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Total Site Heat Integration of Multi-Effect Evaporators with Vapour Recompression for Older Kraft Mills

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This paper aims to apply Total Site Heat Integration (TSHI) to appropriately integrate Mechanical and Thermal Vapour Recompression with multi-effect evaporators at older Kraft Mills, to cause a step reduction in fossil fuel use and its associated emissions. Heat and power demands for older Kraft Mills are chiefly satisfied from Recovery Boilers (RB), heavily supplemented by biomass/fossil fuel boilers, and integrated with steam turbines. Prior to firing, black liquor – the RB fuel – is concentrated from about 18 % to 67 % in a multi-effect evaporator, which demands 20 % of site-wide thermal energy. With access to renewable electricity, this study finds that vapour recompression can be economically integrated into a multi-effect evaporator at older Kraft Mills. The vapour recompression configuration with the greatest economic potential used 2-stages of mechanical vapour recompression and 1-stage of thermal vapour recompression. This system achieved a levelised profit of NZD 8.56 M/y, a payback period of 1.0 y and an internal rate of return of 103 %. An optimum integrated set-up needs to account for site-specific heat demand and utility supply profiles through TSHI.

1. Introduction

Kraft pulping is a critical process for transforming biomass into pulp, which is processed into paper and packaging. Heat and power demands for Kraft Mills are chiefly satisfied by a Recovery Boiler (RB) and integrated with steam turbines for cogeneration. The RB fuel is black liquor (BL), which primarily contains hemicellulose, lignin, and inorganic chemicals. The RB has the twofold purpose of chemical recovery (i.e. reduction of inorganic chemicals) as well as thermal and electrical energy generation. For older mills with older RB technology, BL is fired at about 67 % solids whereas new RB technology fires at >80 % solids. With less water in fired BL, a new RB generates about 10 % additional steam at >10,000 kPa_{ab} (compared to about 4,500 kPa_{ab} for older RB) and significantly greater electricity. Older mills with older RBs normally require an additional 20 – 25 % of thermal energy from biomass and/or fossil fuel, which is often burned in a supplementary boiler.

An energy intensive process in the recovery loop of Kraft pulping is the BL evaporation process, which consumes about 20 – 30 % of site-wide thermal energy demand. Traditionally multi-effect evaporators (MEE) concentrate BL from about 18 % to its firing solids. The first evaporator effect uses low pressure steam (~450 kPa_{ab}) and rejects heat through a condenser (~18 kPa_{ab}) and cooling tower. Maximising the integration of the evaporator with the background pulp mill processes can help minimise its energy demand footprint. Algehed and Berntsson (2003) showed the evaporator may use medium pressure (MP) steam in place of low-pressure (LP) steam and then cascade LP steam from the evaporator process to the steam mains for use in other processes. This reduced energy use by 55 %, but it required significant new capital including a clean steam generator. Diel et al. (2016) applied response surface methodology to optimise the internal flow arrangement of steam and liquor flows to maximise the overall coefficient of thermal performance.

An alternate approach to energy reduction in evaporation systems is the use of thermal vapour recompression (TVR) and mechanical vapour recompression (MVR) technologies (Sharan and Bandyopadhyay, 2016). Integration of MVR and TVR technology fundamentally changes an evaporation system's process design and

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the temperature and quantity of waste heat (Walmsley et al., 2015). Walmsley et al. (2016) recently discussed the appropriate placement of vapour recompression in evaporation systems using a dairy processing case study where a vapour recompression unit acts analogously to a heat pump. MVR technology has seldom been considered for BL evaporators. This is due to the availability of "free" energy gained from the RB as well as BL's high boiling point elevation, which reaches about 15 °C at 67 % solids. However, for an older Kraft Mills that need to burn fossil fuels in supplementary boilers and have access to renewable electricity, MVR and/or TVR technology integrated into a MEE may offer a profitable pathway to reduce fossil fuel use and emissions.

This paper aims to apply Total Site Heat Integration (TSHI) to appropriately integrate a Mechanical and Thermal Vapour Recompression with Multi-Effect Evaporators for older Kraft Mills to cause a step reduction in fossil fuel use and its associated emissions. Theory and methodology for minimising the work input of MVR in combination with a MEE are presented. A Kraft Mill in the Central North Island of New Zealand is offered as a case study, which has access to renewable, low-carbon emission electricity.

2. Multi-stage mechanical vapour recompression evaporators

MVR evaporators are typically a single effect/stage system used to concentrate liquids with small boiling point elevations (BPE). Application of conventional MVR evaporators to liquids with a high BPE, which may significantly vary with concentration, is more challenging and less energy efficient. A multi-stage approach to the design of MVR evaporators can help greatly decrease electricity use. The degree of BPE for BL increases with concentration (Zaman et al., 1998), as shown in Figure 1a. The BPE at a BL feed concentration of 18.5 % solids is 1.7 °C and at an exit concentration of 67.0 % is 14.7 °C. Evaporator effects require a minimum approach temperature to drive heat transfer, ΔT_{min}, which is set at 5 °C and is based on data from the Kraft Mill case study. Concentration is non-linearly related to specific water evaporation, S_{feed}/S_j, using

$$\frac{m_{evap,j}}{m_{feed}} = 1 - \frac{S_{feed}}{S_j} \tag{1}$$

Where $m_{evap,j}$ is the total evaporated water up to point j and S_j is the solids concentration at point j. Specific water evaporation (in t of concentrate per t of feed, t/t$_F$) can be used in place of concentration in Figure 1a to generate Figure 1b. Figure 1b illustrates that about half of the required water removal needs a saturation temperature difference of 8 °C.

Multi-staged MRV fans with multiple evaporator effects is a critical approach for minimising shaft work for concentrating liquids with high BPEs (Figure 2). Figure 2a provides a simple example of 1- and 2-stage MVR fans, where the evaporation side of each effect use the same pressure while the condensation-sides operate at different pressures. The effect of multi-staging on electrical use is shown in Figure 2b. A 1-stage system must upgrade all evaporated vapour to the maximum required saturation temperature, i.e. 18.9 °C. The 2-stage system upgrades vapour to two different pressure levels and therefore requires about 36 % less work. Each MVR stage may service one (as indicated in Figure 2a) or more evaporator effects (in parallel) and individual effects may have multiple passes and recirculation of concentrated liquor.

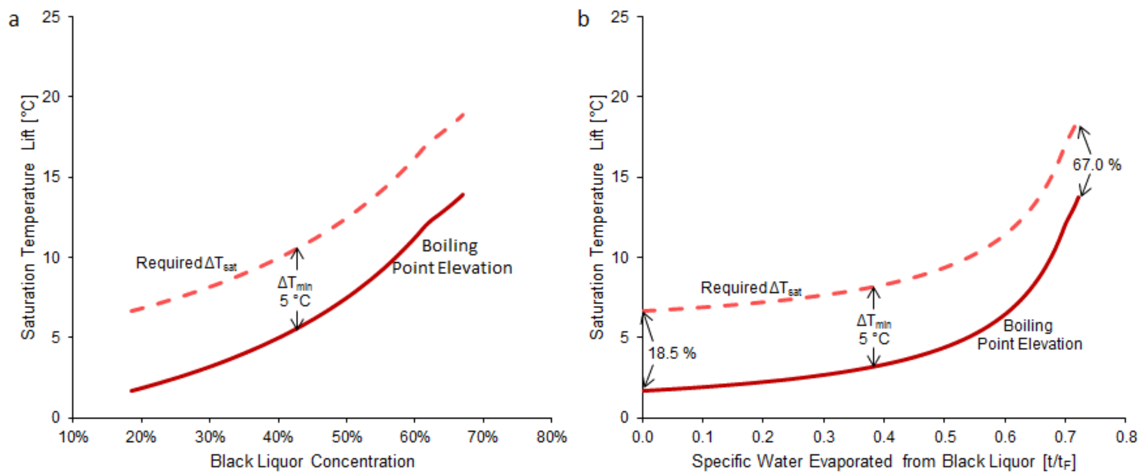

Figure 1: Boiling point elevation for black liquor (Zaman et al., 1998) for concentrating black liquor from 18.5 % to 67.0 %, based on concentration (a) and specific evaporation (b).

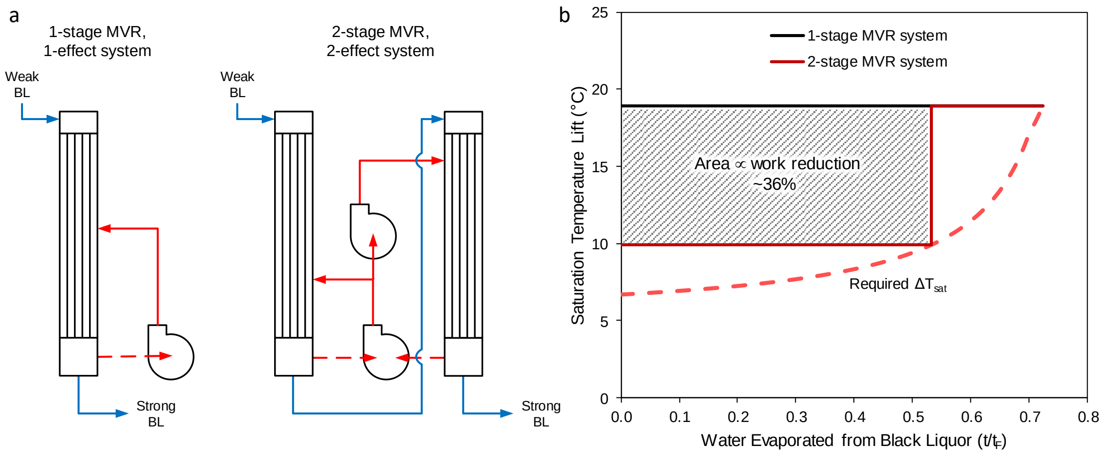

Figure 2: Simple 1- and 2-stage mechanical vapour recompression system designs (a) with the comparison to the required saturation temperature indicating the degree of work reduction (b).

3. Methods

3.1 Total Site Heat Integration

Total Site Heat Integration (TSHI) for evaporation systems with vapour recompression (Walmsley, 2016) has been applied to understand the integration potential between the evaporation system and the remainder of the Kraft Mill. Utility use has been targeted at the process level and later combined and matched for TSHI (Tarighaleslami et al., 2017). Evaporation systems are represented on temperature-enthalpy graphs (e.g. Figure 3) using the method summarised by Westphalen and Wolf Maciel (2000).

3.2 Multi-effect evaporator models

Evaporator models for BL have been implemented in an Excel™ spreadsheet. The models include: (1) the existing LP steam-powered 7-effect cascade evaporation system, (2) 2-stage MVR system, (3) 3-stage MVR system, (4) 4-stage MVR system, and (5) 2-stage MVR, 1-stage TVR system. Each evaporator effect assumes a minimum approach temperature of 5 °C, which matches the average minimum approach temperature of the existing 7-effect cascade in the case study (model 1). Heaters/coolers are added to exit streams from the evaporation system model to ensure the boundary conditions for all investigated options are constant. Correlations for BL density and enthalpy were taken from Picot et al. (2013) and the correlation for BPE was taken from Zaman et al. (1998) for pulping conditions ABAFX059,60. These pulping conditions showed the closest resemblance to the studied industrial mill.

A simple energy quality-weighted net Specific Energy Consumption, SEC, is calculated to determine the net effect of using a MEE with and without integrated multi-stage MVR. This is defined as

$$SEC_{net} \equiv \frac{Q_{LPS} + 3W - Q_{TSHI}}{m_{evap}} \qquad (2)$$

Where Q_{LPS} is the LP steam demand for the evaporator, m_{evap} is the evaporation mass flow, W is the electrical work of the MVR fans, Q_{TSHI} is the reduction in hot utility use resulting from the TSHI of the evaporation system.

3.3 Mechanical and thermal vapour recompression models

MVR units have been modelled based on a constant isentropic efficiency of 79 % and a motor efficiency of 97 % (Piller GmbH, 2016). The overall fan efficiency is therefore 77 %. To ensure sufficient controllability during start-up, production, and shutdown, fans are intentionally oversized by 20 %, as recommended by Piller GmbH. TVR units have been modelled according to the thermocompressor sizing charts of Kadant Johnson Inc. (2011), a leading supply of this technology. Minor pressure losses due to duct bends are not considered in the model.

3.4 Site heat and power utility model

A site utility model of the RB and supplementary boilers, turbine and process heat demands has been implemented in an Excel™ spreadsheet. The boilers assume a constant thermal efficiency of 75 %. The turbine has been modelled based on the extended Willen's line approach of Varbanov et al. (2004). Historical turbine performance data was used to determine turbine model coefficients. Process heat demand from the utility system varies for each of the evaporation system options. LP steam demand greatly decreases while electricity consumption increases for a multi-stage vapour recompression evaporator system compared to a conventional evaporator. The LP steam demand reduction negatively impacts on turbine power generation but also reduces the required VHP steam from the swing boiler that is co-fuelled by wood residue (50 %) and natural gas (50 %).

3.5 Thermo-economic assessment of mechanical vapour recompression evaporator options

A thermo-economic assessment of retrofitting MVR fans with an existing 7-effect evaporator at a Kraft Mill that processes 2,300 t(BL)/d and operates for 8,300 h/y has been undertaken. Estimated site fuel prices are wood residue at NZD 5.0 /GJ, natural gas at NZD 10.0 /GJ, and electricity at NZD 90.0 /MWh. The price of cooling water is NZD 2.5 /MWh and the carbon price is NZD 25.0 /t. Fuel and carbon prices are expected to rise into the future and, for this study, the estimated annual price rise based on recent trends is 3 %. The capital cost of retrofitting MVR fan units have been estimated using

$$C_{capital} = f_{Lang}\left(28{,}600W^{0.489}\right) \tag{3}$$

Where f_{Lang} is a Lang factor (or installation cost factor), W is the rated motor size in kW, and $C_{capital}$ is the installed capital cost in NZD. This simple cost estimation correlation is based on several quoted uninstalled MVR fan prices from Piller. The Lang factor for the case study is 3.0, recognising that retrofit projects incur substantial installation challenges and costs. Key economic indicators – levelised profit and internal rate of return – are evaluated based on a 10 y lifetime and a discount rate of 5 %.

4. Total Site Heat Integration for conventional 7-effect black liquor evaporators

The Total Site Profiles (excluding the evaporator) and the Site Utility Grand Composite Curve for the Kraft Mill case study are shown in Figure 3. Weak BL enters the lowest pressure effect at 85.0 °C, which initially operates with a saturation temperature of 66.8 °C. For each subsequent effect, BL increases in pressure and enters at a temperature lower than its saturation temperature. At present, the 7-effect evaporators bleed 2.6 MW of steam from the 2nd effect to the foul condensate stripper column (in place of LP steam). The net SEC for the 7-effect evaporator is 420 kJ/kg_{evap}.

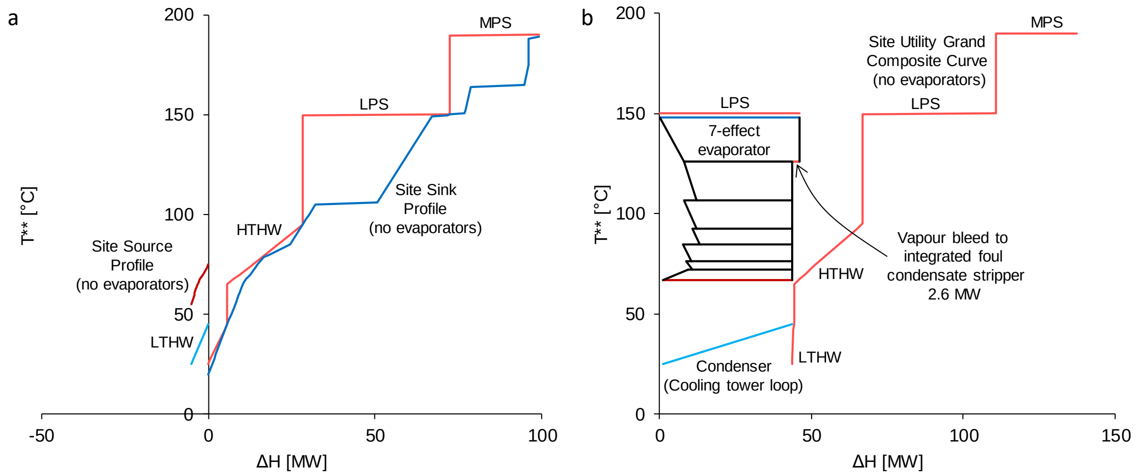

Figure 3: Total Site Profiles (a) and Site Utility Grand Composite Curve (b) with existing integration for a conventional 7-effect black liquor evaporator.

5. Thermo-economic assessment of black liquor evaporators with vapour recompression

A thermo-economic assessment of four options to retrofit BL evaporators with vapour recompression has been investigated with results shown in Table 1. It is important to note that the modelling accounted for electricity use including loss of cogeneration potential, increased heat integration, reductions in LP steam use, cooling tower expenses, carbon emission cost, and added maintenance due to MVR and TVR equipment.

The 2-stage MVR system achieves a simple payback of 1.3 y and an internal rate of return (IRR) of 76 %, which are better than both the 3- and 4-stage MVR systems. However, one challenge with implementing the 2-stage is the required saturation temperature lifts (8.8 and 9.5 °C) for the two MVR fans. These levels of saturation temperature lift push the upper design and operational limits of an MVR fan. The 3-stage MVR system requires lower temperature lifts (7.0, 3.3, and 8.0 °C) and achieves a greater levelized profit than the 2-stage MVR

system. The 4-stage MVR uses less electricity than the 2- and 3-stage MVR systems but the added capital of a fourth MVR fan outweighs the energy benefit.
It is interesting to note that carbon emission costs significantly contribute to boosting levelised profit. The cost of carbon emissions in New Zealand is based on an emissions trading scheme (ETS) market and can be influenced by politics of the day. If carbon costs were excluded, the 3-stage MVR system would have a 23 % lower levelised profit with a longer payback time of 1.8 y and lower IRR of 54 %.

6. Maximising Total Site Heat Integration for vapour recompression evaporators

Figure 4a demonstrates the TSHI of the 3-stage MVR system. There are two integration points: condensate heat recovery and a vapour bleed from stage 2 for the stripper column. Condensate from the 3-stage MVR system is available at 90 °C, which is hotter compared to 72 °C condensate from a conventional 7-effect set-up.

Table 1: Thermo-economic assessment of retrofitting various multi-stage mechanical vapour recompression options with an existing evaporation. The baseline of the assessment is a conventional 7-effect evaporator.

	2-stage MVR		3-stage MVR		4-stage MVR		3-stage MVR-TVR	
	Rate	Benefits (NZD M/y)	Rate	Benefits (NZD M/y)	Rate	Benefits (NZD M/y)	Rate	Benefits (NZD M/y)
Electricity Use								
MVR electricity use	10.1 MW	-7.54	9.1 MW	-6.81	8.7 MW	-6.47	7.7 MW	-5.73
Cogeneration reduction	13.1 MW	-9.75	12.8 MW	-9.59	12.5 MW	-9.37	12.8 MW	-9.54
Steam Use								
LPS use reduction	50.5 MW		50.5 MW		50.5 MW		34.7 MW	
Increased heat recovery	5.1 MW		4.1 MW		2.7 MW		19.6 MW	
Steam flow reduction	98.8 t/h	23.38	97.1 t/h	22.96	94.6 t/h	22.37	96.4 t/h	22.81
Other								
Cooling tower reduction	47.0 MW	0.97	47.0 MW	0.97	47.0 MW	0.97	47.0 MW	0.97
Carbon liability reduction	82.8 kt/y	2.07	81.3 kt/y	2.03	79.2 kt/y	1.98	80.7 kt/y	2.02
Additional Maintenance	1.5 %	-0.17	1.5 %	-0.19	1.5 %	-0.21	1.5 %	-0.15
O&M Cost Reduction		8.96		9.37		9.27		10.39
Capital cost (uninstalled)		3.84		4.30		4.75		3.30
Capital cost (installed)		11.52		12.90		14.24		9.90
Key Indicators								
Levelised profit	NZD 7.08 M/y		NZD 7.32 M/y		NZD 7.09 M/y		NZD 8.56 M/y	
Simple payback	1.3 y		1.4 y		1.5 y		1.0 y	
Internal rate of return	76 %		70 %		63 %		103 %	
SEC_{net}	177		159		159		120	

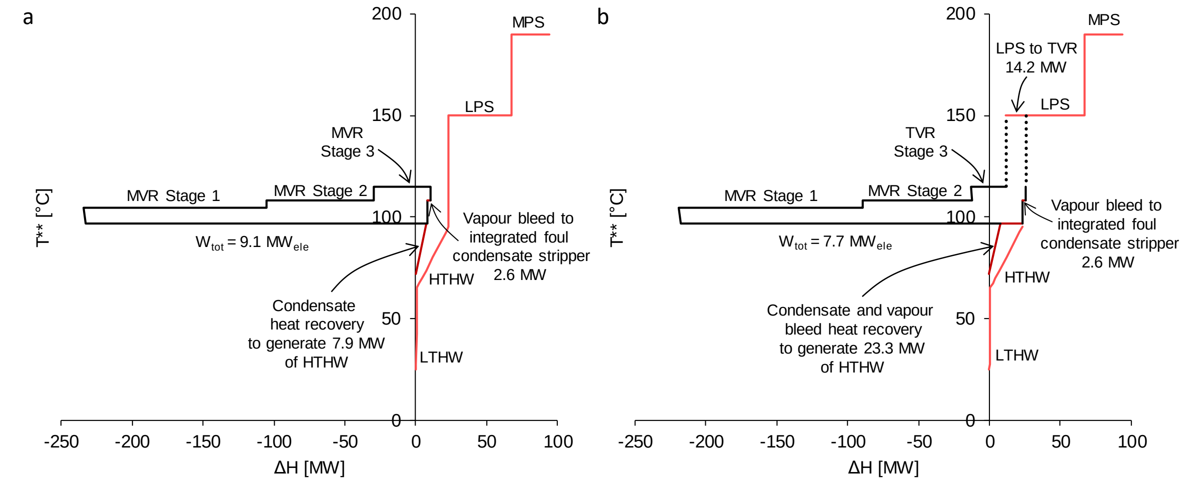

Figure 4: Total Site Heat Integration of 3-stage MVR evaporator (a) and 2-stage MVR, 1-stage TVR evaporator (b) with the site steam and hot water utility system using the Site Utility Grand Composite Curve.

Another retrofit option is to replace the third MVR stage with a TVR unit as shown in Figure 4b with the economics in Table 1. In this retrofit, the first MVR supplies vapour to effects 4-7, the second MVR to effects 2 and 3, and the TVR to effect 1 (the highest pressure effect), which is also called a concentrator. This option takes advantage of using the available exergy in the LP steam to recompress some of the vapour exiting the second MVR stage. The additional LP steam heat cascades through the evaporator system to result in excess low-pressure vapour (22.8 t/h at 90 kPa_{ab}) that has sufficient temperature to integrate with the HTHW system as well as the hot condensate. The integrated 2-stage MVR, 1-stage TVR system helps increase levelised profit by 16.9 % to NZD 8.56 M/y while also reducing the payback period to 1.0 y and increasing IRR to 103 %.
Future work will look at the sensitivity of the thermo-economic assessment with particular focus on the capital cost estimate, the split of the boiler fuel reductions, the electricity price, and the price for carbon emissions. It will also investigate the potential roles that MVR and TVR technology may be able to play at modern Kraft Mills.

7. Conclusions

Vapour recompression can be economically integrated a multi-effect evaporator at Kraft Mills with older recovery boiler technology, causing a step reduction in steam use. Since vapour recompression acts as an open cycle heat pump, the benefit gained from reducing carbon emissions in supplementary fossil fuel boilers is seemingly magnified. The vapour recompression set-up with the greatest economic potential used 2-stages of mechanical vapour recompression and 1-stage of thermal vapour recompression. This system achieved a levelised profit of NZD 8.56 M/y, a payback period of 1.0 y and an internal rate of return of 103 %. An optimum integrated set-up needs to account for site-specific heat demand and utility supply profiles. Total Site Heat Integration provides a critical framework for determining which vapour recompression technology to apply and its maximum integration.

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