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A STUDY OF THE FLOW PROPERTIES OF
NEW ZEALAND WOOD PULP SUSPENSIONS

Thesis submitted for the degree
of Doctor of Philosophy

at the

School of Engineering,
The University of Auckland,
New Zealand

by

G. G. DUFFY

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Happy is the man who finds wisdom,
and the man who gets understanding,
for the gain from it is better than
gain from silver and its profit
better than gold.

Proverbs 3; 13,14

ABSTRACT

One of the most important process operations in the pulp and paper industry is the transport of pulp in pipe lines. Because pipe friction losses are much higher than with water under comparable conditions, accurate design correlations for each pulp are important to the industry. The purpose of this investigation was to design and build a flow rig suitable for investigating a wide range of pulp conditions, to obtain pipe friction loss data for New Zealand pulps, and to produce design correlations and procedures for the industry.

This thesis is therefore concerned primarily with describing the experimental equipment and procedures, presenting pipe friction loss data for a variety of New Zealand pulps, including a design correlation for them, and developing design methods for computing friction losses. It includes, in addition, data on drag reduction observed at high velocities of flow, and a discussion of flow mechanisms in each regime of flow.

The equipment was designed to produce friction loss data from three pipe diameters simultaneously for each consistency of pulp. Flow rate was controlled without throttling the flow. Pipe friction loss data are presented for five Kraft pulps and one neutral sulphite semi-chemical pulp. Data were obtained from 1, 2, 3 and 4 in. diameter PVC pipes for a wide range of consistencies and flow rates up to $0.8 \text{ ft}^3/\text{sec}$. Standard Lampen mill evaluations on hand sheets made from the pulps are presented, as well as data on the characteristics of the fibres.

The Kraft pulps exhibited the characteristic maxima and minima but the semi-chemical pulp did not exhibit these turning points.

For Kraft pulps head losses before the respective maxima were increased by refining the pulp and using rough pipe; and decreased by adding short-fibre Tawa and by drying and reslushing the pulp. In comparison with maxima for the unbeaten Kraft pulp, the maxima of the head loss curves for all Kraft pulps were shifted to lower velocities by the above-mentioned operations. This would reduce the friction loss in many practical cases. In particular, rough pipe lowers the magnitude of friction loss in this regime, and can therefore yield a considerable economic advantage.

A single design correlation for Kraft pulps is presented for the regime of flow before the maxima in the head loss curves. The limits of the correlation are given. Friction losses of New Zealand pulps were found to be lower than those previously reported in the literature.

Two methods of design are presented for the regimes at velocities above the maxima in the head loss curves. A procedure is suggested for pulp and paper mills to obtain their own limits for the design correlation and to verify the correlation proposed in this investigation for their own pulps.

A design correlation for the Tawa NSSC pulp is also presented.

Mechanisms of flow are discussed for Kraft pulps and a semi-chemical pulp. Visual observations in an artificially roughened pipe for the regime of flow before the maxima of the head loss curves have confirmed fibre-wall contact in this regime. Data obtained at the first sign of permanent plug disruption have been correlated with data at the onset of drag reduction. Fully developed turbulence was found to occur at the maximum level of drag reduction. Some velocity profiles are reported for the transition regime using a modified annular-purge probe.

In addition the disruptive shear stress of fibre networks has been correlated by three different methods.

Data for the onset of drag reduction are presented and compared with data previously obtained from large diameter pipes from other investigations. This correlation is used as a method for designing piping systems at high flow rates.

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TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGMENTS	i
TABLE OF CONTENTS	iii
NOTATIONS	viii
LIST OF FIGURES	xi
LIST OF TABLES	xvi
1. INTRODUCTION	1
2. REVIEW OF LITERATURE	3
2.1 General	3
2.2 The nature of fibre suspensions	3
2.2.1 The development of coherent fibre networks	5
2.2.2 Visco-elastic properties of fibre networks	8
2.2.3 The ultimate shear strength of coherent fibre networks	11
2.3 Rheological Models	13
2.3.1 Introduction	13
2.3.2 Application of rheological models to pipe suspension flow	13
2.4 The mechanisms of flow of pulp suspensions in pipes	17
2.4.1 The peripheral water-annulus model	26
2.4.2 The effective slip velocity model	29
2.4.3 A model for the transition regime	31
2.5 Friction loss design data and correlations for the flow of pulp suspensions in pipes	32
2.5.1 Design data used in the industry	32
2.5.2 Available design correlations for friction loss determinations	33

	<u>Page</u>
2.6 Viscous drag reduction	40
2.6.1 Drag reduction in dilute polymer solutions	41
2.6.1.1 Onset of drag reduction	41
2.6.1.2 Mechanisms proposed to explain drag reduction in polymer solutions	42
2.6.2 Drag reduction in soap solutions	45
2.6.2.1 Mechanisms proposed to explain drag reduction in soap solutions	45
2.6.3 Drag reduction in solid suspension flow	47
2.6.3.1 Mechanisms proposed for drag reduction in suspension flow	49
2.7 Determination of velocity profiles in pulp suspension flow	51
3. EXPERIMENTAL	55
3.1 Introduction	55
3.2 The flow circuit	55
3.3 Stock tanks and calibration system	59
3.4 Flow measurement and control	63
3.5 The manometer system	64
3.6 Annular-purge impact probe	65
3.7 Calibration of the flow loop with water	70
3.8 Experimental procedure for obtaining friction loss data	72
3.9 Determination of fibre characteristics	75
3.10 Determination of velocity profiles	75
3.11 Visual and photographic observation of the flow of pulp suspensions	76

	<u>Page</u>
4. PIPE FRICTION LOSS DATA AND VELOCITY PROFILES	78
4.1 Flow resistance data	78
4.1.1 General discussion and results	78
4.1.2 Fibre characteristics	80
4.1.3 Discussion of friction loss results	111
4.1.3.1 General	111
4.1.3.2 The effect of pump action on pulp freeness	115
4.1.3.3 Comparison of results	120
4.1.3.4 Problems associated with equipment and procedures	122
4.2 Velocity profile determinations	124
5. DESIGN CORRELATIONS	128
5.1 Design correlations for velocities below the maxima of the head loss curves	128
5.1.1 The dependence of head loss on velocity	131
5.1.2 The dependence of head loss on diameter	133
5.1.3 The dependence of head loss on consistency	135
5.1.4 A single design correlation for New Zealand Kraft pulps	138
5.1.5 A design correlation for NSSC Tawa	140
5.2 Design correlations for velocities above the maxima of the head loss curves	140
5.2.1 General	140
5.2.2 A simple design correlation - Method 1	141
5.2.3 A design correlation using data obtained in this study - Method 2	144
5.2.4 A suggested design procedure to obtain friction loss data for other pulps under mill conditions	153
5.3 Design of stock pumping systems for maximum efficiency	155
5.4 Summary	159

	<u>Page</u>
6. THE MECHANISMS OF THE FLOW OF PULP SUSPENSIONS IN PIPES	160
6.1 Review of previous interpretations	160
6.2 Visual observation of the mechanisms of flow	162
6.3 Proposed mechanisms for pulp suspension flow	171
6.4 The observed mechanisms of flow of a Tawa NSSC pulp	178
6.5 Rheological models applied to pulp suspension flow	179
6.5.1 The pseudoplastic model compared	179
6.5.2 The wall-slip model	183
7. THE DISRUPTIVE YIELD STRESS OF FIBRE NETWORKS	187
7.1 General	187
7.2 The determination of the disruptive yield stress of a bleached Kraft pine	188
7.2.1 The disruptive yield stress τ_d from visual observation	188
7.2.2 The disruptive yield stress τ_d from a Fischer and Porter Shear Tester	191
7.2.3 The disruptive yield stress τ_d from velocity profile measurements	192
8. DRAG REDUCTION IN PULP SUSPENSION FLOW	195
8.1 Introduction	195
8.2 The onset of drag reduction	195
8.3 The development of drag reduction	202
8.4 The maximum level of drag reduction	204
8.5 Loss of drag reduction at high velocities	213
8.6 Proposed mechanisms for drag reduction	213

	<u>Page</u>
9. CONCLUSIONS	217
10. SUGGESTIONS FOR FURTHER WORK	220
APPENDICES	
APPENDIX A I Average temperature and temperature span for each consistency run	222
APPENDIX A II Calculation of pulp flow parameters	224
APPENDIX A III Precision of pulp consistency measurement	225
REFERENCES	227

NOTATIONS

A	The fibre length-to-diameter ratio A.
A'	Annulus thickness at distance y from the pipe wall.
C	Oven-dry or moisture-free consistency; a constant in equations [2.17], [2.38].
c	The weight concentration of fibres.
c ₀	The upper critical fibre concentration for unimpeded rotation.
c _s	The sedimentation weight concentration.
c _v	The minimum concentration below which continuous networks could not exist.
c'	Constant defined in equation [2.16].
D	Diameter of pipe.
D _R	Drag ratio defined in equation [2.36].
F	Empirical constant.
F ₁ , F ₂ , F ₃	Empirical constants in equation [2.33].
f	Fanning friction factor.
f'	Modified friction factor defined by equation [2.24].
f(τ_y)	Function defined by equation [2.22].
G	Shear modulus of visco-elastic networks.
G'	Empirical constant in equations [2.3], [2.7].
$\frac{\Delta H}{L}$	Friction head loss per unit length.
ΔH	Friction head.
K	Empirical constant; von Kármán constant for Newtonian fluids.
K'	Consistency index for a power law fluid; empirical constant in equation [6.11].
K''	Empirical constant in equation [6.12].
K'''	Empirical constant in equation [6.13].
k _G	Empirical constant in equation [2.3].
k _T	Empirical constant in equation [2.4].
L	Length.
ℓ	Fibre length.
N	Dimensionless flow number defined by equation [2.26].
n	Power law fluid constant in equation [2.9]; exponent defined in equation [5.1].
n'	Flow behaviour index in a power law fluid.
$\left(\frac{\partial P}{\partial \ell}\right)$	Longitudinal pressure gradient in pipe.

Q	Volumetric flow rate.
R	Pipe radius.
Re	Newtonian Reynoldsnumber; water Reynolds number for pulp flow.
Re_t	Annulus Reynolds number.
Re'	Pseudo-Reynolds number in equation [2.31].
R_L'	Generalised Reynolds number defined by equation [2.15].
r	Radial distance from pipe axis.
S	Dimensionless shear parameter.
s	Time; yield shear stress after Head (45).
T	Temperature.
t	Annulus thickness.
u	Local mean velocity.
V	Mean velocity in a pipe.
V_p	Mean velocity of the pulp plug.
V_R	Slip velocity at the wall.
v	Local mean velocity at distance y from pipe wall.
v_s	Effective slip velocity at the wall.
v^+	Dimensionless velocity defined in equation [2.40].
y	Distance from the pipe wall.
y^+	Dimensionless distance defined in equation [2.41].
α	Constants in equation [2.28]; Hydrodynamic specific volume.
β	Constants in equation [2.28].
γ	Constants in equation [2.28]; Kinematic viscosity.
δ'	Thickness of the laminar sublayer.
τ	Shear stress at a distance r from pipe axis.
τ_d	Disruptive yield stress of a fibre network.
τ_0	Empirical constant in equation [2.4].
τ_u	Ultimate shear stress of fibre networks.
τ_w	Shear stress at pipe wall.
τ_y	Shear yield stress of a material.
τ'	Empirical constant in equation [2.5].
ρ	Newtonian fluid density; density of pulp suspension in equation [2.26].
σ	Hydrodynamic specific surface.

μ	Newtonian fluid viscosity.
μ_s	Slope viscosity in equation [2.12].
ϕ	Friction factor used in this investigation and defined by equation [3.1].
$\zeta(\tau_w)$	The effective slip coefficient.

LIST OF FIGURES

<u>Fig. No.</u>	<u>Title</u>	<u>Page No.</u>
2.1	Stress-strain curves for a bleached Kraft pulp fibre network, 2.6 percent consistency, at different strain rates (after Wahren (29)).	10
2.2 (a)	Friction loss curve from the data of Brecht and Heller for sulphite pulp at 3.0 percent consistency. (after Robertson and Mason).	20
(b)	Friction loss curves for sulphite pulp (after Robertson and Mason).	
(c)	Friction factor and flocculation index versus velocity curves for 0.58 percent consistency (after Robertson and Mason).	
2.3 (a)	Head loss versus velocity on linear coordinates (after Condolios and Constans as reported by Serwinski (54)).	24
(b)	Head loss versus velocity on logarithmic coordinates (after Condolios and Constans (36)).	
2.4	Percentage drag reduction versus wall shear stress for soap solutions (after Savins (78)).	46
3.1	Diagram of the flow circuit.	56
3.2 (a)	View of the large stock tank, pump, valve and recycle line.	60
3.2 (b)	General view of generator set, small stock tank and part of the manometer board.	
3.3 (a)	General view of part of the flow circuit.	61
(b)	View of one set of the manometer control valves.	
3.4	View of d.c. control panel and magnetic flowmeter recorders.	62
3.5	Schematic diagram of one set of manometers, the pressure measuring system for determining velocity profiles, and the back flushing pressure system.	66

<u>Fig. No.</u>	<u>Title</u>	<u>Page No.</u>
3.6	Annular-purge impact probe for velocity profile determinations.	67
3.7	Modified annular-purge impact probe for velocity profile determinations.	68
3.8	Annulus-purge probe for the determination of velocity profiles in the 3 in. diameter perspex pipe.	69
3.9	Friction factor ϕ versus Reynolds number Re plot for the calibration of the flow rig with water.	71
4.1 to 4.6	Friction loss data on linear coordinates.	82 - 87
4.7 to 4.26	Friction loss data on logarithmic coordinates.	88 - 107
4.27	Fibre length classification for the Tawa NSSC pulp from a Bauer McNett screen analysis (supplied by N.Z. Forest Products Ltd).	108
4.28	Photomicrograph of unbeaten Kraft pine Batch 2 fibres as received. Freeness 710.	109
4.29	Photomicrograph of refined Kraft pine fibres as received. Freeness 550.	109
4.30	Photomicrograph of bleached Kraft pine, dried and redispersed. Freeness 728.	110
4.31	Photomicrograph of Tawa neutral sulphite semi-chemical fibres as received. Freeness 737.	110
4.32	Wall shear stress versus velocity diagram showing independence of the effect of diameter on the maxima and minima. Consistency is expressed as a percentage.	112
4.33	A typical friction factor ϕ versus water Reynolds number diagram. Consistency is expressed as a percentage.	114
4.34	The effect of pump action in the closed-loop circuit on the freeness of pulp.	116

<u>Fig. No.</u>	<u>Title</u>	<u>Page No.</u>
4.35	Calibration of the annular purge probe with water.	125
4.36	Velocity profile measurements obtained with the N.Z.F.P. bleached Kraft pine in the 3 in. diameter pipe. Consistencies are 0.79 and 1.14 percent respectively.	126
5.1	Comparison of the usual design limits with the correlation limits for the linear region below the maxima. Friction loss data were obtained in a 3 in. diameter hydraulically smooth pipe.	129
5.2	The relation between friction head loss and pipe diameter. Consistency is shown as a percentage.	134
5.3	The relation between friction head loss and consistency. The diameter D is in inches and velocity V is in ft/sec.	137
5.4	Errors in the design limits of the correlations of Riegel and University of Maine compared with the actual data of Brecht and Heller from which the correlations were derived.	142
5.5	Proposed methods for the design of piping systems at velocities above the maximum of the friction head loss curve.	143
5.6	Wall shear stress versus velocity at the upper limit of the linear portion of the head loss curves.	146
5.7	Wall shear stress versus consistency at the upper limit of the linear portion of the head loss curves.	147
5.8 & 5.9	Wall shear stress versus consistency for the minima of the head loss curves.	148 149
5.10	Wall shear stress versus velocity for the minima of the head loss curves.	150

<u>Fig. No.</u>	<u>Title</u>	<u>Page No.</u>
5.11	Wall shear stress versus velocity at the onset of fully developed turbulence.	151
5.12	A design correlation for pipe velocities between 20 and 40 ft/sec and for consistencies ranging from 1.94 to 2.75 percent.	152
5.13	Reduction in friction loss in the design region caused by refining and drying Kraft pulp. Data obtained in this investigation from the 2.09 in. diameter pipe.	156
5.14	Reduction of friction head loss caused by the roughened pipe wall surface. Data obtained from a 4 in. diameter galvanised rough pipe and a 4 in. plastic smooth pipe.	158
6.1	Typical friction loss curves for chemically cooked pulps.	161
6.2	Development of computed annulus thickness with increase in average pipe velocity for N.Z. Kraft pine batch 2. Consistencies are expressed as percentages.	165
6.3	Development of computed annulus thickness with increase in average pipe velocity for Tawa/pine composite. Consistencies are expressed as percentages.	166
6.4	Development of computed annulus thickness with increase in velocity for Tawa NSSC.	168
6.5	Correlations of annulus thickness versus velocity and consistency for N.Z. Kraft pines at the minima of the friction head loss curves.	169
6.6 (a)	A typical plot of wall shear stress versus velocity on linear coordinates.	174
(b)	Shear stress τ versus radial distance from the wall.	

<u>Fig. No.</u>	<u>Title</u>	<u>Page No.</u>
6.7	Wall shear stress τ_w versus wall shear ratio $8V/D$ for a bleached Kraft pine.	182
6.8	Plot of wall shear stress versus $V/R \tau_w$ for the 'wall-slip' model.	184
6.9	Plot of $V/R \tau_w$ versus $1/R$ to determine the effective slip ζ .	186
7.1	Wall shear stress versus consistency to give the disruptive shear stress τ_d of a pulp network.	189
7.2	Wall shear stress versus velocity to determine the disruptive shear stress of a pulp network.	190
7.3	Comparison between the disruptive yield stress determined hydrodynamically from pipe flow, and quasi-statically from a shear tester for a range of consistencies.	193

LIST OF TABLES

<u>Table</u>	<u>Page</u>
3.1 Measured pipe diameters and calming lengths	57
4.1 Summary of pulps studied	79
4.2 Fibre characteristics of pulps studied	81
4.3 Lampen mill evaluation data	117
(a) Pulp properties of samples of Tawa/pine Kraft after 3,000 revolutions in British Disintegrator	
(b) Lampen mill evaluation data for the initial pulp sample	
(c) Extrapolated data	
4.4 Lampen mill evaluation data	119
(a) N.Z.F.P. bleached Kraft pine	
(b) N.Z.F.P. unbeaten Kraft pine	
(c) N.Z.F.P. refined Kraft pine	
4.5 The effect of the type of pulp on the location of the maxima and minima of the head loss curves with reference to N.Z.F.P. Kraft pine batch 1	121
5.1 Approximate velocities at the upper limit and values of friction factor for the linear region of the proposed design correlation for hydraulically smooth pipes	130
5.2 Head loss versus velocity relationship. Average slope for 2, 3 and 4 in. diameter pipes at each consistency	132
5.3 Data obtained in the development of design correlations	136
5.4 Comparison of existing correlations and data with the correlation obtained for N.Z. Kraft pine (equation [5.2])	139
8.1 Data for the linear dependence of drag reduction on annulus area	205
8.2 The average percentage maximum drag reduction for several New Zealand pulps	212