# A NEW METHODOLOGY FOR THE IMPLEMENTATION OF TRIGENERATION IN INDUSTRY: APPLICATION TO THE KRAFT PROCESS

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## ABSTRACT

A systematic methodology is proposed to assist in the positioning of trigeneration units in industrial processes. It provides guidelines for the selection of heat sources and sinks which maximize the benefit derived from the trigeneration while respecting the process constraints and the operating requirements of the turbine and heat pump. The trigeneration unit consists of a steam turbine, a power generator and an absorption heat pump driven by the steam discharge from the turbine. The methodology is applied to the implementation of a unit in a kraft pulping process. It is first illustrated by considering the two components of the trigeneration individually. The retrofit implementation of a complete unit in the spent liquor concentration section of the process is then performed. It is shown that substantial energy gains could be made through the implementation of trigeneration.

***Keywords:*** Energy efficiency, trigeneration, cogeneration, absorption heat pumps, combined process and utility analysis, Pinch Analysis®, kraft pulping process

# 1. INTRODUCTION

In a context of volatile and rising energy costs, industries are implementing aggressive energy cost reduction programs. The pulp and paper (P&P) manufacturing industry which is characterized by a large energy demand in the form of electricity and heat for its pulping, drying, liquor concentration operations, as well as cooling, when intensive internal water reuse is practiced, has reduced its energy consumption by a large proportion over the last few decades (Labidi *et al*., 1999). Maximization of internal heat recovery by Pinch Analysis® is now routine practice (Rouzinou *et al.,* 2003; Savulescu *et al.*, 2005), many P&P mills have installed a cogeneration unit supplied by a biomass boiler fueled by bark and wood residues (Sundberg and Sjödin, 2003). More recently, the industry has become aware of the potential benefits that could be derived from the utilization of more advanced energy conversion technologies such as absorption heat pumps and trigeneration (Bakhtiari *et al.*, 2007; Costa *et al*., 2004).

Trigeneration consists of coupling a co-generator and a heat pump. The heat pump can be a conventional compression chiller driven by the electricity produced by the power generator (Colonna and Gabrielli, 2003). The exhaust heat from a gas turbine can also be used to drive an absorption cycle (Bassols *et al.*, 2002). However, a higher degree of integration is accomplished by coupling a steam turbine with an absorption heat transformer driven by the steam discharged from the turbine (Hernandez-Santoyo and Sanchez-Cifuentes, 2003). This type of system has found practical applications when power, heating and cooling are simultaneously required. Examples are heating and cooling of urban districts (Emho, 2003) or large facilities such as airports (Cardona *et al.,* 2006), the food processing industry (Linnhoff, 1993) and, the chemical and petrochemicals industries (Havelsky, 1999). It also has the advantage of being environmentally benign (Meunier, 2002) and of freeing most of the electricity produced by cogeneration for other more profitable uses.

In order to produce a maximum net benefit, the integration of a trigeneration unit in an industrial process must follow sound process integration practices. This work presents a systematic methodology to identify the optimum positioning of a steam turbine and an absorption heat pump (AHP) taking into account the constraints of the utility distribution network, of the process heat flow diagram and of the trigeneration components. The method is illustrated by retrofit examples of a turbine, an absorption heat pump and a complete unit in an actual kraft wood pulping process located in Eastern Canada.

## 2. REFERENCE KRAFT PROCESS

The kraft process 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 (Smook, 2002). The core of the kraft process is a chemical delignification step in which the individual cellulosic fibers are separated to form the pulp. A key characteristic of the process is that the spent delignification liquor (black liquor) is concentrated and burnt to utilize its energy content and recover the spent reactants which are regenerated. A simplified schematic of the complete kraft process is given in Figure 1.

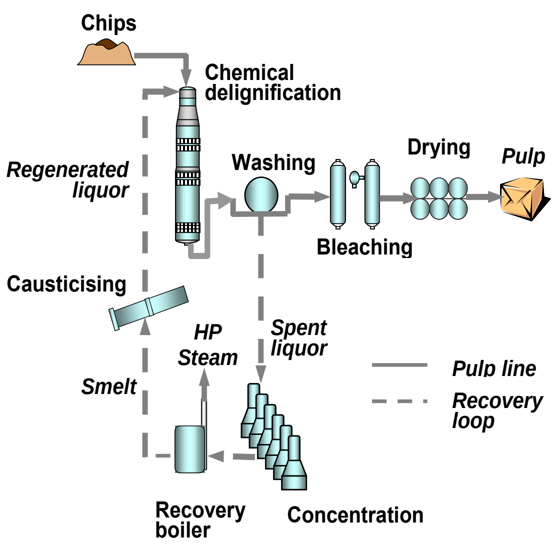


Figure 1. Schematic of kraft process

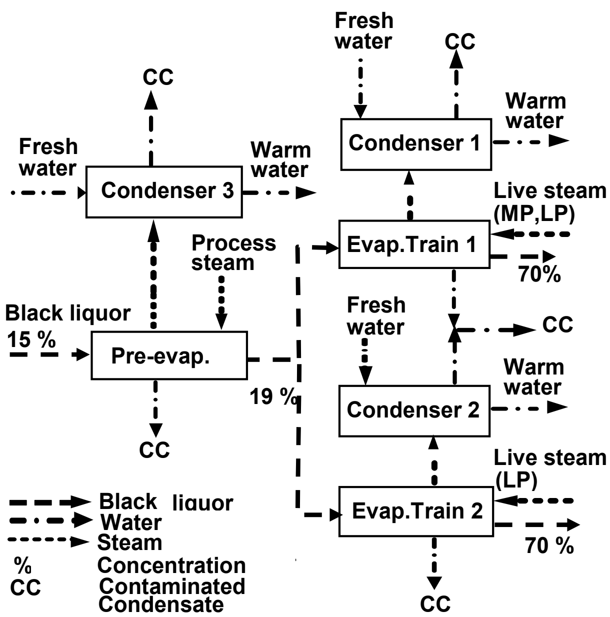


Figure 2. Simplified diagram of the concentration section

The methodology will be illustrated by the retrofit installation of a trigeneration unit in the black liquor (BL) concentration section of the mill (Figure 2). The BL from the washing section is sent to two pre-evaporators in series in which process-generated steam is condensed and the solids content of the BL increased from 15 to 19%. The still dilute liquor is divided into two streams sent to multi-effect counter-current evaporator trains of different configurations. Train 1 also incorporates a finishing concentrator and train 2 a pre-heater. Energy is supplied to the two trains by the utility system medium and low pressure steam (MP: P=965 kPa, T=179.5°C; LP: P=345 kPa, T=143.5°C), both obtained by de-pressurization of the high pressure steam (HP: P=3100 kPa; T=371°C) produced by the mill's power plant. The condensates from the BL and process streams contain volatile contaminants and are segregated from live steam condensates. The 3 condensers use fresh water which is pre-heated for later use in the process. The concentrated black liquor, at 70% solids content, is sent to the recovery boiler. The nominal operating conditions of the concentration section were taken from an existing simulation on CADSIM Plus, and are given in Table 1.

*Table 1: Evaporation unit energy requirements*

| | Tin (°C) | Tout (°C) | Q (MW) |
|---|---|---|---|
| **Heating demand** | | | |
| ***Pre-evaporators*** | | | |
| $BL_{Ev}$ 1 | 73 | 73 | 18.8 |
| $BL_{Ev}$ 2 | 62 | 62 | 25.9 |
| ***Train 1*** | | | |
| $BL_h$ | 113 | 122 | 0.7 |
| $BL_{Ev}$ | 122 | 122 | 10.7 |
| $BL_{sh}$ | 122 | 128 | 0.3 |
| $BL_h$ concentrator | 101 | 108 | 0.3 |
| $BL_{Ev}$ concentrator | 108 | 108 | 6.6 |
| $BL_{sh}$ concentrator | 108 | 127 | 0.5 |
| ***Train 2*** | | | |
| $BL_h$ | 90 | 98 | 0.5 |
| $BL_{Ev}$ | 98 | 99 | 10.1 |
| $BL_{sh}$ | 98 | 104 | 0.2 |
| $BL_h$ preheater | 104 | 113 | 0.3 |
| $BL_{Ev}$ preheater | 113 | 113 | 8.2 |
| $BL_{sh}$ preheater | 113 | 134 | 0.4 |
| CC segregation | 58 | 117 | 4.18 |
| **Steam production** | | | |
| Steam - HP | 106 | 371 | 37.4 |
| **Steam utilization** | | | |
| Steam - MP | 106 | 178.5 | 12.5 |
| Steam - LP | 106 | 143.5 | 22.8 |

| | Tin (°C) | Tout (°C) | Q (MW) |
|---|---|---|---|
| **Cooling demand** | | | |
| ***Pre -evaporators*** | | | |
| V to condenser 3 | 62 | 52 | 29.9 |
| CC condenser 3 | 52 | 30 | 1.2 |
| CC | 73 | 30 | 3.7 |
| Process steam 1 | 80 | 80 | 18.8 |
| Process steam 2 | 73 | 73 | 25.9 |
| ***Train 1*** | | | |
| V to condenser 1 | 76 | 76 | 12.2 |
| CC condenser 1 | 76 | 30 | 1 |
| CC | 86 | 30 | 2.6 |
| ***Train 2*** | | | |
| V to condenser 2 | 60 | 60 | 9.9 |
| CC condenser 2 | 60 | 30 | 0.5 |
| CC | 69 | 30 | 3.6 |
| V reused | 113 | 113 | 8.2 |
| **Cooling water utilization** | | | |
| ***Pre -evaporators*** | | | |
| FW condenser 3 | 57 | 4 | 29.9 |
| ***Train 1*** | | | |
| FW condenser 1 | 40 | 4 | 12.2 |
| ***Train 2*** | | | |
| FW condenser 2 | 40 | 4 | 9.9 |
| Condensate cooling | 30 | 4 | 12.6 |

Abbreviations: BL=Black liquor, h=heating, ev=evaporation, sh=superheating, CC=Contaminated condensate, V=Vapour, FW=Fresh water

## 3. TRIGENERATION & ABSORPTION HEAT PUMP

The diagram of the steam trigeneration unit that will be considered is shown in Figure 3. The turbine is driven by HP steam from the utility system of the mill. It delivers steam at a lower pressure, which is used in part in the process, and in part to drive the absorption heat pump (AHP). A schematic of the AHP coupled to the turbine is given in Figure 4. The steam from the turbine supplies the heat to the generator, $Q_G$. The heat duty to the evaporator is supplied by a low temperature process stream which must be heated, and the pump releases its useful heat from the condenser, $Q_c$, and the absorber, $Q_A$. Since $Q_c + Q_A$ is superior to $Q_G$ the AHP surrenders more heat to the process than it withdraws from the turbine steam output. Therefore the trigeneration unit reduces the net heat demand of the process, supplies electricity to the mill or the grid and, reduces the cooling demand. Critical operating parameters of the trigeneration unit are the pressure of the discharge steam and the choice of the process cold and hot streams connected to the heat pump. The purpose of the proposed methodology is to optimize those parameters within process and equipment constraints for maximum net benefit.

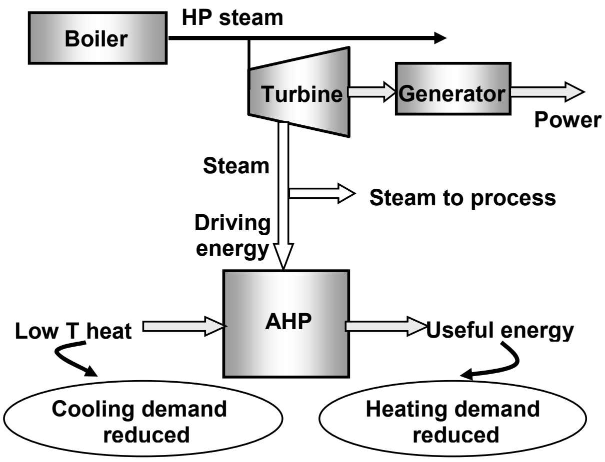


*Figure 3. Schematic of steam turbine and AHP trigeneration unit*

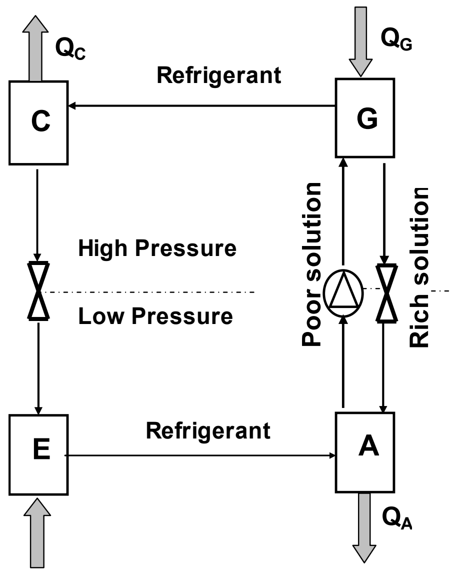


*Figure 4. Absorption heat pump*

## 4. METHODOLOGY

### 4.1 Overview

The methodology is summarized in the organigramme of Figure 5. In a preliminary phase, conventional Pinch Analysis® is used to perform the basic thermal analysis, i.e. process energy targets (maximum process heat recovery, cooling and heating requirements) using the composite curves and, utility levels targets (optimal heat and cold utility use) by means of the Grand Composite Curve (GCC).

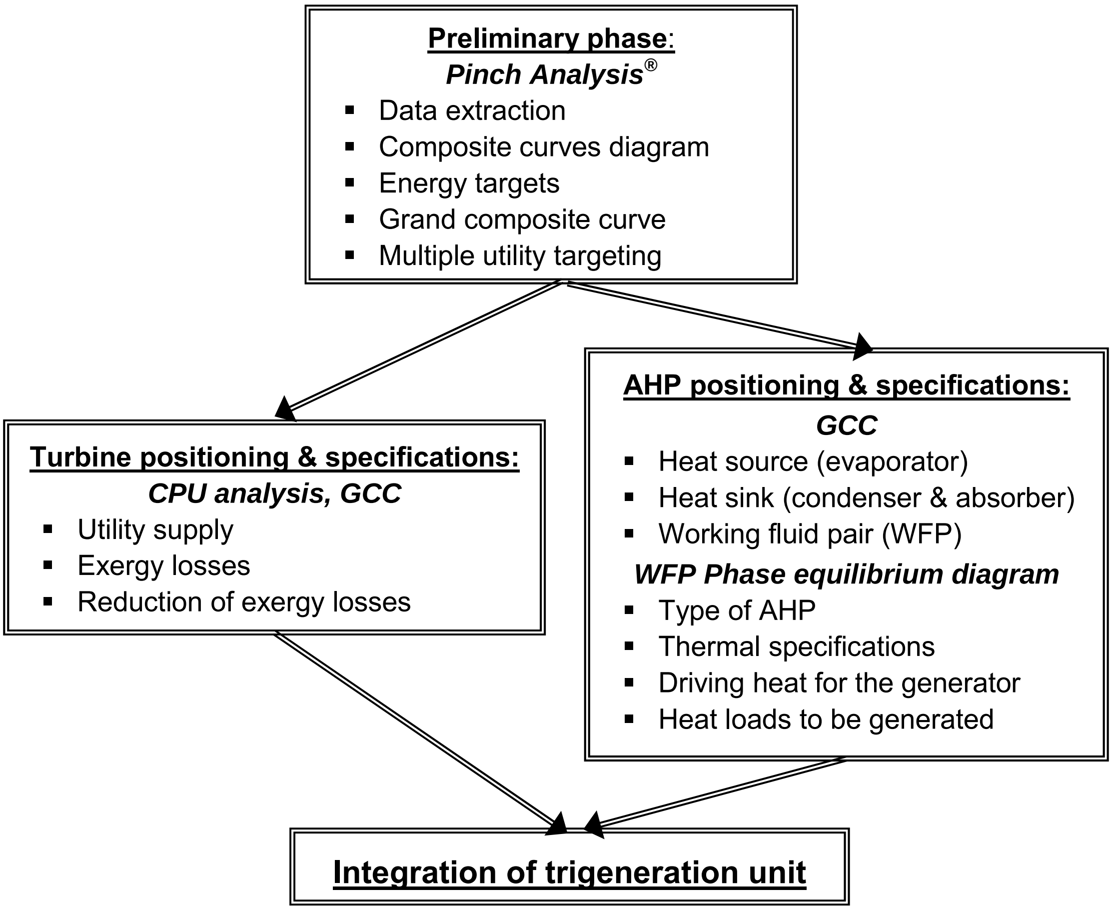


*Figure 5. Integration of trigeneration unit methodology*

The Combined Process and Utility (CPU) analysis is done to determine the appropriate positioning of a turbine and to reduce exergy looses in the energy production and supply chain. In order to specify the AHP, the GCC is first used to identify a heat source suitable for the evaporator and a heat sink for the condenser and absorber pair. The working fluid is tentatively chosen at this point and, using its phase equilibrium diagram, the type, configurations and full thermal specifications of the AHP are determined. If the results show that the AHP is technically feasible, the choice of working fluid pair is confirmed; otherwise the procedure is repeated with another pair. The final step consists of matching the quantity and pressure level of the steam discharged by the turbine to the AHP required driving energy. The net reduction in energy requirements and exergy losses can then be evaluated.

The principal tools utilized in the methodology are developed in the following sections using whenever possible the BL concentration process as illustrative material. Those tools are Pinch Analysis®, CPU analysis and phase equilibrium diagrams of the working fluid pairs.

### 4.2 Pinch Analysis®

Pinch Analysis® is a structured approach used to maximize internal heat recovery within a process and to minimize its need for hot and cold energy supplied by utilities. The principles and application have been described in a number of reference works and engineering manuals (Douglas, 1988; Linnhoff, 1993; Smith, 1995). It is well known that in order to ensure real net energy savings Pinch Analysis® must be applied to a whole process or even to a complete site. It was decided to limit the analysis to a process section for the sake of simplicity. This should not introduce major discrepancies since this section is almost energetically independent and that there are no process streams that can be substituted to utilities as heat sources.

The corner stone of Pinch Analysis® is the display in a temperature vs enthalpy diagram of all possible heat transfers within the process; it consists of the Hot Composite Curve (HCC) and the Cold Composite Curve (CCC) which respectively represent the heat availability and demand in the process. Figure 6a shows the composite curves diagram of the BL concentration section. The minimum temperature interval ($\Delta T_m$) for this process which is characterized by very low temperature approaches has been fixed at 5°C and the pinch point is 73.4°C. The diagram also shows the maximum possible internal heat recovery (54.7 MW) as well as the minimum heat requirement, MHR (34.3 MW), and the minimum cooling requirement, MCR (66.4 MW) which will still be needed by the process once internal heat recovery has been maximized. It is assumed in this study that this has been achieved. The purpose of the implementation of trigeneration is to actually reduce MHR and MCR.

The utilization of the various utilities available to satisfy the remaining heating and cooling demands is done by means of the Grand Composite Curve (Figure 6b). The GCC represents the net thermal requirements in successive temperature zones characterized by a specific set of hot and cold streams. In simple cases it can be graphically generated from the composite curves shifted so that they are in contact at the pinch point. The GCC is a plot of the enthalpy difference between the shifted curves as a function of the temperature and it is represented by a straight segment for each temperature zone. The possibility of heat recovery by exchange between process streams appears as so called “pockets” in the GCC. There are three pockets in the case studied (A,B,C); all other heat requirements must be satisfied by utilities. In the current process configuration MP and LP steam are used to supply the MHR (Figure 6b window) and fresh water is used in the cold side of the GCC.

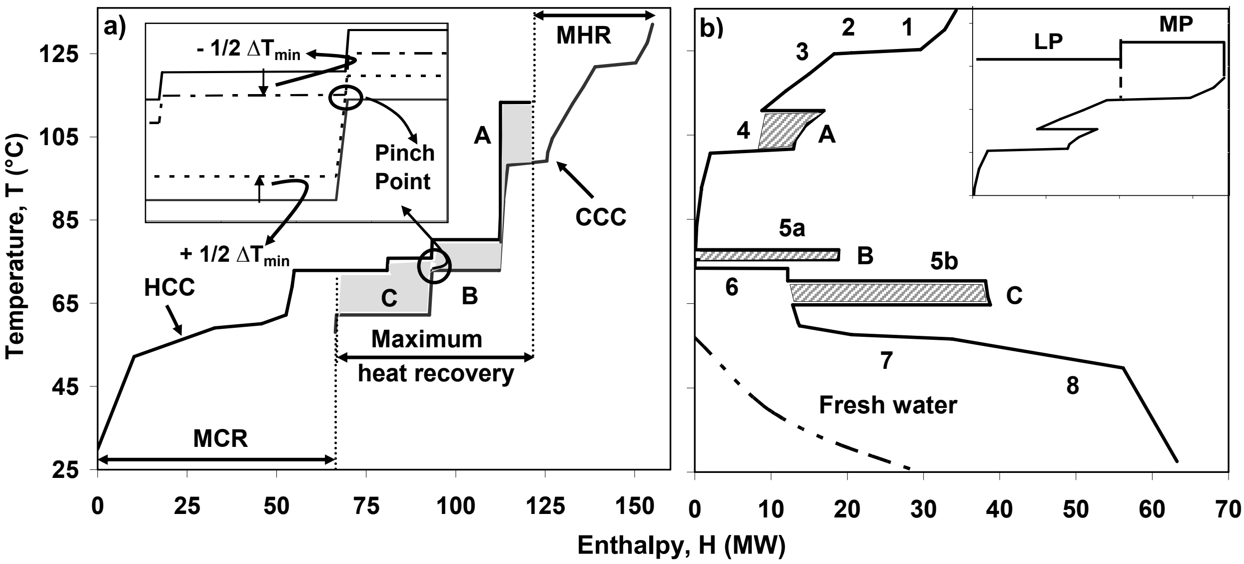


*Figure 6. a: Composite curves diagram; b: Grand Composite Curve and utilities. Legend: 1: Train 1; 2: Concentrator Train 1; 3: Pre-heater Train 2; 4: Train 2; 6a: Pre-evaporator 1; 6b: Pre-evaporator 2; 6: Condenser 1; 7: Condenser 2; 8: Condenser 3*

### 4.3. Combined process and utility analysis

Combined process and utility (CPU) analysis is used to enhance the efficiency of the production and supply of energy by the utilities system. An exploratory form of the CPU analysis called dual representation was developed by Brown *et al*. (2005) and Mateos *et al*. (2007). It will be used in this study to guide the insertion of a steam turbine in the utilities distribution network. This is illustrated in the Carnot efficiency vs thermal energy diagram of Figure 7. The Carnot efficiency is defined as $1\text{-}T_0/T$ where $T_0$ is the temperature of a reference state. The sequence of processes by which the heat is produced and supplied to the end receptor is represented in this diagram. First, the heat is made available by producing HP steam from clean condensates in the recovery boiler. The energy is delivered to the equipment as MP and LP steam obtained by depressurization of the HP steam. Finally, the heat is transferred to various process streams which are heated or vaporized. This last level of the cascade of operations is represented by the section of the GCC above the pinch point. Below the pinch point, energy is withdrawn from process streams which are cooled or condensed by cooling water. A fourth level could be added on the hot side of the GCC to represent the conversion of energy by combustion of concentrated black liquor in the recovery boiler. This very important step which does affect the overall efficiency of the energy production and, the overall energy cost needed not be taken into account in this study.

The shaded areas between the curves represent the exergy lost of each stage of the sequence. Area I between HP steam and the lower levels steam streams (MP and LP) represents the exergy lost by throttling-down and de-superheating the HP steam. Area II represents the exergy lost by irreversibly transferring heat from LP and MP steam to the process streams. On the cold side of the GCC, the exergy losses represented by area III are due to the irreversible heat transfer from process streams to cooling water.

Very significant exergy losses occur in the current process configuration. They are due to the irreversibilities in the pressure release step and in the various heat exchanges. The later are amplified by unnecessarily large ΔT between process streams and LP or MP steam. The losses can be reduced for example by installing a cogeneration unit between the HP and LP steam lines and by limiting the use of MP steam as heat source in the BL concentration section only where required to maintain an adequate ΔT. These possibilities are examined in the example. There are also large heat losses on the cold side of the GCC because of a very poor match between the cooling water temperature and that of the process streams; there are simple remedies to this situation, however, this study considers improvements achievable only with regard to the hot utilities production and utilization.

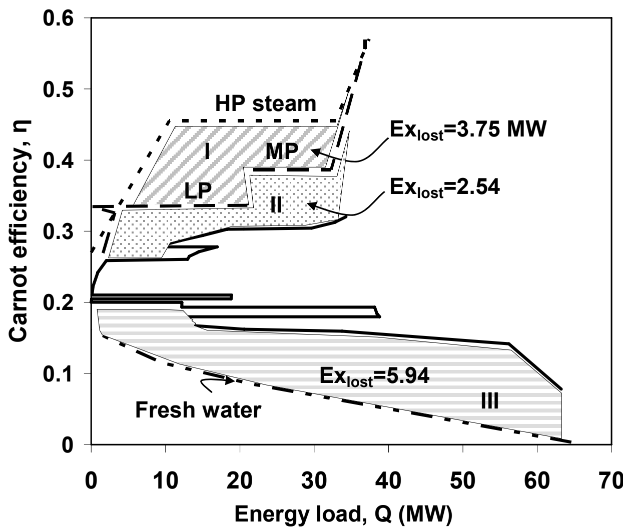


Figure 7. CPU analysis of the black liquor concentration section

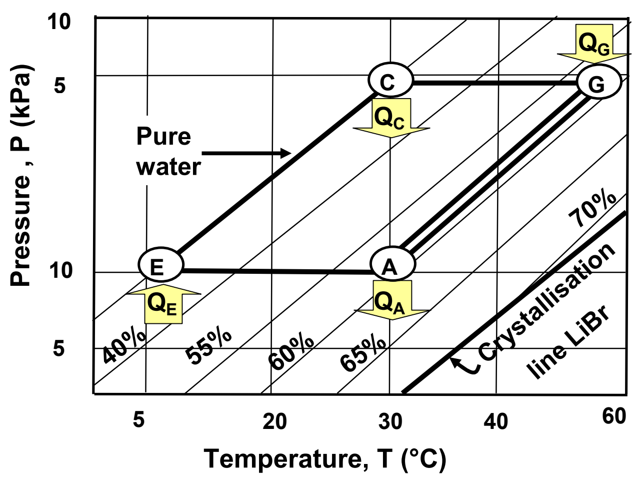


Figure 8. Specification of a LiBr/$H_2O$ AHP using the phase equilibrium diagram

## 4.4. Positioning and specification of an AHP

The proper positioning of a vapour recompression heat pump (VRHP) has been well documented (Linnhoff *et al.*, 1993); in order to produce net energy gains, evaporator and condenser must straddle the pinch point. In the case of an AHP, the matter is somewhat more delicate because there are three thermal connections between pump and process and the temperature level at which the heat exchanges are done are constrained by the pump operating conditions. Process and AHP limitations must be considered as a whole, the former by Pinch Analysis®, the latter by means of the phase equilibrium diagram of the working fluid pair. Bakhtiari *et al.* (2007) have shown how to generalize from VRHP to AHP, when positioning a heat pump on the composite curves diagram. Alternatively, the GCC can be used as was done in this work. The first step consists in selecting a hot stream below the pinch point to supply the energy requirement of the evaporator and a cold stream above the pinch point as receptor of the heat released in the condenser and generator pair. It is unlikely that two streams would match exactly the two heat requirements; one of them will limit the power of the heat pump. The next step of the procedure consists in determining the feasibility of an AHP with the source and sink identified at this point. The temperature approach in all AHP heat exchangers must first be fixed. The phase equilibrium diagram of the working fluid pair (Figure 8) is then employed to determine the temperature span between the evaporation and condensation, and the temperature of the generator in order to choose the appropriate type of AHP. A hot stream at a high enough temperature or a hot utility is used to supply the driving heat to the generator, $Q_G$. The controlling stream determines the total amount of useful heat to be produced by the AHP, $Q_A + Q_C$. The COP can be estimated by means of the empirical correlation proposed by Alefeld (1983) and it is used to determine the heat loads, taking into account the basic relation $Q_G = Q_A + Q_C - Q_E$.

## 5. EXAMPLES

### 5.1. Integration of a turbine

To reduce exergy losses in the depressurisation step between HP steam and the MP and LP pressure levels, a back-pressure steam turbine can be inserted between the HP and LP lines as shown on Figure 9. It is also advantageous to reduce the ΔT in heat exchangers by substituting at least part of the MP steam currently used by LP steam. The turbine is dimensioned to produce the totality of the

LP steam supplied to the BL concentration section in the new configuration. Part of the heat requirement of the process will still be supplied as MP steam (4.4 MW) obtained by HP steam depressurisation; the energy supplied by LP steam is therefore 31.0 MW. The turbine will consume 35.45 MW as HP steam of which 4.45 MW are converted into electricity. For a typical isentropic efficiency of 0.72, the exergy losses in the turbine are 1.3 MW. The reductions of exergy losses by elimination of a depressurisation step and by lower ΔT in some heat exchangers are 3.75 and 0.4 MW respectively. The net reduction of exergy losses is 3.17 MW or 50% of current level.

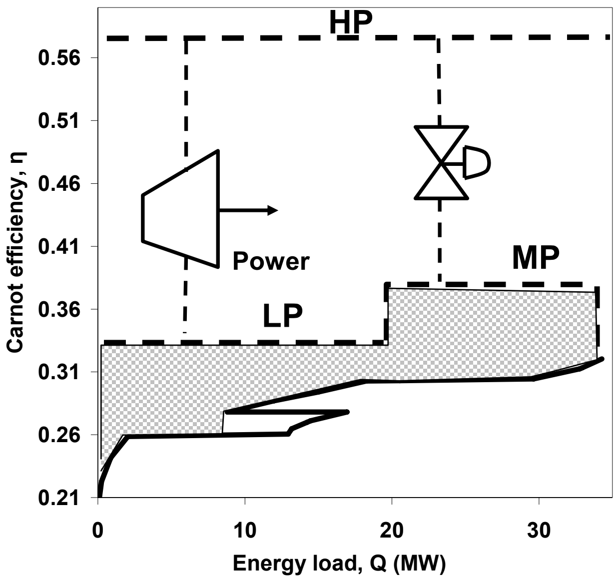


*Figure 9. Turbine integration*

The turbine is dimensioned to supply the full LP steam required in the concentration section (31.0 MW). The former exergy losses due to the depressurisation (3.75 MW) are eliminated and the losses by heat exchange are reduced by 0.4 MW. For a typical isentropic efficiency of 0.72, the exergy losses in the turbine are 1.3 MW. The net reduction of exergy losses is 3.17 MW or 50% of current level. In addition, 4.5 MW of electricity are produced.

## 5.2. Integration of an absorption heat pump

The positioning of stand-alone absorption heat pump is done using the guidelines given in section 4.4. The two streams selected are, the contaminated vapour from train 1 which is sent to condenser 1 (Figure 2) as low temperature heat source and, the BL pre-heated and evaporated in train 2 as heat sink. The maximum heat loads available from those two streams are respectively 12.2 MW at T=76°C and 8.9 MW from 104 to 134°C (Figure 10a). The temperature approach in all AHP heat exchangers is fixed at 10°C. The evaporator will operate at about 65°C and the condenser and absorber pair from 115 to 145°C. As indicated on Figure 10b, this temperature range can be implemented in a single effect AHP working with the LiBr/$H_2O$ working pair. The two pressure zones of the AHP will be at 15 kPa and 170 kPa and the generator temperature will be 205°C. Since there is no hot stream at the required temperature in the BL concentration section, MP steam will be used to supply the generator load. The controlling stream is the BL to the pre-heater which limits the total amount of useful heat, $Q_A + Q_C$ at 8.9 MW. To complete the AHP specifications the COP was estimated at 1.55 and used to compute $Q_G$ (5.56 MW) and $Q_E$ (3.24 MW). In summary the implementation of an AHP in the BL concentration section would reduce the steam demand by 3.24 MW (10% of MHR) and the cooling demand by the same amount (5% of MCR) and consumes 5.56 MW of HP steam.

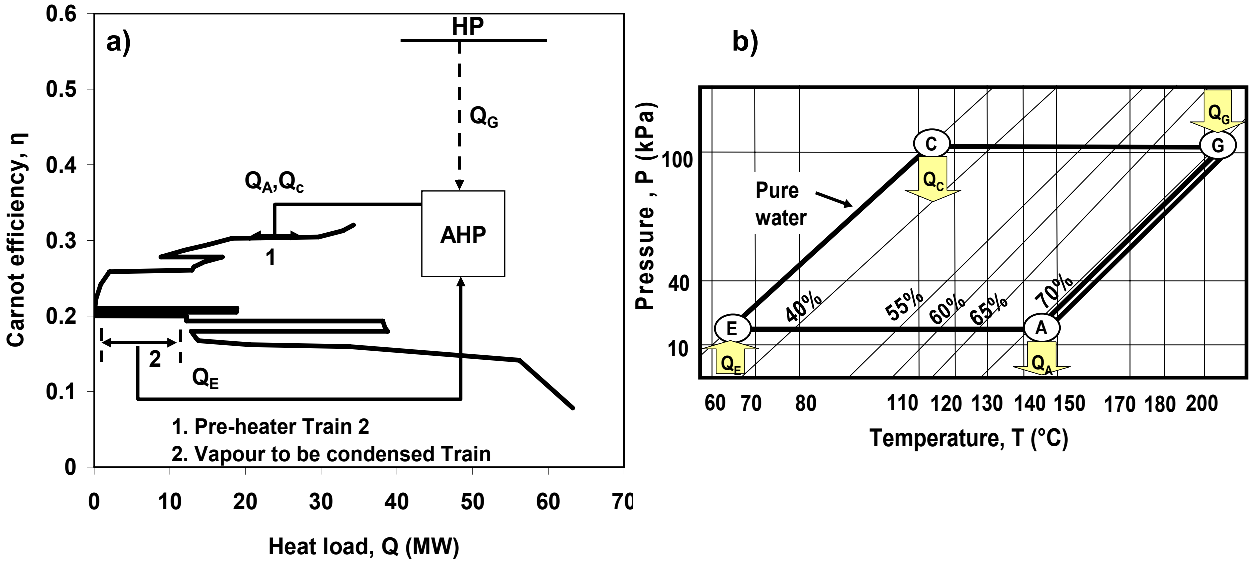


*Figure 10. Implementation of AHP in the BL concentration section; a: Selection of heat source and sink; b: Thermal specifications of AHP*

## 5.3 Trigeneration implementation

The trigeneration unit is designed to supply the full LP (31.0 MW) and MP (4.4 MW) steam required in the concentration section after MP usage had been minimized (Figure 11a). The turbine is driven by LP steam from the utility network and discharges steam at the MP level which is used in part to supply the generator of the AHP and in part the heat requirement of the BL concentration section in the higher temperature range. The AHP receives low temperature heat, $Q_E$, from the condenser as in the previous example but it liberates its useful heat ($Q_C$+$Q_A$) as LP steam which supplies the corresponding requirement of the process. In will again be a single effect LiBr/$H_2O$ pump (Figure 11b). The maximum heat loads are 12.2 MW at T=76°C for low temperature heat and 31.0 MW at T=143.5°C for the heat receptor. The high and low pressure zones of the AHP will be at 15 kPa and 400 kPa respectively and the generator temperature 225°C. The turbine will consume 26.6 MW as HP steam, delivering: 24.4 MW as MP steam (T=245°C) and 2.2 MW of electricity. Using an estimated COP of 1.55 the heat loads were computed: $Q_E$ = 11 MW, $Q_G$ = 20 MW. In summary the trigeneration unit will reduce the steam demand by 11 MW (29%) and the cooling demand by 11 MW (17%), with a production of 2.2 MW of electricity, while also supplying the additional MP steam still required by the process (4.4 MW). The exergy losses are simultaneously reduced by 38% and 32% on the hot and cold side of the GCC, respectively.

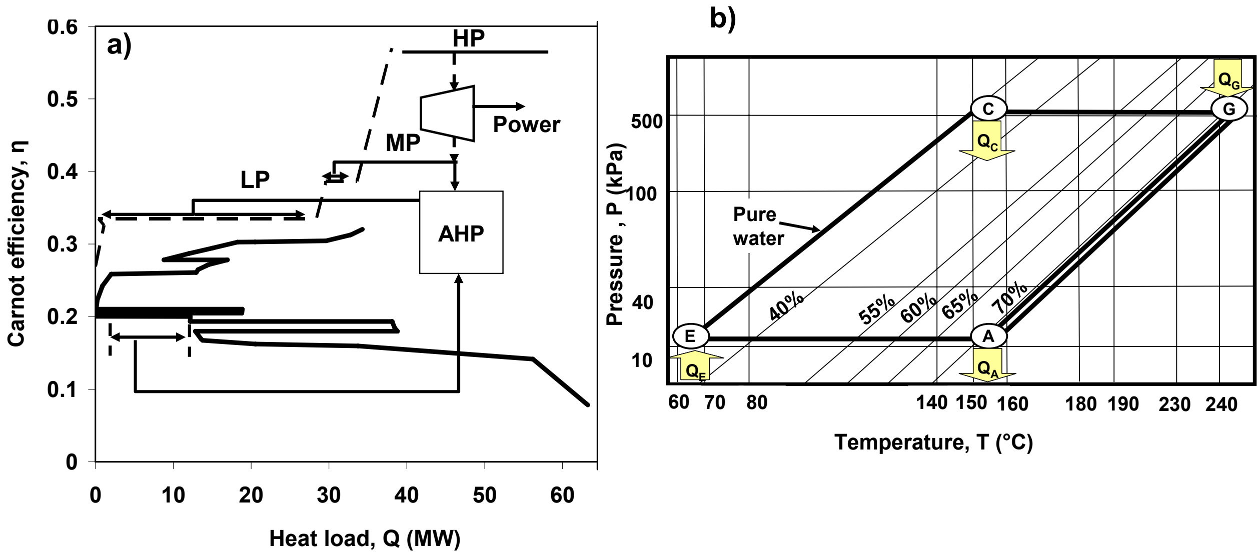


*Figure 11. Implementation of trigeneration unit in the process; a: Selection of heat source and sink; b: Thermal specifications of AHP*

## 6. CONCLUSION

A new methodology for the implementation of trigeneration in industrial processes has been developed. It was validated by a case study based on a kraft BL concentration process. The methodology identifies the optimum utility levels to maximize the power obtained from the turbine, and considers thermal and technical limitations for the positioning of the AHP. By taking into account possibilities and constraints from the process and, the utilities production and distribution system it is possible to ensure significant net gain in process energy efficiency by reducing heating and cooling requirements. The implementation in the process of a trigeneration unit consisting of a back-pressure steam turbine coupled to a LiBr/$H_2O$ AHP could reduce the cooling requirement by 11 MW (17 %) and the HP steam production by 11 MW (29%) while producing 2.2 MW of electrical power.

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