

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

DEPARTMENT OF FOOD TECHNOLOGY
MASSEY UNIVERSITY
PALMERSTON NORTH
NEW ZEALAND

*HEAT TRANSFER AND FOULING
IN FILM EVAPORATORS
WITH ROTATING SURFACES*

A THESIS PRESENTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN FOOD TECHNOLOGY
AT MASSEY UNIVERSITY

HONG CHEN
B.E., M.Tech. (Honours)

1997

ABSTRACT

A study was made on the heat transfer and fouling in thin film evaporators with rotating surfaces. Both theoretical and experimental studies were carried out, in order to gain a better understanding of these evaporators and their design principles, so that this type of evaporator could be effectively used in an on-farm milk evaporation system.

By using Nusselt-type assumptions, a theoretical model, which was used to predict the liquid film thickness and heat transfer coefficients on the rotating cone, was developed. The theoretical equations obtained revealed basic relationships between the variables and provided a fundamental knowledge of the liquid flow and heat transfer in the film evaporators with rotating surfaces.

The experimental studies on heat transfer were conducted on a Centritherm evaporator, which is available commercially (40° half cone angle), a specially made cone evaporator (10° half cone angle) and a falling film evaporator with a rotating tube. Variables evaluated were the rotating speed, the cone angle, the feed flow rate, the evaporating temperature, the temperature difference between the steam condensing and the liquid evaporating temperatures, and sugar concentration when sugar solution was used. The experimentally measured overall heat transfer coefficients were compared with the theoretical values.

It was found that the measured overall heat transfer coefficients increased with increase of the cone rotating speed, and with the rise of the liquid evaporating temperature. The feed flow rate was found to have a more significant effect on the measured overall heat transfer coefficients in the falling film evaporator with a rotating tube than that in the Centritherm and the cone evaporators. The overall heat transfer coefficients decreased with increase of the concentration of sugar solutions, mainly due to the increase of liquid viscosity. It was also found

that the measured overall heat transfer coefficients in the Centritherm evaporator increased with an increase in temperature difference up to 30K (for water, 10% sugar solution and skim milk) and then decreased (for water and 10% sugar solution). The formation of bubbles on the evaporating surface at high temperature differences was likely to be cause of this effect.

Increase of the cone angle resulted in thinner liquid films and higher heat transfer coefficients. This was reflected in the following experimental results: the measured overall heat transfer coefficients in the falling film evaporator with a rotating tube were slightly lower than those measured in the cone evaporator, but much lower than those obtained in the Centritherm evaporator.

The experimental results showed that rotating the tube of a falling film evaporator increased the overall heat transfer coefficient but the increase obtained was very dependent on feed flow rate, and was not sufficient to justify the use of this evaporator in the industry.

With the Centritherm evaporator, good agreement between theoretical and experimental overall heat transfer coefficients as a function of the cone rotating speed was obtained by using water. The theoretical model, however, does not adequately describe the whole evaporation process at conditions other than those assumed in the model, which are: laminar liquid film flow, and heat transfer by conduction through the liquid film. It is suggested that waves existing in the liquid film at high Reynolds numbers, and bubble formation on the heating surface at high temperature difference, are the major reasons for the discrepancy between theoretical and experimental results.

For the fouling study, the Centritherm evaporator was mainly employed, and three liquid systems: reconstituted skim milk, reconstituted whey solutions and sweet cheese whey solution, were selected. It was found that no fouling was detected after 6 hours' operation in the Centritherm evaporator when

reconstituted skim milk and reconstituted whey solutions were used. This indicates that the aggregated whey proteins, which are formed in the manufacture of skim milk powder and whey powder, are less active in inducing fouling. For this reason, only the sweet cheese whey solution was used in further studies.

It was confirmed that fouling is strongly linked with the liquid evaporating temperature and the temperature difference between steam condensing and liquid evaporating temperatures. In general, the higher the evaporating temperature and the temperature difference, the faster the deposition rate and the greater the fouling on the surface. It was found that 72% Bovine Serum Albumins (BSA) denatured after running the evaporator, at a evaporating temperature of 70°C and a temperature difference of 20K, for 6 hours. Though the content of BSA in whey solution is small, the denatured BSA could be easily attached to the surface. By association with other depositable materials existing in the whey solution, the thin layer of deposit could reduce the heat transfer coefficients significantly. This was attributed to the lower thermal conductivity of the deposited layer. Fouling was also found to be a function of the liquid velocity. This effect was more significant at lower evaporation temperatures. Increasing the rotating velocity would delay the formation of an initial layer and reduce the rate of fouling.

It was also found that there was an induction period in the fouling curves when the evaporating temperature was 60°C. The induction period was reduced when new whey solutions were introduced into the evaporator. It proved the fact that depositable materials are much more easily adsorbed on fouled or unclean surfaces than on clean surfaces. The increase of fouling rate when new whey solutions were introduced suggested that the concentration of activated molecules in the solutions strongly affected the fouling process. A possible mechanism of whey fouling on the rotating surface was proposed.

During this study, an attempt was made to develop a new type of evaporator in which a vapour compressor would be integrated with the rotating surface. This was unsuccessful due to the failure of compressing the vapour. Concerning the on-farm evaporation system, which requires an evaporator with high efficiency, compact, and minimum heat load to milk, it is suggested that a rotating surface evaporator with the top cone angle close to 90° (like a disk evaporator) would be optimum and worth to explore.

ACKNOWLEDGEMENTS

I wish to express my deepest appreciation and gratitude to my supervisor, Mr. Selwyn Jebson, for his supervision, guidance, encouragement, patience and friendship, and to my co-supervisor, Dr. Osvaldo Campanella, for his suggestions, valuable advice and encouragement throughout this study at Massey University.

I would like to extend my appreciation to Professor Peter Munro and Mr. Rod Bennett, for their help and care, to Dr. Tuoc Trinh for his stimulating discussions, to Mr. Byron Mckillop for his valuable assistance in setting up the experimental apparatus, to Mr. Palatasa Havea for his assistance in testing whey protein samples, to Mr. Mike Conlon, Mr. Alistar Young, Mr. Garry Radford, Ms. June Latham, Mr. Steve Glassgow, Mr. Hank van Til, Mr. Mark Dorsey for their help in providing technical assistance during the experimental work, to Dr. P.K. Samal and his colleagues at Longburn Cheese Factory of Tui Milk Products Company in Palmerston North for their efforts in arranging the whey solutions.

The staff of the Department of Food Technology were very helpful throughout the duration of my study.

I am also grateful to Professor Alan Williams and Mrs Beverley Williams, for their generous help, continuous care and friendship.

I would also like to mention the enjoyable company and moments provided by my friends, fellows at Massey University, and the members of New Zealand-China Friendship Society, who in many ways contributed to the completion of this work. Especially, I have to mention that when I was involved in an unfortunate car accident, many friends provided their help for my family to go

through a difficult time. Their invaluable assistance is very much appreciated and will be always remembered.

Finally, I would like to express my special thanks to my wife, Xinjun, for her love, encouragement, patience and typing. During this period, my son, John, and my daughter, Helen, came to this world and brought us a newly happy life. I also thank my father, mother, sister, grandmother, parents-in-law as well as the whole family for their understanding and constant support and helpfulness.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGEMENTS	vi
TABLE OF CONTENTS	viii
LIST OF FIGURES	xv
LIST OF TABLES	xix
NOMENCLATURE	xx
LIST OF PUBLICATIONS	xxiv
PART I GENERAL INTRODUCTION	
CHAPTER 1 INTRODUCTION	1
1.1 Evaporation	1
1.2 Evaporation technology used in the dairy industry	7
1.3 The thin film evaporator with rotating heating surface	8
1.4 Fouling in evaporation	9
1.5 On-farm evaporation system	10
CHAPTER 2 OBJECTIVES	13
PART II HEAT TRANSFER IN EVAPORATORS WITH ROTATING SURFACES	
CHAPTER 3 HEAT TRANSFER IN THIN FILM EVAPORATORS - LITERATURE REVIEW	15
3.1 Liquid film flow	15
3.1.1 The flow regimes of the liquid film	16
3.1.2 Flow features of the falling liquid films	18
3.2 Liquid boiling phenomena	19
3.2.1 Pool boiling	19
3.2.2. Flow boiling	22
3.3 Heat transfer through a thin liquid film	24
3.4 Effect of the adjacent gas stream on the liquid film flow and heat transfer	27

3.5 Heat transfer enhancement by rotating the surface	29
3.6 Steam Condensation	32
3.6.1 Film Condensation	33
3.6.2 Dropwise condensation	34
3.6.3 Condensation in the presence of non-condensable gases	36
3.7 The development of evaporation technology in the dairy industry	38
3.8 Thin film evaporators with rotating surfaces	43
3.8.1 The development of this type of evaporator	43
3.8.2 The features of the rotating surface evaporator	45
3.8.3 Industrial use of rotating surface evaporators	48
CHAPTER 4 EXPERIMENTAL METHODS FOR DETERMINING HEAT TRANSFER COEFFICIENT	50
4.1 Objectives	50
4.2 Materials	50
4.2.1 Water	50
4.2.2 Sugar solution	50
4.2.3 Reconstituted skim milk	50
4.2.4 Chemicals used for Cleaning-in-place (CIP)	51
4.3 Equipment	51
4.3.1 Centritherm evaporator	51
4.3.2 Single-tube falling film evaporator with rotating surface	54
4.3.3 Cone evaporator	56
4.4 The evaporation process in thin film evaporators	57
4.5 Instrumentation	59
4.5.1 Steam regulator	59
4.5.2 Flowmeter	59
4.5.3 Temperature measurement	60

4.5.4 Pressure measurement	60
4.5.5 Rotating speed measurement	60
4.6 The variables and their ranges	61
4.7 Operating procedure of thin film evaporator equipment	62
4.7.1 Starting	62
4.7.2 Cleaning	62
4.7.3 Stopping	63
4.7.4 Operating cautions	63
4.8 Experimental Procedure	64
4.9 Data processing	65
CHAPTER 5 DEVELOPMENT OF A THEORETICAL MODEL TO DETERMINE HEAT TRANSFER COEFFICIENTS ON ROTATING CONE SURFACES	67
5.1 Introduction	67
5.2 Theory	67
5.2.1 Liquid film flow and energy analysis	67
5.2.2 Determination of the local heat transfer coefficient	74
5.2.3 Effect of liquid evaporation	75
5.2.4 Overall heat transfer coefficient calculation	75
5.2.5 The relationship between rotational Nusselt number and Reynolds number	77
5.3 Calculation procedure	78
5.4 The determination of the physical properties of the liquids used	78
CHAPTER 6 HEAT TRANSFER IN THIN FILM EVAPORATORS- RESULTS AND DISCUSSION	80
6.1 Theoretical model results	80
6.2 Experimental results and their comparison with those theoretically calculated with the model	88
6.2.1 Centritherm evaporator	90
6.2.1.1 Temperature difference	91
6.2.1.2 Rotating speed	93

6.2.1.3 Feed flow	95
6.2.1.4 Evaporating temperature	100
6.2.1.5 Experiments of sugar solutions at different concentrations	103
6.2.2 Cone evaporator	106
6.2.2.1 Temperature difference	106
6.2.2.2 Rotating speed	106
6.2.2.3 Feed flow	109
6.2.2.4 Evaporating temperature	109
6.2.3 Falling film evaporator with a rotating tube	109
6.2.3.1 Reynolds number	112
6.2.3.2 Rotating speed	114
6.2.3.3 Evaporating temperature	116
6.2.3.4 Feed temperature	116
6.2.3.5 Temperature difference	119
6.3 Conclusions	121
PART III FOULING IN EVAPORATORS WITH ROTATING SURFACES	
CHAPTER 7 LITERATURE REVIEWS OF FOULING IN	
MILK PROCESSING	
7.1 The costs of fouling	123
7.2 The types of fouling	125
7.3 The research history of fouling in dairy industry	126
7.4 Composition and structure of milk fouling deposit	128
7.5 Factors affecting milk fouling on the heating surface	131
7.5.1 Milk properties	131
7.5.1.1 Compositional variations with season	131
7.5.1.2 pH values of milk	132
7.5.1.3 The amino nitrogen level of the milk	132
7.5.1.4 Calcium phosphate	132
7.5.1.5 Air content in milk	133
7.5.1.6 Concentration of milk	135

7.5.2 Plant construction and operation	135
7.5.2.1 Storage time	135
7.5.2.2 Preheating	136
7.5.2.3 Absolute liquid velocity	136
7.5.2.4 Surface conditions	137
7.5.2.5 Temperature	138
7.5.2.6 Processing time	138
7.6 Possible mechanisms for milk fouling on the heating surface	140
7.7 The initial deposited layer of milk fouling	143
7.8 The rate-controlling processes in milk fouling	145
7.9 Whey proteins and their denaturation	146
7.9.1 β -lactoglobulin (β -lg)	147
7.9.2 α -lactalbumin (α -la)	147
7.9.3 Bovine serum albumin (BSA)	148
7.9.4 Immunoglobulins (Ig)	148
7.9.5 Whey protein structure	148
7.9.6 Whey protein denaturation and aggregation	149
7.10 The relationship of whey protein denaturation and milk fouling	149
7.11 Conclusions	150
CHAPTER 8 FOULING IN EVAPORATORS - MATERIALS AND METHODS	152
8.1 Introduction	152
8.2 Materials	152
8.2.1 Equipment	152
8.2.2 Model Solutions	152
8.2.3 Chemicals used for cleaning	153
8.3 Methods	154
8.3.1 The Centritherm evaporator and the falling film evaporator	154
8.3.2 The recycle system	154

8.3.3 The examination of denatured whey proteins	155	
8.4 Instrumentation	155	
8.5 Experimental	155	
8.5.1 Experimental variables	155	
8.5.2 Experiment design	156	
8.5.3 Experimental Procedure	157	
8.5.4 Evaporator cleaning	157	
8.6 Theory and data processing	158	
CHAPTER 9 FOULING IN EVAPORATOR--RESULTS AND		
DISCUSSIONS		160
9.1 Preliminary experimental results	160	
9.2 Effects of evaporation temperature and temperature difference on fouling	162	
9.3 Visual observation of the whey deposits on the surface	167	
9.4 Effect of the rotating speed on fouling	167	
9.5 The interaction of variables on the fouling resistance	170	
9.6 The building up of the deposits	172	
9.7 The possible fouling mechanism of whey solutions on the rotating surface	173	
9.8 The evaporation mechanism on a fouled heat transfer surface . .	173	
9.9 Conclusions	175	
CHAPTER 10 OVERALL DISCUSSION AND		
RECOMMENDATIONS		177
10.1 Overall discussion	177	
10.1.1 Background of the PhD programme	177	
10.1.2 Liquid film flow and heat transfer on the rotating surface	178	
10.1.3 Heat transfer in the Centritherm and the cone evaporators	178	
10.1.4 Heat transfer in the falling film evaporator with rotating tube	181	

10.1.5 Fouling with whey solution in the Centritherm evaporator	181
10.2 Recommendations for the further work	182
REFERENCES	184
APPENDICES	
Appendix I Experimental results of heat transfer in evaporators	214
Appendix II Calculation of surface areas on the cone	225
Appendix III Correlations of physical properties for water, sugar solution and skim milk	226
Appendix IV Results of numerical calculation	230
Appendix V An example of determining the uncertainty for overall heat transfer coefficient	243
Appendix VI Polyacrylamide Gel Electrophoresis (PAGE)	244
Appendix VII Experimental results of fouling in Centritherm evaporator	245
Appendix VIII A typical native-PAGE patterns of whey protein solutions	256

LIST OF FIGURES

Figure 1.1 The different types of evaporator	3 & 4
Figure 1.2 The proposed on-farm evaporation system	12
Figure 3.1 The boiling curve for water at atmospheric pressure	21
Figure 3.2 The different designs of the film evaporator with rotating surfaces	46
Figure 4.1 The whole apparatus of the Centritherm evaporator and the falling film evaporator with a rotating tube	52
Figure 4.2 Schematic diagram of the Centritherm evaporator system	53
Figure 4.3 Schematic of the single-tube falling film evaporator with a rotating surface	55
Figure 4.4 Schematic diagram of the feed tube	56
Figure 4.5 Schematic diagram of cone evaporator and the dimensions of the cone	58
Figure 5.1 Schematic diagram of the system used in the theoretical analysis	68
Figure 5.2 Flow diagram for the numerical calculation of the overall heat transfer coefficient	79
Figure 6.1 Dimensionless film thickness on a rotating cone at different cone angles	81
Figure 6.2 Dimensionless film thickness on a rotating cone at different feed flows	82
Figure 6.3 Dimensionless film thickness versus rotation parameter at different cone angles	84
Figure 6.4 Effect of rotating speed on the Nusselt number at different cone angles	85
Figure 6.5 Calculated heat transfer coefficients on the rotating cone in the Centritherm evaporator	86
Figure 6.6 Calculated local surface temperatures, liquid film thickness and Reynolds number along the cone	87

Figure 6.7 Recorded temperatures during an experimental run in the Centritherm evaporator	89
Figure 6.8 Effect of temperature difference on the overall heat transfer coefficient for water, 20% sugar solution and skim milk in the Centritherm evaporator	92
Figure 6.9 Effect of the cone rotating speed on the overall heat transfer coefficient for water, 20% sugar solution and skim milk in the Centritherm evaporator	94
Figure 6.10 Effect of the feed flow rate on the overall heat transfer coefficient for water, 20% sugar solution and skim milk in the Centritherm evaporator	96
Figure 6.11 Effect of the feed flow rate and the rotational speeds on the overall heat transfer coefficient for water in the Centritherm evaporator	98
Figure 6.12 Effect of the feed flow rate on the overall heat transfer coefficient for water in the Centritherm evaporator	99
Figure 6.13 Effect of evaporating temperatures on the overall heat transfer coefficient in the Centritherm evaporator	101
Figure 6.14 Effect of the temperatures difference on the overall heat transfer coefficient for sugar solutions in the Centritherm evaporator	104
Figure 6.15 Effect of sugar concentration on the overall heat transfer coefficient in the Centritherm evaporator	105
Figure 6.16 Effect of the temperatures difference on the overall heat transfer coefficient for water in a cone evaporator	107
Figure 6.17 Effect of rotating speed on the overall heat transfer coefficient at different evaporating temperature in a cone evaporator with water	108
Figure 6.18 Effect of flow rates on the overall heat transfer coefficient for water in a cone evaporator	110

Figure 6.19 Effect of evaporating temperature on the overall heat transfer coefficient for water in a cone evaporator	111
Figure 6.20 Effect of the Reynolds number on the overall heat transfer coefficient of a rotating tube falling film evaporator	113
Figure 6.21 Effect of the tube rotating speed on the overall heat transfer coefficient in a rotating tube falling film evaporator at different Reynolds numbers	115
Figure 6.22 Effect of the evaporating temperature on overall heat transfer coefficients in a rotating tube falling film evaporator	117
Figure 6.23 Effect of the feed temperature on the overall heat transfer coefficient in a rotating tube falling film evaporator	118
Figure 6.24 Effect of the tube rotating speed on the overall heat transfer coefficient in a rotating tube falling film evaporator at different temperature differences	120
Figure 7.1 The schematic presentation of the milk fouling process induced by an air bubble at a hot stainless steel surface	134
Figure 7.2 Idealised fouling curves	139
Figure 7.3 Schematic presentation of the fouling mechanisms during heating of whey and milk	142
Figure 9.1 Fouling resistance as a function of time for recycled sweet cheese whey in the Centritherm evaporator at an evaporating temperature of 60°C and a rotating speed of 105 rad/s	163
Figure 9.2 Fouling resistance as an function of time for recycled sweet cheese whey in the Centritherm evaporator at an evaporating temperature of 70°C and a rotating speed of 105 rad/s	164

Figure 9.3	Fouling resistance as an function of time at different evaporating temperatures for recycled sweet cheese whey in the Centritherm evaporator	165
Figure 9.4	The fouled rotating surface of the Centritherm evaporator . . .	168
Figure 9.5	Fouling resistance as an function of time for recycled sweet cheese whey in the Centritherm evaporator at an evaporating temperature of 70°C and different rotating speeds.	169
Figure 9.6	Comparison of fouling resistances in the falling film evaporator and the Centritherm evaporator for recycled sweet cheese whey at a temperature difference of 20°C	171
Figure 9.7	Fouling resistance as a function of time for recycled sweet cheese whey, when a new whey solution is introduced	174
Figure 9.8	Overall heat transfer coefficient as a function of temperature difference for different liquids and clean and fouled rotating surfaces in the Centritherm evaporator	176

LIST OF TABLES

Table 4.1 Ranges of experimental variables	61
Table 6.1 Physical properties of water as a function of temperature	102
Table 6.2 Physical properties of a 20% sugar solution as a function of temperature	102
Table 6.3 Physical properties of skim milk as a function of temperature . .	102
Table 7.1 The composition of milk deposits in a pasteurizer and a sterilizer	129
Table 7.2 The protein composition of milk deposits in a pasteurizer and a sterilizer	129
Table 8.1 Ranges of experimental variables	155
Table 8.2 The arranged trials with selected variables	156
Table 9.1 Summary of preliminary experimental results after 6 hours evaporation running	161
Table 9.2 Percentage loss of native whey protein during evaporation at a temperature of 70°C and a temperature difference of 20K	166

NOMENCLATURE

Roman letters

A	heat transfer area (m ²)
A _l	liquid side heat transfer area (m ²)
A _m	average heat transfer area (m ²), defined as: $(A_s - A_l) / \ln(A_s / A_l)$
A _s	steam side heat transfer area (m ²)
a	acceleration due to rotating (m/s ²)
C	constant
C _p	specific heat (kJ/kg.K)
d	inside tube diameter (m)
d _o	outside diameter on the top of cone (m)
D	outside tube diameter (m)
D _o	outside diameter at the bottom of cone (m)
Fr	Froude number, defined as: $[u^2 / (g \cdot d)]$
g	acceleration due to gravity (m/s ²)
g'	corrected gravitational acceleration, defined as $g \cdot \cos\beta$ (m/s ²)
h _{fg}	latent heat of vapour condensation (kJ/kg)
h' _{fg}	effective latent heat of vapour condensation (kJ/kg), defined as: $h_{fg} [1 + 0.68 C_p (T_s - T_{ws}) / h_{fg}]$
h _s	steam side heat transfer coefficient (kW/m ² .K)
h _l	liquid side heat transfer coefficient (kW/m ² .K)
h' _l	corrected liquid side heat transfer coefficient (kW/m ² .K)
H _o	initial overall heat transfer coefficient (kW/m ² .K)
H _{cal}	calculated overall heat transfer coefficient (kW/m ² .K)
H _{exp}	measured overall heat transfer coefficient (kW/m ² .K)
H(t)	measured overall heat transfer coefficient at time t (kW/m ² .K)
Ja	Jacob number, defined as: $C_p (T_s - T_w) / h'_{fg}$
k	thermal conductivity of liquid (W/m.K)
k _d	thermal conductivity of fouling layer (W/m.K)
k _{ss}	thermal conductivity of sugar solution (W/m.K)

k_w	thermal conductivity of wall (W/m.K)
L	characteristic distance (m)
L_1	distance from the vertex to the apex of a truncated cone (m)
l	length of the cone (mm)
Nu	Nusselt number, defined as: h_1L/k
Nu'	modified Nusselt number, defined as eq (3-4)
Nu_{r0}	rotational Nusselt number, defined as eq (5-37)
Pr	Prandtl number, defined as: $C_p\mu/k$
Q	amount of heat (kW)
Q_f	feed flow (m ³ /s)
q	heat flow (kW/m ²)
r	inner radius on the any position of cone (m)
r_i	inner radius on the top of cone (m)
R_f	fouling resistance (m ² .K/kW)
$R_f(t)$	fouling resistance at time t (m ² .K/kW)
Re_a	axial flow Reynolds number, defined as: Du/v
Re_r	rotational flow Reynolds number, defined as: $D^2\Omega/v$
R_i	inner radius at the bottom of cone (m)
R_o	rotation parameter, defined by eq (5-19)
U_m	characteristic velocity (m/s)
U_x	component of liquid velocity in X direction (m/s)
U_y	component of liquid velocity in Y direction (m/s)
U_φ	component of liquid velocity in φ direction (m/s)
u	liquid flow velocity (m/s)
T	temperature (°C)
T_{evp}	evaporating temperature (°C)
T_l	liquid temperature (°C)
T_s	steam temperature (°C)
T_{sat}	saturation temperature (K)
T_w	wall temperature (°C)
T_{wl}	surface temperature of cone on liquid side (°C)

T_{ws}	surface temperature of cone on steam side ($^{\circ}\text{C}$)
ΔT	temperature difference between the evaporating and the steam condensing temperatures (K)
ΔT_B	temperature difference between the wall and liquid saturation temperature (K)
W_{cal}	calculated flow rate of vapour condensate (kg/s)
W_{exp}	measured flow rate of vapour condensate (kg/s)
We	Weber number, defined as: $[(\rho \cdot u^2 \cdot \delta / \sigma)^{1/2}]$
X	downward distance along cone surface (m)
Y	distance from surface (m)

Greek symbols

α	thermal diffusivity (m^2/s)
β	half angle of the cone
δ	thickness of liquid film (mm)
δ_d	thickness of the fouling layer (mm)
δ_w	thickness of wall (mm)
μ	dynamic viscosity (Pa.s)
ν	kinematic viscosity (m^2/s)
ρ	density of liquid (kg/m^3)
ρ_v	density of vapour (kg/m^3)
ρ_{ss}	density of sugar solution (kg/m^3)
Ω	angular velocity (rad/s)
φ	angular co-ordinate
Γ	local mass flow rate in the film per unit width of surface ($\text{kg}/\text{m}\cdot\text{s}$)
τ_{yx}	radial shear stress (N/m^2)
$\tau_{y\varphi}$	tangential shear stress (N/m^2)
σ	surface tension (N/m)

Superscripts

*	dimensionless quantity
---	------------------------

Abbreviations

BPE	Boiling Point Elevation
CIP	Cleaning In Place
DM	Dry Matter
ET	Evaporation Temperature
FF	Feed Flow
FFE	Falling Film Evaporator
FT	Feed Temperature
PAGE	Polyacrylamide Gel Electrophoresis
RS	Rotating Speed
TS	Total Solids

LIST OF PUBLICATIONS

H.Chen, R.S.Jebson and O.H.Campanella, 1993, Factor Affecting Heat Transfer in the Centritherm Evaporator, *Proceedings, the APCChE/CHEMECA 1993 Conference, Vol.3*, pp 227-233, Melbourne, Australia.

H.Chen, R.S.Jebson & O.H.Campanella, 1994, Heat Transfer Coefficients for Evaporation from the Inner Surface of the Rotating Cone, *Proceedings, CHEMECA 1994 Conference, Vol.2*, pp 695-702, Perth, Australia.

H.Chen, R.S.Jebson & O.H.Campanella, 1994, Performance of the Centritherm Evaporator for Concentration of High Viscosity Solutions, *Proceedings of the Inaugural New Zealand Postgraduate Conference for Engineering and Technology Students*, Department of Production Technology, Massey University, pp 60-65.

R.S.Jebson, H.Chen, & O.H.Campanella, 1995, Heat Transfer Coefficients on the Inner Surface of the Rotating Cone, *Proceedings, 1995 Asian Pacific Confederation of Chemical Engineer, Vol.2*, pp 125-136, Taipei Taiwan.

H.Chen, R.S.Jebson & O.H.Campanella, 1996, Fouling in the Centritherm Evaporator with Whey Solutions, *Proceeding of IPENZ 1996 Conference, Vol.2, Part 2*, pp 308-313, Dunedin, New Zealand.

R.S.Jebson, H.Chen & O.H.Campanella, 1997, Study on a Rotating Tube Falling Film Evaporator, *Proceeding of IPENZ 1997 Conference, Vol.2*, pp 41-45, Wellington, New Zealand.

H.Chen, R.S.Jebson & O.H.Campanella, 1997, Determination of Heat Transfer Coefficients in Rotating Cone Evaporators Part I, *Food and Bioproducts Processing, Trans IChemE, Vol. 75, Part C*, pp 17-22.

R.S.Jebson and H.Chen, 1997, Performances of Falling Film Evaporators on Whole Milk and a Comparison with Performance on Shim Milk, *Journal of Dairy Research*, **64**, pp 57-67.

H.Chen, R.S.Jebson & O.H.Campanella, 1997, Determination of Heat Transfer coefficients in Rotating Cone Evaporators Part II, a paper to be submitted to *Food and Bioproducts Processing*, Trans IChemE, Part C.

H.Chen, R.S.Jebson & O.H.Campanella, 1997, Fouling of Heat Transfer Surface by Whey Solution in Rotating Film Evaporators, a paper to be submitted to *International Journal of Food Science and Engineering*.
