Continuous Flow Rheometry for Settling Slurries

by

Timothy James AKROYD

Thesis submitted for the degree of
Doctor of Philosophy

School of Chemical Engineering
Faculty of Engineering, Computer and Mathematical Science
The University of Adelaide

November 2004

It's kind of fun to do the impossible.

Walt Disney

Declaration

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

SIGNED : …………………………. **DATE : ………………..**

Acknowledgements

I am extremely grateful to my supervisor A/Professor Dzuy Nguyen for his guidance, support and advice throughout the entirety of this project.

This work is supported by a grant from the Australian Research Council under the Strategic Partnership with Industry- Research and Training Scheme, in conjunction with Rio Tinto Technical Services. I also would like to acknowledge and thank the involvement of Mark Coghill and Nick Vagias in this project and their kind hospitality during my visits to Melbourne.

I would like to thank Dr Denier from the Department of Applied Mathematics for some invaluable discussions on instabilities in fluid flow.

I would also like to extend my sincere appreciation to the Chemical Engineering workshop staff; Brian, Peter and Jason, for their assistance in the construction and development of the numerous pieces of experimental apparatus which I required for this project. I cannot thank you enough. To Mary and Elaine thank you for your assistance in all non-technical matters and to Andrew thank you for your assistance in laboratory matters.

To Peng thank you for your assistance, advice and friendship over the years we worked together in room A309, though I’ll never look at coal in the same way again!

To all my friends, thank you for your friendship, support and numerous creative diversions during the course of this project. It was much appreciated!

Finally I would especially like to thank my Parents, Philip and Sarah for their endless support and assistance throughout this entire project. I could not have done this without you.

To my much-loved family I dedicate this thesis.

Publications

Akroyd, T.J. and Nguyen, Q.D., (1999), 'Continuous On-Line Rheological Measurements for Mineral Slurries', *Chemeca '99*, Newcastle.

Akroyd, T.J., Nguyen, Q.D. and Vagias, N., (2001), 'Rheological Characterisation of Rapid Settling Slurries', *Aust. Korean Rheol. Conference*, Melbourne.

Akroyd, T.J. and Nguyen, Q.D., (2001), 'Rheological Characterisation of Heavy Mineral Slurries', *Chem. Eng. World Congress 2001*, Melbourne.

Akroyd, T.J. and Nguyen, Q.D., (2001), 'Continuous Rheometry for Industrial Slurries', *14 Aust Fluid Mech Conference*, Adelaide.

Akroyd, T.J., Nguyen, Q.D., and Denier, J.P., (2003), 'The Stability of Helical Flow of Pseudoplastic Fluids', *Chemeca '03*, Adelaide.

Akroyd, T.J. and Nguyen, Q.D., (2003), 'Effect of Density Difference between the Solids and Suspending Liquid on the Rheological Properties of Settling Slurry', *Chemeca '03*, Adelaide.

Papers

Akroyd, T.J. and Nguyen, Q.D., (2003), 'Continuous On-line Rheological Measurements for Rapid Settling Slurries', *Minerals Eng.*, **16**, pp. 731-738.

Akroyd, T.J. and Nguyen, Q.D., (2003), 'Continuous rheometry for industrial slurries', *Exp. Thermal and Fluid Science*, **27**, pp. 507-514.

Summary

The rapid settling nature of some industrial mineral slurries can cause problems in the measurement of their rheological properties. To address this problem a flow rheometer based on the principles of helical flow was developed. The rheometer designed, is a modified Couette flow system, whereby slurries are circulated through the concentric cylinders by the addition of an axial flow. The purpose of this axial flow is to prevent particles from settling and to maintain a homogeneous suspension. However, the addition of an axial flow component to Couette flow complicates the analysis procedure for non-Newtonian fluids particularly in wide gap geometries. Thus a specific emphasis in this study was placed on developing a correct analysis procedure for helical flow that eliminated the need for rudimentary calibration procedures.

Experimental measurements with different liquids, including those with Newtonian and non-Newtonian flow properties showed good agreement between data obtained from the flow rheometer and data obtained using other standard laboratory instruments. Typical differences between the results from the flow rheometer and results from other laboratory instrument varied between 1-2%, with standard deviations in the flow rheometer data of between 2-4%. The flow properties of several non-Newtonian slow settling slurries were examined using the flow rheometer and also with a specially modified tube rheometer. As with the pure liquid results good agreement was obtained between the results from the flow rheometer and those obtained with the modified tube rheometer. Several rapid settling slurries were examined using the flow rheometer, but due to the rapid settling nature of these slurries they could not be examined with any other laboratory instruments. However, internally consistent results were obtained from different tests with the flow rheometer using different values of axial flow rate. These results demonstrate that the correct data analysis method was developed for the helical flow of non-Newtonian fluids

Particle migration is a phenomenon known to affect the results of both rotational and axial flow rheological equipment. Whilst the motion of particles within the helical

flow geometry could not be directly observed, careful examination of the results from several experiments with slurries showed that the effects of particle migration were minimal or non-existent within the flow rheometer. It is presumed that the circulation of the fluid through the geometry minimises the residence time in the geometry, which reduces the likelihood of particle migration.

The development of Taylor vortices in a Couette type geometry can cause substantial errors in any rheological measurements. The flow rheometer is based on helical flow, which is a combination of both Couette and axial flow and as such may also suffer from measurement errors if instabilities develop in the flow. A stability criterion for the helical flow of non-Newtonian fluids is therefore required to ensure measurements from the flow rheometer were obtained in the laminar flow region. The stability criterion for laminar Couette flow of a Newtonian fluid was well known, as was the effect of imposing axial flow on Newtonian Couette flow. However, the effect of the rate of acceleration of the inner cylinder and the effect of non-Newtonian fluids on the onset of Taylor vortices was unknown. An increase in the rate of acceleration of the inner cylinder was found to have a destabilising effect on Couette flow. A modified Taylor number was developed for non-Newtonian fluids using the power-law model and was experimentally validated for a range of non-Newtonian fluids. These results were then used to develop a laminar flow stability criterion for rheological measurements of non-Newtonian fluids in the flow rheometer.

To test the suitability of the results from the flow rheometer for use in the design and optimisation of process units, the power requirements to turn an impeller in a small baffled mixing vessel were investigated. Good agreement was obtained in the laminar and turbulent flow regions for a variety of Newtonian and non-Newtonian fluids between measured values of impeller power and those predicted using rheological measurements from the flow rheometer.

Altering the density of the solid particles in a slurry is known to affect the overall rheological properties of the slurry. However, the effects of changing the liquid density were not so clearly defined and thus several artificial slurries of PMMA (poly-methylmethacrylate) spheres in water/NaCl and water/glycerol solutions were used to investigate this phenomenon. It was found that the slurry rheology was altered by changes in the suspending liquid density, however, these changes could be entirely attributed to changes in the liquid viscosity associated with the changes in liquid density.

To summarise, the work presented in this Thesis provides a fundamental approach for the absolute measurement of the rheological properties of settling slurries, under conditions that more accurately represent those found in actual mineral processing operations.

Table of Contents

APPENDICIES

List of Figures

List of Tables

Nomenclature

English Letters

A	pre-exponential parameter, power-law model	Pas^n
a	shear stress calculation parameter, vane	
a_x	Shi and Napier-Munn (1996) model parameters	$mV(s/rad)^x$
b	constant of integration	
C	height of the impeller above the base of the tank	m
c	differential pressure parameter	$kg/(m^2s^2)$
D_T	turbine diameter	m
d_x	x% of particles have a smaller diameter	m
dv	particle diameter (volume average)	m
ELF	entrance length parameter	
e	displacement of inner cylinder axis from centre axis	m
g	gravitational acceleration	m/s^2
H	axial length of a Taylor vortex	m
He	Headstrom number	
h	gap width between parallel plates	m
I_P	impeller blade pitch	m
J	width of baffles	m
k	ratio of cylinder speeds (inner/outer)	
k_1	Krieger and Maron model parameter	
k_2	Krieger and Maron model parameter	
k_n	mixing parameter used by Sinevic et al. (1986)	
L	length	m
L_B	length of impeller blade	m
L_e	entrance development length	m
M	torque	Nm
N_B	number of baffles in a tank	
N_I	number of impeller blades	
n	exponential parameter, power-law model	
P	Taylor's turbulence parameter	
p	pressure	Pa

Q	flow rate	m^3/s
R	outer cylinder radius	m
Re	Reynolds number	
Re'	modified Reynolds number for mixing tank systems	
S	radius ratio (outer/inner) (=1/κ)	
SC	stability criterion	
Ta	Taylor number	
Ta'	Taylor number (= Ta^2)	
Ta_c	critical Taylor number	
v	velocity	m/s
v_m	minimum velocity to maintain homogeneous conditions	m/s
$\langle v_z \rangle$	average annular axial velocity	m/s
W	width of an impeller blade	m
z	axial length	m

Greek Symbols

α	angle between cone and plate	rad
Δ	difference	
ε	eccentric Ratio (= e / average gap width(R-κR))	
η	apparent viscosity	Pas
Φ	solids volume concentration	
Φ_P	power number	
ϕ	fluidity function (=1/η)	1/Pas
$\dot{\gamma}$	shear rate	1/s
φ	co-axial cylinder shape factor	
κ	radius ratio (inner/outer) (=1/S)	
λ	radius ratio (axial velocity peak/outer)	
Ω	angular velocity	rad/s
$\wp$	combined pressure (= p + ρgz)	Pa
μ	viscosity	Pas
ν	kinematic viscosity	m^2s
ρ	density	kg/m^3

τ	shear stress	Pa
τ_y	yield stress	Pa
θ	cone and plate angle (= $\pi/2-\alpha/2$)	rad
υ	acceleration of the inner cylinder	rad/s
Ψ	wave number	

Subscripts

b	property at bob (inner cylinder) wall
l	property of the liquid
p	property of the solid fraction (particle)
r	radial direction, cylindrical co-ordinates
w	property at the system wall
s	property of the slurry
z	axial direction, cylindrical co-ordinates
θ	annular direction, cylindrical co-ordinates

Superscripts

c	CMC solution
g	glucose-water solution
m	moderate gap geometry
n	narrow gap geometry
p	polyox (PEO) solution
w	wide gap geometry