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1994

## Low-velocity pneumatic transportation of bulk solids

Bo Mi

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# **LOW-VELOCITY PNEUMATIC TRANSPORTATION OF BULK SOLIDS**

A thesis submitted in fulfilment of the requirements  
for the award of the degree of

**DOCTOR OF PHILOSOPHY**

from

**UNIVERSITY OF WOLLONGONG**

by

**BO MI**

**B.Sc. (USTB ), M.Sc. (USTB)**

Department of Mechanical Engineering

1994

## **DECLARATION**

This is to certify that the work presented in this thesis was carried out by the author in the Department of Mechanical Engineering at the University of Wollongong and has not been submitted for a degree to any other university or institution.

Bo Mi

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## SUMMARY

Low-velocity pneumatic conveying is being used increasingly in industry to transport a wide range of bulk solids due to reasons of low power consumption and low product damage, etc. However, investigations into this type of conveying still are at an elementary stage. For example, the existing procedures to estimate pipeline pressure drop during low-velocity pneumatic conveying still are inaccurate and inefficient. For this reason, this thesis aims at developing a pressure prediction model that is a function of the physical properties of the material, pipeline configuration and conveying condition.

During low-velocity pneumatic conveying, particles are conveyed usually in the form of slugs. This thesis studies initially the pressure drop across a single particle slug and the stress state and distribution in the slug through theoretical analysis.

To obtain detailed information on low-velocity pneumatic conveying, a test rig is set up and four types of coarse granular material are conveyed in the rig. Major parameters such as mass flow-rate of air and solids, pipeline pressure, slug velocity and wall pressure, etc. are measured over a wide range of low-velocity conveying conditions.

Based on the experimental results and a dimensional analysis, the relationship between the slug velocity and superficial air velocity is established in terms of the physical properties of the material and pipe size. Also by using particulate mechanics, a semi-empirical correlation is developed to determine the stress transmission coefficient for the slugs flowing in the pipe with rigid and parallel walls. A model then is developed to predict the overall horizontal pipeline pressure drop of low-velocity pneumatic conveying.

This model is used to predict the pneumatic conveying characteristics and static air pressure distribution for different test rig pipelines and materials. Good agreement is obtained between the predicted and experimental results. Based on the developed model, a method for determining the economical operating point in low-velocity pneumatic conveying is presented.

Additional experimental results from the conveying of semolina show that the performance of fine powders is quite different in low velocity. Based on these experimental results, an appropriate modification to the model is made so that it can be applied to the prediction of pressure drop in low-velocity pneumatic conveying of fine powders.



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## NOMENCLATURE

|            |  |
|------------|--|
| $A$        | Cross sectional area of pipe ( $m^2$ )                             |
| $A_c$      | Cross sectional area of the shear ring of a Jenike shearing tester |
| $A_f$      | De-aeration factor ( $mbar \cdot sm^{-1}$ )                        |
| $A_{st}$   | Cross sectional area of stationary bed, $m^2$                      |
| $a, b$     | Ergun constant   |
| $C$        | Integration constant in Equation (3.10)                            |
| $c$        | Interparticle cohesion   |
| $c_d$      | Coefficient in Equation (6.29)                                     |
| $c_w$      | Particle-wall cohesion   |
| $D$        | Diameter of pipe (m)   |
| $d$        | Particle diameter (mm)   |
| $F_d$      | Drag force of fluid (N)  |
| $F_b$      | Buoyant force (N)  |
| $F_r, F_s$ | Friction forces for particles (N)                                  |
| $Fr$       | Froude number of material, $Fr = U_s^2/gD$                         |
| $Fr_{cF}$  | Variable in Equation (2.10)  |
| $F_w$      | Gravity force (N)  |
| $f$        | Sampling frequency (Hz)  |
| $f_K$      | Constant in Equation (6.23)  |
| $g$        | Acceleration due to gravity ( $ms^{-2}$ )                          |
| $H_b$      | Height of fixed bed (m)  |
| $h_c$      | Critical depth of the shearing flow at transition (m)              |
| $h_s$      | Stationary bed thickness (mm)                                      |
| $ID$       | Internal diameter of pipe (m)                                      |



|          |   |
|----------|---|
| $K$      | Slope in Equation (6.25)  |
| $k$      | Constant in Equation (6.35) and (6.36)                                    |
| $k_1$    | Constant in Equation (6.1)  |
| $L$      | Distance of two neighbouring pressure transducers (m)                     |
| $L_h$    | Length of horizontal pipe (m)   |
| $L_t$    | Total pipeline length (m)   |
| $L_{th}$ | Total horizontal pipeline length (m)                                      |
| $L_v$    | Vertical pipeline length (m)  |
| $l_A$    | Distance between a test point and pipe end (m)                            |
| $l_d$    | Distance between two neighbouring slugs (m)                               |
| $l_g$    | Air gap length (m)  |
| $l_s$    | Single slug length (m)  |
| $M$      | Total mass of the moving solids in a pipe (kg)                            |
| $m$      | Mass of particles (kg)  |
| $m_f$    | Mass flow-rate of air ( $\text{kgs}^{-1}$ )                               |
| $m_{fl}$ | Rotary valve air leakage ( $\text{kgs}^{-1}$ )                            |
| $m_{ft}$ | Total supplied mass flow-rate of air ( $\text{kgs}^{-1}$ )                |
| $m_s$    | Mass flow-rate of solids ( $\text{kgs}^{-1}$ )                            |
| $m_{st}$ | Mass of particles collected by a slug per unit time ( $\text{kgs}^{-1}$ ) |
| $m^*$    | Mass flow ratio   |
| NB       | Number of bends   |
| $N_s$    | Number of the pressure peaks in a certain period of time                  |
| $n$      | Number of test materials  |
| $n_b$    | Number of the particles contained in the back area of a slug              |
| $n_f$    | Number of the particles contained in the front area of a slug             |
| $n_i$    | Number of the particles having velocity $u_{pi}$ , $i = 1, \dots, n$      |
| $n_m$    | Number of the particles contained in the middle area of a slug            |
| $n_p$    | Numbers of the particles of a given mass                                  |

|                    |  |
|--------------------|--|
| $P_i$              | Air pressure at different points along a pipe (Pag), $i = 1, \dots, n$         |
| $P_B$              | Air pressure during a slug flowing through a bend (Pag)                        |
| $P_S$              | Air pressure during a slug flowing in a straight pipe (Pag)                    |
| $P_{f1}, P_{f2}$   | Pressure force (N)   |
| $P_n$              | Nominal power  |
| $P_u$              | Dissipated energy (J/kgm)  |
| $p$                | Interstitial air pressure (Pag)  |
| $p_2, p_3$         | Pressure in Equation (5.2) (Psig)  |
| $p_f$              | Permeability factor ( $m^3skg^{-1}$ )  |
| $Q_g$              | Air flow rate ( $m^3s^{-1}$ )  |
| $Q_w$              | Shearing force acting on a slug (N)  |
| $R$                | Radius of pipe (m)   |
| $R_b$              | Radius of Bend (m)   |
| $Re$               | Reynold's number   |
| $R_f$              | Friction force between the sliding slug and pipe wall (N)                      |
| $R_{s1}, R_{s2}$   | Resistant forces (N)   |
| $R_{xy}$           | Cross correlation function   |
| $\hat{R}_{xy}$     | Estimation of $R_{xy}$   |
| $r$                | Radius of Mohr circle  |
| $S, S', S'', S'''$ | Shearing forces in Jenike shearing test  |
| $S_v$              | Specific surface (i.e. particle surface per unit particle volume) ( $m^{-1}$ ) |
| $S_{xy}$           | Cross spectral density   |
| $\hat{S}_{xy}$     | Estimation of $S_{xy}$   |
| $T$                | Time range of a signal record (s)  |
| $T_s$              | Sampling time interval (s)   |
| $t_i$              | Different times (s), $i = 0, 1, \dots, n$                                      |
| $t_f, t_l$         | Time of the first and last slug occurring in a pressure record (s)             |
| $t_p$              | Closing time of a solenoid valve (s)   |

|                    |  |
|--------------------|--|
| $t_s$              | Time taken by the slug to travel across a pipeline (s)                                   |
| $t_T$              | Opening and closing time of a solenoid valve (s)   |
| $U_a$              | Superficial air velocity ( $\text{ms}^{-1}$ )  |
| $U_{\text{amin}}$  | Minimum superficial air velocity ( $\text{ms}^{-1}$ )                                    |
| $U_{\text{mf}}$    | Incipient fluidisation air velocity ( $\text{ms}^{-1}$ )                                 |
| $U_{\text{ra}}$    | Mean air velocity ( $\text{ms}^{-1}$ )   |
| $U_p$              | Superficial particle velocity ( $\text{ms}^{-1}$ )                                       |
| $U_{\text{pb}}$    | Particle velocity in the back area of a slug ( $\text{ms}^{-1}$ )                        |
| $U_{\text{pf}}$    | Particle velocity in the front area of a slug ( $\text{ms}^{-1}$ )                       |
| $U_{\text{pm}}$    | Particle velocity in the middle area of a slug ( $\text{ms}^{-1}$ )                      |
| $U_{\text{pst}}$   | Particle velocity in stationary bed ( $\text{ms}^{-1}$ )                                 |
| $U_s$              | Slug velocity ( $\text{ms}^{-1}$ )   |
| $U_{\text{sb}}$    | Velocity of the back surface of a slug ( $\text{ms}^{-1}$ )                              |
| $U_{\text{sf}}$    | Velocity of the front surface of a slug ( $\text{ms}^{-1}$ )                             |
| $U_{\text{sp}}$    | Slip velocity ( $\text{ms}^{-1}$ )   |
| $U_t$              | Single particle terminal velocity ( $\text{ms}^{-1}$ )                                   |
| $u_{\text{pi}}$    | Velocity of each particle contained in a slug ( $\text{ms}^{-1}$ ), $i = 0, 1, \dots, n$ |
| $V, V', V'', V'''$ | Normal forces in Jenike shearing test  |
| $V_1, V_2$         | Principle forces   |
| $V_a$              | Added cell volume of a stereo pycnometer ( $\text{cm}^3$ )                               |
| $V_c$              | Sealed sample cell volume of a stereo pycnometer ( $\text{cm}^3$ )                       |
| $V_p$              | Powder sample volume ( $\text{cm}^3$ )   |
| $V_s$              | Total volume of the moving solids in a pipe  |
| $X$                | Variable in Figure 2.3   |
| $x, y, z$          | Co-ordinates   |
| $x_1, \dots, x_5$  | Coefficients in Equations (6.26) and (7.19)  |
| $x(t), y(t), z(t)$ | Time history records   |
| $\alpha$           | Cross sectional area ratio of stationary bed to pipe                                     |

|                                    |  |
|------------------------------------|--|
| $\alpha_b$                         | Incline angle of bend with respect to the horizontal (°)               |
| $\beta$                            | Coefficient in Equation (6.36)   |
| $\beta_b$                          | Incline angle of the back surface of a slug (°)                        |
| $\beta_f$                          | Incline angle of the front surface of a slug (°)                       |
| $\delta$                           | Effective internal friction angle (°)                                  |
| $\Delta\theta=\theta_1-\theta_2$   | Radian of bend in Equation (2.15) (°)                                  |
| $\Delta p$                         | Pressure drop across a single slug (Pa)                                |
| $\Delta p_i$                       | Pipeline pressure drops at different locations (Pa), $i = 1, \dots, n$ |
| $\Delta p_t$                       | Total pipeline pressure drop (Pa)                                      |
| $\Delta p_{th}$                    | Total horizontal pipeline pressure drop (Pa)                           |
| $\Delta t$                         | Interval time (s)  |
| $\varepsilon$                      | Bulk voidage   |
| $\phi$                             | Internal friction angle (°)  |
| $\phi_s$                           | Static internal friction angle (°)                                     |
| $\phi_w$                           | Wall friction angle (°)  |
| $\gamma$                           | Coefficient of correlation   |
| $\gamma_b$                         | Bulk specific weight with respect to water at 4 °C                     |
| $\gamma_s$                         | Particle specific weight with respect to water at 4 °C                 |
| $\eta$                             | Dynamic viscosity of fluid, $\text{Nsm}^{-2}$                          |
| $\lambda$                          | Stress transmission coefficient  |
| $\lambda_A$                        | Stress transmission coefficient at active failure                      |
| $\lambda_{\min}, \lambda_{\max}$   | Minimum and maximum stress transmission coefficient                    |
| $\lambda_o$                        | Static stress transmission coefficient                                 |
| $\lambda_{o\min}, \lambda_{o\max}$ | Minimum and maximum static stress transmission coefficient             |
| $\lambda_P$                        | Stress transmission coefficient at passive failure                     |
| $\mu$                              | Coefficient of internal friction                                       |
| $\mu_w$                            | Coefficient of wall friction   |
| $\theta$                           | Angle in Figure (3.8) (°)  |

|                                   |  |
|-----------------------------------|--|
| $\theta_s$                        | Angle in Figure (8.12) ( $^\circ$ )                                      |
| $\rho_a$                          | Air density ( $\text{kgm}^{-3}$ )  |
| $\rho_b$                          | Bulk density ( $\text{kgm}^{-3}$ )                                       |
| $\rho_{bst}$                      | Bulk density of stationary bed ( $\text{kgm}^{-3}$ )                     |
| $\rho_s$                          | Particle density ( $\text{kgm}^{-3}$ )                                   |
| $\sigma$                          | Normal stress (Pa)   |
| $\sigma_1, \sigma_2$              | Principle stresses (Pa)  |
| $\sigma_b$                        | Stress on the back face of a slug (Pa)                                   |
| $\sigma_f$                        | Stress on the front face of a slug (Pa)                                  |
| $\sigma_r$                        | Radial stress (Pa)   |
| $\sigma_g$                        | Gravity pressure (Pa)  |
| $\sigma_n$                        | Normal stress coordinate   |
| $\sigma_{tw}$                     | Total wall pressure (Pa)   |
| $\sigma_w$                        | Wall pressure (Pa)   |
| $\sigma_{wm}$                     | Average wall pressure (Pa)   |
| $\sigma_x, \sigma_y, \sigma_z$    | Normal stresses in x, y, z direction (Pa)                                |
| $\sigma_{xm}$                     | Average stress in x direction  |
| $\tau$                            | Shearing stress (Pa)   |
| $\tau_d$                          | Time delay between two signals (s)                                       |
| $\tau_p$                          | Specific time delay for the peak value of cross-correlation function (s) |
| $\tau_n$                          | Shearing stress coordinate   |
| $\tau_{tw}$                       | Total shear stress at a wall (Pa)  |
| $\tau_{xy}, \tau_{xz}, \tau_{yz}$ | Shear stresses at the planes perpendicular to x, y, z coordinates        |
| $\omega$                          | Angle defined in Figure 7.17 ( $^\circ$ )                                |