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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.

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

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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
Cp	Specific heat capacity (J/(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) (m^3/(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 (°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.

2 Background and Literature Survey

2.1 Pumps

Definition

A pump is a device that transforms mechanical energy into pressure energy. The pressure energy generated can then be transformed into kinetic energy (mass flow rate) if there is a sufficient pressure gradient in the system. The flow in the system can therefore be related to pressure delivered by the pump to the fluid (Dorsey *et al.*, 1998).

Types of pumps

Pumps usually fall into either of two classes: (i) positive displacement pumps, or (ii) rotodynamic pumps. Positive displacement pumps generally have one or more chambers that are alternately filled with the liquid to be pumped, and then emptied again; their rate of discharge consequently depends on the speed of rotation and not on working pressure. Positive displacement pumps can be broken into two categories, reciprocating action (such as diaphragm and piston and plunger) or rotodynamic (such as gear, vane, screw, or peristaltic). Positive displacement pumps are suited to applications where small quantities of a clean liquid are to be forced against a high pressure.

Rotodynamic pumps have a wheel or rotor of some kind whose rotary blades or vanes accelerate the liquid in a direction at right angles to the direction of flow to impart kinetic energy to the liquid. The motion of the rotor is continuous, without any of the reversals of direction that characterise a piston and plunger pump. The geometries of the rotor are centrifugal, axial or mixed flow (a combination of both). The flow in a centrifugal rotor, or impeller, is radially outwards and exits the pump at a tangent to the direction of movement of the impeller. The flow through an axial rotor, or propeller, is helical in line with the axis of rotation of the propeller. Rotodynamic pumps are simple, cheaper, smaller and can move large volumes of liquid making them the most common type of pump (Addison, 1966; Pump Characteristics, 1976).

Pump characteristic curves

Most pumps do not deliver a constant pressure; the pressure can depend on the flow rate through the pump. In that case, the relationship between the increase in pressure across the pump and the flow rate is called the pump head curve. The characteristic curve of a pump (or the 'pump head curve') is a function of the design of the pump and may be used to characterise the pump. Pump head curves must therefore be measured for each pump design. Figure 2.1 shows an ideal pump head curve. However the pump head capacity is reduced by three effects: (i) head slip; (ii) at high pressures there are shock and eddy effects; (iii) friction at high flow rates. The pump head curve therefore typically takes on the form of a second order polynomial (Addison, 1966).

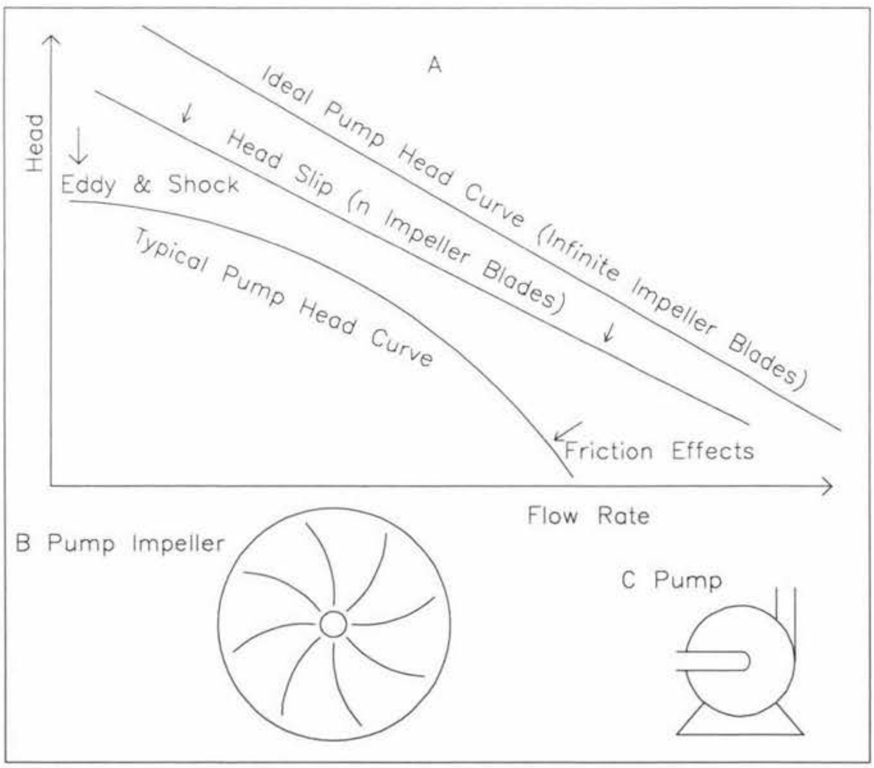

Figure 2.1 Diagram showing ideal and typical pump head curve (A), the impeller in the pump head (B), and the schematic of a centrifugal pump (C).

Rotational speed, size of the impeller and the physical properties of the fluid also affect the pump head curve. Viscosity is a measure of internal friction in a liquid and is known to have an influence on some pump head curves (Steven, 1996). It is therefore not practical for industry to generate pump head curves for individual pumps (Steven, 1996). Pump curves are produced for each type of pump, but the curves will differ with each fluid being pumped. Non-Newtonian fluids are potentially difficult to correlate, however a method has been discussed in literature that may present the data in a more useful fashion (Steven, 1996).

The effect of a pseudoplastic fluid on a pump characteristic curve is to flatten it. An equation for the head curve of the Fristam FP712 pump for milk concentrate can be calculated if milk is a power law fluid and its rheological parameters n and K are known (Steven, 1996).

Equation (2.1) can be used to calculate the pump head from measurements of pressure where the density of the fluid is known.

$$H = \frac{\Delta P}{\rho \cdot g} \tag{2.1}$$

Where:

H	= Head (m)
ρ	= Density of milk (kg/m^3)
g	= Acceleration due to gravity (m/s^2)
ΔP	= Pressure difference across pump (kPa)

For skim milk, the density is affected by temperature and total solids content (Physical Properties of Dairy Products, 1993).

Pump cavitation

The boiling point of water at sea level is 100°C, but at higher altitudes/lower pressures, the boiling point reduces. During pumping, liquid is sucked in the inlet and then pushed out of the outlet. The vacuum caused by the sucking at the inlet can be sufficient for the vapour bubbles to begin to form in the liquid – boiling. For example, if the liquid is water at body temperature, 37°C, the vacuum required for boiling will be –95kPa. However, after the pump inlet, the pressure increases as the fluid travels towards the exit, to the point that the bubbles rapidly collapse again. This process is called cavitation. As the bubbles collapse, tiny jets of fluid rush into the empty space created. The forces in the liquid resulting from the impact of these tiny jets can reach 1000 MPa – strong enough to cause stainless steel tips on centrifugal pumps to become pitted. It is therefore important to ensure that unwanted cavitation does not occur. This can be done by ensuring the pressure at the pump inlet, or net positive suction head (NPSH), is sufficient to avoid cavitation. This can be achieved by good design of the process layout (Pump Characteristics, 1976) or by process control.

Pump control

Control of pumps is generally limited to speed control. Stroke volume in a positive displacement pump, or blade pitch, as sometimes found in generators, could be adjusted during pumping operation, but these techniques are infeasible in most applications. Speed control options range between on/off, continuous (frequency) and multi-speed control – a combination of the previous.

The speed of the pump can be changed in response to a number of factors: human intervention; timers; external sensors such as pressure, temperature, flow, level and acoustic (sometimes used for cavitation detection); internal sensors such as centripetal devices (to boost performance during start up), temperature (over heating); and the pump controller itself may shut down in response to fault currents, unbalanced loads and modelled parameters such as thermal overload.

2.2 Milk

2.2.1 Milk handling

Milk handling is the transportation and treatment of the milk from the cow to the preheater at the milk powder plant while avoiding detrimental changes and preserving the original quality of the milk from the mammary gland. Milk handling therefore focuses on preserving milk quality (Trinh, 1997).

Milk handling begins with harvesting at farms such as Massey University No. 1 Dairy Unit shown in Figure 2.2.

Figure 2.2 Photograph of Massey University No. 1 Dairy Unit race and milking shed.

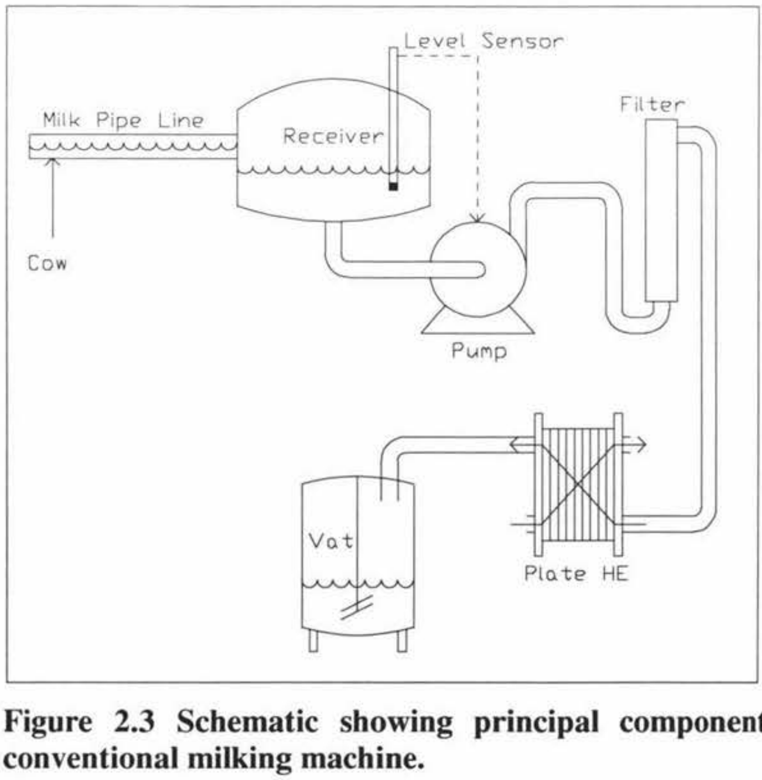

Figure 2.3 Schematic showing principal components of milk transport in a conventional milking machine.

Figure 2.3 shows milk handling processes and operations for Massey University No. 1 Dairy Unit milking system. Once the milk has been released from the cow's udder, the milk is drawn up in to the milkline under vacuum, where it flows under gravity to the receiver. From the receiver the milk is pumped through a filter and then a plate heat exchanger (PHE) to the bulk storage vat. A level sensor is incorporated into the receiver so that cavitation does not occur, and foaming doesn't result from air being admitted into the pump.

2.2.1.1 Milking shed configurations

There are two common milking shed configurations, the herringbone and the rotary. Figure 2.4 shows the herringbone layout. Herringbone sheds have a pit for the milker, and the cows are positioned either side of the pit at an angle of 30-35° facing outwards. The milker can attach the milking cluster to the cow's udder through the cow's hind legs. Once the cows are lined up either side of the pit, the milker goes from cow to cow applying each cluster. Once the cows have been stripped of their milk, the milker transfers the clusters to the cow on the opposing side. Once all cows on one side have had their cups removed, they leave and the next lot of cows are milked. The total milk flow rate from the cows varies considerably during milking due to the repeating pattern of, all cups on, all milking, all being stripped, and then transferring the cups.

Rotary milking machines are raised rotating platforms. The cow steps on to the platform, and as the cow travels past, the milker applies the cups, one cluster at a time, as the cows slowly travel past. When the cow has been stripped, a second milker removes the cups and the cow exits from the platform. The rotary system is continuous and any cows that are still being stripped do not hold up milked cows. As it is a continuous process of cows getting on, milked, and off, the milk flow rate is more stable than for the herringbone (Machine Milking, 1989).

Where operation of the pump is on/off depending on a level sensor, a common rule of thumb is that the milk pump should be running for at least 50% of the milking time in herringbone sheds, and 90% of the milking time in rotary sheds (van Hezik and Cleland, 1999).

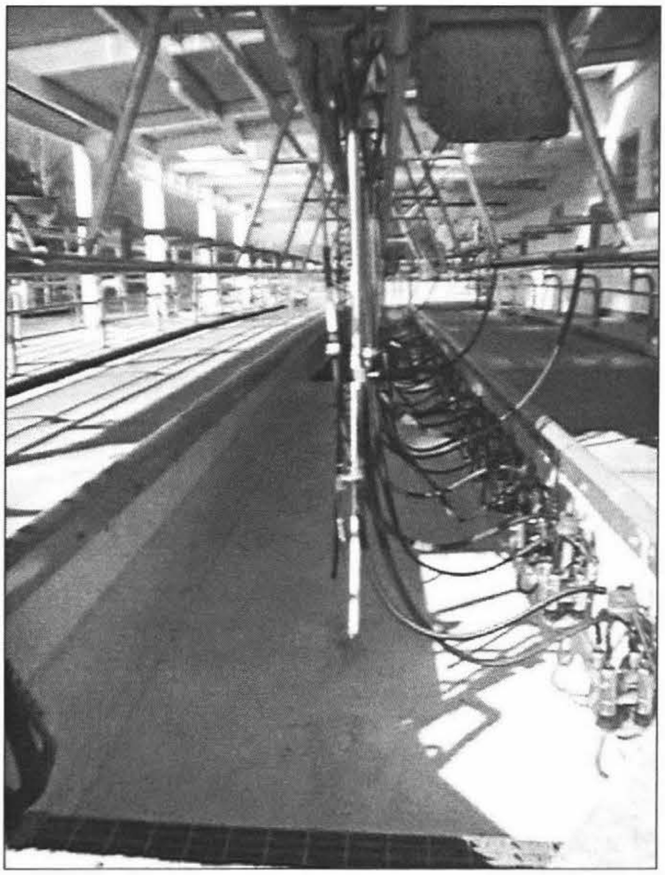

Figure 2.4 Photograph of milking area at Massey University No. 1 Dairy Unit.

2.2.1.2 Milk handling chain

Cow

A typical cow produces about 15.6 litres of milk per day, peaking at 20.2 litres per day during the flush of the season (van Hezik and Cleland, 1999). Cows let down their milk after a conditional reflex where a hormone (oxytocin) is released into the blood stream. In a well run shed, the cow will associate a let down with the milking routine. This requires a constant routine in which the cow is quietly and considerately treated. A break in routine or unusual stimulus will break the reflex and block let down. In the 6 minutes that a cow is milked, there are four phases of milk flow: (i) increasing flow rate 0-.75 minutes, (ii) peak flow rate, 0.75-2.75 minutes (iii) decreasing flow rate, 2.75-5.5

minutes and (iv) stripping, 6 minutes (Thiel and Dodd, 1977). The body temperature of the cow and thus the temperature of the milk is about 38.6°C (Bramley *et al.*, 1992).

Teat cup

The teat cup is comprised of a rigid shell, flexible liner, and two tubes (ISO 3918 Milking Machine Installations – Vocabulary, 1996). The milking process is affected by vacuum pulsation in the chamber formed between the shell and liner of the teat cup. This causes the teat to be alternately squeezed and released; this action promotes circulation in the teat and prevents discomfort.

The first tube is the short milk tube and it takes milk from the teat to the cluster. The other tube is the short pulse tube connected to the pulsation chamber and the claw. The short pulse tube alternates between vacuum and atmospheric pressure, and the short milk tube remains under constant vacuum. The vacuum in the short milk tube is used to pull the milk out of the teats and to keep the cups attached to the cow's udder.

Cluster

Figure 2.4 shows how clusters are attached to jetter assemblies after milking, ready for cleaning in place (CIP). A cluster is an assembly comprising of teat cups and a claw (ISO 3918 Milking Machine Installations - Vocabulary, 1996). The claw is connected to a number of teat cups, the milk from the teat cups drain into the claw. Air enters the claw via the air admission hole at the speed of sound; this provides the mechanism of transporting the milk up the long milk tube to the milkline. The entrained milk to air ratio is from 1:1 to 1:100 depending on the stage of milking.

The temperature of the milk in the long milk tube drops to about 38°C due to air cooling and losses to the environment (Bramley *et al.*, 1992). If too much air is admitted into the cluster, then the pressure loss may result in the cluster dropping off the udder. If too little air is admitted, then the friction and higher ratio of milk to air in the long milk tube will result in a greater hydrostatic head, again dropping the pressure in the cluster to the point that it could fall off the udder.

Milkline

Figure 2.5 shows a looped milkline above the milking pit. The milkline has a dual function of providing milking vacuum and conveying milk to the receiver (ISO 3918 Milking Machine Installations - Vocabulary, 1996). Ideally there should be stratified two phase flow of milk and air in the milkline. The milk flows to the receiver under gravity and the milkline can be used for separating the air from the milk. However, if the line is too small, the air passing over the water can create waves, combined with the effects of foam and a high milk level slug flow can easily result in a drop in vacuum along the milkline and at the clusters (Bramley *et al.*, 1992; Machine Milking, 1989).

Receiver

The receiver is a vessel that receives the milk from the milkline and feeds the releaser milk pump (ISO 3918 Milking Machine Installations - Vocabulary, 1996). The receiver in conjunction with the milkline is also used for removing air dispersed in the milk.

Figure 2.5 shows a looped milkline [2] entering the receiver [3] from both sides. The receiver feeds the releaser pump [4], which pumps the milk to the PHE via the delivery line [5].

A level sensor is positioned in the receiver and is used by the pump control system to ensure that the head pressure is adequate to prevent cavitation. The level is also maintained to ensure that air is not sucked in to the pump resulting in foaming of the milk.

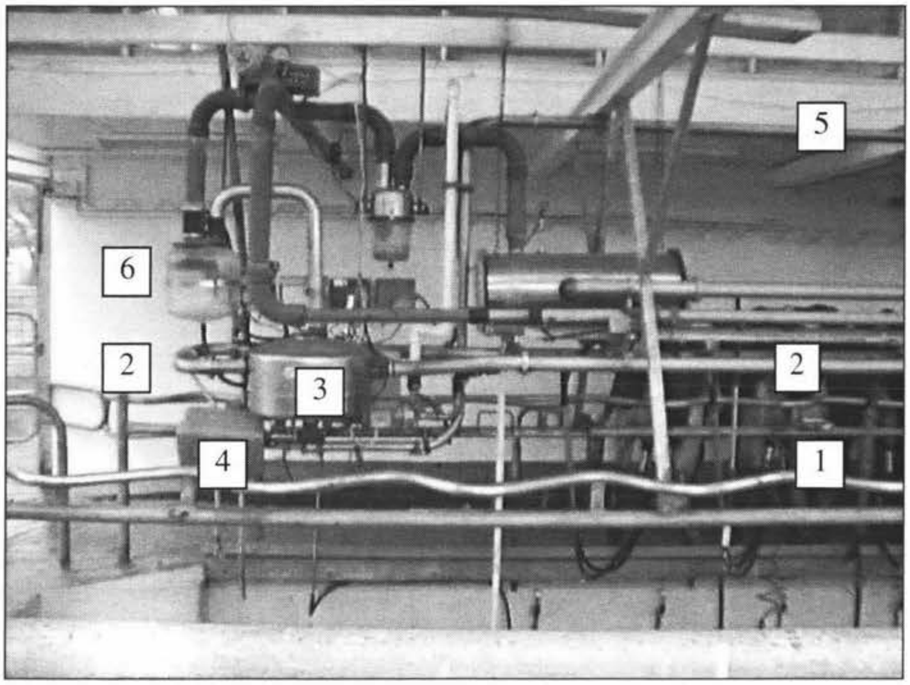

Figure 2.5 Photograph of milking receiving area at Massey University No. 1 Dairy Unit.

1 Cluster.
2 Milkline.
3 Receiver.
4 Releaser pump.
5 Delivery line – line in which milk flows from releaser to storage vessel (ISO 3918 Milking Machine Installations - Vocabulary, 1996).
6 Sanitary trap – vessel between milk system and vacuum system to limit movement of liquids and other contaminants between the two systems (ISO 3918 Milking Machine Installations - Vocabulary, 1996).

Releaser pump

The releaser milk pump removes the milk from vacuum and discharges it to atmospheric pressure (ISO 3918 Milking Machine Installations - Vocabulary, 1996). The milk is pumped through the filter and PHE to the bulk storage vat.

The releaser pump must be able to cope with peak milk flow rates in the flush of the season. (120-150 litres per cluster per hour) It must also be able to pump CIP fast enough to ensure that the machinery is cleaned appropriately (180 litres per cluster per hour) (van Hezik and Cleland, 1999). If the pump used is a centrifugal pump, then a non-return valve is used after the pump to prevent a backflow of air or milk into the pump when it is not filled with milk or cycles off by the float switch (Machine Milking, 1989).

Filter

The milk is pumped through a filter before the PHE to remove foreign material and contamination such as cigarette butts and mastitis clots. The New Zealand Dairy Industry Farm Dairy Code of Practice (1994) requires that all milk be filtered: "All milk shall be filtered before entering the farm bulk milk tank".

Figure 2.6 shows the delivery line [1] from the milking area entering a 'sock' type filter [2]. The milk is then pumped through the PHE [3] and to the bulk milk vat via the delivery line [5].

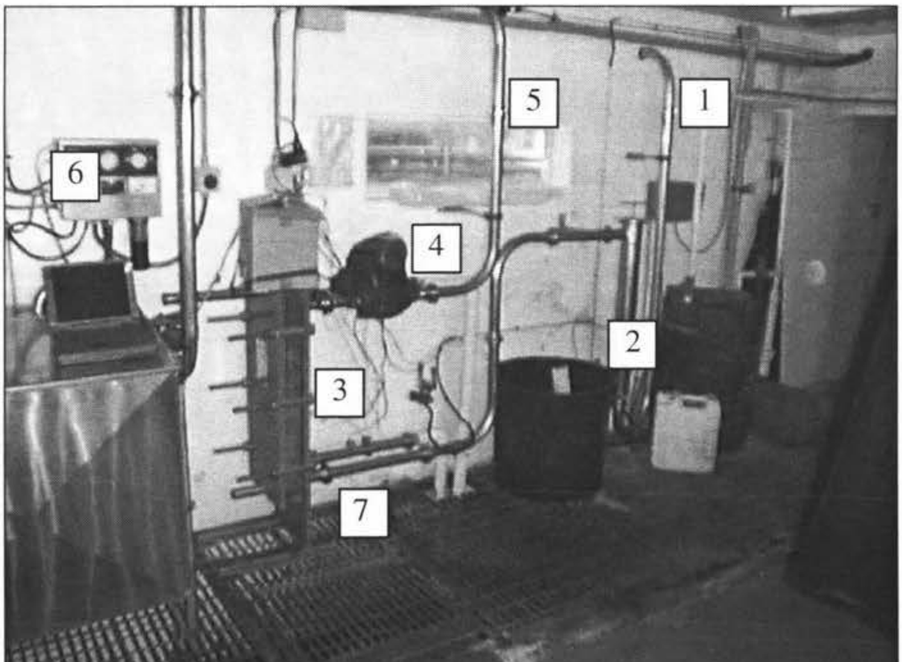

Figure 2.6 Photograph of precooling area at Massey University No. 1 Dairy Unit.

1 Delivery line from milking area.
2 Sock filter
3 PHE
4 Milk flow meter used for this research.
5 Milk pipe to storage vat
6 CIP control and detergent dispenser (Circomat)
7 PHE Milk Inlet

PHE

Figure 2.6 shows a PHE type precooler [3]. The New Zealand Dairy Industry Farm Dairy Code of Practice (1994) requires that all milk be precooled: "There shall be primary cooling after filtering" this is normally done using a PHE. It is also recommended that the precooler "should be capable of cooling the milk to 18°C or lower". The PHE must be able to handle the maximum flow rate that the pump can deliver; this is normally determined by the CIP flow rate required. If cooling water is in short supply, it is possible to fit a solenoid valve in the cooling water circuit so that the flow may be interrupted if the pump cycles 'off'. The water flow rate should be about 2.5 times the milk flow rate and enter the bulk milk tank at the lowest practical temperature (within 2°C of water temperature) (Machine Milking, 1989). Cooling water can be recycled as warm water for yard wash down (Bramley *et al.*, 1992).

Refrigerated farm bulk milk tank

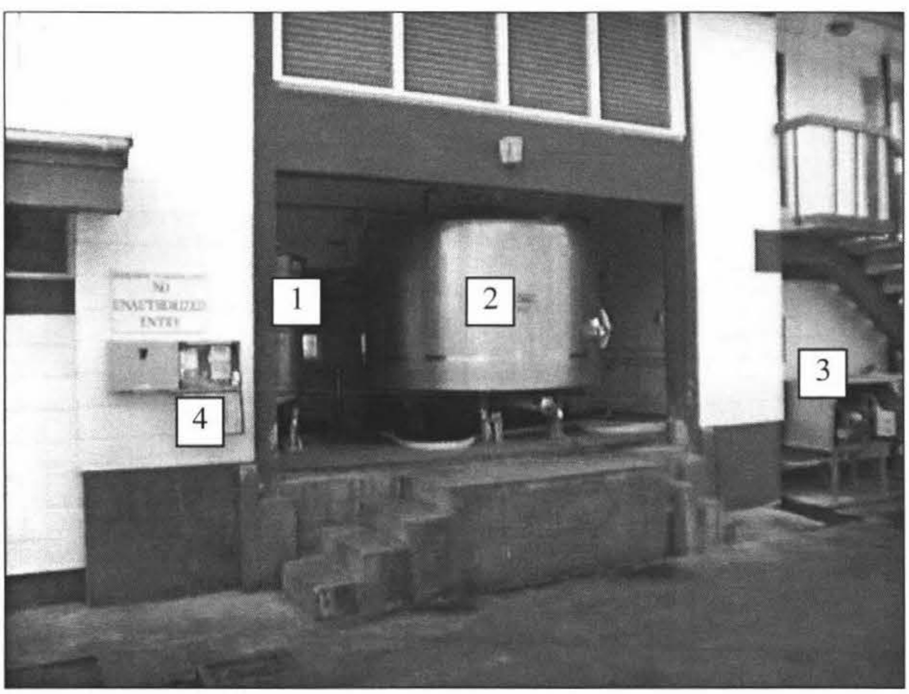

Figure 2.7 Photograph of bulk milk storage area at Massey University No. 1 Dairy Unit.

1	Milk vat 1
2	Milk vat 2
3	Refrigeration unit for vat 1
4	Data logger and CIP control unit for vat 2

Figure 2.7 shows milk storage and cooling facilities. In New Zealand, direct expansion of refrigerant at the base of the milk vat is the typical method of cooling in farm milk vats.

Milk is required to be cooled and maintained at 7°C or below within 3 hours of the completion of milking (New Zealand Dairy Industry Farm Dairy Code of Practice, 1994).

2.2.1.3 Releaser pump control

Control of releaser pumps falls into four main categories: no control, on/off, multi speed, or variable speed control (van Hezik and Cleland, 1999). Systems with no control generally use diaphragm pumps, and controlled systems are commonly on/off control of a centrifugal pump.

The control is directly related to level of milk in the receiver, although control partially based on the temperature of milk exiting the PHE would also be possible. There are three main types of liquid level probes: Electrical Probes, magnetic float switches and weight operated switches (Thiel and Dodd, 1977).

It is desirable for releaser pumps to operate continuously at a constant speed to maintain a low average milk flow rate. The benefits of a constant milk flow are efficient cooling as the water and milk flows can be more easily matched, cooling water is not wasted during periods of no milk flow, and the precooling system does not need to be oversized. The amount of time that a pump spends switched off can be reduced by fitting an impeller of reduced diameter to the releaser pump, or by installing an orifice plate on centrifugal releaser pumps. An orifice will results in some lipolysis, but not of economic significance. However the flow rate should still provide sufficient turbulence and wetting for CIP (Machine Milking, 1989).

2.2.2 Milk composition

Milk consists of approximately 12.7% solids, and 87.3% water. The solids are made up of lactose (4.8%), proteins (3.4%), fat (3.7%) and ash (0.7%). Milk also has several hundred minor constituents including vitamins, metal ions and flavour compounds. The concentrations and chemistry of the constituents varies from animal to animal, with breed, health, nutritional status, stage of lactation, age, and interval between milkings. These variations (except for seasonal variations) tend to be evened out when the milk reaches the factory and is added to large bulk milk silos for processing.

Most of the milk is a solution of lactose (sugar), salts, vitamins and other small molecules in water. In this aqueous solution are dispersed proteins (small whey proteins to large colloidal aggregates of casein) and lipids (fats) that exist in an emulsified state.

Milk is a dynamic system owing to the instability of many of its structures. It is designed to be consumed directly from the mammary gland, and expressed from the mammary gland at frequent intervals. However, in this age of consumerism, milk is processed, packaged, stored and sold before being consumed this makes the instability of the milk a problem for processors so milk handling and processing is important so that the quality of the milk can be maintained (Fox and McSweeny, 1998).

2.2.3 Milk quality

Milk quality is compromised by contamination, adulteration and damage, where the damage could be due to chemical, physical or microbiological effects. Not only is the product of poorer quality, but the lower quality milk can also result in greater problems during processing, notably fouling of the milk powder plant (Trinh, 1997).

Foreign products such as mud, hair, insects and cigarette buts could contaminate milk. Chemical contaminants could include pesticides, cleaning agents and antibiotics. Adulteration of the milk by dilution occurs when water is used to flush the remaining milk in the system into the vat after milking or if equipment has not been properly drained after CIP. Mastitis clots may also contaminate the milk.

Milk damage – chemical

Milk contains lipase enzymes that can attack fat in a process called lipolysis resulting in rancidity (Machine Milking, 1989). Most of the lipase (90%) is linked to casein micelles and are not able to attack the fat globules. A delicate membrane, the MFGM, helps to protect the fat globules.

Once the MFGM has been damaged, the exposed fat will be coated by serum proteins, but this new membrane is porous to enzymes and lipolysis of the fat exposed will occur, resulting in the formation of monodiglycerides and free fatty acids (FFA). Some of the FFA is absorbed at the fat interface, inhibiting further enzyme activity but can be dislodged again during further handling. Fang (1998) has devised methods of measuring MFGM damage by the use of a newly proposed lipolysable Free Fat Test.

Milk damage – physical

The forces experienced during cavitation easily damage the MFGM. Air inclusion also results in damage. When air comes into contact with the fat globules, the surface tension tends to pull on the MFGM resulting in damage. The surface area of milk exposed to air increases with foaming when the milk falls into the refrigerated farm vat, and air entrainment. Turbulence of milk and air in the milkline will tend to break up the air bubbles into smaller ones, resulting in a greater surface area for interaction. The bubbles can also result in surface denaturation of whey proteins. Turbulence alone results in forces strong enough to damage the MFGM (Fang, 1998). The MFGM is particularly susceptible to damage at temperatures of 25°C (Kessler and Fink, 1992).

Milking machines are designed to minimise the amount milk to air interaction. This is achieved by drawing the transport air out of the milk in the milkline and receiver. Using pipe diameters 51 mm or larger, minimising bends, falls and rises and using wide angle pipe bends also help to reduce damage to the milk (Machine Milking, 1989). Milking machines designed by Ruakura Research Centre use only 3% air to transport the milk to the receiver but they are not in widespread use because of their cost (Trinh, 1997).

Milk damage - microbiological

There are always microorganisms present in a cow's udder and so milk is never sterile; contamination from the plant also increases the number of microorganisms. Microbiological damage occurs when the microbes in the milk propagate rapidly at elevated temperatures. At temperatures over 10°C, mesophyllic lactic acid bacteria reproduces causing an increase in acidity which affects the milk behaviour during processing. Psychotrophs can also produce bacterial lipase enzymes that can attack the fat globules (Trinh, 1997).

New Zealand Dairy Code of Practice

The New Zealand Dairy Code of Practice (COP) sets out recommended procedures for milk handling. The COP recommends that the performance of the milking machine be tested at least once annually. It goes on to say that the performance of the milking machine can affect milk quality: "the breakdown of fat particles can occur as a result of excessive agitation and the mixing of air with milk when the speed of the milk pump is too fast or when to much air is admitted into the machine". This can result in a Farm Dairy Assessment Standards classification of 'non-compliance with specified compositional standards' which is deemed to be a major hazard that "should be attended to within a week". Further information given states "that a deterioration in milk composition may be caused by: excessive frothing; excessive pumping rates; excessive agitation".

2.3 Massey University No. 1 Dairy Unit

Massey University No. 1 Dairy Unit has two herds producing milk for town supply. One herd calves in Spring, and the other in Autumn.

The milking shed is a Westfalia single 24 aside herringbone with a high level looped milkline. That is, there are 24 sets of cups, and 24 cows can be lined up on each side of the pit, and the milkline is 1.25m above ground level. A looped milkline is one that forms an enclosed circuit with two full-bore connections to the receiver resulting in a reduction in pressure loss of 4 times that of a dead end line (Bramley *et al.*, 1992).

The milkline descends to a receiver, which incorporates a magnetic float switch used to sense the level in the tank. The sensor is made from a reed switch housed in a stainless steel guide tube and is fastened to the top of the receiver extending almost to the bottom. The switch is operated by a ring magnet concentric with the guide tube and contained in a float (Thiel and Dodd, 1977).

The releaser pump controller is a Teil model NR7038-5985-00. It has a single relay level sensor input that indicates that the high level limit for the milk has been reached. Once the relay is switched, the control closes a 230V relay output. The 230V relay output remains closed for a period varying between 3 and 30 seconds as set by the pump delay potentiometer on the pump controller. The original setting was 6 seconds. The 230V relay output is used to drive the control coil of a three pole contactor supplying power to the releaser pump.

The releaser pump is a 3∅, 1.1kW, Hanning centrifugal pump operating at 2810 rpm.

The volume of the delivery line and filter between the releaser pump and the PHE is about 35 litres. The holding capacity of the pipe work may have been less if air was trapped in the head space of the pipe shown in Figure 2.5 [5].

The PHE is a Schmidt Sigmaflex X19 industrial milk cooler. There are 31 plates (15 Y type, 15 H type, and 1 terminal) giving a total surface area of 5.5 m^2 with a design surface heat transfer coefficient of 7000 W/m^2K). The holding capacity is 5.4 litres of milk and 5.4 litres of water. Designed for a milk flow rate of 10 m^3/hr (Reynolds number = 8652) and water flow rate of 30 m^3/hr (Reynolds number = 2444) (Hatch, 2000). Heat exchangers are sized for a milk inlet temperature of 37°C as a drop of 3°C is expected by the time the milk is transported to the heat exchanger from the cow (Bramley *et al.*, 1992).

The bulk milk vat is cooled by direct expansion using a 2 kW air cooled refrigeration unit by Refrigeration Eng Co. Ltd. A direct expansion system is where the refrigerant evaporator is bonded to bottom of tank so that no ice is used as a heat transfer medium or store (Thiel and Dodd, 1977).

3 Materials and Methods

3.1 Initial Characterisation of Massey University No. 1 Dairy Unit Precooling System

An initial process analysis was carried out on the precooling system of Massey University No. 1 Dairy Unit. The aim of the analysis was to determine and quantify the process characteristics so that rational consideration could be given to how the system performed, and how the performance could be improved.

The goal of the precooling system is to maintain the quality of the milk by reducing the milk temperature to 18°C before it is pumped into the bulk storage vat. The milk experiences some physical damage during the precooling process due to the forces experienced in the pump, turbulence in the milk line, and surface tension due to air inclusion. Samples of milk before and after pumping were taken for chemical analysis to determine the magnitude of damage. The pressure at the inlet and outlet of the releaser pump were also measured to check for the occurrence of cavitation.

Precooling is achieved by pumping the milk through the PHE. To quantify this process, the milk and cooling water flowrates through the PHE, and the temperatures at the Inlet and Outlet of the PHE were recorded so that the performance of the PHE could be determined. The operation of the pump was also logged to investigate the effect of the variable milk flow rate in the milk line on the precooling system.

Figure 3.1 shows the receiver [2] with the milk line [1] descending to it. The milk accumulates in the receiver until the milk level is high enough to trigger the float sensor [7]. The pump controller [9] responds by operating the pump [4] for six seconds. The milk was pumped through the delivery line [4] to the sock filter and PHE. The milk in the clusters, milk line and receiver was kept under vacuum via the receiver air line [6]. The inspection port [5] allowed access to the receiver (Figure 3.2 [2]). A cooling water timer [9] was installed to allow the cooling water solenoid to be activated by the pump controller. Milk that was unsaleable due to infection or presence of colostrum is collected using a separate milking system.

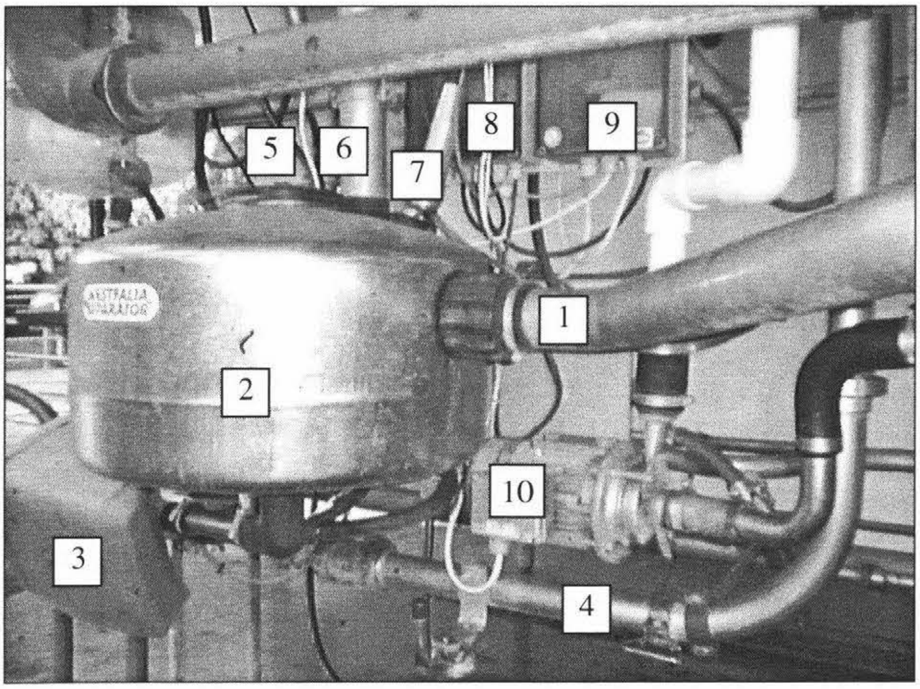

Figure 3.1 Photograph of milk receiver and surrounding equipment at Massey University No. 1 Dairy Unit.

1	Milk line
2	Receiver
3	Releaser milk pump
4	Delivery line
5	Receiver inspection port
6	Receiver air line
7	Receiver level sensor
8	Pump Controller
9	Cooling water timer
10	Releaser milk pump for milking system for rejected milk

Figure 3.2 shows the inside of the receiver after CIP. The pipe to the pump is shown towards the top and a baffle is positioned over the entrance. Note the float sensor down to the left.

Milk samples were taken before and after the pump so that chemical tests could be performed to quantify the damage done by the pump. The chemical test used to quantify the damage was the Lipolysable Free Fat Test as described in Appendix 2.1.

The before-pump milk sample was collected from the receiver. The receiver had to be kept under vacuum during milking. For the sample to be taken, the cups were put away and the vacuum turned off so that the lid on top of the receiver could be removed and the sample of milk taken.

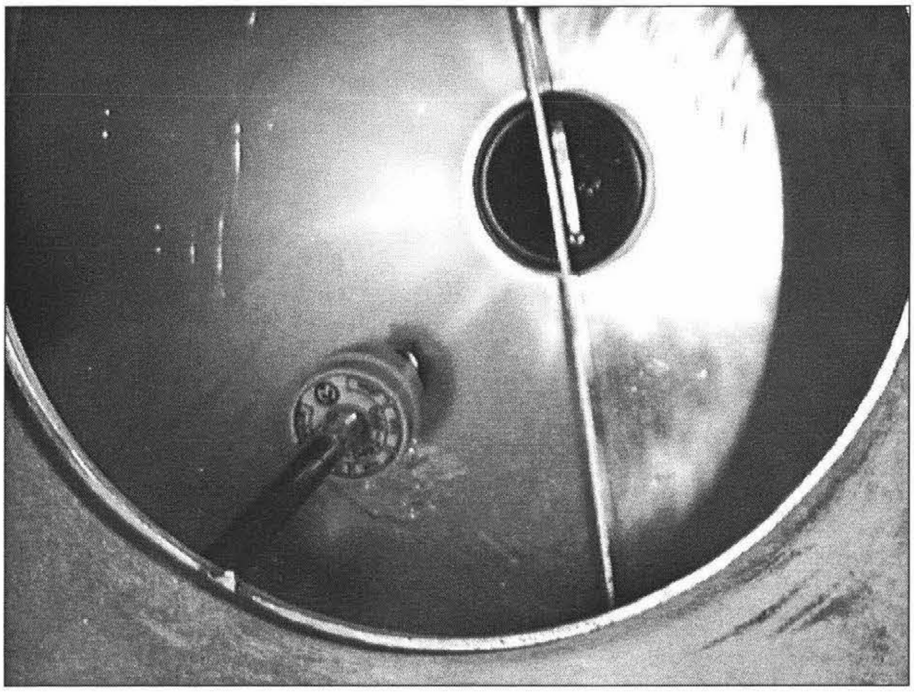

Figure 3.2 Photograph of inside of milk receiver at Massey University No. 1 Dairy Unit.

The after-pump milk sample was taken from a port in the pipe work just before the heat exchanger. The port was kept blanked off during milking, but the blanking plate was replaced with a pneumatic drain valve for CIP when milking was not taking place. The CIP drain valve is shown in the top left of Figure 3.3. Figure 3.3 illustrates how the milk sample after the pump was obtained.

Figure 3.4 shows the underside of the releaser milk pump. Two pressure sensors, (DPI201 & DPI260, Druck Ltd, England), were mounted near the inlet and outlet of the pump to measure the pressure drop across the pump. The original pipe between the receiver and the pump was replaced with a pipe [1] that had a pressure sensor fitting welded on. The outlet pressure sensor [4] was mounted on a fabricated pipe joiner on a vacuum tube that was connected to the pump outlet pipe [2]. The schematic plan for the pipes is located in Appendix 3.1.

Figure 3.3 Photograph demonstrating method for obtaining milk sample after releaser pump at Massey University No. 1 Dairy Unit.

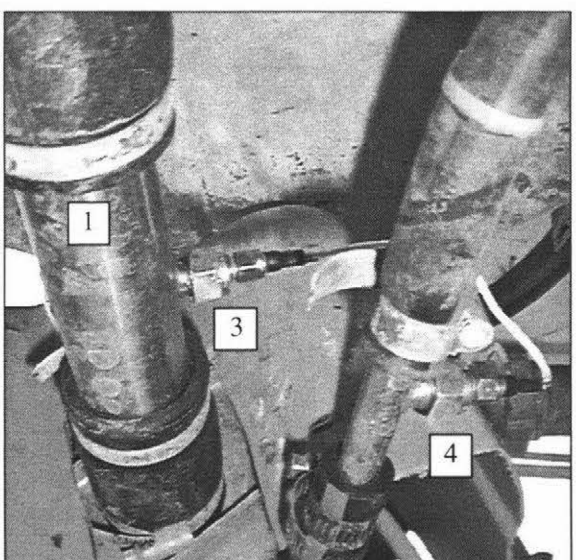

Figure 3.4 Photograph showing releaser pump inlet and outlet at Massey University No. 1 Dairy Unit.

1 Milk line entering pump
2 Delivery line leaving pump
3 Pressure sensor on pump inlet
4 Pressure sensor at pump outlet

The inlet pressure sensor was also used to measure the inlet pressure to detect pressures that would result in cavitation.

The voltage across Terminals 6 and 7 on the pump controller [8] in Figure 3.1 was used to determine when the pump was off or on (A voltage of approximately 5 V was present at the terminals during pump operation. This was unexpected as the markings on the controller indicated a 12 V relay, and the suppliers had said that the signal was not related to the level controlled operation of the pump).

Flow rates of the milk and water through the PHE, as well as the temperatures of the milk and water entering and exiting, were required to analyse the milk precooling process.

Extension pipes were made up so that the flow meters and temperatures sensors could be installed more easily, and without modifying the farm's existing pipe work. The PHE was shifted, and the four fabricated extension pipes were installed. The extension pipes were 50mm in diameter (1mm thick walls) and had swage type dairy fittings, which were supplied and swaged by Westfalia and Professional Maintenance Services. Argon welding at Massey University was used to modify the pipes so that the sensors could be fitted. The schematic plan for the pipes is located in Appendix 3.2.

The milk flow rate was measured using a 1" internal diameter magnetic flow meter (Promag 30F, Endress & Hauser, Switzerland). The water flow rate was measured using a 31mm internal diameter square edge orifice plate (Flow of Fluids, Through Valves, Fittings and Pipe, 1986). The orifice plate dimensions required were calculated using estimated flow rates from previous research as shown in Appendix 4 (Wall, 1998). The milk flow meter was briefly installed on the water inlet of the PHE to calibrate the water flow rate against the pressure drop across the orifice plate. Figure 2.4 shows the milk flow meter when installed [4], and Figure 3.5 shows the orifice plate. The pressure transducers used were 0-15 PSIG, 0-25 PSIA XPRO (Data Instruments, USA).

Temperature sensors were required to measure the temperatures at the inlet and outlet of the PHE. The sensors to be installed had to be sensitive enough to measure fast temperature changes. The bulk milk vat CIP control unit (Figure 2.7 [4]) was used by farm personnel and tanker drivers to measure the weight and temperature of the milk in the vat. It also displayed the temperature of the milk entering the vat. The temperature sensor was housed in a lug and was hose clipped to the outside of the delivery line several meters downstream of the PHE. Attaching the sensor with a hose clip to the outside of the pipe would make servicing easier, and avoided contamination by micro organisms, but this also resulted in a greater thermal lag, and the sensor was more prone to error due to changes in ambient temperature. The thermal lag in the sensor may be large enough for bursts of cold, or hot, milk to flow past the sensor without being detected.

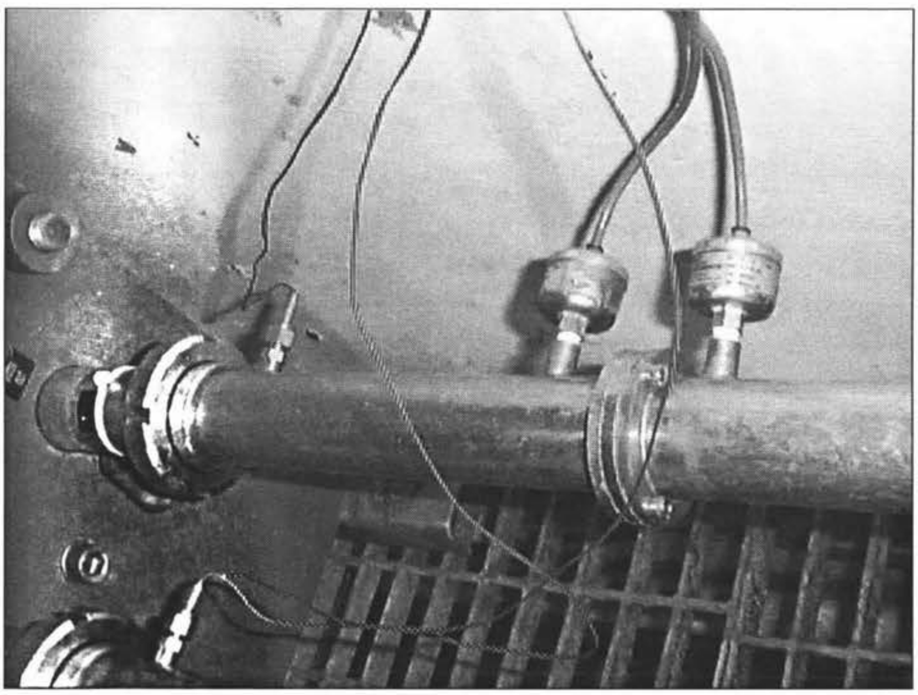

Figure 3.5 Photograph of PHE sensors (water flow rate and temperature) at Massey University No. 1 Dairy Unit.

It was not possible to mount the temperature sensors directly in the inlet and outlet of the PHE without affecting the seals. However, they were mounted as close as practical to the inlet and outlet pipes. The sensors used were T-type thermocouples with soldered junctions (Nicholas and White, 1982). The thermocouples were inserted through stainless steel tubes, 6 mm diameter and 70 mm long. The junction was coated, and the tubes were filled with Araldite epoxy adhesive to minimise electrical interference and to protect against corrosion of thermocouple metals by the milk and cleaning liquids. The thermocouple probes were fixed in the pipe work with swage fittings. Two probes can be seen in Figure 3.5.

The solenoid valve shown in Figure 3.6 controlled the cooling water flow rate through the PHE. The solenoid was located in the pit beneath the heat exchanger. During milking, the solenoid valve was on and fully open. When milking was finished, the valve closed. A Circomat controller (Figure 2.4 [6]) actuated the valve using a 230V/24V AC/AC transformer. The solenoid had an inrush current of 0.34 A, and a holding current of 0.2 A.

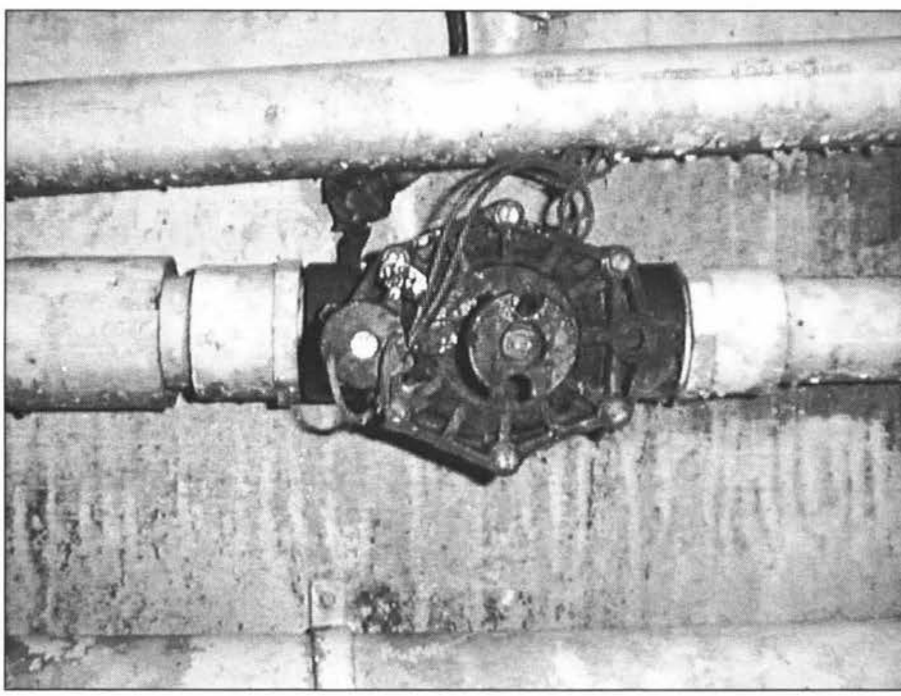

Figure 3.6 Photograph of solenoid used for controlling water flow rate through PHE at Massey University No. 1 Dairy Unit.

A Grant 1250 Squirrel data logger was used to collect data initially. The Squirrel sample rate (1 second for 1 channel, 3 seconds for 10) was not adequate for profiling the dynamic behaviour of the milking system. To collect the required data, a CR10 (Campbell Scientific Inc., USA) was then used, the data was logged at a 0.5 second interval. An AM416 multiplexer (Campbell Scientific Inc., USA) and a thermistor ice point were used originally for the overall process analysis. In the final recordings where the control schemes were modified, the CR10 (with no multiplexer), and crushed ice slush for the thermocouple cold junction compensation point (Nicholas and White, 1982), were used. To convert current (4-20 mA) signals to voltage for the CR10, 120 ohm resistors were used. The programs used for the CR10 are shown in Appendix 5. The amount of data recorded required that the information had to be downloaded from the ring memory of the CR10 before it was written over with new data.

3.2 Modifications to Precooling System Control Regime

The initial analysis of the plant revealed that the precooling system was not cooling the milk to the temperatures required and that the efficiency of cooling water usage was extremely low. Two low cost modifications for improving the efficiency of cooling water usage were trialed and analysed.

The first modification was to adjust the releaser pump-on duration. Initial analysis had shown that substantial milk cooling occurred during the pump-off period. Decreasing the pump-on duration would increase the number of times that milk was held up in the PHE, so more milk would experience cooling during hold up, and so improve the efficiency of cooling water usage.

The initial analysis revealed that the water was not achieving any cooling during long pump-off periods. The second modification trialed was to link the control of the releaser pump to the control of the water supply solenoid so that the cooling water flowed when the releaser pump was on, and turned of n seconds after the releaser pump switched off (where n is selectable by the user).

The performance of the two modifications was followed by comparing the efficiencies of cooling water usage. This meant that only the water flow rate, water inlet, water outlet and milk inlet temperatures needed to be logged.

The modification to the pump control regime was achieved by adjusting the delay potentiometer for the pump duration on the pump controller [8] shown in Figure 3.1.

The modification to the cooling water control system was achieved by installing an on/on switch on the Circomat [6] shown in Figure 2.5 in section 2.2.2.2. The switch allowed the solenoid to be operated in normal mode, or in pump activated mode. The timer and relay required to drive the solenoid were located near the pump controller (Figure 3.1 [9] in section 3.1). The timer (an Omron H3CR-A) was set to mode D (Signal OFF delay operation) and the time unit was set to seconds. The time spans used were 6 and 12 seconds. The dial was adjusted so that the solenoid operated with 0, 1.5, 3, 6, 12 seconds off delay.

A 230V signal was taken from one phase of the 3-phase contactor used to power the pump. A DP/DT (double pole, double throw) relay was used to convert the signal into a switch circuit suitable for driving the timer.

While the pump was on, the relay closed and the output indicator lit up, when the pump was turned off, the indicator light flashed for the time selected on the dial and then turned off. During the time that the indicator light was on and flashing, the timer's relay output was closed. The timer's relay contact was used to switch the 24 volt power supply to the water solenoid, on and off. The inductive load of the solenoid was deemed low enough to be controlled directly from the Omron timer without causing damage to the timer (the current rating for the timer relay was 5A, 250VAC. Refer to Appendix 6 for further information).

3.3 Data Analysis

Sample calculations may be found in Appendix 9.

Calculation of milk pump duty cycle

The pump duty cycle is the proportion of time that the pump is running over a length of time, as shown in equation 3.1.

$$\text{Pump duty cycle} = \frac{\text{Time pump is on}}{\text{Total time}} \tag{3.1}$$

If the pump duty cycle varies over time, then equation 3.2 can be used to calculate the instantaneous pump duty cycle.

$$\text{Pump duty cycle} = \frac{\text{Time pump is on in one period}}{\text{Time pump is on and off in one period}} \tag{3.2}$$

where the (time) period begins with the last transition, and ends at the next similar transition. For example, if the last transition that occurred was the pump being turned on, then the time period would extend until the pump was turned on again.

Calculation of log mean temperature difference across the heat exchanger

The log mean temperature difference across the PHE can be calculated using equation 3.3.

$$\Delta\theta = \frac{\Delta\theta_1 - \Delta\theta_2}{\ln\left(\frac{\Delta\theta_1}{\Delta\theta_2}\right)} \tag{3.3}$$

where $\Delta\theta_1$ is the temperature difference at end 1 of the HE, and $\Delta\theta_2$ is the temperature difference at end 2 of a HE. For a counter current PHE:

$$\Delta\theta_1 = \theta_{mi} - \theta_{wo} \tag{3.4}$$

$$\Delta\theta_2 = \theta_{mo} - \theta_{wi} \tag{3.5}$$

where:

θ_{mi} = The temperature of the milk exiting the PHE (^oC).

θ_{wo} = The temperature of the water exiting the PHE (^oC).

θ_{mo} = The temperature of the milk entering the PHE (^oC).

θ_{wi} = The temperature of the water entering the PHE (^oC).

Calculation of heat transfer rates

The milk heat transfer rate across the PHE can be calculated using equation 3.6.

$$\phi_{\text{milk actual}} = \frac{\rho_{\text{milk}} \times M \times Cp_{\text{milk}} (\theta_{mi} - \theta_{mo})}{3600} \tag{3.6}$$

where:

$\phi_{\text{milk actual}}$= The actual milk heat transfer rate (J/s).

ρ_{milk} = Density of milk (kg/m^3).

M = Volumetric flow rate of milk (m^3/hr).

Cp_{milk} = Specific heat capacity of milk (J/(kgK)).

Similarly, the water heat transfer rate can be calculated from equation 3.7.

$$\phi_{\text{water actual}} = \frac{\rho_{\text{water}} \times W \times Cp_{\text{water}} (\theta_{wo} - \theta_{wi})}{3600} \tag{3.7}$$

where:

$\phi_{\text{water actual}}$= The actual water heat transfer rate (J/s).

ρ_{water} = Density of water (kg/m^3).

W = Volumetric flow rate of water (m^3/hr).

Cp_{water} = Specific heat capacity of water (J/(kgK)).

The ideal heat transfer rate is calculated using equation 3.8.

$$\phi_{\text{water ideal}} = \frac{\rho_{\text{water}} \times W \times Cp_{\text{water}} (\theta_{mi} - \theta_{wi})}{3600} \tag{3.8}$$

where:

$\phi_{\text{water ideal}}$= The ideal water heat transfer rate (J/s).

Calculation of efficiency of cooling water usage

The apparent efficiency of cooling water usage can be calculated using equation (3.9).

$$\eta = \frac{\phi_{\text{water actual}}}{\phi_{\text{water ideal}}} \tag{3.9}$$

Equation 3.9 does not account for the cooling of milk held up in the system during the pump-off phase. This term cannot be measured because the temperature sensors were not located exactly at the position of hold-up. Thus equation 3.9 does not describe exactly the instantaneous efficiency of cooling water usage in an intermittent pumping system, but the average over time does capture the overall efficiency as calculated by equation 3.10.

$$\eta = \frac{\sum_{\text{Start of milking}}^{\text{End of milking}} \phi_{\text{water actual}}}{\sum_{\text{Start of milking}}^{\text{End of milking}} \phi_{\text{water ideal}}} \quad (3.10)$$

In equation 3.10 the start of milking is the time that milk first reached the PHE at the start of the session (indicated by an increase in the milk inlet temperature probe) or first operation of releaser pump if recorded, and the end of milking is the time at which the temperature probe at the water outlet drops to the same temperature as the water inlet probe before the final purge of milk from precooling system using water.

Equations used to convert logged data into time, pressure, flow and temperature data may be found in Appendix 8.

4 Results

Section 4.1 characterises the precooling system at Massey University No. 1 Dairy Unit. Section 4.2 presents results showing the outcome of a change to the settings of the releaser pump control system. Section 4.3 presents results showing the outcome of a modification to the cooling water control system.

4.1 Characterisation of Precooling System

The precooling system of Massey University No. 1 Dairy Unit was characterised through a series of monitoring runs. The data gathered formed the basis of a process analysis upon which rational control procedures could be devised. The results include the pumping (4.1.1), milk temperature (4.1.2), cooling water (4.1.3), and the heat transfer profile of the precooling system (4.1.4).

4.1.1 Pumping profile of precooling system

This section describes the pumping profile of the existing system. The pump system is analysed for evidence of cavitation and physical damage to the milk. Operation of the pump is detailed, showing the variation in the milk flow rate from the cows, and how it affects the milk flow rate after the pump.

4.1.1.1 Cavitation

Figure 4.1 shows the pressure at the inlet and outlet of the pump over a 2 minute period. When the pump was off, the pressure at the pump inlet and outlet remained at –40 kPa.g (60 kPa.a). When the pump turned on, there was a slight pressure drop to –45 kPa.g (55 kPa.a) at the pump inlet, and the pressure at the outlet increased to 80 kPa.g. With such a high pressure at the pump outlet, the likelihood of cavitation can be ignored.

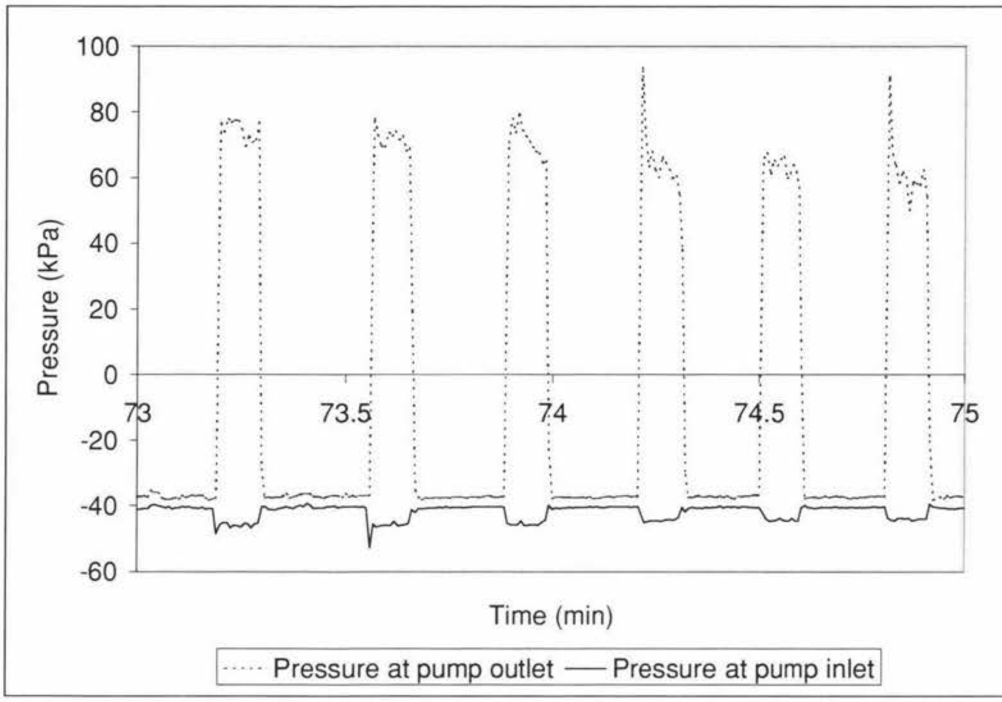

Figure 4.1 Typical trace of pressure at the inlet and outlet of the releaser pump - run 3 recorded 1 September 1999, time period 73-75 minutes after start of milking session.

An attempt to determine the amount of damage done to the milk by the releaser pump was made by testing for Lipolysable Free Fat (Fang, 1998). The results showed that there was more lipolysable free fat present at the inlet of the releaser pump than after it. Detailed results from the Lipolysable Free Fat test are shown in Appendix 11.

4.1.1.2 Pump control regime

Figure 4.2a shows the operation of the releaser pump over a period of 2 minutes and that the pump operated for six seconds at a time. Figure 4.2b shows the operation of the pump 1 minute before Figure 4.2a. The pump duty cycle increased from 5% (1×6s/120s) in Figure 4.2b to 33% (6.5×6s/120s) in Figure 4.2a during the period from 10 min to 15 min after the start of the milking session.

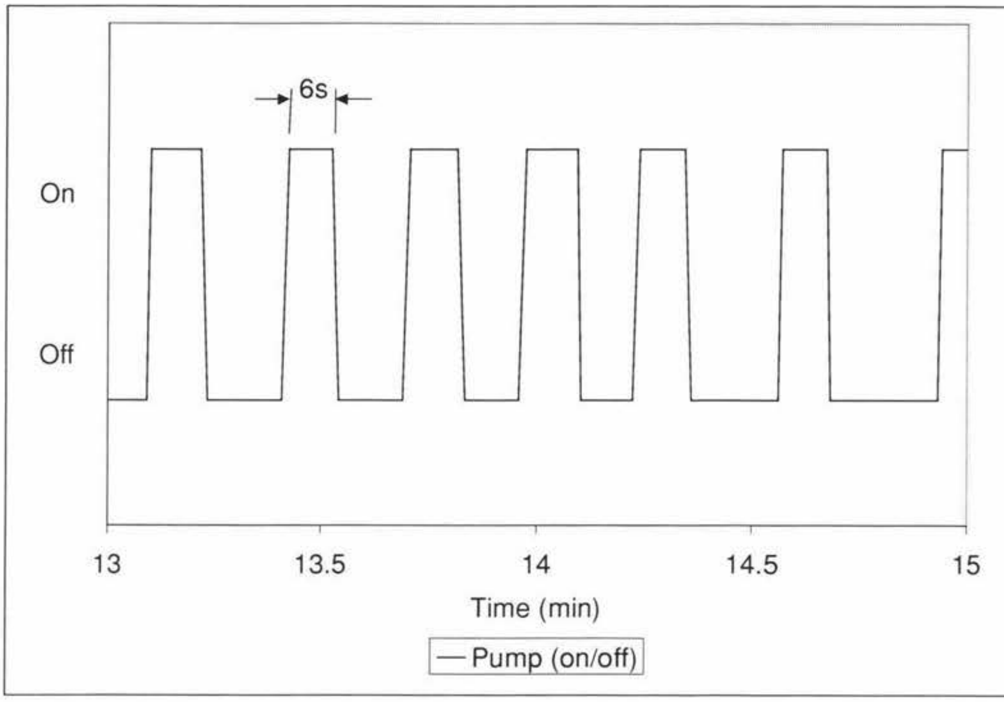

Figure 4.2a Typical trace of releaser pump operation - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.

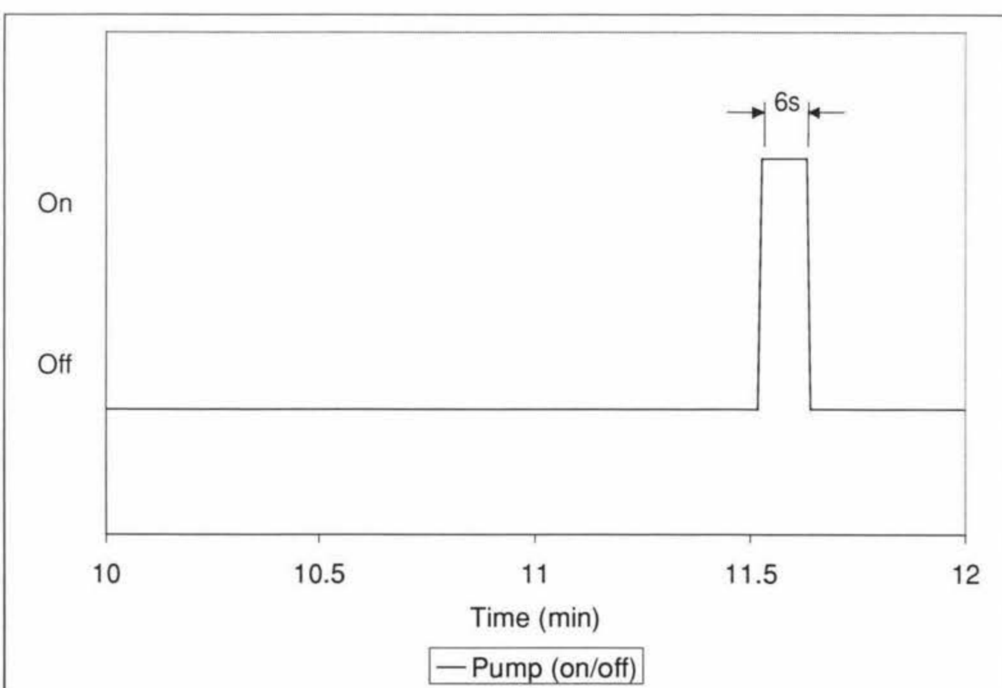

Figure 4.2b Typical trace of releaser pump operation - run 8 recorded 19 November 1999, time period 10-12 minutes after start of milking session.

4.1.1.3 Pump duty cycle

Figure 4.3a shows a graph of pump duty cycle over a 2 minute period. The pump duty cycle is the proportion of time that a pump was on in one cycle (ratio of time on to total time). At 14 minutes into the pumping session, the pump duty cycle was 50%. This can be can be calculated using Appendix 13, run 8 19 November 1999. The pump ran from 13.994 to 14.100 minutes (6.36s) and was previously off from 13.850 to 13.975 minutes (4.5s). The pump duty cycle at 14 minutes into the milking session was therefore 6.36/(6.36+4.5) = 59% and the cycle length was 14s.

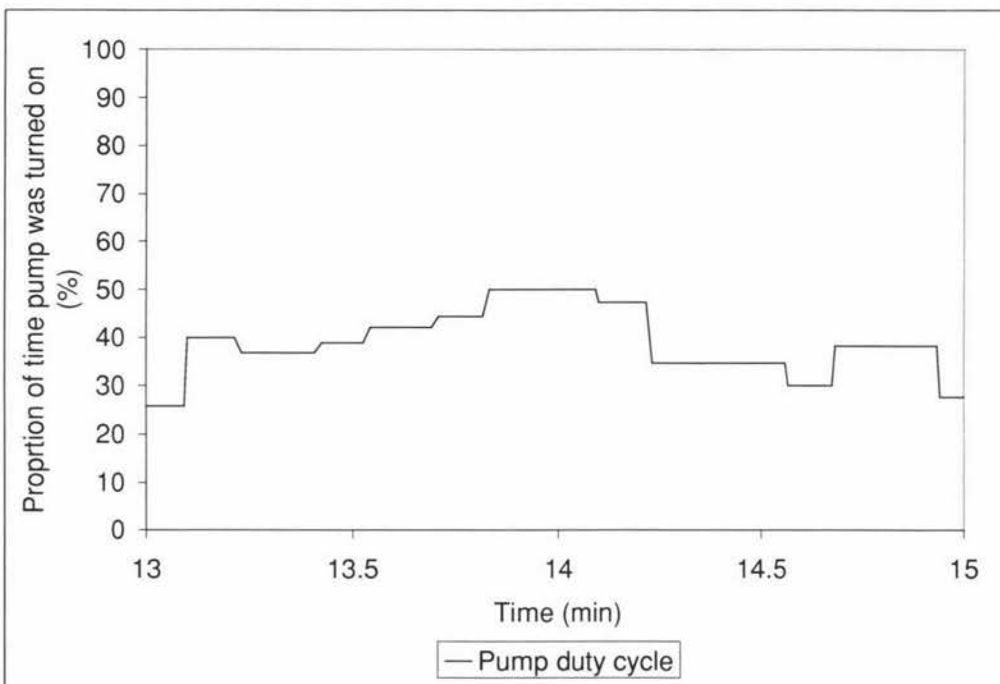

Figure 4.3a Typical trace of releaser pump duty cycle - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.

Figure 4.3b shows the pump duty cycle for the entire milking session including CIP. The milking session finished at 95 minutes and then water was pumped through at 100 minutes to flush out the remaining milk in the line. Once the remaining milk had been flushed into the vat, the CIP regime began. The pump duty cycle varied substantially over the milking session, quickly alternating between peaks greater than 50%, and troughs as low as 5%.

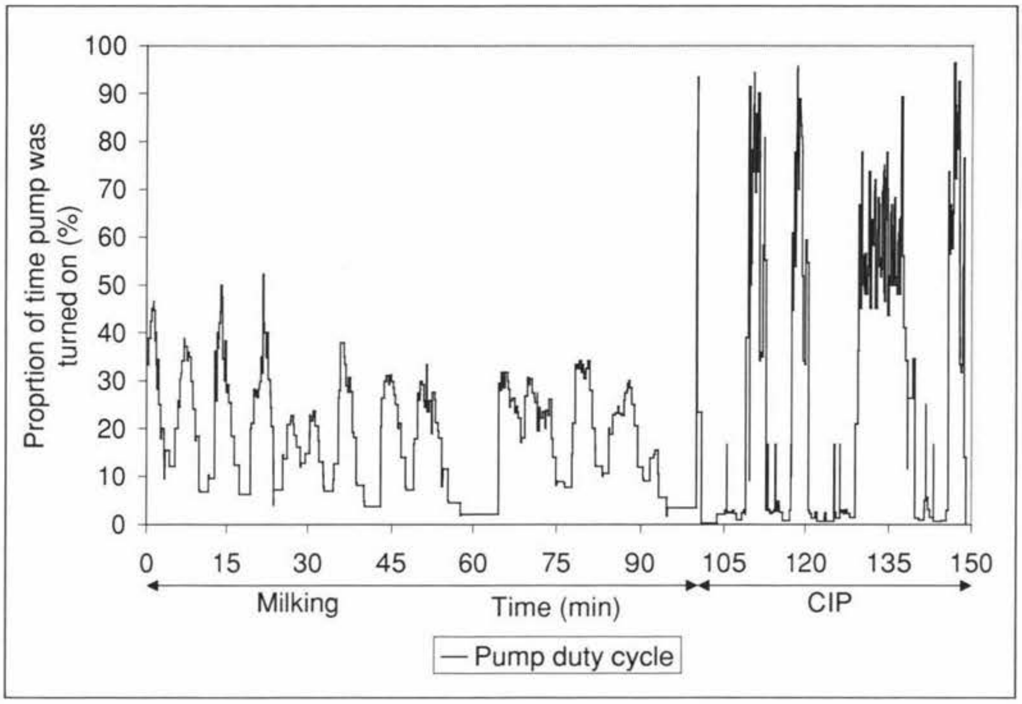

Figure 4.3b Typical trace of releaser pump duty cycle - run 8 recorded 19 November 1999, entire milking session including CIP.

4.1.1.4 Milk flow rate

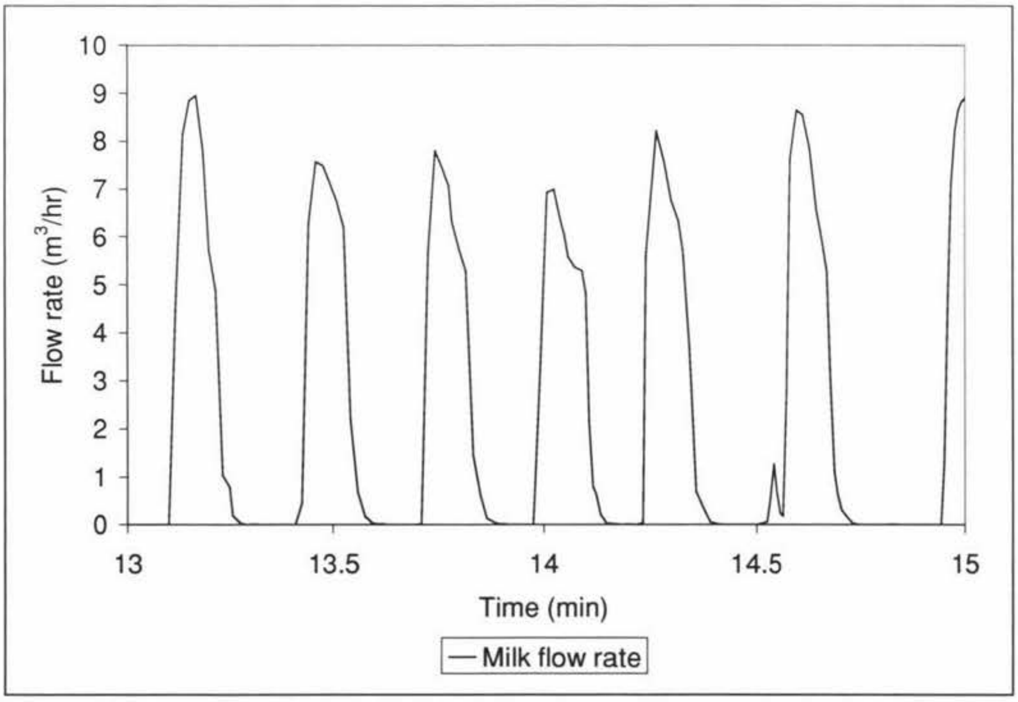

Figure 4.4 Typical trace of milk flow rate - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.

Figure 4.4 shows a typical plot of milk flow rate over two minutes. The flow profile does not follow an ideal square wave pattern. When the releaser pump was turned on, the stationary milk began to flow and kept increasing in flow rate until the pump turned off, at which time the flow decreased back to zero.

4.1.2 Milk temperature profile of PHE

Figure 4.5a shows milk temperatures at the inlet and outlet of the PHE over a period of 2 minutes. The temperature trace was obtained near the start of the milking session and at a point in time when there was a greater amount of milk coming from the cows.

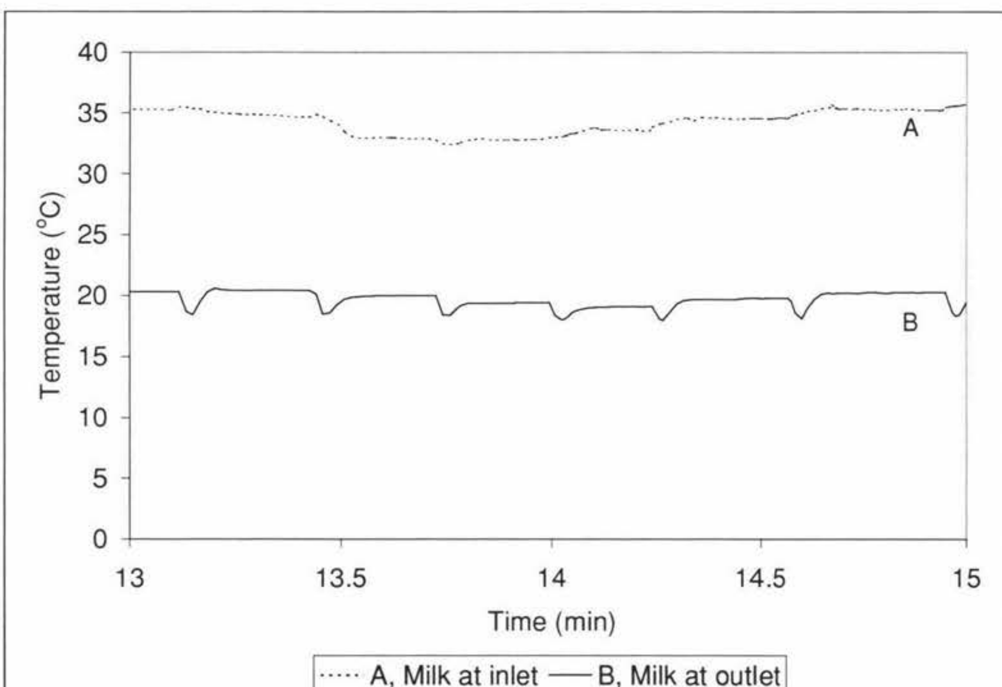

Figure 4.5a Typical trace of milk temperatures at the inlet and outlet of the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.

The temperature of the milk at the inlet of the PHE was about 34°C. The temperature of the milk at the exit of the PHE was higher than 20°C most of the time (Figure 4.5a). This was 2°C hotter than the maximum of 18°C recommended in the COP (1994).

Figure 4.5b also shows the milk temperatures at the inlet and outlet of the PHE, but one minute before Figure 4.5a. The dip in the exit milk temperature occurred when the releaser pump operated at 11.5 minutes into the milking session (Figure 4.2b) causing the milk to flow through the PHE. The exit milk temperature dropped to below 20°C less than 1% of the time. The COP recommendation that the precooler should be able to cool the milk down to 18°C or lower was definitely not being achieved. Note that the milk inlet temperature gradually decreased over a period of one minute before the releaser pump ran.

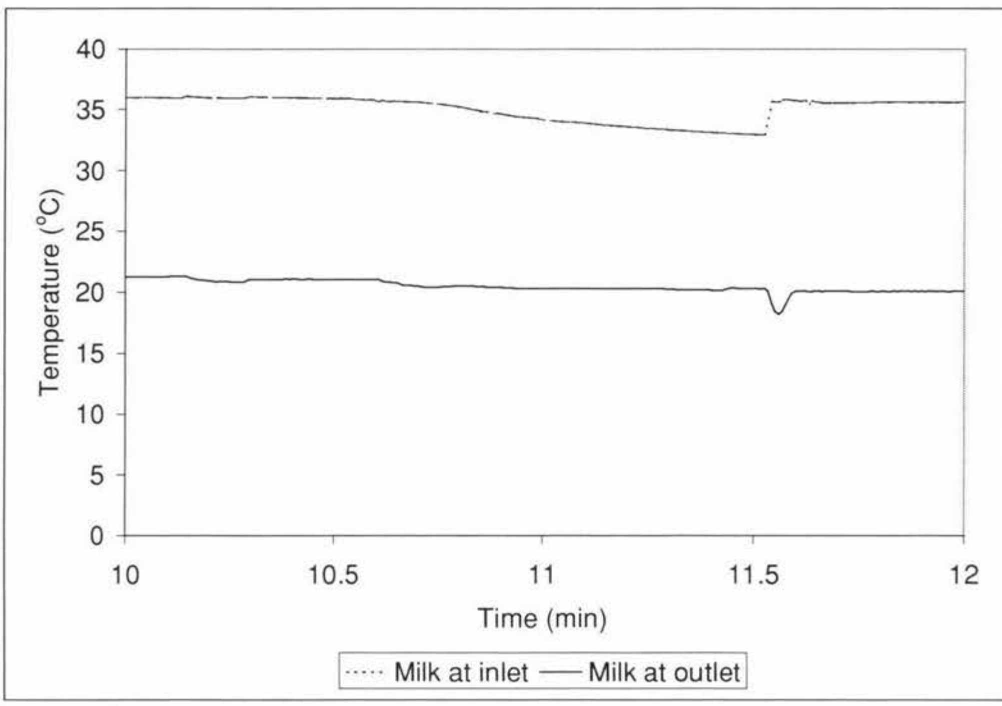

Figure 4.5b Typical trace of milk temperatures at the inlet and outlet of the PHE - run 8 recorded 19 November 1999, time period 10-12 minutes after start of milking session.

4.1.3 Cooling water profile of PHE

Cooling water temperatures

The temperatures of the cooling water entering and leaving the heat exchanger are shown in Figure 4.6 during a time of high milk flow rate from the cows. The water was entering the heat exchanger at 17°C, only 1°C lower than the maximum milk out temperature suggested in the COP.

The water outlet temperature in Figure 4.6 was between 0 and 6.7°C higher than the water inlet temperature. The temperature of the outlet water was the same as the inlet water for about half of the time.

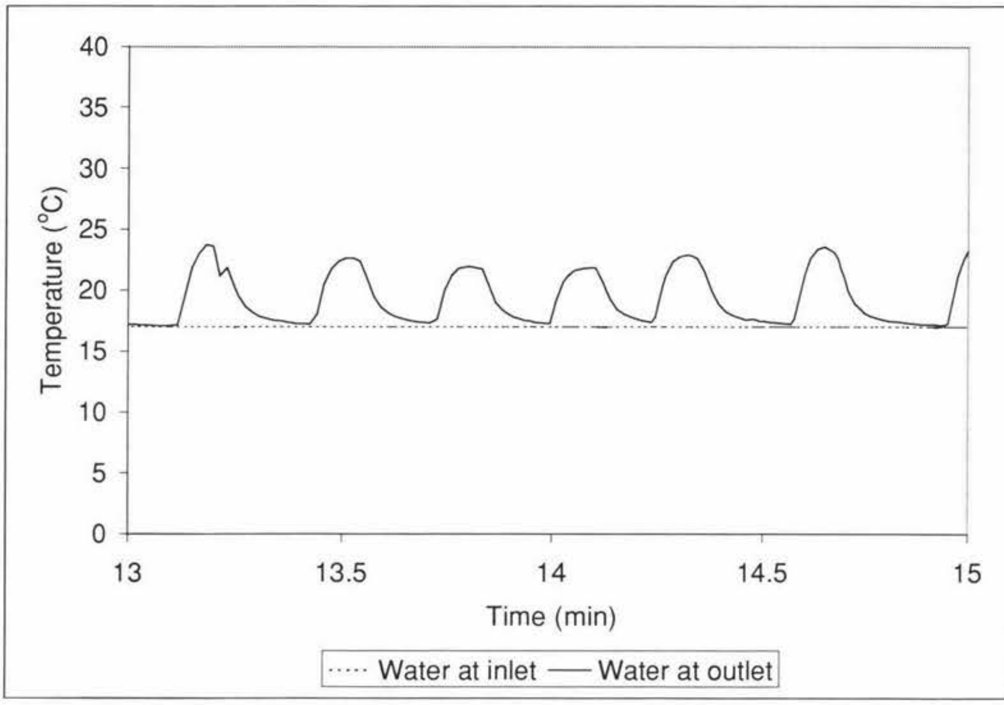

Figure 4.6 Typical trace of water temperatures at the inlet and outlet of the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.

Cooling water flow rate

Figure 4.7a shows that the cooling water flow rate was mostly constant. The curve also shows two distinct drops in the water flow rate. This phenomenon occurred because of a drop in supply pressure when other water consuming activities took place around the milking shed. The water consuming activities on the farm included the PHE, sprinklers, tip drums, backing gates, pit hoses, pit pump and wash down hose. The flow rate of the water shown in Figure 4.7a was 14.2 m^3/hr at normal supply pressure, and 11.1 m^3/hr when a pit hose was running.

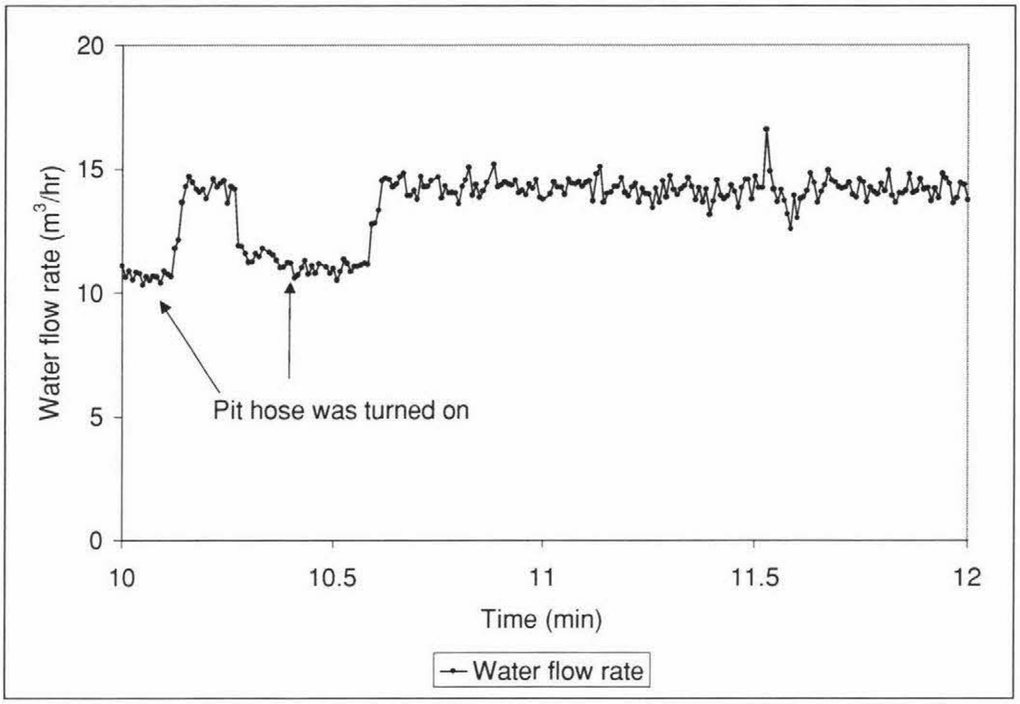

Figure 4.7a Typical trace of water flow rate through the PHE - run 8 recorded 19 November 1999, time period 10-12 minutes after start of milking session.

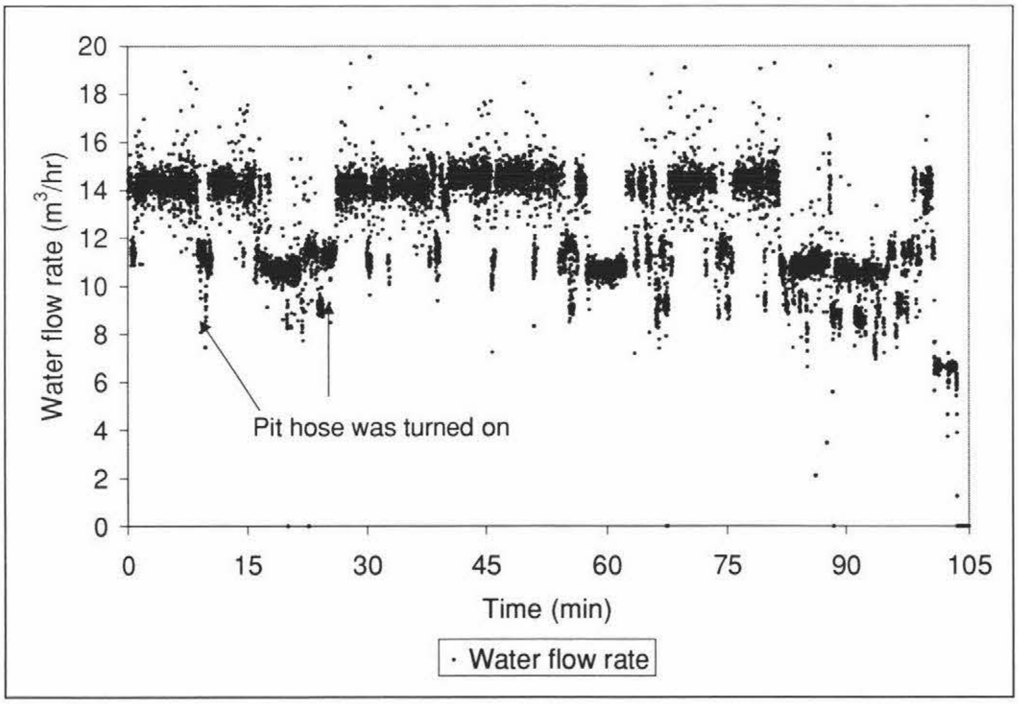

Figure 4.7b Typical trace of water flow rate through the PHE - run 8 recorded 19 November 1999, entire milking session.

Figure 4.7b shows the water flow rate throughout the entire milking session. The water flow rate was mostly steady at 15 m^3/hr. The period of low water flow rate at 60 minutes corresponded to a change over in the herd being milked and there were only a few cows still being milked from herd 1 (the two herds were required to be milked separately so that total milk production for the two herds could be compared in another separate research). The lull in the workload while the remainder of the first herd finished milking afforded time for the milkers to use the pit hoses to wash away organic material that accumulated about the pit.

4.1.4 Heat transfer profile of PHE

This section contains results of calculations on efficiency of cooling water usage for the precooling system. Figure 4.8a shows the log mean temperature driving force across the plates in the heat exchanger. Figure 4.8b shows the log mean temperature difference 3 minutes earlier than the data presented in Figure 4.8a.

Figure 4.8a and Figure 4.8b were calculated using Equation 3.3. The log mean temperature was steady at about 8°C while the pump was off.

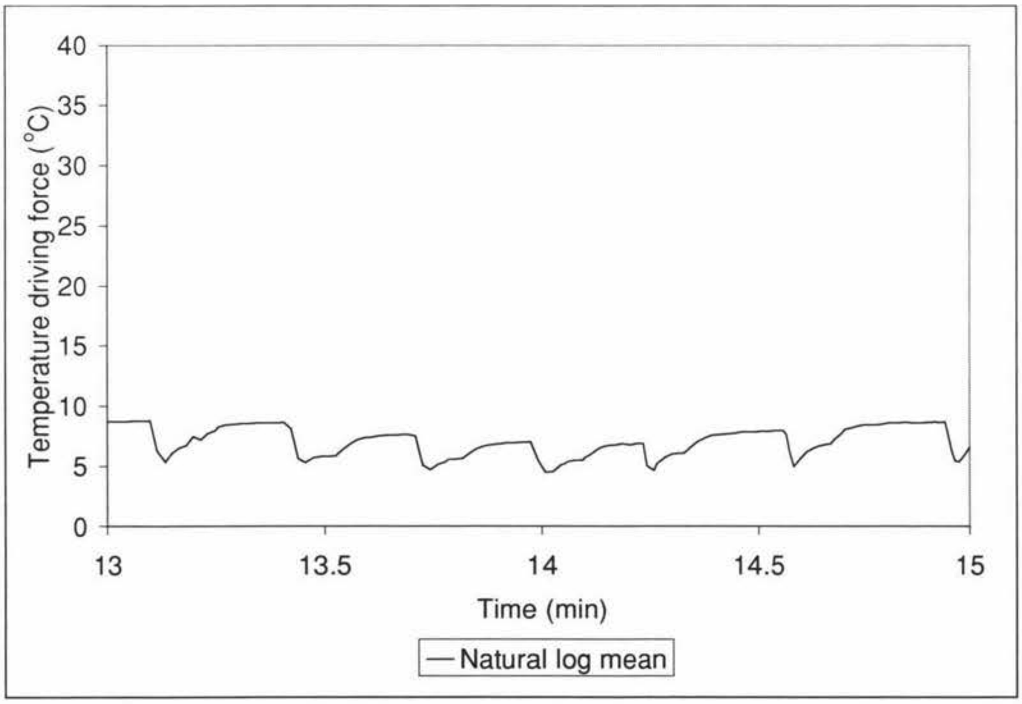

Figure 4.8a Typical trace of the log mean temperature difference across the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.

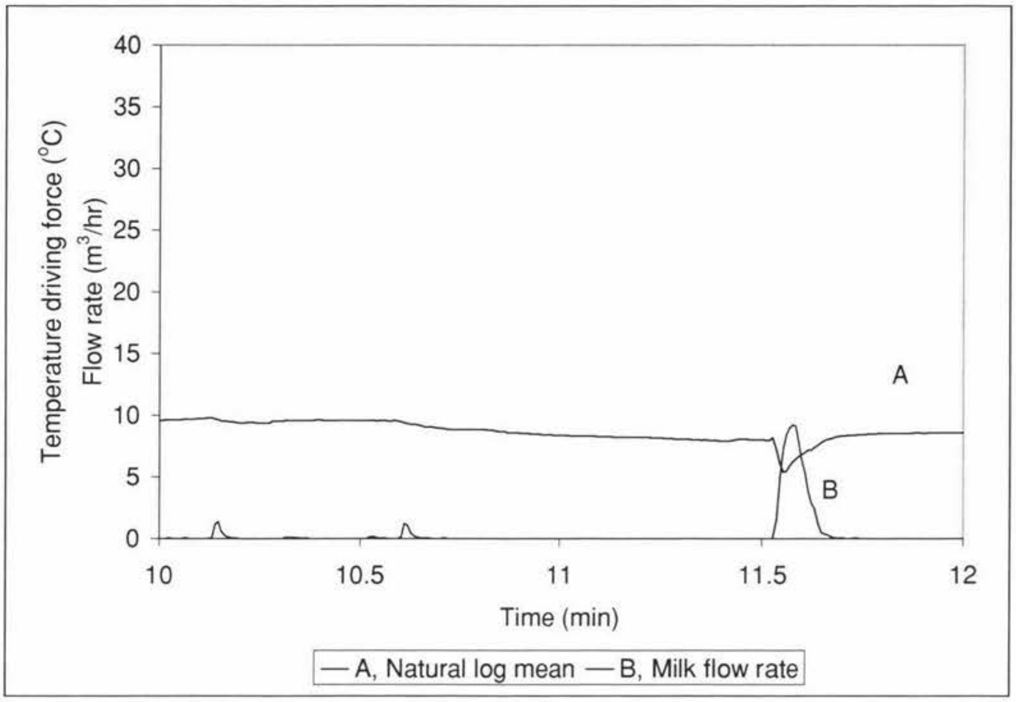

Figure 4.8b Typical trace of the log mean temperature difference across the PHE - run 8 recorded 19 November 1999, time period 10-12 minutes after start of milking session.

4.1.4.1 Heat transfer rate

The rate of heat transfer in the heat exchanger could not be determined using the log mean temperature difference because the system was not at steady state, so the heat transfer must be determined by another way. The method adopted was an energy balance:

$$\phi_{PHE} = \phi_{milk\ actual} = \phi_{water\ actual} \qquad (4.1)$$

where:

ϕ_{PHE} = Heat transfer rate across PHE

The milk heat transfer rate can be calculated using equation 3.6, and the water heat transfer rate can be calculated using equation 3.7

Figure 4.9 shows both water heat gain and milk heat loss over a period of 2 minutes. The energy balance equation 4.1 states that the plots should coincide, but they do not. Water continued to gain heat even after the milk flow has stopped.

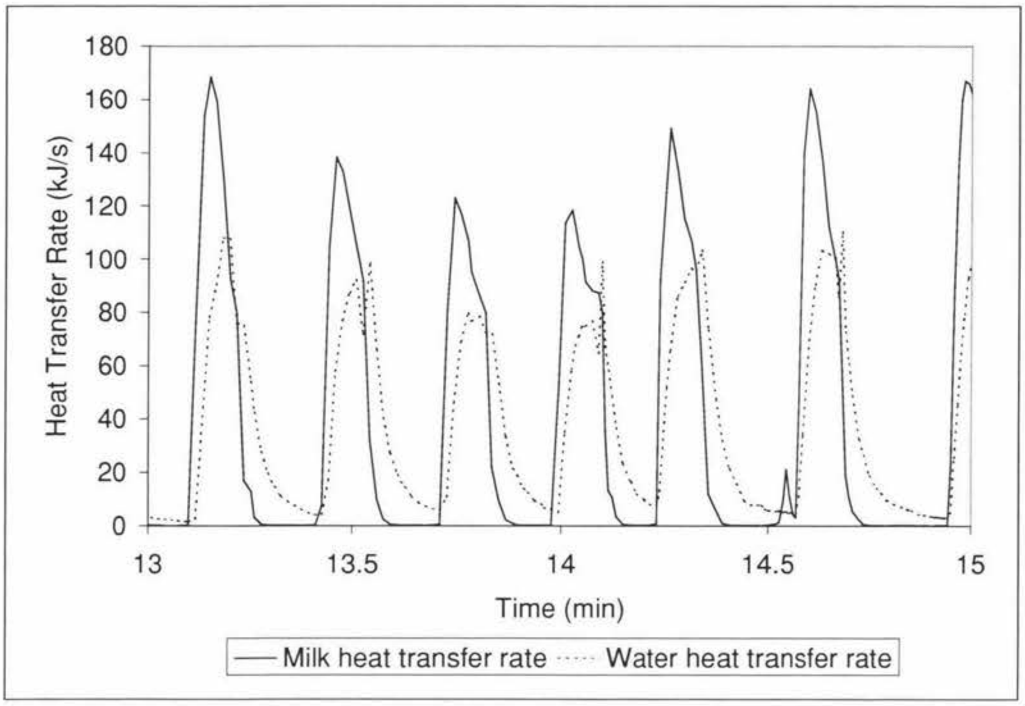

Figure 4.9 Typical trace of the heat transfer rate of milk and water across the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.

4.1.4.2 Ideal heat transfer rate

Figure 4.10 shows a plot of the maximum driving force. The driving force was the temperature difference between the milk inlet and water inlet temperatures. The coldest temperature that the milk could be cooled to was the water inlet temperature. So the maximum amount of cooling, or the maximum possible heat transfer rate for the cooling water could be expressed as in equation 3.8.

As shown in Figure 4.11, the actual heat transfer rate measured and calculated from equation 3.7 was much lower than the ideal heat transfer rate calculated from equation 3.8.

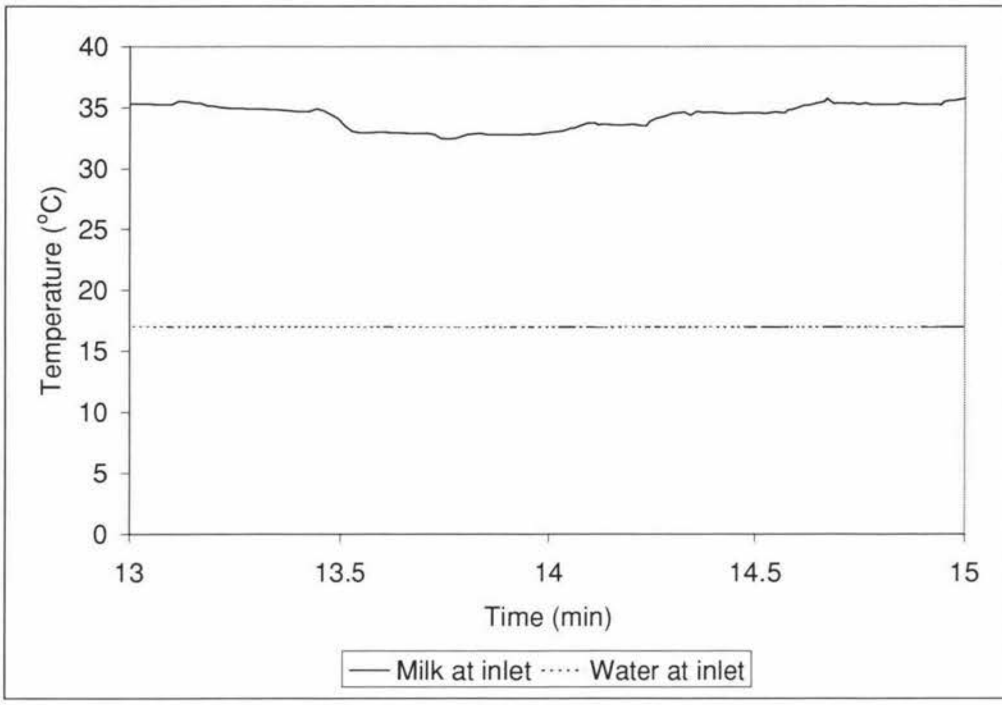

Figure 4.10 Typical trace of the maximum temperature driving force across the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.

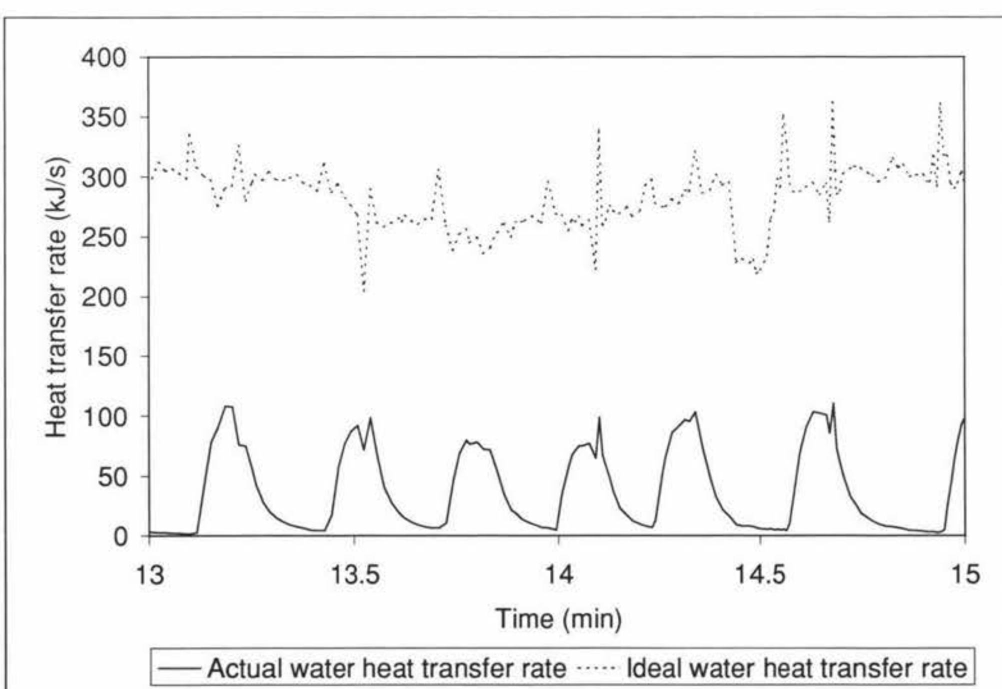

Figure 4.11 Typical trace of the ideal and actual water heat transfer rates across the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.

4.1.4.3 Efficiency of use of water cooling capacity in precooling system

The efficiency of use of the cooling capacity of water was calculated using equation 3.9. Figure 4.12a and Figure 4.12b show the trace of efficiency for the cooling water heat transfer in the precooling system. The traces in Figure 4.12a and Figure 4.12b are separated by one minute yet they are significantly different. The average efficiency over the two minute period from 13 to 15 minutes after the start of the milking session in Figure 4.12a was 13.4%, and the efficiency for the two minute period in Figure 4.12b was 2.4%.

Table 4.1 shows the efficiency of cooling water usage for November and February. Note that in November, two herds were being milked. The efficiency figures were calculated for the entire milking session.

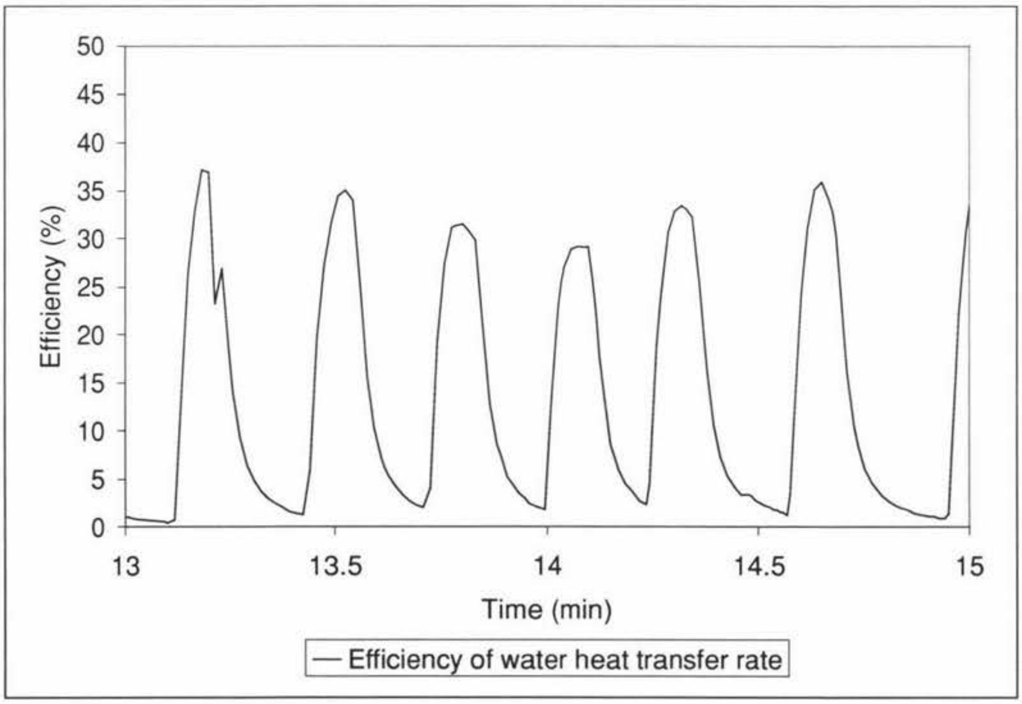

Figure 4.12a Typical trace of efficiency of water heat transfer rate across the PHE - run 8 recorded 19 November 1999, time period 13-15 minutes after start of milking session.

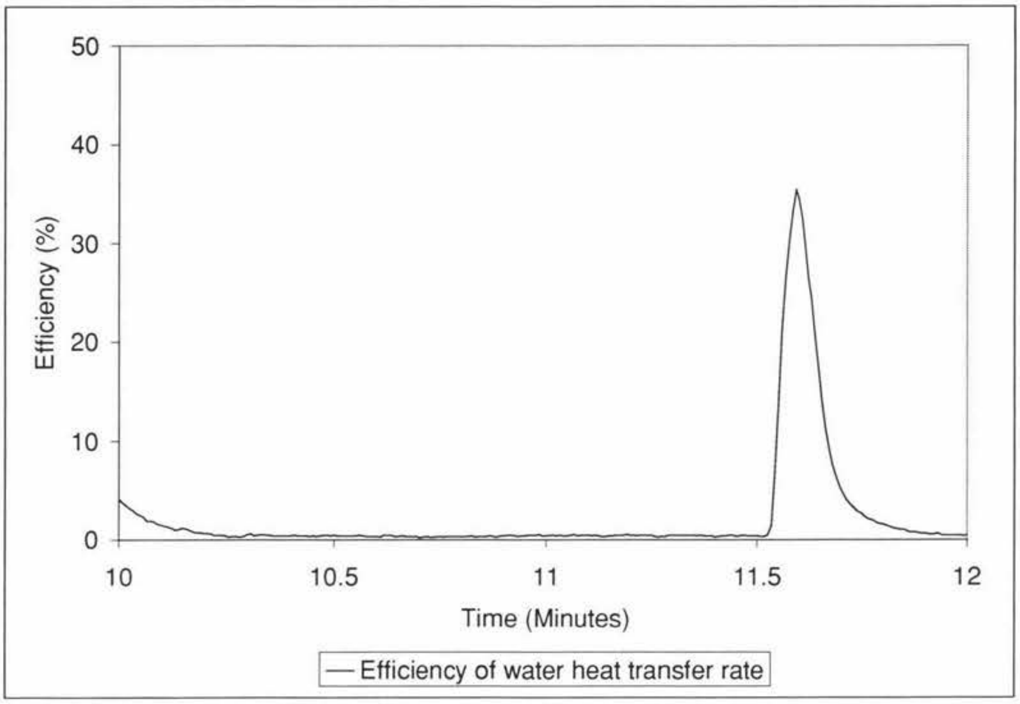

Figure 4.12b Typical trace of efficiency of water heat transfer rate across the PHE - run 8 recorded 19 November 1999, time period 10-12 minutes after start of milking session.

Table 4.1 Daily cooling water usage efficiencies for existing system.

Run Number	Date	Efficiency of cooling water usage (%)
6	17 November 1999	7.2
8	19 November 1999	7.3
12	23 November 1999	7.5
14	14 February 2000	5.86
16	17 February 2000	5.72
18	19 February 2000	7.09
20	25 February 2000	7.09
22	28 February 2000	8.46
28	8 March 2000	6.2

4.2 Control of Pumping Regime

This section presents results showing the outcome of a change to the settings of the releaser pump control system.

The outcome of the change was characterised through a series of monitoring runs. The data gathered formed the basis on which a rational comparison between the two control schemes could be made. The results include the pumping (4.2.1), temperature (4.2.2), and the cooling water usage efficiency (4.2.3) profiles.

4.2.1 Pumping profile of precooling system with pump-on duration set to 3s

Figure 4.13 shows the operation of the releaser pump over a period of 2 minutes. The pump ran for 3s at a time, half of the existing phase length (Figure 4.2a). This resulted in the pump operating twice as often, and twice as much milk being held up in the PHE when the pump stopped – but the residence time was halved.

Figure 4.14 shows the pump duty cycle over the entire milking session including the CIP phase. The pump duty cycle is similar to that in Figure 4.3b, The peaks and troughs in the first 45 minutes of the milking session are mostly less than that found in Figure 4.3b. However, from 45 to 90 minutes the pump duty cycles was peaking at about 80% compared with the 30% peaks observed for the second herd in Figure 4.3b

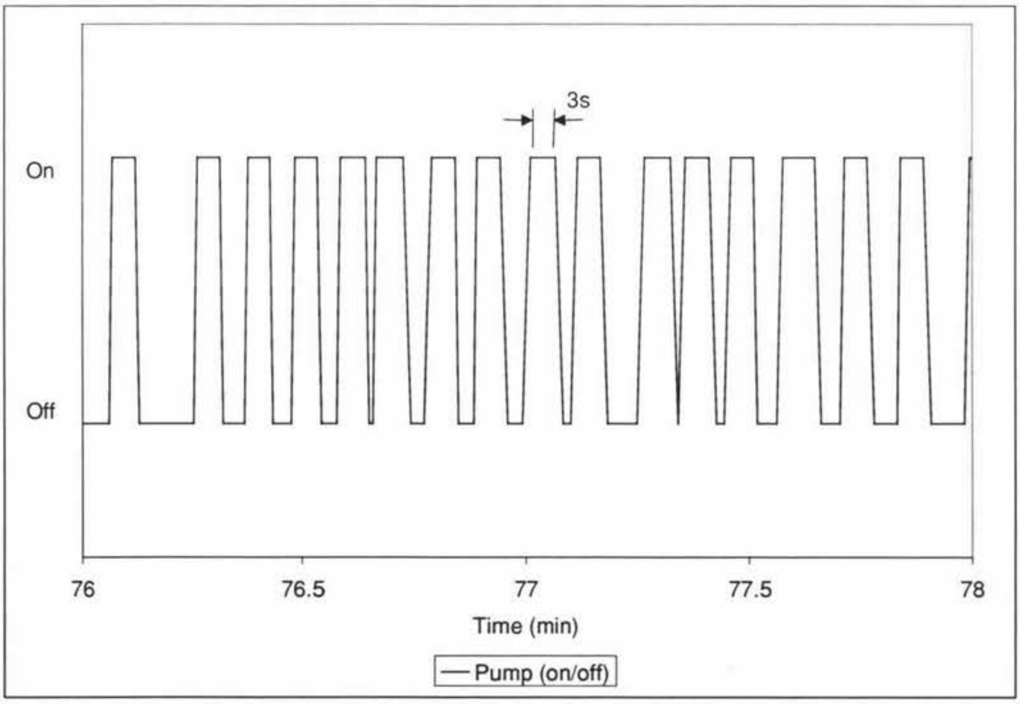

Figure 4.13 Typical trace of releaser pump operation with pump-on duration set to 3s - run 10 recorded 21 November 1999, time period 76-78 minutes after start of milking session.

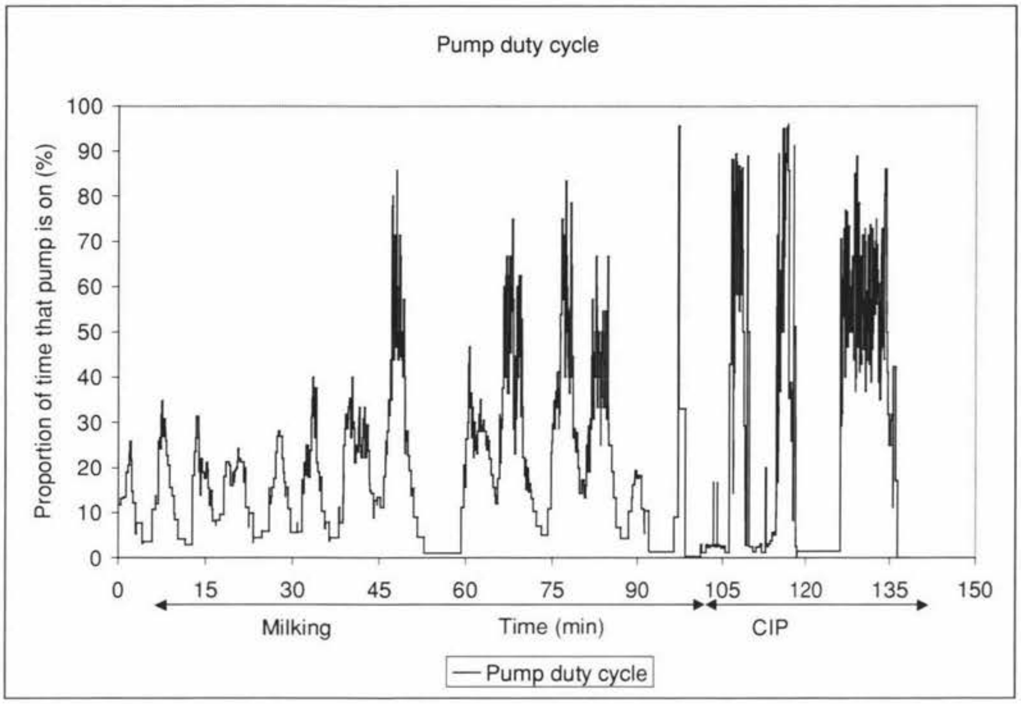

Figure 4.14 Typical trace of releaser pump duty cycle with pump-on duration set to 3s - run 10 recorded 21 November 1999, entire milking session including CIP.

4.2.2 Temperature profile of PHE with pump-on duration set to 3s

Figure 4.15 shows the milk temperatures at the inlet and outlet of the PHE over a two minute period. The milk leaving the PHE reached temperatures as high as 19.2°C, which was higher than the maximum of 18°C specified in the COP. However, the milk temperature was still 1.4°C (8%) cooler than the milk temperatures obtained using the original 6s-pumping regime (20.6°C, Figure 4.5a).

Figure 4.16 shows the temperatures of the cooling water at the inlet and outlet of the PHE. Note that unlike Figure 4.6, the water outlet temperature was not the same as the water inlet temperature at any time during the pump off phase. Thus the water was cooling the milk all the time, while in Figure 4.6 the water cooling capacity was used for only half of the time. The peaks in the water temperature shown in Figure 4.16 were 8.0°C higher than the water inlet temperature while the peaks in Figure 4.6 were only 7.6°C higher than the water inlet temperature of 17°C.

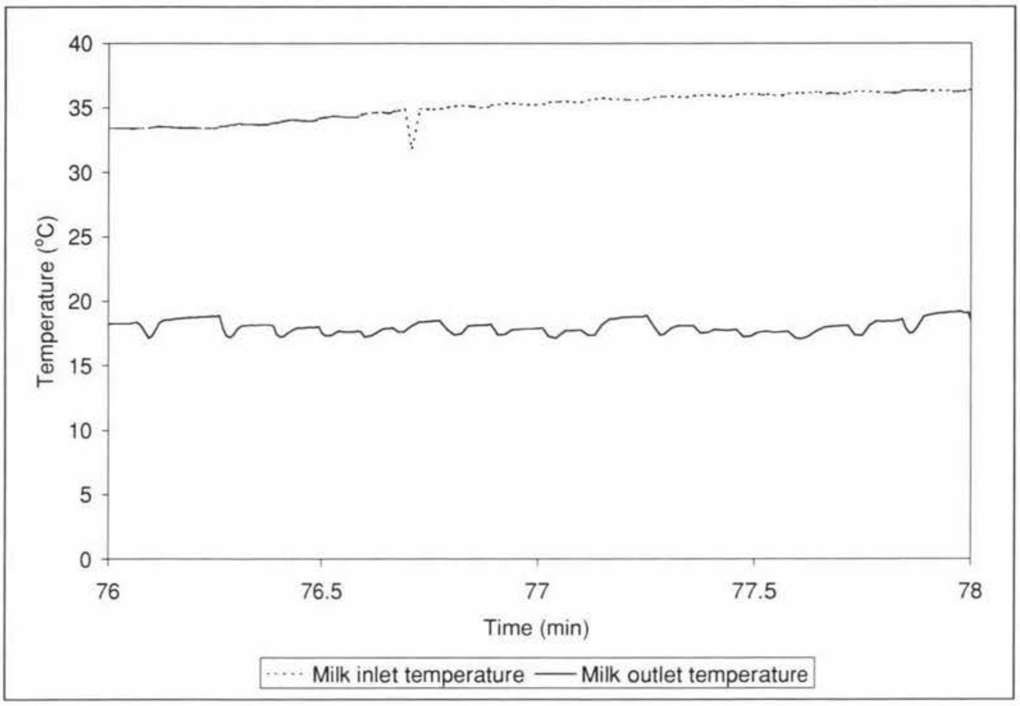

Figure 4.15 Typical trace of milk temperatures at the inlet and outlet of the PHE with pump-on duration set to 3s - run 10 recorded 21 November 1999, time period 76-78 minutes after start of milking session.

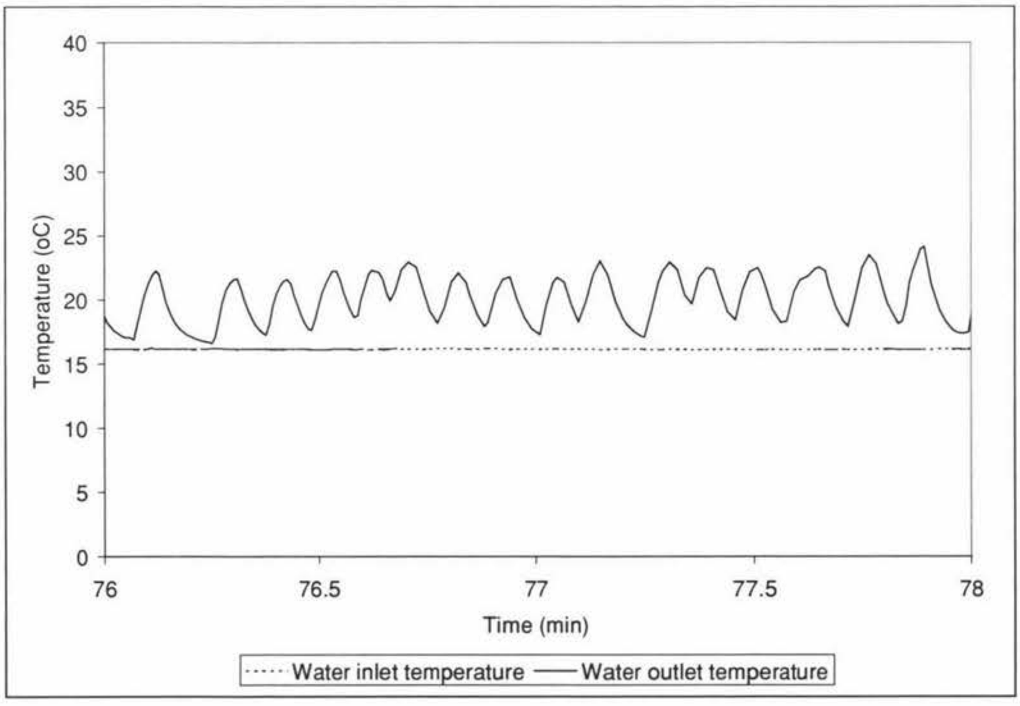

Figure 4.16 Typical trace of water temperatures at the inlet and outlet of the PHE with pump-on duration set to 3s - run 10 recorded 21November 1999, time period 76-78 minutes after start of milking session.

4.2.3 Efficiency of use of water cooling capacity in precooling system with pump-on duration set to 3s

Figure 4.17 shows the efficiency of cooling water usage over a two minute period calculated using equation 3.9. Comparison with Figure 4.12a of the 6s pumping regime does not give any clear evidence as to which was the more efficient scheme because it is difficult to recognise the average performance from cyclic graphs.

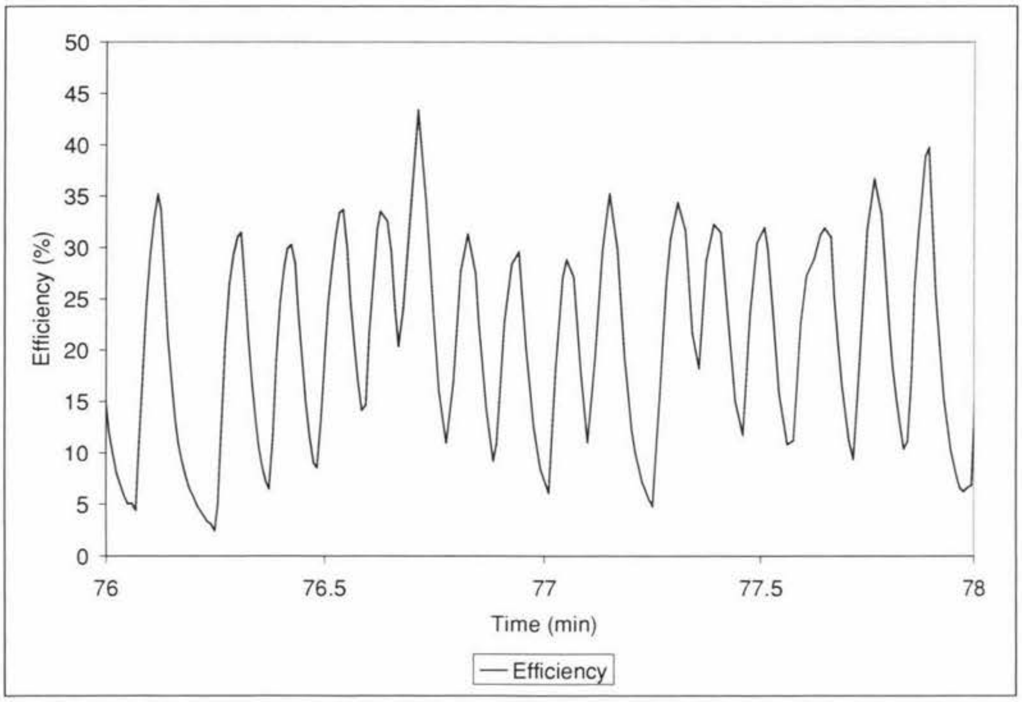

Figure 4.17 Typical trace of efficiency of water heat transfer rate across the PHE with pump-on duration set to 3s - run 10 recorded 21 November 1999, time period 76-78 minutes after start of milking session.

The efficiencies over the whole milking session were carried out to allow a numerical comparison. The results for both regimes are shown in Table 4.2. On average, the efficiencies obtained with the 3s pumping regime were 6.7% higher than the efficiencies obtained with the 6s pumping regime for November, and 13.4% higher for February.

Table 4.2 Comparison of cooling water usage efficiencies for 6s and 3s pump-on duration regimes.

6s regime		3s regime	
Date	Efficiency (%)	Efficiency (%)	Date
17 November 1999	7.2		
		8.1	18 November 1999
19 November 1999	7.3		
		7.7	21 November 1999
		7.9	22 November 1999
23 November 1999	7.5		
		6.68	12 February 1999
14 February 2000	5.86		
		7.53	15 February 1999
17 February 2000	5.72		
		6.96	18 February 1999
19 February 2000	7.09		

4.3 Control of Cooling Water Regime

This section presents results showing the outcome of a modification to the cooling water control regime. The outcome of the change was characterised through a series of monitoring runs. The results include the cooling water flow rate (4.3.1), temperature (4.3.2), heat transfer rate (4.3.3), and the cooling water usage efficiency (4.3.3) profiles.

4.3.1 Cooling water flow rate when synchronized with releaser pump operation

Figure 4.18 shows the cooling water flow rate over two minutes. The operation of the cooling water is synchronised with that of the releaser pump to conserve the cooling water when the milk is not flowing through the PHE.

There are two components to the cooling water flow rate, a main peak (11.3 to 11.4 minutes), and a secondary peak (11.4 to 11.5 minutes). This shows that the cooling water flowed for 6s when the releaser pump was operating; when the pump stopped and the solenoid closed (11.4 minutes), the cooling water continued to flow at a reduced flow rate for a further 6s.

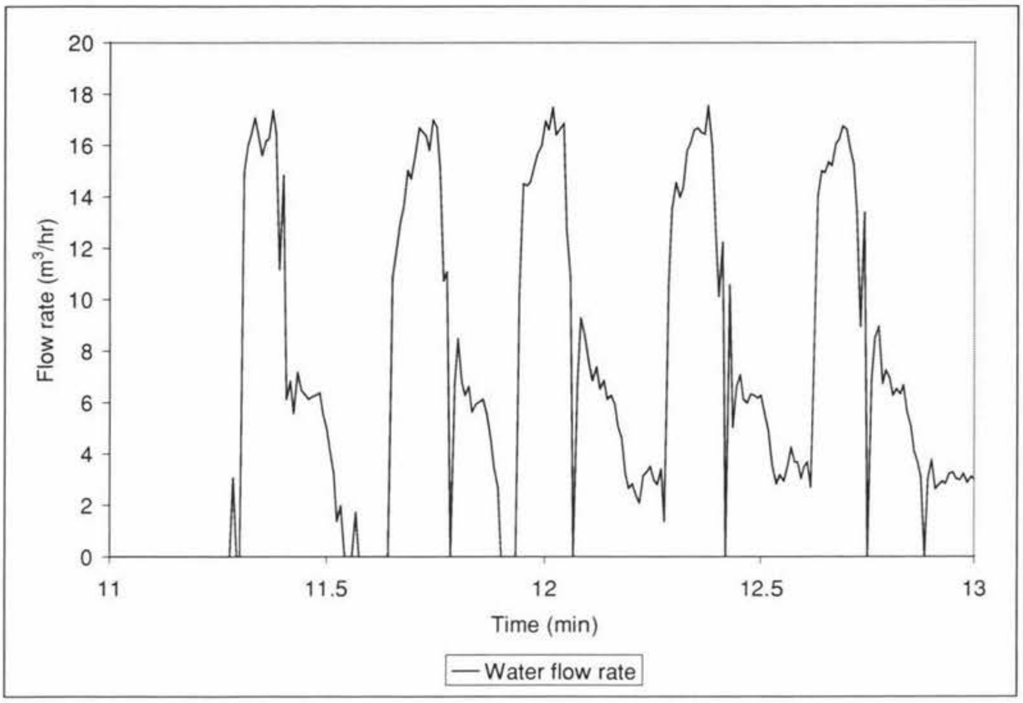

Figure 4.18 Typical trace of cooling water flow rate through the PHE with solenoid-off delay set to 0s - run 25 recorded 2 March 2000, time period 11-13 minutes after start of milking session.

4.3.2 Temperature profile of PHE when cooling water flow rate was synchronized with releaser pump operation

Figure 4.19 shows the temperature of the cooling water at the inlet and outlet of the PHE. The water entered at 17.3°C, and exited at 21.4°C at 10 minutes from the start of milking. This was a 4.1°C change in cooling water temperature, compared to the 8.0°C peaks (3.9°C average) seen in Figure 4.16.

Figure 4.20 shows the milk temperatures at the inlet and outlet of the PHE. The average milk out temperature between 8 to 10 minutes from the start of milking (20.0°C) was 2.7°C higher than the cooling water going in (Figure 4.19). As in Figure 4.5a, the milk inlet temperature in Figure 4.20 was also lower than typical, as the pipe work had not completely heated up yet. Between 8 to 10 minutes from the start of milking, the milk inlet temperature remained below 34°C.

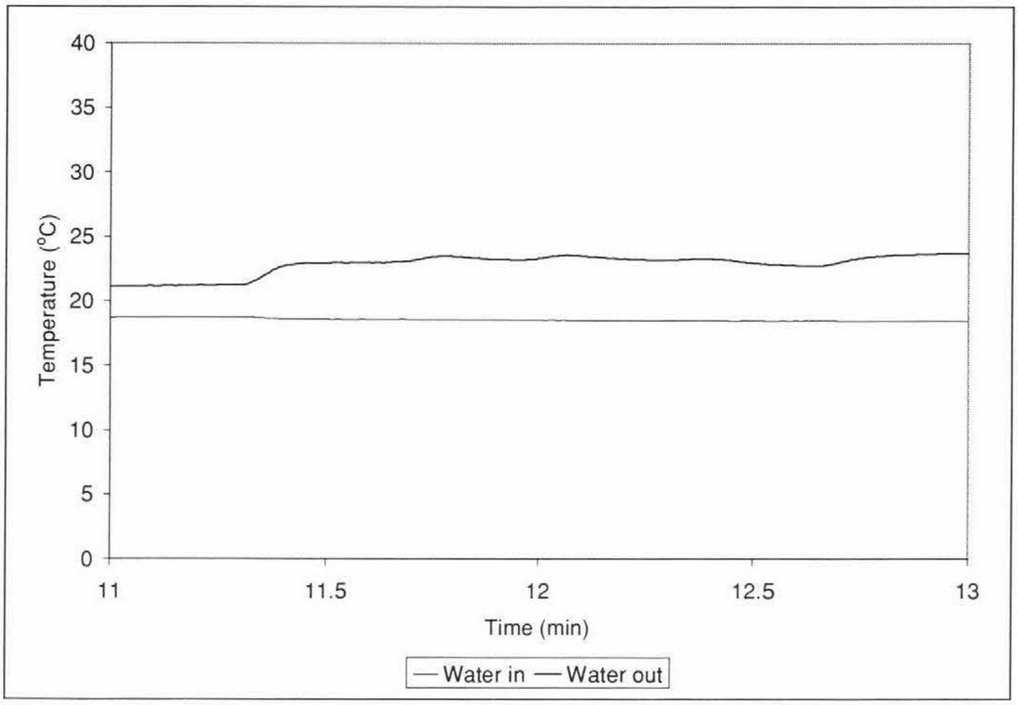

Figure 4.19 Typical trace of water temperatures at the inlet and outlet of the PHE with solenoid-off delay set to 0s - run 25 recorded 2 March 2000, time period 8-10 minutes after start of milking session.

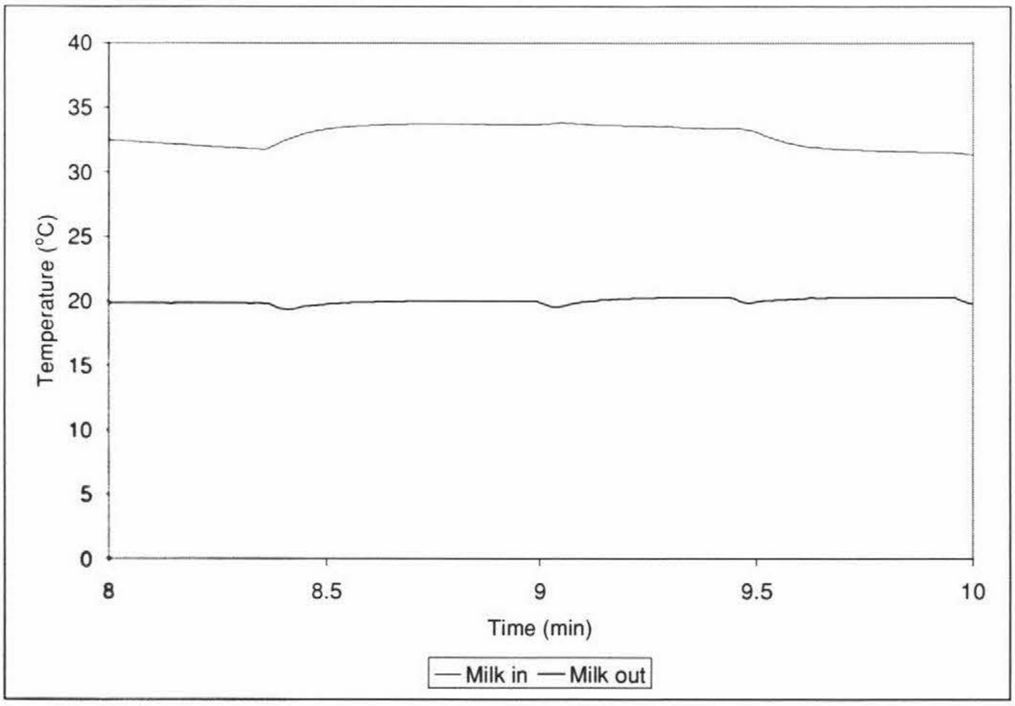

Figure 4.20 Typical trace of milk temperatures at the inlet and outlet of the PHE with solenoid-off delay set to 0s - recorded 14 March 2000, time period 8-10 minutes after start of milking session.

Even though the milk that entered the plate heat exchanger was colder than normal, the milk exiting was two degrees hotter than the maximum 18°C required in the COP.

4.3.3 Heat transfer rate across PHE when cooling water flow rate was synchronized with releaser pump operation

Figure 4.21 shows the ideal heat transfer rate (calculated using equation 3.8) over a period of two minutes. The ideal heat transfer rate alternated between 0 and 280 J/s whereas it had remained steady in the original control scheme (Figure 4.10).

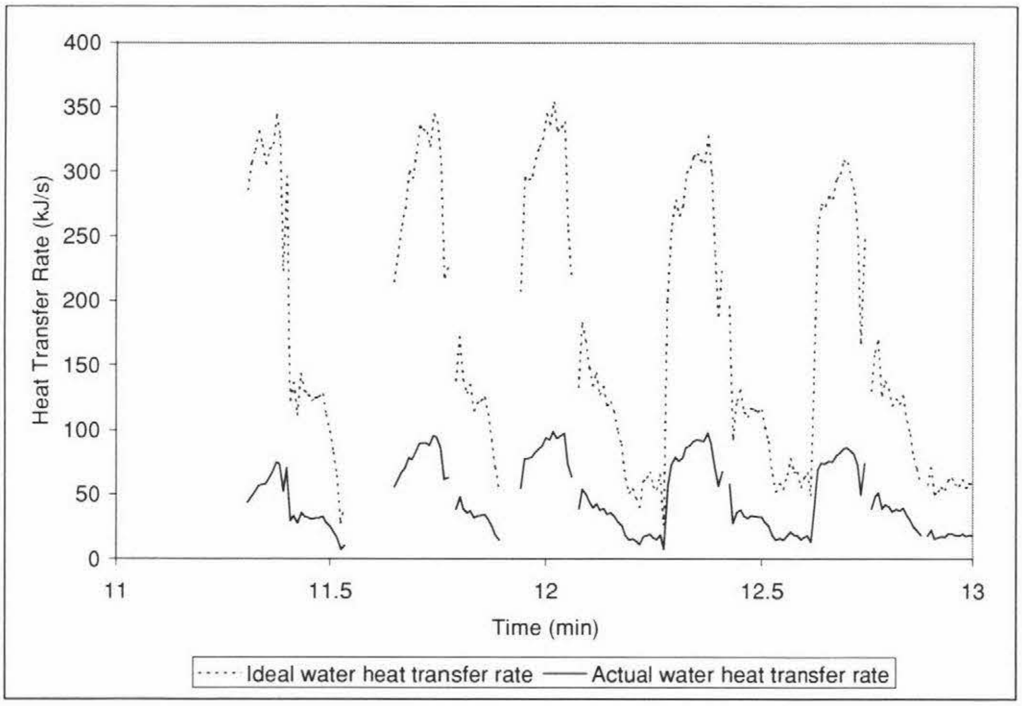

Figure 4.21 Typical trace of ideal and actual water heat transfer rates, with solenoid-off delay set to 0s - run 25 recorded 2 March 2000, time period 11-13 minutes after start of milking session.

4.3.4 Efficiency of use of cooling water capacity in precooling system when cooling water flow rate was synchronized with releaser pump operation

Figure 4.22 shows the efficiency of cooling water usage over a period of two minutes when the control of the cooling water flow rate had been linked to the operation of the milk pump. The gaps are when the efficiency was undefined because the cooling water was not flowing. The graph shows that the efficiency of the cooling water usage was about 25%, which was much higher than the values of about 7% in Table 4.1.

Table 4.3 shows the results of milking sessions where the closing of the solenoid was delayed by n seconds after the releaser pump had turned off. The results for the existing system are also included to allow a comparison to be made.

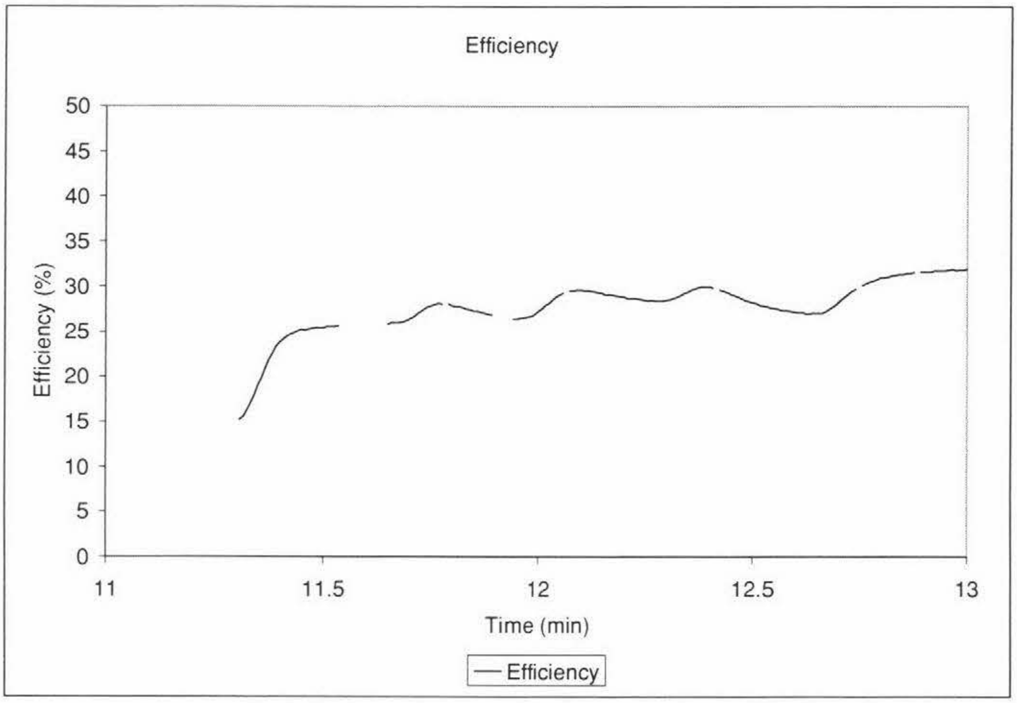

Figure 4.22 Typical trace of efficiency of water heat transfer rate across the PHE with solenoid-off delay set to 0s - run 25 recorded 2 March 2000, time period 11-13 minutes after start of milking session.

Table 4.3 Cooling water usage efficiencies with varying water-off delay times.

Date	Efficiency (%)					
	Continuous Flow	9s	6s	3s	1.5s	0s
25 February 2000	7.09					
28 February 2000	8.46					
29 February 2000			14.31			
1 March 2000				17.87		
2 March 2000						27.24
4 March 2000		13.17				
6 March 2000					23.00	
8 March 2000	6.20					

5 Discussion

5.1 Characterisation of Precooling System

Cavitation and milk damage

Figure 4.1 shows that the pressure at the inlet of the pump did not go below –45kPa. It is therefore unlikely that milk damage, due to cavitation of the releaser pump occurred, as the vacuum required for cavitation at 37°C is -95kPa.

The results from the Lipolysable Free Fat test indicated that the milk before the releaser pump was more damaged than the milk exiting the pump. This was contrary to the results expected. Poor sampling methods are likely to be the reason for the unexpected results. The sample at the pump inlet was obtained from the receiver after the first herd had finished milking. However, some of the sample would have contained froth that had collected in the receiver during the milking session. At the time of collection, it was possible to see a few small globules of fat floating on the milk. Although the amount of cream that separated out from the milk seemed normal, Figure A.6 shows a 30 ml conical flask containing significant quantities of aggregated globules of fat. The flask contained the titrated product that had originated from 10 ml of milk. The solution was originally clear, but during titration, the fat precipitated to give a cloudy appearance, over time the fat coalesced to form the large fat globules seen in Figure A.6. The amount of fat globules indicates that the composition of the 10 ml of milk included significantly more than 3% fat.

It was decided that careful design of tests for measuring MFGM damage was complex and more suited to the skills of dairy chemists. It was therefore decided to accept previous observations that MFGM damage would be minimised if cavitation did not occur (Fang, 1998; Thomson, 1999).

Pump duty cycle

Figure 4.3a shows that the pump duty cycle 14 minutes into the milking session was 50%, but in section 4.1.1.2, the duty cycle was correctly calculated to be 46%. This difference was due to the assumption by equation A.7 and A.8 that the records were logged at a constant interval. Unfortunately, when the CR10 was periodically connected to the laptop to download data, the CR10 was unable to communicate and log data every 0.5 seconds and so some records were logged at 1 second intervals resulting in occasional calculation errors.

Figure 4.3b shows large variations in pump duty cycle and reflects on the large changes in the milk flow rate. If the fluctuations could be reduced, then the pump and precooling system would not have to be sized to cope with the peak flow rates. This could be achieved by using larger receivers, multiple level sensors or variable speed drives. The flow rate through the precooling system could then be reduced to a quarter of the existing flow rate resulting in a greater residence time of milk in the current PHE.

Figure 4.4 shows that the milk only flows through the PHE some of the time, and so the cooling capacity of the PHE is under utilised.

Milk temperatures of the plate heat exchanger

Figure 4.5a shows that the PHE milk inlet temperature was lower than body temperature (38.9°C (Russell, 1981)) by 3°C. The readings were taken near the beginning of the milking session and the milk plant pipe work was still heating up. Even though the milk inlet temperature was low, the milk outlet temperature was 2°C higher than the recommendation of the COP resulting in faster reproduction of microbiological organisms present in the milk.

The milk temperature at the PHE outlet dipped regularly (line B in Figure 4.5a). This temperature dip corresponded with the operation of the milk pump. When the pump was switched on, milk flowed through the PHE; but when the pump was turned off, some milk was held up in the PHE until the next pumping cycle. While the pump was off, the milk in the heat exchanger was being cooled to a temperature lower than that of the milk that had been pumped directly through the heat exchanger. However, the milk outlet temperature sensor did not detect the cooling as it was located 150 mm down stream from the heat exchanger. The temperature measured while the pump was off was that of the stationary milk surrounding the sensor. This stationary milk was quite warm, as it had been pumped continuously through a warmed up heat exchanger. During the pumping phase (6 seconds), the volume of milk flowing through (12 litres) was higher than the holding capacity of the PHE (5 litres). The temperature of the cooler milk was only measured once the pump operated again and dislodged the milk held up in the PHE. The 5 litres of milk that had been held up in the PHE flowed pass the temperature sensor in 2.5 s. The average milk out temperature must then be found by taking the flow rate into consideration.

The temperature dips in the milk outlet occurred in a short space of time, and were quite fast temperature changes. It is common for industrial temperature sensors to have lag times in the order of 5 seconds or more depending on their size and outer sheathing. It is therefore necessary to use a temperature sensor with a low thermal lag time to measure accurately the extent of cooling. The thermocouple junction in this case was small with only a layer of epoxy separating it from the milk. The pre-existing temperature sensor at the farm for measuring the temperature of milk entering the vat (section 3.1) exhibited a lag in response due to the thermal mass of the pipe holding the sensor and the sensor never detected the temperature dips reported, for example, in Figure 4.5a. This meant that the lag was large enough for bursts of cold, or hot milk to flow past the sensor without being detected. This could give a wrong estimate of the average temperature of the milk entering the vat. But more important was that there was no measurement of the milk flow rate and so the sensor therefore gives instantaneous temperatures, not a mixing cup average temperature.

The difference in pumping duty between Figure 4.5a and Figure 4.5b was due to the change in flow of milk to the receiver, where ideally a constant flow rate would be more desirable for optimising the cooling of the pre cooling system.

Figure 4.5b showed that the milk held up in the piping at the PHE inlet also cooled for some time during the pump off phase, particularly the minute before the pump operated at 10.5 minutes into the pumping session. Several explanations are possible.

i) Cooling by conduction along the stainless steel pipe. The PHE has cooling water continually flowing through it at cooler temperatures that could cool the PHE and connecting pipe during the pump off phase after it had been heated by the milk at 37°C.

ii) Cooling by conduction through the milk held up in the pipe. The PHE is at a low point in the piping network. The pipe enters into the precooling area at ceiling level (Figure 2.6 [1]) Then enters the PHE at floor level [7], and then runs along the ceiling [5] to the bulk milk vat. The milk held up in the pipe is cooled by conduction from milk held up in the PHE during the pump of phase.

iii) Heat losses from the pipe to the cooler ambient air.

Detailed measurements were not made during this work to analyse this effect. Further investigation will be required for a complete proof.

In analysing or designing any system, it is important that the constraints are known. In the COP, it is stated that "there shall be primary cooling....which should be capable of cooling the milk to 18°C". This is straightforward to interpret where milk flow rate is continuous and the PHE is operating at steady state. However, this occurrence is rare. At Massey University No. 1 Dairy Unit the milk flow rate through the PHE was intermittent, the temperature of the milk at the PHE outlet varied each time the pump operated. At times the temperature at the milk outlet reached 19.2°C (section 4.2.2), but on mass average temperature of 17.7°C (section 5.2) As discussed in section 5.2, it is ambiguous as to whether the value of 18°C refers to the maximum allowed instantaneous temperature of the milk exiting the PHE, or the maximum milk average temperature. Clarification is therefore required in the COP.

Cooling water profile

Figure 4.6 shows that the temperature at the cooling water inlet and outlet of the PHE were the same for half of the time. This indicates that heat exchange had not occurred and so the water used during that time was wasted.

The cooling water entered the PHE at 17°C. An efficient single pass heat exchanger (as used on farms) can cool milk to within 2°C of the cooling water temperature and so complying to the recommendations of the COP can be difficult, impossible sometimes as on some days the water supply temperature can be above 18°C.

The flow rate of 14.2 m^3/hr recorded in Figure 4.7a was significantly lower than the value of 27 m^3/hr recommended by the suppliers of the plate heat exchanger. If less water is used then the Reynolds numbers and therefore heat transfer coefficients are reduced. To compensate for the reduced water flow rate, then ideally the milk flow rate should be reduced or the number of plates in the PHE should be increased. The cooling water flow rate at Massey University No. 1 Dairy Unit was originally higher, but had long since been reduced so that water supply pressure could be maintained for other equipment.

The sprinklers were used more often in summer to keep flies away and to keep the race wet, which made the wash down after milking easier. The five tip drums lining the race by the shed helped to dislodge and wash away manure. The sprinklers and tip drums normally operated throughout the milking session. The water consuming activities that occurred intermittently during milking were the backing gates, pit pump and pit hoses. The backing gates were water driven, and were used to push the cows round into the milking area, the water being expelled was also used to drive away manure. The pit pump was water driven and used to pump out excess liquid from the pit. The pit hoses were used for washing away manure during milking in case of accidental milk contamination if the clusters fell off during the milking process. Each time the water sprinklers and pit pump was used the flow rate of water through the PHE was reduced as shown in Figures 4.7a and 4.7b. The fluctuations in the water flow rate have a direct impact on the rate of heat exchange from the milk.

Heat transfer profile of precooling system

Figure 4.8a shows that the log mean temperature was steady at about 8°C while the pump was off. This did not represent events inside the PHE because the log mean temperature difference was calculated using the inlet and outlet temperatures. When the pump was turned on, the driving force represented the real temperature difference between the milk and water inlets. However, when the pump was turned off, the driving force represented the temperature difference between the water inlet and some milk held up in the pipe – instead of milk flowing into the inlet. Because of the intermittent flow, use of equation 5.1 (with $\Delta\theta$ calculated from equation 3.3) to calculate the amount of heat transfer to milk would lead to erroneous results.

$$\phi = UA\Delta\theta \qquad (5.1)$$

Figure 4.9 shows the heat transfer rates of the milk and cooling water. From equation 4.1 one might mistakenly expect that the plots for milk and water heat transfer rates should coincide, but they do not. The water continues to gain heat after the milk flow has stopped. But the milk heat transfer rate in Figure 4.9 suggests that no heat transfer took place once the pump has stopped. This is incorrect because, as discussed previously in section (Figure 4.8b), the milk in the heat exchanger continued to be cooled while the pump was off. But the milk temperature sensors did not detect this effect as they were mounted on the inlet and outlet pipes, not inside the PHE itself where the milk was being cooled.

The curve indicates that the rate of gain for the milk during the pumping phase was much higher than the rate in the cooling water heat loss at the start of pumping. This was also an artefact of the measuring system. When the pump was started, it first pushed the milk held previously in the PHE through the outlet pipe. At that moment the rate of milk heat loss was perceived to be higher than normal. The cooling that was reported in the milk at the start of pumping did not occur at that point in time only; the extra cooling that was observed can be attributed to the cooling that had occurred previously when the milk was held up in the PHE. Therefore the amount of heating in the tail of the water transfer rate should equal the amount of extra cooling over that of the milk heat transfer at the start of the pumping phase.

Since the precooling system was not operating at steady state, the thermal mass of the PHE may also affect these rate kinetics as the PHE mass could be accumulating and loosing heat over time.

Figure 4.11 shows plots of actual and ideal rates of heat transfer to the water. The ideal heat transfer rate was calculated using the maximum temperature driving force shown in

Figure 4.10. Clearly the use of the water cooling capacity was very low. This was to be expected as the PHE at Massey University No. 1 Dairy Unit was designed to run most efficiently (high heat transfer rate) when the water flow rate was three times the milk flow rate (Hatch, 2000).

The fluctuation in average efficiency from 2.4 to 13.4% at different periods of the milking session as discussed in section 4.1.4.3 was due to variations in the flow of milk harvested from the cows while the cooling water flow rate remained constant. At all times in the milking session, the cooling capacity of the water was used very inefficiently.

5.2 Control of Pumping Regime

The pumping cycle was modified to achieve better cooling water usage, based on the following reasoning. It has been shown that when the pump switched off, some milk remained held up in the PHE and was further chilled (section 4.1.3). When the pump turned on again, this held up milk was displaced by new milk. Some new milk from the receiver also passed straight through the PHE until the pump stopped again. By changing the length of the pumping phase, less milk passed straight through the PHE and more milk could be cooled during the hold up phase.

Pumping profile with pump duration set to 3s

Figure 4.14 shows that the pump stopped at twice the frequency of the existing scheme, which was a pumping duration of 6s, and so twice as much milk experienced hold up in the PHE. Even though the residence time in the PHE was halved, the stationary milk experienced more cooling as the cooling driving force during the first half of the hold up phase is greater than that of the second half.

The effect of shortening the pump-on phase was to decrease the buffering action of the receiver by half. This may have resulted in the higher peaks in the pump duty cycle for the milking session shown in Figure 4.15 (maximum 85%) compared to the peaks for a 6s pump duration shown in Figure 4.3b (maximum 50%).

Temperature profile of PHE when pump duration was set to 3s

Although the modification improved the temperature at the milk outlet by approximately 8% (section 4.2.2), the improvement may not have been due to the new pumping regime alone, as other factors influenced the cooling achieved such as the pump duty profile and day to day variations in the water inlet temperature. For example, the water inlet temperature in Figure 4.6 (run 8, 19 November 1999) was 17°C, 0.7°C higher than the inlet water temperature of 16.3°C shown in Figure 4.16 (run 10, 21 November 1999). Cooler water temperatures increase the maximum temperature driving force and result in a lower milk outlet temperature. Thus the performance of the PHE could not be measured by comparison of temperature profiles only. The efficiency of usage of cooling water capacity calculated in section 4.1.4.3 was used to compare performance instead.

Figure 4.16 shows that the water outlet temperature fluctuated with pumping cycles. The difference in outlet and inlet water temperatures reached 8.0°C. This was greater than the differences found in the cooling water in the six second pumping regime as measured in Figure 4.6 (which was 6.7°C), which may possibly indicate that more cooling was achieved.

The water entered the PHE at about 16.3°C, in principle this water was cool enough to cool the milk from 37°C to 18.0°C as required by the COP, provided that sufficient cooling water was used as specified by the supplier. However, the instantaneous temperature of the milk during the pumping phase at Dairy Farm #1 exceeded 18°C as shown in Figures 4.5a, 4.5b. This gives a milk outlet average temperature of 17.7°C. A sample calculation can be found in Appendix 9

Unfortunately, the COP is vague regarding requirements for milk cooling in a precooler. Section 6.15 of the code of practice states "there shall be primary cooling after filtering, which should be capable of cooling the milk to 18°C".

It is ambiguous as to whether the value of 18°C refers to the maximum instantaneous temperature of the milk allowed at the exit of the precooler, or to the maximum milk mixing cup average temperature. The COP should be revised to be more specific.

However the mixing cup temperature of the milk at the PHE outlet is lower than the peak. This average milk outlet temperature can be calculated from equation 5.2 by taking account of variation in milk flow rate over time. For the 2 minute period from 76 to 78 minutes after the beginning of the milking session on 21 November 1999, shown in Figure 4.15, the average temperature obtained from equation 5.2 was 17.7°C.

$$\overline{\theta_{MO}} = \frac{\sum_{76}^{78} \theta_{MO} M \Big/ n}{\sum_{76}^{78} M \Big/ n} \tag{5.2}$$

where M = volume flow rate of milk

θ_{MO} = milk out temperature

n = number of readings taken between 76 and 78 minutes into the milking session

The main reason for cooling the milk is to limit the microbiological growth rate and enzymatic action, which increases exponentially with increasing temperature. So the retardation of microbiological growth in milk at an average temperature of 18°C is smaller than if the milk was all the time at 18°C. However this reasoning may be of little consequence as the milk all ends up mixed up (averaging the temperature) in the storage vat within a short time of exiting the precooler so the time that microbiological growth occurs at a higher temperature is minimal.

To summarise, on average, the milk exiting the PHE in Figure 4.15 complied with the COP milk outlet requirement, because the average milk temperature was lower than 18°C, but the temperature ranged between 17.1°C and 19.2°C. To obtain a maximum temperature of 18°C, the milk average temperature would have to be at 16.8 degrees, and the minimum 15.9°C, which is highly unlikely when the cooling water itself entered the PHE 16.3°C.

Efficiency of cooling water usage with a 3s pumping phase

Table 4.2 shows that the modification to the pumping regime resulted in a 6.7% overall improvement in November (7.3% to 7.9%), and a 13.4% improvement (6.2% to 7.1%) in February. The difference in improvement of efficiency in cooling water usage between November and February may be explained in terms of seasonal variations in pumping duties. In general, the efficiency of cooling water usage improves with the amount of milk flowing during a milking session because the pump works harder and the pump off phase is therefore shorter.

5.3 Control of Cooling Water Regime

Control of the cooling water regime was achieved by linking the operation of the solenoid on the water line (Figure 3.6) with the operation of the releaser pump.

Figure 4.18 shows the flow rate of the cooling water when the water solenoid valve was synchronised with the releaser pump. The primary peak at 17 m^3/hr occurs during the pump on-phase. A small flow of water of approximately 6 m^3/hr continued for 6s after the solenoid was closed. This can be attributed to water draining out of the PHE under gravity.

Temperature profile of PHE when cooling water flow rate was synchronized to operation of pump

Figure 4.19 shows that the temperature of the cooling water exiting the PHE was steady compared to the fluctuating temperatures of the original control scheme shown by Figure 4.6. The temperatures in Figure 4.19 would be typical of steady state values obtained if the milk and cooling water flowed continuously through the heat exchanger.

In Figure 4.20, the average milk out temperature was 2.7°C hotter than the cooling water entering the PHE. This is greater than the 2°C that a PHE can achieve, however, as mentioned in section 4.1.4 the PHE needs to run at greater cooling water flow rates to achieve this.

Efficiency of cooling water usage when cooling water flow rate was synchronized with pump operation

Table 4.3 shows the efficiencies in cooling water usage achieved when the operation of the cooling water is synchronized with the operation of the pump. The efficiency improved from 7.09%, 8.46% and 6.20% (25, 28 February, 8 March 2000) for continuous water flow to 27.24% when the solenoid and pump operation were synchronised on (2 March 2000).

Although less water has been used in this control scheme, the price is that the milk outlet temperature has increased further beyond the maximum temperature recommended in the COP. For example, the average milk outlet temperature in Figure 4.20 was 20°C (2.7°C hotter than the cooling water inlet temperature) compared to the 19.1 (2.0°C hotter than cooling water inlet temperature) of run 8 19 November 1999 (Figure 4.5a).

Previously in section 4.1.3, when the pump stopped, and the cooling water flowed continuously, there was some cooling of the milk held up in the PHE. In the cooling water controlled regime, any extra cooling of the held up milk during the pump-off phase would be minimal as the driving force between the milk and the water temperature would reduce as the stationery water held up in the system heated up by heat exchange with the milk.

The dropping level of cooling water in the plate heat exchanger, due to gravity, further curtailed extra cooling to the stationery milk.

Table 4.3 also shows the efficiencies when the closing of the solenoid is delayed by n seconds after the releaser pump has turned off. The benefit of delaying the closing of the solenoid was to allow the cooling water to do extra cooling to the held up milk, and to cool down the PHE plates themselves. This resulted in cooler milk exit temperatures, but also reduced the efficiency of usage of cooling water capacity.

By delaying the closing of the solenoid valve for a few seconds after the releaser pump had stopped, the mixing cup temperature of the milk exiting the PHE outlet was brought closer to the COP requirement of 18°C but efficiency of usage of the water cooling capacity decreased because more water was used from 27.24% with no delay, to 23.00% with a 1.5s delay, and to 13.17% for a 9s delay. Thus the final control scheme must take into account the conflicting objectives.

5.4 Recapitulation of Process Analysis

The analysis of the precooling system at Massey University No. 1 Dairy Unit shows that:

1 The pump duty cycle varied significantly during milking, from a high of 50% to a low of 10%, with an overall duty cycle of 20% for the session. These figures indicate that the pump was significantly oversized for the current milk pumping duties. The pump was sized for CIP and to keep up with the flow of milk to the receiver that the milking machine delivers. This flow rate is not constant during the milking session or over the season and so the pump must be adequate for peak flow conditions. There is therefore a danger of draining the receiver during periods of low milk flow with consequent cavitation and MFGM damage.

2 To avoid this problem the receiver was fitted with a level sensor connected to the pump controller which incorporated an 'off-delay' timer. Cavitation and subsequent damage to the MFGM is therefore unlikely because the NPSH at the pump inlet is always relatively high. The pump switched on when the liquid level reached a predetermined level and operated for a period of 6s before switching off. The off-delay timer is set so that there is always some milk in the receiver while the pump is operating.

3 In the current precooling system at the Massey University No. 1 Dairy Unit cooling water flows continuously. Since the milk pump is only switched on 20% of the time, 80% of the water supply to the PHE is not used for cooling and is just wasted.

4 The efficiency of usage of the water cooling capacity ranged from 6% to 8% depending on the rate of milk flow from the milking machine.

5 Some milk is held up in the PHE and piping of the precooling system. The milk held in the PHE continued to be cooled during the pump-off phase while the cooling water flowed. In the following pump-on phase this milk held up in the PHE is displaced by new milk resulting in a typical dip in the temperature trace at the milk outlet.

6 There were also fluctuations in the water flow rate to the PHE. This was due to competing usage at the farm, notably, intermittent usage of the pit hose and backing gate. This resulted in further disturbances to the rate of heat transfer across the PHE.

7 While the average mixing cup temperature of the milk at the outlet of the PHE could be kept below the value recommended by the COP, 18°C, the instantaneous temperature often exceeded this value.

8 Two methods were introduced to improve the efficiency of usage of the cooling water capacity. In both methods, cavitation was still avoided by maintaining the NPSH. The milk temperature was also recorded to monitor compliance with the COP.

9 The first method introduced was for the cooling water to flow continuously while the duration of the on-phase was decreased from 6s to 3s. For a specific design of precooling system, the exact duration of the pump-on phase could be set so that the amount of milk pumped in each pump-on phase was equivalent to the holding capacity of the PHE. This minimises the amount of milk flowing straight through the PHE and maximises the amount of milk held up in the PHE over the milking session. This trivial manipulation to the control scheme resulted in a 10% improvement in the efficiency of the existing system, and was done at no cost. However, given that the existing system is only 6% efficient, there is a large scope for improvement.

10 A second modification trialed on the precooling system was to control the solenoid used to shut off the flow of cooling water to the PHE. The modification was for the cooling water to flow only when the releaser pump operated instead of continuously throughout milking. After the pump stopped running, the cooling water could be shut off straight away, or after a delay of 0-12s (or more). A timer and a relay were the only extra equipment required to be installed to achieve this.

Setting the cooling water to flow only when the pump ran resulted in a 400% (7% to 28%) improvement in efficiency of cooling water usage. The efficiency obtained is the same as if the milk and water flowed continuously at peak flow rate during the flush of the season. However, as the cooling water temperature and flow rate were not within the PHE manufactures specifications, the milk out temperature did not achieve the $18^{\circ}C$ as required by the COP.

By increasing the amount of time that the cooling water flowed for after the pump stopped running, extra cooling could be done to the milk held up in the PHE, and the PHE itself could be cooled down. Setting the water off delay to 6s – so that the pump ran for 6s and the water flowed for 12s, resulted in a 200% improvement of usage of cooling water capacity compared to the existing control scheme.

5.5 Proposals for Further Improvements

The key issue to be resolved is summarised in Figure 5.1. The ideal heat transfer curve represents the amount of heat that the continuously flowing water can take up and the actual heat transfer rate curve illustrates how inefficiently that cooling capacity is used. Most of the time the water is wasted.

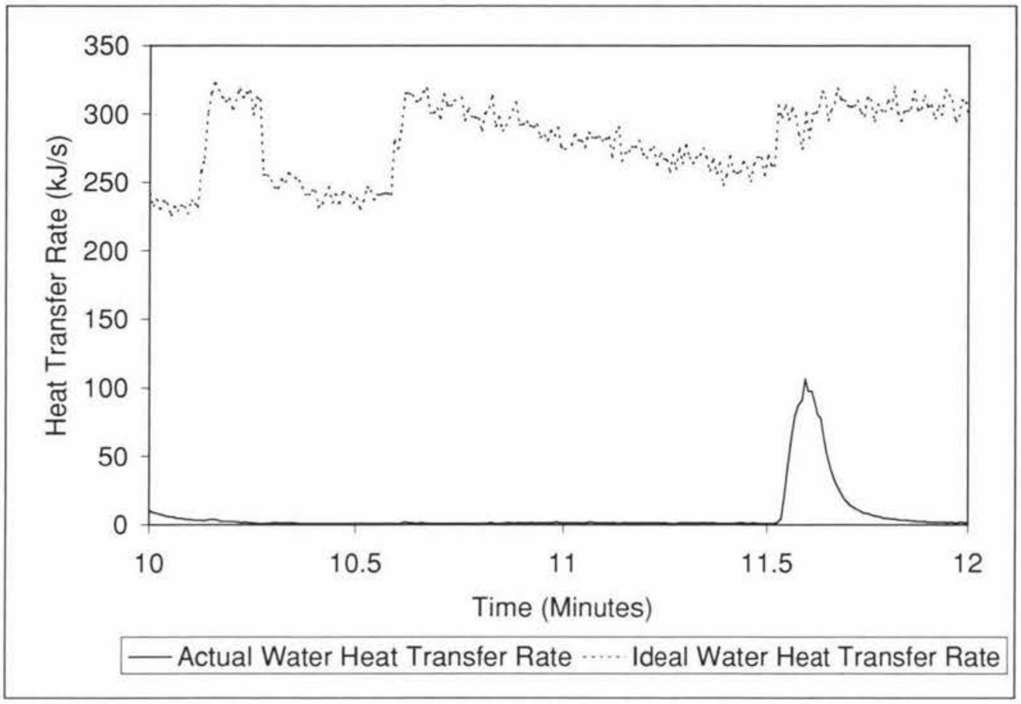

Figure 5.1 Typical trace of ideal and actual water heat transfer rates across the PHE - recorded 19 November 1999, time period 76-78 minutes after start of milking session.

The efficiency of the system could be improved significantly by reducing the cooling water flow rate to minimise the ideal heat transfer rate, or as has been done, by turning off the flow when the releaser pump is not operating. However, control of water flow rate has a detrimental impact on the compliance with the COP's requirement that milk should be cooled to 18°C. But if the water was cooler, then water usage could be minimised while ensuring that compliance with the COP was maintained. As the temperature of the water supply is sometimes in excess of 18°C, cooling of the water is required if compliance with the COP is to be maintained with the present process scheme.

Use of a cooling tower

A cooling tower could be used to cool the water entering the PHE. The advantages of a cooling tower are that a higher temperature driving force could be obtained, thus a smaller PHE would be required, and the milk can be cooled further in the PHE, which would reduce refrigeration costs. If the cooling water that had exited the PHE was recycled back to the cooling tower, and fed to a storage tank, then the flow rate of the cooling water through the PHE can be increased without an increase in water requirements. The water no longer has to be conserved by using the solenoid valve either, so the gain from cooling held up milk can be retained. This also means that the supply pressure will not limit the cooling flow rate. However, the costs of such a scheme include capital items such as a cooling tower, storage tank, and pumps. Operational costs include electricity to power the pumps, but the water requirement would also drop dramatically which is important, as many farms have limited water supplies.

Many configurations and many scenarios are possible, for example, cooling of the water could be done at nighttime only to take advantage of cheaper power rates. The scheme selected would need to be based on economic analysis of each particular design, and for each farm to obtain an optimum solution. A further storage tank could also be used to reuse the warm cooling water for other purposes such as wash down; this would incur a higher capital cost, and would again require financial analysis of the process and the impact of the control system.

Interaction between pump control system and precooling system

The analysis of the pump control regime should be carried out in conjunction with each proposed water scheme and its control. With any changes to the water scheme used, the efficiency of the water usage could be improved by manipulation of the milk flow regime.

With safeguards against cavitation in place, variable speed control (Wall, 1999) could be used to smooth out variations in the milk flow rate so that the pump duty cycle would be higher, resulting in an increase in the residence time of the milk in the PHE. The speed of the releaser pump could be based on level or time control, or a combination of both. The pump control regime should avoid cavitation and minimise the hold up of milk at 37°C in the precooling system. The precooling system is often greatly over sized as it is designed to cope with the maximum peak milk flow rate expected in the flush of the season. The releaser pump was also sized to ensure that the minimum CIP flow rate required was achieved. This resulted in milk being pumped through the precooling system in bursts at the flow rate required for CIP. The high flow rate resulted in the specification of an oversized precooling system as demonstrated by Figure 5.1. Figure 5.1 shows that most of the time no heat transfer takes place because the milk was not being pumped continuously through the heat exchanger. When the flow rate of milk entering the receiver was low, there was also the danger of cavitation because of the over sizing of the pump. A speed controller would also help in resolving the conflict between CIP and milk flow rate requirements by allowing the pump to run at a high flow rate during CIP, and at a much reduced flow rate during milking. This would then allow for a substantial reduction in the size of the PHE required.

6 Conclusions

The precooling system at Massey University No. 1 Dairy Unit has been analysed and modified to improve its efficiency.

It was found that the system had been designed to achieve two different aims:

i) Lowering of the temperature of the milk to minimise microbial growth and damage.

ii) Minimising structural damage to the milk fat globule membrane by avoiding cavitation.

The pump control scheme used to avoid cavitation was found to have a detrimental impact on the fulfilment of requirement (i). Analysis has shown that the design of the process control for the pump should be based on the equipment characteristics and the process kinetics. In this particular case, making use of the cooling of the held up milk in the plate heat exchanger (PHE) during the pump-off phase has made the cooling process more efficient. This was achieved by reducing the pump-on phase from 6 to 3 seconds and resulted in a 10% improvement in the efficiency of cooling water usage. This gain was made without additional capital investment (making it an attractive option), and was based on the analysis of the interaction between performance of the process and design of the control system, which has previously not been performed sufficiently for precooling systems.

The efficiency of usage of cooling water capacity at Massey University No. 1 Dairy Unit was found to be very low, 6-8%. This inefficiency was undesirable considering that many farms have limitations in water supply. It was identified that this low efficiency stemmed from the fact that the cooling water flowed continuously whereas milk flowed intermittently due to controlled pumping.

The implications of controlling the water flow to match the milk flow were investigated. It was found that the efficiency of cooling water usage improved significantly from 7% to 27 %. However, the milk temperature no longer complied with the New Zealand Dairy Industry Farm Dairy Code of Practice (COP) because the system no longer utilised the cooling performed on the held up milk in the PHE during the pump-off period.

It is proposed that in order to reduce water consumption, while achieving the COP requirements of minimising microbial damage by lowering temperature, and structural damage to the milk fat globule membrane by pumping, can only be achieved in cooling the water itself, for example by using a cooling tower. There are other possibilities that have not been discussed, as they are not within the scope of this thesis. However it is recommended that whatever option is taken, it is important that the process analysis and equipment design are carried out in conjunction with analysis and design of the control system. This would ensure optimum performance of the system.

There were findings specific to the case study of Massey University No. 1 Dairy Unit:

i) Temperature measurement of the milk entering the bulk milk vat using the pre-existing temperature sensor on the vat Clean In Place control unit was not reliable. The instantaneous temperature measurement may not be representative of the temperature of milk entering the vat. No measurement of the mixing cup temperature of milk entering the vat was made.
ii) The releaser pump was oversized as the duty cycle of the pump was found to cycle between about 10 and 50% instead of the recommended overall duty cycle of 50% for a herringbone shed.
iii) The flow rate of cooling water through the PHE varied and was much lower than that designed. This resulted in difficulties in cooling the milk to the temperature required by the COP.

The COP is not clear whether the capacity to the cool milk to 18°C or below pertains to the average, or the instantaneous temperature. It is recommended that the COP should be made clearer regarding this requirement.

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Appendices

Most of the experiments in this work were computerised and the data collected during this process was substantial. The writer felt that it was important to present the raw data, so the data has been included with the thesis in the form of a CD (Appendix 13). The structure of the data on the CD is given in Appendix 12. However, excerpts of the raw data and calculations required to convert the digitised output from the data logger to process variables are also presented in the Appendices. These short excerpts are presented in Appendix 7 to 10 to demonstrate how the data on the CD can be more easily navigated. The excerpts do not show the calculations required to convert the data so the equations and sample calculations are also presented.

Work done as part of this Masters to determine characteristic curves of a Fristam pump with milk of high total solids contents is also presented. The work was not followed up as it was not pertinent to the precooler operation at Massey University No. 1 Dairy Unit. However, the findings are interesting, so a paper and preliminary findings may be found in the Appendix 1. The raw data, calculations, and measurements of density, and viscosity are also presented in Appendix 13. If the reader wishes to use this data to develop characteristic curves for a pump, then they should contact the author separately.

Chemistry tests, schematics of fabricated equipment, programs and data sheets are also presented in Appendix 2, 3, 5 and 6.

A copy of the thesis itself will also be found on the CD.

Appendix 1 Pump Characteristic Curves at Different Total Solids Contents

Appendix 1.1 Paper: Characteristic pump curves at different evaporator effects in a milk powder plant

Characteristic Pump Curves at Different Evaporator Effects in a Milk Powder Plant

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Abstract

Characteristic curves for a Fristam FP712 pump were determined for skim milk of differing total solids contents typical of those found in a milk powder plant. The pressure head developed at any given flow rate decreased significantly with increasing total solids contents. Therefore pump head curves must be measured for solutions at particular total solids contents before pump sizing and selection can be performed.

1. Introduction

This report is concerned with the pumping of milk between the effects of an evaporator.

A *pump* is a device which transforms mechanical energy into pressure energy. The pressure energy generated can then be transformed into kinetic energy (mass flow rate) if there is a sufficient pressure gradient in the system. The flow in the system can therefore be related to pressure delivered by the pump to the fluid. However, most pumps do not deliver a constant pressure; the pressure can depend on the flow rate through the pump. In that case, the relationship between the increase in pressure across the pump and the flow rate is called the pump head curve. The *characteristic curve* of a *pump* (or the 'pump head curve') is a function of the design of the pump and may be used to characterise the pump. Pump head curves must therefore be measured for each pump design. Viscosity is a measure of internal friction in a liquid and is known to have an influence on some pump head curves [4].

Milk powder plants remove water from milk until only the solid components of the milk remain. The key processes used in milk powder plants are evaporation and drying, with other equipment used to condition the milk. Evaporation is carried out in multistage *evaporators*. Each stage is called an *effect*. In the milk powder industry evaporators can have between three and seven effects. Evaporators are very energy efficient and as much water as possible is removed at the evaporation stage which is therefore important to understand and control.

Evaporators in milk powder plants are used to concentrate *milk* from approximately 9% total solids (TS) content for skim milk or 12% for whole milk to about 48% or 50% TS. Each effect will handle milk of a differing TS content. The *viscosity* of the milk in the effects varies with TS content, as well as temperature [1].

Pumps are used to transport milk from one effect to another. When designing a milk powder plant, it is important to size the pumps correctly as over sized pumps can result in cavitation with possible increases in fouling and consequent cleaning costs. To size a pump for a milk powder plant, it is necessary to know the characteristic head curve of the pump for the total solids predicted at the evaporator effects.

To the authors' knowledge, no experimental work has been done to investigate the effect of milk TS content on pump head curves. There are also no correlations for the effects of changes in total solids found in literature searches, although a computer program exists for estimating the effect of viscosity [3].

This report will attempt to present some pump head curves that will be useful to the milk powder manufacturing industry.

2. Experimental

A pump typical of those used in the New Zealand dairy industry was chosen, a Fristam FP712/110KF, 1.5 kW, 2900 rpm centrifugal pump. The pump was connected to an experimental rig as shown figure 1. Two pressure sensors, P_1 & P_2 (DPI201 & DPI260, Druck Ltd), were mounted in 1½" stainless steel pipe on either side of the pump. The pressure difference, ΔP, between the two pressures P_1 and P_2 can be expressed as hydrostatic head (h) using the equation (1) where ρ is the liquid density, and g is the acceleration of gravity.

$$h \cdot \rho \cdot g = \Delta P \qquad \textbf{(1)}$$

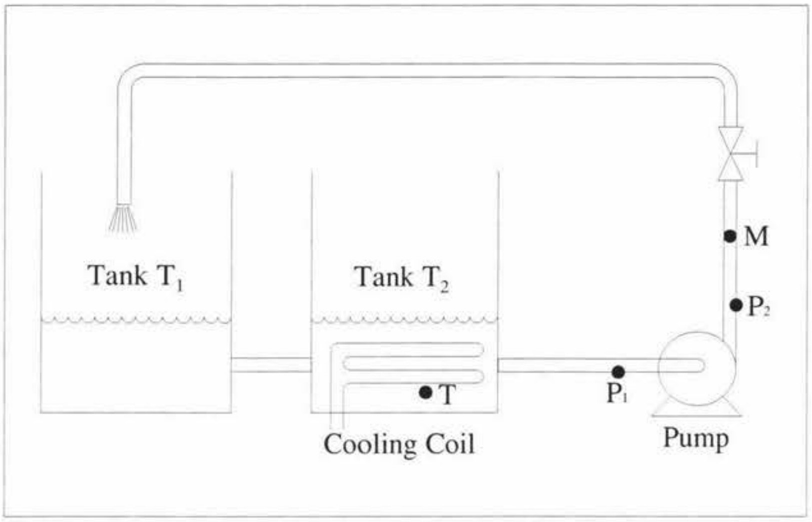

Figure 1. Diagram of experimental pump rig

A manual control valve was used to adjust the flow rate which was measured using a magnetic flow metre, M (Promag 30F, Endress + Hauser). Tank T_2 was used as the milk feed tank and an additional tank, T_1, was used as the pump outlet tank to reduce disturbances to the pump inlet.

The pressure and flow rate data were acquired using an Allen Bradley SLC500 Programable Logic Controller. The temperature data was acquired using a Keithley Metrabyte Das-TC card. The data obtained using the Allen Bradley and Das-TC were logged using the SCADA (Supervisory Control And Data Acquisition) software package FIX DMACS by Intellution Inc.

Pump head curves were then generated using milk of three different concentrations. The concentrations of milk used were those calculated for a three effect direct steam evaporator (DSE - no vapour recompression) with direct stream injection (DSI) preheating (48%, 28% and 16% TS content respectively). The values were calculated by simply assuming that one kilogram of steam will evaporate one kilogram of water present in milk. Heat losses were ignored [5].

Reconstituted milk was used instead of fresh milk because it was more convenient to handle, store and process within the limited facilities available. It was also flash preheated in the original milk powder production process so further preheat treatment was not required after reconstitution. The milk powder used was medium heat skim milk powder obtained from the New Zealand Dairy Research Institute. The milk was first reconstituted to 48% total solids by recirculating a mixture of water and milk powder in the pump rig for 40 minutes. After collection of experimental data for the 48% TS content pump head curve, the same milk was diluted to 28% and a further test run was made. Finally another run was made after further dilution to 16%. In all runs the volume of liquid used in the pumping rig was kept constant.

The pumping part of the experiment lasted for seven hours in total. During pumping, the temperature of the milk increased because of internal fluid friction. A cooling coil was incorporated in tank T_2 to attempt to keep the milk temperature constant. This is important as viscosity varies with temperature. The milk remained within a temperature range between 16.5 and 28°C by circulating cold tap water (15°C) in the copper coil. No attempt was made to regulate the milk temperatures in the system to the typical operating temperatures of a three effect DSE evaporator (70, 60 & 50°C).

The total solids contents of the milk were tested using a total solids oven test at 108°C for three hours [2]. tempts were made to measure the density and viscosity of the milk at different concentrations, but because of air inclusion during reconstitution, the results were deemed unreliable (densities less than one were being obtained!).

3. Results & Discussion

The TS content of the reconstituted milk samples measured by the oven method were within ±0.6% of the target TS concentrations.

Reliable values of density could not be obtained due to air inclusion during reconstitution therefore the hydrostatic pressure could not be calculated as implied by equation 1. The characteristic curves of the pump for the three milk solutions is therefore given as pressure difference between the outlet and the inlet of the pump versus flow rate, as shown in figure 2. Results were first obtained as the flow rate was reduced (descending), and then again as the flow rate was increased (ascending).

The ascending and descending curves for each TS solution are expected to coincide when the physical properties of the solution are not time dependent. Figure 2 shows a difference between the ascending and descending curves for the 16% and 28% TS solutions.

It is possible that the amount of air inclusion in the milk changed during pumping and affected both the density and viscosity of the air/milk mixture.

The pump head curves generated for the three milk solutions reduce significantly as the TS content

The pump head curves generated for the three milk solutions reduce significantly as the TS content increases. Buckingham (1978) showed that the viscosity of skim milk increases for increasing TS. Pump head curves generated using water are therefore not appropriate for high TS content applications.

In figure 2, the pump head curves are seen to plateau with constant TS content at low head pressures. These plateaus lengthened with increasing concentration and are present in the 28% and particularly in the 48% TS content milk solution. This trend was unexpected as pump characteristic curves generally take on the form of a second order polynomial, a pseudo-plastic fluid for example flattens and elongates the characteristic curve for a pump but plateau effects are not know of in the non Newtonian fluids analysed in the Food Technology Department, nor in any work known to the authors (Steven, 1996).

The effect of the plateau in the pump head curves seen in figure 2 would greatly effect the sizing and selection of a pump because the pressure differential generated over most of the high flow rate range of the pump is very low compared to the pressure differential generated at the lower flow rates.

Air inclusion in the milk during the experiment, may have affected some of the results of the experiments. The exact amount of air inclusion that occurred could not be measured due to lack of time. It is possible that air inclusion is the reason for the plateau effects observed in figure 2 but this cannot be proved at the present time.

4. Conclusion

It is necessary to know the exact pump head curve for each solution before pump selection is possible. This further work must be carried out to confirm the preliminary results obtained in this work.

Air inclusion, and plateauing in the pump head curve as a possible consequence, are of particular interest since they may also occur in real plants. Improvements in experimental design are required to minimize any air inclusion. Whole milk could be used as a test fluid as it is more commonly found in industry.

5. References

[1] Buckingham, J.H, "Kinematic Viscosities of New Zealand Skim Milk", *J. of Dairy Research*, 1978, pp. 25.

[2] Monotype Composition Company Inc, "Method 16.032", *Official Methods of Analysis of the Association of Official Analytical Chemists*, 13th edition, George Banta Company Inc., Washington DC, 1980.

[3] Sorrell, T., Taylor, R., Hodge, B, "Estimating Pump Curves for High-Viscosity Fluids", *Heating/Piping/Air Conditioning*, October 1990, pp. 75.

[4] Steven, M, *"Non-Newtonian Pump Characteristic Curves"*, BTech Report, Department of Food Technology, Massey University, 1996.

[5] Trinh, K.T., "Chapter 3", *Dried Milk Technology. Course Notes*, Department of Food Technology, Massey University, 1997.

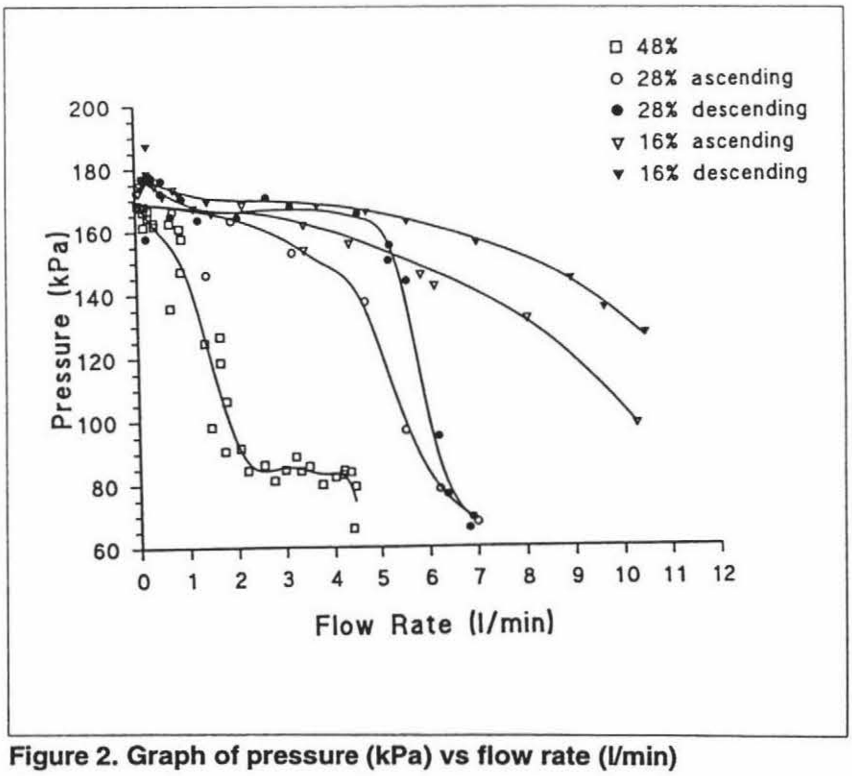

Figure 2. Graph of pressure (kPa) vs flow rate (l/min)

Appendix 1.2 Preliminary data for characteristic curves of whole milk at different total solids contents

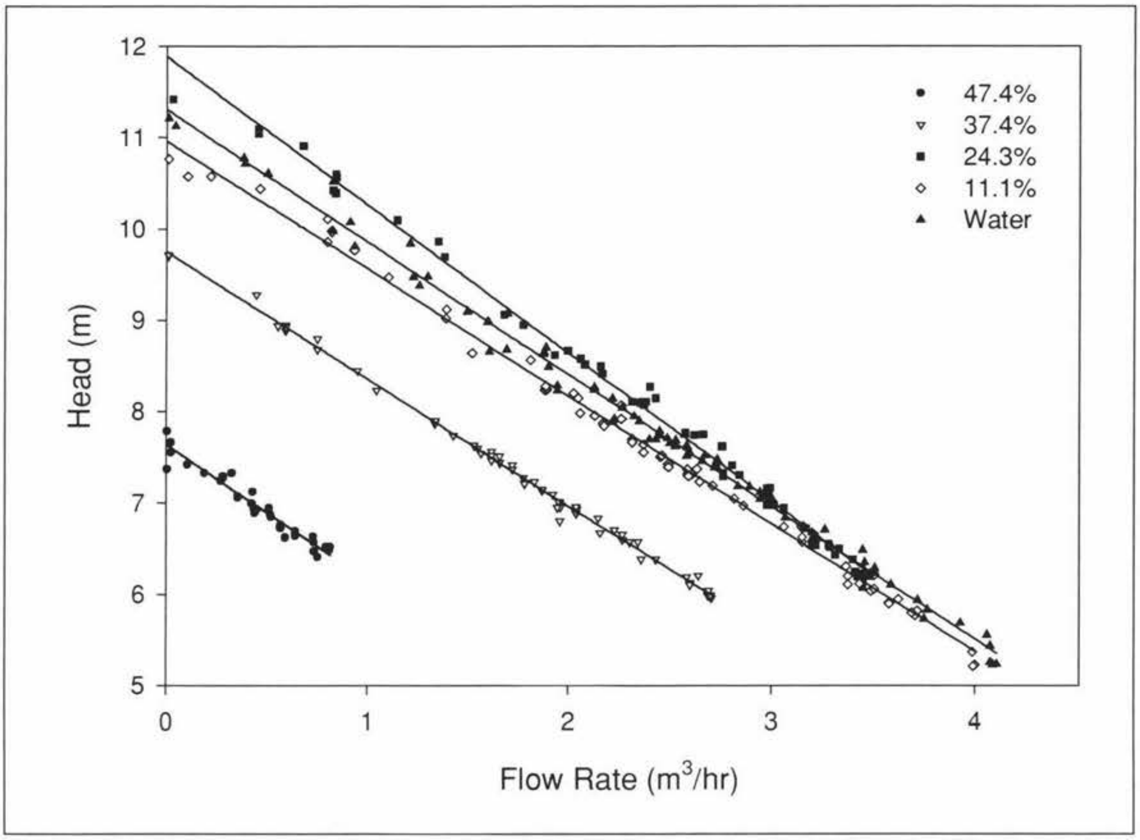

Figure A.1 Pump head curve for Fristam FP712 pump with milk of differing total solids contents (run 5).

Appendix 2 Method For Determining Damage to MFGM

Appendix 2.1 Lipolysable free fat test

The Lipolysable free fat test as proposed by Fang, 1998, was used to determine the amount of damage done to the milk fat globule membrane by the action of the pump. This was achieved by adding external pancreatic lipase to the milk sample. The lipase attacked the lipids that lacked the protection of the natural MFGM resulting in free fatty acids. The free fatty acid content was then measured to determine the amount of damage that had occurred in the milk.

Apparatus:

1. Burette, 1ml with 0.02 ml graduations
2. 30°C warm room

Reagents:

Pancreatic lipase solution, 50 mg,100 ml.

Procedure:

1. Pipette 1 ml pancreatic lipase solution into 100 ml milk sample.
2. Mix the sample with glass rod gently.
3. Put the sample in a warm room at 30°C and incubate for 24 hours.
4. Measure the free fatty acid content by the following method.

Appendix 2.2 Free fatty acid content

(Dairy Division Standard Method, 1980)

Free fatty acids are extracted using ether and determined by titration against alcoholic potassium hydroxide using alpha-naptholphthalein indicator.

Apparatus:

1. Extraction flasks (Mojonnier tube).
2. Centrifuge, Mojonnier type.
3. Burette, 10 ml with 0,05 ml graduations.
4. Erlenmeyer flasks, 100 ml.

Reagent:

1. Bromophenol blue indicator, 0.5% aqueous solution.
2. Sulphuric acid, 0.5M
3. Mixed solvent, two parts of diethyl ether to one part petroleum spirit (B.P. 50/60°C).
4. Alpha-naphtholphthalein indicator, 1% solution in ethanol.
5. Neutralized ethanol.
6. Neutralized methanol. To neutralise reagent 5 to 6, add 0.5 ml of reagent 4 to 100ml of the alcohol, neutralize with alcoholic potassium hydroxide to the first sign of greenish tinge in the yellow solution.
7. Alcoholic potassium hydroxide, 0.01M in ethanol, standardized frequently against benzoic acid dissolved in the mixed solvent.

Procedure:

1. Pipette 10.0 ml of well-mixed sample at 20±2°C into a Mojonnier extraction flask.
2. Carry out a blank using 10.0 ml of water.
3. Add 3 drops of bromophenol blue indicator.
4. Add 0.5M sulphuric acid drop wise until the colour changes to greenish/yellow (usually 0-1.5 ml required)

5. Add 5 ml of neutralized ethanol, stopper and shake vigorously for one minute.
6. Add 15 ml of mixed solvent, stopper and again shake vigorously for one minute.
7. Centrifuge for 5 minutes.
8. Pipette 10.0 ml of the clear supernatant ether layer into a 100 ml Erlenmeyer flask.
9. Add 10 ml neutralized methanol.
10. Titrate against 0.01M alcoholic KOH to the first sign of a greenish tinge in the yellow solution.

Calculation and Report:

Free fatty acid content as % oleic acid = $1.35 \times 0.0284 \times (T-B)$

where T= sample titration figure.

B = blank titration figure.

Report to the nearest 0.05 mmols/litre or 0.001% as oleic

The Technical Characteristics of Pancreatic Lipase

Supplied by SIGMA chemical Co.

The product is Type II, Crud; from Procine Pancreas.

It contains approximately 25% protein. One unit will hydrolyse 1.0 microequivalent of fatty acid from a triglyceride in one hour at the indicated pH and incubation time. 7.5 g protein (Burette) 43 units/mg protein (using triacetin at pH 7.4). 190 units/mg protein (using olive oil at pH 7.7).

Caution Desiccate, Store at 2-8°C. Avoid contact and inhalation.

Appendix 3 Schematics Of Pipes Used For Mounting Sensors

Appendix 3.1 Schematic of pipes used for mounting pressure sensors at inlet and outlet of releaser pump

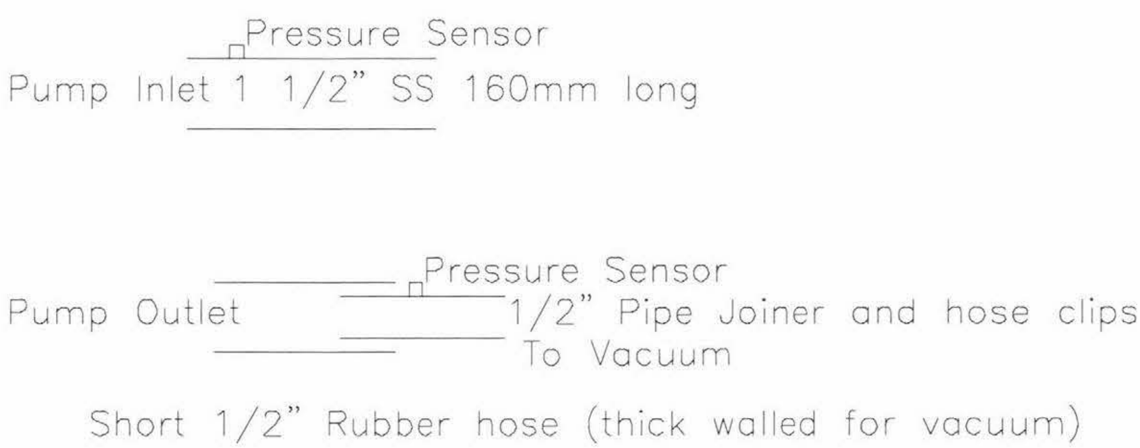

Figure A.2 Schematic for fittings used to install sensors for measuring pressure at inlet and outlet of Massey University No. 1 Dairy Unit releaser pump.

Appendix 3.2 Schematic of pipes used for mounting temperature sensors and flow meters on inlet and outlet of PHE

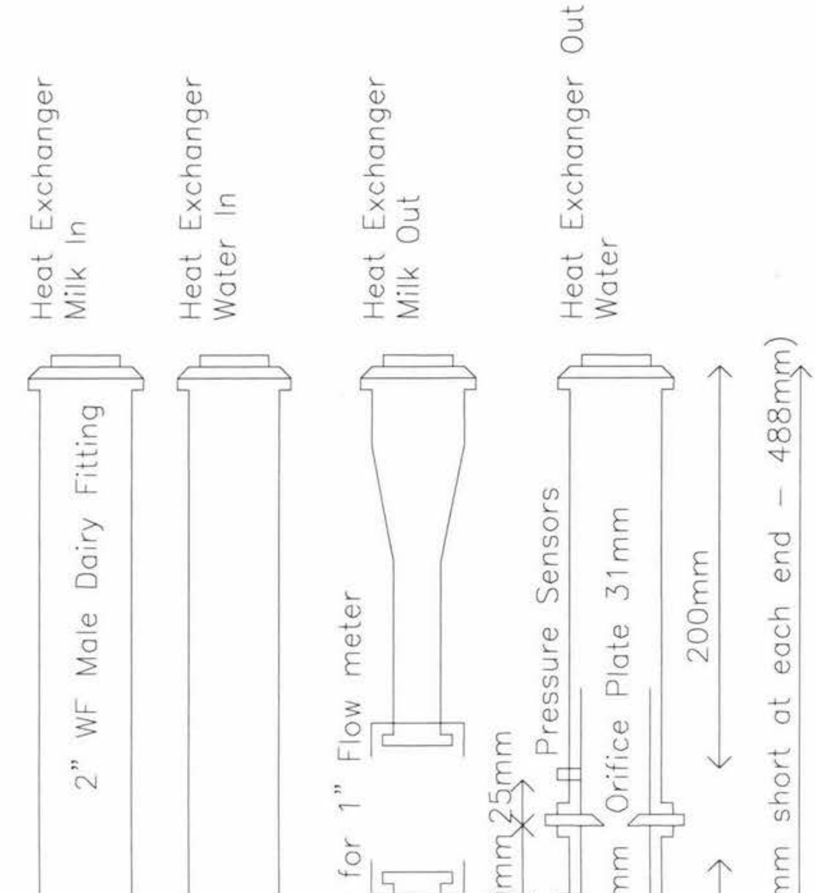

Figure A.3 Schematic for pipes used to install measuring devices in Massey University No. 1 Dairy Unit precooling system.

Appendix 4 Flow Rate Data For Sizing Orifice Plate

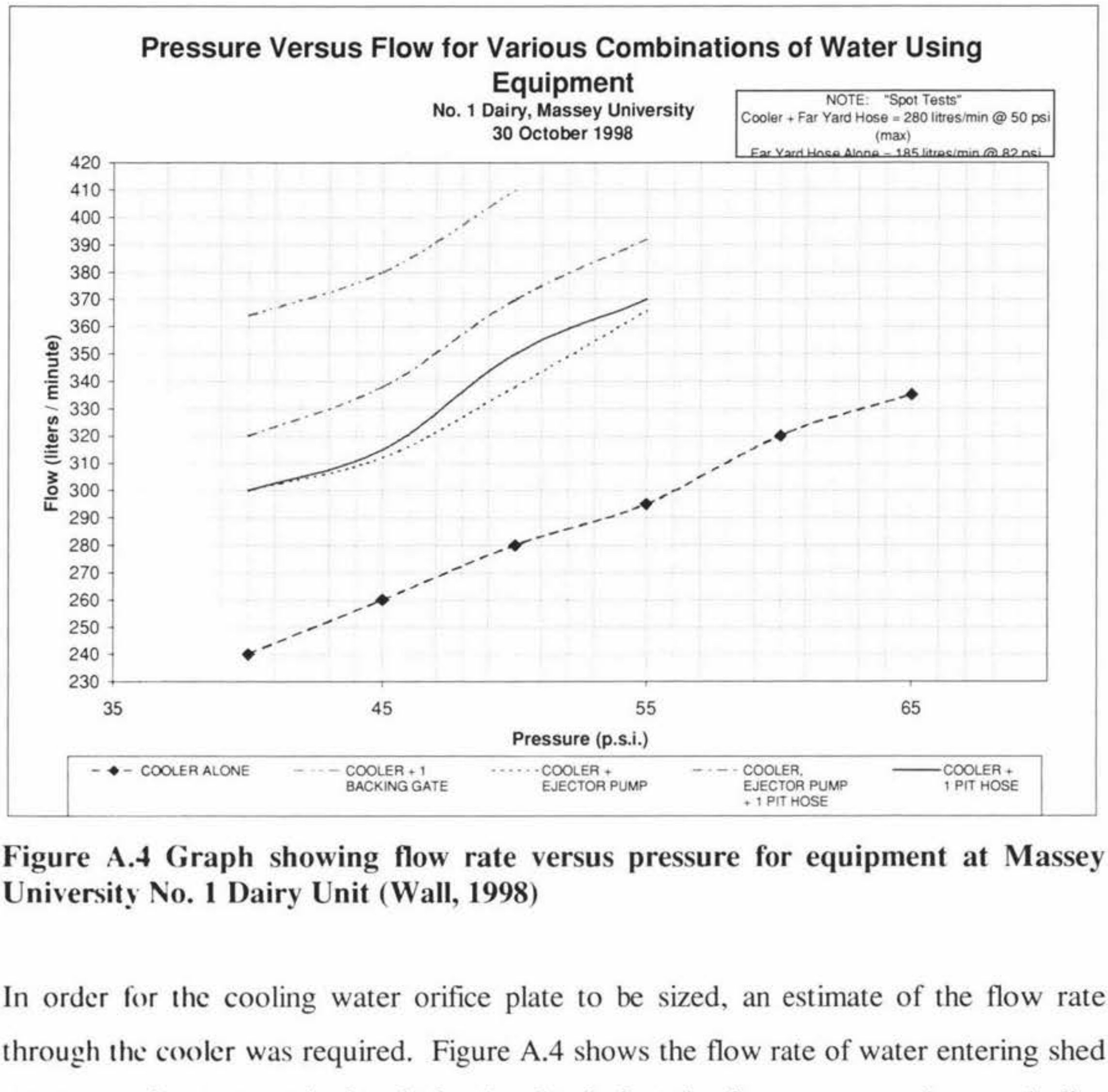

Figure A.4 Graph showing flow rate versus pressure for equipment at Massey University No. 1 Dairy Unit (Wall, 1998)

In order for the cooling water orifice plate to be sized, an estimate of the flow rate through the cooler was required. Figure A.4 shows the flow rate of water entering shed versus supply pressure in the shed. A valve before the flow meter on the supply line was closed in varying degrees to reduce the pressure and flow rate to the shed. The data was collected when no milking was being carried. To estimate the flow rate of cooling water through the heat exchanger during milking, the pressure at the precooler was observed during milking, and the flow rate determined from Figure A.4.

Appendix 5 CR10 Data Logger Programs

The number of measurements required initially to characterize the precooling operation was more than the 6 channels available on the CR10. A Campbell AM416 multiplexer was used to multiplex the signals into channels 1 and 2 of the CR10. While channel 4 was used for the cold junction compensation. The program was then used to record the time and measurements in volatile memory. The data was required to be downloaded every 10 minutes to a laptop before the CR10's memory was exhausted.

The second program was used to record only the data required to calculate the cooling efficiency of the heat exchanger, the CJC (Cold Junction Compensation) reference temperature, and the water inlet, outlet and, milk inlet temperatures as well as the two pressures across the orifice plate used for measuring flow rate.

Appendix 5.1 CR10 program using multiplexer

The CR10 program used for acquiring data via the multiplexer worked as follows:

Line *: Execute following program every .5 seconds (program records results every .5 seconds).

Line 01: Obtain CJC reference temperature and poke result into memory location 2. Note: Memory location 1 was set to 0 on power up and the polarity of the CJC reference thermocouple was reversed, giving the temperature difference between 0°C (ice slush) and ambient. The thermocouple was connected to CR10 channel 4.

Line 02: When digital output 1 on CR10 is set high ("res" input on multiplexer), the multiplexer is initialised and the channel select is set to channel 1.

Line 03: A program loop was set up between line 03 and line 07, to be repeated 6 times.

Line 04: When digital output 2 on CR10 is pulsed ("clk" input on multiplexer), the channel select is incremented by 1.

Line 05:	Record temperature input of channel 1 on CR10 and record in memory location 2+loop count. Use memory location 2 for reference temperature.
Line 06:	Record voltage input of channel 2 on CR10 and record in memory location 8+loop count.
Line 07:	End loop.
Line 08:	Deactivate multiplexer.
Line 09:	Record output to ring memory. Begin new record.
Line 10:	Read year, day, hour-minute, seconds.
Line 11:	Read memory locations 1 through to 14
Line 12:	Cease output to ring memory

The code listing of the program used when the CR10 was used in conjunction with the mulitplexer is shown below:

```
Program:

Flag Usage:
Input Channel Usage:
Excitation Channel Usage:
Control Port Usage:
Pulse Input Channel Usage:
Output Array Definitions:

*      1        Table 1 Programs
  01: .5        Sec. Execution Interval

01:  P14        Thermocouple Temp (DIFF)
  01: 1         Rep
  02: 31        2.5 mV 50 Hz rejection Range
  03: 4         IN Chan
  04: 1         Type T (Copper-Constantan)
  05: 1         Ref Temp Loc
  06: 2         Loc :
  07: 1         Mult
  08: 0         Offset

02:  P86        Do
  01: 41        Set high Port 1

03:  P87        Beginning of Loop
  01: 0000      Delay
  02: 6         Loop Count

04:  P86        Do
  01: 72        Pulse Port 2

05:  P14        Thermocouple Temp (DIFF)
  01: 1         Rep
  02: 31        2.5 mV 50 Hz rejection Range
  03: 1         IN Chan
  04: 1         Type T (Copper-Constantan)
  05: 2         Ref Temp Loc
  06: 3--       Loc :
  07: 1         Mult
  08: 0.0000    Offset

06:  P2         Volt (DIFF)
  01: 1         Rep
  02: 35        2500 mV 50 Hz rejection Range
  03: 2         IN Chan
  04: 9--       Loc :
  05: 1         Mult
  06: 0.0000    Offset

07:  P95        End

08:  P86        Do
  01: 51        Set low Port 1


09:  P86        Do
  01: 10        Set high Flag 0 (output)

10:  P77        Real Time
  01: 1221      Year,Day,Hour-Minute,Seconds
```

```
11:  P70       Sample
  01: 14       Reps
  02: 1--      Loc

12:  P86       Do
  01: 20       Set low Flag 0 (output)

13:  P         End Table 1

*     2        Table 2 Programs
  01: 0.0000   Sec. Execution Interval

01:  P         End Table 2

*     3        Table 3 Subroutines

01:  P         End Table 3

*     A        Mode 10 Memory Allocation
  01: 28       Input Locations
  02: 64       Intermediate Locations
  03: 0.0000   Final Storage Area 2

*     C        Mode 12 Security
  01: 0        LOCK 1
  02: 0        LOCK 2
  03: 0000     LOCK 3

Page 3    Input Location Assignments (with comments):

 Key:
 T=Table Number
 E=Entry Number
 L=Location Number

 T:  E:  L:
 1:  1:  2:  Loc :
 1:  5:  3:  Loc :
 1:  6:  9:  Loc :
```

Appendix 5.2 CR10 program used for collecting data for efficiency calculations

```
Program:
Flag Usage:
Input Channel Usage:
Excitation Channel Usage:
Control Port Usage:
Pulse Input Channel Usage:
Output Array Definitions:

*      1       Table 1 Programs
  01: .5       Sec. Execution Interval

01:  P14       Thermocouple Temp (DIFF)
  01: 1        Rep
  02: 31       2.5 mV 50 Hz rejection Range
  03: 1        IN Chan
  04: 1        Type T (Copper-Constantan)
  05: 1        Ref Temp Loc
  06: 2        Loc :
  07: 1        Mult
  08: 0        Offset

02:  P14       Thermocouple Temp (DIFF)
  01: 1        Rep
  02: 31       2.5 mV 50 Hz rejection Range
  03: 2        IN Chan
  04: 1        Type T (Copper-Constantan)
  05: 2        Ref Temp Loc
  06: 3        Loc :
  07: 1        Mult
  08: 0.0000   Offset

03:  P14       Thermocouple Temp (DIFF)
  01: 1        Rep
  02: 31       2.5 mV 50 Hz rejection Range
  03: 3        IN Chan
  04: 1        Type T (Copper-Constantan)
  05: 2        Ref Temp Loc
  06: 4        Loc :
  07: 1        Mult
  08: 0.0000   Offset

04:  P14       Thermocouple Temp (DIFF)
  01: 1        Rep
  02: 31       2.5 mV 50 Hz rejection Range
  03: 4        IN Chan
  04: 1        Type T (Copper-Constantan)
  05: 2        Ref Temp Loc
  06: 5        Loc :
  07: 1        Mult
  08: 0.0000   Offset
```

```
Page 2   Table 1

05:  P2         Volt (DIFF)
  01: 1         Rep
  02: 35        2500 mV 50 Hz rejection Range
  03: 5         IN Chan
  04: 6         Loc :
  05: 1         Mult
  06: 0.0000    Offset

06:  P2         Volt (DIFF)
  01: 1         Rep
  02: 35        2500 mV 50 Hz rejection Range
  03: 6         IN Chan
  04: 7         Loc :
  05: 1         Mult
  06: 0.0000    Offset

07:  P86        Do
  01: 10        Set high Flag 0 (output)

08:  P77        Real Time
  01: 0021      Hour-Minute,Seconds

09:  P70        Sample
  01: 6         Reps
  02: 2--       Loc

10:  P86        Do
  01: 20        Set low Flag 0 (output)

11:  P          End Table 1

*      2        Table 2 Programs
  01: 0.0000    Sec. Execution Interval

01:  P          End Table 2

*      3        Table 3 Subroutines

01:  P          End Table 3

*      A        Mode 10 Memory Allocation
  01: 28        Input Locations
  02: 64        Intermediate Locations
  03: 0.0000    Final Storage Area 2


*      C        Mode 12 Security
  01: 0         LOCK 1
  02: 0         LOCK 2
  03: 0000      LOCK 3
```

```
Page 3    Input Location Assignments (with comments):


Key:
T=Table Number
E=Entry Number
L=Location Number

T:  E:  L:
1:  1:  2:  Loc :
1:  2:  3:  Loc :
1:  3:  4:  Loc :
1:  4:  5:  Loc :
1:  5:  6:  Loc :
1:  6:  7:  Loc :
```

Appendix 6 Data Sheets for Relay and Omron Timer

The relay and timer were used in the control of the cooling water regime.

Relay Used To Start Omron Timer:

Figure A.5 shows a DPDT (Double Throw, Double Pole) relay similar to that used to convert the 230V (Phase-Neutral) milk pump contactor signal to an open/close signal required for the Omron controller.

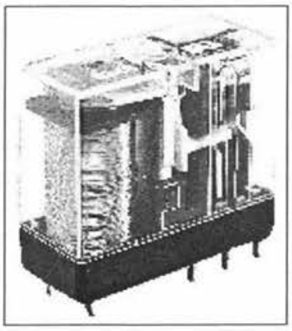

Figure A.5 DPDT relay, 230V, 10 amp (Dick Smith, 2000).

Omron Timer:

An Omron timer was used to operate the solenoid. When the milk pump started, the timers relay closed. When the milk pump stopped, the timer counted up to the preset time and then opened it's relay output – on, off delay, control mode. The timer, and further details of its operation are shown in Figure A.6 and Table A.1.

Timers

H3CR-A

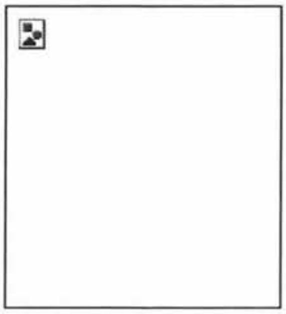

Figure A.6 Omron timer

Table A.1 Data sheet for Omron timer (Omron Asia Pacific, 2000).

Model	Approved Standards
H3CR-A	UL, CSA, Lloyds/NK, CE
Classification	Solid-state Timer
Features	- Multi-functional with many time ranges, operating modes and wide power supply ranges - Time setting Rings enable consistent settings and limit the setting range
Time Range	0.05 s to 300 h
Supply Voltage	100 to 240 VAC/100 to 125 VDC, 24 to 48 VAC/12 to 48 VDC
Power Consumption	2 VA/0.8 W (A and A8 type); 2.5 VA/0.9 W (AP type)
Accuracy of Operating Time	±0.2% FS max. (±0.2% FS ±10 ms in ranges of 1.2 s)
Control Output	DPDT: 5 A, 250 VAC Solid-state output: 100 mA, 30 VDC
Contact Configuration	Time-limit: DPDT, Solid-state
DIN size	48 x 48 mm
Weight	90 g
Enclosure Ratings (Front Panel)	IEC: IP40

Last modified on : 27/03/2000

Appendix 7 Raw Data from CR10

Table A.2 Typical raw data – run 8 recorded 19 November 1999 13-13.77 minutes after start of milking session, File Name: RawData_19Nov99_2.dat).

Campbell Generated	Year	Day	Hour:Minute	Seconds	CJC Reference	CJC (°C)	Water Inlet (°C)	Spare (°C)	Milk Inlet (°C)	Milk Outlet (°C)	Spare (°C)	Water Outlet (°C)	Pump (On/Off) (mV)	Milk Flow Rate (mV)	Orifice Out IPres. (mV)	Orifice In Pres. (mV)	Pump Outlet Pres. (mV)	Pump Inlet Pres. (mV)
109	1999	323	1520	56.88	0	17.7	17	-6999	35.3	20.32	17.08	17.52	-552.9	482.3	1435	749	82.1	-42.86
109	1999	323	1520	57.88	0	17.7	17	-6999	35.29	20.32	17.08	17.48	-556.2	483.3	1430	748	81.6	-42.86
109	1999	323	1520	58.88	0	17.7	17	-6999	35.28	20.32	17.07	17.47	-558.2	483	1400	754	81.7	-42.86
109	1999	323	1520	59.88	0	17.7	16.99	-6999	35.26	20.32	17.08	17.45	-549.9	482.7	1420	756	81.1	-42.86
109	1999	323	1521	0.875	0	17.7	17	-6999	35.27	20.34	17.08	17.44	-561.5	482.8	1415	758	81.4	-42.86
109	1999	323	1521	1.875	0	17.7	16.98	-6999	35.25	20.32	17.08	17.41	-549.4	482.5	1425	760	81.4	-42.53
109	1999	323	1521	2.375	0	17.7	16.99	-6999	35.24	20.32	17.07	17.4	-597.9	483	1440	765	80.7	-42.69
109	1999	323	1521	3.375	0	17.7	-6999	-6999	35.5	20.32	17.08	17.46	-6999	483	1364	799	79.9	-48.2
109	1999	323	1521	4.5	0	17.7	-6999	-6999	35.47	18.67	17.09	20.04	-6999	1016	1426	763	79.7	-48.87
109	1999	323	1521	5.375	0	17.7	8.46	-6999	35.37	18.4	17.08	22.15	-6999	1455	1421	729	80.1	-48.53
109	1999	323	1521	6.375	0	17.7	6.449	-6999	35.32	19.44	17.08	23.34	-6999	1537	1419	720	80.2	-48.7
109	1999	323	1521	7.38	0	17.7	8.96	-6999	35.14	20.26	17.09	24.07	-6999	1550	1438	667.9	80.1	-46.2
109	1999	323	1521	8.38	0	17.7	15.16	-6999	35.06	20.59	17.09	23.99	-6999	1415	1423	714	80.4	-44.36
109	1999	323	1521	9.38	0	17.7	8.52	-6999	34.97	20.48	17.08	21.5	-6999	1164	1432	740	80.6	-40.69
109	1999	323	1521	10.38	0	17.7	16.99	-6999	34.95	20.42	17.08	22.15	-6999	1066	1422	876	81.4	-43.7
109	1999	323	1521	11.38	0	17.7	16.96	-6999	34.9	20.43	17.08	20.57	-921	605.4	1421	678.4	81.9	-43.03
109	1999	323	1521	11.88	0	17.7	16.98	-6999	34.9	20.42	17.08	19.83	-723	576.7	1438	773	81.6	-43.2
109	1999	323	1521	12.88	0	17.7	16.96	-6999	34.86	20.42	17.08	18.96	-587.1	505	1406	749	81.6	-43.03
109	1999	323	1521	13.88	0	17.7	16.98	-6999	34.88	20.44	17.09	18.46	-578.5	486.5	1422	755	82.2	-42.53
109	1999	323	1521	14.88	0	17.7	16.98	-6999	34.86	20.43	17.1	18.18	-575.5	483.5	1406	757	81.2	-43.2
109	1999	323	1521	15.88	0	17.7	16.98	-6999	34.83	20.42	17.09	17.98	-577	483.8	1416	749	81.6	-42.36
109	1999	323	1521	16.88	0	17.7	16.99	-6999	34.81	20.42	17.1	17.86	-579.4	483.3	1422	758	81.2	-42.19
109	1999	323	1521	17.88	0	17.7	16.98	-6999	34.77	20.44	17.09	17.76	-569.4	483.5	1413	753	82.1	-41.86
109	1999	323	1521	18.88	0	17.7	16.98	-6999	34.71	20.43	17.09	17.68	-604.1	483.3	1399	743	81.9	-42.36
109	1999	323	1521	19.88	0	17.7	16.99	-6999	34.67	20.43	17.1	17.61	-535.2	482.7	1411	741	81.4	-42.36
109	1999	323	1521	20.88	0	17.7	16.98	-6999	34.68	20.43	17.1	17.56	-554.7	483.5	1420	751	81.7	-42.53
109	1999	323	1521	21.88	0	17.7	16.98	-6999	34.66	20.44	17.09	17.54	-591.6	483.5	1426	738	81.6	-44.2
109	1999	323	1521	22.88	0	17.7	14.99	-6999	34.89	20.07	17.09	18.37	-6999	536.9	1399	795	79.6	-46.86
109	1999	323	1521	23.88	0	17.7	16.33	-6999	34.73	18.46	17.1	20.8	-6999	1235	1431	728	80.2	-47.2
109	1999	323	1521	24.88	0	17.7	16.73	-6999	34.38	18.56	17.09	22.05	-6999	1386	1415	741	80.6	-46.03
109	1999	323	1521	25.88	0	17.7	5.828	-6999	34.06	19.24	17.08	22.71	-6999	1376	1425	731	80.1	-46.53
109	1999	323	1521	26.88	0	17.7	-6999	-6999	33.45	19.67	17.09	22.98	-6999	1334	1432	739	80.1	-45.86
109	1999	323	1521	27.88	0	17.7	-6999	-6999	33.05	19.83	17.09	22.94	-6999	1288	1415	719	80.2	-45.7
109	1999	323	1521	28.88	0	17.7	9.12	-6999	32.91	19.88	17.1	22.72	-6999	1222	1425	505.2	81.1	-41.69
109	1999	323	1521	29.88	0	17.7	16.97	-6999	32.92	19.94	17.1	21.32	-890	746	1343	749	81.6	-43.53
109	1999	323	1521	30.88	0	17.7	16.98	-6999	32.92	19.94	17.1	19.81	-543.7	563.5	1444	778	81.4	-43.2
109	1999	323	1521	31.88	0	17.7	16.98	-6999	32.97	19.97	17.12	18.96	-564	503	1428	733	81.9	-43.03
109	1999	323	1521	32.88	0	17.7	16.98	-6999	32.96	19.98	17.12	18.46	-529.8	486	1425	740	81.9	-42.36
109	1999	323	1521	33.38	0	17.7	16.98	-6999	32.93	19.99	17.11	18.3	-524.7	484.8	1412	739	81.9	-42.53
109	1999	323	1521	33.88	0	17.7	16.98	-6999	32.94	19.98	17.11	18.17	-542.5	484.3	1422	744	81.6	-42.53
109	1999	323	1521	34.88	0	17.7	16.98	-6999	32.92	19.99	17.1	17.98	-520.8	483.5	1407	745	81.6	-42.53
109	1999	323	1521	35.88	0	17.7	16.99	-6999	32.87	20.01	17.11	17.85	-515	483	1427	757	81.9	-43.2
109	1999	323	1521	36.88	0	17.7	16.98	-6999	32.88	19.99	17.1	17.75	-532.3	483	1433	757	81.7	-42.36
109	1999	323	1521	37.88	0	17.7	16.98	-6999	32.87	20	17.11	17.68	-520.8	482.7	1419	753	81.1	-42.36
109	1999	323	1521	38.88	0	17.7	16.97	-6999	32.86	19.99	17.1	17.62	-589.1	483.7	1421	756	82.2	-42.69
109	1999	323	1521	39.88	0	17.7	12.95	-6999	32.76	20.02	17.11	17.95	-6999	485.2	1361	868	79.9	-47.53
109	1999	323	1521	40.88	0	17.7	2.828	-6999	32.46	18.41	17.1	20.3	-6999	1159	1418	736	79.7	-47.03
109	1999	323	1521	41.88	0	17.7	8.19	-6999	32.38	18.37	17.1	21.52	-6999	1414	1450	714	79.9	-46.36
109	1999	323	1521	42.88	0	17.7	3.101	-6999	32.43	18.93	17.1	22.11	-6999	1371	1410	715	80.4	-45.36

Appendix 8 Conversion Equations

Convert time into minutes from start of milking

Year, day of the year, hour:minute, and seconds data were logged with all sensor data in each 0.5s record in the CR10. Time (minutes) after milking was calculated using equation A.1.

$$\text{Time} = 60 \times \text{INT}\left(\frac{\text{hr : min}}{100}\right) + \text{MOD}(\text{hr : min}, 100) + \frac{\text{seconds}}{60} - \text{time}_{\text{zero}} \quad \text{(A.1)}$$

where:

Time = Time after start of milking session

$\text{Time}_{\text{zero}}$= Time when milk pump first operated (or time of first temperature increase observed at heat exchanger when pump on/off information was not logged)

hr:min, and seconds as in the raw data in the log file.

Calculation of pressures at pump inlet and outlet

The pressure at the inlet of the pump can be calculated using equations A.2 and A.3.

$$P_{\text{in}} = (V_{\text{pump in}} - V_{\text{pump in zero}})c_1 \quad \text{(A.2)}$$

where:

P_{in} = Pressure at inlet of pump (kPa)

$V_{\text{pump in}}$ = Pressure at inlet of pump (mV)

$V_{\text{pump in zero}}$ = Adjustment so that P_{in} is 0 at atmospheric pressure (mV)

c_1 = 1 kPa/mV.

$$P_{\text{out}} = (-V_{\text{pump out}} - V_{\text{pump out zero}})c_2 \quad \text{(A.3)}$$

where:

P_{out} = Pressure at outlet of pump (kPa)

$V_{\text{pump out}}$ = Pressure at outlet of pump (mV)

$V_{\text{pump out zero}}$ = Adjustment so that P_{out} is 0 at atmospheric pressure (mV)

c_2 = 0.5 kPa/mV.

Calculation of milk pump operation

Equation A.4 shows how pump on/off operation was calculated.

$$\begin{aligned}\text{Pump(On/Off)} &= 1, \text{if } \text{Pump(On/Off)}_{\text{raw}} > -2000 \\ &= 0, \text{if } \text{Pump(On/Off)}_{\text{raw}} \leq -2000\end{aligned} \quad \text{(A.4)}$$

where:

$\text{Pump(On/Off)}_{\text{raw}}$ is the value recorded by CR10.

0 = Pump is off

1 = Pump is on.

Calculation of milk pump duty cycle

The duty cycle was calculated using Equation A.5.

$$\text{Pump duty cycle}_i = 100 \times \frac{\text{Pump on duration}_i}{\text{Pump on duration}_i + \text{Pump off duration}_i} \quad \text{(A.5)}$$

where:

i = current row.

$$\begin{aligned}\text{Pump on duration}_i &= \text{Pump on duration}_{i+1}, \text{if count on}_i = 0 \\ &= \text{Pump on duration}_{i+1}, \text{if count on}_i \neq 0 \,\&\, \text{count on}_{i+1} \neq 0 \\ &= \text{Count on}_{i+1}, \quad \text{if count on}_i \neq 0 \,\&\, \text{count on}_{i+1} = 0\end{aligned} \quad \text{(A.6)}$$

$$\begin{aligned}\text{Pump off duration}_i &= \text{Pump off duration}_{i+1}, \text{if count off}_i = 0 \\ &= \text{Pump off duration}_{i+1}, \text{if count off}_i \neq 0 \,\&\, \text{count off}_{i+1} \neq 0 \\ &= \text{Count off}_{i+1}, \quad \text{if count off}_i \neq 0 \,\&\, \text{count off}_{i+1} = 0\end{aligned} \quad \text{(A.7)}$$

$$\text{Count on}_i = (\text{Count on}_{i-1} + 1) \times \text{Pump on/off}_i \quad \text{(A.8)}$$

$$\text{Count off}_i = (\text{Count off}_{i-1} + 1) \times (1 - \text{Pump on/off}_i) \quad \text{(A.9)}$$

Equation A.8 counts up the length of time that the pump has been on. Equation A.9 counts up the length of time that the pump has been off. Equation A.6 contains the number of records that the pump has been on in the current period, similarly for equation A.7. Equation 3.5 calculates the pump duty cycle as a percentage.

Calculation of milk flow rate

The milk flow rate was calculated from the logged data using equation A.10.

$$M = \left(\frac{V_{milk} - V_{milk\ zero}}{R_{milk}} \right) c_3 \tag{A.10}$$

where:

M = Volumetric milk flow rate (m^3/hr)

V_{milk} = Voltage recorded by data logger (mV)

$V_{milk\ zero}$ = V_{milk} when the milk flow rate is 0 m^3/hr (mV)

R_{milk} = Resistance of resistor used to convert mA signal into volts (Ω)

c_3 = 1 mA/mV.

Standardization of temperature readings for water exiting the heat exchanger

The temperature difference between the inlet and outlet temperature sensor was averaged when only cooling water was flowing through the heat exchanger. To standardize the water outlet temperature with the water inlet temperature sensor, the difference was subtracted from the raw water temperature out data (equation A.11).

$$\theta_{wo} = \theta_{wo\ raw} - \theta_{wo\ c} \tag{A.11}$$

where:

θ_{wo} = The standardized water outlet temperature of the heat exchanger (°C)

$\theta_{wo\ raw}$ = The raw water outlet temperature of the heat exchanger (°C)

$\theta_{wo\ c}$ = The difference between the water inlet and outlet temperatures (°C)

Calculation of water flow rate

The water flow rate was determined by means of an orifice plate and two pressure sensors. The pressures either side of the orifice plate were calculated using equations A.12 and A.13.

$$P_1 = \frac{15}{16} \times \left(\frac{V_{\text{orifice in}}}{R_{P1}} - 4 \right) \times 6.894 \tag{A.12}$$

where:

P_1 = Pressure at the orifice inlet (kPa)

$V_{\text{orifice in}}$ = Raw pressure at orifice inlet (mV)

15 = Range of pressure sensor (psi.g)

16 = To convert from 4-20mA signal to 1 unit (mA)

R_{P1} = Resistor used to convert mA to voltage (Ω)

6.894 = Units conversion factor (kPa/psi).

$$P_2 = \frac{25}{16} \times \left(\frac{V_{\text{orifice out}}}{R_{P2}} - 4 \right) \times 6.894 - 100 \tag{A.13}$$

where:

P_2 = Pressure at the orifice outlet (kPa)

$V_{\text{orifice out}}$ = Raw pressure at orifice outlet (mV)

25 = Range of pressure sensor (psi.a)

R_{P2} = Resistance of resistor used to convert mA to voltage (Ω)

100 = To convert pressure from absolute to gauge (kPa).

The pressure difference ΔP was calculated using equation A.14 and substituted into equation A.15 to give the volumetric flow rate of the cooling water.

$$\Delta P = (P_1 - P_{1\,\text{zero}}) - (P_2 - P_{2\,\text{zero}}) \tag{A.14}$$

where:

$P_{1\,\text{zero}}$ = P_1 when water flow rate is 0 m^3/hr (kPa)

$P_{2\,\text{zero}}$ = P_2 when water flow rate is 0 m^3/hr (kPa).

$$W = m_{grad}\sqrt{\Delta P} + c \qquad (A.15)$$

where:

W = Volumetric flow rate of water (m^3/hr)

m_{grad} = Gradient from plot of water flow rate vs. square root of pressure drop (Figure A.7) ($m^3/(hr.kPa^{0.5})$)

c = Intercept of plot in Figure A.7 (m^3/hr).

Appendix 9 Sample Calculations

Convert time into minutes from start of milking

$$\text{Time} = 60 \times \text{INT}\left(\frac{\text{hr : min}}{100}\right) + \text{MOD}(\text{hr : min}, 100) + \frac{\text{seconds}}{60} - \text{time}_{\text{zero}} \qquad \text{(A.1)}$$

Data taken from Table A.3 row 1

$\text{time}_{\text{zero}}$ = 907.9396666 (run 5, file name: 19Nov99_6s, sheet:Calculations, cell A2633)

$$\begin{aligned}\text{Time} &= 60 \times \text{INT}\left(\frac{1520}{100}\right) + \text{MOD}(1520, 100) + \frac{56.88}{60} - 907.9396666 \\ &= 60 \times 15 + 20 + 0.948 - 907.9396666 \\ &= 13.0083334 \text{ minutes since start of milking}\end{aligned}$$

Calculation of pressures at pump inlet and outlet

$$P_{\text{in}} = (V_{\text{pump in}} - V_{\text{pump in zero}})c_1 \qquad \text{(A.2)}$$

Data taken from Table A.4 row 1

$V_{\text{pump in zero}}$ = -4.17 mV (run 3, file name: 1Sep99_6s, sheet:Calculations, cell S2)

$$\begin{aligned}P_{\text{in}} &= (-44.53 - -4.17) \cdot 1 \\ &= -40.36 \text{ kPa}\end{aligned}$$

$$P_{\text{out}} = (-V_{\text{pump out}} - V_{\text{pump out zero}})c_2 \qquad \text{(A.3)}$$

$V_{\text{pump out zero}}$ = -4.6 mV (run 3, file name: 1Sep99_6s, sheet:Calculations, cell S2)

$$\begin{aligned}P_{\text{out}} &= (-78.4 - -4.6) \cdot 0.5 \\ &= -36.9 \text{ kPa}\end{aligned}$$

Calculation of milk pump operation

$$\begin{aligned}\text{Pump(On/Off)} &= 1, \text{if } \text{Pump(On/Off)}_{\text{raw}} > -2000 \\ &= 0, \text{if } \text{Pump(On/Off)}_{\text{raw}} \leq -2000\end{aligned} \qquad \text{(A.4)}$$

Data taken from Table A.5 row 1

$$\text{Pump(On/Off)}_{\text{raw}} = -552.9$$
$$\text{Pump(On/Off)} = 0$$

Calculation of milk pump duty cycle

$$\text{Pump duty cycle} = \frac{\text{Time pump is on in one period}}{\text{Time pump is on and off in one period}} \tag{6.2}$$

Data taken from Table A.5 row 10

$$\begin{aligned}
\text{Time} &= 13.14992 \\
\text{Time}_{\text{Last Transition}} &= 13.11658 \text{ (Start of period)} \\
\text{Time}_{\text{Next SimilarTransition}} &= 13.44167 \text{ (End of Period)} \\
\text{Pump duty cycle} &= \frac{8}{8+12} \\
&= 40\%
\end{aligned}$$

$$\text{Count on}_i = (\text{Count on}_{i-1} + 1) \times \text{Pump on/off}_i \tag{A.5}$$

$$\text{Count on}_{i-1} = 2, \text{Pump on/off}_i = 1$$
$$\begin{aligned}
\text{Count on}_i &= (2+1) \times 1 \\
&= 3
\end{aligned}$$

$$\text{Count off}_i = (\text{Count off}_{i-1} + 1) \times (1 - \text{Pump on/off}_i) \tag{A.6}$$

$$\text{Count off}_{i-1} = 0, \text{Pump on/off}_i = 0$$
$$\begin{aligned}
\text{Count off}_i &= (0+1) \times 0 \\
&= 0
\end{aligned}$$

$$\begin{aligned}
\text{Pump on duration}_i &= \text{Pump on duration}_{i+1}, \text{if count on}_i = 0 \\
&= \text{Pump on duration}_{i+1}, \text{if count on}_i \neq 0 \,\&\, \text{count on}_{i+1} \neq 0 \\
&= \text{Count on}_{i+1}, \qquad \text{if count on}_i \neq 0 \,\&\, \text{count on}_{i+1} = 0
\end{aligned} \tag{A.7}$$

$$\text{Pump on duration}_{i+1} = 8, \text{count on}_i = 3, \text{ count on}_{i+1} = 4$$
$$\text{Pump on duration}_i = 8$$

$$\begin{aligned}
\text{Pump off duration}_i &= \text{Pump off duration}_{i+1}, \text{if count off}_i = 0 \\
&= \text{Pump off duration}_{i+1}, \text{if count off}_i \neq 0 \,\&\, \text{count off}_{i+1} \neq 0 \\
&= \text{Count off}_{i+1}, \qquad \text{if count off}_i \neq 0 \,\&\, \text{count off}_{i+1} = 0
\end{aligned} \tag{A.8}$$

$$\text{Pump off duration}_{i+1} = 12, \text{count off}_i = 0, \text{count off}_{i+1} = 0$$
$$\text{Pump off duration}_i = 12$$

$$\text{Pump duty cycle}_i = 100 \times \frac{\text{Pump on duration}_i}{\text{Pump on duration}_i + \text{Pump off duration}_i} \tag{A.9}$$

$$\begin{aligned}\text{Pump duty cycle}_i &= 100 \times \frac{8}{8+12} \\ &= 40\end{aligned}$$

Calculation of milk flow rate

$$M = \left(\frac{V_{\text{milk}} - V_{\text{milk zero}}}{R_{\text{milk}}} \right) c_3 \tag{A.10}$$

Data taken from Table A.6 row 12

$V_{\text{milk zero}}$ = 482.67 mV, R_{milk} =119.3 Ω (run 5, file name: 19Nov99_6s, sheet:Calculations, cell M2753)

$$\begin{aligned}M &= \left(\frac{1550 - 482.67}{119.3} \right) \cdot 1 \\ &= 8.95 \text{ m}^3/\text{hr}\end{aligned}$$

Standardization of temperature readings for water exiting the heat exchanger

$$\theta_{\text{wo}} = \theta_{\text{wo raw}} - \theta_{\text{wo c}} \tag{A.11}$$

Data taken from Table A.7 row 1

θ_{wo} = .3304°C (run 5, file name: 19Nov99_6s, sheet:Raw, cell T5)

$$\begin{aligned}\theta_{\text{wo}} &= 17.52 - .33 \\ &= 17.19°\text{C}\end{aligned}$$

Calculation of log mean temperature difference across the plate heat exchanger

$$\Delta\theta = \frac{\Delta\theta_1 - \Delta\theta_2}{\ln\left(\frac{\Delta\theta_1}{\Delta\theta_2}\right)} \tag{6.3}$$

$$\Delta\theta_1 = \theta_{\text{MI}} - \theta_{\text{WO}} \tag{6.4}$$

$$\Delta\theta_2 = \theta_{\text{MO}} - \theta_{\text{WI}} \tag{6.5}$$

Data taken from Table A.8 row 1 and TableA.1 row 1

$$\Delta\theta_1 = 35.3 - 17.19$$
$$= 18.11°C$$
$$\Delta\theta_2 = 20.32 - 17$$
$$= 3.32°C$$
$$\Delta\theta = \frac{18.11 - 3.32}{\ln\left(\frac{18.11}{3.32}\right)}$$
$$= \frac{14.79}{\ln(5.454)}$$
$$= 8.7°C$$

Calculation of water flow rate

$$P_1 = \frac{15}{16} \times \left(\frac{V_{\text{orifice in}}}{R_{P1}} - 4\right) \times 6.894 \tag{A.12}$$

Data taken from Table A.9 row 1.

R_{P1}=119.2 Ω (run 5, file name: 19Nov99_6s, sheet:Calculations, cell R2742)

$$P_1 = \frac{15}{16} \times \left(\frac{749}{119.2} - 4\right) \times 6.894$$
$$= .9375 \times (2.283) \times 6.894$$
$$= 14.75 \text{ kPa}$$

$$P_2 = \frac{25}{16} \times \left(\frac{V_{\text{orifice out}}}{R_{P2}} - 4\right) \times 6.894 - 100 \tag{A.13}$$

Data taken from Table A.9 row 1.

R_{P2}=119.5 Ω (run 5, file name: 19Nov99_6s, sheet:Calculations, cell S2742)

$$P_2 = \frac{25}{16} \times \left(\frac{1435}{119.5} - 4\right) \times 6.894 - 100$$
$$= 1.562 \times (8.0084) \times 6.894 - 100$$
$$= -14.86 \text{ kPa}$$

$$\Delta P = (P_1 - P_{1\,zero}) - (P_2 - P_{2\,zero}) \tag{A.14}$$

$P_{1\,zero}$=-.88 kPa, $P_{2\,zero}$=.75 kPa (run 5, file name: 19Nov99_6s, sheet:Calculations, cell R17478..S17478)

$$\Delta P = (14.76 - -.88) - (-14.86 - .75)$$
$$= 31.25 \text{ kPa}$$

$$W = m_{grad}\sqrt{\Delta P} + c \quad (A.15)$$

$$W = 2.4413\sqrt{31.25} + .3236$$
$$= 13.97 \text{ m}^3/\text{hr}$$

Calculation of heat transfer rates

$$\phi_{milk\ actual} = \frac{\rho_{milk} \times M \times Cp_{milk}(\theta_{mi} - \theta_{mo})}{3600} \quad (6.6)$$

Data taken from row 10 of Table A.6, A.7.

ρ_{milk}= 1026 kg/m^3, Cp_{milk} = 3.938 kJ/kgK (run 5, file name: 19Nov99_6s, sheet:Calculations, cell Z2751)

$$\phi_{milk\ actual} = \frac{1026 \times 8.15 \times 3.938(35.37 - 18.4)}{3600}$$
$$= 155.22 \text{ kJ/s}$$

$$\phi_{water\ actual} = \frac{\rho_{water} \times W \times Cp_{water}(\theta_{wo} - \theta_{wi})}{3600} \quad (3.7)$$

ρ_{water}= 999 kg/m^3, Cp_{milk} = 4.184 kJ/kgK (run 5, file name: 19Nov99_6s, sheet:Calculations, cell Y2742)

$$\phi_{water\ actual} = \frac{999 \times 14.04 \times 4.184(21.82 - 16.99)}{3600}$$
$$= 78.74 \text{ kJ/s}$$

$$\phi_{water\ ideal} = \frac{\rho_{water} \times W \times Cp_{water}(\theta_{mi} - \theta_{wi})}{3600} \quad (3.8)$$

$$\phi_{water\ ideal} = \frac{999 \times 14.04 \times 4.184(35.37 - 16.99)}{3600}$$
$$= 299 \text{ kJ/s}$$

Calculation of efficiency of cooling water usage

$$\eta = \frac{\phi_{\text{water actual}}}{\phi_{\text{water ideal}}} \tag{3.9}$$

$$\eta = \frac{78}{299}$$
$$= 26\%$$

$$\overline{\theta_{mo}} = \frac{\sum_{76}^{78} \theta_{mo} M \Big/ n}{\sum_{76}^{78} M \Big/ n} \tag{5.2}$$

Data taken from (run 10, file name: 21Nov99_3s, sheet:Calculations, cell AA15339..AB15340)

$$\overline{\theta_{mo}} = \frac{50.1897}{2.838} \tag{5.2}$$
$$= 17.68°C$$

Appendix 10 Results

Appendix 10.1 Time from start of milking

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.

Hours	Minutes	Seconds	Time from start of milking (Minutes)
15	20	56.88	13.00833
15	20	57.88	13.025
15	20	58.88	13.04167
15	20	59.88	13.05833
15	21	0.875	13.07492
15	21	1.875	13.09158
15	21	2.375	13.09992
15	21	3.375	13.11658
15	21	4.5	13.13533
15	21	5.375	13.14992

Appendix 10.2 Pressure at pump inlet and outlet

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.

Time (minutes from start of pumping)	Pressure at pump outlet (mV)	Pressure at pump inlet (mV)	Pressure at pump outlet (kPa)	Pressure at pump inlet (kPa)
73.10837	78.4	-44.53	-36.9	-40.36
73.1167	79.6	-44.7	-37.5	-40.53
73.12503	79.4	-44.53	-37.4	-40.36
73.13337	78.1	-44.87	-36.75	-40.7
73.1417	78.9	-44.87	-37.15	-40.7
73.15003	78.6	-45.03	-37	-40.86
73.15837	78.2	-44.7	-36.8	-40.53
73.1667	79.6	-45.2	-37.5	-41.03
73.17503	81.1	-45.03	-38.25	-40.86
73.18337	80.6	-45.03	-38	-40.86
73.1917	80.2	-52.71	-37.8	-48.54
73.20003	-148.8	-49.87	76.7	-45.7
73.20837	-142.9	-49.37	73.75	-45.2
73.2167	-151.1	-49.37	77.85	-45.2
73.22503	-148.9	-51.04	76.75	-46.87
73.23337	-150.5	-50.04	77.55	-45.87
73.2417	-149.9	-50.37	77.25	-46.2
73.25003	-145.1	-50.71	74.85	-46.54
73.25837	-134.3	-49.54	69.45	-45.37
73.2667	-140.6	-49.71	72.6	-45.54
73.27503	-136.8	-51.04	70.7	-46.87
73.28337	-138.3	-49.71	71.45	-45.54
73.2917	-149.1	-49.54	76.85	-45.37
73.30003	62.05	-44.54	-28.725	-40.37
73.30837	79.9	-44.54	-37.65	-40.37
73.3167	79.4	-45.2	-37.4	-41.03

Appendix 10.3 Pump operation and duty cycle

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.

Time (Minutes from start of pumping)	Pump (On/ Off) (mV) (Raw Data)	Pump (On/Off) (1/0)	Pump on count	Total duration of latest pump on period	Pump off count	Total duration of latest pump off period	Pump Duty Cycle (%)
13.00833	-552.9	0	0	8	17	23	25.80645161
13.025	-556.2	0	0	8	18	23	25.80645161
13.04167	-558.2	0	0	8	19	23	25.80645161
13.05833	-549.9	0	0	8	20	23	25.80645161
13.07492	-561.5	0	0	8	21	23	25.80645161
13.09158	-549.4	0	0	8	22	23	25.80645161
13.09992	-597.9	0	0	8	23	23	25.80645161
13.11658	-6999	1	1	8	0	12	40
13.13533	-6999	1	2	8	0	12	40
13.14992	-6999	1	3	8	0	12	40
13.16658	-6999	1	4	8	0	12	40
13.18333	-6999	1	5	8	0	12	40
13.2	-6999	1	6	8	0	12	40
13.21667	-6999	1	7	8	0	12	40
13.23333	-6999	1	8	8	0	12	40
13.25	-921	0	0	7	1	12	36.84210526
13.25833	-723	0	0	7	2	12	36.84210526
13.275	-587.1	0	0	7	3	12	36.84210526
13.29167	-578.5	0	0	7	4	12	36.84210526
13.30833	-575.5	0	0	7	5	12	36.84210526
13.325	-577	0	0	7	6	12	36.84210526
13.34167	-579.4	0	0	7	7	12	36.84210526
13.35833	-569.4	0	0	7	8	12	36.84210526
13.375	-604.1	0	0	7	9	12	36.84210526
13.39167	-535.2	0	0	7	10	12	36.84210526
13.40833	-554.7	0	0	7	11	12	36.84210526
13.425	-591.6	0	0	7	12	12	36.84210526
13.44167	-6999	1	1	7	0	11	38.88888889
13.45833	-6999	1	2	7	0	11	38.88888889

Appendix 10.4 Milk flow rate

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.

Time (Minutes from start of pumping)	Milk Flow Rate (mV)	Milk Flow Rate (m^3/hr)
13.00833	482.3	-0.003101425
13.025	483.3	0.005280805
13.04167	483	0.002766136
13.05833	482.7	0.000251467
13.07492	482.8	0.00108969
13.09158	482.5	-0.001424979
13.09992	483	0.002766136
13.11658	483	0.002766136
13.13533	1016	4.470494552
13.14992	1455	8.150293378
13.16658	1537	8.837636211
13.18333	1550	8.946605197
13.2	1415	7.815004191
13.21667	1164	5.711064543
13.23333	1066	4.889606035
13.25	605.4	1.028751048
13.25833	576.7	0.788181056
13.275	505	0.187175189
13.29167	486.5	0.03210394
13.30833	483.5	0.006957251
13.325	483.8	0.00947192
13.34167	483.3	0.005280805
13.35833	483.5	0.006957251
13.375	483.3	0.005280805
13.39167	482.7	0.000251467
13.40833	483.5	0.006957251
13.425	483.5	0.006957251
13.44167	536.9	0.454568315
13.45833	1235	6.30620285

Appendix 10.5 PHE temperatures

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.

Time from start of milking (Minutes)	Water inlet temperature (°C)	Water outlet temperature (°C)	Water temperature difference (°C)	Adjusted water outlet temperature (°C)
13.00833	17	17.52	0.52	17.18958904
13.025	17	17.48	0.48	17.14958904
13.04167	17	17.47	0.47	17.13958904
13.05833	16.99	17.45	0.46	17.11958904
13.07492	17	17.44	0.44	17.10958904
13.09158	16.98	17.41	0.43	17.07958904
13.09992	16.99	17.4	0.41	17.06958904
13.11658	16.99	17.46	0.46999999	17.12958904
13.13533	16.99	20.04	3.04999999	19.70958904
13.14992	16.99	22.15	5.15999999	21.81958904

Appendix 10.6 PHE log mean temperature difference and milk heat transfer rate

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 × 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.

Time (minutes from start of pumping)	Milk In (°C)	Milk Out (°C)	Water In (°C)	Adjusted Water Out (°C)	Ln Mean (°C)	Milk Flow Rate (m^3/hr)	Milk Heat Transfer Rate (kJ/s)	Milk In x Milk Flow Rate (°Cm^3/hr)	Milk Out x Milk Flow Rate (°Cm^3/hr)
13.0083	35.3	20.32	17	17.18	8.71	-0.0031	-0.0521	-0.109	-0.062
13.025	35.29	20.32	17	17.14	8.72	0.0052	0.0887	0.186	0.107
13.0417	35.28	20.32	17	17.13	8.72	0.0027	0.0464	0.097	0.056
13.0583	35.26	20.32	16.99	17.11	8.73	0.0002	0.0042	0.008	0.005
13.0749	35.27	20.34	17	17.10	8.75	0.0010	0.0182	0.038	0.022
13.0916	35.25	20.32	16.98	17.07	8.75	-0.0014	-0.0238	-0.050	-0.028
13.0999	35.24	20.32	16.99	17.06	8.74	0.0027	0.0463	0.097	0.056
13.1166	35.5	20.32	16.99	17.12	8.80	0.0027	0.0463	0.097	0.056
13.1353	35.47	18.67	16.99	19.70	6.28	4.4704	76.1636	158.703	90.840
13.1499	35.37	18.4	16.99	21.81	5.36	8.1502	153.6749	289.091	152.166

Appendix 10.7 Cooling water flow rate through PHE

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.

Time from start of milking (Minutes)	Orifice out pressure (mV)	Orifice in pressure (mV)	Orifice in pressure (kPa)	Orifice out pressure (kPa)	Pressure drop across orifice plate (kPa)	Cooling water flow rate (m^3/hr)
13.00833	1435	749	14.75891464	-14.86485879	31.25944	13.97294379
13.025	1430	748	14.70469379	-15.31556485	31.65593	14.05923308
13.04167	1400	754	15.03001888	-18.01980126	34.68549	14.70148712
13.05833	1420	756	15.13846057	-16.21697699	32.99111	14.34591115
13.07492	1415	758	15.24690227	-16.66768305	33.55026	14.46424003
13.09158	1425	760	15.35534396	-15.76627092	32.75729	14.29613161
13.09992	1440	765	15.6264482	-14.41415272	31.67627	14.06364567
13.11658	1364	799	17.46995701	-21.26488494	40.37051	15.83508153
13.13533	1426	763	15.5180065	-15.67612971	32.82981	14.31158995
13.14992	1421	729	13.67449769	-16.12683577	31.437	14.01165443

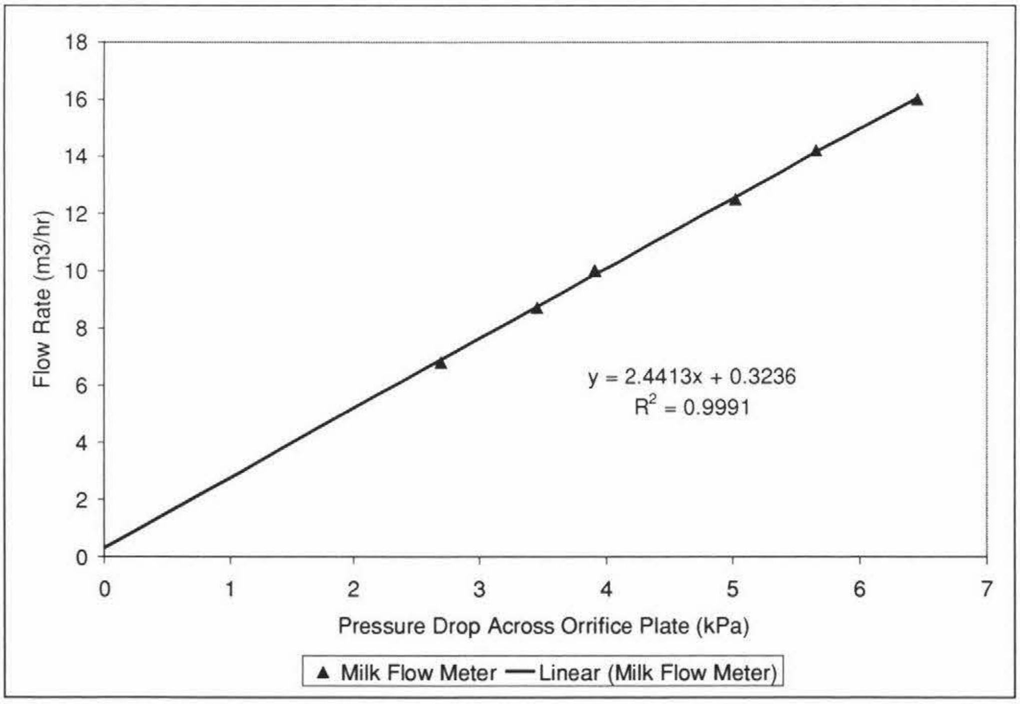

Figure A.7 Orifice plate calibration graph. Graph of cooling water flow rate versus the square root of the pressure drop across the orifice plate - recorded 24 November 1999.

Appendix 10.8 Actual and ideal cooling water heat transfer rate and efficiency of cooling water heat transfer rate

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.

Time (minutes from start of pumping)	Milk inlet (°C)	Water inlet (°C)	Adjusted water outlet (°C)	Cooling water flow rate (m^3/hr)	Water heat transfer rate (kJ/s)	Ideal water heat transfer Rate (kJ/s)	Efficiency (%)
13.0083	35.3	17	17.18958904	13.95335619	3.071	296.4725	1.0360
13.025	35.29	17	17.14958904	14.05479191	2.441	298.4646	0.8178
13.0417	35.28	17	17.13958904	14.77835582	2.395	313.6584	0.7636
13.0583	35.26	16.99	17.11958904	14.36623111	2.162	304.7446	0.7093
13.0749	35.27	17	17.10958904	14.4976771	1.845	307.5329	0.5998
13.0916	35.25	16.98	17.07958904	14.30020731	1.654	303.3441	0.5450
13.0999	35.24	16.99	17.06958904	14.02153144	1.296	297.1071	0.4361
13.1166	35.5	16.99	17.12958904	15.9836921	2.59	343.5091	0.7541
13.1353	35.47	16.99	19.70958904	14.31133368	45.19	307.0695	14.7163
13.1499	35.37	16.99	21.81958904	14.04301559	78.75	299.6819	26.2763

Appendix 11 Chemical Analysis

The data presented in Table A.11 is the titrated ml of KOH required. The more KOH required, the more damaged the milk was.

Table A.11 Results of lipolysable free fat test showing milk damage before and after releaser pump.

Day/Sample #	Before Pump	After Pump	Blank
1/1	-	3.1	.06
½	5.8	2.78	-
1/3	8.71	3.59	-
2/1	5.03	2.98	0
2/2	4.48	2.92	-
2/3	4.44	2.68	-

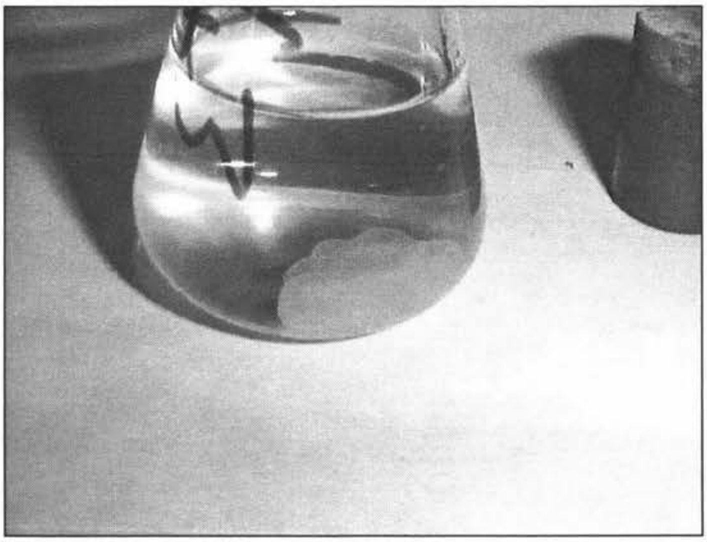

Figure A.8 Photo of accumulated milk fat after all fat should have been removed - taken 17 September 1999.

Appendix 12   CD Directory Structure

```
Directory of CDROM:\Massey University No. 1 Dairy Unit

<DIR>          .
<DIR>          ..
<DIR>          Run 01, 1999aug21_Initial Investigations,
     Squirrel
<DIR>          Run 02, 1999aug28_Initial Investigations,
     Squirrel
<DIR>          Run 03, 1999sep01_6s
<DIR>          Run 04, 1999sep07
<DIR>          Run 05, 1999sep08
<DIR>          Run 06, 1999nov17_6s milk in TC is dodgy
     swapped with water in for rest of experiments
<DIR>          Run 07, 1999nov18_3s
<DIR>          Run 08, 1999nov19_6s
<DIR>          Run 09, 1999nov20_no temp
<DIR>          Run 10, 1999nov21_3s
<DIR>          Run 11, 1999nov22_3s
<DIR>          Run 12, 1999nov23_6s
<DIR>          Run 13, 2000feb12_3s
<DIR>          Run 14, 2000feb14_6s
<DIR>          Run 15, 2000feb15_3s WATER IN OVER 18
     DEGREES
<DIR>          Run 16, 2000feb17_6s
<DIR>          Run 17, 2000feb18_3s
<DIR>          Run 18, 2000feb19_6s
<DIR>          Run 19, 2000feb24_0df
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     signal
<DIR>          Run 30, 2000mar11_0d bad pressure o out
     signal
<DIR>          Run 31, 2000mar13_6s
<DIR>          Run 32, 2000mar14_temp
<DIR>          1999nov some written records from notebook
<DIR>          1999nov24HE_flow_only
<DIR>          2000 datalogger programdisk used in 2000
<DIR>          2000mar21tempcalibration
<DIR>          AgEng
```

```
<DIR>          misc
<DIR>          photo's
<DIR>          Program used for end of(all) November
```

Directories starting with "Run" contain the raw data files and spreadsheet calculations for the milking session on that afternoon.

"`Run 08, 1999nov19_6s`" was experimental run number 8 carried out on the 19nth of November 1999, the pump duration was set to 6 seconds.

"`Run 25, 2000mar02_0d`" was experimental run number 25 carried out on the 2nd of March 2000, the water off delay was set to 0 seconds.

"misc" contains various software and files such as the holding capacity of the pipe work and equipment.

"AgEng" contains results from previous research carried out on precooling system by the department of agricultural engineering.