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Pinch Analysis of an Industrial Milk Evaporator with Vapour Recompression Technologies

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The present study focuses on applying Pinch Analysis to an industrial milk evaporator case study. 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 modifying the set-up of the concentration processing pathway in combination with an improved heat exchanger network design. To effectively perform the Pinch Analysis, a validated mass and energy balance model of the milk evaporator case study has been implemented in an Excel spreadsheet from which appropriate stream data may be extracted. In particular the Grand Composite Curve plays a critical role in identifying where vapour recompression units, which are a type of heat pump, may be applied to reduce thermal energy use by as much as 67 %, which represents an annual utility cost saving between 640 – 820 k$/y.

1. Introduction

Increasing sustainability in food processing through reducing energy use is a topic of global interest (Klemeš et al., 2008). In New Zealand, food processing is dominated by dairy processing with milk powders being the principal export product. Conversion of liquid milk to powdered milk is an energy intensive two stage process. The first dewatering stage is a multi-effect evaporator train. Modern evaporators are integrated with mechanical vapour recompression (MVR) and thermal vapour recompression (TVR) units for improved heat efficiency (Palacios-Bereche et al., 2014). The second dewatering stage is spray drying, which typically has minimal heat integration.

A series of recent studies into the reduction in energy use of milk powder production have chiefly focused on 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 (Walmsley et al., 2012), development of heat exchanger networks (Walmsley et al., 2013), and a comprehensive economic optimisation of the dryer exhaust heat recovery system (Walmsley et al., 2014). Although the evaporator plant was included in some of these studies, the finer details surrounding the entire process, which includes a milk heat treatment section, were not fully appreciated and so improvements in the thermal and electrical energy efficiency for the milk evaporator plant were limited.

Few available studies have looked at increasing the energy efficiency of industrial milk evaporators using Process Integration techniques. Available documentation from a global supplier presents set-ups and operation techniques for milk evaporators, which achieve a high energy economy (Westergaard, 2010), but, as will be demonstrated, their standard solution is sub-optimal. In other literature Hanneman and Robertson (2005) compared a five effect milk evaporator train integrated with TVR to a single evaporator effect integrated with MVR. Their analysis reported the MVR scheme required 55 % less fuel use, however their analysis failed to account for any required vapour bleeds that may be integrated as a heat source in the surrounding process. Application of Process Integration techniques to non-milk evaporators have identified economic steam savings in the range of 20 – 40 % (Westphalen and Wolf Maciel, 2000).

The aim of this study is to apply Process Integration to an industrial milk evaporator that is integrated using vapour recompression technologies to identify any energy savings potential. The industrial evaporator

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case study is set in the context of a milk powder plant that nominally produces 30 t/h of powder. The Grand Composite Curve plays an important role in the analysis to help identify where process modifications can be considered to provide a step change in energy efficiency.

2. An Elementary Understanding of Evaporators Integrated with Vapour Recompression

Integrating evaporators with vapour recompression technologies is intended to return high level energy efficiency with much less capital expenditure than traditional multi-effect evaporator systems. Evaporated vapour from one effect may be compressed using mechanical work (MVR) or thermal input (TVR). Figure 1 presents a simplified heat balance for a single evaporator effect integrated with MVR (a) and TVR (b). It is important when considering which of the two technologies to apply, the quantum and temperature of any excess vapour that is generated. In the case of MVR, usually all of the evaporated vapour exiting the effect, including any flash that occurs as the feed enters the evaporator, is mechanically recompressed to a higher pressure and temperature and re-injected on the condensing shell-side. As a result, a vapour bleed from the shell-side of the evaporator is requisite (Figure 1a). In the case of TVR, only a portion of the evaporated vapour exiting the effect is recompressed using a thermo-compressor (also called a steam ejector) with high pressure steam being the driving force for compression. The remaining lower pressure vapour is sent to a condenser without being upgraded (Figure 1b). Due to the high quality of energy used, the enthalpy addition required for vapour compression in MVR is between 10 – 20 times less than for TVR. As a result, the quantity of excess vapour in TVR integrated effects is always much greater than for MVR integrated effects, based on the same evaporator load. Ideally excess vapour arising in the two integration schemes is integrated with the surrounding process to maximise overall energy efficiency. TVR is preferable in situations where the condenser heat may be effectively cascaded to the surrounding process as a substitute for steam utility. If this is not possible, then MVR or a combination of MVR and TVR integrated effects provides the most cost-effective solution. A combination of MVR and TVR integrated effects has emerged as the most common design approach for modern milk evaporator plants.

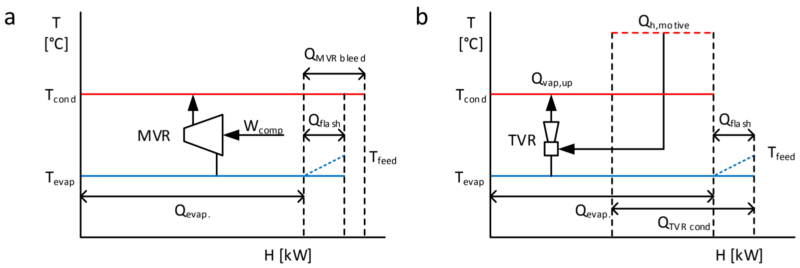

Figure 1: Evaporator heat balance with integrated MVR (a) and TVR (b) when the feed temperature is higher than the evaporation temperature

3. Methods

A detailed heat and mass balance of the multi-effect falling film milk evaporator system integrated using MVR and TVR has been implemented in an Excel™ spreadsheet. The model is validated using the industrial plant data. Standard water/steam properties (IAPWS IF-97) and milk properties (MAF Quality Management, 1996) are applied in the model. Based on industrial data, mechanical compressors have a calculated isentropic efficiency of 70 %, whereas thermo-compressor performance is modelled using the empirical correlation of Al-Juwayhel et al. (1997).

Pinch Analysis techniques for evaporation systems (Westphalen and Wolf Maciel, 2000) have been applied to calculate utility and heat recovery targets. Targets are based on a ΔT_{cont} of 2.5 °C for liquid streams and 0.5 °C for vapour streams, which mirror the difference in typical heat transfer resistance for the two fluids (4 kW/[m^2°C] for liquid streams and 8 kW/[m^2°C] for condensing/evaporating streams). The exchanger minimum approach temperature (EMAT) for the industrial case study is 1 °C. Area targets have been calculated using balanced Composite Curves and the BATH formula.

4. Industrial Milk Evaporator Case Study

The industrial milk evaporator case study is presented as a process flow diagram and as a grid diagram in Figure 2. Standardised milk initially at 8 °C is heat treated at 95 °C before being concentrated from 13 % to 52 % solids in a multi-train two-effect falling film evaporator system integrated with MVR and TVR

technologies. The milk heat treatment process is a combination of temperature (80 – 120 °C) and holding time (1 – 60 s), which affects the degree of protein denaturisation (Oldfield et al., 2005) and the flavour of the milk powder (Baldwin et al., 1991). Conventional heat recovery via heat exchangers is suitable up to a milk temperature of about 80 °C, above which it is important to limit the contact surfaces and tightly control the residence time at specific heat treatment temperatures (GEA Niro, 2014). Once at about 80 °C, milk is rapidly heated 95 °C using direct steam injection (DSI). After being held for a short time at 95 °C, milk is flashed at 81 °C for instantaneous cooling and generation of low pressure vapour for heat recovery.
The first evaporator effect is integrated with MVR while the second effect is integrated TVR. The MVR effect operates at 68 °C (milk-side) and duty of 95.3 MW and the TVR effect operates at 56 °C and duty of 5.4 MW, both with approach temperatures of 5 °C. Some vapour from the TVR effect is upgraded in a secondary thermo-compressor and transferred to the MVR effect to make-up for a small shell-side vapour deficit, which is caused by an excessive vapour bleed for milk pre-heat. The maximum milk temperature in the first effect is set at 70 °C to avoid further denaturing of proteins (Hinton, 2003). Each evaporator train is washed clean-in-place (CIP) about every 16 h to maintain food grade processing hygiene.
Stream flow rates are a function of the scale of production. Whereas most stream temperatures, including evaporator pressures/temperatures, are soft and independent of production scale. Hard temperatures include the incoming temperature of the standardised milk (8 °C), the milk heat treatment temperature (95 °C), the final temperature of the milk concentrate (70 °C), and the CIP water supply and target temperatures (15 °C and 85 °C). Utility prices for the site in New Zealand dollars are 25.00 $/t for indirect steam heating, 27.50 $/t for direct steam use in thermo-compressors, and 100 $/MWh for electricity.

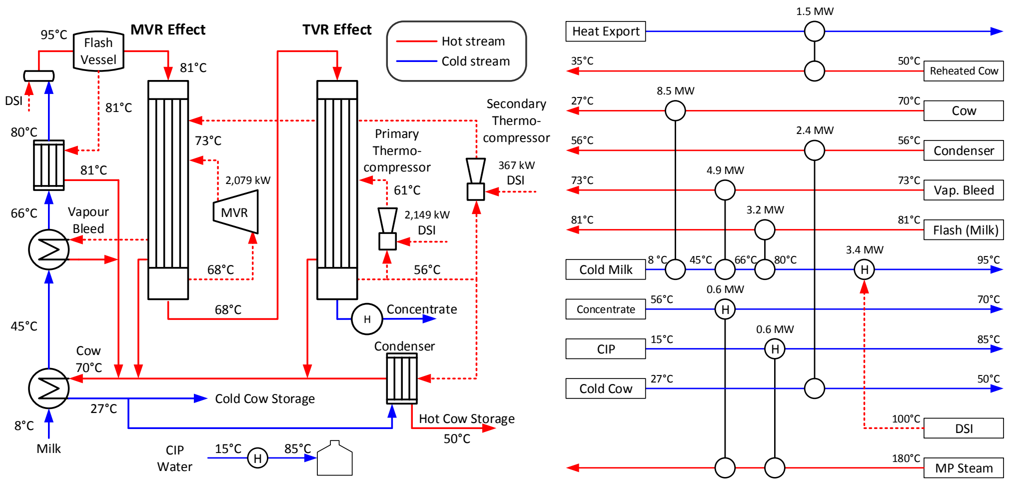

Figure 2: Base-case industrial milk evaporator integration illustrated using a process flow diagram (left) and grid diagram (right)

5. Results and Discussion

5.1 Initial Heat Integration Targeting

Composite Curves (CC) and Grand Composite Curves (GCC) for the milk evaporator case study are plotted in Figure 3 together with the actual stream's current heating and cooling demand. Heat transfer within the evaporator effects totalling 101 MW have been excluded from the CCs in Figure 3a. Figure 3a shows that if the CCs were to pinch, a steam savings of 0.6 MW is achievable based on a ΔT_{cont} previously defined and an EMAT for the flash vapour/cold milk match. Figure 2B plots the GCC, the heat transfer occurring within the two effects and the steam used in the primary (TVR1) and secondary (TVR2) thermo-compressors. Excess vapour drawn from the two effects in the form of a vapour bleed or condenser is included as part of the GCC.
To clearly show where the energy savings arise from, Table 1 divides hot utility (Q_h) use into three categories: cold milk heating (excludes concentrate heating), direct use in thermo-compressors, and other uses. The target for Figure 3 shows the heat recovery increase is derived from reduce steam use in areas other than milk heating and TVRs, $Q_{h,other}$, e.g. heat recovery to CIP water. A hot utility savings of 0.6 MW equates to a utility cost saving of $136k $/y for a plant that operates for 6000 h/y. Cooling utility targets reported in Table 1 are strongly dependent on the soft target temperature, T_t, of a few hot streams, e.g. Cow stream T_t is set at 13 °C. Increasing these soft target temperatures can eliminate the cooling demand

with no adverse effects on the process, hence cooling requirement is also soft. Some of the cooling load may be exported (Q_{export}) from below the Pinch Temperature (PT) to the neighbouring spray drying process for preheating air streams. The remainder, $Q_{c,other}$, may be viewed as unrecovered heat that under a different scheme may have been able to be meaningfully recovered.

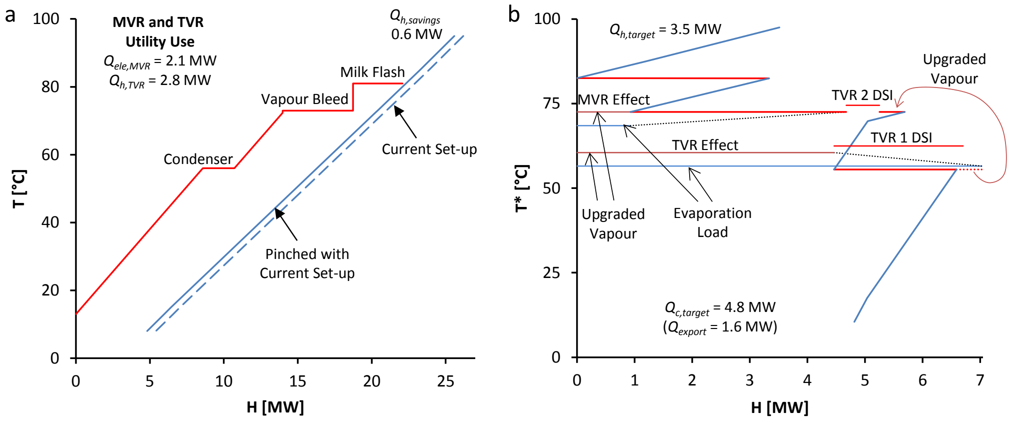

Figure 3: Composite Curves, CC, (a) and Grand Composite Curves, GCC, (b) for the current set-up

Table 1: Summary of soft temperature selection, utility targets and projected cost savings

Scheme	*PT* [°C]	Q_{ele} [kW]	$Q_{h,milk}$ (pre-heat) [kW]	$Q_{h,TVR}$ [kW]	$Q_{h,other}$ [kW]	ΣQ_h [kW]	Q_{export} [kW]	$Q_{c,other}$ [kW]	Area Target [m^2]	Utility Savings [$/y]
Current	82.5	2,080	3,471	2,823	645	6,939	1,554	3,861	619	-
Fig. 3	82.5	2,080	3,471	2,823	46	6,340	1,554	3,262	968	136k
Fig. 4A	72.5, 81.0	2,081	2,127	2,243	138	4,508	1,155	1,607	1,026	504k
Fig. 4B	72.5, 84.4	2,354	-	2,243	28	2,271	827	-	1,583	822k
Fig. 4C	10.5, 80.2	2,214	2,273	-	73	2,347	-	-	932	701k
Fig. 4D	10.5, 79.8	2,330	2,274	-	32	2,306	-	-	991	641k

5.2 Using the Grand Composite Curve to Improve the Integration of the Evaporator Plant

The GCC is an essential tool for identifying methods to increase energy efficiency in industrial milk evaporators. Since changes to the evaporator set-up and operation, in addition to the HEN, are being considered as ways to increase energy efficiency, a close link in the analysis between the evaporator mass and energy balance model and the extracted Pinch Analysis stream data is needed for representative heat recovery and utility targets for the various schemes.

The GCC in Figure 3b show that under the current set-up the plant upgrades some TVR condenser vapour using a secondary thermo-compressor before injecting it into the shell-side of the MVR effect. The placement of the thermo-compressor, which is a heat pump, is inappropriate because the heat pump fails to upgrade the heat from below the Pinch Temperature to above it. In this situation, hot utility is used below the Pinch, which increases the cold utility target with no impact on the hot utility target. Removing the secondary TVR represents 0.6 MW of steam savings beyond the target in Figure 3. To accommodate this modification in a retro-fit of the current HEN structure, heat recovery from the Cow stream can feasibly increase by 1.0 MW since the amount of excess vapour in the MVR effect has decreased by 1.0 MW, i.e. 0.6 MW of steam use and 0.4 MW of upgraded vapour.

Effective heat recovery from the heat treated milk at 95 °C is important for unlocking more energy savings. At present, heat is recovered by flashing the hot milk at 81 °C and using the flash vapour for pre-heating milk (66 °C → 80 °C) in a shell and tube heat exchanger. The temperature of the flash vapour (81 °C) drives the Pinch Temperature resulting in a hot utility requirement of 3.5 MW for milk heating. As noted previously, it is a process requirement that the final heating stage of the milk (80 °C → 95 °C) requires direct contact with hot vapour. Some industrial plants use multiple milk flash stages to step the temperature of the milk down in smaller increments, which leads to a higher Pinch Temperature and a reduction in hot utility use. For example, if two flash stages with temperatures of 75 °C and 85 °C is used, the hot utility requirement for the milk would decrease to 2.3 MW. However, this solution is relatively bulky and struggles to meet plant space constraints in the more modern plants. A second strategy for improved heat recovery from the milk is to increase the pressure and temperature of the flash vessel. For this situation, the flash temperature can be increased to 84 °C before a second Pinch occurs driven by the MVR vapour bleed temperature. Application of this approach can reduce the hot utility target to 3.0 MW.

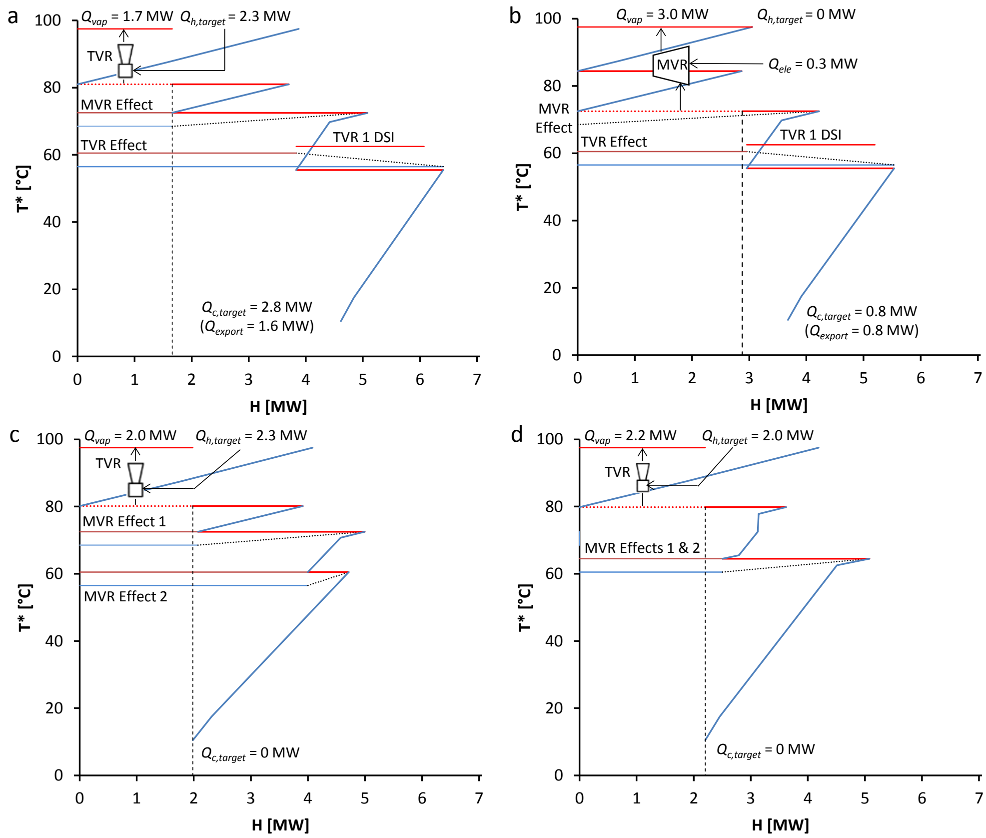

Figure 4: Grand Composite Curves for various energy saving schemes

A third strategy for improving heat recovery is to apply the heat pump concept at the Pinch. Figure 4a shows how thermo-compressor may be applied to upgrade the excess milk flash vapour from below the Pinch to above it. MVR is much less suited to this application because the enthalpy added through mechanical compression to the flash vapour to raise its temperature to 95 °C is minimal (~0.1 MW), which means about 2.2 MW of steam utility is still necessary. The TVR solution is also compact and inexpensive. Using the empirical correlation of Al-Juwayhel et al. (1997), actual thermo-compressor performance ratios as a function flash vapour pressure; utility steam pressure and recompressed vapour outlet pressure may be calculated and applied to further optimise the milk flash temperature selection. In Figure 4a, the temperature of the milk flash is decreased resulting in excess milk flash duty of 1.7 MW, which is recompressed using the 2.3 MW of steam utility. Further reductions in the milk flash temperature yields greater amounts of excess milk flash duty, but the targeted steam use is now insufficient to adequately recompress the vapour.

A combination of the second and third strategies is also possible (Figure 4b). In this case, the temperature of the milk flash is increased until a second Pinch driven of the vapour bleed temperature occurs. The excess vapour bleed duty may be upgraded using the MVR techniques to above the Pinch so that it can be used for heating the milk to 95 °C. MVR is better suited for this application because the excess vapour flash duty and the milk heating duty are similar in magnitude. With this approach, the cold utility target falls to 0.8 MW, all of which may be exported to pre-heat air streams in the spray dryer plant. The estimated savings gained by moving to this new set-up is 822 k$/y. However the target area of the HEN has increased by 2.5 times compared to the current set-up.

The two energy savings schemes presented thus far have all involved exporting heat from below the Pinch to the neighbouring spray dryer plant. Even with the best intra-plant heat integration scheme for the current MVR-TVR evaporator set-up, a minimum of 0.8 MW of heat export is needed. Heating air streams with low-grade heat is also capital intensive due to the large amount of heat transfer area that is required. As a result, eliminating the need to export heat from the evaporator plant to the spray dryer plant is an area of interest to industry as a way of lowering the total production lifecycle cost. Area targets in Table 1 do not include the area required in the spray dryer plant to integrate the exported heat.

Figures 4C and 4D present two cases where all effects are integrated using MVR and a TVR is applied in the milk heat treatment section of the plant. Figure 4c presents the case where the temperatures of the two effects are the same as the base case, whereas Figure 4d presents the case where the two effects are both the same, which is an evaporation temperature of 60 °C. Two effects are still required because the geometry of the two effects differ. Operating the two effects at the same pressure can simplify the HEN by reducing the number of heat exchangers, since there are fewer hot streams, and enable the use of one compressor, instead of two compressors. With the optimal selection of the milk flash temperature, the MVR-MVR evaporator set-up no long requires heat export as all heat is recovered internally. Under these schemes, the hot utility target is reduced by about 67 % compared to the base case, while the electrical use slightly increases. The scheme in Figure 4c saves an estimated 701 k$/y, while the scheme in Figure 4d saves 641 k$/y. Although these savings are considerable less than the scheme presented in Figure 4b, the area target for the schemes in Figures 4C and D requires about 40 % less area and therefore more likely to be more economic.

Future work will look at optimising the evaporation load between a MVR-TVR two effect set-up, the operating pressures of the evaporator effects and the cascading of some excess vapour bleed in a feed forward arrangement. A thermo-economic optimisation of the various schemes will also be carried out to determine which scheme has the lowest total cost. Effects of changing the evaporator plant's integration on the milk and its functional properties is another area for further consideration.

6. Conclusion

The Grand Composite Curve is a powerful tool for identifying process modifications to key temperatures and operations that minimise energy use. For the industrial milk evaporator case study, thermal energy use can decrease by as much as 67 %, which represents an annual utility cost saving between 640 – 820 k$/y, although the network area target increases by 50 – 150 %, depending on the scheme.

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