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Systems interactions analysis for the energy efficiency improvement of a Kraft process

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ABSTRACT

Several techniques are available to improve the energy performance of a process (internal heat recovery, water reutilization, condensates return, energy upgrading and conversion, elimination of non-isothermal mixing). They are applied to specific energy systems on the utility or process side (steam production and distribution, hot or cold water networks, process heat sources and sinks). Since those systems are interconnected, actions taken on one of them may have effects on another. These effects can be positive (synergies) or negative (counter-actions). A systematic, stepwise methodology has been developed to ensure that synergies are exploited and counter-actions avoided, and is presented. It has been validated by application to an existing Kraft pulping mill. Key performance indicators and the evolution of the thermal composite curves were used to monitor progress as the successive steps of the methodology were implemented. It was found that the combined direct and indirect effects of water reutilization constituted the most important source of potential energy savings. Water reutilization also reduced the need for additional purchased heat exchanger area. Overall, the water intake by the mill could be reduced by 33% and steam savings could be 26% of current production. This would liberate sufficient steam production capacity for the installation of a 44.4 MW cogeneration unit.

1. Introduction

There is a broad range of techniques available to the engineer and that should be considered in a retrofit project to enhance the energy efficiency of an operating process. The two best known techniques and most often utilized are internal heat recovery by means of process to process heat exchange and water reutilization by the application of systems closure measures. The development of a heat recovery program aided by Pinch Analysis is well documented [1]. Similar approaches such as Water Pinch are also available to assist in the development of a system closure program [2]. They are usually applied independently yet, the results generated by either of the techniques may restrict the options available to the other. To maximize the global benefit to the process, they should be applied in conjunction.

There are other energy enhancing techniques, such as: the increment of the rate of condensates return to the utility system, the elimination of non-isothermal mixing for heating or cooling and the adjustment of the temperature or pressure levels of the utilities. These techniques are often ignored in energy retrofit projects yet, they can have a significant effect on the overall steam consumption but they may also limit the extent of internal heat recovery and system closure achievable. There are also vast amounts of heat at low potential in various process streams near ambient temperature which cannot practically be recovered by heat exchanger. Upgrading some of this heat to a useful level by means of a heat pump can, in some cases, yield significant energy gains. Absorption heat pumps can be attractive because of their specific characteristics [3]. Finally the availability of excess steam production capacity generated by an energy integration project can be used to produce electric power for sale thus generating revenues to offset investments costs required for the implementation of heat enhancing measures.

The methodology which has been developed and is presented herein could certainly be applied effectively to most energy intensive product manufacturing processes. A wood chemical pulping process, where water plays an important role as material and energy transporting medium, has been chosen for this first illustrative application. Also, reducing its energy cost and its emissions of greenhouse gases is a priority of the pulp and paper (P&P) industry world wide [4].

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The P&P industry is Canada's most energy intensive sector, accounting for 25% of the total industrial energy consumption [5]. Even though 60% of its energy requirement is generated from biomass or process by-products, its consumption of fossil fuel remains a heavy burden. Its high water consumption compounds its energy challenge [6]. Overall, energy accounts for up to 30% of the total wood pulp manufacturing cost in Canada. Facing increasing energy costs and more stringent environmental regulations, the industry has refocused its R&D efforts towards energy efficient practices and technologies and, water conservation programs.

This work proposes a methodology which applies several energy enhancing techniques in a sequence that exploits the synergies between the techniques, and the interactions between the utilities systems and the process so as to maximize steam and water savings. The method has been applied to an operating Kraft pulping mill.

2. Literature review

There is a wide variety of studies on process retrofit projects in Kraft mills. They range from analysis of specific process units or sections to the investigation of the overall site. These studies usually tackle only one of the aspects which affect the energy efficiency. Attempts to study the possible synergistic effects between energy and water have been reported. Some focus on the improvement of the water systems while considering thermal and water constraints. Savulescu et al. [7] suggested a combined water and energy analysis for application to water networks based on a set of two-dimensional diagrams that consider both the streams temperature and contamination level. Mateos-Espejel et al. [8] studied the complete water system in order to identify a broad spectrum of water reutilization measures and to determine their effect on the global thermal balance. Better utilization of the heat required, by the water system, has also been investigated by Nordman and Berntsson [9]; Alva-Argaez et al. [10] and Mateos-Espejel et al. [11]. Others have performed sequential water and energy studies but have not considered their combined impacts on steam consumption. It is the case, for example of Schaareman et al. [12] who have utilized thermal Pinch Analysis and Water Pinch in sequence. Towers [13] first applied Pinch Analysis to identify internal heat recovery opportunities, and proposed additional measures to reduce the water used for cooling by increasing the heat transfer areas and installing a cooling tower in the water network. Savulescu et al. [14] used Pinch Analysis combined with water and energy analysis in the water network to improve the energy efficiency. The energy profile of a process with minimum effluents production has been studied by Wising et al. [15] who proposed the utilization of the available excess heat as the driving energy for a new type of evaporation plant.

Studies concerning the efficiency of non-isothermal mixing points have also been performed. Brown et al. [16] analyzed the process in the perspective of the utilization and production of the utilities required by the unit operations. The measures proposed concern the better utilization of the utilities so as to increase the potential for combined heat and power production. The water usage is associated to the corresponding heat requirement. Lafourcade et al. [17] proposed a methodology where the water reutilization strategies are figured out from benchmarking and Pinch Analysis. In this study, the composite curves are used to determine the appropriate direct heat transfer between cold and hot streams, taking only thermal constraints into account. Savulescu and Alva-Argaez [18] proposed a methodology for the appropriate utilization of non-isothermal mixing used for direct heat recovery, to reduce the steam demand.

The interactions between internal heat recovery and the implementation of cogeneration and absorption heat pumps have been the subject of several studies. The potential for power production generated by internal heat recovery to generate additional revenues has also been investigated [16,19–23]. Examples of implementation of absorption heat pumps and trigeneration units to reduce the minimum cooling and heating demands of a process, and produce power but without regard to Pinch Analysis have been presented [24]. The appropriate positioning in the process of the cogeneration unit and absorption heat pump by means of the composite curves have since been proposed [20,25–27].

Exergy is not often used in engineering analysis despite its usefulness to assess the efficiency of energy transfer and conversion operations. It combines in a single function the quality (temperature) and quantity (enthalpy) of the heat content of material streams. Therefore, while energy is preserved in transformation processes by virtue of the first law of thermodynamics, exergy can be destroyed by virtue of the second law. Much work has been devoted to the use of exergy in process design. Lambert et al. [28] determined the best operating conditions for steam methane reforming process based on the exergy efficiency. Sorin and Paris [29] combined exergy and pinch analysis for the development of heat exchanger networks. Exergy analysis has also been used for process synthesis [30,31] and to determine the efficiency of equipment [32] where it has been used in combination with pinch analysis. It has been applied in the P&P industry [16,19,33–35].

These studies tackle individual issues or specific interactions but fail to take a global view of the problem to determine the optimal mix of individual measures.

3. Context

The process analyzed in this work is an operating Kraft mill situated in Eastern Canada for which a nominal model was defined, simulated and benchmarked in a previous study [36]. The mill has an average production of 700 adt/d (adt = air dried metric ton) of high grade bleached pulp.

Kraft pulping is the prevalent manufacturing process by which wood chips are transformed into paper pulp, the intermediate material from which a very broad spectrum of finished or semi-finished paper products are made [37]. A simplified schematic of the typical Kraft process is given in Fig. 1. The core of the process is a chemical delignification step performed in a digester where the individual cellulosic fibers are separated to form the pulp. The delignification agent (white liquor) is a mixture of sodium hydroxide and sodium sulfide. After delignification the fibers are washed and chemically bleached. Finally they are drained, pressed and thermally dried. A key characteristic of the process is that the spent delignification liquor, black liquor, separated from the fibers in the washing step, is concentrated and burnt in the recovery boilers to produce steam. The spent inorganic chemicals form a smelt, composed of sodium carbonate and sodium sulfide, which is collected at the bottom of the recovery boilers. It is dissolved to form green liquor which is recaustified with quick lime, produced on site in a lime kiln, to regenerate the white liquor.

The energy efficiency of the Kraft process is strongly related to the proper management of water and steam. Water is used for dilution, cooling, steam production and, for washing. Steam is used in the chemical delignification, black liquor concentration, and pulp drying sections and, to heat the mill water supply.

4. Previous work

In a chemical conversion process such as Kraft pulping, there are strong interactions between the utilities (steam and water) and the process units which affect the overall thermal energy consumption of the mill. These interactions must be characterized. This preliminary

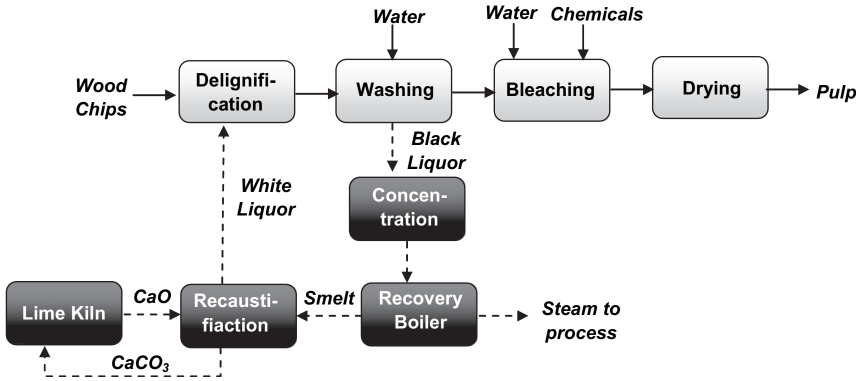

Fig. 1. Simplified diagram of the Kraft process.

work is done in two steps: definition and characterization of the process and, benchmarking analysis.

4.1. Definition and characterization

Mateos-Espejel [36] has performed a detailed definition and characterization of the nominal process operating conditions and constructed a water and energy oriented computer simulation on CADSIM PLUS, a software broadly used in the P&P and related industries in Canada. The steam and water utility systems have been modeled in detail and each process section shown on Fig. 1 has been considered as a steam and water consumer. The difference between measured and computed values for the production of steam is 0.9%. All individual steam-using operations are within 10% of mill collected consumption data. The difference between the computed water intake and the measured value is 6%. The pertinent characteristics of the utility systems are summarized below.

The steam required by the mill (Fig. 2), is supplied by four boilers that generate high pressure steam (HP = 3100 kPa, $T = 371$ °C): two spent liquor recovery boilers (RB), a biomass boiler (Bi) and a small fossil fuel boiler (FF). Medium (MP = 965 kPa, $T = 179$ °C) and low pressure (LP = 345 kPa, $T = 143.5$ °C) steam is produced by desuperheating and depressurization of HP steam in pressure reduction valves (PRV). Part of the condensates produced in the process is recovered and mixed with make-up water in the deareator. Table 1 gives the steam consumption by process section for winter conditions. The steam consumption is reduced by 10% during the summer.

The water intake of the mill undergoes two pretreatments before being used: During summer, the period of highest water consumption, 65% of the feed water, referred to as treated water, is screened and demineralized for steam production and for utilization in process sections where it is in direct contact with the pulp. Those sections are pulp washing, pulp bleaching, pulp drying and the ClO_2 making plant (ClO_2 is a bleaching agent used in the mill and produced on site). The remaining 35% of the feed water is only screened (screened water) and is used for cooling, vent gases scrubbing and housekeeping. Table 2 gives the water consumption by process section. The consumption of screened water varies appreciably between summer and winter. The cooling requirement of the ClO_2 making plant during the summer requires a large amount of screened water chilled by a dual equipment, an absorption chiller and a steam ejector. The overall water consumption increases 18% during summer.

The treated water is used at 5 temperature levels (Fig. 3): cold (winter: 4 °C, summer: 20 °C), warm (44 °C), and hot (58, 62 and 71 °C). The warm water is generated in the condensers of the black liquor concentration section. Hot water at 58 °C is produced by indirect heat exchange with the effluents from the concentration section. To produce the rest of the hot water the following procedure is followed: the temperature of the warm water is increased to 53 °C by means of internal heat recovery, then to 62 °C using direct steam injection in the hot water tank. Part of the water at 62 °C is directly used and the rest is heated to 71 °C by indirect heat exchange with steam.

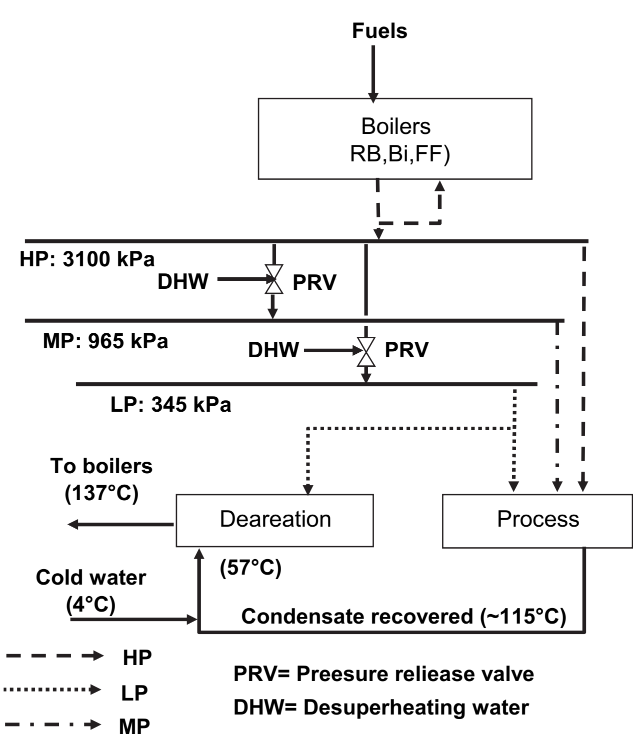

Fig. 2. Steam production [36].

Table 1
Steam consumption by process section.

Process section	GJ/adt
Delignification	3.99
Bleaching	1.75
Concentration	4.2
Drying	4.76
Water heating	1.54
Recaustification	0.57
Deareation	2.66
Steam export	0.69
Boilers, and other equip.	0.98
Total process consumption	21.14

Table 2
Water consumption by process section.

Process section	m^3/adt
Treated water	
Delignification & Washing	10.1
Bleaching	30.7
Concentration	1.0
Drying	10.7
Recaustification	2.0
Deareation	4.8
Steam exports	0.0
Boilers	0.2
Non process uses	4.6
Screened water	
Bleaching	24
Recaustification	4.6
Non process uses	11.1
Unaccounted water	6.4
Total process consumption	110.1

On the process side a number of possible inefficiencies or poor practices which affect the water and steam systems have been identified:

- Non-isothermal mixing such as direct injection of steam in the hot water tank and the deareator, and the mixing of streams at different temperature levels in the warm water tank.
- Low condensate recovery rate of 43% as compared to the typical Canadian average of 75%.
- Low efficiencies of the recovery boilers (58%) and of the biomass boiler (43%), below the typical Canadian average of 65%.
- Depressurisation of HP and MP steam in PRV's reducing the potential for electricity generation.

4.2. Benchmarking analysis

Mateos-Espejel [36] has performed a benchmarking analysis of the case study by a three-pronged procedure: comparison with the current practice, targeting by means of the heat and water composite curves and the monitoring by means of new performance indicators. The new indicators relate the exergy and energy contents of the unused hot streams such as flue gases (EC_{FG}), and effluents (EC_E) to the total energy used as heat. The energy wasted in these heat sources is a flag of excess steam utilization. In this work the exergy function of the heat exchanges is represented in the Carnot space (Carnot efficiency vs heat load). In this representation, the exergy destroyed in a heat exchange is graphically displayed as a function of temperature approach [38]; it can thus be used to determine efficiency, while maintaining realistic heat exchange conditions.

The following results were obtained:

- Steam (21.1 GJ/adt) and water (110 m^3/h) consumptions of the mill are above the typical Canadian average values (18.5 GJ/adt; 75 m^3/h)
- The process has a net thermal energy deficit of 8.1 GJ/adt. This deficit is the difference between the steam produced by the RB and the steam required by the process. It is compensated by the utilization of fossil and biomass boilers.
- The production of effluents at the bleaching (58.6 m^3/h), drying (8.3 m^3/h), and concentration (15.8 m^3/h) sections is above the typical Canadian averages (48.5, 6.2 and 4.6 m^3/h, respectively).
- The cooling demand of the process is 62 MW in winter and increases by 22 MW during the summer. A major contributor to the summer cooling demand is the ClO_2 making plant.
- A large fraction of the exergy supplied to the process is destroyed (74.5 MW; 61%) by the combustion of fuels because of large temperature gradients in the boilers (HP steam production) and subsequent depressurization (MP and LP production).

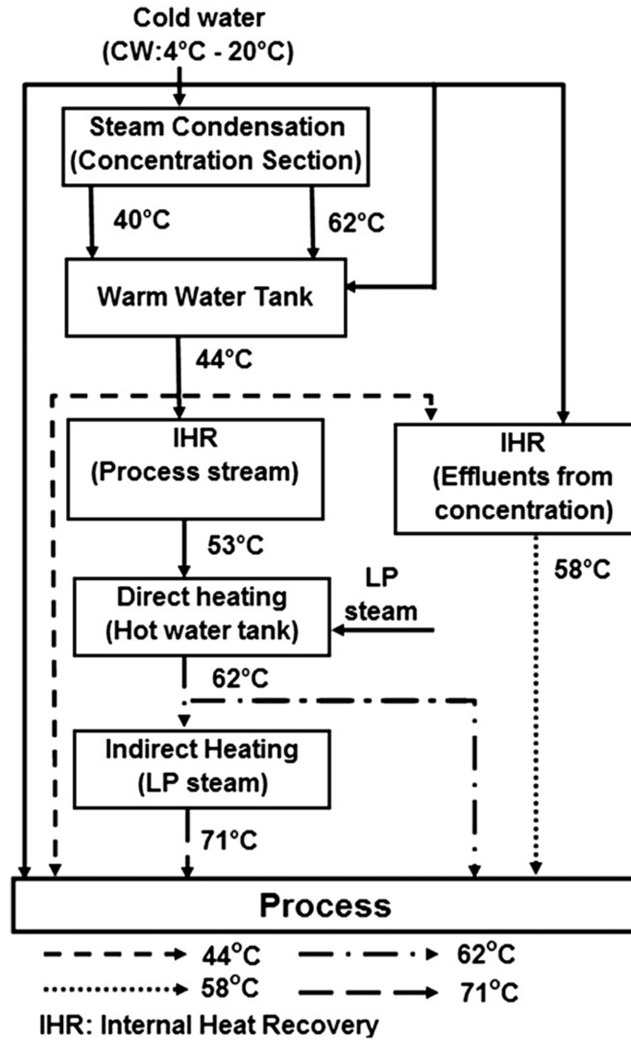

Fig. 3. Water production [36].

- The unused heat content rejected to the environment by liquid effluents and flue gases represents 33% and 25% of the energy and exergy requirements respectively. The effluents are situated below the pinch point (PP) while the flue gases are above.
- The steam used for water heating represents 22% (37.1 MW) of the total consumption by the process. About 33% of the exergy supplied (12.1 MW) to the water heating systems (Fig. 3) is destroyed.
- The thermal composite curves of the process are shown in Fig. 4; the minimum heating requirement (MHR) is 123 MW, the minimum cooling requirement (MCR) is 10 MW and the pinch point is at 71 °C. The water composite curves are shown in Fig. 6. The minimum water consumption (MWC) is 1000 m^3/h, the minimum effluent production (MEP) is 880 m^3/h and the PP is at a dissolved solids concentration (DSC) of 0 ppm that is for pure water.
- The theoretical maximum internal heat recovery and water reutilization indicated by the composite curves are 192 MW and 1360 t/h respectively. As a result, the steam consumption could decrease by 29% and the water consumption by 31%.
- Fig. 5 shows the thermal composite curves after water reutilization. The MHR would then be 119 MW and the MCR 17 MW;

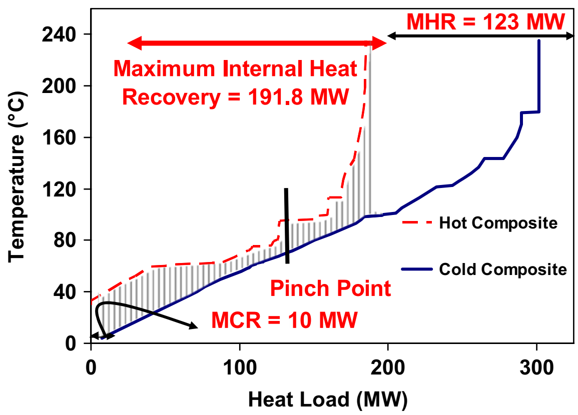

Fig. 4. Thermal composite curves of the process in initial configuration.

the PP would be lowered to 57 °C. The causes of these changes will be given in section 5.

- All process modifications involved to change the thermal profile of the process from Fig. 4 to that of Fig. 5 may not be feasible because of technical or economic constraints. As will be seen later, lowering the pinch point may facilitate the installation of heat pumps to upgrade low potential heat.

The results from benchmarking analysis suggest that there is a broad spectrum of possibilities for energy efficiency improvement in this case study. However, they are all interrelated and should not be tackled individually. The process retrofit must involve an analysis of the systems interactions in order to propose a set of complementary measures. The passage from the thermal profile of Figs. 4 and 5 illustrates the fact that water usage and energy consumption are interdependent and must be analyzed in conjunction. The methodology presented in the next section is based on this premise.

5. Methodology

As illustrated above, a large amount of work has been devoted to the improvement of the energy performance of the Kraft process. The most commonly used techniques have been internal heat recovery and water reutilization. Recently other techniques which can generate further improvements have also been applied to the problem. They are, the elimination of non-isothermal mixing points, energy upgrading, condensates return and energy conversion. From

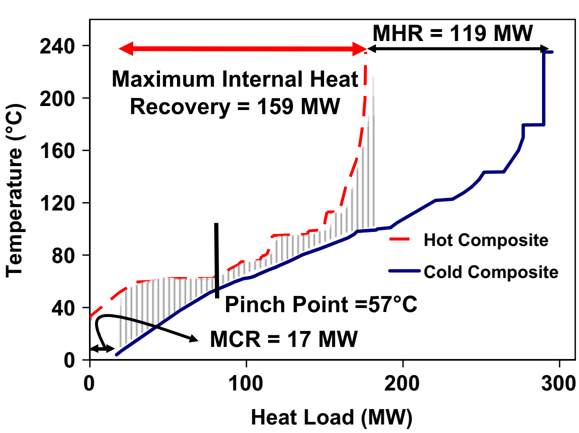

Fig. 5. Thermal composite curves of the process after water reutilization.

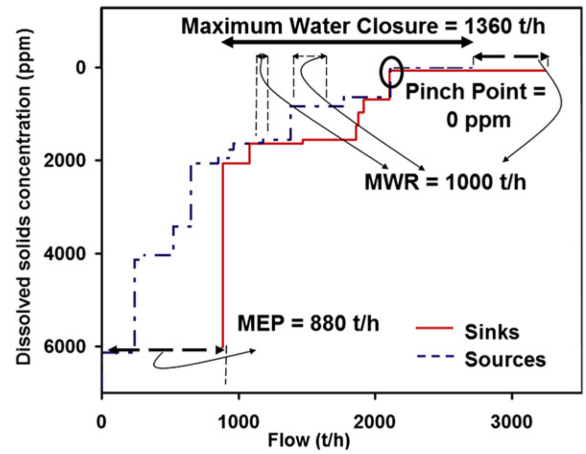

Fig. 6. Water composite curves of the process.

the trends and patterns observed in the case of the Kraft process, general guidelines can be derived for the appropriate application of these techniques as a unified tool for the energy enhancement of transformative processes since the underlying fundamental principles are common to all. Differences in relative effectiveness and degree of interaction between the various techniques are bound to occur from process type to type.

5.1. Principles

Cross effects between the techniques are unavoidable since they are applied from various perspectives: steam and water networks, process and utilities (Fig. 7). Some effects will be positive, the synergies, and some negative, the counter-actions. The methodology presented below is unique in that it takes into account the six techniques identified in a structured manner that makes the best use of synergies and avoids counter-actions. Two of those techniques modify the overall energy balance of a process when they are applied; they are water reutilization (WR) and elimination of non-isothermal mixing (NIM). They will therefore interact very strongly with internal heat recovery and will modify the pinch diagram and any heat exchanger network that may have already been designed or implemented. The utilization of direct mixing

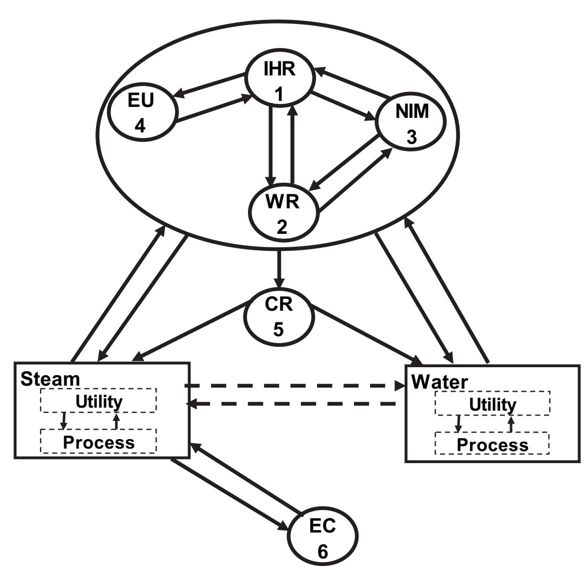

Fig. 7. Interaction analysis.

(NIM) of water for preheating and cooling also influences the possibility to save fresh water by water reutilization (WR). Therefore, those three techniques form an intensive interactions triangle as shown in Fig. 7. The installation of a heat pump in a process requires the connexion of hot and cold streams to the device (two streams in the case of conventional recompression heat pumps, three in the case of an absorption pump). This will eliminate hot and cold streams from the pool available for internal heat recovery but will not modify the pinch diagram Those 4 techniques and the way they are applied in synergy determine by how much the steam and water demands of a chemical process can be decreased. They constitute the first steps of the procedure described in the following section. Once they have been applied, the collection of condensates and the return network are examined to determine if the recovery rate can be improved so as to reduce the water make-up required at the deareator and the steam needed to preheat the feed water to the boilers. Finally, once all the corresponding energy efficiency measures have been applied, part of the installed steam production capacity of the power plant should have been liberated for non process utilization such as power production by steam turbines. If backpressure steam turbines are used, the discharged steam can be returned to the process steam distribution network. The application of all energy enhancing techniques affects the steam and water systems. Modifications introduced in one of the systems impacts the other. For instance, the less water is consumed the less steam needs to be used for water heating. The elimination of steam injections also affects the water consumption in the deareator as less make-up water is required. Cross effects are also identified and can thus be avoided or mitigated.

The systems interactions that modify the process thermal balance are assessed by analyzing the changes to the thermal composite curves, to the minimum energy requirements and to the pinch point position. Performance indicators are used to quantify the improvement of the overall energy efficiency. Variations in steam and water usage are also computed.

5.2. Description

The order in which the techniques should be applied to a process is a question of efficiency, the objective being to avoid counter-actions and redundancies. It seems natural to start with the triangle IHR-WR-NIM which will account for the larger part of the potential savings. Any of the summits could be the starting point. However, considering the importance of the pinch diagram and the resulting heat exchanger network design which are modified by the water reutilization and the elimination of NIMs, it seems logical to start by the IHR and to proceed with the technique which is likely to have the higher subsequent impacts. The rest of the sequence is then rather obvious. The resulting order of implementation of the techniques is indicated by the numbers in Fig. 7.

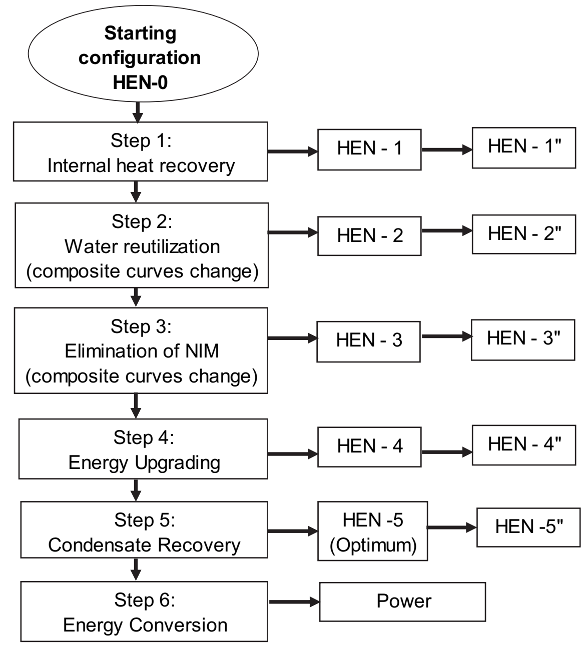

Fig. 8. Interactions identification sequential approach.

Fig. 8 illustrates the sequence. The process can in principle be interrupted at any stage. However, savings increase at each step and it is strongly advised, for optimum results, to perform the complete sequence. The work done at each step is summarized below.

Step 1. Internal heat recovery. The starting point of the procedure is the process in its current configuration. The pinch diagram for this configuration is constructed and the corresponding heat exchanger network is designed (HEN-1). However, it is very likely that some heat recovery measures have already been implemented and constitute the installed heat exchanger network (HEN-0). It may no have been based on a full Pinch Analysis and may contain pinch violations; they must be identified and imperatively corrected. Other already installed heat recovery measures may not conform to the optimal network (HEN-1) without violating the pinch rules. It may not be advantageous or even feasible to replace them for economic or technical reasons. These measures should be treated as technical constraints in the design of the heat exchanger network and create variants of the network design HEN-1: HEN-1″. Those variants will be carried on through the subsequent steps of the procedure in parallel to the main path.

Step 2. Water reutilization. The possibilities of water reutilization are identified by means of Water Pinch Analysis. This will reduce steam consumption and effluents productions; it is also likely to eliminate some of the NIM points. Most important, the water streams which are reused in the process will become heat or cold

Table 3
Steam savings after implementation of each HEN by process section.

Process Section	Consumption	HEN-1	HEN-1″	HEN-2	HEN-2″	HEN-3	HEN-3″	HEN-4	HEN-4″	HEN-5	HEN-5″
Delignification	32.4	0	0	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Bleaching	14.2	0	0	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
Concentration	34.1	0	0	0.5	0.5	0.5	4.0	7.8	4.0	7.8	4.0
Drying	38.5	3.5	4	4	4	4	4.0	5.2	4.0	5.2	4.0
Water heating	12.9	5.4	12.1	12.9	12.2	12.9	12.3	10.7	12.9	10.7	12.9
Recaustification	4.6	0	0	0	0	0	0.0	0	0	0	0
Deareation	21.5	13.6	16.9	9.4	12.7	17.8	21.3	17.1	21.3	19.4	21.3
Steam export	5.6	0	0	0	0	0	0.0	0	0	0	0
Boilers, and other equip.	7.9	0	0	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Total (MW)	171.7	22.5	33.1	29.7	32.3	38.1	44.5	43.7	44.5	46	44.5
Savings as % of current		13	19	17	19	22	26	25	26	27	26

Table 4
Indicators Assessment.

	Current	HEN 1	HEN 1″	HEN 2	HEN 2″	HEN 3	HEN 3″	HEN 4	HEN 4″	HEN 5	HEN 5″
MHR	122.8	122.8	122.8	119.1	119.1	118.9	118.9	118.9	118.9	118.9	118.9
MCR	10	10	10	17	17	15.9	15.9	15.9	15.9	15.9	15.9
Pinch point (°C)	71	71	71	57	57	57	57	57	57	57	57
EC_E (MJ effluents/MJ steam produced)	0.26	0.2	0.13	0.18	0.14	0.13	0.09	0.10	0.09	0.09	0.09
EC_{FG} (MJ flue gases/MJ steam produced)	0.07	0	0	0	0	0	0	0	0	0	0
Surface area needed (m^2)		3580	6650	2120	3660	2990	6030	5130	6030	5350	5800

streams thus modifying the pinch diagram; the pinch point and the minimum energetic requirements will be changed. Pinch rules violations may be eliminated or created because of the pinch point modification. A new heat exchanger network and its variant must be designed on the basis of the new pinch diagram: HEN-2, HEN-2″

Step 3. Elimination of non-isothermal mixing. Some NIMs remain after step 2. They constitute wasteful inefficiencies. They are identified in step 3 by quantifying the exergy destroyed at each point and correcting measures are developed. Some of these measures will consist of using internal heat recovery in combination with streams mixing and will therefore modify the pinch diagram. Therefore a new network (HEN-3, HEN-3″) will be developed.

Step 4. Energy upgrading. When feasible, the implementation of a heat pump in a process can be an efficient way to reduce the demands on hot and cold utilities, i.e. the MHR and MCR. However, since the investment cost is often substantial this should be forseen only after internal heat recovery has been maximized. A limiting factor is often the temperature lift required to match the heat pump internal requirements in heat loads and the available heat sinks and sources, particularly in the case of AHPs which are linked to process streams at three levels. The temperature lift can be reduced by rearrangement of the HEN in order to use streams close to the pinch point, thus producing new configurations (HEN-4, HEN-4″).

Step 5. Condensate recovery. Following the maximization of steam savings by the other techniques, the recovery of condensates is identified as well as the possible replacement of steam injections by heat exchangers (HEN-5, HEN-5″).

Step 6. Energy conversion. The temperature profile of the process is analyzed to adjust the pressure steam levels. After, the proper size and type of turbines are computed so as to maximize the power production from the amount of steam available.

6. Application to the case study

The benchmarking analysis of the reference Kraft pulping mill has been performed in a previous study [36] and summarized in Section 4.2. It showed that the process is characterized by a low level of water reutilization, poor heat recovery and the presence of inefficient non-isothermal mixing points. This situation is not atypical of older Kraft pulping mills in Canada and in other countries. The results of this situation compounded with the counteractions of presumed energy savings measures in place are high water and steam consumptions, and large quantities of heat rejected in flue gases and liquid process effluents. Furthermore, poor management of the steam production and distributions systems preempts potentially profitable power co-production.

The computer simulation has been used to determine the changes to the thermal and water balances resulting from the application of the enhancing techniques. The successive HEN designs have been performed by means of conventional Pinch Analysis using the ASPEN-HXNET software. The design of the HEN for step four is presented because it illustrates the modifications required to implement an AHP.

The steam savings, the effluents energy content (EC_E) and flue gases (EC_{FG}), and surface area for all HENs produced by the stepwise procedure are given in Tables 3 and 4. These values are for the winter period. It must be noted that the overall power required as steam is 10% lower in summer than in winter and that the fraction of that power used for water heating is 35% lower. The energy savings measures proposed are applicable to both conditions.

Step 1: Internal heat recovery (IHR)

The installed heat recovery measures of HEN-0 which affect the operation of the process and that are technical constraints respected in the design of HEN-1 are the following:

Constraint 1. Heating fresh water by steam condensation in the BL concentration section. The vacuum required to concentrate BL is produced by an ejector coupled to the condensers. Constraint 1 limits the amount of steam that could be saved below the pinch point. An alternate heat exchanger network that corrects this situation has been developed (HEN-1″).

Constraint 2. Heating contaminated water by direct injection of process steam. A pinch rule violation occurs in an accumulation tank used for process controllability. The tank is connected to the water system (heat exchanger after warm water tank in Fig. 3) and the BL concentration section.

Constraint 3. Delignification. Medium pressure steam is used to increase the temperature of wood chips from 60 °C to 170 °C and thus is a pinch rule violation. However, modifying this configuration by implementing process to process heat exchanger affects the digesters controllability.

Table 5 shows the amount of energy associated with the existing pinch violations. There are three types of violations:

1. Utilization of a hot stream above the pinch point to heat a cold stream below (12.5 MW)
2. Utilization of a hot utility to heat a cold stream below the pinch point (22.2 MW)
3. Utilization of a cold utility to heat a hot stream above the pinch point (14.3 MW). In the current process, this is linked to unused

Table 5
Violations to the pinch rules in the current process (values in MW).

Section	Pinch violations		
	HXTP	UHAP	SUBP
Delignification	5.3		0.9
Bleaching			2.1
Concentration			
Drying			6.8
Water heating	1.7		9.8
Recaustification			
Deareation	5.5	0.8	2.6
To sell			
Boilers, & other		13.5	
Total	12.5	14.3	22.2

Abbreviations: HXTP: heat transfer through the pinch; UHAP: unused heat sources above the pinch; SUBP: steam used below the pinch; TSU: total steam used.

Table 6
Violations to the pinch rules after water reutilization.

Section	Pinch violations		
	HXTP	UHAP	SUBP
Delignification	3.5		
Bleaching		4.9	0.05
Concentration	5.5		
Drying			2.5
Water heating	0.09		
Recaustification			
Deareation	6.1	0.8	
Steam export			
Boilers, and other		13.5	
Total	15.2	19.2	3

heat sources (effluents and flue gases) and release of heat to the environment.

The elimination of all pinch violations constitutes the maximum savings that can be achieved by improving internal heat recovery (49 MW).

The network HEN-1 (savings = 22.5 MW) involves only the utilization of heat currently wasted in bleaching effluents and flue gases to reduce the amount of steam used for water heating and deareation. On the other hand, the better usage of the available heat below the pinch in HEN-1″ represents more steam savings (33.1 MW). These additional savings should compensate for the extra surface required (higher that that of HEN-1) and for the possible technical problems caused by the elimination of constraint 1. The surface area and the complexity of the HEN increases as its energy requirements become closer to the MER.

The measures that produce the steam savings above the pinch point recover all heat available from the flue gases, therefore EC_{FG} is reduced to zero. The increased utilization of heat from effluents, below the pinch, in HEN-1″ results in a larger reduction of effluents energy content (ECE).

Step 2: Water reutilization (WR)

The potential increase of water reutilization by means of a combined Water Pinch and thermal analysis has been reported previously by Mateos-Espejel et al. (2008b). The measures proposed are:

1. Reutilization of the effluents from the BL concentration section in the pulp washing and in the recaustification sections (savings = 350 m^3/h).
2. Reutilization of whitewater in the bleaching section (savings = 110 m^3/h).
3. Increased reutilization of filtrate within the bleaching section (savings = 70 m^3/h).
4. Reutilization of the sealing water of the vacuum pumps (savings = 70 m^3/h).

The implementation of these measures reduces the steam demand by 15.1 MW before the new HEN is designed. The largest

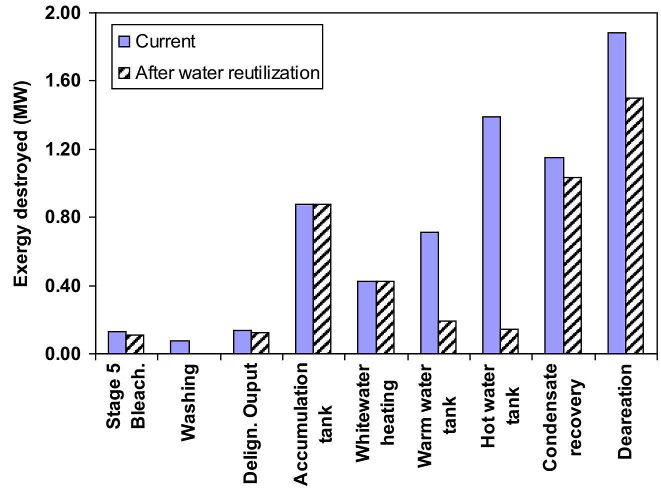

Fig. 9. Exergy destroyed for different NIM points: current and after water reutilization configuration.

steam savings come from the reduction of the need for heating water (9.5 MW). Other significant savings are obtained in the deareator (2.3 MW) because less water make-up is required. The make-up water in the warm water tank and the steam injection in the hot water tank are no longer required. Therefore, the NIMs in these tanks are eliminated. The utilization of effluents from the BL concentration section (~75 °C) to replace the hot water used for pulp washing (~70 °C), increases the temperature of the washing filtrates and weak BL. Therefore, the steam demand is reduced by 0.7 MW in the delignification section and by 0.5 MW in the BL concentration section. A similar effect occurs in the pulp bleaching where replacing hot water by a warmer stream increases the temperature of the pulp, thus reducing the steam required by 1.6 MW. Subsequently, the cold water make-up and the heating needs of the deareator are reduced.

After water reutilization, the total energy required by the process is reduced. The MHR decreases by 3.7 MW while the MCR increases by 7 MW. The MCR changes because the hot water production is decreased. Part of the cold water used for steam condensation in the BL concentration section becomes an additional cooling demand. As the pinch point is reduced to 57 °C a pinch rule violation is created because a cold utility is used above the pinch. The violations to the pinch rules after water reutilization are shown in Table 6. The maximum savings that can be achieved by eliminating all violations are 37.4 MW.

The steam savings achieved by the water reduction measures (15.1 MW) have been included in the results of HEN-2 and HEN-2″. The design of HEN-2 saves steam by 29.7 MW which is more than in HEN-1 and less surface area is required. HEN-2″ produces more steam savings; however the exchange area needed is substantially larger.

The reduction of the effluents energy content (EC_E) is produced by reutilization of the effluents and increased heat recovery below

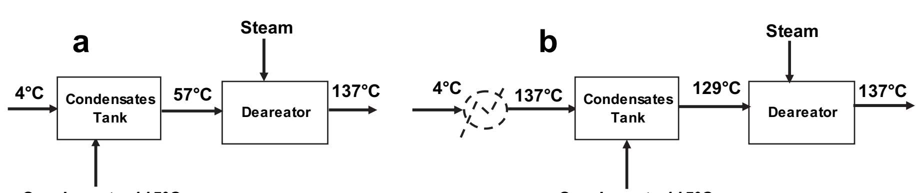

Fig. 10. a) Current deareation system; b) retrofit system.

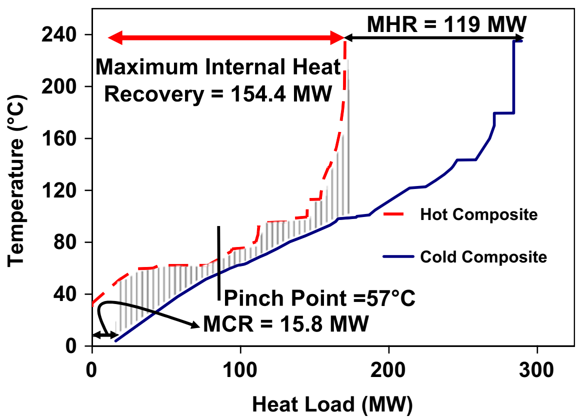

Fig. 11. Thermal composite taking into account the elimination of NIM points (HEN-3).

the pinch. A better usage of the low temperature energy in the process is achieved.

Step 3: Non isothermal mixing (NIM)

An analysis of the exergy destroyed has been done to identify the most inefficient NIM points (Fig. 9) for the current process configuration and after water reutilization. The exergy destroyed in NIMs is substantially reduced after water reutilization because no cold make-up water (4 °C) and no steam injections are required in the warm and hot water tanks. The injection of process steam to heat contaminated water in an accumulation tank corresponds to the constraint 2. The NIMs in the deareator and condensate recovery should be eliminated. These NIM point are connected as shown in Fig. 10a.

The preheating of the cold make-up water to 137 °C by internal heat recovery before it is mixed with condensate substantially reduces the need for LP (Fig. 10b) in the deareator. This requires the addition of a heat exchanger operating at 350 kPa. It is also assumed that the condensate tank and the deareator can support this pressure. The appropriate hot stream is determined by the design of HEN-3. After eliminating NIM points the MER are modified. The new MHR and MCR are 118.9 MW and 15.9 MW respectively as shown in Fig. 11. HEN-3 also makes a better usage of the low temperature energy below the pinch where the effluents energy content indicator (EC_E) is reduced to 0.13. The steam savings are increased by 8.4 MW but more surface exchange is required than in HEN-2. The savings obtained by HEN-3″ are larger by 6.4 MW that in HEN-3, however the surface required is doubled.

The elimination of the NIM before the deareator shifts the energy demands of this part of the process from high (steam) to low temperature heat sources (effluents). Therefore, the steam savings achieved by internal heat recovery are increased.

Step 4: Energy upgrading

The HEN-3 design above the pinch point is shown in Fig. 12. Hot utilities are required for cold streams in the range of 100–137 °C and the streams close to the pinch are used in process to process exchangers (HX 3 and 4). Considering that the pinch point after water reutilization is 57 °C, the temperature lift required for a hot stream close to the pinch (i.e. bleaching effluents at 55 °C) would be ~80 °C. To implement an AHP (Fig. 13), the hot streams above the pinch should satisfy the energy requirement of the high temperature cold streams (100–137 °C) as performed by HX B and D in HEN-4. The heat receptors close to the pinch (water heating: 65–71 °C; deareation: 59–95 °C) are available for the AHPs. However, the surface area required by the process to process heat exchangers would increase because the $\Delta T_{approach}$ is reduced. The investment required will increase due to the cost of the AHP and due to a larger surface for the HEN. On the other hand, the increase in steam savings also increases the power production potential.

Bakhtiari et al. [3] have made an analysis of the mill to implement AHPs. They have proposed to use an AHP driven by MP steam to upgrade the heat from the bleaching effluents. This AHP reduces the heating demand by 2 MW. The heat receptors where steam is saved are the BL concentration and the deareator. Another AHP driven by MP steam can be placed to recover the heat rejected in the production of chilled water during the summer. The steam demand of the process is reduced by 3.6 MW and the consumption of water by 540 m^3/h. The heat receptors where steam is saved are the deareator, hot water production and whitewater heating.

HEN-3″ cannot be redesigned to fit an AHP because the low temperature energy sources below the pinch are already employed in process to process heat exchangers. The data for HEN-4′ shown in Tables 3 and 4 are the same as for HEN-3″.

Step 5: Condensate recovery (CR)

Two measures have been identified: replacement of steam injection used to heat whitewater by a heat exchanger and the collection of condensates produced in the recaustification unit. The reduction of the steam consumption for deareation in HEN-5 is of 2.3 MW because less cold make-up water is required. In HEN-5″ the

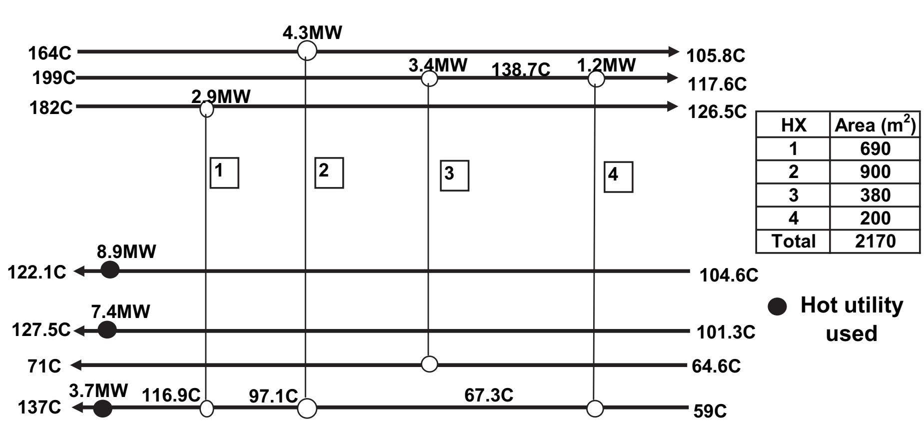

Fig. 12. HEN-3: network design above the pinch [36].

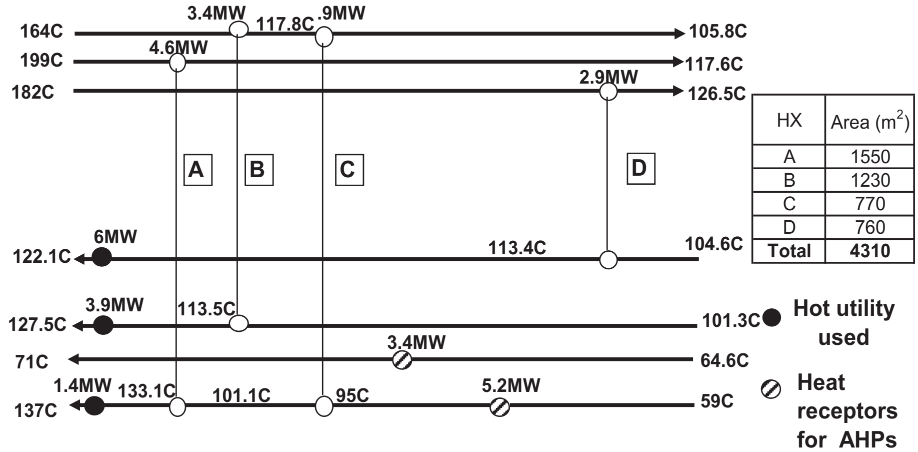

Fig. 13. HEN-4: network design above the pinch [36].

surface required is slightly lower than in HEN-4″. Some process to process heat exchangers considered in HEN-4″ are not required because steam consumption in the deareator is reduced after the increase of condensate return.

Step 6: Energy conversion

Cakembergh-Mas et al. [22] studied the implementation of cogeneration to replace the pressure release valves in this process. They considered condensing and backpressure turbines, and the related economic factors (turbines cost, price of electricity and of biomass). The potential replacement of the biomass boiler by a new one (twice the size and producing steam at VHP: 8800 kPa) was also taken into account. Mateos-Espejel et al. (2009a) adjusted the steam pressure levels to improve its fit to the temperature profile of the process. In addition, the energy improvement of the process and the shutdown of the fossil fuel boiler were taken into account.

The implementation of two turbines is envisaged after the implementation of HEN-5: a backpressure turbine driven by HP (3100 kPa) produced by the recovery boilers and a condensing turbine driven by VHP (8800 kPa) produced by the new biomass boiler. A maximum production of 44.4 MW is obtained.

7. Conclusions

A methodology that integrates in a synergetic way all techniques now available to improve the thermal energy efficiency of a process has been developed and validated by application to an operating Canadian Kraft mill.

The main features of this methodology are:

- Utilization of several energy enhancing techniques
- Analysis of the thermal composite curves evolution as a result of water reutilization and elimination of non-isothermal mixing
- Development of HEN designs at each step
- Development of scenarios with complementary measures to maximize steam savings and power production

The heat recovery measures currently installed and that cannot be modified must be carefully identified. These technical constraints impact the surface area required by the optimal heat exchanger networks and the steam savings that can be achieved. As several techniques are considered, it is possible to maximize steam savings (HEN-5) without violating the technical constraints (HEN-5″).

The heat from flue gases is the principal source of steam savings above the pinch point in the design of all heat exchanger networks. However, to maximize the steam savings below the pinch, the utilization of all techniques is required. After water reutilization is performed, the overall steam savings are increased and the surface area of the heat exchanger network is reduced.

The savings obtain by this methodology are superior to the individual application of each technique. This is proven by the gap between the final savings achieved (46 MW) and the initial savings achieved by HEN-1 (22.5 MW). The large power production potential (44 MW) is another benefit of applying the methodology.

The methodology is not specific to a process or a type of industry. However the level of integration between steam and water systems will vary from process type to process type because of the very wide range of ways in which water is used in manufacturing process. Therefore, the interactions (synergies and counter-actions) between steam and water systems could be very different. Other factors will also influence the approach that should be taken to the energy consumption of a process: the way in which the thermal energy is produced, and the relative importance of thermal and mechanical energy. It is therefore recommended that the methodology be validated and illustrated in different industrial contexts.

Acknowledgements

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