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

PART III FOULING IN EVAPORATORS WITH ROTATING SURFACES

APPENDICES

LIST OF FIGURES

LIST OF TABLES

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: $[u^2/(g.d)]$
g	acceleration due to gravity (m/s^2)
g'	corrected gravitational acceleration, defined as $g.\cos\beta$ (m/s^2)
h_{fg}	latent heat of vapour condensation (kJ/kg)
h'_{fg}	effective latent heat of vapour condensation (kJ/kg), defined as: $h_{fg}[1+0.68C_p(T_s - T_{ws})/h_{fg}]$
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: $h_l L/k$
Nu′	modified Nusselt number, defined as eq (3-4)
Nu_{ro}	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/ν
Re_r	rotational flow Reynolds number, defined as: $D^2\Omega/\nu$
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 (°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: $[(\rho.u^2.\delta\ /\sigma)^{1/2}]$
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 (kg/m.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, Taibei 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.*