Impact and feasibility of a membrane pre-concentration step in kraft recovery

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ABSTRACT: Emerging robust membrane systems can perform the first section of black liquor (BL) concentration by separating clean water from the black liquor stream using only mechanical pressure. By doing so, they can reduce the steam and energy required for BL concentration. Because of the high osmotic pressure of strong BL, a membrane system would not replace evaporators but would operate in series, performing the first section of BL concentration.

In this work, we use a multi-effect evaporator (MEE) model to quantify the steam and energy savings associated with installing membrane systems of different sizes. When maintaining a constant BL solids throughput, we find that a pulp mill could reduce steam usage in its evaporators by up to 65%. Alternatively, a membrane system could also serve to increase BL throughput of the recovery train. We find that a membrane system capable of concentrating BL to 25% could double the BL solids throughput of a mill's evaporators at the same steam usage. We also demonstrate that installing a membrane system before an MEE would minimally affect key operating parameters such as steam pressures and BL solids concentrations in each effect. This indicates that installing a membrane pre-concentration system would be nonintrusive to a mill's operations.

Application: In this work, the authors quantify the economic implications of installing a membrane system to pre-concentrate weak black liquor. The results presented will be useful for pulp mills considering the use of membrane technology to decrease evaporator energy costs or to increase black liquor throughput.

Black liquor (BL) evaporation is the process by which black liquor, a kraft pulping waste stream, is concentrated from ~15% to ~75% total dissolved solids (TDS). Once the stream reaches ~75% TDS, it can be fed into a recovery boiler and used as fuel. BL evaporation is crucial to the feasibility of kraft pulping as it takes a continuous, multi ton per hour, hazardous waste stream and repurposes it as an energy source, while simultaneously recovering spent pulping chemicals [1,2].

Black liquor evaporators

Pulp mills use multi-effect evaporators (MEEs) to concentrate the BL stream. The MEEs operate at higher energy efficiencies than single-effect evaporators by using one evaporator's vapor product as the next evaporator's heat source [2]. In many MEE configurations, flash separation tanks vaporize part of each evaporator's condensate stream and add that water vapor to the next evaporator's steam stream, further improving the overall energy efficiency [1]. MEEs separate water from BL solids quickly, effectively, and relatively efficiently.

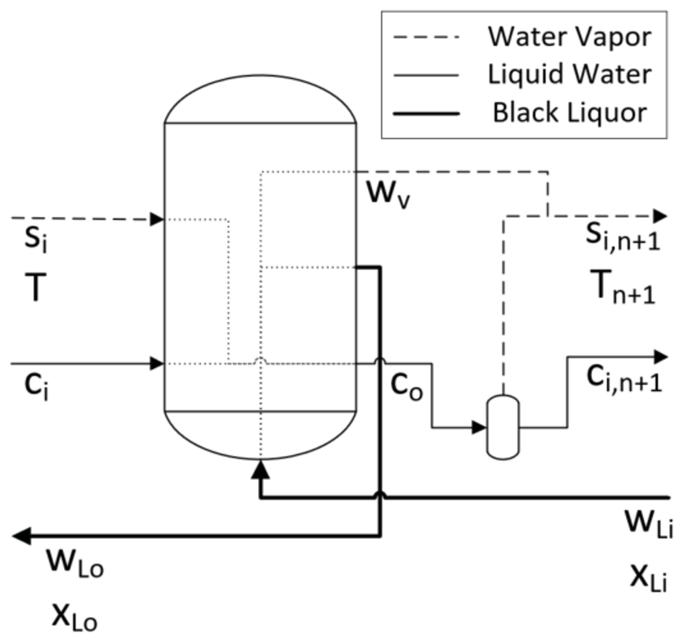
Despite the maturity of MEE technology and its improvements to energy efficiency over time, BL evaporation still accounts for a significant portion of energy and steam use in pulp mills. The process accounts for 13.1% to 16.5% of the total energy used in the pulp and paper industry and roughly 10% of the direct costs of pulp production [3].

Pulp mills' throughputs are often constrained by their evaporators due to the high capital costs of BL evaporators and the frequent downtime needed to clean and maintain them. Evaporator-constrained mills could improve their overall production capabilities by increasing the capacity of their evaporator trains, either by adding more evaporators, or employing another separation technique.

Membrane systems

Emerging membrane platforms may be able to perform the separation between BL and water with lower operational and capital costs than evaporators [4,5]. Membrane systems separate molecules based on size by applying pressure differentials across semipermeable barriers rather than employing energy-intensive thermal separations [6]. Because thermal separations must overcome a phase change from liquid to vapor, it would be impossible, even with the best available technology, for an evaporator train to reach the low energy requirements of a membrane system [7]. If the water permeated by these membranes is of a quality that can be used elsewhere in the mill or treated in the same manner as evaporator condensate, we can assume the overall water balance remains the same, regardless of separation technique.

Membrane systems have already partially or fully replaced evaporators in other industries, resulting in substantial cost and energy savings. In the desalination industry,



1. Flow paths of steam, condensate, and weak black liquor (BL) streams for one effect in a multi-effect evaporator (MEE). See Table I for definition of variables.

for example, capital and operating costs were cut by 50% in the 1960s when water treatment facilities pivoted from distillation to reverse osmosis [6]. The same pivot has not been seen yet in the pulp and paper industry because membranes have historically been unable to operate in high temperature, high pH conditions. New technologies, however, are being developed that will soon allow for this possibility [8,9].

If these temperature and pH resistant membranes can be produced at scale, they will be able to remove evaporator constraints without capital-intensive investments into more or larger evaporators. Membrane systems would not fully replace BL evaporators because of the high osmotic pressure of strong BL. But they could be installed before an evaporator system to perform the first section of BL concentration. Membrane "pre-concentration," potentially up to 30%–40% solids, would offset significant energy costs and/or increase BL throughput by effectively increasing the capacity of already installed MEEs [10].

Despite the potential benefits afforded by membrane systems, there has been little analysis on how they will affect the economics of the pulp and paper industry. One model, developed for the Agenda 2020 Roadmap, analyzes the impact of a membrane pre-concentration step to 30% TDS on an evaporator train's steam usage [11]. That pioneering work, using precise WinGEMS (Valmet; Espoo, Finland) modeling, illustrates gross steam savings of $5.2 million for a mill processing 2000 a.d. metric tons/day of pulp with a high amount of membrane concentration. However, because existing mills have already invested in MEEs, it seems likely that mills may not see the greatest benefits from using a membrane system to pre-concentrate BL all the way to 30% TDS. Rather, mills may use a membrane system to implement more moderate changes to evaporator feed solids or to increase BL throughput. In doing so, they will take advantage of emerging membrane technology, as well as already existing evaporators.

In this work, we use an Excel-based model to better understand the utility of membrane concentration to a kraft pulp mill. We report: a) the impact of smaller membrane systems that output BL below 30% TDS; b) the change in evaporator operating parameters as a function of the increase in feed solids concentration; and c) the effectiveness of a membrane system for increasing BL throughput in mills constrained by their evaporator trains.

METHODS AND MODELS

Our Excel-based model simulates a 6-effect evaporator system, as 6-effect MEEs are currently most common in the industry [7]. Although 7-effect MEEs with integrated steam strippers are the best available technology, we choose to analyze the scenario in which a membrane platform is augmenting the capacity of a 6-effect MEE, since this will be applicable to the greatest number of pulp mills. Additionally, the results drawn regarding any single MEE configuration should still be indicative of larger trends for other designs.

Figure 1 shows the flow paths of the steam, conden-

Symbol	Definition	Units
s_i	Steam flow rate in	kg/s
T	Steam inlet temperature (this temperature determines the operating temperature of the evaporator)	°C
c_i	Condensate flow rate in	kg/s
w_{Lo}	Liquid black liquor (BL) flow rate out	kg/s
x_{Lo}	BL total dissolved solids (TDS) out	%
w_v	Vapor BL flow rate in	kg/s
c_o	Condensate flow rate out	kg/s
$s_{i,n+1}$	Steam flow rate to next evaporator	kg/s
$c_{i,n+1}$	Condensate flow rate to next evaporator	kg/s
w_{Li}	Liquid black liquor flow rate in	kg/s
x_{Li}	BL TDS in	%
q_g	Heat gained by BL	kJ/s
c_{Li}	Specific heat of inlet BL	kJ/kg*K
λ_T	BL heat of vaporization at evaporator operating temperature	kJ/kg
q_l	Heat lost by steam	kJ/s
$H_{v,T}$	Saturated water vapor enthalpy at evaporator operating temperature	kJ/kg
$H_{l,T}$	Saturated liquid water enthalpy at evaporator operating temperature	kJ/kg
ΔT_b	BL boiling point rise	°C
ΔT_{b50}	BL boiling point rise at 50% TDS	°C
U	Heat transfer coefficient	kJ/m²*K
A	Heat transfer area	m²
T_s	Steam temperature	°C
T_{BL}	BL temperature	°C

I. Definition of variables used in Fig. 1 and Eqs. 1-9.

sate, and BL streams for one effect in an MEE. For the first evaporator, s_i is the fresh steam to the MEE and there is no c_i. Each subsequent evaporator receives its s_i from the w_v of its predecessor. For the rightmost evaporator, w_{Li} is the fresh BL stream to the system. For all other evaporators, w_{Li} is the w_{Lo} of that evaporator's neighbor to the right. Steam flows from left to right and BL from right to left. **Table I** defines the variables used in Fig. 1, along with those in Eqs. 1-9 described in the sections below.

The fresh steam to the system (s_i) transfers its heat to the BL stream (w_{Li}) in evaporator 1. Afterwards, the newly condensed water (c_o) is fed to a flash tank, where a small portion of that stream vaporizes and joins the steam inlet to the next evaporator. For evaporators beyond the first, the steam inlet ($s_{i,n+1}$) is the BL vapor outlet stream from the evaporator before (w_v) plus the vapor recovered from the condensate in the flash tank. The now-concentrated BL liquid outlet (w_{Lo}) is simply pumped to the next evaporator, where it is further concentrated. The overall flow direction of the BL is opposite that of the vapor, as seen in Fig. 1. By orienting these paths in opposite directions, the highest energy vapor stream sees the most concentrated BL, which requires the most energy to be evaporated.

In modeling a multi-effect evaporator system, the two governing equations are mass balances and energy balances for each evaporator.

Mass balances

Steam side

$$s_i + c_i = c_o \tag{1}$$

Liquor side

$$w_{Li} = w_{Lo} + w_v \tag{2}$$

Liquor solids

$$w_{Li}\, x_{Li} = w_{Lo} x_{Lo} \tag{3}$$

Energy balances

Liquor side

$$q_g = w_{Li,n}\, c_{Li,n}\, (T_n - T_{n-1}) + w_{v,n} \lambda_{Tn} \tag{4}$$

Steam side

$$q_l = s_i\, (H_{v,Tn} - H_{l,Tn}) \tag{5}$$

Combined

$$q_l - q_g = 0 \tag{6}$$

Enthalpies

Saturated pressures, saturated liquid enthalpies, and enthalpies of vaporization of water are calculated as functions of reduced temperature using equations of state.

The BL liquid enthalpies as a function of temperature and TDS are calculated by Eq. 7, a modified linear regression equation from a data set formulated by Stoy and Fricke [12]. Boiling point rise (BPR) of BL is calculated as a function of TDS using Eq. 8 and a ΔT_{b50} of 13.2 [1].

$$\lambda(T, x) = (169.9x^2 - 408x + 504.5) * \frac{T^{0.999}}{120} \tag{7}$$

$$\Delta T_b(x) = \Delta T_{b50}\left(\frac{x}{100-x}\right) \tag{8}$$

Model constraints

Our Excel-based model has two major design constraints: evaporator properties and overall outlet TDS. The model keeps constant major evaporator properties such as heat exchanger area, A, and heat transfer coefficient, U, regardless of inlet TDS. In reality, it is likely that U would change due to the altered TDS profile across evaporators. We suspect that this change in U in the TDS range studied would be small (see Appendix). The likely impacts of the expected changes in U are also highlighted in the Results and Discussion section of this paper, but not directly modeled. By making this assumption, we were able to use the heat transfer equation, Eq. 9, to predict changes in operating pressure.

$$q_g - q_l = \mathrm{U\,A}(T_s - T_{BL}) \tag{9}$$

Heat, q, is calculated from energy balances and T_{BL} is the sum of ΔT_b and the known saturation temperature of water. Because these four values (U, A, T_{BL}, and q) are known, we can solve for steam temperature, T_s. From steam temperature, by assuming a saturated vapor, we can derive steam pressure. This steam pressure is the evaporator operating pressure that would need to be adjusted as the membrane system is implemented. Unlike heat exchanger area and heat exchanger coefficient, evaporator operating pressure is an easily configurable metric for the re-optimization of an evaporator system.

The other design constraint is the MEE outlet TDS. We choose 50% TDS outlet for this model because it is the point at which black liquor's physical properties start to change significantly [13]. This point is known as the critical solids and it can vary due to liquor chemistry, but is roughly 50%. The most consequential change when liquor reaches the critical solids point is in viscosity. Because viscosity rises quickly starting around 50% TDS, it is at this point when most mills switch to a different type of evaporator. For the purposes of this paper, we use "evaporator" to refer to those operating below 50% TDS and "concentrator" for those above 50% TDS.

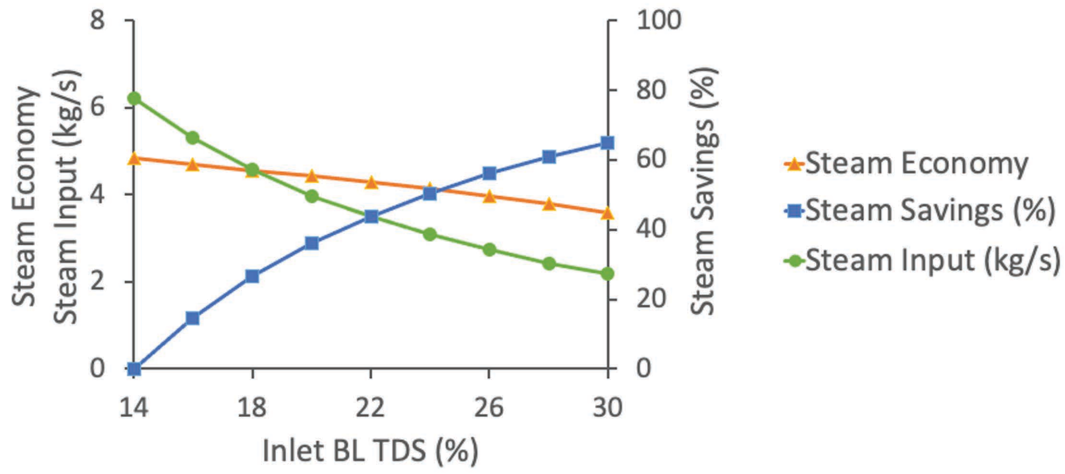
One final note pertaining to our MEE modeling is that we did not include in this analysis the costs of the membrane system, only its implications on an MEE. As such, the results here provide guidance on how to get the most value from integrating a membrane system. Results from this approach should be compared to and optimized against the membrane expenses. As previously stated, we expect that membrane systems optimized for BL concentration will prove quite affordable based on studies in other industries. For example, one study looking into the water desalination industry demonstrated a ~50% decrease in capital and operating expenses by switching from MEEs to reverse osmosis [6]. The WinGEMS model developed for the Agenda 2020 Roadmap corroborates this prediction; it calculated $5.2 million per year in gross steam savings and estimated only $2.4 million in electricity for the membrane system, for a net savings of $2.8 million/year.

RESULTS AND DISCUSSION

Using our Excel-based model, we calculate operating conditions and energy/steam savings at a variety of inlet TDS concentrations. Typically, mills feed BL at ~14% TDS to their evaporator trains. We vary this feed concentration to model scenarios in which a membrane system performs a pre-concentration before the BL is fed to the evaporators. An inlet concentration of 22% TDS, for example, corresponds to a scenario in which the pre-evaporator membrane system is designed to efficiently concentrate BL from 14% to 22%.

Steam and cost savings

A pre-concentration membrane system could be implemented before an evaporator train in two distinct ways. The first is to use the upgrade in energy efficiency to de-



2. Steam savings from initial concentration of a BL stream with constant BL solids flow rate in and 50% total dissolved solids (TDS) BL out.

crease the energy and money used for the BL separation. **Figure 2** demonstrates the scenario in which a mill uses a membrane system for this purpose.

As the inlet BL TDS increases, the steam input required to perform the separation (green trace) in the evaporator decreases because the membrane system reduces the load on the evaporator train. Naturally, the bigger the membrane system, or the higher the inlet BL TDS, the more steam is saved. Based on our analysis, a membrane system capable of concentrating BL up to 30% could decrease steam usage by 65% (blue trace) for this section of the separation. That translates to $5.0 million gross savings per year for a mill processing 2000 metric tons/day of BL solids if we assume a boiler efficiency of 80% and a steam price of $8 per metric ton of steam. The steam savings from smaller membrane systems can be seen by moving left along the x-axis.

The net energy savings from a membrane system installation would be these gross steam savings minus the electricity cost to pump the black liquor through the membranes. Because this electricity requirement is dependent on the often-proprietary design of these new membrane systems, it is not detailed here. As discussed in the Membrane Systems section at the beginning of this paper, this electrical requirement should be significantly lower than the steam savings, even given the typically higher value of electricity than fuels.

In Fig. 2, evaporator steam economy (orange trace) represents the ratio of water evaporated during the process to fresh steam input to the process [1]. This metric represents how efficiently an evaporator train utilizes steam. In this case, it decreases from 4.85 to 3.60 as the feed solids increase. This decrease in steam economy was expected because higher feed solids result in higher boiling points, and higher boiling points result in higher energy demand. Given the evaporator system is sized to operate for a higher feed rate and lower solids, it is intuitive that it should not perform as efficiently in the adjusted conditions. However, the moderate reduction in steam economy does not offset the decrease in demand on the evaporators. The result is still an overall reduction in steam requirements.

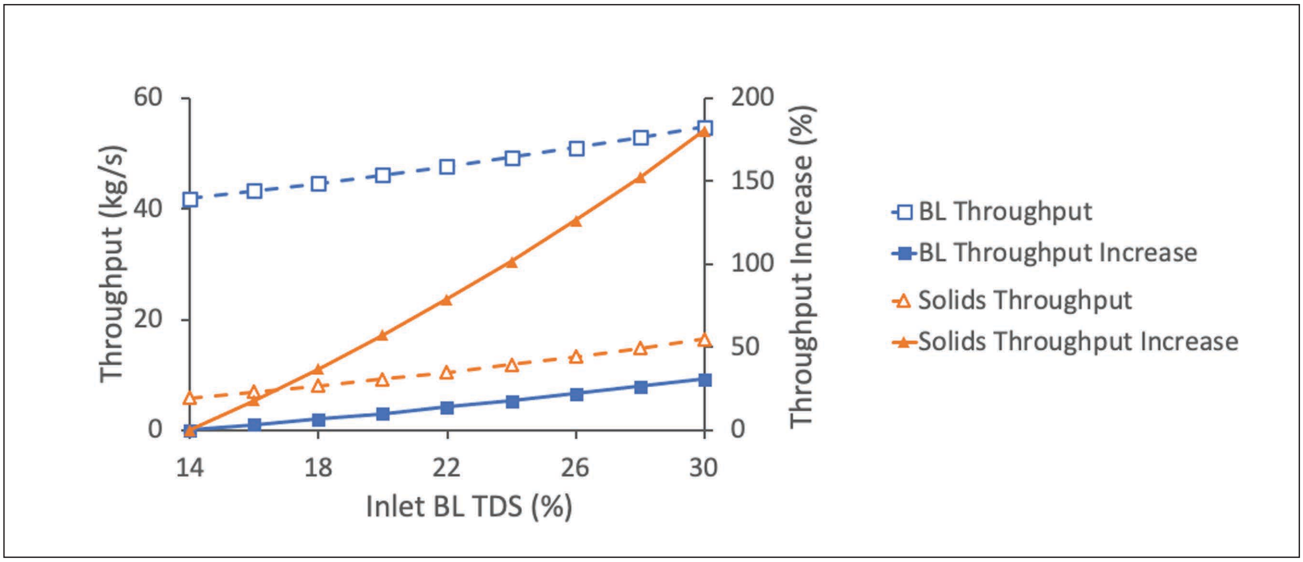
Increasing evaporator throughput

Steam is often valued at cents per ton, while pulp is valued at hundreds of dollars a ton. For this reason, we investigated the case in which a mill uses a membrane system to increase production rather than to save steam. It is likely that, in this scenario, a mill would actually benefit from some combination of increased production *and* saved steam, but for the purposes of generating clear, independent results, we assumed no steam savings for this scenario.

Generally speaking, a mill's rate of pulp production is limited by its rate of processing BL; it cannot produce pulp faster than it can handle the byproduct. For a mill that is constrained by its evaporators and is therefore limited by its rate of processing BL, a membrane pre-concentration step could be a game changer. By using a membrane system to augment evaporator capacity, a mill could increase its BL processing capacity and its pulp production.

To model this scenario, we again increase the inlet concentration of the liquor. This time, however, rather than fixing the BL solids feed rate, we allow that property to vary so that the same amount of steam used was constant. The resulting flow rates of BL and BL solids are shown in **Fig. 3**.

For each 2% increase in inlet TDS, BL throughput increases by an average of 3.9% (solid blue trace). Because both BL TDS and BL throughput are increasing, BL solids throughput, the product of those two metrics, increases



3. The BL throughput increase from initial concentration of BL stream. Constant steam flow rate in; 50% TDS BL out.

more rapidly. For each 2% increase in inlet TDS, BL solids throughput increases by an average of 22.6% (solid orange trace). This is important, because BL solids throughput increase characterizes a membrane system's impact on a mill constrained by its evaporator train.

Based on this analysis, a pulp mill's production could, in theory, be doubled by installing a pre-concentration step to 25% TDS. In practice though, it would be unrealistic for a pulp mill to double production without other costly upgrades. Still, these results demonstrate how a pre-concentration step could be used to provide a much smaller production increase (3% or 5%, for example) as well as significant steam savings; any membrane system capacity not used to increase BL throughput could be used to decrease the necessary steam flow rate.

Additional benefits for concentrators and recovery boilers

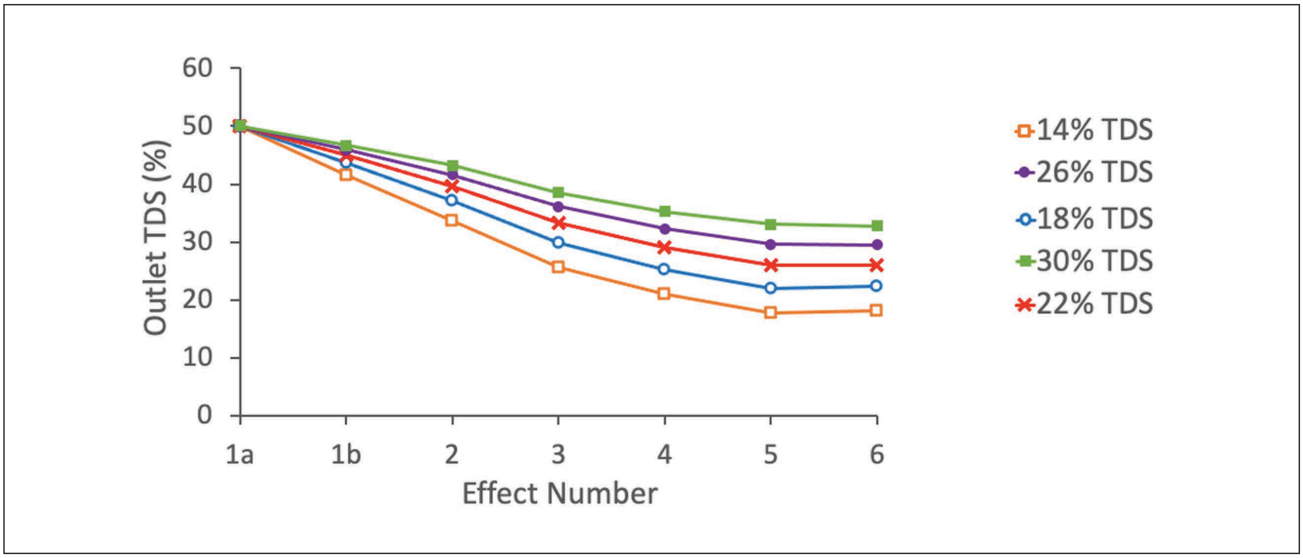
This analysis shows very explicitly how powerful a membrane system could be for mills constrained by their evaporators. However, it is worth considering the potential benefits for additional constraints in the concentrators. As previously explained, we use "evaporator" to reference evaporators that operate below ~50% TDS, and "concentrator" to reference those operating above ~50% TDS. If a mill's BL concentration is constrained by its concentrators, the mill could still augment evaporator capacity by shifting the transition point between evaporators and concentrators to a higher TDS concentration. The range of concentrations over which concentrators must operate can be shortened by using a membrane system for the first portion of BL concentration and shifting up the TDS values over which the evaporators operate. By shortening this range, the concentrator throughput could be increased so long as the feed to the concentrator remains at or below the first critical solids. Burkeite and/or decarbonate crystallization begins 1% to 5% after the first critical solids, at which point the BL must be in the concentrators [14].

In addition to potential improvements to evaporator and concentrator throughput, membrane systems may also benefit other unit operations not considered in this analysis. For example, rather than narrowing the operating range of the concentrators or evaporators, their outlet solids concentration (the recovery boiler feed) could be increased, reducing particulate carryover and addressing airflow limitations. The increase in the feed solids to the evaporator train could also increase the concentration in the soap tank (see discussion of Fig. 4) and thus improve the removal of valuable soaps if that tank is operating below the minimum solubility of soap in BL [2]. Improved soap removal could have further benefits in the recovery boiler by reducing the heat of combustion of the BL.

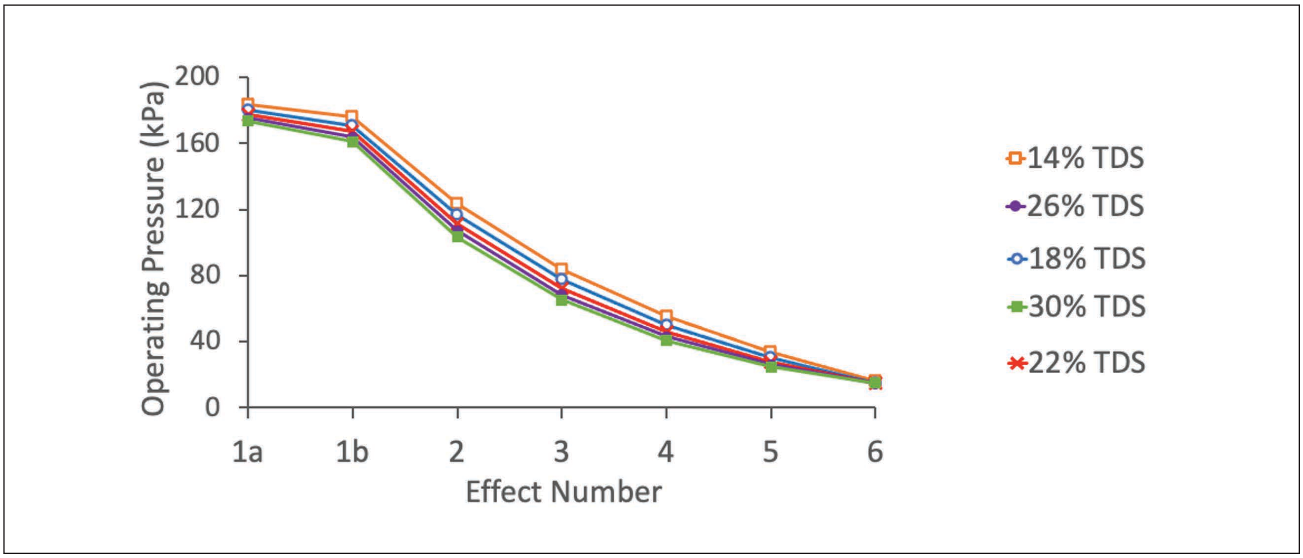
Operational considerations—TDS profile

Fouling is impacted by major changes in the TDS profile across evaporators. For this reason, we examine how the membrane pre-concentration step would alter TDS profile across a 6-effect evaporator train. **Figure 4** shows the TDS profile for the scenario in which BL throughput is held constant and steam flow rate is decreased. The results for the scenario in which steam flow rate is held constant and BL throughput is increased are very similar. As the inlet TDS increases, the operating TDS of each evaporator increases. The outlet TDS of 50% is held constant because this is roughly the point at which mills transition from evaporators to concentrators.

Although the TDS in each effect changes as the inlet TDS increases, the shape of the TDS profile remains constant. In other words, the change in operating TDS is well distributed among all six evaporators. As a result, it is likely



4. The TDS profile at varying BL concentrations with constant BL flow rate, heat exchanger area, and heat transfer coefficient.



5. Operating pressures across a 6-effect evaporator at varying inlet TDS.

that mills will have an easier time adjusting to a new TDS profile than if there were a more significant change in any single evaporator.

The other notable aspect about a changing TDS profile is that by using a membrane pre-concentration step, pulp mills could gain more control over said TDS profile. Rather than treating this change as a consequence of a membrane system installation, it could be a design specification that mills use to decide how exactly to implement a membrane system. By doing so, mills could more precisely control the concentration at which processes such as soap skimming take place [2].

Operational considerations—operating pressure

The operating pressure of evaporators is another important operating parameter for mills to consider. Operating pressures are important for evaporator trains because they determine the condensation point of the steam. The desired operating pressure of the first evaporator is achieved by adjusting the supply pressure of fresh steam. The desired operating pressure of the final evaporator is achieved by pulling a vacuum on the final steam stream [1,15]. Intermediate pressures self-equilibrate over the initial few hours of operation. Because changing the initial TDS changes the TDS profile across evaporators, and because altered TDS concentrations result in altered saturation temperatures, the operating pressures are affected when the initial TDS increases. **Figure 5** demonstrates how the operating pressure profile varies depending on BL TDS inlet for a scenario in which steam flow rate is held constant and BL throughput is increased. Again, the resulting figure for the scenario in which BL throughput is held constant and steam flow rate is decreased is very similar.

As can be seen in Fig. 5, the outlet pressure stays almost perfectly constant independently of inlet TDS. All scenarios modeled from 14% to 30% inlet TDS resulted in an operating pressure of 18 to 19 kPa in effect 6. This means that the vacuum pulled on effect 6 does not need to be adjusted to implement a pre-concentration step. Operating pressure in effect 1a was found to decrease by only 10 kPa between 14% and 30% inlet TDS. Because neither pressure changes substantially, little to no re-configuration or control upgrades would be required to implement a membrane pre-concentration system.

Our assumption that the heat transfer coefficient, U, remains constant regardless of evaporator inlet TDS (at low TDS values) should be revisited in the context of the pressure profiles. It may be the case that U does in fact vary with evaporator inlet TDS, though we have reason to believe that change would be minimal (see Appendix for further discussion). If U does change, a pulp mill could alter the pressure profile of its evaporators to offset that change. By slightly increasing the feed pressure of fresh steam, a mill could increase the saturated steam temperature in its evaporators, which in turn would increase the temperature difference between steam and BL seen in Eq. 9. By changing this temperature difference to compensate for the change in U, a pulp mill could keep constant Q, the heat being transferred between the steam and BL streams. And while there is certainly a limit to how far an MEE's pressure profile could be altered, we predict that mills will not need to drastically change it. If a detailed understanding of the change in U for different liquor solids in each effect was known, mills could further refine the accuracy of this analysis.

CONCLUSION

Advanced membrane platforms that can withstand the harsh conditions of BL can greatly benefit pulp mills. Pulp mills constrained by their evaporator train can use a membrane platform to augment their evaporator capacity and increase their total throughput and annual revenue. Our analysis found that a membrane system capable of pre-concentrating BL to 25% could double the BL solids throughput of a mill's evaporators.

Mills that are not constrained by their evaporator train can see benefits from a membrane pre-concentration step in the form of steam savings. Our analysis found that a membrane system capable of pre-concentrating BL to 30% could reduce the steam required to operate an evaporator train by 65%. For a mill processing 2000 metric tons per day of BL solids, that translates to $5.0 million/year in gross savings.

We also investigated the impact of membrane systems on evaporator operating parameters, namely TDS and pressure profiles. Because an increase to inlet TDS, by definition, changes the TDS profile across a multi-effect evaporator, a pulp mill may need to monitor the rate at which scaling occurs in its evaporators and adjust maintenance protocol accordingly. However, based on our findings that the change in TDS profile is well distributed across evaporator effects, we suspect this maintenance adjustment would be minimal. We also found that a membrane pre-concentration step would impact steam pressures minimally, if at all.

Regardless of how a membrane system is implemented in a pulp mill, whether it is used to augment evaporator capacity or decrease steam usage, the end result is the same: the energy efficiency, or the pulp throughput per energy used, will increase and the steam usage per pulp throughput will decrease. **TJ**

LITERATURE CITED

1. Empie, H.J., Frederick, W.J., and Clay, D.T., in *Black Liquor Evaporation* (J. Frederick and N. DeMartini, Eds.), TAPPI Press, Peachtree Corners, GA, USA, 2019, Chap. 5.
2. Empie, H.J., *Fundamentals of the Kraft Recovery Process*, TAPPI Press, Atlanta, 2009, Chap. 3.
3. "Pulp and paper industry energy bandwidth study," Report for American Institute of Chemical Engineers (AIChE), Project number 16CX8700, Prepared by Jacobs Engineering, Greenville, SC, USA and Institute of Paper Science and Technology at Georgia Institute of Technology, Atlanta, 2006. Available [Online] https://www.energy.gov/sites/prod/files/2013/11/f4/doe_bandwidth.pdf <1May2021>.
4. Ren, X. "Evaluation of membrane filtration for treatment of black Liquor in small-scale pulp and paper mills in India," M.S thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2016.
5. Wallberg, O., Jönsson, A.S., and Wimmerstedt, R., *Desalination* 154(2): 187(2003). https://doi.org/10.1016/S0011-9164(03)80019-X.
6. Van der Bruggen, B. and Vandecasteele, C., *Desalination* 143(3): 207(2002).
7. Kinstrey, B. and White, J., *Pulping and Environmental Conf.*, TAPPI Press, Atlanta, 2007.
8. Frayne, S., MacLeod, M., MacDonald, B.I., et al., U.S. pat. application 20,200,360,869 (Nov. 19, 2020).
9. MacLeod, M., Frayne, S., MacDonald, B.I., et al., U.S. pat. application 20,200,360,868 (Nov. 19, 2020).
10. Kelvich, N.S., Shofner, M.L., and Nair, S., *Sep. Sci. Technol.* 52(6): 1070(2017). https://doi.org/10.1080/01496395.2017.1279180.
11. "Black liquor concentration research roadmap," Report sponsored by Agenda 2020 Technology Alliance, April 2016. Available [Online] https://www.researchgate.net/publication/304013184_Black_liquor_concentration <03May2021>.
12. Stoy, M.A. and Fricke, A.L., *Tappi J.* 77(9): 103(1994).
13. Zhang, L. and Chen, K.L., *BioResources* 11(2): 4252(2016). https://doi.org/10.15376/biores.11.2.4252-4267.
14. Clay, D.T., "Evaporator fouling," *TAPPI Kraft Recovery Course*, TAPPI Press, Atlanta, 2008. Available [Online] https://www.tappi.org/content/events/08kros/manuscripts/3-3.pdf <03May2021>.

15. Bonhivers, J. and Stuart, P.R., "Applications of process integration methodologies in the pulp and paper industry," in *Handbook of Process Integration (PI)*, Woodhead Publishing Series in Energy, Woodhead Publishing, Cambridge/Sawston, UK, 2013, pp. 765-798. https://doi.org/10.1533/9780857097255.5.765.

16. Karlsson, E., Gourdon, M., Olausson, L., et al., *Int. J. Heat Mass Transfer* 65: 907(2013). https://doi.org/10.1016/j.ijheatmasstransfer.2013.07.003.

APPENDIX

For both heat transfer area and heat transfer coefficient, we used the values in Table A-I proposed by Empie, Frederick and Clay in Black Liquor Evaporation [1].

A-I. Values for constant heat transfer areas,* A*, and heat transfer coefficients,* U *[1].

Effect Number	A, m^2	U, J/m^2s*K
IA	409	981
IB	409	1230
II	818	2229
III	818	2186
IV	818	1792
V	818	1363
VI	818	1076

All four sets of results presented in this analysis—the two installation options and two operating considerations—were modeled with the assumption of a constant heat transfer area, A, and constant heat transfer coefficient, U. A constant heat transfer area was assumed because installing a membrane system has no effect on the physical design of an already installed evaporator train.

The justification for a constant heat transfer coefficient, on the other hand, is less obvious. It is well known that a heat transfer coefficient for a given solution is not a singular value. It is a value that depends on changeable properties of that solution: temperature, concentration, flow rate, etc. To our knowledge, only one study has been conducted to quantify the heat transfer coefficient of black liquor, and it concluded that, for black liquor, the heat transfer coefficient is a strong function of viscosity [16].

Many studies have also been conducted to quantify the viscosity of black liquor. These studies concluded that the viscosity of black liquor above 90°C remains constant until it is concentrated up to 50% TDS [15]. Because all the evaporators we modeled fall within this operating regime, we are satisfied assuming a constant viscosity and constant heat transfer coefficient in the absence of complete data. See the Results and Discussion section of this paper for analysis of the implications of a loss in heat transfer coefficient and compensation by an increase in steam pressure.

ABOUT THIS PAPER

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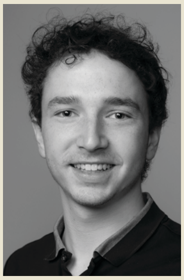

Kleiman-Lynch

Rivera

Frayne

Keller

Via Separations is a spin-out from the Massachusetts Institute of Technology that manufacturers membrane units for the concentration of weak black liquor. In this work, we expand upon the results from a previous economic analysis of membrane technology, one which originally inspired us to focus our efforts on the pulp and paper industry and develop the world's first complete weak black liquor reverse osmosis units [11].

To expand on said previous analysis, we investigate various sizes of membrane systems and various potential installation strategies, as well as how such an installation would affect the key operating parameters of black liquor evaporators. By providing the evaluation in this paper, we hope to demonstrate the power of robust membrane systems and expedite the implementation of membrane technology in the pulp and paper industry.

Mills can use this economic analysis as a starting point to determine how a membrane system could lower their operating expenses and/or increase their annual revenue. However, this research only begins to address the potential benefits of membrane systems in the pulp and paper industry. Additional analysis must be conducted to analyze how membrane platforms could debottleneck washers and improve recovery boiler efficiency.

Kleiman-Lynch is a Chemical Engineering cooperative education student from Northeastern University; Rivera is a Mechanical Engineering cooperative education student from Northeastern University; Frayne is senior chemist; and Keller is co-founder and CTO for Via Separations in Watertown, MA, USA. Email Keller at bkeller@viaseparations.com.