel pipe as shown in Figure 4.

The slug is produced by filling material between two porous plates held together by five thin supporting wires. The central wire is longer than the others so it protrudes into the glass section to observe when the slug begins moving. The rig was then reassembled and air was gradually added to the rig until the slug began to move. This air mass flow rate was then recorded. An empty slug, ie. the porous plates and wires only, was tested to check for any friction. On analysis, a pressure of 0.3kPa was recorded resulting in all tests being adjusted by this amount.

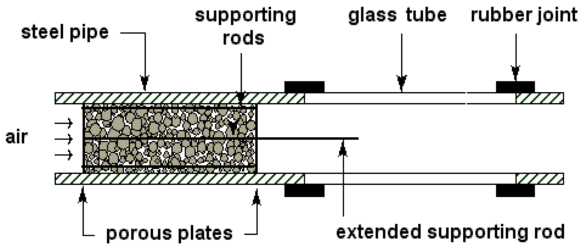

Figure 4 Lower boundary simulation

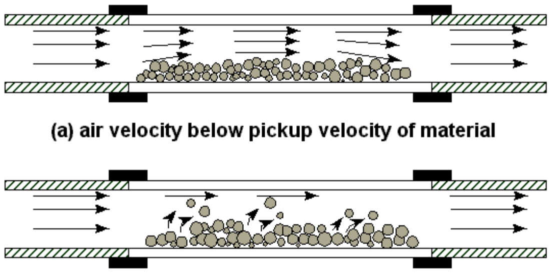

Figure 5 Upper boundary simulation

The upper boundary is simulated by measuring the pickup velocity of the material from the stationary bed. This is performed by depositing a layer of material in the glass section of the pipeline and levelling it, as shown in Figure 5a. Air is supplied to the pipeline at a low mass flow rate and slowly increased until particles begin to be lifted from the layer into the air stream. The air mass flow rate is then left constant for the equilibrium condition to be achieved. As material lifts from the layer, see Figure 5b, the cross sectional area in which the air flows increases and thus the air velocity decreases to a point lower than the pickup velocity and no more material is picked up. Once equilibrium has been achieved, the air supply is turned off and the air mass flow rate and height of the bed are recorded.

3.2.3 Test materials

A range of products was used during the test programs. The material properties are displayed in Table 1. Of the products, the polythene pellets were the only product tested in the full-scale test rig to date, however all products have been tested in the simulation rig.

Table 1 Physical properties of test products

Product	$d_p^{\#}$ (μm)	ρ_b (kg m^{-3})	ϕ_w^{*} (°)
Polythene pellets	4473	578	12
Plastic pellets	2493	535	16
Milo	3005	783	12
Corn	6010	778	19.5
Wheat	3176	833	19

Equivalent volume diameter   * Wall material 304 stainless steel

4. TEST RESULTS

4.1 Full-scale tests

On completion of the full-scale testing program, the data are analysed and plotted, as shown in Figure 6. Although this paper is focused on the dense phase region, both dilute phase and dense phase tests have been performed for completeness. Based on the observation in each test, the approximate boundaries for both dilute and dense phase are displayed appropriately on Figure 6.

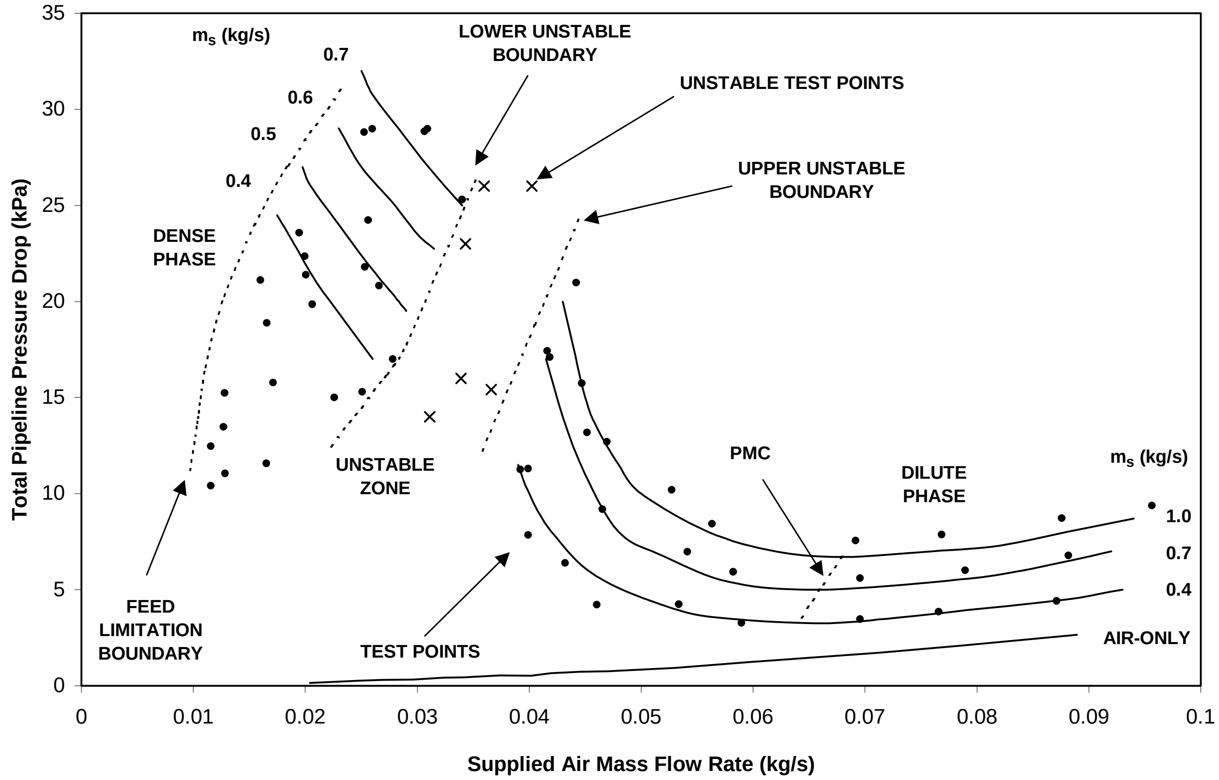

Figure 6 Pneumatic conveying characteristics for the polythene pellets in a 60.3mm ID horizontal stainless steel pipeline, L=21m

4.2 Constants a and b

Once testing is completed, the data are collected and entered into a spreadsheet and the required parameters determined.

The air mass flow rate is found by:

$$m_f = Q_a \rho_f$$

where $\rho_f = P / RT$

The mean pressure in the chamber is found by:

$$P_m = P_1 + \Delta P/2$$

The mean air velocity is found by:

$$U_a = m_f / \rho_m A$$

The pressure gradient, δp_m, is found by dividing the measured differential pressure by the distance between the pressure tappings. From these calculations $\delta p_m/U_a$ can be plotted against m_f/A to yield a linear relationship and develop the equation $\delta p_m/U_a = a + bm_f/A$. The gradient of the line being the 'a' value and the y-intercept being the 'b' value. Refer to Figure 7.

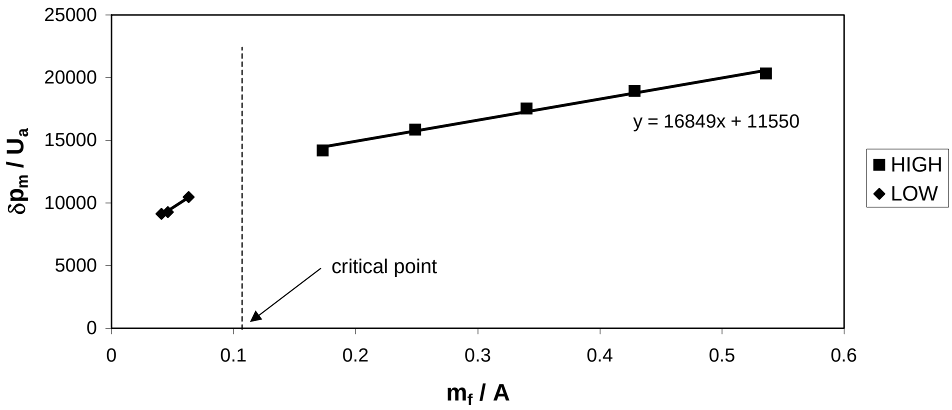

Figure 7 Determining packed bed model constants for the polythene pellets

A trend line is placed through the points on the high side of the critical point and the equation is given as shown in Figure 7, giving the packed bed model parameters as a=11550 and b=16849. These values are then used in the packed-bed model to predict the total pipeline pressure drop, see Section 5.1.

4.3 Lower boundary

Testing requires that the slug of material is extremely close to incipient motion to simulate the point at which blocking will occur. This sometimes results in the air supply being finely adjusted if the slug started moving too quickly in the pipeline. Once a slug of product is found to be moving, the air supply is left running for an adequate time to allow steady state to occur. The tests are recorded using a computer and the results analysed. The results obtained from testing the polythene pellets in the simulation rig are m_f = 0.0039 kg/s and P = 3.711 kPa. These values are then used to determine the location of the lower dense phase boundary, see Section 5.2

4.4 Upper boundary

Some uncertainty as to the actual bed height was observed due to particles at the front of the bed being entrained then dislodging particles further along. This resulted in the bed having more depth at the beginning and less at the end. An average bed height was finally decided upon and from the height of the material bed, the cross sectional area of the airflow can be determined and using atmospheric conditions the air velocity can be calculated.

The air velocity is found by:

$$U_a = m_f / \rho_f A$$

where $\rho_f = P_{atm} / RT$

From the data recorded and analysed, the average pickup velocity, U_a = 9.7 m/s. This value is then used to locate the upper dense phase boundary, see Section 5.3.

5. THEORETICAL PREDICTION

5.1 Pressure drop prediction

The packed-bed model [1,2] is used to predict the total pipeline pressure drop. Starting with an initial 'guess' of the mean air density in the pipeline, the total pipeline pressure drop is calculated, after which the mean air density is recalculated and if the values vary an iterative approach is used until the mean air density converges. Once a full set of results has been produced for different solids mass flow rates, the pneumatic conveying characteristics can be produced, as shown in Figure 8.

5.2 Location of lower boundary

From the pressure determined experimentally to overcome the friction between the pipe and the slug, the mean air density can be calculated by the equation:

$$\rho_{fm} = (P_{atm} + \Delta p/2) / RT$$

Followed by the minimum superficial air velocity:

$$U_{a,min} = m_f / (\rho_{fm} A)$$

The theoretical pressure gradient across the slug in the test rig can the be calculated:

$$\delta_{pm} = aU_{sp} + b\rho_{fm}U_{sp}^2$$

where $U_{sp} = U_{a,min}$

The determined pressure drop is compared with the pressure obtained from the lower boundary tests and if the two pressure values differ, the air mass flowrate is adjusted and the process repeated in an iterative approach. The boundary point is therefore determined for a certain solids mass flow rate.

5.3 Location of upper boundary

The criterion to locate the upper boundary on the PCC is when the air velocity equals the pickup velocity of the material:

$$U_a = V_p$$

Due to the compressibility of air, the maximum air velocity occurs at the end of the pipeline and the air velocity can be calculated as:

$$U_a = m_f RT / (p_{atm} A)$$

If the maximum air velocity is found to be less than the re-entrainment velocity, it is certain that the material can be transported in slugs along the entire pipeline. Therefore, the maximum air mass flowrate for the slug can be calculated by:

$$m_f = V_p p_{atm} A / RT$$

Since relative parameters (eg. ρ_b, 'a', 'b') for a given material are constant, the maximum air mass flowrate used to locate the upper boundary is also constant. In practice, the predicted boundary point at lower material mass flow rates is slightly higher than the actual boundary location determined experimentally. However, when designing a low-velocity slug-flow pneumatic conveying system, a point midway between the two theoretical boundaries is suggested for suitable operating conditions. It is for this reason that the theoretical upper dense phase boundary location is considered safe.

Plotting the data obtained from the packed-bed model for various material mass flow rates, a PCC can be produced, as shown in Figure 8 by the solid curves. Also plotted on this figure are the lower and upper boundaries as predicted using the previously explained methods, represented as dashed lines. The data recorded from the full-scale pneumatic conveying tests for the polythene pellets are superimposed onto the theoretical predictions, as indicated by the numbers overlaid on the theoretical curves. These experimental results compare well with the theoretical predictions.

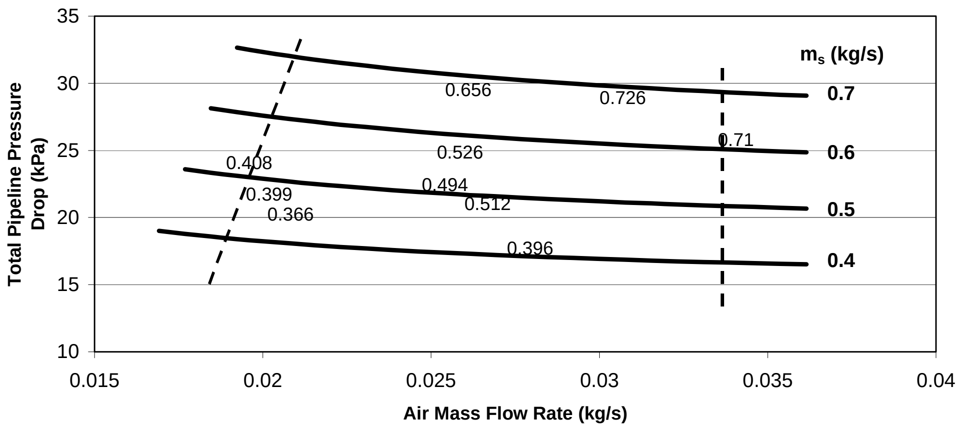

Figure 8 Theoretical PCC showing lower and upper boundaries as well as full-scale experimental data

6. RELATIONSHIPS BETWEEN MATERIAL PROPERTIES AND BOUNDARY LOCATIONS

A brief investigation was carried out to determine whether there is any relationship between the material properties and the location of the lower dense phase boundary. Five material properties were plotted against air velocity, they being, loose-poured bulk density, wall friction angle, mean particle size and packed bed model constants 'a' and 'b'. Of the five products tested in the simulation rigs, there seems to be no relationship for loose-poured bulk density and mean particle size to the location of the lower dense phase boundary. There seems to be a distinct linear relationship for the wall friction angle and possible curved relationships for both packed bed model constants.

For the upper dense phase boundary, the relationship between mean particle size and air velocity at the boundary point was investigated. For the five products tested there is a possible trend present, that being as mean particle size increases the air velocity at the boundary decreases before rising again.

These observations are extremely preliminary and testing on more products should be performed to verify these initial findings.

7. CONCLUSION

To reliably design a low-velocity slug-flow pneumatic conveying system, the total pipeline pressure drop as well as the lower and upper dense phase boundaries must be predicted for a given material. The prediction of the pipeline pressure drop has already been found to be accurate [2], so the purpose of current research is to accurately predict the lower and upper boundaries.

The total pipeline pressure drop and lower and upper dense phase boundaries have been predicted for five products, however, at present only the predictions for the polythene pellets have been compared to full-scale test results, showing good accuracy. Work is to continue with various other full-scale pipeline materials such as aluminium and mild steel, as well as other pipeline diameters and also performing other full-scale test programs with other products such as those used in the simulation test rigs to verify the results obtained.

Preliminary investigation into the relationship between particle properties and the location of the dense phase boundaries has been performed with mixed results and testing on a wider range of products should be continued for further verification.

The final objectives of this research are to give a better understanding as well as a more accurate method of determining the location of both the upper and lower boundaries of low-velocity slug-flow pneumatic conveying.

8. ACKNOWLEDGEMENTS

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