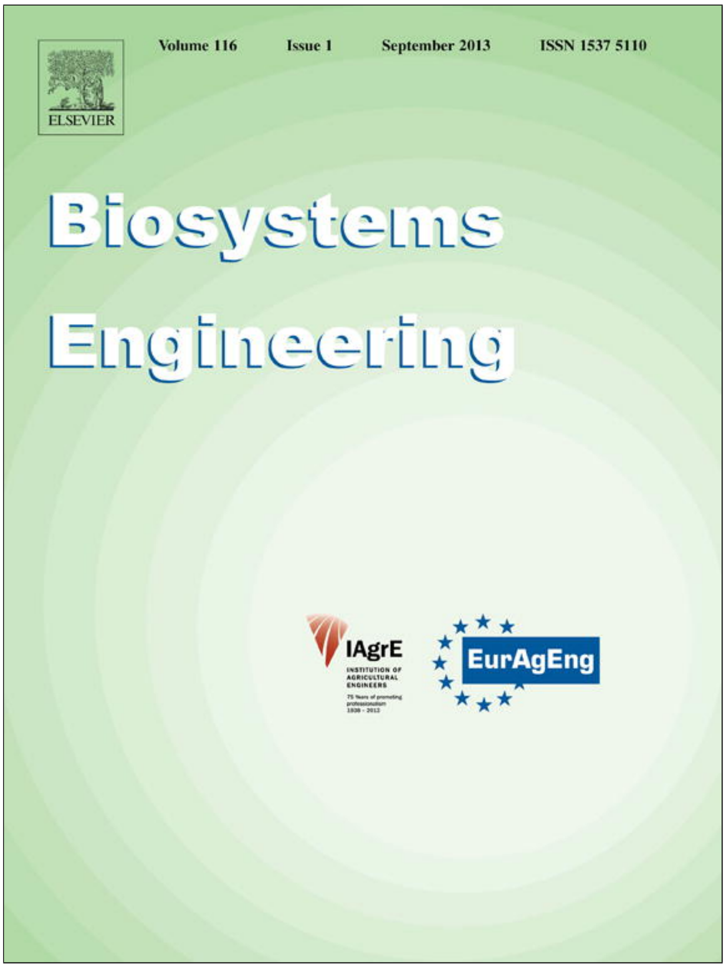
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Research Paper

Rapid milk cooling control with varying water and energy consumption

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A control system for rapid milk cooling plant connected to a variable flow milking machine is presented. The plant consisted of a pre-cooler in the first stage that utilised ground water as a cooling medium and an ice bank that provides ice chilled water for the second cooling stage. The control system comprised of two proportional integral derivative controllers applied to each cooling stage in tandem. The set point of the first controller was the desired milk pre-cooling temperature while the set point of the second controller was the desired final milk temperature. Eight different precooling set points (13 °C–20 °C) were tested for feedback and feedback–feedforward controller configurations. Selection of low temperature pre-cooling set points resulted in larger volumes of ground water being consumed in the first stage per unit milk in comparison to the selection of higher temperature set points (three times higher). However, low pre-cooling temperatures resulted in less ice storage utilisation and therefore less power consumption. Introduction of a feedforward loop to the controllers reduced the disturbance from the varying milk flow and by doing so reduced the final milk temperature deviation from the set point. Optimum water utilisation rates were calculated for varying water cost at the current price of electricity. These points represent the ideal combination of ground water and power consumption per unit milk to produce the most financially efficient means of cooling. Potential cost reductions of up to 34.5% through the selection of the ideal water rates were discovered.

1. Introduction

Dairy production is an energy intensive process with milk cooling being the largest contributor to electricity use on Irish dairies (Upton, Murphy, French, & Dillon, 2010). The amount of energy needed for cooling depends primarily on the efficiency of the refrigeration system and the temperature differential in the milk between the start and finish of the cooling process. The most common method of reducing the cost of milk cooling is to employ a two stage process comprising of a pre-cooling unit and a main refrigeration system. Plate heat exchangers (PHE) are the most commonly utilised pre-coolers. PHEs use tepid ground water (GW) to reduce the milk temperature. The amount of GW available for pre-cooling usage depends on a number of factors such as; herd size, number of milking clusters, farm infrastructure, well depth and climate conditions. Effective utilisation of GW in the pre-cooling process has a significant influence on milk temperature. However, there is also a financial cost associated with the use of GW. Most dairy farms have a borehole where water is pumped

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Nomenclature

Abbreviations

COP	coefficient of performance
FB	feedback
FB–FF	feedback–feedforward
FF	feedforward
GW	ground water
IB	ice bank
ICW	ice chilled water
PHE	plate heat exchanger
PID	proportional integral derivative
VSD	variable speed drive
WC	water chiller

Symbols

d	disturbance (min^{-1})
e	error (°C)
G_d	transfer function between the output milk temperature and the disturbance
G_p	transfer function between the output and manipulating variable
K_b	feedback controller
K_f	feedforward controller
k_D	derivative term (s)
k_I	integral term (1 s^{-1})
k_P	proportional term
q	feedforward controller output (mA)
r	set point (°C)
u	manipulating variable (mA)
u_{max}	maximum manipulating variable limit (mA)
u_{min}	minimum manipulating variable limit (mA)
w	controller output (mA)
y	milk output temperature (°C)

from the ground, in certain cases the water is partly or wholly supplied by a district scheme where it is charged per volume (m^3). GW used for pre-cooling is typically re-used for parlour wash down, as pre-heated water for cluster rinsing and can be used as animal drinking water (depending on temperature and storage time). Audits on milk cooling equipment carried out by the Teagasc Moorepark Animal and Grassland Research Innovation Centre (AGRIC) in 2010 revealed poor levels of PHE pre-cooling on dairy farms. In each case, insufficient water flow rate was found to be the underlying cause of the PHEs ineffectiveness, a cognate study in the UK found similar problems regarding GW utilisation in PHE pre-cooling (Milk Development Council, 1995). Due to the varying costs per unit of water between dairy farms, a standard GW to milk pre-cooling ratio cannot be applied in every situation. A method of controlling water utilisation in pre-cooling could yield substantial benefits for costs and energy reduction in milk refrigeration.

Modern milking machines operate by extracting milk from a cow's udder using a cluster of suction cups. The suction is generated using sinusoidal negative pressure. The milk from each cluster is collected in a receiver jar from where it is then pumped to the pre-cooler or directly to the refrigeration system. The milk flow profile contains peak and troughs at irregular intervals. Modern milking machine receiver jars contain level sensors that measure the height of the milk level and control the speed of the milk pump via an analogue signal to a variable speed drive (VSD). This method reduces the variation in milk flow, reducing peak the flow rate and enabling more effective pre-cooling. Despite the improvement of the situation with a VSD, a simple on/off controller for the GW flow still results in sub-optimal pre-cooling as the rate of cooling cannot be controlled. To facilitate the control of pre-cooling levels, an automatic system that is capable of manipulating the GW flow is needed.

Chilled water can be used in the second stage of a dual stage PHE to instantly cool milk; it can also be used to gradually cool the milk in a bulk tank. Gradual cooling is less energy intensive than instant cooling as the pumping demand for the chilled water (CW) is lower. Water can be chilled using a water chiller (WC), which usually consists of an insulated water tank with an evaporator and a holding vessel of equal volume. The water is chilled to approximately 1 °C at off peak hours (on the electricity grid) and the milk is cooled to below 4 °C. Used chilled water cannot be re-circulated to the insulated tank as this may lead to a rise in the total chilled water temperature to above 4 °C, so the water is directed to the holding vessel. Another method of chilling water is by circulation through an ice bank (IB). IBs consist of an insulated water tank that houses a copper tube evaporator array. Ice builds up around the copper tubes in a cylindrical formation. Water is circulated through the cooling device (PHE or bulk tank) and back to the IB in a closed loop. WCs operate with higher coefficients of performance (COP) than IBs due to the lower evaporating temperature required for producing ice, but IBs are much more compact due to the high energy density of ice and are cheaper to purchase and install.

During the milk cooling period some microorganisms may multiply (Holm, Jepsen, Larsen, & Jespersen, 2004), especially fast growing psychrotrophic bacteria that re-produce in the temperature range of 4 °C–7 °C. Rapidly cooling the milk to below 4 °C prevents further psychrotrophic bacteria growth. However, systems that effectively pre-cool and then gradually refrigerate the milk below 4 °C within the regulated time (in Ireland 30 min from the end of milking) greatly reduce the possibility of significant bacterial growth. One major advantage of instant cooling is that the milk is always ready for collection and transport to the processing plant. Not only is this useful in situations where direct collection occurs, but is also helpful where uncertain collection schedules exist. Having a rapid cooling system gives the farm manager freedom to set milking routines without having to strictly conform to the collection schedule of the milk processor.

Because the milk flow from modern milking machines is variable, rapid milk cooling is technically difficult. One strategy to combat this situation would be to operate the cooling plant at full capacity by running the GW and CW pumps at maximum speed; this insures that the cooling system can deal with the peak flow rates from the milking machine. However, running the GW pump at full power consumes excessively large volumes of water. Also, constantly operating the CW pump at full speed throughout the cooling circuit leads to increased thermal losses and pump running costs.

The aim of this study was to demonstrate by proof of principle that a control system that can optimise both the milk pre-cooling process with GW and the rapid cooling of milk below 4 °C with CW for milk and assess the cooling costs, energy use, and variable GW availability in milking systems with variable flow milk pumps. Such a system would allow farm mangers to utilise their water supply more effectively and also give a greater degree of control over energy and water consumption for milk cooling.

2. Materials and methods

2.1. *Cooling apparatus*

The milk refrigeration system chosen for this study was a dual stage PHE with the GW pre-cooling taking place in the first stage and the main CW cooling in the second stage. An IB was selected, as chilled water is required for instant cooling. However, either a WC or IB system could be selected for this application. A full scale test rig was designed and built (Fig. 1) consisting of a dual stage PHE and an IB. The dual stage PHE had both a GW and ice chilled water (ICW) in a single pass arrangement with 25 channels each. The corrugated plates were gasket sealed with a chevron angle of 65°. Two VSD pumps controlled the flow rates of the GW and ICW. The IB is an external melt ice on coil thermal storage unit with an inline coil array.

Class A PT100 temperature resistance thermometers and type K thermocouples were used to measure in-flow milk and water temperatures. Ultra sonic flow meters measured milk, GW and ICW flow. Temperature and flow measurements were taken in-pipe immediately before entering and immediately after exiting the PHE for GW, ICW and milk. Temperature and flow rates were recorded every 0.5 s. Power meters (Type EM24 DIN energy analyser, Fluke 123 scope meter, Fluke 902 HVAC clamp meter and Powersoft logging software) recorded the electricity consumption of each individual electrical device. LabVIEW 2010 software was used for control and data logging.

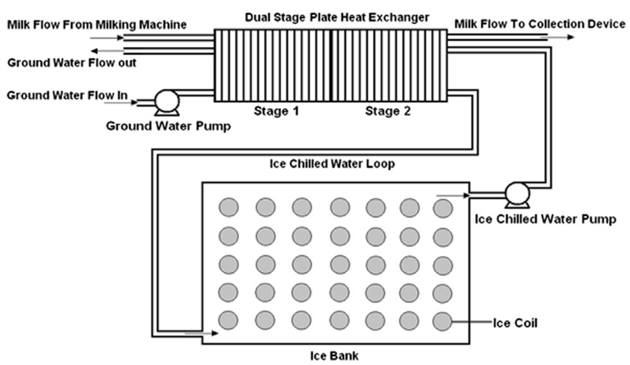

Fig. 1 – Schematic of the dual plate heat exchanger (PHE) used for instant milk cooling with ground water (GW) used for pre-cooling in the first stage and ice chilled water (ICW) used in the second stage (arrows indicate flow direction).

All laboratory equipment was calibrated to ISO17025 standards. Instrumentation was supplied by Radionics Ireland and National Instruments.

2.2. *Milk cooling energy and cost model*

An energy balance model was used to calculate and optimise the electrical energy consumption and monetary cost of cooling the milk with the apparatus used in this study. The ice mass depletion per unit of milk was calculated based on the specific heat capacity of milk and the specific heat of fusion of ice. The electricity consumption of the system to produce the ice depends on the system COP. The COP of refrigeration units with air cooled condensers are greatly affected by variations in ambient temperature (Yu & Chan, 2005; Zaman & Hussain, 2011). The average ambient air temperature at the Moorepark Met Eireann metrological observation station from 12:00 PM to 8:00 AM over the entire year of 2011 was used as on operating parameter. The COP was calculated by interpolation of empirical test data. The mean annual COP was found to be 2.6 at an average ambient temperature of 8.3 °C and an average pre-evaporating refrigerant temperature of −8.1 °C. Air agitation, GW and ICW pumping energy use was also factored into the model. Several assumptions were made. 1. No thermal leakage occurred in the PHE. 2. The IB and piping was perfectly insulated. 3. The IB was fully charged before milk cooling and was fully discharged during cooling. 4. No stand-off losses occurred in the IB. 5. Total ice mass was generated during the night (using night rate electricity). It is not assumed that instant cooling was achieved. The specific heat and density difference between milk and water were taken into account using the same method as Stinson, Studman, and Warburton (1987). Day and night rate electricity tariffs were set at €0.183 kW h^{-1} and €0.097 kW h^{-1}, respectively. Putting an exact financial cost on GW usage on Irish dairies is very difficult; most farms have a deep well from where the GW is sourced and any excess is returned down a borehole. In this scenario the only cost involved is in pumping GW from the well. In exceptional cases water is purchased from the local grid. If the GW used in the PHE is recycled and used for cleaning purposes this water can be considered as being of no extra cost to cooling. For these reasons GW costs ranging from €0.00 m^{-3} to €0.20 m^{-3} were selected for the financial analysis.

2.3. *Process*

Milk exits a cow's udder at 37 °C and it is cooled below 4 °C to prevent bacterial growth. In the cooling apparatus described above, the milk is cooled using GW and ICW in the first and second stages of the PHE, respectively. GW is pumped from an underground well or reservoir and stored in a holding vessel after usage for parlour wash down and other purposes. The ICW is circulated in a continuous loop between the IB and PHE. The ice is generated during off peak electricity periods. A certain ice mass is produced to ensure the cooling demand is met. The cooling load depends on the milk volume and temperature. The ice building is controlled by an ice mass sensor. By limiting the ice charge to the required level, surplus ice production is eliminated, thus preventing excessively low evaporating temperatures and therefore increasing the efficiency of the refrigeration unit (Chaichana, Charters, & Aye, 2001). The ice building is also assisted by an air agitation system; the introduction of air to the water surrounding the ice causes agitation which increases the heat transfer between the ice surface and the water. Studies on cold storage have shown air agitation to be very beneficial in the ice production process, increasing growth rates by 20–45% (Mohamed, 2005).

2.4. Controller

The milk temperature leaving the dual stage PHE is varied by manipulating the flow rates of GW and ICW. This is achieved by controlling the speed of the pumps using VSDs. Proportional integral derivative (PID) controllers are the most commonly utilised controllers in the process industry (Astrom & Hagglund, 2001). The popularity of PID control is due to its successful application over a wide range of control problems. The input to the VSD or the output of the PID controller is the combination of the proportional gain, integral action and derivative action, which is expressed as (equation of the ideal PID controller in the Laplace domain):

$$w(s) = [k_P + k_I/s + k_D]e(s) \tag{1}$$

where $w(s)$ is the controller output, $e(s)$ is the error between the set point and the manipulating variable, k_P is the proportional term, k_I is the integral term and k_D is the derivative term. An increase in the proportion gain results in a faster rise time, a larger overshoot and a small increase in settling time. Increasing the integral action removes steady state error and increases settling time and overshoot. The derivative term reduces the overshoot and settling time and improves the stability of the system (closed-loop response) (Heong, Chong, & Yun, 2005). In order to apply the correct proportional derivative and integral values the controllers were heuristically tuned using the Zeigler–Nichols ultimate gain method (Ziegler & Nichols, 1942).

The varying flow rate of incoming milk creates a disturbance in the control loop. Since the variation in milk flow is quite unstable, a basic feedback (FB) loop would not be capable of rejecting this disturbance from the system. The disturbance is measured using a flow meter before it influences the system. It is then possible to eliminate the effects of the disturbances before they create control errors. The feedforward (FF) controller compensates for variation in milk flow approximately, before it has a chance to influence process dynamics. The FF and FB loops can be integrated into a single control circuit. When the disturbance is measurable, the implementation of a combined feedback–feedforward (FB–FF) controller is advisable (Adam & Marchetti, 2004). Figure 2 shows a block diagram of a combined FB–FF control system where $K_b(s)$ is the FB controller, $K_f(s)$ is the FF controller, $G_d(s)$ is the transfer function between the output $y(s)$ (milk temperature after the first or second stage of the PHE) and the disturbance $d(s)$ (incoming milk flow rate), $G_p(s)$ is the transfer function between the output and manipulated variable $u(s)$ (input for the GW or ICW VSD pump), $r(s)$ is the set point temperature of the milk after stage one or two of the PHE, $e(s)$ is the error signal, $w(s)$ is the FB controller output and $q(s)$ is the FF controller output.

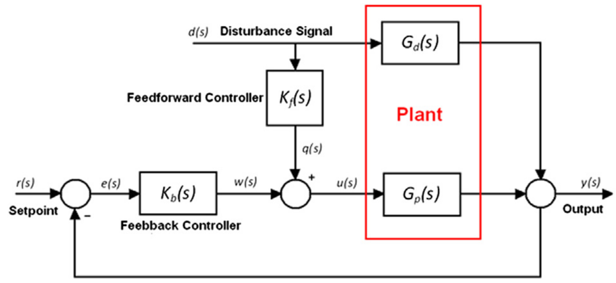

Fig. 2 – Feedback–feedforward control system block diagram where $K_b(s)$ is the feedback controller, $K_f(s)$ is the feedforward controller, $G_d(s)$ is the transfer function between the output $y(s)$, the disturbance is $d(s)$, $G_p(s)$ is the transfer function between the output and manipulated variable $u(s)$, $r(s)$ is the set point temperature of the milk after stage one or two of the PHE, $e(s)$ is the error signal, $w(s)$ is the feedback controller output and $q(s)$ is the feedforward controller output.

In the above system the role of the FF controller is to negate the undesirable effect of the disturbance signal. In this control system the ideal FF controller is defined by:

$$K_f(s) = G_d(s)/G_p(s) \tag{2}$$

The input to the plant has an upper and lower operational limit, any input outside this range will be processed just the same as the nearest corresponding limit and will lead to saturation of input $u(s)$ resulting in impeded controller response. In the FB loop the controller $K_b(s)$ operates within the same fixed range as the plant in order to generate a maximum and minimum output $w(s)$ that is always within the maximum manipulating variable limit $u_{max}(s)$ and the minimum manipulating variable limit $u_{min}(s)$. In the absence of an FF loop $w(s) = u(s)$. However, when the FF loop is introduced, its output $q(s)$ is combined with $w(s)$, $u(s)$ is liable to deviate outside the range of $u_{max}(s)$ and $u_{min}(s)$ resulting in controller output saturation. To insure this does not occur in the control loop the fixed output range of $K_b(s)$ (PID controller) is dynamically shifted in the opposite direction and magnitude of the FF vector $q(s)$, while the set point $r(s)$ remains constant. This guarantees that:

$$w(s) + q(s) \le u_{max}(s) \tag{3}$$

$$w(s) + q(s) \ge u_{min}(s) \tag{4}$$

This method of dynamically regulating the combined output of the FF and FB loops eliminates the possibility of saturation in the control loop. The operation of the FB controller is not inhibited whilst the influence of the disturbance rejection ability of the FF controller remains, resulting in a highly responsive control system capable of handling frequent disturbances.

2.5. Test procedure

Testing was carried out under controlled laboratory conditions designed to emulate "real world" settings. Water was chosen as a substitute for milk due to its similar thermodynamic properties. The milking clusters were placed upright in basins with a continuous feed of 37 °C water. The experiment simulated the operation of a 16 cluster milking machine with one receiver jar, a level sensing probe and a VSD milk pump. The milking machine pumped milk through the PHE and into a bulk tank for storage. During this process the controller manipulated the flow rate of GW to achieve a desired set-point for pre-cooing and the flow rate of ICW to insure instant cooling to the constant set-point of 3.5 °C. Both the GW and ICW VSD pumps were controlled by two independent controllers identical to that described in section 2.4. Both controllers had the same FF input signal. The set point of the ICW controller determines the final temperature of the milk and was kept constant at 3.5 °C. This ensured instant cooling of the milk for each test. The set point of the GW controller determined the pre-cooling temperature of the milk. Change of the pre-cooling temperature set point affected the GW usage for pre-cooling and the ice consumption for instant cooling in the second stage, which in turn altered the energy costs. Eight pre-cooling set points (S1–S8) were tested (13 °C–20 °C, with 1.0 °C increments) for two control schemes, 1) using only the FB loop, and 2) using both the FB and FF control loops. GW temperature was kept constant at 10 °C for all tests. The same test procedure, including the operation of the milking machine, was carried out 5 times for the 16 (8 temperature set-points × two control schemes) control settings, giving 80 tests in total. The mean milk flow rate for all tests was 34.05 l min^{-1} with a standard deviation of 0.59 l min^{-1}. The mean milk peak flow was 53.31 l min^{-1} with a standard deviation of 0.94 l min^{-1}.

2.6. Analysis of results

To compare the performance of the system for the 16 control settings, the following indicators were calculated: 1) the minimum and maximum temperature of the outgoing milk. 2) Bulk milk temperature was weighted relative to the milk flow rate and was the final temperature of the whole mass of milk. 3) The root of the mean squared error (RMSE) (Eq. (5)) of the control systems ability to maintain the final milk temperature at the desired set point.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(\varepsilon_i)^2}{N}} \quad (5)$$

where for the ith record, ε is the residual error term and N is the total number of records. RMSE squares the residual errors before averaging, thus a quadratic weighting is applied to the error value. In this way large residual errors have a relatively high weight in the RMSE. 4) The mean GW to milk flow, and 5) the mean ICW to milk flow. The indicators were based on the measurement of the related variables that were measured every 0.5 s.

3. Results and discussion

3.1. System performance

Table 1 shows the performance indicators of the PHE control system with FF control (indicated as FB–FF) and without FF control (indicated as FB) for eight pre-cooling settings (S1–S8). The addition of the FF loop had a substantial impact on the stability of the temperature of the outgoing milk. The mean minimum milk temperature below the set point reduced from 1.0 °C for the FB controller to 0.57 °C for the FB–FF controller

Table 1 – Results of the performance indicators for the feedback (FB) controller and feedback–feedforward (FB–FF) controller for eight controller settings (S1–S8).

Control setting	Min milk temp (°C)	Bulk milk temp (°C)	Max milk temp (°C)	RMSE[a] (°C)	GW milk ratio[b]	ICW milk ratio[c]
S1 FB–FF[d]	2.8	3.5	4.3	0.19	5.90	3.34
S1 FB[e]	2.5	3.6	5.5	0.49	5.98	3.41
S2 FB–FF	3.2	3.5	3.9	0.15	4.44	3.85
S2 FB	2.5	3.5	5.3	0.40	4.54	3.86
S3 FB–FF	2.9	3.5	4.1	0.18	3.36	4.14
S3 FB	2.6	3.6	5.1	0.39	3.38	4.34
S4 FB–FF	3.0	3.5	4.3	0.19	2.92	4.49
S4 FB	2.5	3.7	6.0	0.52	2.97	4.62
S5 FB–FF	2.9	3.5	4.3	0.19	2.68	4.66
S5 FB	2.2	3.6	5.8	0.52	2.69	4.79
S6 FB–FF	3.0	3.6	4.6	0.19	2.46	4.83
S6 FB	2.5	3.7	5.8	0.59	2.51	4.92
S7 FB–FF	2.9	3.6	4.5	0.17	2.19	4.99
S7 FB	2.5	3.7	5.9	0.52	2.21	5.03
S8 FB–FF	2.7	3.6	4.5	0.19	1.98	5.11
S8 FB	2.5	3.7	5.8	0.58	2.02	5.19

a Root mean squared error.
b Ground water to milk flow ratio (dimensionless).
c Ice chilled water to milk flow ratio (dimensionless).
d Feedback–Feedforward.
e Feedback.

(43% reduction). The FB controller achieved a mean bulk temperature of 3.64 °C (0.14 °C above target) while the FB–FF controller's mean bulk temperature was 3.54 °C (0.04 °C above target). The mean maximum milk temperature above the set point reduced from 2.1 °C for the FB controller to 0.81 °C for the FB–FF controller (61% reduction). The mean RMSE for the FB controller was 0.18 °C while the RMSE for the FB controller was 0.5 °C (2.8 times higher). The final milk output temperature deviated from the set point (3.5 °C) much less for the FF–FB controller (between 2.8 °C and 4.3 °C) in comparison to the FB controller (between 2.5 °C and 5.5 °C). The main difference between settings was the GW and ICW ratios; as the GW consumption reduced the level of pre-cooling also reduced leading to an increase in ICW utilisation. Figure 3 and Fig. 4 represent the operating characteristics of the FB and FB–FF controller for S1, respectively. The dynamic control of GW and ICW flow rates in response to the variation in milk flow is also shown. Figure 5 shows the operating characteristics of the FB–FF controller for S8. The GW flow rate per unit milk was considerably lower for S8 (Fig. 5) compared to S1 (Fig. 4). The GW to milk ratio was 1.98 for S8 FB–FB and 5.90 for S1 FF–FB (3 times higher). This reduction in GW resulted in higher ICW usage and therefore more ice consumption per unit of milk. From the results it is clear that the FF–FB controller is capable of precisely and rapidly cooling incoming milk from a variable flow milking machine using different combinations of GW and ice. The most economic mixture of both systems should be selected depending on the costs of electricity and GW.

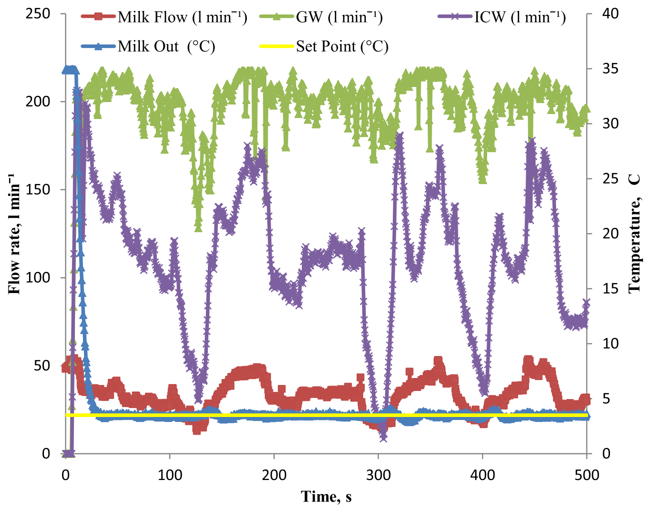

Fig. 4 – Operating characteristics for feedback–feedforward (FB–FF) controller S1. Flow rates (l min^{-1}) of milk (red), ground water (GW) (green) and ice chilled water (ICW) (Purple) on left axis. Temperature (°C) of outgoing milk (blue) and set-point (°C) (blue) on right axis.

3.2. *Energy consumption and cooling cost*

The results in Fig. 6 were produced by the model described in section 2.2 and represent the cooling energy consumption per litre of milk with varying GW to milk ratios. The amount of cooling energy required reduced as the GW to milk ratio increased. However, the influence of the GW on the energy consumption became increasingly less substantial as the ratio increases. This is largely due to the decrease in PHE effectiveness per additional litre of water since the temperature differential between the pre-cooled milk and the GW reduces and the energy consumption of the water pump increases as the water flow increases.

Figure 7 shows the cost of cooling milk with varying GW to milk ratios. The cost of cooling per litre of milk fluctuates as the GW to milk ratio increases. There is an optimum GW to milk ratio for each fixed water cost that yields the minimum cooling cost. These points can be seen as the optimum combination of cooling power (ice storage) and GW consumption

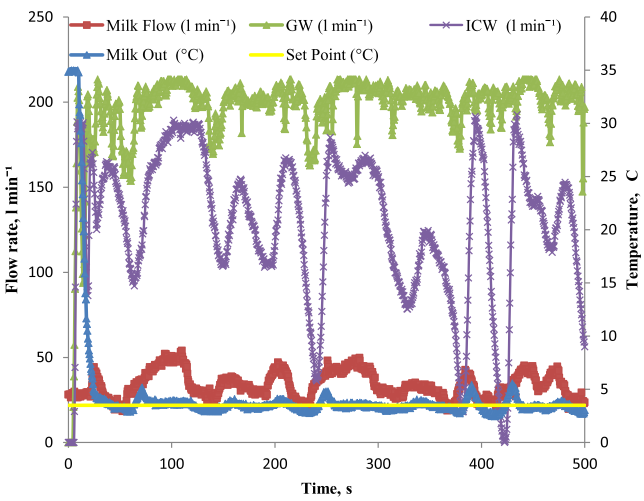

Fig. 3 – Operating characteristics for feedback (FB) only controller S1. Flow rates (l min^{-1}) of milk (red), ground water (GW) (green) and ice chilled water (ICW) (Purple) on left axis. Temperature (°C) of outgoing milk (blue) and set-point (°C) (blue) on right axis.

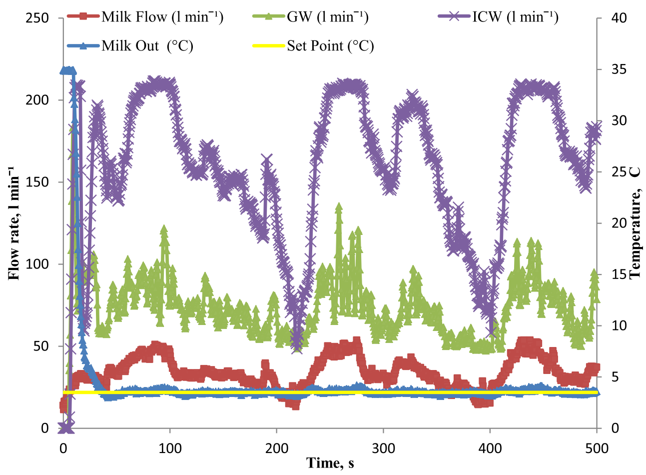

Fig. 5 – Operating characteristics for feedback–feedforward (FB–FF) controller S8. Flow rates (l min^{-1}) of milk (red), ground water (GW) (green) and ice chilled water (ICW) (Purple) on left axis. Temperature (°C) of outgoing milk (blue) and set-point (°C) (blue) on right axis.

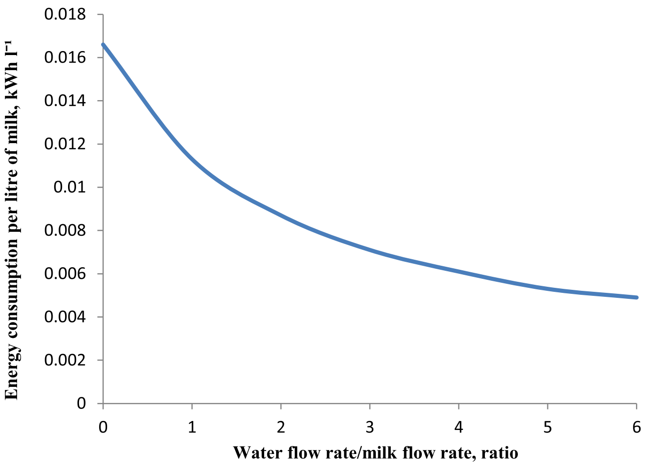

Fig. 6 – Energy consumption per litre of milk (kWh l^{-1}) with varying ground water ratios.

for specific water and electricity costs. The economic optimum water to milk ratio varies greatly with water cost. Where water is supplied without cost the optimum solution is to keep increasing the water flow rate until the added cooling effect of the water is cancelled out by the increasing pumping cost. However, in practice producing GW at no cost is unlikely as some working infrastructure and capital financing is required. Applying even a very small monetary cost to the GW (€0.05 m^{-3}) has a profound effect on the optimum economic water ratio. As the water cost increases this optimum ratio continues to reduce.

3.3. *Optimisation potential*

Between 2010 and 2012 Teagasc AGRIC conducted energy audits on 25 commercial dairy farms in Ireland. The average IB milk cooling energy consumption and cost were 0.013 kWh l^{-1} and €0.0016 l^{-1} (excluding water cost), respectively. In each case either insufficient levels of pre-cooling or no pre-cooling were observed. Audits carried out specifically on pre-cooling found that 80% of PHEs had a GW to milk ratio of 1:1 or less. In similar energy audits completed in 1995 in the UK, average IB milk cooling energy consumption was found to be 0.0222 kWh l^{-1} with the average PHE GW to milk ratio 1:1 (Milk Development Council, 1995). A study in New Zealand found that increasing the GW to milk ratio considerably increased pre-cooling levels (Morrison, Gregory, & Hopper, 2007). Figure 7 gives a clear representation of possible savings which could be achieved on a typical dairy farm if a control system was introduced to optimise the usage of GW. If it is assumed that the current dairy farm modus operandi for PHE pre-cooling is a GW to milk ratio of 1:1, then potential for system optimisation clearly exists. For a water cost of €0.05 m^{-3} a GW to milk ratio of 1:1 results in a milk cooling cost of €0.00115 l^{-1}, however a cooling cost of €0.00076 l^{-1} (34.5% less) can be achieved through correct water utilisation (Fig. 7). Similarly savings of 17.9%, 9.6% and 0.5% can also be made for set water costs of €0.1 m^{-3}, €0.15 m^{-3} and €0.2 m^{-3}, respectively. Only operational costs are included in this study, the initial investment and depreciation costs of a VSD and a PID controller are not included.

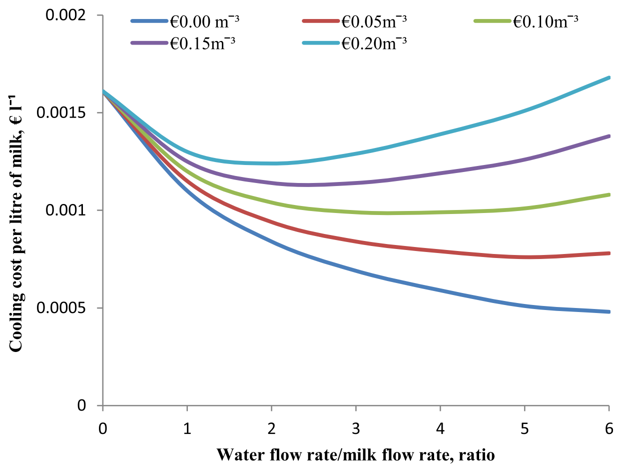

Fig. 7 – Milk cooling cost per litre of milk (€ l^{-1}) with varying water to milk ratios for five different ground water prices €0.00 m^{-3} (blue), €0.05 m^{-3} (red), €0.10 m^{-3} (green) €0.15 m^{-3} (purple), €0.20 m^{-3} (cyan).

Optimisation of GW usage is not only advantageous for instant milk cooling but for all milk cooling systems that employ pre-cooling with GW. The controller described in section 2.4 controls GW based on desired pre-cooling temperature. The control system's ability to instantly cool milk by balancing GW and ice consumption enables the selection of the optimum economic GW to milk ratio. Farmers can adjust the setting of the controller based on specific farm conditions, electricity cost and water cost/availability, this capability could also help farmers to negotiate any future spikes in energy costs or shortages in water supply. The controller setting can be adjusted manually using heuristic knowledge or can be automatically updated based on milk production, wash down water usage, electricity cost, and GW cost. With seasonally varying herd sizes and milk production levels, the optimum controller set point could be dynamically updated throughout the season.

Changes in controller setting could also be used to facilitate herd size expansion without increasing plant capital cost. Increased usage of GW will allow for the cooling of more milk without an increase in IB capacity, this attribute could help farmers cope with large increases in milk production in the near future.

4. Conclusion

A rapid milk cooling system was designed, built and tested for a variable flow milking machine and tested under various configurations. The system was capable of rapidly cooling a dynamic milk flow over a wide range of operating conditions. The introduction of a control system allows for potentially substantial energy and cost savings. The introduction of a FF loop to the controller significantly increased the accuracy of the output temperature; this is particularly useful for direct milk collection and non-agitated storage. However, for bulk storage with mechanical agitation a FF loop is not vital as the bulk temperature is only slightly above target (0.2 °C maximum).

The system has the ability to operate under varying GW supply and pricing scenarios allowing the user to select either low cooling costs and high water usage, or low water usage and higher cooling costs. This is because the ice water usage will autonomously increase or decrease to achieve the desired instant cooling temperature allowing for the optimisation of pre-cooling for a given water or electricity cost. The same GW optimisation scheme can be applied to conventional cooling systems.

Future development of the system will involve a mathematical tool that automatically selects the optimum controller setting based on specific on site conditions using information from other on-farm databases.

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