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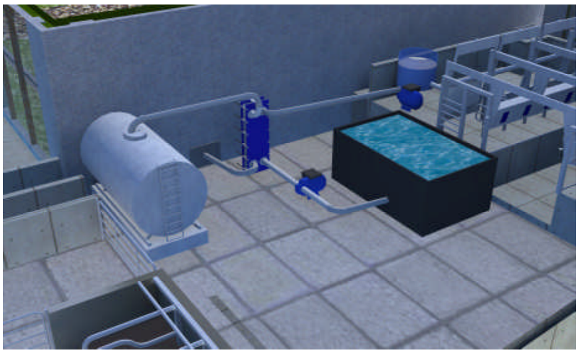
Optimised milk cooling



Key external stakeholders:

Dairy farmers, dairy advisors and planners, technology manufacturers, academic staff working in the area of milking and cooling technology.

Practical implications for stakeholders:

The outcome of this project includes an analysis of advanced milk pre-cooling technologies capable of realising significant savings over baseline milk cooling energy consumption data for commercial Irish dairy farms.

- Control systems were developed to implement optimised pre-cooling with either well supplied water or iced water.
- The user of the system can adjust the controller settings to optimise either milk cooling energy consumption or on-farm water consumption making it suitable for application on a range of farm types.
- Opportunities to reduce costs associated with milk cooling energy consumption have been identified through more intelligent application of both well water and iced water for cooling milk.

Main results:

- Optimised the single stage milk pre-cooling process by developing a flow rate controller capable of achieving optimal cooling performance in milk pre-cooling plate heat exchangers.
- Developed and implemented an intelligent dual stage plate heat exchanger capable of controlling cold water flow rates and iced water flow rates to guarantee instant milk cooling while eliminating well water and ice water wastage.
- Developed a load shifting dairy farm ice builder system capable of predicting iced water demand whilst implementing the least cost method of building the desired quantity of iced water operating in a varying time of use tariff electricity market.
- Published results of the research in a peer reviewed journal.

Opportunity / Benefit:

A trend is emerging whereby only large farms invest in energy/water saving technologies due to the high capital cost involved, and small farms tend to follow a business as usual procedure. By providing a low capital cost solution to the control of plate cooling, the improvements that will be delivered by the technologies described in this project (especially the implementation of more sophisticated cooling control of existing plate coolers) will help to improve the energy efficiency and hence the market position of both well established farms and smaller start-up new entrant farms where capital is limited thereby reducing long term running costs of cooling systems, improve competitiveness and reduce CO_2 impacts associated with milk production.

Collaborating Institutions:

Cork Institute of Technology (CIT); Dairymaster; Enterprise Ireland

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1. Project background:

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 0.013kWh 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 ground water (GW) to milk ratio of 1:1 or less. It was discovered in particular that current milk pre-cooling practices were not optimal resulting in large and avoidable milk cooling costs. Milk leaves the udder at approximately 35°C, but only rapid cooling to a storage temperature of around 4°C prevents or minimises micro-organism growth. Cooling with ice water could achieve this goal, while building ice at times when electricity is at off-peak rates would have the potential to keep cooling costs to a minimum. An intelligent milk pre cooling control system for optimising the performance of plate heat exchangers does not exist commercially which presents a significant opportunity to exploit the deliverables of this project immediately. The significance of the project is heightened at the present time due to the abolition of the European Union milk quota regime in 2015. To facilitate this expansion in milk production there will be a requirement for increased energy efficiency while at the same time improved milk quality.

2. Questions addressed by the project:

- Can milk cooling costs be reduced by developing an optimised single stage milk pre-cooling process in milk pre-cooling plate heat exchangers?
- Can milk cooling costs be reduced by developing an intelligent dual stage plate heat exchanger capable of controlling cold water flow rates and iced water flow rates?
- Can milk cooling costs be reduced by developing a load shifting dairy farm ice builder system?

3. The experimental studies:

The milk refrigeration system chosen for this study was a dual stage plate heat exchanger (PHE) with the GW pre-cooling taking place in the first stage and the main chilled water (CW) cooling in the second stage. An ice bank (IB) was selected, as chilled water is required for instant cooling. A full scale test rig was designed and built (figure 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. 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 recorded the electricity consumption of each individual electrical device. LabVIEW 2010 software was used for control and data logging. All laboratory equipment was calibrated to ISO17025 standards. Instrumentation was supplied by Radionics Ireland and National Instruments.

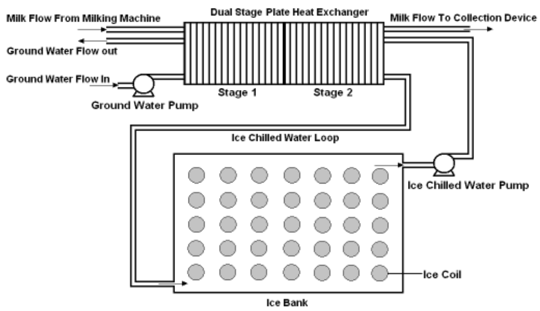

Figure 1. Schematic of the dual plate heat exchanger (PHE) used for instant milk cooling with ground water (GW) used for pre-cooling in the first stage and ice chilled water (ICW) used in the second stage (arrows indicate flow direction).

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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 systems coefficient of performance (COP). The COP of refrigeration units with air cooled condensers are greatly affected by variations in ambient temperature. 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. Day and night rate electricity tariffs were set at €0.183 kWh^{-1} and €0.097 kWh^{-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.

The milk temperature leaving the dual stage PHE was varied by manipulating the flow rates of GW and ICW. This was achieved by controlling the speed of the pumps using variable speed drives (VSDs). A proportional integral derivative (PID) controller was used to control the VSD in booth control loops. In order to apply the correct proportional derivative and integral values the controllers were tuned using the Zeigler-Nichols ultimate gain method.

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 ^{o}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. 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 were tested (13°C to 20°C, with 1.0 °C increments). GW temperature was kept constant at 10 ^{o}C for all tests. The same test procedure, including the operation of the milking machine, was carried out 5 times for each test. 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}.

4. Main results:

In this study an instant milk cooling system was designed built and tested for a variable flow milking machine and tested under various configurations. The system was capable of instantly 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 Feed Forward 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 Feed Forward 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 choose 1) low cooling costs and high water usage or 2) low water usage and higher cooling costs. This is because the ice water usage will autonomously increase or decrease to achieving the desired instant cooling temperature allowing for the optimization of pre-cooling for a given water or electricity cost. The same GW optimization scheme can be applied to non-instant cooling systems.

Figure 2 gives a clear representation of possible savings which could be achieved on a typical dairy farm if a control system was introduced to optimize 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

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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. 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.

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 developed in this project 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.

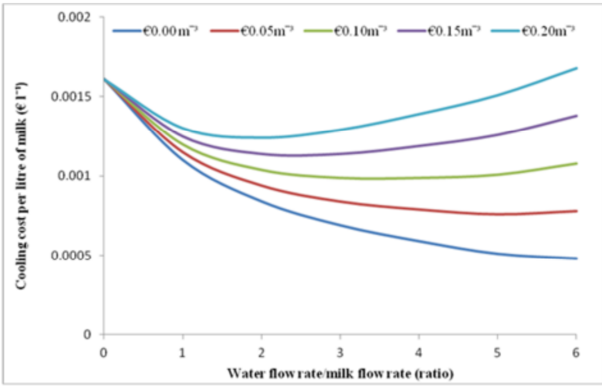

Figure 2. Milk cooling costs per litre of milk (€ l-1) with varying water to milk ratios for five different ground water prices €0.00 m^{-3} (blue), €0.05 m^{-3} (red), €0.10 m^{-3} (green) €0.15 m^{-3} (purple), €0.20 m^{-3} (cyan).

5. Dissemination:

Main publications:

1. Murphy, M.D., J. Upton and M. J. O’Mahony, Rapid milk cooling control with varying water and energy consumption. (2013). Biosystems Eng. 116(1): 15-22.
2. Murphy, M., O'Mahony, M. J., Upton, J. (2013). A control system with disturbance rejection for variable flow milk cooling. Proceeding from the 30th International Manufacturing Conference, Pages 62-72, September 2013, University College Dublin. (This paper won the 1st place award for best original research paper).
3. Murphy, M., O'Mahony, M. J., Upton, J. (2012). A load shifting controller for Cold Thermal Energy Storage systems, Proceeding from the IEEE International Conference on Green Technologies (ICGT) International Conference, Pages 14-19, 18-20 Dec. India

6. Compiled by: John Upton

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