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Appropriate placement of vapour recompression in ultra-low energy industrial milk evaporation systems using Pinch Analysis

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ABSTRACT

This study focuses on applying Pinch Analysis to an industrial milk evaporator case study to quantify the potential energy savings. Modern milk evaporators are typically integrated using both mechanical and thermal vapour recompression technologies as the primary means for attaining a high level of energy efficiency. A significant step change in energy efficiency for milk evaporators is achieved in this study by appropriate placement of vapour recompression in a new improved two-effect milk evaporation system design. The Grand Composite Curve helps identify areas for process modifications and placements of vapour recompression that result in energy reduction. In particular, the innovative placement of Mechanical Vapour Recompression in the system unlocks significant energy, energy cost, and emissions savings. The new design requires 78% less steam (6397 kW) at the expense of 16% (364 kW_{ele}) more electricity use. The estimated cost savings associated with the improved design is $942,601/y and the emissions reduction is 3416 t CO_2-e/y. Further energy efficiency improvements and cost savings of $1,411,844/y are gained through improved Total Site Heat Integration through recovery of waste heat from the dryer exhaust air and boiler return condensate streams.

1. Introduction

Increasing sustainability in food processing through increased processing energy efficiency is a topic of significant global interest [1]. Rising pressure to lower energy use and emissions in all sectors of society are driving the need for energy efficiency related research and implementation [2]. In New Zealand, the food processing sector is dominated by dairy processing with milk powders being the principal product for export. Conversion of liquid milk to powdered milk is an energy intensive two-stage process that uses between 5.2 and 11.1 GJ/t of product depending on the plant's vintage [3]. The first dewatering stage, which is the focal point of the present study, is a multi-effect evaporator train. The second dewatering stage is spray drying, which typically has minimal heat integration [4].

A series of recent studies into the reduction of energy use of milk powder production using Process Integration techniques have chiefly given attention to spray dryer exhaust heat recovery as the key to advancing to the next level of energy efficiency. Focuses of these studies have included optimisation of soft temperatures for minimising energy use [5], development of HEN (Heat Exchanger Networks) [6], dryer heat recovery modelling [7], and development of a comprehensive economic optimisation of the dryer exhaust heat recovery system [8]. Although the evaporation system was included in some of these studies, the finer details and constraints surrounding the entire evaporation system, including the milk heat treatment section, were not fully appreciated. As a result, improvements in the thermal and electrical energy efficiency for the milk evaporator plant were limited.

Published studies on milk evaporation systems have chiefly focused on the stand-alone energy efficiency of the individual process; without considering a holistic Process Integration approach to designing an evaporation system that optimally integrates with the entire milk powder process [9]. For example, Hanneman and Robertson [10] compared a five-effect milk evaporator train integrated with TVR (thermal vapour recompression) to a single evaporator effect integrated with MVR (mechanical vapour recompression). Their analysis reported the MVR scheme required 55% less fuel use, however their analysis failed to account for any required vapour bleeds and condensers that may be integrated as a heat source in the surrounding process. Available industrial documentation from GEA Niro, a global industrial milk evaporator supplier, presents set-ups and operation techniques for

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Nomenclature

Roman

COP	coefficient of performance
H	heat flow (kW)
HSR	heat savings ratio (kW/kW)
PR	thermo-compressor performance ratio (kg/kg)
PT	Pinch Temperature (°C)
Q	duty (kW)
T	temperature (°C)
T^*	shifted temperature (°C)
TS	supply temperature (°C)
TT	target temperature (°C)
W	work (kW)

Greek

Δ	difference between two states

Subscripts

bleed	vapour bleed
c	cold
cond	condensation/condenser
comp	compression
cont	contribution
ele	electrical
evap	evaporation
feed	feed to evaporator effect
flash	flash vapour of the liquid feed
h	hot
in	inlet
r	recovery
sens	sensible heating of the liquid feed
steam	steam utility use

Abbreviations

CC	Composite Curves
CIP	clean-in-place
DSI	direct steam injection
FB	fluidised bed
GCC	Grand Composite Curve
HEN	heat exchanger network
HPS	high pressure steam
HT	high temperature
HTHW	high temperature hot water
HVAC	heating, ventilation and cooling
LTHW	low temperature hot water
MPS	medium pressure steam
MVR	mechanical vapour recompression
TSHI	Total Site Heat Integration
TVR	thermal vapour recompression

milk evaporators, which achieve a high-energy economy [11], but these are often sub-optimal with respect to an entire site. It is anticipated that applications of Process Integration techniques to the milk evaporation system problem will yield substantial economic steam savings, as have been found for other industries [12].

Thermal and mechanical vapour recompression technologies find excellent application in a wide range of processing systems. TVR uses a thermocompressor with high pressure vapour (steam utility) to recompress low pressure vapour (often under vacuum) to a slightly higher pressure and temperature. MVR uses a mechanical fan, normally driven by electricity, to recompress low pressure vapour to a slightly higher pressure and temperature. In distillation systems, MRV can directly compress top distillate vapour for use in the reboiler or can indirectly recovery heat from the distillate vapour using a separate working fluid such as n-pentane before upgrade and use in the reboiler. These processing structures led to a step-change in energy integration [13]. In desalination systems, multi-effect evaporation systems integrated with an absorption heat pump and vapour compression cycles can effectively synthesize to generate cooling and fresh clean water at 26% lower total cost compared to [14]. TVR has found application in carbon capture processes to upgrade and recovery of waste, resulting in energy savings between 10 and 14% [15]. In milk evaporation systems, vapour recompression units directly compress vapour flows drawn from the product on the tube-side ("evaporator") to a higher pressure and temperature for use as the condensing vapour on the shell-side ("condenser"). As a result, this arrangement creates a so called open cycle heat pump. The analogy between vapour recompression and conventional heat pumps also extends to the idea of appropriate placement in Pinch Analysis, which states that a heat pump should upgrade heat from below the Pinch for use above the Pinch [16].

Purposeful design and integration of the evaporation system to complement the heat demands of neighbouring processes provides greater opportunities for energy and emissions savings. TSHI (Total Site Heat Integration) provides a valuable framework for understanding and optimising the site-wide heat balance [17,18]. Application of TSHI has recently led to substantial utility savings in slaughter and meat processing [19], large industrial parks in Japan [20] and Thailand [21], chemical processing clusters [16,17], and Kraft pulp mills [23]. With respect to the milk evaporation system design problem, TSHI can help determine the value of heat exports from the evaporation system to neighbouring processes.

The aim of this study is to develop an ultra-low energy design for a milk evaporation system through the appropriate placement of vapour recompression, given the context of a stand-alone milk powder factory. To achieve this aim, a combination of Pinch Analysis, TSHI, and process modelling techniques are applied to the milk evaporation system problem to identify critical components of an ultra-low energy evaporation system design. A modern industrial two-effect evaporator case study provides a useful starting point, comparison, and scope for the new evaporation system design. To ensure a fair comparison, the new design is constrained to have the same number of effects as the industrial base case. Milk processing constraints related to product quality, thermal treatment, and thermophile growth, are important considerations in the solution development. In particular, the GCC (Grand Composite Curve) plays an important role in the analysis to help identify where process modifications and vapour recompression can be considered to provide a step change in energy efficiency. Targets for energy use, energy cost, and emissions are calculated to determine the benefits of shifting towards an ultra-low energy milk evaporation system. The presented analysis is an extension of the early work by the authors [9].

2. Historical developments in energy efficiency of industrial milk evaporation systems in New Zealand

Over the past four decades, there has been significant progress in the design and efficiency of milk evaporators in the New Zealand

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