



Dynamic Modelling, Measurement and Control of Co-rotating Twin-Screw Extruders

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requirements for the degree of
Doctor of Philosophy

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Declaration

I hereby declare that the work presented in this thesis is solely my own work. To the best of my knowledge the work presented is original except where otherwise indicated by reference to other authors. No part of this work has been submitted for any other degree.

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25 August, 2002

Summary

Co-rotating twin-screw extruders are unique and versatile machines that are used widely in the plastics and food processing industries. Due to the large number of operating variables and design parameters available for manipulation and the complex interactions between them, it cannot be claimed that these extruders are currently being optimally utilised. The most significant improvement to the field of twin-screw extrusion would be through the provision of a generally applicable dynamic process model that is both computationally inexpensive and accurate. This would enable product design, process optimisation and process controller design to be performed cheaply and more thoroughly on a computer than can currently be achieved through experimental trials.

This thesis is divided into three parts: dynamic modelling, measurement and control. The first part outlines the development of a dynamic model of the extrusion process which satisfies the above mentioned criteria. The dynamic model predicts quasi-3D spatial profiles of the degree of fill, pressure, temperature, specific mechanical energy input and concentrations of inert and reacting species in the extruder. The individual material transport models which constitute the dynamic model are examined closely for their accuracy and computational efficiency by comparing candidate models amongst themselves and against full 3D finite volume flow models. Several new modelling approaches are proposed in the course of this investigation. The dynamic model achieves a high degree of simplicity and flexibility by assuming a slight compressibility in the process material, allowing the pressure to be calculated directly from the degree of over-fill in each model element using an equation of state. Comparison of the model predictions with dynamic temperature, pressure and residence time distribution data from an extrusion cooking process indicates a good predictive capability. The model can perform dynamic step-change calculations for typical screw configurations in approximately 30 seconds on a 600 MHz Pentium 3 personal computer.

The second part of this thesis relates to the measurement of product quality attributes of extruded materials. A digital image processing technique for measuring the bubble size distribution in extruded foams from cross sectional images is presented. It is recognised that this is an important product quality attribute, though difficult to measure accurately with existing techniques. The present technique is demonstrated on several different products. A simulation study of the formation mechanism of polymer foams is also performed. The

measurement of product quality attributes such as bulk density and hardness in a manner suitable for automatic control is also addressed. This is achieved through the development of an acoustic sensor for inferring product attributes using the sounds emanating from the product as it leaves the extruder. This method is found to have good prediction ability on unseen data.

The third and final part of this thesis relates to the automatic control of product quality attributes using multivariable model predictive controllers based on both direct and indirect control strategies. In the given case study, indirect control strategies, which seek to regulate the product quality attributes through the control of secondary process indicators such as temperature and pressure, are found to cause greater deviations in product quality than taking no corrective control action at all. Conversely, direct control strategies are shown to give tight control over the product quality attributes, provided that appropriate product quality sensors or inferential estimation techniques are available.

Original Work and Publications

The conditions of candidature for the degree of Doctor of Philosophy at The University of Sydney require the candidate to state the sources from which they have derived their information, the extent to which they have availed themselves of the work of others, and the portions of the work they claim as original. The following papers are associated with the work presented in this thesis, while the table below summarises the work in this thesis that is claimed to be original.

J. Elsey, J. Riepenhausen, B. McKay, G.W. Barton, and M. Willis. Modelling and control of a food extrusion process. *Computers in Chemical Engineering Supplementary Series*, 21:S361–S366, 1997

J. Elsey, G.W. Barton, S. Jungk, G. Francis, J. Sellahewa, and C. Chessari. Acoustics based on-line quality estimation. *Computers in Chemical Engineering Supplementary Series*, 22: S925–S928, 1998

J. Elsey, B. McKay, M. Willis, and G.W. Barton. Extruder modelling using genetic programming. *MODSIM 95, Newcastle, Australia, 27-30 November*, 1:276–283, 1995

B. McKay, J. Elsey, M.J. Willis, and G.W. Barton. Evolving input-output models of chemical process systems using genetic programming. *13th World Congress, International Federation of Automatic Control (IFAC'96), San Francisco, 30 June - 5 July*, M:277–282, 1996

J. Elsey, J. Riepenhausen, B. McKay, G.W. Barton, and M. Willis. Dynamic modelling of a cooking extruder. *CHEMECA'96 Sydney, Australia, 30 September - 2 October*, 2:43–48, 1996

G.W. Barton, J. Elsey, B. McKay, and M. Willis. Modelling extrusion cooking: A comparison of neural networks and genetic programming. *7th International Congress on Engineering and Food, Part 2, Brighton, England, 13-17 April*, pages N9–N12, 1997

G.W. Barton, J. Elsey, B. McKay, and C. Sanderson. AI based hybrid modelling. *Australasia-Pacific Forum on Intelligent Processing and Manufacturing of Materials, Gold Coast, 14-17 July*, 1:356–362, 1997

G.W. Barton, J. Elsey, S. Jungk, G. Francis, J. Sellahewa, and C. Chessari. Acoustics based on-line quality estimation. *Australian MATLAB Conference, Sydney, 23-24 October, 1997*

G.W. Barton, J. Elsey, C. Chessari, G. Francis, and J. Sellahewa. The application of genetic programming in extruder modelling and control. *Automatic Control of Food and Biological Processes, Goteborg, Sweden, 21-23 September*, 2:557–562, 1998

J. Elsey and G.W. Barton. Measurement of bubble size distributions in extruded food products. *CHEMECA'99, Newcastle, Australia, 26-29 September, Proceedings on CD-ROM*, 1999. Paper 122

D. Pomerleau, J. Elsey, and G.W. Barton. Model-predictive control of an extrusion cooking process. *APCChE/CHEMECA 2002, 29 September – 3 October 2002, Christchurch, New Zealand*, 2002. In press

Table 1: Original work performed in this thesis.

<i>Chapter</i>	<i>Description</i>	<i>Other similar published work</i>
2	Expression for the surface area of trapezoidal flight screws.	Booy (1980) derived an expression for the surface area of self-wiping screws.
2	Analysis of the leakage gap geometries in co-rotating screw pairs.	Janssen (1978) analysed leakage gap geometries in counter-rotating screw pairs.
3	Analysis of flow in co-rotating screw pairs using a flow structure based on a repeating sequence of six elements to represent the geometry.	None to author's knowledge.
3	Simplified 1D mesh approach for calculating forward and reverse flow rates of a non-Newtonian fluid in a 2D conduit.	None to author's knowledge.
3	Calculation of 3D non-Newtonian isothermal flow in co-rotating screw pairs using correct boundary conditions.	None to author's knowledge.
4	Direct comparison of 1D, 2D and 3D models for calculating flow in kneading discs.	None to author's knowledge.
4	Prediction of reversing net flow direction in kneading discs at high stagger angles.	None to author's knowledge.
6	Dynamic simulation of the co-rotating twin-screw extrusion process using fixed model elements and an equation of state to calculate the pressure directly from the degree of over-fill in each model element.	None to author's knowledge.
6	Inclusion of starch gelatinisation kinetics and product bubble growth dynamics in a dynamic model of the extrusion cooking process.	None to author's knowledge.
6	Dynamic simulation of non-isothermal start-up of a co-rotating twin-screw extruder.	Kim and White (2000) modelled isothermal start-up.
6	The modelling of uneven fill across the screws in the partially filled zone of a co-rotating twin-screw extruder.	None to author's knowledge.
6	Calculation of residence time distributions using a first principles dynamic process model.	None to author's knowledge.
7	Analysis of the pore size distribution in extruded products using a digital image processing algorithm.	Campbell et al. (1991) used a manual measurement technique for measuring bubbles in bread doughs
8	Simulation of bubble nucleation, growth and coalescence during puffing.	None to author's knowledge.
9	Estimation of bulk density and hardness of extruded products using an acoustic sensor.	None to author's knowledge.
10	Simulation of model predictive controller performance to compare the effect on product quality attributes when both indirect and direct control strategies are used.	None to author's knowledge.

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