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Energy Analysis for Conversion of a Kraft Pulp Mill into a Dissolving Pulp Mill

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Currently, kraft pulp mills in Europe and North America are facing several challenges and have been forced to think along new products and new business areas. One opportunity is the conversion of chemical pulp mills into dissolving pulp mills by extracting hemicellulose prior to digesting via pre-hydrolysis. From the extracted wood chips, the more valuable dissolving pulp can be produced whereas the hydrolysate can be upgraded to high-value products. In this paper, pinch analysis is used to evaluate the consequences in the energy balance and utility system of a kraft mill converted into dissolving pulp production as well as to identify the potential for heat integration within the host mill itself, between the host mill and the pre-hydrolysis unit and with a hemicellulose upgrading process. The results show that proper heat integration within the host mill itself, and between the host mill and the pre-hydrolysis unit gives significant amounts of surplus steam which could be exported to a hemicelluloses upgrading process, used for power generation or to facilitate lignin extraction.

1. Introduction

Recently, there has been growing concern about the economic performance of conventional kraft pulp mills. Many kraft pulp mills, particularly in North America and Nordic countries, are facing severe challenges such as rising energy costs, strong competition from countries with significantly lower feedstock and production costs, and decreasing demand for some paper grades (Marinova et al., 2010). Consequently, efforts have been made to increase the energy efficiency of mills and to develop biorefinery concepts to produce additional revenue streams. One biorefinery concept that allows for new revenue streams and that can be integrated to an existing kraft mill is hemicellulose extraction for conversion to dissolving pulp production (Marinova et al., 2010; Schild et al., 2010). Up-to-date, fourteen mills around the world have announced expansions or conversion to dissolving mills (Macdonald, 2011).The major driving force behind such conversion is the possibility to produce a pulp product with a growing market and a potential long-term price of about 1200-1800 US$/t (Macdonald, 2011) as compared to the current price of bleached softwood kraft pulp of about ~ 900 US$/t. For production of dissolving pulp, it is crucial to remove hemicellulose prior to pulping, via pre-hydrolysis. Various methods for the extraction of hemicellulose have been presented in the literature, e.g. steam-phase and hot-water pre-hydrolysis methods. According to the current practice, the hemicelluloses degradation products formed during steam-phase extraction are neutralized in a subsequent alkaline extraction step and burned together with the removed lignin (Leschinsky et al., 2009). In the case of water pre-hydrolysis, the extracted hemicelluloses are found in the extraction liquor, so called hydrolysate and could be upgraded to high-value products, e.g. furfurals, xyloses and xylitol (Mateos-

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Espejel et al., 2010). The choice of the best high-value product is highly mill specific and depends for example on the mill's business plan, supply chain as well as future market estimations and should therefore be done on the base of a proper techno-economic assessment. While considerable experimental research has been performed to find the optimal conditions for the extraction of hemicellulose, less attention has been paid to process development and implementation from an energy perspective. Nevertheless, conversion into dissolving pulp production requires significant changes in different process units, not least in the energy system of the mill. It has been stated that the pre-hydrolysis kraft pulping is not commercially utilized because of the high investment and energy costs of this pre-hydrolysis step (Schild et al., 2010). However, with proper process integration, the costs could be reduced significantly, facilitating thus the implementation of this biorefinery concept. After extraction, the wood chips are cooked under modified conditions e.g. higher temperature and chemical load, in order to produce highly pure cellulose fibers (90 % or higher purity). Under these modified conditions, the total pulp yield is decreased considerably and thereby the pulp production for a constant wood input. In a greenfield mill, the pulp production level could be chosen freely. However, in the case of a conversion, the existing equipment (particularly the recovery boiler) will most likely limit the throughput (see Section 4). In addition, the downstream processing of the hydrolysate may also have large consequences in the energy system of the mill and in the pulp production. If the hydrolysate is upgraded, the type of the upgrading process determines whether, and to what extent, the heat in the hydrolysate may be used at the mill for internal heat recovery previous to export. On the other hand, if the hydrolysate is used on-site for energy recovery, the hydrolysate would have to be evaporated and burned in the recovery boiler, which could affect the pulp production rate if the recovery boiler is the bottleneck of the mill. Accordingly, careful process design and implementation is needed for successfully converting a kraft mill into dissolving pulp production. Furthermore, the downtime required for the conversion would represent an excellent opportunity to simultaneously carry out other process modifications at the mill that could lead to improved energy efficiency. In this study, we present the most important energy consequences of converting a kraft pulp mill into dissolving pulp production, as well as possible retrofits that could result in steam savings.

2. Aim

Very limited information can be found in the literature focusing on the energy consequences of converting a kraft pulp mill into a dissolving pulp production. Hence, the aim of this paper is to investigate the main changes in steam demand and production and to identify how the existing equipment at the mill affects the possible pulp production. The aim is also to identify the potential for steam savings at the host mill and the potential for heat integration between the host mill and the pre-hydrolysis unit, as well as the potential for exporting heat from the host mill to a hemicellulose upgrading process.

3. Method

In this paper, relevant process data has been gathered from computer models of a kraft mill and a dissolving pulp mill (See Section 5). From the models, the energy consequences on different process units (e.g. steam production and consumption) upon conversion from kraft to dissolving pulp production have been identified as well as the main process units at the mill that could limit the pulp production. With this information, the possible pulp production with the existing equipment was calculated. Thereafter, pinch analysis (Klemeš et.al. 2010; Smith, 2005) has been used to identify opportunities for heat integration at the host mill and to examine how the pre-hydrolysis unit could be efficiently integrated. In this study, it is assumed that the hydrolysate may be evaporated and burned at the mill or it may be exported to a nearby hemicellulose upgrading process. Since many different alternatives for upgrading hemicellulose are possible and the most profitable option is mill specific, the hemicellulose upgrading process has not been defined in this study and consequently considered outside of the system boundaries (See Figure 1). However, from the results of the pinch analysis, the potential for exporting heat from the host mill to an unspecified upgrading facility has been investigated.

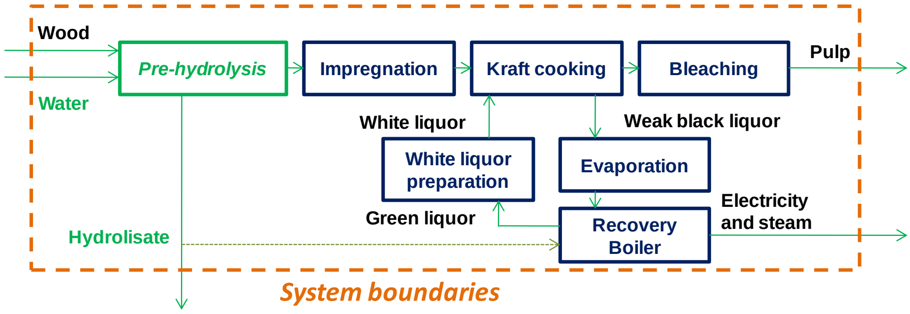

Figure 1: The converted Kraft pulp mill into the dissolving pulp mill. Note: new equipment and changes in process streams are highlighted in green colour. Modifications in existing process units described in introduction and below, are not considered in the picture

4. Use of hydrolysate stream and possible pulp production

The downstream processing of the hydrolysate may affect the energy system of the mill considerably. One alternative is to evaporate and burn the hydrolysate in the recovery boiler. However, according to a preliminary mill simulation, an increase of capacity in the evaporation plant of about 100% is needed in order to concentrate the highly dilute hydrolysate stream and an increase of capacity in the recovery boiler of about 60% in order to burn the organic content of the hydrolysate to maintain a constant pulp production rate. Still, upgrading the recovery boiler is often expensive and sometimes not possible. Therefore, the recovery boiler is often considered the bottleneck for pulp production. If the recovery boiler is not upgraded, a decrease in pulp production of about 40 % is needed according to the preliminary model, which would significantly reduce the potential for increased revenues. The large decrease in pulp production can be avoided to certain extent if the recovery boiler can be debottlenecked. A way to debottleneck the recovery boiler that has been previously studied is the possibility to extract lignin from black liquor (Axelsson et al., 2006). It was shown that lignin separation can be more profitable than a conventional recovery boiler upgrade for a capacity increase of 25 %. In the current paper however, a much more extensive upgrade is required. Further studies are required to assess the viability of separating lignin and the consequences in the recovery boiler e.g. in the adiabatic flame temperature. Nevertheless, evaporating and burning the hydrolysate, probably requires very large investment costs and/or decreased pulp production and, hence, revenues. A preferable alternative than burning the hydrolysate may be to use it as a feedstock for a variety of high-value products. In this case, a decrease in pulp production of about 25 % is needed (Section 5). Such decrease in pulp production may also be sufficient to avoid any large upgrades in the evaporation plant (Table 1). Decreasing the pulp production by 25 % may thus still be an economically attractive option since the price of dissolving pulp is up to the double of price of Kraft pulp.

5. The studied pulp mill

The studied kraft pulp mill is designed as a computer model in WinGEMS within the Swedish national research programme “Future Resource Adapted Pulp Mill” (FRAM) and represents a Scandinavian, state-of-the-art (year 2003) softwood mill, producing 2000 ADt/d softwood bleached market pulp (Delin et al., 2005). However, the mill design may also be applicable for modern mills around the world in the near future. The dissolving mill model has evolved from the kraft mill model and therefore shares almost the same process configuration. However, a pre-hydrolysis unit is added which requires heat e.g. in the form of steam - see Figure 1 and Table 1 (Samuelsson, 2012). According to the mill models, the total pulp yield is expected to decrease from approximately 43 % to 33 % upon the conversion from kraft to dissolving pulp production - a decrease of about 25 % (Samuelsson, 2012). In the dissolving pulp model, it is assumed that the hemicellulose-lean black liquor has approximately the same heating value than regular black liquor from the kraft mill (Samuelsson, 2012). Consequently the maximum load of the recovery boiler (441 MW) limits the pulp production. As previously mentioned, a decrease in pulp production of about 25 % is expected for the mill studied (from 1999 ADt/d to 1495 ADt/d) (Table 1). The steam produced in the recovery boiler, (25.5 GJ/ADt) is enough to satisfy all the steam demand of the process (18.9 GJ/ADt) and for the enthalpy change in the back-pressure turbine (3.9 GJ/ADt). However the excess steam is decreased upon conversion and thereby the condensing power generation. By increasing the heat integration at the mill, the process steam demand could be reduced, resulting in excess steam that could be used for condensing power generation, lignin separation or could be exported from the mill to a hemicellulose upgrading process.

Table 1: Steam and water demand of the kraft and dissolving pulp mills

	Kraft pulp mill		Dissolving pulp mill*	
	[ADt/d]	[BDt/h]	[ADt/d]	[BDt/h]
Wood consumption	4605	173	4532	170
Pulp production	1999	75	1495	56
Yield		43 %		33 %
STEAM PRODUCTION	[GJ/ADt]	[MW]	[GJ/ADt]	[MW]
Recovery boiler	19.0	441	25.5	441
STEAM DEMAND				
Extraction	0	0	6.0**	104
Digesting	1.2	27	1.6	27
Evaporation	4.3	100	5.9	102
Soot blowing	1.0	23	1.3	22
Heat demand for rest	4.1	95	4.1	72
Sub-total process heat	*10.6*	*245*	*18.9*	*378*
Back-pressure turbine	2.9	67	3.9	67
Excess steam e.g. steam to condensing turbine	5.6	129	2.7	46
Total	*19.0*	*441*	*25.5*	*441*
WATER DEMAND	[t/ADt]	[t/h]	[t/ADt]	[t/h]
Water demand for extraction	0	0	8.1	507
Water demand for rest	20.9	1738	27.5	1714
Total	*20.9*	*1738*	*35.6*	*2220*

** Assuming 25 % reduction in pulp production to have the same load on the recovery boiler.*
*** Before any heat integration of new streams from pre-hydrolysis (unrealistic option)*

6. Pinch analysis

A pinch analysis was carried out to identify the potential for heat integration at the mills, as well as the potential for exporting heat from the dissolving pulp mill to a hemicellulose upgrading process. To establish stream data for the pinch analysis, it is considered that the new process streams (extraction water and hydrolysate) do not exchange heat between each other or with the rest of the process. Thereafter, the potential for increased heat integration is studied. The Grand Composite Curves for the kraft and dissolving mill are shown in Figure 2. The pinch temperature in both mills is 73 °C. The temperature of the hydrolysate (175 °C) is well above the pinch temperature, which means that it could theoretically be used on-site for internal heat recovery. Furthermore, the fact that the mill has a relatively low pinch temperature indicates that there are no significant opportunities for exporting high temperature excess heat from the host mill to a hemicellulose upgrading process. The theoretical minimum heating demand of the dissolving mill is 14.1 GJ/ADt. This target represents only the process steam demand, which is 18.9 GJ/ADt in the base case (see Table 1) and excludes therefore electricity production. Moreover, it includes boiler water and combustion air preheating (2.6 GJ/ADt), which are not net steam users as such (and consequently not shown in Table 1) but that can result in steam savings if preheated with internal process heat. Accordingly, there is a heat integration potential of 7.45 GJ/ADt (18.9+2.6-14.1). The heat integration potential can be achieved by identifying and removing the pinch violations at the host mill causing the increased steam demand and by proper heat integrating the pre-hydrolysis unit according to pinch principles.

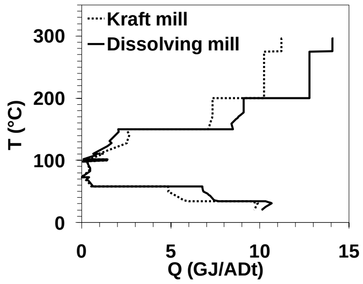

Figure 2: Grand Composite Curves for the kraft and dissolving pulp mill

Table 2: Summary of steam saving opportunities

Theoretical heat integration potential	GJ/ADt	Possible steam saving measures	GJ/ADt
Pinch violations and heat integration potential within the host mill			
Stack losses (heat in flue gases non-utilised)	0.8	Use flue gases to preheat air to recovery boiler	0.6
Heating of air to recovery boiler with steam	0.1	Use excess heat from the HWWS (turbine condenser and turpentine condenser)	0.1
Others	0.2	-	0
Sub-total	*1.1*		*0.6*
Heat integration potential in the pre-hydrolysis unit and between the host mill and the pre-hydrolysis unit			
Cooling of extracted wood chips before impregnation	2.2	Replace steam in the digester and pulp dryer	1.6
Heat available in hydrolysate above pinch temperature	2.6	Use hydrolysate for top heating of extraction water	2.5
Heating of extraction water below pinch temperature	1.6	Use excess heat from the hot and warm water system, HWWS (surface condenser and effluents) to heat extraction water	1.5
Sub-total	*6.4*		*5.4*
TOTAL	**7.4** **100 %**		**6.3** **84 %**

Most of the steam saving potential can be achieved by properly integrating the streams from the hemicellulose pre-hydrolysis unit with each other and with the rest if the mill; see Table 2. A straight forward retrofit (not presented in Table 2) would be to use the hydrolysate directly to heat the extraction water and in this way decrease the steam demand by approximately 3.3 GJ/ADt. However, significantly larger steam savings than this straight forward one may be achieved if the new streams are heat integrated with the rest of the mill. The retrofits presented in Table 2 have been identified based on general pinch analysis heuristics, e.g. correct placement of heating and cooling utilities, heat exchange streams located close to each other, re-use existing equipment, etc. The retrofits are independent and may be implemented stepwise, e.g. depending on which degree of heat integration is most profitable For example, extraction water could be preheated with excess heat from the hot and warm water system (HWWS) of the mill and thereafter top-heated with the hydrolysate (which in turn could be cooled from 175 °C to 78 °C). In this way, the steam demand of the pre-hydrolysis unit may be only 6 % of the total heat demand. In order to make the excess heat available, it may be needed to rebuild the HWWS, purchase new heat exchangers or upgrade existing heat exchangers with additional heat exchange area. The extent to which the extraction water is preheated affects therefore the complexity of the HWWS as well as the temperature of the hydrolysate to be exported to the hemicellulose upgrading process. In order to estimate the profitability of the proposed retrofits and to find the optimal degree of process integration, an economic analysis is necessary. The results presented demonstrate that proper process integration results in up to 6.3 GJ/ADt (145 MW) of surplus steam in addition to the existing excess steam previous to heat integration 2.7 GJ/ADt (46 MW) (Table 1). Hence, the total excess steam at the converted mill is higher than at the kraft mill. As a consequence, the condensing power generation at the mill does not need to be decreased. Moreover, the addition surplus steam may be exported to a hemicellulose upgrading process or may facilitate lignin separation, which could increase the mill revenues if lignin is sold as a biofuel or as a raw material for high-value products. By separating lignin it is moreover possible to debottle the recovery boiler and in this way increase the pulp production. An interesting option for hydrolysate upgrade is ultra-filtration. The hydrolysate contains hemicellulose that could be concentrated by membranes and possibly upgraded to high-value products, for example, films or fiber additives. Another advantage of using membranes is the possibility to reuse the water in the hydrolysate and reduce thus the water consumption of the mill considerably.

7. Conclusion

This paper investigated the conversion of a kraft pulp mill into dissolving pulp production. It was shown that the downstream processing of the hydrolysate may have large consequences in the energy system of the mill and in the pulp production. Evaporating and burning the hydrolysate requires extensive investments to upgrade equipment limiting the pulp production or results in a significantly decreased pulp production. Using the hydrolysate as a feedstock for high-value products seems to be a more interesting option. The results from the Pinch Analysis indicate that there is no excess heat available at high temperature to export from the host mill to the hemicellulose upgrading process. A total surplus of steam of about 9.0 GJ/ADt of steam can be achieved through proper process integration, which could be exported, used for condensing power generation, or for lignin separation from black liquor. It has been demonstrated that increasing process integration has the potential to increase the revenues of a Kraft pulp mill converted into dissolving pulp production. The level of heat integration and the choice of bi-products should be done on the basis of a proper economic evaluation.

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