

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.

A thesis presented in partial
fulfilment of the requirements

for the degree
of Masters of Technology

at

Massey University

Mark Richard Dorsey

2000

Characterisation & Process Control of Pumping
Systems in the Dairy Industry

Abstract

The interaction between control of pumping systems in the dairy industry and the performance of the process has been investigated. Pumping in a precooling system at Massey University No. 1 Dairy Unit was chosen as a case study.

The requirements of the precooling system were determined from previous work done by dairy technologists. Part of these requirements were that:

- i) microbial damage to milk must be minimised by good temperature control, specifically by cooling the milk down to 18°C immediately after milking as specified in the New Zealand Dairy Industry Farm Dairy Code of Practice (COP).
- ii) handling should be gentle to minimise damage to the milk fat globule membrane by avoidance of cavitation and foaming.

However controlled pumping, which minimises damage to the fat globule membrane, has been reported to decrease the cooling capacity of the plate heat exchanger (PHE). The precooling system at No. 1 Dairy Unit was modified to allow continuous monitoring of key process variables (temperatures, flows and pressures). These were logged continuously and automatically to allow analyses to be carried out for whole milking sessions.

The analysis shows that the releaser pump in the precooling system at No. 1 Dairy Unit was oversized. This resulted in the pump only operating for 10 to 50% of the time and consequent inefficient usage of cooling water.

In general the average temperature of the milk entering the vat complied with the COP requirement. However, as a consequence of the pump control system, the instantaneous temperature at times exceeded the COP recommended temperature.

The analysis showed that cooling of the milk held up in the PHE during the pump-off phase contributed significantly to the cooling performance of the system. The present set up of the releaser pump pumping regime is based on a fixed pump-on phase of 6

seconds. The pump starts when the milk level reached a predetermined level in the milk receiver tank, which holds the milk coming from the cows. The duration of the pump on phase was set so that there would always be a milk fluid head in the receiver tank; which was decided by the relative size of the pump and receiver tank. The present pumping regime did not make best use of the ability of the system to cool the milk held up in the PHE during the pump-off phase. By simply changing the pump-on phase to 3s, more milk could be held up during the pump off phase in the PHE, giving a 10% increase in efficiency in the use of the cooling capacity of the water. This was achieved without changing the size of the PHE or any additional capital investment.

Synchronising the water with milk flow rate resulted in further gains in efficiency of cooling water usage but this resulted in an increase in the temperature of milk exiting the PHE. This conflict of goals made evident that an improvement in efficiency could only be attained by using cooler water, which could be achieved by additional equipment such as a cooling tower. However it is recommended that any modification to the process must be accompanied by a reanalysis of the performance of the system in conjunction with an appropriate control system to optimise the performance of the system.

Acknowledgments

I wish to express my deep appreciation and gratitude to my supervisor, Dr Tuoc Trinh for his supervision, guidance, encouragement and for fostering my engineering discipline and knowledge, and to my second supervisor, Dr Huub Bakker for his suggestions and advice throughout this study.

I would like to extend my appreciation to Professor Andrew Cleland for the initial guidance and role that he played in setting up my postgraduate studies.

I would like to thank the following people for their technical support: Mr Mark Downey (PhD student), Mr Steve Glasgow, Ms June Latham, Mr Don McClean (Institute of Technology & Engineering), Mr Byron McKillop, Mr Garry Radford and Mrs Geedha Reid. Thanks also to the team at Agricultural Services: Mr. Alistair. MacDonald, Mr Mike Lundman, Mat, Brad and John.

I would also like to extend my thanks to Mr Barry Hatch (Schmidt Thermal Processing Ltd), Mr David Salmon (West Falia), The New Zealand Dairy Research Institute and Kiwi for supplying milk powder, and to my employer, Massey University, for fees concessions.

Also thanks to my parents without whom I wouldn't be here, and for the great parenting job they have done.

To my dear wife for her patience, perseverance, understanding, encouragement, tolerance and love.

Last, but most of all, to God, to whom I dedicate all of my life.

Table of Contents

	pg
Abstract	i
Acknowledgements	iii
List of Figures	vii
List of Tables.....	xi
Nomenclature.....	xiii
1. Introduction	1-1
2. Background and Literature Survey	2-1
2.1 Pumps.....	2-1
2.2 Milk.....	2-4
2.2.1 Milk handling.....	2-4
2.2.1.1 Milking shed configurations.....	2-6
2.2.1.2 Milk handling chain.....	2-7
2.2.1.3 Releaser pump control	2-13
2.2.2 Milk composition	2-14
2.2.3 Milk quality.....	2-14
2.3 Massey University No. 1 Dairy Unit	2-16
3. Materials and Methods.....	3-1
3.1 Initial Characterisation of Massey University No.1 Dairy Unit Precooling System	3-1
3.2 Modifications to Precooling System Control Regime	3-8
3.3 Data Analysis.....	3-9
4. Results	4-1
4.1 Characterisation of Precooling System.....	4-1
4.1.1 Pumping profile of precooling system	4-1
4.1.1.1 Cavitation	4-1
4.1.1.2 Pump control regime.....	4-2
4.1.1.3 Pump duty cycle	4-4
4.1.1.4 Milk flow rate.....	4-5
4.1.2 Milk temperature profile of PHE.....	4-6

4.1.3	Cooling water profile of PHE	4-7
4.1.4	Heat transfer profile of PHE	4-10
4.1.4.1	Heat transfer rate	4-11
4.1.4.2	Ideal heat transfer rate.....	4-12
4.1.4.3	Efficiency of use of water cooling capacity in precooling system	4-14
4.2	Control of Pumping Regime.....	4-15
4.2.1	Pumping profile of precooling system with pump-on duration set to 3s.....	4-16
4.2.2	Temperature profile of PHE with pump-on duration set to 3s.....	4-17
4.2.3	Efficiency of use of cooling water capacity in precooling system with a pump-on duration set to 3s.	4-19
4.3	Control of Cooling Water Regime.....	4-20
4.3.1	Cooling water flow rate when synchronized with releaser pump operation	4-20
4.3.2	Temperature profile of PHE when cooling water flow rate was synchronized with releaser pump operation.....	4-21
4.3.3	Heat transfer rate across PHE when cooling water flow rate was synchronized with releaser pump operation.....	4-23
4.3.4	Efficiency of use of cooling water capacity in precooling system when cooling water flow rate was synchronized with releaser pump operation	4-24
5.	Discussion	5-1
5.1	Characterisation of Precooling System	5-1
5.2	Control of Pumping Regime.....	5-7
5.3	Control of Cooling Water Regime.....	5-10
5.4	Recapitulation of Process Analysis.....	5-12
5.5	Proposals for Further Improvements.....	5-14
6.	Conclusions	6-1
7.	References	7-1
	Appendices	A-1
Appendix 1	Pump Characteristic Curves at Different Total Solids Contents ...	A-1
Appendix 1.1	Paper: Characteristic pump curves at different evaporator effects in a milk powder plant.....	A-1

Appendix 1.2	Preliminary data for characteristic curves of whole milk at different total solids contents	A-5
Appendix 2	Method for Determining Damage to MFGM	A-6
Appendix 2.1	Lipolysable free fat test	A-6
Appendix 2.2	Free fatty acid content	A-7
Appendix 3	Schematics of Pipes Used for Mounting Sensors	A-9
Appendix 3.1	Schematic of pipes used for mounting pressure sensors at inlet and outlet of releaser pump.....	A-9
Appendix 3.2	Schematic of pipes used for mounting temperature sensors and flow meters on inlet and outlet of PHE	A-10
Appendix 4	Flow Rate Data For Sizing Orifice Plate.....	A-11
Appendix 5	CR10 Data Logger Programs	A-12
Appendix 5.1	CR10 Program using multiplexer.....	A-12
Appendix 5.2	CR10 Program used for collecting data for efficiency calculations	A-16
Appendix 6	Data Sheets for Relay and Omron Timer	A-19
Appendix 7	Raw Data From CR10	A-21
Appendix 8	Conversion Equations	A-22
Appendix 9	Sample Calculations.....	A-27
Appendix 10	Results	A-33
Appendix 10.1	Time from start of milking	A-33
Appendix 10.2	Pressure at pump inlet and outlet	A-34
Appendix 10.3	Pump operation and duty cycle.....	A-35
Appendix 10.4	Milk flow rate	A-36
Appendix 10.5	PHE temperatures.....	A-37
Appendix 10.6	PHE log mean temperatures and milk heat transfer rate	A-37
Appendix 10.7	Cooling water flow rate through PHE.....	A-38
Appendix 10.8	Actual and ideal cooling water heat transfer rate and efficiency of cooling water heat transfer rate.....	A-39
Appendix 11	Chemical Analysis	A-40
Appendix 12	CD Directory Structure	A-41
Appendix 13	Enclosed CD	

List of Figures

Figure 2.1 Diagram showing ideal and typical pump head curve (A), the impeller in the pump head (B), and schematic of a centrifugal pump (C).....	2-2
Figure 2.2 Photograph of Massey University No. 1 Dairy Unit race and milking shed	2-5
Figure 2.3 Schematic showing principal components of milk transport in a conventional milking machine.....	2-5
Figure 2.4 Photograph of milking area at Massey University No. 1 Dairy Unit	2-7
Figure 2.5 Photograph of milking receiving area at Massey University No. 1 Dairy Unit.....	2-10
Figure 2.6 Photograph of precooling area at Massey University No. 1 Dairy Unit. ...	2-11
Figure 2.7 Photograph of bulk milk storage area at Massey University No. 1 Dairy Unit.....	2-12
Figure 3.1 Photograph of milk receiver and surrounding equipment at Massey University No. 1 Dairy Unit	3-2
Figure 3.2 Photograph of inside of milk receiver at Massey University No. 1 Dairy Unit	3-3
Figure 3.3 Photograph demonstrating method of obtaining milk sample after releaser pump at Massey University No. 1 Dairy Unit	3-4
Figure 3.4 Photograph showing releaser pump inlet and outlet at Massey University No. 1 Dairy Unit	3-4
Figure 3.5 Photograph of PHE sensors (water flow rate and temperature) at Massey University No. 1 Dairy Unit.	3-6
Figure 3.6 Photograph of solenoid used for controlling water flow rate through PHE at Massey University No. 1 Dairy Unit.....	3-7
Figure 4.1 Typical trace of pressure at the inlet and outlet of the releaser pump - run 3 recorded 1 September 1999, time period 73-75 minutes after start of milking session	4-2
Figure 4.2a Typical trace of releaser pump operation - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session	4-3
Figure 4.2b Typical trace of releaser pump operation - run 8 recorded 19 November 1999, time period 10-12 minutes after start of milking session	4-3

Figure 4.3a Typical trace of releaser pump duty cycle - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session	4-4
Figure 4.3b Typical trace of releaser pump duty cycle - run 8 recorded 19 November 1999, entire milking session including CIP.....	4-5
Figure 4.4 Typical trace of milk flow rate - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.....	4-5
Figure 4.5a Typical trace of milk temperatures at the inlet and outlet of the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session	4-6
Figure 4.5b Typical trace of milk temperatures at the inlet and outlet of the PHE - run 8 recorded 19 November 1999, time period 10-12 minutes after start of milking session	4-7
Figure 4.6 Typical trace of water temperatures at the inlet and outlet of the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session	4-8
Figure 4.7a Typical trace of water flow rate through the PHE - run 8 recorded 19 November 1999, time period 10-12 minutes after start of milking session.	4-9
Figure 4.7b Typical trace of water flow rate through the PHE - run 8 recorded 19 November 1999, entire milking session.....	4-9
Figure 4.8a Typical trace of the log mean temperature difference across the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.	4-10
Figure 4.8b Typical trace of the log mean temperature difference across the PHE - run 8 recorded 19 November 1999, time period 10-12 minutes after start of milking session	4-11
Figure 4.9 Typical trace of the heat transfer rate of milk and water across the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.	4-12
Figure 4.10 Typical trace of the maximum temperature driving force across the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.	
Figure 4.11 Typical trace of the ideal and actual water heat transfer rates - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.	4-13

Figure 4.12a Typical trace of efficiency for water heat transfer rate across the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.	4-14
Figure 4.12b Typical trace of efficiency for water heat transfer rate across the PHE - run 8 recorded 19 November 1999, time period 10-12 minutes after start of milking session.	4-15
Figure 4.13 Typical trace of releaser pump operation with pump-on duration set to 3s - run 10 recorded 21 November 1999, time period 76-78 minutes after start of milking session	4-16
Figure 4.14 Typical trace of releaser pump duty cycle with pump-on duration set to 3s - run 10 recorded 21 November 1999, entire milking session including CIP...	4-17
Figure 4.15 Typical trace of milk temperatures at the inlet and outlet of the PHE with pump-on duration set to 3s - run 10 recorded 21 November 1999, time period 76-78 minutes after start of milking session.....	4-18
Figure 4.16 Typical trace of water temperatures at the inlet and outlet of the PHE with pump-on duration set to 3s - run 10 recorded 21 November 1999, time period 76-78 minutes after start of milking session.....	4-18
Figure 4.17 Typical trace of efficiency for water heat transfer rate across the PHE with pump-on duration set to 3s - run 10 recorded 21 November 1999, time period 76-78 minutes after start of milking session.....	4-19
Figure 4.18 Typical trace of cooling water flow rate through the PHE with solenoid- off delay set to 0s - run 25 recorded 2 March 2000, time period 11-13 minutes after start of milking session.....	4-21
Figure 4.19 Typical trace of water temperatures at the inlet and outlet of the PHE with solenoid-off delay set to 0s - run 25 recorded 2 March 2000, time period 8- 10 minutes after start of milking session.....	4-22
Figure 4.20 Typical trace of milk temperatures at the inlet and outlet of the PHE with solenoid-off delay set to 0s - recorded 14 March 2000, time period 8-10 minutes after start of milking session	4-23
Figure 4.21 Typical trace of ideal and actual water heat transfer rates with solenoid- off delay set to 0s - run 25 recorded 2 March 2000, time period 11-13 minutes after start of milking session.....	4-24
Figure 4.22 Typical trace of efficiency for water heat transfer rate across the PHE with solenoid-off delay set to 0s - run 25 recorded 2 March 2000, time period 11-13 minutes after start of milking session	4-25
Figure 5.1 Typical trace of ideal and actual water heat transfer rates across the PHE - recorded 19 November 1999, time period 76-78 minutes after start of milking session	5-14

Figure A.1 Pump head curve for Fristam FP712 pump with milk of differing total solids contents (run 5)	A-5
Figure A.2 Schematic for fittings used to install sensors for measuring pressure at inlet and outlet of Massey University No. 1 Dairy Unit releaser pump.....	A-9
Figure A.3 Schematic for pipes used to install measuring devices in Massey University No. 1 Dairy unit precooling system.....	A-10
Figure A.4 Graph showing flow rate versus pressure for equipment at Massey University No. 1 Dairy Unit (Wall, 1998)	A-11
Figure A.5 DPDT relay, 230V, 10 amp relay. (Dick Smith, 2000)	A-19
Figure A.6 Omron timer	A-20
Figure A.7 Orifice plate calibration graph. Graph of cooling water flow rate versus the square root of the pressure drop across the orifice plate - recorded 24 November 1999	A-38
Figure A.8 Photo of accumulated milk fat after all fat should have been removed - taken 17 September 1999	A-40

List of Tables

Table 4.1 Daily cooling water usage efficiencies for existing system	4-15
Table 4.2 Comparison of cooling water usage efficiencies for 6s and 3s pump-on regimes	4-20
Table 4.3 Cooling water usage efficiencies with varying water off-delay times	4-25
Table A.1 Data sheet for Omron timer (Omron Asia Pacific, 2000).....	A-20
Table A.2 Typical raw data – run 8 recorded 19 November 1999 (13-13.77 minutes from start of milking session, File Name: RawData_19Nov99_2.dat).....	A-21
Table A.3 Typical excerpt of spreadsheet with calculated hours, minutes, seconds, and ‘Time from start of milking’ - run 8 recorded 19 November, time period 13-13.15 minutes after start of milking session.....	A-33
Table A.4 Typical excerpt of spreadsheet with raw and calculated values of pressure at inlet and outlet of pump - run 3 recorded 1 September 1999, time period 73.1-73.3 minutes after start of milking session.....	A-34
Table A.5 Typical excerpt of spreadsheet with calculated pump on/off data and pump duty cycle - run 8 recorded 19 November, time period 13-13.45 minutes after start of milking session.....	A-35
Table A.6 Typical excerpt of spreadsheet with raw and calculated milk flow rate data - run 8 recorded 19 November, time period 13-13.45 minutes after start of milking session	A-36
Table A.7 Typical excerpt of spreadsheet with water out temperatures calibrated against water in temperatures - run 8 recorded 19 November, time period 13-13.15 minutes after start of milking session.....	A-37
Table A.8 Typical excerpt of spreadsheet with calculated values of log mean temperature difference for the heat exchanger, milk heat transfer rate, and milk in/out \times flow rate time (Used for calculating mass average temperatures) - run 8 recorded 19 November, time period 13-13.15 minutes after start of milking session	A-37
Table A.9 Typical excerpt of spreadsheet with pressure drop across orifice plate, and calculated values of cooling water flow rate - run 8 recorded 19 November, time period 13-13.15 minutes after start of milking session.....	A-38
Table A.10 Typical excerpt of spreadsheet with calculated values of actual water heat transfer rate, ideal water heat transfer rate, and the efficiency of cooling	

water usage - run 8 recorded 19 November, time period 13-13.15 minutes after start of milking session.....	A-39
---	------

Table A.11 Results of Lipolysable Free Fat Test showing milk damage before and after releaser pump.....	A-40
--	------

Nomenclature

Roman

c	Intercept of plot in Figure A.7 (m^3/hr)
c_1	Conversion constant in equation A.2 = 1 kPa/mV
c_2	Conversion constant in equation A.3 = 0.5 kPa/mV
c_3	Conversion constant in equation A.10 = 1 mA/mV
C_p	Specific heat capacity ($\text{J}/(\text{kgK})$)
g	Acceleration due to gravity (m/s^2)
H	Head (m)
i	Current row
M	Volumetric flow rate of milk (m^3/hr)
m_{grad}	Gradient from plot of water flow rate vs square root of pressure drop (Figure A.7) ($\text{m}^3/(\text{hr.kPa}^{0.5})$)
n	Number of readings
ΔP	Change in pressure (kPa)
P	Pressure (kPa)
R	Resistance (used to convert mA to mV voltage) (Ω)
V	Voltage (mV)
W	Volumetric flow rate of water (m^3/hr)

Greek

ϕ	Heat transfer rate (J/s)
η	Efficiency of cooling water usage
θ	Temperature ($^{\circ}\text{C}$)
ρ	Density (kg/m^3)

Subscripts

1	First end of the plate heat exchanger
2	Second end of the plate heat exchanger
in	At inlet
mi	Milk in
mo	Milk out
out	At outlet
wi	Water in
wo	Water out

Abbreviations

CIP	Cleaning in place
COP	New Zealand Dairy Industry Farm Dairy Code of Practice (1994)
FFA	Free fatty acids
MFGM	Milk fat globule membrane
NPSH	Net positive suction head
PHE	Plate heat exchanger
TS	Total solids

1 Introduction

The dairy industry is one of the major industries in New Zealand. In 1999 it had a turnover of 7.4 billion NZ dollars. In the year 1998/1999 the amount of milk processed was nearly 10.5 billion litres including the production of about 347 000 tonnes of whole milk powder (New Zealand Dairy Board, 2000).

The transport of milk at the farm and through the different processes at the factory, such as milk powder manufacture, is often achieved by centrifugal pumps, which are relatively easy to maintain. One requirement in milk processing is for the gentle handling of the milk as damage to the milk can have negative effects on process efficiency, for example fouling (Fang, 1998) and product quality.

Automatic control of dairy processes is based on fixed set point control, that is, the process is regulated at temperatures or flow rates that have been determined by results from previous production trials. A more efficient strategy would be to control the operations to maximise the desirable outcomes and to minimise undesirable outcomes. However, this strategy requires a greater understanding of the manufacturing process to identify desirable and undesirable outcomes and their causes. Thus process control involves not only the design of controllers but also a full analysis of the process being controlled.

In milk transport, one undesirable outcome that has been clearly identified in previous work is the damage done to the milk fat globule membrane (MFGM). One of its causes is pump cavitation (Fang, 1998), which therefore must be avoided. The desirable outcomes in milk handling must be identified by the analysis of each individual operation.

Previous work in the Food Technology Department (Steven, 1996) had indicated that the characteristic pump head curves of a Fristam FP712 pump varied with the rheological properties of the fluid. Without a detailed knowledge of these characteristic curves it would not be possible to design suitable process control systems for

evaporators where the total solids (TS) content, and hence the viscosity, varies from one effect to the other.

The performance of a pump with milk concentrates of different TS contents was investigated as a means of familiarisation with the operation of centrifugal pumps. This work was performed on reconstituted milk solutions to simulate pumping between the effects of an evaporator. It confirmed that the TS content affected the pumping head curves substantially. But there were significant difficulties with air entrainment during the experiment, which also had a substantial effect on the pump head curves. These findings were reported in a paper presented at a conference (Dorsey *et al.*, 1998) and can be found in Appendix 1.1. The paper deals with the effect of air inclusion in the pumping of reconstituted skim milk concentrates. Preliminary results were also obtained for whole milk concentrates and a summary of the pump head curve obtained is given in Appendix 1.2. However, much further work needs to be done before the pump head curves for water can be used to predict the performance of the pump when pumping milk concentrates; this was not the main interest of this thesis, which focuses on process control.

The purpose of a farm milk handling system is to milk the cow and to transport the milk to the bulk storage vat for tanker collection. The fresh milk is filtered, and must be cooled as fast as possible to minimise microbial growth and enzymatic damage.

Previously, uncontrolled pumping of milk had been used to transport milk from the milking area to the bulk storage vat. However, this resulted in the milk receiver being pumped empty resulting in cavitation and foaming, which are both known to cause damage to the MFGM. The introduction of pump control to avoid cavitation and foaming also resulted in a reduction of cooling performance of farm precooling systems (Thomson, 1998).

This work investigates the process control of centrifugal pumps in the precooling system at a farm. Since fresh milk is Newtonian, with a viscosity similar to water (Bloore, 1981), the pump characteristic head curve is well known.

An analysis of the pumping and cooling characteristic of a farm precooling system is reported. While the analysis method used is generic, the analysis is performed on a specific case study: Massey University No.1 Dairy Unit, which was used because of convenience of access.

Previous work at this farm shows that temperature requirements for the precooling system are not always met and that there is a prospect that cooling water previously available free of charge will be billed at approximately \$27 000 per annum (Roberts, 1998).

This study will focus on the precooling system requirements for milk microbial and enzymatic quality and on the efficiency of water usage while maintaining the no cavitation requirement.