Modelling, Optimisation and Control of a Falling-Film Evaporator

A thesis presented in partial fulfilment of the requirements for the degree of Doctor of philosophy in Production Technology

at
Institute of Technology and Engineering
Massey University
Palmerston North
New Zealand

Shabeshe Paramalingam
2004

Acknowledgements

My primary thanks are to my supervisor, Dr. Huub Bakker, for his support, guidance, friendship, patience and encouragement throughout this project. Without his direction, motivation, committed attitude, help and advice this project would never have succeeded.

I would like to express my appreciation to my second supervisor Dr. Hong Chen, Fonterra-Ingredients, Whareroa, Fonterra Co-operative Ltd, for sharing his wealth of knowledge in evaporation and drying technology and for his support during this project. I thank him also for providing me with the tools, permission to conduct trials in a commercial evaporator and support to complete my project successfully. I really appreciate his encouragement and helpful attitude. My thanks go also to Clive Marsh for his valuable input to this project. I appreciate him spending his valuable time in supporting this project.

I would like to thank many staff at Whareroa with whom I have had the privilege to become familiar during my time at site. Special thanks go to the whey products managers, supervisors and operators for their encouragement, support and involvement during the evaporator trials.

Thanks to the Foundation for Research in Science and Technology for their sponsorship through the Graduate Research in Industry Fellowship programme. I am indebted to the staff of the Institute of Engineering and Technology, Massey University, New Zealand, for assistance with this work and for the facilities provided. Also thanks to my colleges and friends who made my time at Massey very enjoyable.

I would like to thank the Hawera community, in particular Neil and Helen Walker, for their hospitality, support and friendship during my stay. Finally, I would like to express my special thanks to my wife, Ahalya for her encouragement, patience and moral support throughout this project.

Contents

List of figures

List of tables

Summary

Falling-film evaporators are widely used in dairy industry for concentrating products. With increasing demand and competition, there is always a need for process improvement. This is made more difficult when using the same evaporator for concentrating different products. Therefore, it is vital to gain a greater understanding of the industrial falling-film evaporator process. This is possible through process modelling.

The aim of this work was to improve the process of whey products evaporation at Fonterra Ingredients-Whareroa, Fonterra Co-operative Ltd. This was done by an investigation of the evaporation process and optimisation of the operating conditions. Mathematical models were derived for this purpose, including dynamic and steady state models for the evaporator system and models for the physical properties of whey products. Complete evaporator simulations were established for process understanding, optimisation, and control. The steady state model was used for optimisation studies and the dynamic model was used for controllability studies.

Experiments were carried out on the physical properties of whey product. Regression models were developed in relation to the total solids concentration and to the temperature. Physical properties were also estimated from literature semi-empirical models (model constants were identified using the experimental data) and compared with the experimental values. The application of regression models is limited to one product within a predefined operating range with less than 5% error. The semi-empirical models are applicable to a variety of products and in a wider range of operating conditions with less than 10% error. The liquid height above the distribution plate in the evaporator is important to filter high frequency feed disturbances. The discharge coefficient has strong influence on the liquid height prediction but there were no investigation in the literature that applicable to the evaporator. Experiments were conducted to measure the discharge coefficient and to investigate how orifice shape affects discharge coefficient. The distribution plate model derivation was improved and showed that the distribution plate thickness influences the discharge coefficient and discharge flow calculations.

Trials in a commercial evaporator showed that protein content has no influence on the evaporation process. Protein type, air content and viscosity have a significant influence on the evaporation process. A modified evaporator configuration proved that poor evaporator performance for whey protein isolate is caused by the heat treatment given prior to the evaporation. It was shown that 15% increase in the evaporator capacity can be achieved when operating at optimum operating conditions compared to standard industry practice. The energy savings resulting from the optimisation was about NZ$70,000/season.

The plant controllability studies focused on the disturbance rejection capabilities of current control loops, product density and effect temperature. Experience has shown that the use of a single feedback PI controller for product density control is not sufficient. The applicability of a cascade controller to this problem was tested and was shown that the disturbance rejection properties can be significantly improved.

Overview of work and contribution

A brief overview of the research work and the contributions made to the field of falling film evaporator modelling and control are outlined.

1) Modelling of a two-effect thermal vapour recompression falling film evaporator Fonterra Ingredients-Whareroa, Fonterra Co-operative Ltd.
   a. Dynamic modelling.
   b. Steady state model development and complete evaporator simulation.
   c. Linear dynamic model development and complete evaporator simulation.
   d. Identification of model constants.
   e. Model testing with whey products, water and milk products.

2) Product Property models **("Physical properties of whey product", Journal of Food Technology, February 2003, pp. 8 -15)**
   a. Experimental data on density, viscosity, contact angle and surface tension of whey products.
   b. Calibration data of Refractive Index against the actual total solids concentration of whey products.
   c. Regression equation for actual total solids concentration as a function of Refractive Index of whey products.
   d. Regression equation for density and viscosity as a function of temperature and total solids concentration.
   e. Semi-empirical models for density, viscosity, thermal conductivity and specific heat capacity.
   f. Model testing of whey products, milk products and water.
   g. Investigation and measurements of the discharge coefficient for different products.

3) Optimisation of falling-film evaporator (***Journal of Food Engineering, submitted)***)
   a. Determination of the optimum operating conditions for each whey product.
   b. Heat transfer coefficient data for whey products.
   c. Improved preheat condenser performance by re-routing the non-condensable gas line to the vacuum pumps.
   d. Demonstration of the need for correct control valve sizing and control of steam pressure in the falling film evaporator.
   e. Demonstration that the total whey protein content has no influence on the heat transfer coefficient but that the protein type and the product viscosity do.
   f. Demonstration from trials that the heat transfer coefficient of high whey protein content products can be improved with low heat treatment prior to the evaporator.

g. Demonstration of the need for increased feed flows with water pre and post product runs to avoid fouling due to film breakdown.

h. Demonstration of the need for viscosity measurements in the whey evaporator to determine the optimum solids concentration.

4) Cascade controller design for concentration control in a falling-film evaporator (**Journal of Food Control, in press**)
   a. A complete evaporator simulation with one pass model and three pass model.
   b. Demonstration that the feed solids and the 2nd effect temperature have significant influence on the product total solids concentration compared to the feed temperature.
   c. Demonstration that the 2nd effect temperature control is quick and can be tuned so that it can be assumed to be constant.
   d. Demonstration that the product total solids control is slow due to the large falling film residence time and pipe delays.
   e. Demonstration that the use of cascade control for controlling product total solids improved the disturbance rejection bandwidth, allowing the controller to be tuned to correct the disturbances quickly.

5) Recommended future work
   a. Study of the influence of the compositions, component interactions and shear rate on the viscosity of whey products. Development of a generic viscosity model for both milk and whey products.
   b. Measurement of thermal conductivity of whey products, development of a reliable method for measurement of air content in the product and development of a generic model that can calculate the film heat transfer coefficient from product composition.
   c. Study of the influence of whey protein types and their interactions at different temperatures on foaming and its relevance to the film heat transfer coefficient.