Title: Transport boundaries for pneumatic conveying

Author: Jianglin Yi

Year: 2001

Repository DOI:

Transport boundaries for pneumatic conveying

Jianglin Yi
University of Wollongong

TRANSPORT BOUNDARIES FOR PNEUMATIC CONVEYING

A thesis submitted in fulfilment of the requirements

for the award of the degree of

DOCTOR OF PHILOSPHY

from

UNIVERSITY OF WOLLONGONG

bY

JIANGLIN YI

B.Sc.(U.TSINGHUA), M.Sc.(U.TSINGHUA)

FACULTY OF ENGINEERING, WOLLONGONG UNIVERSITY

2001

CERTIFICATION

I, Jianglin Yi, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Jianglin Yi

9 July, 2001

ACKNOWLEDGMENTS

" I believe you will make an excellent contribution to this Centre", I still very clearly remember what my supervisor told me when I commenced my PhD candidate. Now my PhD candidate is approaching the end and I am quite confident and proud to say:" Yes I did it". Also it is with great pleasure and gratitude that I acknowledge the excellent supervision and constant encouragement of my supervisor, A/Prof. P W Wypych, throughout the duration of this work.

I gratefully acknowledge that University of Wollongong provided UPA scholarship and Australian Government provided OPRS scholarship.

Acknowledgement also is made to the staff of the Centre of Bulk Solids and Particulate Technologies, especially David Hastie, who conducted the conveying tests of this project.

I would like to thank Dr. Renhu Pan, who helped me come to Australia and gave me a lot of support during my PhD candidate.

Finally, special acknowledgement is made to my family for their love, encouragement and unfailing support.

SUMMARY

Pneumatic conveying is being selected for an increasing number of industrial applications and products and is playing a more vital and integral role in the transportation of solid materials such as plastic pellets, grain and chemicals. However, despite all the minimum conveying velocity research (one of the operating boundaries for pneumatic conveying) that has been undertaken for several decades, the wide scatter and contradictions in the predictions of the minimum conveying velocity for dilute phase pneumatic conveying exist yet, determination of the operating boundaries for pneumatic conveying (mainly maximum conveying velocity for dense phase and minimum conveying velocity for dilute phase) still has been one of the most important tasks to be solved for the design, optimising and upgrade of pneumatic conveying systems as a consequence of that the mechanisms involved in the formation of boundaries between dilute-phase and dense-phase pneumatic conveying through a horizontal pipeline have not been well explored.

Saltation velocity was investigated initially in this thesis and then the emphasis was placed on the transition between dilute-phase and dense-phase. With careful observations, it is found that pneumatic conveying of granular solid materials through a horizontal pipeline can exhibit five different flow modes (as the air velocity is decreased): fully suspended flow; strand flow; stable or unstable strand flow over a stationary layer for low solid mass flow rates; stable or unstable strand flow over a slowly moving bed for high solid mass flow rates; low-velocity slug-flow. The pressure fluctuations within the unstable zone result from the flow mode alternation

between a strand flow over a stationary layer (or slowly moving bed) and slug flow starting at the inlet due to a decrease in air velocity. The first slug moves quickly at a relatively high velocity and picks up a relatively thick stationary layer in front of it but only deposits a small amount of the material behind it. The increase in slug length and large increase in pressure cause severe pressure fluctuations and pipeline vibrations. Two different flow modes may exist simultaneously in the conveying pipeline: strand flow over a stationary layer or slowly moving bed near the feed point followed by the dilute-phase (suspension) flow of particles. For the latter, material erodes away from the end of the stationary layer or slowly moving bed and is conveyed in the form of small dunes (or pulsating strand flow).

Based on the mass balance, force balance, momentum balance and the unstable flow forming mechanism, a theoretical three-layer model for the prediction of the transition zone boundaries has been established. With stability analysis, the boundaries of the transition zone in the state diagram have been identified, and have been found to agree very well with experimental data. According to the model established, the discussion on the influence of design parameters of particle and bulk properties of the material being conveyed and pipe wall properties on boundaries in the state diagram has been conducted.

The discussion on the operating boundaries for pneumatic conveying of granular materials has been extended to conveying of powder materials and a principle for classification of granular materials and powder materials, which have different flow mode in PCC, has been proposed.

The research also has been carried out on the pressure drop prediction for pneumatic conveying of granular materials in the form of low-velocity slug-flow in order to have a perfect PCC state diagram. A new approach for the direct measurement of stress transmission factor has been developed in this thesis. The effect of the weight of the granular material in the slug on pressure drop is taken in account according to the experimental test results. The model for pressure drop prediction also includes a modified equation for the frontal force of the moving slug – allowing for momentum balance of accelerating particles and the additional force from the stationary layer to resist the movement. The modelling predictions agree very well with test results obtained on poly pellets conveyed through 98 mm and 60.3 mm ID horizontal stainless steel pipelines, each 21m in length.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A	cross-sectional area of pipe, m^2
B	Model constant for Equation 2.3.15
c	Constant
C_1	Constant for Equation 12.8.4
C_2	Constant for Equation 12.8.4
d_p	Particle diameter, m
D	Pipe internal diameter, m
f_r	Friction factor in Equation 2.3.9
f_p	Particle-particle friction factor
f_w	Particle-wall friction factor
F	Force, N
F_{meter}	Output of force meter, N
F_{min}	Froude number at minimum transport velocity, $F_{min}=U_{min}\,(g\,D)^{-0..5}$
$F_{lateral}$	Lateral force along slug, N
F_{ri}	Non-dimension friction number

F_{slug} Total resistance force on slug, N

F_{weight} Weight force of slug, N

g Gravitational acceleration, m s^{-2}

G_s Solids mass flow rate per unit area, kg s^{-1} m^{-2}

H Height, m

ΔJ Change in momentum for Equation 5.2.12, kg m s^{-1}

ΔH Height of element, m

L Length, m

L_s Length of slug, m

L_{st} Total length of slugs within pipeline, m

L_t Length of pipeline, m

ΔL Length of element, m

l Length of spring, m

l_0 Length of spring in free state, m

l_w Width of stationary layer or strand layer, m

K Model constant for Equation 2.3.15

K_w Stress transmission coefficient

K_{spring}	Spring constant, N m^{-1}
m	mass of particle, kg
m_f	Air mass flow rate, kg s^{-1}
m_s	Solids mass flow rate, kg s^{-1}
m^*	Mass flow rate ratio of solids to gas
n	number flow rate of particles per unit of cross-sectional area, m^{-2} s^{-2}
N_1	Axial stress on a slug element, Pa (spring above material)
N_2	Axial stress on a slug element, Pa (spring underneath material)
N_{Slug}	Number of slugs in pipeline
Δp_f	Pressure drop due to air, Pa
Δp_p	Pressure drop due to particles, Pa
Δp_t	Total pipeline pressure drop, Pa
ΔP	Pressure difference, Pa
P_z	Axial stress on slug, Pa
$\overline{P_z}$	Average axial stress on slug, Pa
P_r	Radial stress on slug, Pa
R	Friction force, N

S Shear force exerted at the strand, N

S_Δ Particle size distribution parameter in Equation 2.3.1

U_{criti} Critical velocity, m s^{-1}

U_{gp} Interstitial air velocity, m s^{-1}

U_{min} Minimum transport velocity, m s^{-1}

U_p article velocity, m s^{-1}

U_s Saltation velocity, m s^{-1}

U_{s0} Single particle saltation velocity, m s^{-1}

U_{slug} slug velocity, m s^{-1}

U_{slip} Superficial slip velocity, m s^{-1}

U_t Single particle terminal velocity, m s^{-1}

W_{plate} Weight of plate, N

W_{rig} Weight of rig, N

W_{slug} Weight of slug, N

Z Height, m

Subscripts

st Strand section

su Suspension section

Greek letter

α Relative area of stationary bed

α_{cri} critical relative area occupied by stationary bed for Equation 7.3.1

γ_b Bulk specific gravity with respect to water at 4 °C

ε Voidage

η Viscosity of air, Pas

θ Angle

θ_r Angle of repose for equation 2.3.15

λ_h Momentum transfer factor

μ Mass flow rate ratio of solids to gas, $\mu = m_s/m_f$

ν Air velocity, m s^{-1}

ρ' Superficial bulk density, kg m^{-3}

ρ_f Air density, kg m^{-3}

ρ_b Loose-poured bulk density, kg m^{-3}

ρ_p Particle density, kg m^{-3}

σ_f Axial stress at front of slug, Pa

σ_{f1} Axial stress at front of slug caused by force balance of stationary layer, Pa

σ_{f2} Axial stress at front of slug caused by momentum balance of stationary layer, Pa

τ Shear stress, N m^{-2}

ϕ Section of pipe cross-sectional area not occupied by strand and stationary bed

ϕ_s Static internal friction angle, °

ϕ_w Wall friction angle, °

ω Angle defined by Equation 10.1.3