Energy study of tissue machines

A computer simulated machine and an existing mill

Master's Thesis within the Sustainable Energy Systems programme

CHARLOTTE LUNDIN

Department of Energy and Environment
Division of Heat and Power Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011

MASTER'S THESIS

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Cover:

Chalmers Reproservice
Göteborg, Sweden 2011

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ABSTRACT

In a world where global warming and environmental issues are becoming more relevant questions regarding the use of energy are becoming more important. Metso Paper Karlstad and Metsä Tissue are among many companies striving towards increasing the energy efficiency of their tissue paper machines. This was the objective of this Master's Thesis; to perform an energy study with the tool named pinch analysis to investigate potential energy efficiency improvements of tissue paper machines. Pinch analysis indentifies potential reduction in external hot and cold utilities and also the potential in increased energy efficiency through process integration.

The study was performed on an existing mill; Katrinefors mill, a computer simulated machine including only the Yankee hood and also the same computer simulated Yankee hood in a scaled model of the Katrinefors mill. A separate pinch analysis was performed on the three machines. The results showed potential reduction in utilities for all three machines; 17% for the Katrinefors mill, 21,5% for the computer simulated Yankee hood and 21% for the computer simulated Yankee hood in a scaled model of the Katrinefors mill.

In this work retrofits are also proposed which presents alternatives on how to reduce the utility demand. Other indications, not originating directly from the pinch analysis were also taken into consideration in the retrofit that can contribute to a reduced utility demand. These were mainly potential process integration possibilities which implied integrations that would increase the energy efficiency of the machine. Two possibilities were visible and the most important one, which was present for all three machines, implied that parts of the steam used inside the Yankee cylinder could be generated with the moist air extracted from the Yankee hood. Further cooling and condensing the moist air contributed to the increased energy efficiency since the heat available was utilised to a greater extent.

For the suggested retrofits the amount of energy saved for the Katrinefors mill is 182 kWh per tonne tissue paper, 270 for the Yankee hood and the same number for the computer simulated Yankee hood in a scaled model of the Katrinefors mill. There are two main benefits for the suggested retrofit; first and foremost the system would become more energy efficient since the energy available would be utilized more effectively through further condensation and cooling of the moist air. Secondly the demand for hot utilities would be decreased as part of the steam could potentially be generated by the moist air stream.

Key words: Paper machine model, Katrinefors mill, Pinch analysis, Energy efficiency

Energistudie av mjukpappersmaskiner

En datasimulerad maskin och en existerande maskin
Examensarbete inom master programmet *Sustainable Energy Systems*
CHARLOTTE LUNDIN
Institutionen för Energi och Miljö
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Chalmers tekniska högskola

SAMMANFATTNING

I en värld där global uppvärmning och miljöproblematiken blir allt mer relevant kommer frågor kring energianvändningen upp till ytan. Metso Paper Karlstad och Metsä Tissue är två av många företag som strävar efter att öka energieffektiviteten, i deras fall på sina mjukpappersmaskiner. Syftet med detta examensarbete var att undersöka potentiella förbättringar för att öka energieffektiviteten hos mjukpappersmaskiner med hjälp av verktyget pinchanalys. Med pinchanalys identifieras potentialen för en reduktion av behovet av extern värme och kyla samt ökad energieffektivisering genom att finna värmeintegreringsmöjligheter i en process.

Arbetet utfördes på en existerande maskin; Katrinefors bruk, en datorsimulerad maskin som endast inkluderar Yankee kåpan samt samma datorsimulerade modell tillsammans med en skalad modell av Katrinefors bruks maskin. En pinchanalys genomfördes på alla tre maskiner. Resultatet visade på att behovet för extern värme kan potentiellt bli reducerat med 17 % för Katrinefors bruket, 22 % för Yankee kåpan och 21 % för den datorsimulerade och skalade Katrinefors modellen.

I detta arbete föreslås även alternativ för hur behovet av extern värme kan minskas. Andra indikationer, som inte uppkommit genom pinchanalysen, togs också i beaktande i förbättringsförslagen som kunde bidra till ett minskat behov. De främsta indikationerna var de integreringsmöjligheter som både den datorsimulerade Yankee kåpan och Katrinefors bruket uppvisade. En av dessa antydde att den fuktiga luften som lämnar den våta änden av Yankee kåpan kan användas för att generera delar av den ånga som används i Yankee cylindern under torkningsprocessen. Genom att ytterligare kyla och kondensera den fuktiga luften bidrar till en ökad energieffektivitet hos maskinen då den tillgängliga värmen utnyttjas i större utsträckning.

Genom de förbättringsförslag som föreslagits kan man spara 182 kWh per ton producerad mjukpapper för Katrinefors bruket, 270 för den datorsimulerade Yankee kåpan samt den datorsimulerade Yankee kåpan skalad enligt Katrinefors bruket. För förbättringsförslagen finns två huvudsakliga fördelar; systemet blir mer energieffektivt då den tillgängliga värmen i den fuktiga luften utnyttjas i högre grad. För det andra kan behovet av externa värmekällor minskas genom att generera delar av ångan med hjälp av den fuktiga luften som finns tillgänglig i systemet.

Nyckelord: Poppermaskinsmodell, Katrinefors, Pinchanalys, Energieffektivitet

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Preface

In this Master's Thesis, an energy study comparing a computer simulated tissue paper machine and an existing mill have been performed in order to investigate whether the energy efficiency of the two machines could be increased. The existing mill is located in Mariestad, Sweden and the computer simulated machine is a standardized DCT 200TS tissue machine. The project has been carried out in cooperation with Metso Tissue Karlstad AB, Metsä Tissue and the Division of Heat and Power at Chalmers University of Technology.

I would like to thank my supervisor Mathias Gourdon at Chalmers University of Technology, Division of Heat and Power Technology together with my supervisors Joakim Aronson at Metso Paper Karlstad and Elin Petterson at Metsä Tissue for their time spent on this project as well as their valuable help.

Göteborg, October 2011

Charlotte Lundin

Notations

Abbreviations

AC	Air to the ceiling
CC	Composition curve
C-KKAB	Condensate to KKAB
CWC	Cooling water condenser
DW	Deinking water
FA	Fresh air
FWQGV	Fresh water to heat exchanger QGV
FW-WT	Fresh water white water tank
GCC	Grand composite curve
HEX	Heat exchanger
LPG	Liquid Petroleum Gas
MA	Moist air from the Yankee hood
PM35	Paper machine 35
RV	Room ventilation
SEK	Swedish crowns
ST	Steam
STC	Steam for the condenser
STLPG	Steam for the LPG evaporation
VP	Vacuum pump
WE	Wire evacuation
WS	Water scrubber
WW	Waste water

Symbols

$A_{heat\ exchanger}$	Heat exchanger area
bar(g)	Gauge pressure; pressure above ambient pressure
C	Inside battery limits cost
$C_{e,}$	Equipment cost
$\dot{m}$	Mass flow
ΔT_{lm}	Logarithmic mean temperature difference
ΔT_{min}	Minimum temperature difference
T	Temperature

Q	Load
U	Overall heat transfer coefficient

1 Introduction

Environmental issues such as global warming are becoming more relevant in a world with increasing population and use of energy. Questions that are brought to the surface are how the future energy demand is going to be met. In addition, the development of the fuel prices and scarcity of fuels need to be taken into account. Parts of the industrial sector are rather energy intense and are in the need to review its energy consumption. In order to save money and also spare the environment, the industries need to improve their energy efficiency.

In 2009 the total energy consumption for the Swedish industry was 156 TWh. The pulp and paper industry was by far the most energy consuming and accounted for roughly 47 percent. The energy composition consisted of approximately 64 percent bio fuels and biomass, 30 percent electrical energy and 6 percent fossil fuels (Industrins årliga energianvändning 2009, 2011).

Many industries and companies are striving at becoming as energy efficient as possible. It is first and foremost beneficial from the economic perspective. With a reduced external energy requirement the costs would be reduced as the internal energy is utilized to a greater extent. Other benefits include additional revenues if surplus of heat were to be used externally for example in a potential district heating system in a nearby city or village. Depending on the quality of the heat it could also be used to produce electricity or be used in another part of the process. From an environmental point of view the emissions of carbon dioxide and other environmentally harmful emission could potentially also be reduced.

Metso Tissue Karlstad AB and Metsä Tissue AB are among many companies striving to enhance their energy efficiency. This study will investigate if the companies' tissue machines have the potential to be improved from an energy perspective.

1.1 Purpose

The purpose of this master's thesis is to perform a study where the energy consumption connected to the tissue production is analyzed with the help of pinch analysis. Pinch analysis identifies the theoretical potential for energy savings and improved energy efficiency by means of reducing the demand of external cooling and heating utility through process integration. Two tissues machines are included in the study; a standardized computer simulated machine and an existing machine. The two are compared in different aspects such as potential improvements and whether the improvements are general or specific. Suggested results regarding possible investments and rearrangements are evaluated economically in order to explore the feasibility. There could be other substantial economical differences between the two compared since Metso Paper Karlstad AB sell entire machines and the result may affect the offer machines.

The computer simulated machine is based on a standard DTC 200TS machine produced by Metso Paper Karlstad AB. An existing machine located in Mariestad, Metsä Tissue AB Katrinefors mill is compared with the simulated machine.

1.2 Limitations

Metso Paper Karlstad AB is a company that provides services within the tissue production industry. The services range from upgrading and evaluating paper machines to offer entire machines. The company does not have any own production of tissue paper but uses a computer simulated machine to simulate the offered machines. Metsä Tissue AB, Katrinefors mill on the other hand produces different types of tissue paper without having the pulp production on site. The pulp production will not be included in this master's thesis.

Only one existing tissue machine will be compared with the results from the pinch analysis based on the computer simulated machine. Since the thesis is performed in 20 weeks this is what is suitable within the time frame.

For both the computer simulated machine and the Katrinefors mill the preparation, forming and pressing is not included in the study. However, white water is used in these processes and considered as a stream in the study, though what it is used for is not included.

1.3 Method

The method involves a literature study on pinch analysis and the general method for tissue production. Gathering and processing of data from both the computer simulated machine and existing machine is also included. A simulation program developed by Metso, Italy and operating in Microsoft Office Excel 2007 is used to simulate the drying process in the Yankee hood and cylinder. When all components of the processes are known, the streams that are relevant for the energy study are identified. Three pinch analyses are performed; one for the Katrinefors mill, one for the computer simulated machine and one combining both, that is the simulated Yankee hood in a scaled model of the Katrinefors mill. The results show the potential energy savings within the process. A description of pinch analysis follows in the next section. Potential investments or rearrangements are suggested based on the analysis and economically evaluated regarding payback period, annual savings and investment costs.

2 Methodology

Pinch analysis is a useful tool for performing an energy analysis of a complex process within an industrial system with numerous of units and streams. The result identifies the theoretical reduction of external hot and cold utilities and therefore also the potential increase in energy efficiency through process integration.

2.1 Pinch analysis

Initially all streams in the process are identified, a stream is defined as a flow which requires heating or cooling. In pinch analysis two types of streams are present; cold and hot. A cold stream requires heating and a hot stream requires cooling. The loads, total heat or cold content, of the streams within the temperature range of the process is calculated and presented in a composite curve (CC). The overlap between the cold and hot composite curves demonstrate the potential heat recovery in the process. While the non overlapping parts demonstrate the external heating and cooling demand. See Figure 1 for an example of a composite curve (Kemp, 2007).

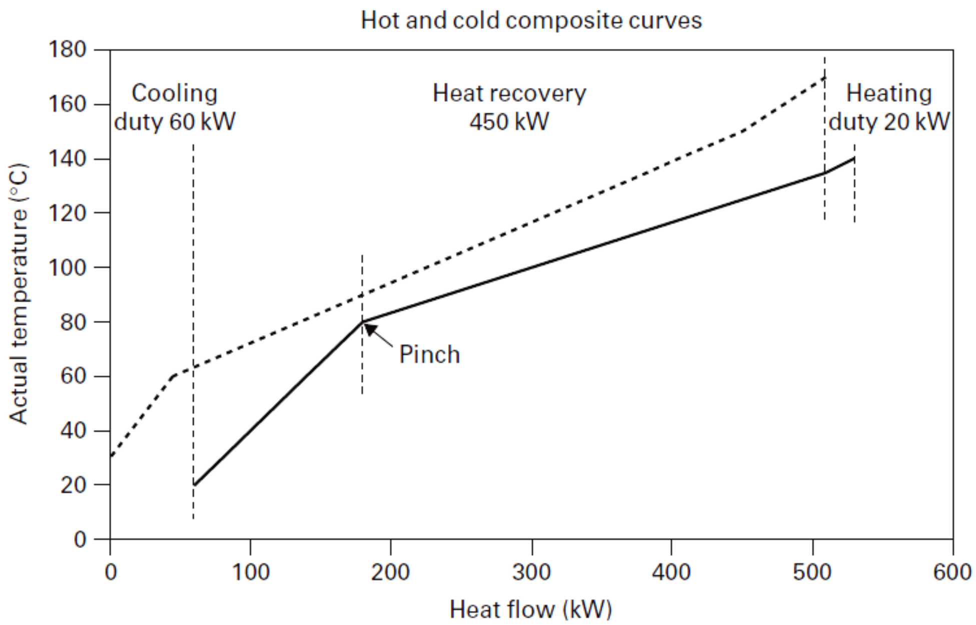

Figure 1 Composite curve (CC) (Kemp, 2007).

An acceptable minimum temperature difference, ΔT_{min}, for the heat exchangers is selected in order to determine the pinch point. The pinch point defines the minimum driving force in the heat exchanger. With a selected ΔT_{min} the potential heat recovery and the minimum external heating and cooling demand can be determined from the composite curve. Choosing a suitable ΔT_{min} is a balance between the capital costs of the heat exchanger and the cost for external utilities. A high ΔT_{min} will give small heat exchanger areas and thus low capital costs. The demand for external utilities will, however, be large thus leading to high energy costs. The same principle applies for the opposite (Kemp, 2007).

The area above the pinch has a deficit of heat and the area below a surplus of heat, the heat flow through the pinch should ideally be zero. To minimize the demands for heating and cooling there are three golden rules which should not be violated i.e. pinch violation. These rules are:

- Do not use external heating below the pinch.
- Do not use external cooling above the pinch.
- Do not transfer heat through the pinch as that would be a violation of both the above.

A violation of these rules prevents the system from working with a minimum demand for external utilities. Because heating below the pinch leads to an increased demand for external cooling and cooling above the pinch leads to an increased heating demand. Transferring heat trough the pinch will increase the demand for both external heating and cooling (Kemp, 2007).

The grand composite curve (GCC) is another way to represent the hot and cold composite curves combined into one. Temperatures used are called shifted temperatures where the cold streams are subtracted with ½ ΔT_{min} and the hot streams added with ½ ΔT_{min}. The GCC shows where heating and cooling is needed and at what temperature. An example of a GCC is seen in Figure 2. A negative slope in the GCC represents a cooling demand and a positive slope a heat demand (Kemp, 2007).

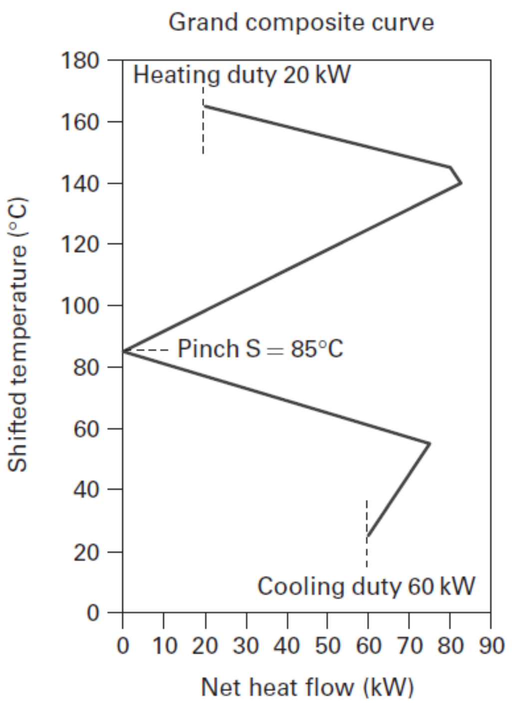

Figure 2 Grand composite curve (GCC) (Kemp, 2007).

Reducing the number of pinch violations in a heat exchanger network maximizes the internal energy recovery and reduces the demand for external utilities. It might, however, not be preferable to have a network that is maximized since it may require a large amount of investments, rearranging and new piping. This would normally be very costly and might not even be possible in an existing, complex network (Kemp, 2007).

Streams relevant for the pinch analysis were chosen from gathered data and available information. The assumptions and necessary estimations were used to calculate the temperature intervals and heat loads of the streams. Depending on the type of fluid in a heat exchanger the ΔT_{min} differ. ΔT_{min} and heat transfer coefficient used were taken from a previous study and can be seen in Table 1 (Axelsson, 2008). LPG is assumed to behave like water.

Table 1 Minimum temperature difference and heat transfer coefficients.

Fluid	ΔTmin/2 [K]	h [W/m²·K]
Clean water	2,5	3000
Contaminated water	3,5	1000
Live steam	0,5	8000
Contaminated steam	2	6000
Steam with NCG*	4	4000
Air	8	100

*Non-condensable gases

An add-in for Microsoft Office Excel named Pro-pi was used to execute the pinch analysis. The composite curve (CC) and grand composite curve (GCC) presented the amount of potential heat recovery and minimum heat and cooling demand. The pinch temperature was extracted as well. Pinch violations present were eliminated to possible extent and heat exchangers which did not cause pinch violations were considered for other arrangements to utilize the heat available to a greater extent.

2.2 Economics

2.2.1 Investment cost heat exchanger

The cost of a heat exchanger was estimated through the size of it, i.e. the area of the heat exchanger. Through Equation 2.1 the area is calculated, where Q is the total amount of heat transferred in kW, U is the overall heat transfer coefficient and ΔT_{lm} is the mean logarithmic temperature difference. ΔT_{lm} is calculated through Equation 2.2.

$$Q = U \cdot A_{heat\,exchanger} \cdot \Delta T_{lm} \qquad [kW] \qquad (2.1)$$

$$\Delta T_{lm} = \frac{\left(T_{hot,out} - T_{cold,in}\right) - \left(T_{hot,in} - T_{cold,out}\right)}{\ln\left(\frac{T_{hot,out} - T_{cold,in}}{T_{hot,in} - T_{cold,out}}\right)} \qquad [K] \tag{2.2}$$

New heat exchangers is assumed to be of a U-tube shell and tube kind and the cost for one made of cast-iron is estimated with Equation 2.3. *A* is the heat transferred area in m^2 and $C_{e,CS\ 2007}$ is the equipment cost for this type of heat exchanger with a US Gulf Coast basis in January 2007 (Sinnot & Towler, 2009).

$$C_{e,CS\,2007} = 24000 + 46 \cdot A_{heat\,exchanger}^{1,2} \qquad [\$] \tag{2.3}$$

In January 2007 the US Gulf Coast index was 509, 7 and in December 2010 it was 560, 3 (Chemical engineering, 2011). Giving the cost in 2010 according to Equation 2.4 to:

$$C_{e,CS} = C_{e,CS\,2007} \cdot \frac{CE\,index\,2010}{CE\,index\,2007} \qquad [\$] \tag{2.4}$$

In addition to the equipment cost, costs for installation, piping and so on where included in the total cost estimation. Equation 2.5 includes these factors which are presented in Table 2. *C* is the inside battery limits (ISBL) cost and $C_{e,\ CS}$ is the equipment cost for carbon steel (Sinnot & Towler, 2009).

$$C = C_{e,CS} \cdot \left(\left(1 + f_p\right) \cdot f_m + \left(f_{er} + f_{el} + f_i + f_c + f_s + f_l\right)\right) \qquad [\$] \tag{2.5}$$

Table 2 Typical factors for estimation of project fixed capital costs (Sinnot & Towler, 2009).

Type	**Constant**	**Value**
Piping	f_p	0.8
Material cost factor, Carbon steel	f_m	1
Equipment erection	f_{er}	0.3
Electrical	f_{el}	0.2
Instrumental and control	f_i	0.3
Civil	f_c	0.3
Structures and buildings	f_s	0.2
Lagging and paint	f_l	0.1

Finally the inside battery limit cost where calculated according to Equation 2.6.

$$C = C_{e,CS\,2007} \cdot \frac{CE\ index\ 2010}{CE\ index\ 2007} \cdot \left((1+f_p)\cdot f_m + \left(f_{er}+f_{el}+f_i+f_c+f_s+f_l\right)\right) \qquad [\$] \tag{2.6}$$

In August 2011 the average exchange rate for USD and SEK was 6, 39 SEK per USD (Dagens Industri , 2011). This was used to convert the final equipment cost into Swedish currency.

2.2.2 Annual savings

A steam price of 320 SEK per MWh has been assumed and is use for both the computer simulated machine and the Katrinefors mill. Steam is bought from KKAB and the condensate is sold back to the same company. The present utility is then calculated as the steam purchased subtracted with the condensate sold back to KKAB. This gives the annual saving calculated with Equation 2.8. For simplicity it is assumed that the tissue machine runs all year around.

$$Annual\ savings\left[\frac{SEK}{yr}\right] = \left(Present\ utility\,[MW] - New\ utility\,[MW]\right)\cdot 8760\left[\frac{h}{year}\right]\cdot 320\left[\frac{SEK}{MWh}\right] \tag{2.8}$$

2.2.3 Payback period

In order to calculate the time it takes to recover the investment payback period is used. This is done with the annual utility cost savings and the investment cost, see Equation 2.9.

$$Payback\ period = \frac{Investment\ cost\,[SEK]}{Annual\ savings\left[\frac{SEK}{year}\right]} \qquad [yr] \tag{2.9}$$

3 Tissue production

Paper used for wiping and hygiene purposes are called tissue paper and will have different properties depending on the use of raw material. The paper is built up as a sheet that may consist of two or three layers. It is crucial that the paper produced easily can be converted into goods that fulfill the consumers demand. Important features include quick absorption of liquid or ability to absorb a lot of liquid (Gavelin, Söder, & Jonsson, 1999).

3.1 Stock preparation

The stock consists of dried pulp and before it enters the tissue machine it needs to be pretreated. It is placed in a pulper and white water is added to regulate the concentration. White water is a re-circulated flow of water containing residues of fibers, but also other residues such as coloring and fillers. Chemicals can be added at this stage which gives the paper certain properties. Before the screening the stock enters another stage for regulation of the concentration. These steps can also be performed in batches. (Gavelin, Söder, & Jonsson, 1999)

Beating follows and aims at increasing the tensile strength of the paper and the softness of the fibers. The paper should also get a proper pasting for the Yankee cylinder, which is situated further on in the tissue production. Before entering the tissue machine the stock is screened additionally to ensure that the amount of contaminations is reduced. (Gavelin, Söder, & Jonsson, 1999)

3.2 Process

Initially the stock is injected and distributed evenly over a wire which serves as carrier during the forming and de-watering. The wire consists of a weaved cloth and runs through several dewatering steps. During the de-watering the paper is formed when a network of fibers is created, the water that drains off through the wire is the white water. As written above the white water is re-circulated and reused in the preparation of the stock. Further water is removed when the paper enters the press section and is nipped in one or two press roll nips. (Gavelin, Söder, & Jonsson, 1999)

The paper is then transferred to the Yankee dryer, a large cylinder made of cast-iron. Steam inside the cylinder dries the paper placed on the outside through the surface area. A casing covers the dryer where hot air is sprayed on the paper to enhance the drying. The Yankee dryer has three main purposes besides the actual drying. It transports the paper, deliver energy during the drying and serve as the base surface for the final step called the creping. (Gavelin, Söder, & Jonsson, 1999)

During the creping the paper is peeled off from the Yankee dryer. Creping give the paper lower density and creates crossing creases. The paper then becomes elastic and soft. The quality of the paper depends mainly on how the creping is performed; under wet or dry conditions (Gavelin, Söder, & Jonsson, 1999). An overview of the machine is seen in Figure 3.

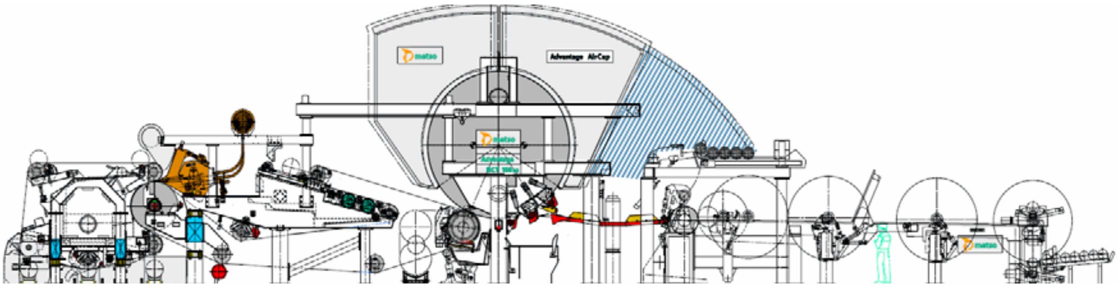

Figure 3 Overview of a tissue paper machine. (Metso Paper Karlstad AB, 2008)

On the left hand side, the stock is injected onto the wire, further passing the forming and press section. In the middle is the Yankee cylinder with the hood placed on top. The paper is transferred onto the cylinder on the left hand side, wet end and is creped off on the right hand side, dry end and rolled onto large paper rolls.

3.3 Drying section

The drying section i.e. the Yankee hood and cylinder, is the most energy intensive part. As written before, steam inside the Yankee cylinder dries the paper through the surface of the cylinder. Additional hot air dries the paper lying on the outer side of the cylinder. The hot utility demand consists of the energy essential for the drying section i.e. steam and fuel burnt to produce the hot air. Steam stands for roughly 27% and the hot air for 65 % of the total energy entering the drying section. The remaining 8 percent is from the paper web, fan motors and the infiltration of air (Metso Paper , 2010).

The two main energy flows exiting the drying section is the energy released to the atmosphere and the energy used in the surrounding ventilation. Further energy flows includes; process water, fresh air for the burners, heat losses and also the energy content of the paper leaving the dryer (Metso Paper , 2010).

4 Katrinefors mill, Metsä Tissue AB

The Katrinefors mill is situated in Mariestad, Sweden and is one of twelve production plants within Metsä Tissue AB. It provides tissue paper for hygiene use and also papers for baking and cooking. Metsä Tissue is a part of the Metsäliitto Group (Metsä Tissue, 2011). There are two tissue machines situated in the Katrinefors mill; PM35 and PM36. PM35 is the one that is studied in this master's thesis.

4.1 PM35

The PM35, paper machine 35, produces roughly 120 tons of tissue paper per day with a double press section and a Crescent former. LPG is burnt in two Maxon Ovenpak EB-6 burners to produce hot air used to dry the paper. The diameter of the Yankee cylinder is 5500 mm and has a steam pressure of 4.6 bar(g). For machine data and specifications see Appendix 1.

The entire process can be divided into four sections; Yankee hood, steam and condensate system, white water system and spray water system. The white water system and spray water system is not included in the study but briefly explained in Section 4.1.3. In Figure 4 an overview of the process can be seen. The blue lines are water or white water streams and the green line is an air stream; in this case a moist air stream. The dotted box on the right hand side of the Yankee hood represents the rest of the tissue machine such as forming and pressing which are not included.

Fresh water is taken from the largest lake in Sweden, Vänern and is heated in both the condenser and another heat exchangers named QGV. This fresh water is transferred to the warm water tank. The white water is heated in the scrubbers and used in the deinking process of news paper which is used as a raw material. When the temperature is too low in the hot water tank it is increased with an external source of steam. Parts of the white water are used in the spray system as well. The hot water and white water used in the spray system passes a micro flotation before it is sent back to the white water tank to avoid contamination. Hot and moist air extracted from the Yankee hood is used as a heat source for five different heat exchangers which are further explained in section 4.1.1.

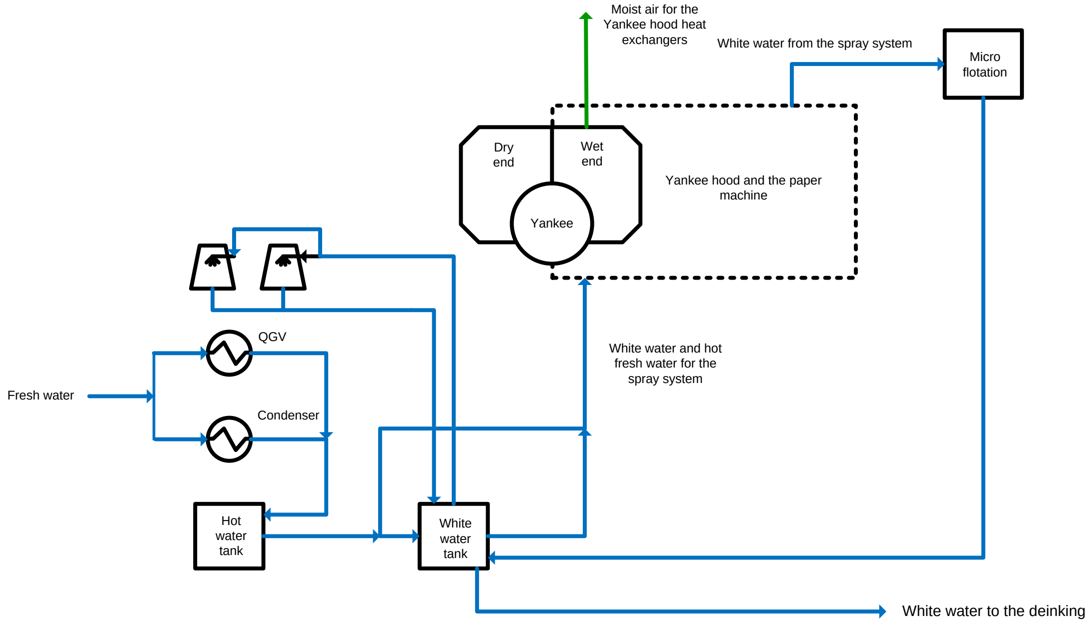

Figure 4 Overview of the paper machine.

4.1.1 Yankee hood

The stock is first prepared through dilution with white water. It is further passed through the forming and finally pressed in the press section before entering the Yankee section. The paper is transferred onto the Yankee cylinder at the wet end and dried with hot air from one of the burners. Halfway through the cylinder the paper is further dried on the dry end side with additional hot air from the other burner. The moisture content in the hot air exiting the Yankee hood is roughly 40% and is used in a series of heat exchangers to extract the heat available.

Fresh air needed for the LPG combustion is the first stream to be heated with the moist air. This temperature is preferably as high as possible in order to maximize the capacity of the burners. The second heat exchanger heats fresh water for the warm water tank. Before the fresh water enters the heat exchanger it is mixed with an external stream of water. This water comes from the ventilation of a nearby company's ventilation system and is not a continuous flow. It varies both in flow and temperature.

Further, a stream of fresh air is heated to 50°C and used for the ceiling in the machine hall in order to avoid condensation. The ventilation for the building is also heated to 20 $^{\circ}$C and is used during all year except during the summer. The final heat exchanger is the scrubbers which extracts heat by spraying white water through the moist air stream. See Figure 5.

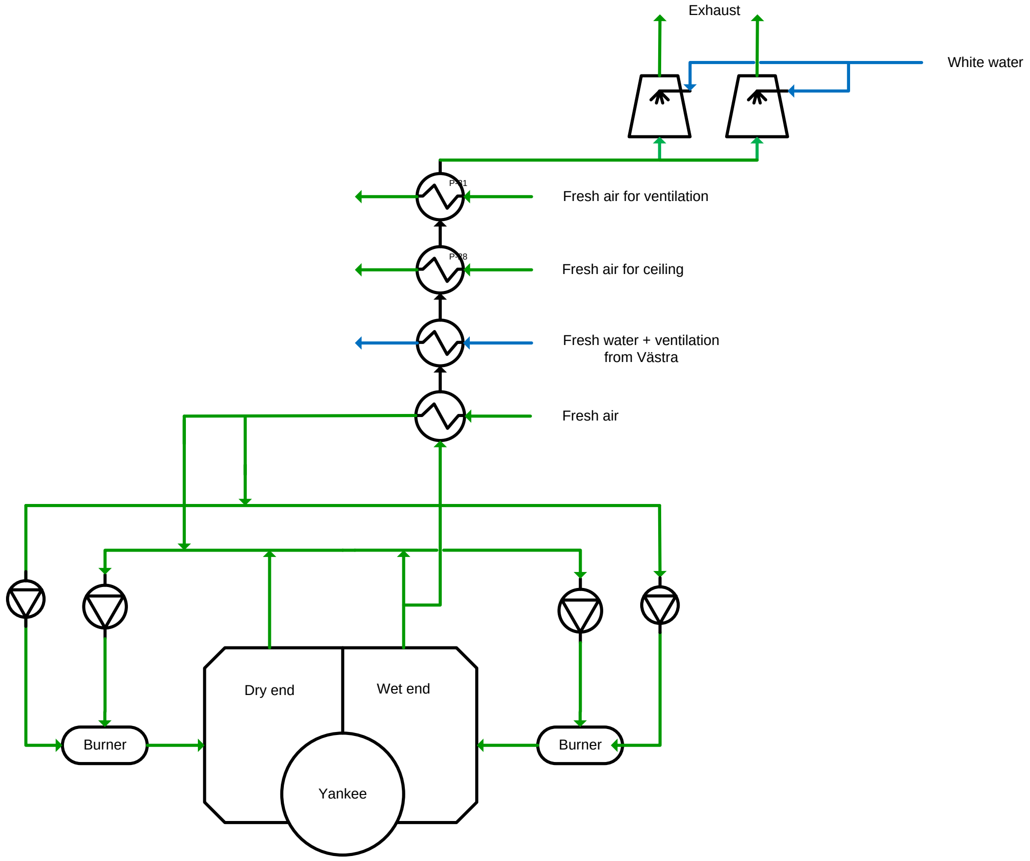

Figure 5 Yankee hood.

4.1.2 Steam- and condensate system

The steam passing through the Yankee cylinder dries the paper which is placed on the surface of the cylinder and is bought from KKAB, a combined heat and power plant. Part of the steam coming directly from KKAB is used to upgrade steam produced in a flash, the input to the flash is the condensate exiting the cylinder. A thermo compressor is used for this purpose which increases the flow of a low pressure steam source with a high pressure steam source and discharges the mixture at an intermediate pressure (Soucy & Timm, 2010). In this flash the pressure is decreased with 1 bar. Another flash produces additional steam from the same condensate and reduces the pressure down to 0.5 bar(g). A portion of the steam flashed in the second flash is used to evaporate LPG that is burnt in the burners. The rest of the steam is used in the condenser to heat fresh water for the warm water tank. The condensate from the two heat exchangers is mixed with condensate from the second flash and sold back to KKAB. A simplified figure can be seen in Figure 6; the red streams are steam, blue are water/condensate and the black one is LPG:

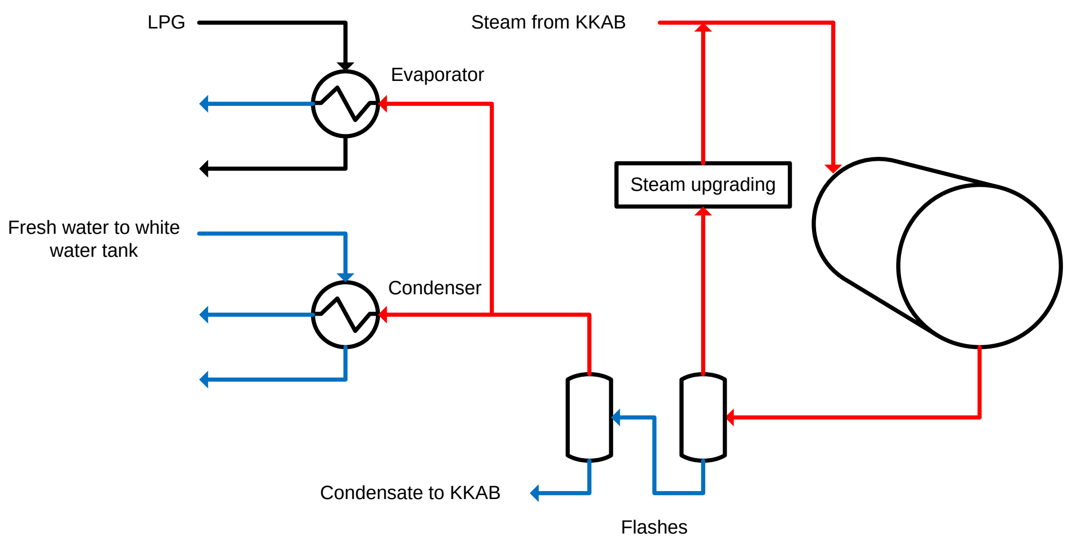

Figure 6 Steam and condensate system.

4.1.3 White water- and spray system

The white water is used more or less in the entire system for different purposes. It is for example used in the spray system as a cooling fluid and lubricant. It is also used during the deinking process of new papers which is one of the raw materials. All the white water that is brought back to the system goes through a micro flotation. This cleans the water in order to avoid the paper to be contaminated and affect among many things the quality of the paper.

4.2 Data collection

The Katrinefors mill has a rather extensive logging system with several measuring points within the machine. It measures and logs temperatures, flows and pressures every two seconds. Data were taken from the time period 2010-06-01 to 2011-06-13. Average values over the entire year were used which were based on the average value per hour.

Several measuring points and values regarding the heat exchangers within the Yankee hood were lacking and the dimensioning where used as guidelines. Additional information regarding the LPG consumption and certain air flow in the Yankee hood was taken from a simulation program explained in section, 5.2. See Appendix 2 for specific value and information on what type of data were used. No physical measurements were neither possible nor necessary.

As written in section 4.1 the fresh water which is used in the system is taken from the lake Vänern. The temperature used is the yearly average, 6,6 °C (SMHI, 2007). The fresh air temperature is also used as the yearly average in Mariestad, where the site is situated. The average air temperature is 6°C (SMHI, 2010).

4.3 Assumptions and estimations

The temperatures and flows needed for the calculations were available through the data provided from the company. Where there was lack of data reasonable assumptions where made. The exhaust stream, fresh air inlet, LPG consumption and the amount of heat necessary for the evaporation were taken from the simulation program explained in Section 5.2.

Yankee hood

As explained in section 4.1.1, the inlet fresh water stream in the second heat exchanger after the Yankee hood is mixed with an additional stream before entering the heat exchanger. No data were available regarding the amount of water or the temperature. The amount of fresh water was though known and also the capacity of the pump which pumps these two streams; 60m^3 per hour. But in order for the system to be working this flow had to be set at 25 m^3 per hour, which was set as a soft target. Changing this however affected the results significantly. Since the temperature was not known either, it was given a soft target of 27°C. A soft target is set when there are no specific requirements and can be alternated.

The pump for the white water to the scrubbers has recently been replaced and the scrubbers have also been cleaned which has increased the capacity. In the data provided by the company the capacity for this pump was approximately 50m^3 per hour but with the improvements the present amount of water passing the pump is 120m^3 per hour.

The temperature interval of the LPG was not known, but the amount burnt in the burners was. With this information the energy required to evaporate the LPG could be calculated and the temperature interval were set to 25 to 50 °C. Within this temperature interval, the result of the pinch analysis was not significantly affected.

The moisture content of the exhaust stream was not known. From a functional check-up for the hood and air system, executed by Metso, Gorizia on the Katrinefors mill, this value were reported as 0,137 kg water per kg air. This was set as a soft target which could be varied.

As the data is based on an average yearly value, the demand which the moist air should be covering is not possible. In addition to this; when the temperature of the white water is too low an external source of heat is used which have not been considered. For this reason the flow of the moist air had to be modified in order to cover the demand i.e. increased with 16%.

Steam and condensate system

The amount of fresh water heated in the condenser is not measured in the system. By calculating the fraction of steam produced in the second flash and knowing the amount of LPG needed to be evaporated, the amount of water that could be heated was calculated.

The condensation stream which is presently sold back to KKAB is a stream which could potentially be utilized in the system. For that reason the target temperature of this stream was set as a soft target at 20°C.

Others

Two additional streams of air, which is not utilized within the system at the moment, are present in the study and included in the pinch analysis; the wire evacuation and vacuum pumps. These streams have fairly large flows and keep a temperature a couple of degrees lower than the white water. It is estimated that both have a temperature roughly 3°C below the white water temperature. Additionally two streams of water where also included; the waste water and another stream of fresh water. The waste water keeps the same temperature as the wire evacuation and vacuum pumps and the fresh water keeps the same temperature as the other fresh water streams; 6,6°C. The effluent temperatures of the wire evacuation, vacuum pumps and the waste water were set as a soft target. The targets were set to 10°C for the reason that the minimum inlet temperature of the fresh air flow was 6°C and could possibly be heated with one of these flows.

4.4 Stream data

In Figure 7 an overview of the machine can be seen. The figure shows the streams which was chosen for the pinch analysis. 17 streams were chosen and there is no cooling demand in this system but a rather large heating demand. There are three cold streams which are important to notice; WE and DE in the Yankee hood and also the steam in the Yankee cylinder (ST). These are colored blue i.e. cold streams but are in fact hot stream. The reason for this is that they are covering the evaporation of the water in the paper which is a cold stream. The streams supplying the energy are included, for that reason they are colored blue.

There are four additional stream included in the pinch analysis that is not visible in Figure 7; one additional stream of fresh water, wire evacuation, vacuum pumps and waste water. These are stream which are not utilized today and are included in order to investigate applicability. Table 3 follows a clarification on the stream names included in Figure 7.

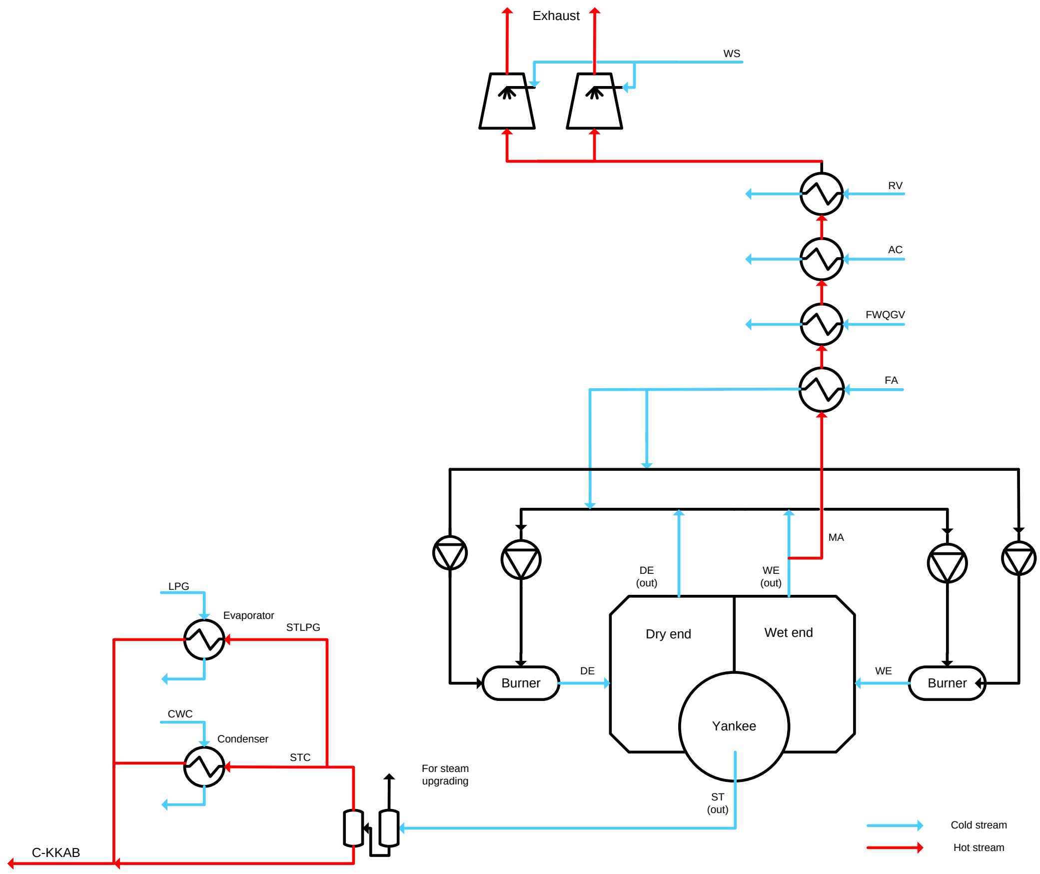

Figure 7 Presentation of the system and the streams used in the pinch analysis.

Table 3 Clarifications to Figure 7.

Stream	**Short**
Ceiling air	AC
Condensate to KKAB	C-KKAB
Cooling water condenser	CWC
Dry end	DE
Fresh air	FA
Fresh water QGV	FWQGV
LPG	LPG
Moist air	MA
Room ventilation	RV
Steam	ST
Steam condenser	STC
Steam LPG	STLPG
Wet end	WE
White water scrubber	WS

The major heat source is the moist air with a heat content of 5599 kW. In the pinch analysis this stream has been divided into two; the first part where the air present in this stream is cooled down to the dew point and then the second part where simulations cooling and condensation along the dew line occurs.. The dew point for this composition of hot air and moisture (approximately 40 mass% of moisture) is at 75°C, see Appendix 3 for further explanation. Today, the moisture content and temperature at which this moist air stream is released to the atmosphere is 14 mass % and 58°C. In the pinch analysis, two cases are performed; one with the current temperature and one where the moist air is further cooled and condensed to 40 °C.

The waste water is also a stream which contains a rather large amount of heat. Further, the two streams that heat the fresh water in the condenser (STC) and evaporate the LPG (STLPG) are also rather large. These two streams are mixed with the condensate from the second flash and sold back to KKAB. The hot streams are presented in Table 4.

Table 4 Hot streams included in the pinch analysis.

Hot streams	**Short**	**T_{start} [°C]**	**T_{target} [°C]**	**Q [kW]**
Moist air	MA	271	58/40	5599
Steam condenser	STC	111	111	148
Steam LPG	STLPG	111	111	41
Vacuum pumps	VP	36	10	192
Wire evacuation	WE	36	10	596
Waste water	WW	36	10	1305
Total				***7881***

Nearly 1700 kW of heat is needed to heat the fresh water (FWQGV) passing through heat exchanger QGV which is where most heat is required. The two scrubbers also require 1700 kW to heat the white water (WS). There are three heat sources; steam and hot air for the wet and dry end in the Yankee hood that are considered as cold streams, which was written earlier. This is due to the fact that these streams are covering the demand which is required for the drying process of the paper. Comparatively smaller amount of heat is utilized in the machine hall to prevent condense (AC) and the room ventilation (RV). In total the heat demand is 13000 kW, see Table 5.

Table 5 Cold streams included in the pinch analysis

Cold streams	**Short**	**T_{start} [°C]**	**T_{target} [°C]**	**Q [kW]**
Fresh air	FA	6	165	715
Fresh water QGV	FWQGV	27	73	975
Ceiling air	AC	6	50	665
Room ventilation	RV	6	20	353
Scrubber	WS	46	58	1686
Cooling water condenser	CWC	7	59	148
LPG	LPG	25	50	41
Fresh water white water tank	FW-WT	7	50	1208
Wet end	WE	271	371	1130
Dry end	DE	290	373	1190
Steam	ST	150	150	3133
Total				***12278***

The present hot utility demand for the Katrinefors mill is presented in Table 6. LPG is used to produce the hot air for the drying. The steam is bought from KKAB and is also used in the drying process. Since the Katrinefors mill purchases steam and sells the condensate back to KKAB the difference in these is considered as the utility. There is no cold utility demand for this process.

Table 6 Present hot utility demand for the Katrinefors mill.

Utility	**Q [kW]**
LPG	2290
Steam	3384
Total	***5674***

5 Computer simulated machine, Yankee hood

Metso Paper Karlstad AB is part of the Metso Corporation and provides services, products and technology within the tissue production industry. The variety ranges from replacing and upgrading components to evaluating an entire process. Metso Paper Karlstad also sell entire offered machines (Metso Paper Karlstad AB, 2009).

5.1 Yankee hood

The computer simulated machine is based on a standardized machine which only includes the Yankee cylinder and hood. It is designed to produce roughly 220 tons of tissue paper per day with a basis weight varying between 12 and 45 grams per square meters. For this master's thesis a basis weight of 17 grams per square meters is used. The Yankee diameter is 5500 millimeters and the operating steam pressure is 8 bar(g). After the last press roll the dry content of the paper is approximately 39, 5 percent and at the reel 95 percent. See Appendix 2 for further machine specifications.

Figure 8 shows an overview of the Yankee hood and cylinder where the green lines represent air streams. The hood consists of two parts; wet and dry end. After the stock has been formed and pressed it is transferred onto the cylinder on the wet end and is peeled off at the dry end. Fresh air is heated with a moist air stream extracted from the wet end of the Yankee hood. The fresh air is split into two streams; combustion air and make-up air. Combustion air is used in two burners to produce hot air which dries the paper placed on the surface of the Yankee cylinder. Liquid Petroleum Gas (LPG) is burnt in the burners to produce the hot air. Make-up air is blended with air exiting the dry end of the Yankee hood and re-circulated back to the burner and used for the same purpose as the combustion air.

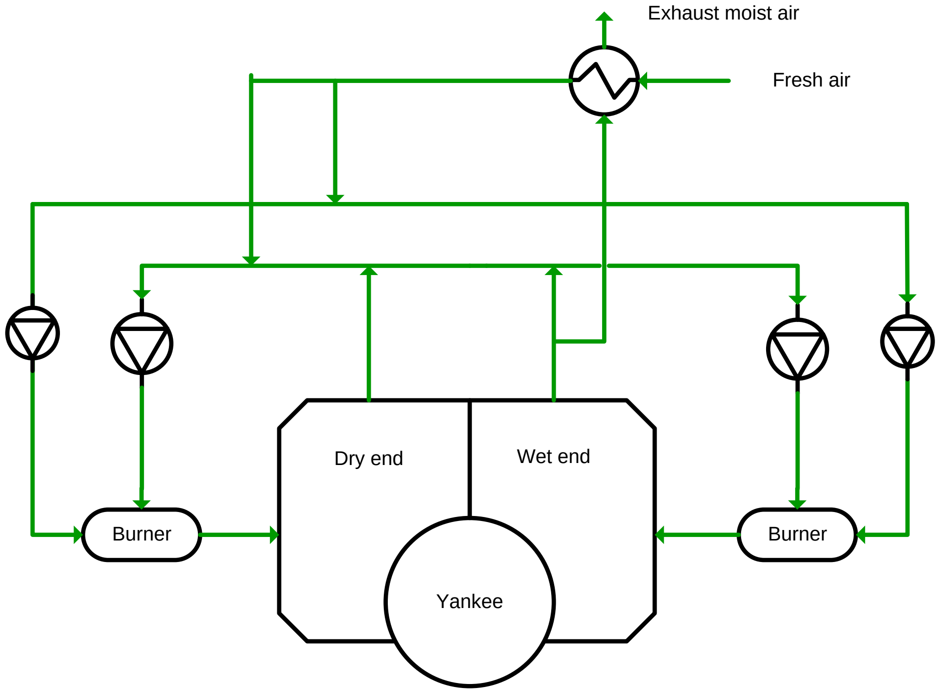

Figure 8 Yankee hood of the standardized Yankee hood.

5.2 Data collection

Data has been collected from a simulation program and a technical specification sheet on the machine can be found in Appendix 2. The data were used as an input in a simulation program developed by Metso, Gorizia in Italy and provides information on the Yankee hood and cylinder.

The simulation program simulates the drying process in the Yankee hood and cylinder and is developed in Microsoft Office Excel 2007. The program is confidential and the working method will not be further explained. Inputs to the program are divided into different parts; burner, fuel, cylinder, hood, make-up air and combustion air. These include specifications of the machine such as speed and diameter on the cylinder, steam pressure, temperature and basis weight of the paper at the Yankee. Other inputs are the type of fuel and burners, temperature and humidity of the make-up and combustion air entering the system. Where there was a lack of data on the machine the standard values for the program were used.

The output data consists of information on the evaporation, air flow within the system and exhaust stream. Yankee production, total burner power and fuel flow are other outputs. Thorough information on the drying process over the Yankee hood is also provided from the program; a graph representing the temperature and moisture content of the paper at different angles on the cylinder.

5.3 Assumptions and estimations

All data for the simulated machine were taken from the technical specification and standard values from the simulation program. An estimation regarding the humidity of the air entering the dry end side of the Yankee hood was made. It was assumed to be 280 grams of water per kg of dry air.

5.4 Stream data

There are six streams given from the simulation program; steam, hot air in the wet and dry end of the Yankee hood, LPG, moist air and fresh air. As can be seen in Table 7, there is only one hot stream; the moist air (MA) extract from the wet end of the Yankee hood. This stream consists of roughly 50 % moisture and in the pinch analysis this stream has be divided in to two parts for the same reason as for the Katrinefors mill, see Section 4.4 for further explanation.

Table 7 Hot stream included in the pinch analysis.

Hot stream	Short	T_{start} [°C]	T_{target} [°C]	Q [kW]
Moist air	MA	343	58	13454

Four cold streams are present for the Yankee hood; fresh air, hot and moist air in the dry and wet end of the Yankee hood and the steam.

Table 8 Cold streams included in the pinch analysis.

Cold streams	Short	T_{start} [°C]	T_{target} [°C]	Q [kW]
Fresh air	FA	6	200	1435
Wet end	WE	343	480	3804
Dry end	DE	340	480	3812
Steam	ST	175	175	6207
Total				***15258***

The present hot utility demand consists of the heat required in the drying process; steam (ST) in the cylinder and LPG for producing the hot air. There is no cooling demand for the Yankee hood and the present utility demand is presented in Table 9.

Table 9 Present hot utility demand.

Utility	Q [kW]
LPG	7616
Steam	4803
Total	***12422***

6 Computer simulated Yankee hood in a scaled model of the Katrinefors mill

As the computer simulated machine only includes the Yankee hood it was put into a larger perspective to get a picture of how it would look like in a mill. This was performed by using the computer simulated machine as the base for the Yankee hood. For the other parts of the machine, the Katrinefors mill was used as the basis and was scaled through the relation in produced amount of paper. The computer simulated machine produces 70% more paper.

6.1 Machine model

In Figure 9 an overview of the scaled machine can be seen which also shows the streams chosen and used in the pinch analysis. In total 17 streams was chosen and used in the pinch analysis. The system does not have any cooling demand but a rather extensive heat demand. As can be seen in Figure 9 there are seven heat exchangers within the system. The steam entering the Yankee cylinder condenses and is used as a heat source in two heat exchangers to heat fresh water and evaporate LPG burned in the two burners. Another heat source is the hot and moist air extracted from the Yankee hood and used for the remaining five heat exchangers.

Four additional streams which are not visible in Figure 9 are included in the pinch analysis. These streams are one additional stream of fresh water, the wire evacuation, vacuum pumps and waste water. In Table 10 follows a clarification on the stream names included in Figure 9.

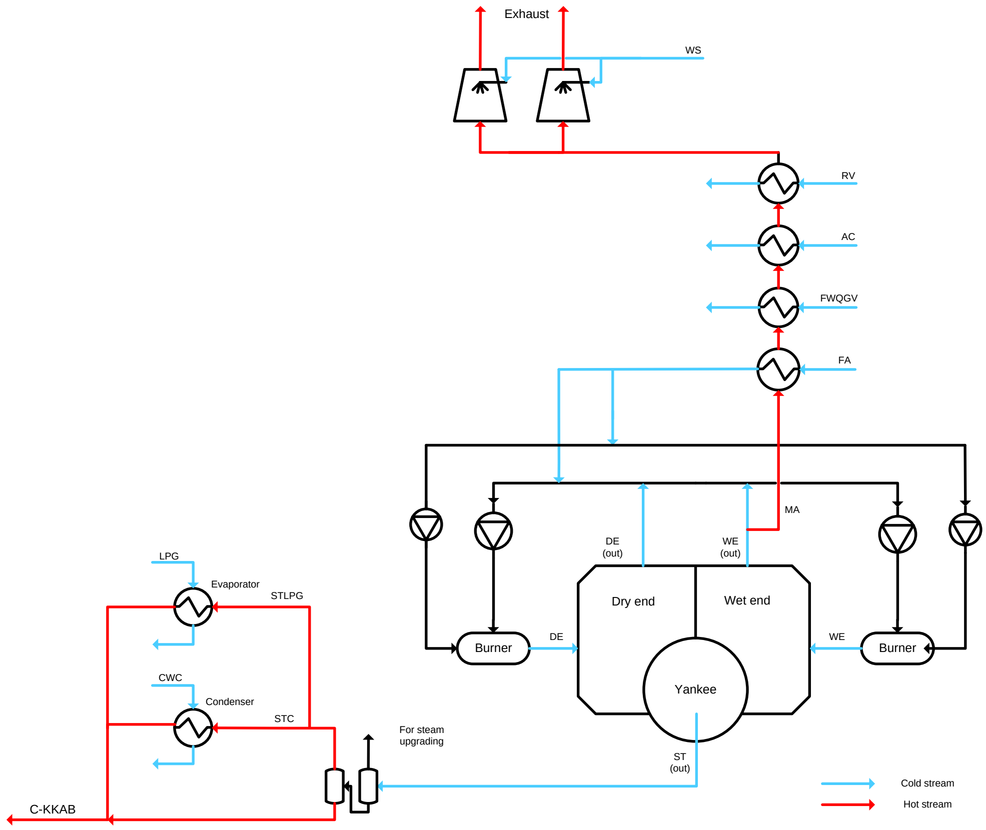

Figure 9 Presentation of the system and the streams used in the pinch analysis.

Table 10 Clarifications to Figure 9.

Stream	**Short**
Ceiling air	AC
Condensate to KKAB	C-KKAB
Cooling water condenser	CWC
Dry end	DE
Fresh air	FA
Fresh water QGV	FWQGV
LPG	LPG
Moist air	MA
Room ventilation	RV
Steam	ST
Steam condenser	STC
Steam LPG	STLPG
Wet end	WE
White water scrubber	WS

6.2 Data collection

For the scaled machine the data collection have been a combination of the computer simulated Yankee hood and Katrinefors mill. The data for the Yankee hood have been the same as for the Yankee hood explained in Section 5.2 i.e. data from the computer simulation program. The rest of the machine have been based on the data for the Katrinefors mill and scaled to fit this size of paper machine.

6.3 Assumptions and estimations

As the entire machine is not simulated, the Katrinefors mill is used as a base and scaled by the proportions of the total production of tissue paper. The simulated machine produces roughly 70 % more tissue paper than the Katrinefors.

The scaled machine has the same assumptions and estimations as the Katrinefors mill with two alternations; the soft targets on the stream named FWQGV and also the increase of the flow of the moist air. The soft targets for the FWQGV could be set as low as 10°C and a flow of 61 m^3 per hour and the flow of the moist air had to be increased with 15% in order to cover the demand. The one estimation set for the computer simulated Yankee hood was also set for the scaled machine.

6.4 Stream data

The moist air is the main heat source and used as a heat source in five heat exchangers. For the pinch analysis this stream has been divided into two parts for the same reason as for the Katrinefors mill, see Section 4.4 for further explanation. The steam used for heating fresh water in the condenser (STC) and steam used for the LPG (STLPG) evaporation are rather small comparatively but serves an important purpose. Both of these streams are condensing. As the scaled machine is based on the Katrinefors mill these streams are mixed and sold back to KKAB. There are three hot streams within the systems which are not utilised today but included in the pinch analysis; vacuum pumps (VP), wire evacuation (WE) and waste water (WW). They are fairly large in terms of flow and heat content and could potentially be utilized within the system. The total amount of heat available is 18071 kW. The stream names including an asterisk are stream which have been scaled.

Table 11 Hot streams included in the pinch analysis.

Hot streams	**Short**	**T_{start} [°C]**	**T_{target} [°C]**	**Q [kW]**
Moist air	MA	343	58	13754
Steam condenser	STC	111	111	667
Steam LPG	STLPG	111	111	93
Vacuum pumps*	VP	36	10	326
Wire evacuation*	WE	36	10	1013
Waste water*	WW	36	10	2218
Total				***18071***

The fresh water stream (FWQGV) which is heated with the moist air is the cold stream that requires most heat, see Table 12. A great deal of heat is also required in the two scrubbers to increase the temperature of the white water. The hot air in the Yankee hood (WE & DE) as well as the steam inside the cylinder (ST) is the main heat demands in the system. Minor heat is required from the moist air to heat air for the ventilation in the machine hall to prevent condensation (AC) and the room ventilation (RV). In total the heat demand is 27140 kW.

Table 12 Cold streams included in the pinch analysis.

Cold streams	**Short**	**T_{start} [°C]**	**T_{target} [°C]**	**Q [kW]**
Fresh air	FA	6	200	1435
Fresh water QGV*	FWQGV	10	73	4487
Ceiling air*	AC	6	50	1131
Room ventilation*	RV	6	20	600
Scrubber*	WS	51	64	3206
Cooling water condenser	CWC	7	59	667
LPG	LPG	25	50	93
Fresh water white water tank*	FW-WT	7	50	2295
Wet end	WE	343	480	3804
Dry end	DE	340	480	3812
Steam	ST	175	175	6207
Total				***27137***

The present hot utility demand is the heat required in the drying process; steam in the cylinder and LPG for producing the hot air. These values are based on the simulation program. The present utility demand is presented in Table 13, there is not cooling demand present in this process.

Table 13 Present hot utility demand.

Utility	**Q [kW]**
LPG	7616
Steam	4805
Total	***12422***

7 Results

The results including the pinch analysis, retrofit suggestion and the economic evaluation are presented separately for the Katrinefors mill, the computer simulated Yankee hood and the computer simulated Yankee hood in a scaled model of the Katrinefors mill.

7.1 Katrinefors mill

For the Katrinefors mill two different pinch analyses were performed; one representing the current system and one where the moisture present in the moist air stream is further cooled and condensed in order to utilize the heat available to a greater extent.

7.1.1 Pinch analysis

7.1.1.1 Current moist air existing temperature and moisture content

The grand composite curve for the current system is presented in Figure 10 and the pinch temperature is present at 9,1°C. What can be seen from this figure is that the system does not have a cooling demand. The minimum hot utility demand is given as the same as the present utility demand but the system display potential process integration possibilities. There are two potential process integration possibilities present and the one on top implying that parts of the steam can be generated through the moist air stream and the other one implying further integration.

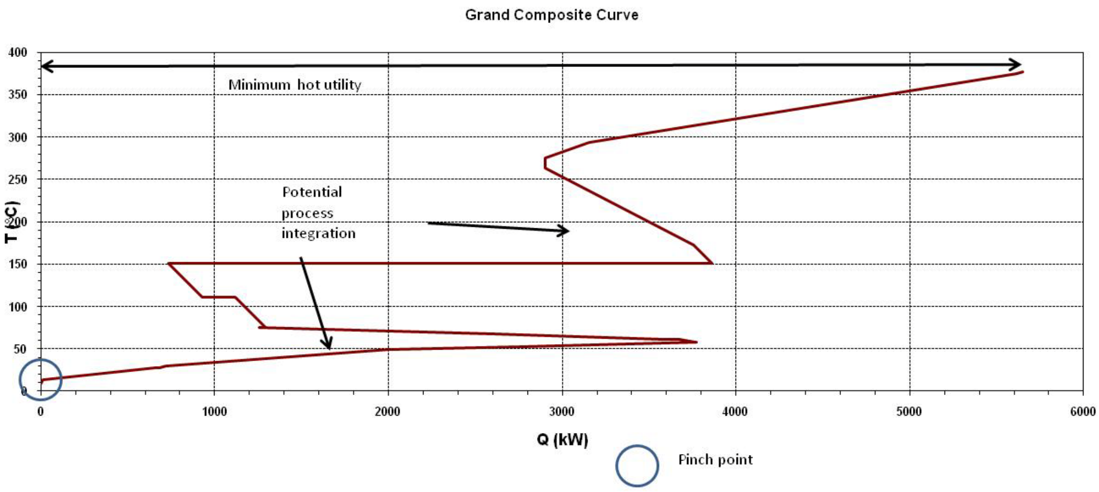

Figure 10 Grand composite curve for the current system, Katrinefors mill.

For the Katrinefors mill there are three additional streams that can potentially be utilized within the system; wire evacuation, vacuum pumps and also the waste water. These were added to the system and also a fresh water stream which is not heated in today´s system. By adding theses streams the grand composite curve is slightly changed, the pinch temperature for example is instead at 34°C. The main difference is the minimum cooling/excess heat present below the pinch. As there is no cooling demand for this system this part of the curve can therefore be considered as excess heat. In the grand composite curve this excess heat is visible due to the soft targets on the three streams which have been added to the system. The grand composite curve for this system can be seen in Figure 11.

The minimum hot utility demand is for this system at roughly 5000 kW. This implies that approximately 12% of the utility could potentially be saved. The two process integration possibilities are present here as well. The one on top implying that the moist air extracted from the Yankee hood could cover parts of the steam demand and the other implying further integration.

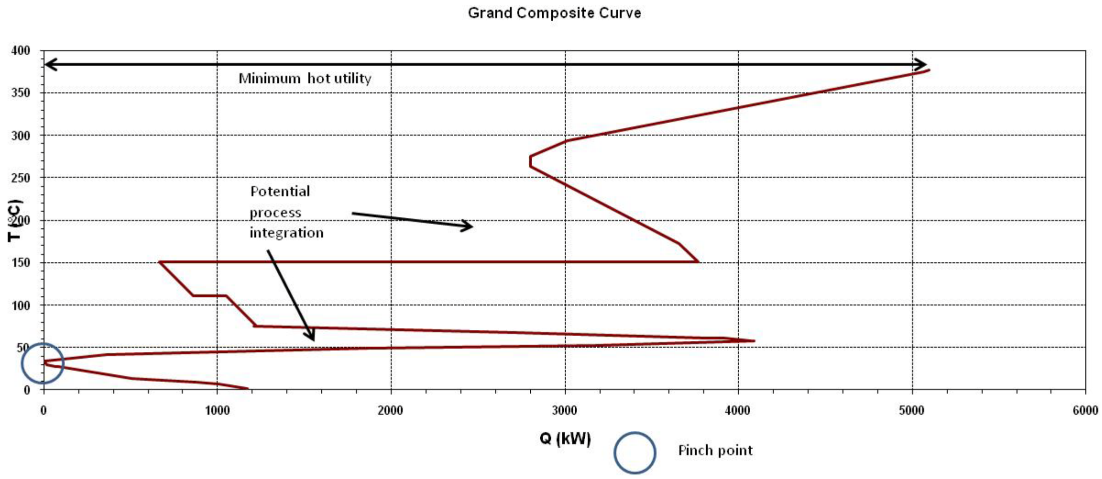

Figure 11 Grand composite curve for the Katrinefors mill.

There are in total 793kW of pinch violations in this system, all these are transferring heat across the pinch. All pinch violations are listed in Table 14. The main one is where fresh air is heated with the moist air stream for the room ventilation (MA-RV); 353 kW. The second largest is as the moist air heats the fresh air stream to prevent condensation in the ceiling in the machine hall (MA-AC); 280 kW. Additionally 90 kW is also transferred through the pinch as fresh air, used for the burners, is also heated with the moist air.

Table 14 Pinch violations for the Katrinefors mill.

Heat exchanger	Streams	Pinch violation	Q [kW]
1	MA-FA	Heat through pinch	90
3	MA-AC	Heat through pinch	280
4	MA-RV	Heat through pinch	353
6	STC-CWC	Heat through pinch	70
Total			***793***

In addition to the pinch violations listed above the moist air is released at a temperature above the pinch temperature and is considered to require cooling; i.e. cooling above the pinch. This is a violation of one of the golden rules and is not visible in the grand composite curve shown in Figure 11. This pinch violation reduces the minimum utility demand further. By further cooling and condensing the moist air stream the grand composite curve is shifted which is explained and presented in the following section.

7.1.1.2 Further cooled and condensed moist air stream

There is a potential to further utilise the energy present in the moist air stream as this stream is released to the atmosphere with almost 14 mass % moisture and a temperature of 58°C. It is possible, at 40°, to have a moisture content of 5% with a relative humidity of 100%. This is further explained in Appendix 3. By cooling the stream down to a temperature of 40°C more energy can be utilised. This type of change provides a different grand composite curve and is presented in Figure 12. What differentiates this curve from the other one is mainly the pinch temperature, which has been shifted to 151°C because more energy is available in the moist air that can be utilised within the system. The amount of energy that can potentially be saved is nearly 17%.

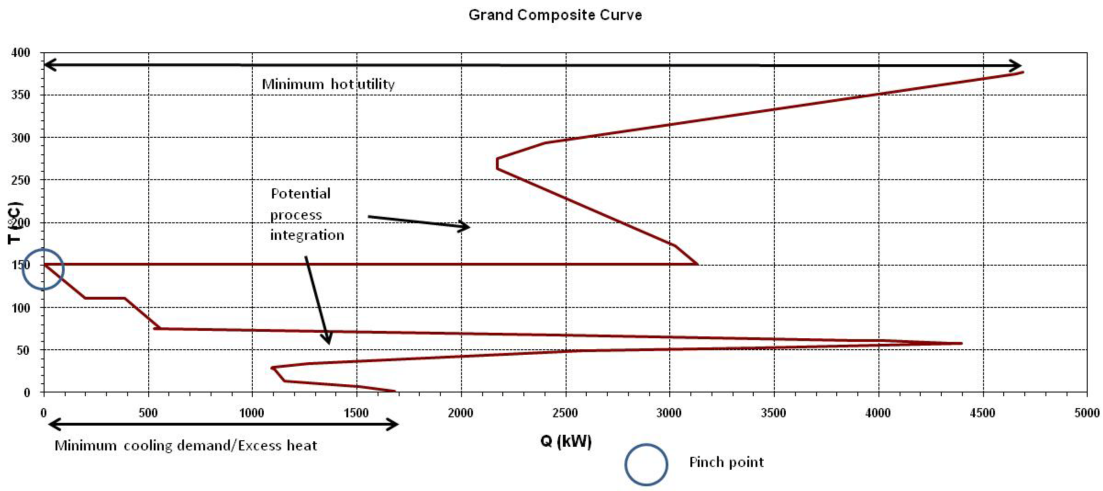

Figure 12 Grand composite curve for the Katrinefors mill with further cooled and condensed moist air stream.

For this system, where the energy available in the moist air stream is further utilised, two pinch violations are present. The difference between this system and the current is that the pinch temperature is elevated which results in two other pinch violations emerging. The main one is as the fresh air for the burners is heated with the moist air stream and the other pinch violation is as the moist air is used as the heat source to increase the temperature of the fresh water stream passing the QGV heat exchanger. Both pinch violation are as heat is transferred through the pinch. These two pinch violations are listed in Table 15.

Table 15 Pinch violations for the Katrinefors mill as the moist air stream is further cooled and condensed.

Heat exchanger	Streams	Pinch violation	Q [kW]
1	MA-FA	Heat through pinch	616
2	MA-FWQGV	Heat through pinch	347
Total			***963***

7.1.2 Retrofit suggestion

Two different retrofit suggestions will be presented in this section for the Katrinefors mill. The first one including the current system of the Katrinefors mill and one where the steam in the moist air is further condensed.

7.1.2.1 Current moist air existing temperature and moisture content

As written in Section 4 there are seven heat exchangers in this system. The original stream presentation for this system can be seen in Appendix 4. As written in the previous Section 7.1.1, Table 14, there are in total 793 kW of pinch violations for the Katrinefors mill. These should be eliminated in order to have a system working as effectively as possible.

The starting point for the retrofit was the results from the grand composite curve which implied that the moist air could potentially cover parts of the steam demand. The pinch violations including the heat exchangers were also taken into consideration. There are two heat exchangers which were not considered for the retrofit which are the condenser and evaporator, see Figure 13. This is due to the complexity of the steam system which these heat exchangers are a part of. Fortunately they are not contributing considerably to the pinch violations, in total 56kW.

From the grand composite curve it could be seen that approximately 29% of the steam demand could be covered by the moist air stream. For this reason the steam stream was divided into two fractions where one consisted of 29%. A heat exchanger was added between this fraction and the moist air stream. The part of the moist air stream that covers the steam demand is where the air is cooled down.

The heat exchangers present in the current system was kept even though some of them contributed to the pinch violations. Because, first and foremost the total amount of pinch violations is not considerably large which implicate that eliminating them would not affect the system substantially. Secondly some of these pinch violations might be difficult to eliminate due to the rather low pinch temperature and temperature intervals of the stream contributing to the violations. It is however possible to eliminate the major pinch violation, where the fresh air used for the room ventilation is heated with the moist air. This can be accomplished with a heat exchanger between either the wire evacuation or the waste water stream, which are not utilized today. This will on the other hand require heat exchanger with areas between 190 and 455 m^2 depending on which stream is used as the heat source. Whether this is feasible or not in a long term perspective, when considering the investment cost and the benefits of reducing the pinch violation, need to be further investigated. A presentation of the retrofit is presented in Figure 13 and the one heat exchanger required for this retrofit is the first one which uses the moist air stream, MA, as the heat source to generate parts of the steam.

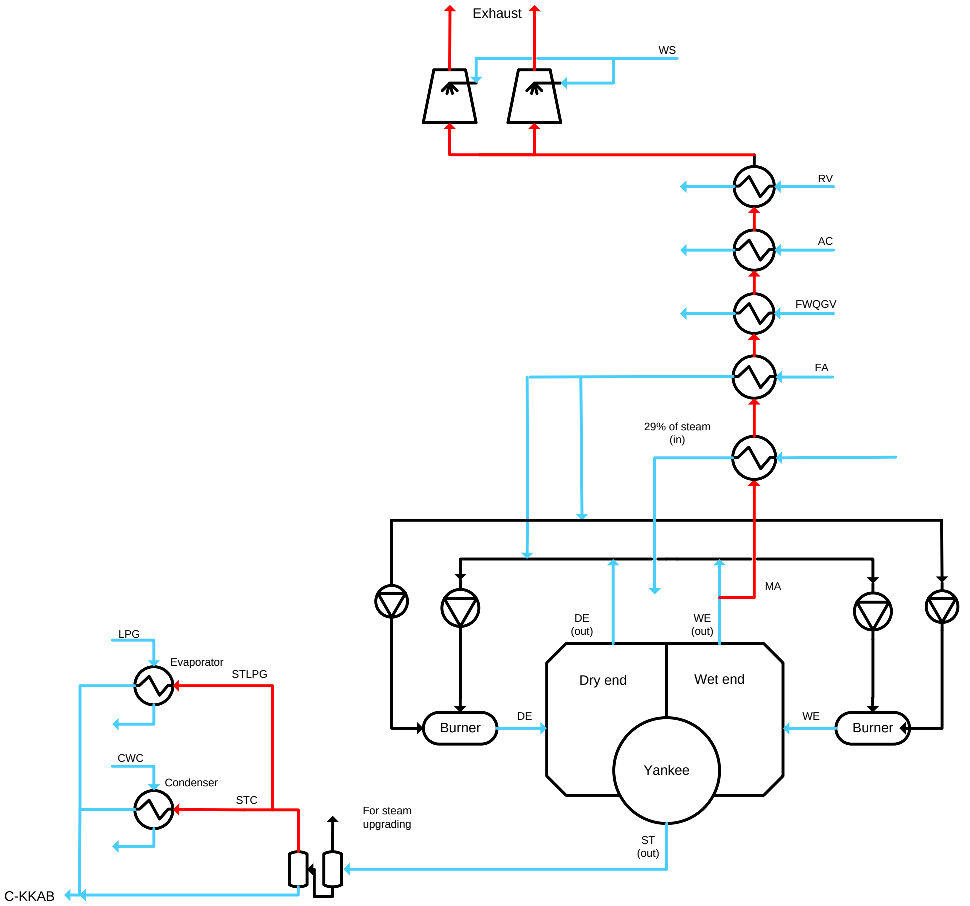

Figure 13 Presentation of the retrofit suggestion of the Katrinefors mill.

For this suggested retrofit the steam demand could be reduced with as much as 29% and the total hot utility demand would be reduced with 16%. The heat exchanger required for the retrofit is presented in Table 16. With the suggested retrofit the pinch violation where cooling above the pinch is violated is reduced with 60% and the energy available is utilities to a greater extent.

Table 16 Heat exchanger required in the suggested retrofit for the current system.

Unit	$T_{H,in}$ [°C]	$T_{H,out}$ [°C]	$T_{C,in}$ [°C]	$T_{C,out}$ [°C]	ΔT_{lm} [°C]	Q [kW]	U [W/m^2·K]	A [m^2]
HEX	271	175	150	150	61	908	97	154

7.1.2.2 Further cooled and condensed moist air stream

By decreasing the moisture content of the moist air stream released to the atmosphere more energy available could be utilised. This was the starting point for this retrofit;

the moisture content could be reduced down to 5% and cooled down to a temperature of 40°C. From the grand composite curve it was implied that the moist air could potentially generate a part of the stream used in the drying process. A heat exchanger was therefore added between a fraction, 29%, of the steam stream and moist air stream where the air is initially cooled. Since there was no pinch violations including heat exchangers in the system the current heat exchangers were kept intact.

The energy available through further condensation can be used to heat more water passing the QGV heat exchangers and also at a lower temperature. This reduces the soft targets of the mixed stream passing this heat exchanger. The temperature can be reduced to 10°C and the flow can be increased to 36 m^3 per hour. As this stream affects the system to such an extent, this type of improvement provides a better presentation of the process. The stream presentation for the suggested retrofit can be seen in Appendix 5 and Figure 13 represents the retrofitted system.

For this suggested retrofit the amount of steam that can be saved is 29% which is 16% of the total hot utility demand. The heat exchanger required for this retrofit is presented in Table 17 and is the same as for the current system and can be seen in Figure 13. The pinch violations present for this system are reduced with almost 94% with the suggested retrofit.

Table 17 Heat exchanger required in the suggested retrofit with further cooled and condensed moist air stream.

Unit	$T_{H,in}$ [°C]	$T_{H,out}$ [°C]	$T_{C,in}$ [°C]	$T_{C,out}$ [°C]	ΔT_{lm} [°C]	Q [kW]	U [W/m^2·K]	A [m^2]
HEX	271	175	150	150	61	908	97	154

7.1.3 Economic evaluation

An economic evaluation was made for the suggested retrofit regarding investments and reduced utility. As the retrofit suggestions are the same for both systems this evaluation regards both. The annual savings in terms of energy is 29% of the steam demand which is 16% of the entire hot utility demand. This equals 908 kW of steam. The price for purchasing steam and selling the condense to KKAB is assumed to be 320 SEK per MWh and has been the basis for the economic evaluation. With the suggested retrofit 2.6 million SEK can annually be saved.

Table 18 Annual energy and cost savings.

	Q [kW]	LPG [kW]	Steam [kW]	Steam cost [MSEK/yr]
Present hot utility	5674	2290	3384	9.5
New utility	4766	2290	2476	6.9
Savings	***908***	***0***	***908***	***2.6***

One new unit is required for the suggested retrofit which is a heat exchanger that generates steam from the moist air with a heat exchanger area of 154 m^2. The cost for investing in a heat exchanger is based on the size of it, i.e. the heat exchanger area.

The equations presented in Section 2.2 have been used to calculate the investment cost. The cost for investing in this heat exchangers amounts to 1.0 million SEK and is presented in Table 19.

Table 19 Equipment cost for the suggested retrofit.

Unit	A [m^2]	Equipment cost December 2010 [$]	Total fixed capital cost [$]	Total fixed capital cost [MSEK]
HEX	154	47728	152729	1.0

With an annual saving of 2.6 million SEK and an investment cost of 1.0 million SEK for the heat exchanger required in the suggested retrofit the payback period is 0,4 year or 5 months. Assuming that the machine is running all year approximately 182 kWh per tonne tissue paper is saved with the suggested retrofit.

7.1.4 Other suggestions

There are other improvements which can be suggested for the Katrinefors mill or other systems like it. First of all when considering the grand composite curve where the wire evacuation, vacuum pumps and also the waste water is present there is a cooling demand/excess heat present below the pinch. A system which has this and also a heat demand at fairly low temperatures above the pinch is a good candidate for a heat pump.

A heat pump would of course require an investment but could potentially have a short payback period depending on the size of it and on the available and required temperatures. A heat pump would be beneficial for a system with a cooling demand below the pinch that could be lifted above the pinch. This is not necessary for the Katrinefors mill since this demand is already covered, which can be seen in the grand composite curve. However, as there are several soft targets within this system the demand for a heat source at low temperatures are of interest.

Another suggestion is to purchase warm water instead. This requires that either KKAB or another nearby company provides this type of services. Both the heat pump and hot water are presented in the same manner in the grand composite curve and can be seen in the example shown in Figure 14 as the two red lines.

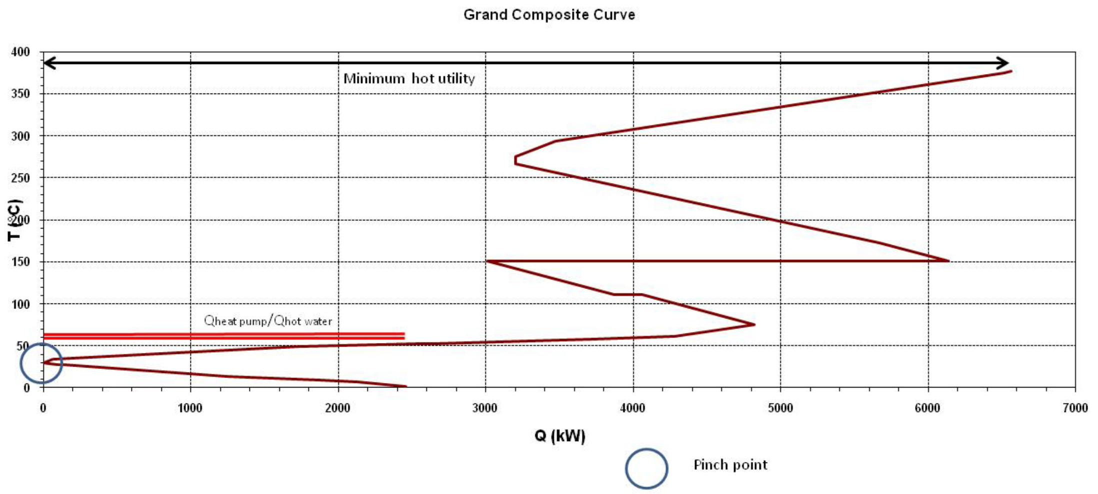

Figure 14 Grand composite curve for an example, including a heat pump/warm water heat source.

7.2 Yankee hood

7.2.1 Pinch analysis

This system consists only of five streams; moist air, fresh air, air for the hood WE and DE and steam used inside the Yankee hood. All streams were given from the simulation program. For this part of the machine the hot utility demand is 12422 kW. In Figure 15 the grand composite curve is presented and the pinch temperature is present at 176 °C. What can also be seen is that the minimum hot utility is almost 9750 kW and with a present demand of 12422 kW the amount of heat which can be saved is 21,5%.

There is one potential process integration possibility visible in Figure 15. This implies that the moist air could potentially be used to generate parts of the steam used in the Yankee cylinder. A minimum cooling demand/excess heat is present in the grand composite curve as well. If this energy is not utilised within the system it is considered as a cooling demand but if it could be utilised it is instead considered as an excess heat source.

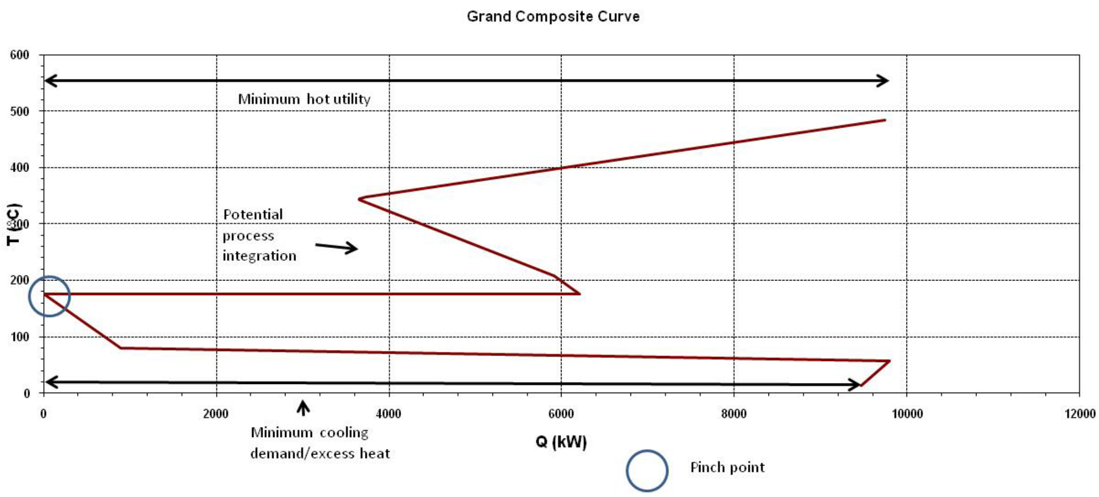

Figure 15 Grand composite curve for the simulated Yankee hood.

There is only one heat exchangers present in this system which heats fresh air for the burner. This heat exchanger violates one of the golden rules, transferring heat through the pinch, with as much as 1200kW. Another pinch violation which is also present is that parts of the steam can be generated through the moist air instead of being for example purchased.

7.2.2 Retrofit suggestion

From the grand composite curve it was implied that the moist air could potentially be used to generate parts of the steam used in the Yankee cylinder. In the same way as for the second retrofit suggestion for the Katrinefors mill the moisture content of the stream released to the atmosphere is reduced to 5% and the temperature to 40°C. This is to further utilize the heat available in the moist air stream. As much as 40% of the steam can potentially be generated with the moist air stream which is presented in Figure 16 as the first heat exchangers that utilizes the moist air as the heat source. In the original system the pinch violation was 1200 kW but through generating the steam, which resulted in that the fresh air could only be heated to 190°C, this violation was reduced with 88%. The other “pinch violation” was completely eliminated.

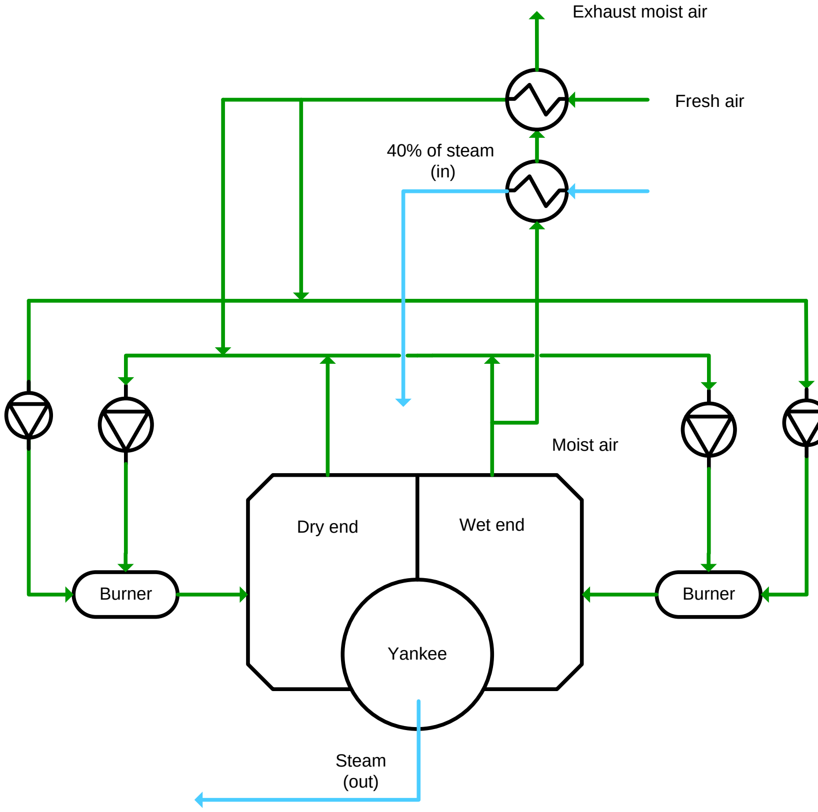

Figure 16 Presentation on the retrofit for the computer simulated Yankee hood.

By adding the heat exchanger, that generates 40% of the total steam demand, the hot utility demand can be reduced with 20%. The remaining energy can be utilised as a heat source within the system the machine is integrated in. This heat exchanger is presented in Table 20.

Table 20 Heat exchanger required in the suggested retrofit.

Unit	**$T_{H,in}$ [°C]**	**$T_{H,out}$ [°C]**	**$T_{C,in}$ [°C]**	**$T_{C,out}$ [°C]**	**ΔT_{lm} [°C]**	**Q [kW]**	**U [W/m^2·K]**	**A [m^2]**
HEX	343	194	175	175	68	2483	97	375

7.2.3 Economic evaluation

The retrofit based on the computer simulated Yankee hood only requires an investment of one heat exchanger which generates 40% of the total steam demand. In Table 21 the results from the economic evaluation are presented. What can be observed is that considerable savings can be obtained by generating the steam using the moist air; 7 million SEK per year. The steam price used is the same that have been assumed for the Katrinefors mill; 320 SEK per MWh.

Table 21 Annual energy and cost savings for the Yankee hood.

	Total [kW]	**LPG [kW]**	**Steam [kW]**	**Steam cost [MSEK/yr]**
Present utility	12422	7616	4805	13
New utility	9936	7616	2319	7
Savings	***2486***	***0***	***2486***	***6***

One heat exchanger is required to generate the steam and has an area of approximately 375m^2. The investment cost for this heat exchanger is calculated to 1,8 million SEK. This investment has a payback period of almost 4 months which can be considered as good. With this suggested retrofit roughly 270 kWh per tonne tissue paper can be saved.

7.3 Computer simulated Yankee hood in a scaled model of the Katrinefors mill

In the same way as for the Katrinefors mill two pinch analyses was performed for this machine; one for the current system and one where the moisture in the moist air stream is further cooled and condensed in order to further utilise the heat available.

7.3.1 Pinch analysis

7.3.1.1 Current moist air existing temperature and moisture content

The current system has the pinch temperature at 9,1°C and the grand composite curve is presented in Figure 17. The minimum hot utility equals the present utility demand but there are two potential process integrations possibilities within this system which are of great importance. The one on top implies that the moist air can generate parts of the steam. The other one implies further integration of multiple streams.

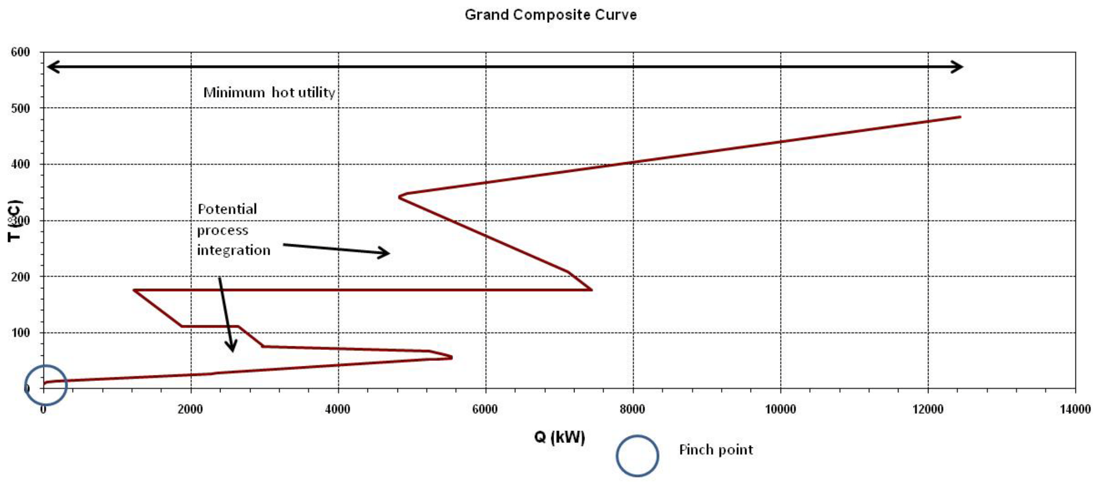

Figure 17 Grand composite curve for the computer simulated Yankee hood in a scaled model of the Katrinefors mill.

There are three streams that is not utilised within this system currently but could potentially be; wire evacuation, vacuum pumps and waste water. Another stream of fresh water is also added which is presently not heated before entering the system. For this reason these four streams where added which gave a new grand composite curve presented in Figure 18. In this grand composite curve the pinch temperature is present at 12,5 °C. The potential to saved energy is not significant in this system only 2% can potentially be saved as there is an only pinch violation of 43kW which is through transferring heat through the pinch. However, there is plenty of heat which is not utilised within the system that would reduce the utility further. The moist air stream is presently released to the atmosphere at a temperature above the pinch temperature and is considered to require cooling which means cooling above the pinch which is a violation of one of the golden rules. This pinch violation is not visible in the grand composite curve in Figure 18 but reduces the minimum hot utility further and is presented and further explained in the following section; 7.3.1.2.

For the new grand composite curve there is a small amount of cooling demand/excess heat present below the pinch. This represents the hot effluent set as soft targets of the stream which have been added to the system. This is the same as for the Katrinefors mill. It can also be seen from the grand composite curve in Figure 18 that the system has a minor heat demand nearly 1000 kW at fairly low temperatures, below 60 °C, feasible for a heat pump installation as discussed in section 7.1.4. The most important observation however in the grand composite curve is the two potential process integration possibilities present, that was also present for the original system. These possibilities show where the process could potentially be integrated. The one on the top implies that the moist air extracted from the wet end of the Yankee hood could potentially be used to generate parts of the steam used inside the Yankee cylinder. The other one imply further integration of multiple streams within the system.

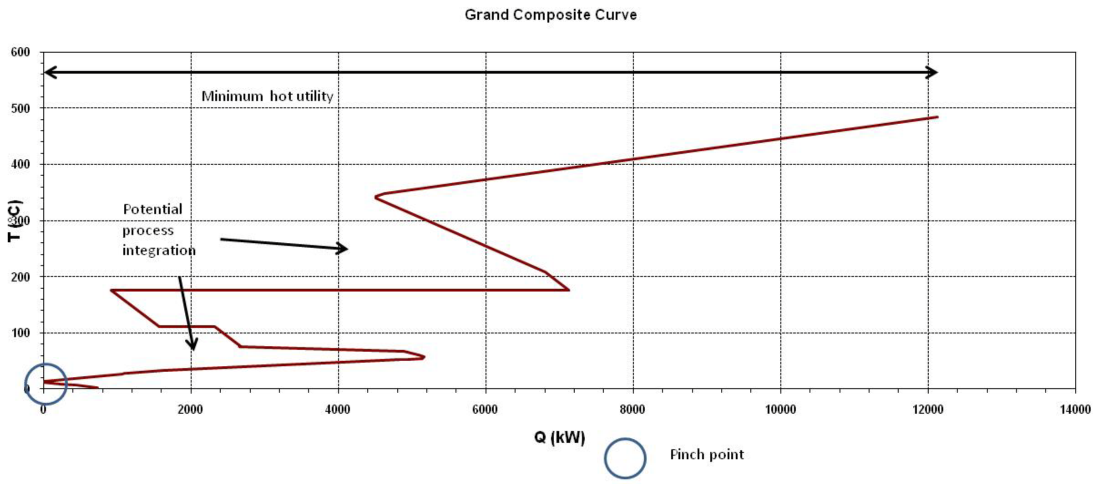

Figure 18 Grand Composite curve for the computer simulated Yankee hood in a scaled model of the Katrinefors mill.

7.3.1.2 Further cooled and condensed moist air stream

It is possible to further condense the steam present in the moist air stream to 5% moisture and cool it down to 40°C. For this reason a grand composite curve is presented in Figure 19 in order to display that the heat available can be further utilised within the system. This curve displays rather large potential process integrations possibilities. The pinch temperature is also elevated to 176°C. When further utilising the heat available the hot utility demand can be reduce with 21% and approximately 40% of the steam can potentially be generated with the moist air stream.

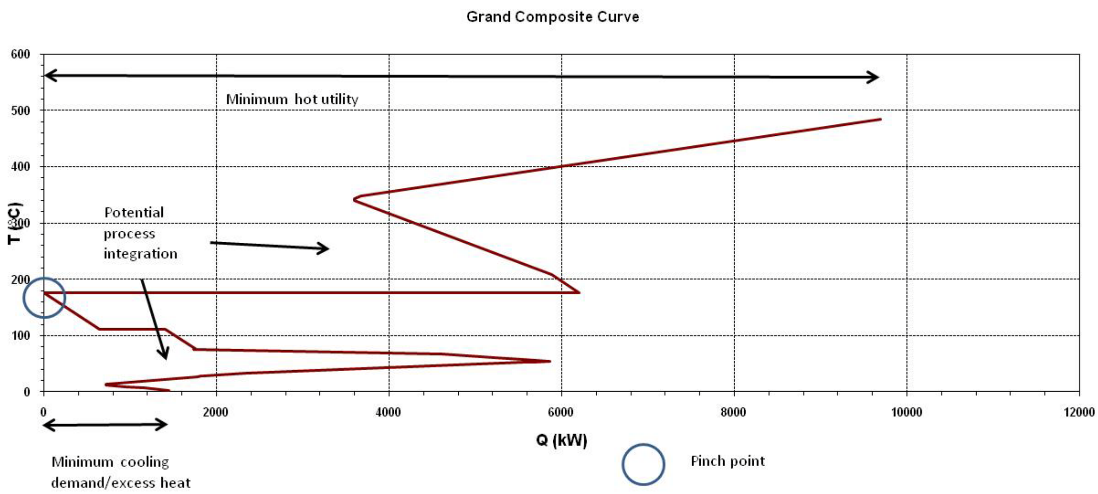

Figure 19 Grand composite curve for the computer simulated Yankee hood in a scaled model of the Katrinefors mill with a further cooled and condensed moist air stream.

For this system there are two pinch violations present both where heat is transferred through the pinch and are presented in Table 22. For both pinch violations is the moist air stream used as the heat source to increase the temperature of the fresh water stream passing the QGV heat exchanger and also the fresh air stream essential for the burners.

Table 22 Pinch violations for the computer simulated Yankee hood in a scaled model of the Katrinefors mill with a further cooled and condensed moist air stream.

Heat exchanger	Streams	Pinch violation	Q [kW]
1	MA-FA	Heat through pinch	1196
2	MA-FWQGV	Heat through pinch	1414
Total			***2610***

7.3.2 Retrofit suggestion

7.3.2.1 Current moist air existing temperature and moisture content

As written in the previous section there is only minor pinch violation present which has not been taken into consideration, since it is of only 43kW. The major pinch violation is though that the moist air stream is released to the atmosphere at a temperature above the pinch temperature thus requiring cooling i.e. cooling above the pinch which is a pinch violation. This was the starting point for the retrofit to further utilize the energy present within the system. The condenser and evaporation was not considered for any retrofit. Partly because their contribution to the pinch violations are rather small and that the steam system, which both are a part of, are rather complex.

The first step in the retrofit was to consider what was implied from the grand composite curve that parts of the steam could be generated with the moist air stream. As much as 40% of the steam could be generated and is represented with a heat exchanger; the first heat exchanger that uses the moist air stream as a heat source. See Figure 20for the suggested retrofit stream presentation.

As the rest of the heat exchangers did not contribute to any major pinch violations theses was not considered for any retrofits. Though as the steam is generated with the moist air there is not enough heat left in the moist air stream to increase the temperature of the white water. For this reason a heater has to be added which may lead to a shift in the type of utility since it is possible to use a hot water utility instead of one based on steam. By shifting the utility is might be possible to save money if the hot water based utility is less expensive than the one based on steam.

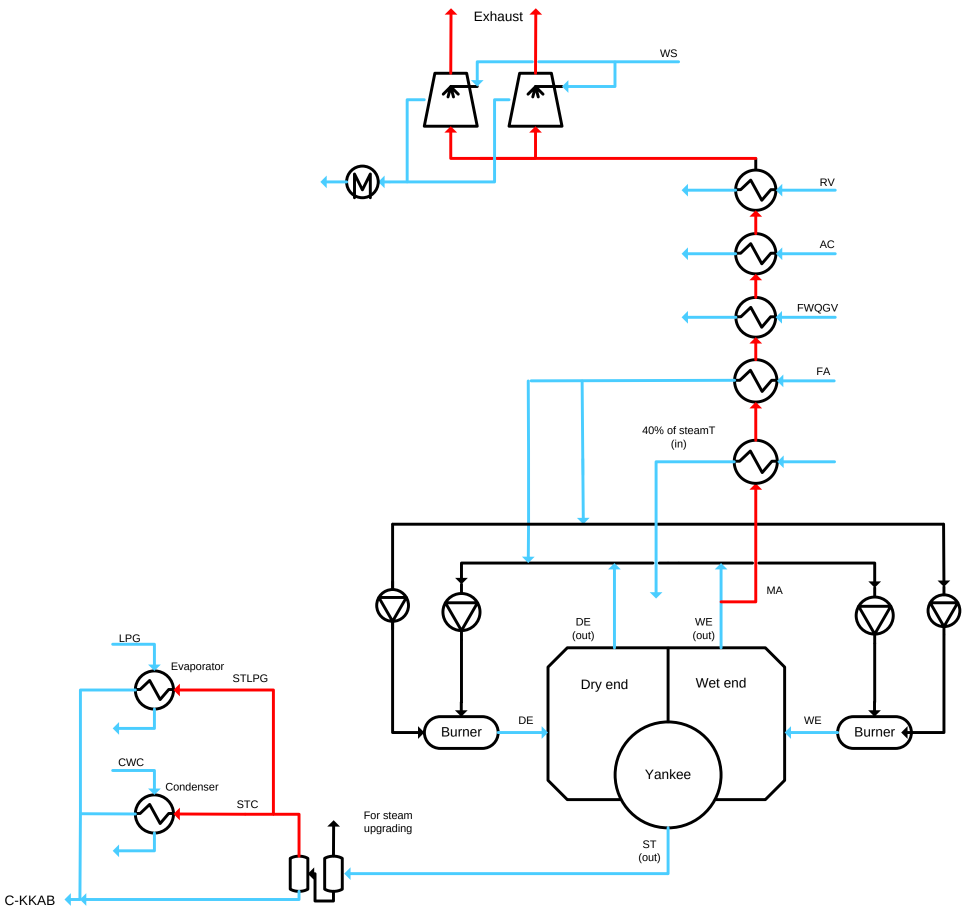

Figure 20 Presentation of the retrofit for the computer simulated Yankee hood in a scaled model of the Katrinefors mill.

For the suggested retrofit the amount of energy that can be saved is approximately 1200 kW. This is the difference between saved steam and increase in utility in order to increase the temperature of the white water. The hot utility demand would be decreased with 9,3% with this retrofit suggestion. Table 23 shows the heater and the heat exchanger required for the suggested retrofit.

Table 23 Heat exchanger required in the retrofit.

Unit	$T_{H,in}$ [°C]	$T_{H,out}$ [°C]	$T_{C,in}$ [°C]	$T_{C,out}$ [°C]	ΔT_{lm} [°C]	Q [kW]	U [W/m^2·K]	A [m^2]
HEX	343	201	175	175	76	2483	97	337
Heater	145	145	64	59	83	1325	2182	7

7.3.2.2 Further cooled and condensed moist air stream

Since the moisture content of the moist air stream could be further condensed a retrofit suggestion was also performed for this alternation. The moisture content in the exhaust stream was reduced to 5% and the temperature to 40°C. When the steam is further condensed and cooled there is more heat available that can be utilised within the system. This leads to a further reduced utility demand for the computer simulated

Yankee hood in a scaled model of the Katrinefors mill as the heat in the moist air can be used to cover parts of the steam demand. The heater that is required in the current system is not necessary when further condensing the moisture.

In the same way as for the current system a heat exchanger was added to generate 40% of the steam demand. Given that this was the only pinch violation no other changes is necessary nor possible to further reduce the hot utility demand. A presentation of the suggested retrofit is presented in Figure 21.

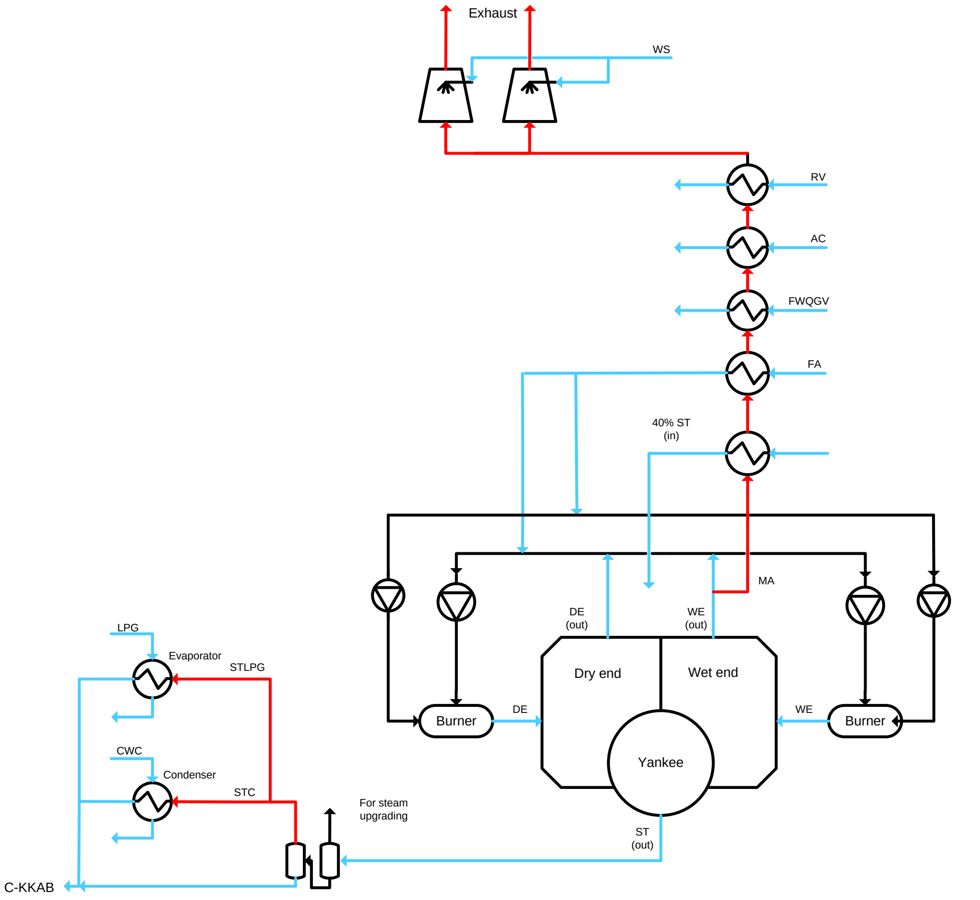

Figure 21 Presentation of the retrofit suggestion for the computer simulated Yankee hood in a scaled model of the Katrinefors mill with a further cooled and condensed moist air stream.

One new unit is required in this retrofit which is the heat exchanger that generates 40% of the steam. By generating parts of the steam with the moist air the hot utility demand can be reduced with 20%. The required heat exchanger is presented in Table 24. With this retrofit suggestion the pinch violations are reduced with as much as 95%.

Table 24 Heat exchanger required for the suggested retrofit with further cooled and condensed moist air stream.

Unit	$T_{H,in}$ [°C]	$T_{H,out}$ [°C]	$T_{C,in}$ [°C]	$T_{C,out}$ [°C]	ΔT_{lm} [°C]	Q [kW]	U [W/m^2·K]	A [m^2]
HEX	343	201	175	175	76	2483	97	377

7.3.3 Economic evaluation

The economic evaluation is presented separately for the two suggested retrofits.

7.3.3.1 Current moist air existing temperature and moisture content

With the suggested retrofit 1200 kW of the utility can be reduced which is approximately 3 million per year in savings. These savings are based on that the external steam demand could be reduced by generating steam with the moist air and that the temperature of the white water is increased with an external heat source.

Table 25 Annual energy and cost savings for the computer simulated Yankee hood in a scaled model of the Katrinefors mill for the current system.

	Total [kW]	LPG [kW]	Steam [kW]	Steam cost [MSEK/yr]
Present utility	12422	7616	4805	13
New utility	11261	7616	3647	10
Savings	***1158***	***0***	***1158***	***3***

For the current system one heat exchanger is added to generate the steam with the most air and a heater to increase the temperature of the white water passing the scrubbers. The heater is considered as a heat exchanger for the economic evaluation. The economics for the heat exchanger and heater are presented in Table 26, the heater is considered as a heat exchanger.

Table 26 Equipment cost for the required heat exchanger.

Unit	A [m^2]	Equipment cost December 2010 [$]	Total fixed capital cost [$]	Total fixed capital cost [MSEK]
HEX	337	80988	259161	1.7
Heater	7.3	26930	86175	0.6
Total				***2.3***

With the suggested retrofit 3 million SEK could potentially be saved annually and with an investment cost of 2,3 million SEK required the payback period is almost 9 months. The amount of energy saved is almost 130 kWh per tonne tissue paper.

7.3.3.2 Further cooled and condensed moist air stream

In total almost 2500 kW of the total steam demand can be saved which is approximately 6 million SEK per year. The price for purchasing steam was assumed to be the same that was assumed for the Katrinefors mill i.e. 320 SEK per MWh.

Table 27 Annual energy and cost savings for the computer simulated Yankee hood in a scaled model of the Katrinefors mill with further cooled and condensed moist air stream.

	Total [kW]	LPG [kW]	Steam [kW]	Steam cost [MSEK/yr]
Present utility	12422	7616	4806	13
New utility	9939	7616	2322	7
Savings	***2483***	***0***	***2483***	***6***

For the suggested retrofit only one heat exchanger is required that generates steam from the moist air stream. The investment cost for this heat exchangers is presented in Table 28 and amount to roughly 1,8 million SEK.

Table 28 Equipment cost for the heat exchanger required.

Unit	A [m^2]	Equipment cost December 2010 [$]	Total fixed capital cost [$]	Total fixed capital cost [MSEK]
HEX	375.3	88489	283164	1.8

For the suggested retrofit, with an increased condensation of the moisture present in the moist air, 6 million SEK per year could be saved in utility costs and with an investment cost for the steam generating heat exchanger the payback period is only 4 months. Roughly 270 kWh per tonne tissue paper is saved with the suggested retrofit.

7.4 Comparison

The results from the pinch analysis show similarities for the Katrinefors mill and the computer simulated Yankee hood. First and foremost both systems does not utilise the heat available to as great extent as possible. Both did though display potential process integrations possibilities that imply more effective integration within the system. Here were the main implications that the moist air extracted from the wet end of Yankee hood could potentially be used to generate parts of the steam used inside the Yankee cylinder. This would reduce the utility demand.

A difference these two machines demonstrate are that the computer simulated machine display more heat recovery or heat available for further process integration. This may be related to the fact that the Katrinefors mill provides a more realistic image of a process and the computer simulated machine does not consider losses such as heat losses. Or even that the standardized machine is more effective and modern.

Comparing the Katrinefors mill and the computer simulated Yankee hood in a scaled model of the Katrinefors mill these also display similarities. Some of the similarities are present since the model is partly based on the Katrinefors mill. But what can be seen from the results is that the same retrofit can be suggested for different types and size of machines. The same can be used for the potential process integration making the results of a general orientation.

8 Discussion

There are numerous factors which affects the results in different aspects as well as to a greater or less extent. First and foremost is the data provided by the two different companies which affect the results greatly. The data given for the computer simulated Yankee hood is based on a simulation program developed by Metso Gorizia in Italy and standard measurements. This program does not include for example heat and pressure losses within the system. These types of losses may affect the results greatly and therefore this data can be slightly misleading. By looking further into this or to estimate the losses and take them into consideration may provide a more realistic picture of the machine.

The data provided for the Katrinefors mill was one year values based on an average value per hour. For the pinch analysis an average yearly value was used. This type of simplification shows a rather simplified picture of the process. This is because the machine is not running all days of the year and also this particular machine does not only produce one type of paper. It can produce papers with different weights. Another thing to consider is the demand, since the machine produces more or less paper during the different seasons of the year. An option to get a better view over the machine would be to divide the year into seasons and/or according to shifting demands. It would be of even more importance if both these factors would be taken in to consideration. Neither one of these options was taken into consideration in this master's thesis due to time limitations.

For both the scaled machine and Katrinefors mill estimations and simplifications had to be made. The reason for this was that some data was not available and also due to the fact that the data used was based on a yearly average value. One particular estimation that affects the result significantly is the soft target on the fresh water entering the heat exchanger QGV. Since the Katrinefors mill does not have any information about the water stream coming from the ventilation of a nearby company, which is mixed with fresh water, this soft target was set at 27 °C. The soft target was set this high in order for the energy balance over the system to be fulfilled. This temperature is not reasonable as a yearly average but if it were to be reduced the heat demand would increase considerably as the flow of this stream is rather large. The scaled machine on the other hand could have a soft target set at 10°C which could be considered reasonable since the average temperature of Vänern, where the fresh water is taken from, is 6°C.

As parts of the scaled machine was based on the Katrinefors mill and scaled according to the amount of paper produced it may not provide the most realistic picture of this machine. But this was performed mainly to see the scaled machine in a larger perspective and to get a, to some extent, realistic image. The better option would primarily be to compare two tissue machines which are of the same size or at least produces the same type of paper. The other option would have been, instead of scaling another machine, to compare the Katrinefors mill with a machine of the same type or even compare the scaled machine with an existing machine of the same type.

The Katrinefors mill is striving for increasing the white water temperature with 10°C. The reason for this is that it would increase the dryness of the paper with 1% and therefore reduce the demand for drying with approximately 4-6%. For the suggested retrofit there are plenty of heat that can be saved and also money. This result opens the possibilities to increase the temperature of the white water further in order to supplementary decrease the demand for external utilities. If the temperature of the white water would be increased and therefore reduce the demand for the drying process other benefits would emerge. For example, if the reduced demand is the hot air which is produced from burning LPG then it would be environmentally beneficial. Suppose that the LPG demand is reduced with 4% then the CO_2 emissions would also be reduced with 4%. Since the Katrinefors mill is producing the hot air by burning LPG a reduction in the emissions is probably what the company is striving for. Another scenario could be that the steam demand is reduced instead and if the steam is produced through burning a fossil based fuel these emissions would also be reduced.

The retrofits suggested for the scaled machine and Katrinefors are rather similar and both would theoretically result in two systems working more effectively. Initially, in respect to space and the complexity of the machine, adding a heat exchanger should not be hard to achieve. This is due to the layout of the machine. Heat exchangers and other parts of the machine such as the micro flotation are placed separately from the machine; in the machine hall. This means that adding an extra heat exchanger does not require for example any particular piping since the system is not as complicated as a chemical plant for instance.

The difficulties on the other hand, for the suggested retrofit, might lie in the investment which depends on the companies what they think is acceptable and reasonable. For the Katrinefors mill the payback period is 1 and a half year. But as these investments are beneficial in the long term perspective this period might, however, not be that difficult to overcome. In the long term more than 2,6 million SEK will be saved every year with the suggested retrofit for the Katrinefors mill. In addition to this, if the white water temperature were to be increased by heating it with the remaining heat in the moist air the hot utility demand would be decreased further and reducing the energy costs further.

Adding the steam generating heat exchanger gives rise to issues regarding the other heat exchangers that follows. The temperature of the moist air entering the heat exchangers are lowered which result in reduced driving forces i.e. the minimum temperature difference. This will then require larger heat exchange areas as the load is the same and the existing areas might not be enough. This can however be solved by expanding the existing heat exchangers in order to cover the demand.

9 Conclusions

What can be concluded from this energy study, performed on the two types of tissue machines, is that there are room for improvements of different kinds. First and foremost roughly 40% of the utility demand could potentially be saved for the Katrinefors mill, 21% for the computer simulated Yankee hood in a scaled model of the Katrinefors mill and finally 20% for the computer simulated Yankee hood with the suggested retrofits. This would be achievable if two major alternations were to be implemented. The first one is to further cool and condense the steam present in the moist air in order to utilise the available heat as much as possible. Secondly is to use this moist air to generate parts of the steam vital for the drying process.

What can also be concluded is that for the Katrinefors mill the utility source could potentially be changed. Currently the hot utility demand is based on LPG and steam. With the suggested retrofit, where parts of the steam could potentially be generated with the moist air extracted from the Yankee hood. Part of the steam demand could be replaced with a hot water utility instead and be used in the system. This is though only possible when the moist air stream is not further cooled and condensed.

For the suggested retrofits investments are required that result in payback periods of 5 months for the Katrinefors mill. For the computer simulated Yankee hood as well as the computer simulated Yankee hood in a scaled model of the Katrinefors mill the payback period is 4 months. The amount of energy saved for the Katrinefors mill is approximately 182 kWh per tonne tissue paper, for the computer simulated Yankee hood and the computer simulated Yankee hood in a scaled model of the Katrinefors mill the same number is 270. These number put into perspective to the total use of energy is 16% and 20%. The suggested retrofits indicated a reduced utility demand and therefore decreased utility costs which are good incentives for changing the system.

10 Future work

Primarily the data for both the computer simulated Yankee hood and Katrinefors mill has to be evaluated and confirmed. This is order to validate the result from the pinch analysis. Additionally, the estimations and assumptions made also need to be confirmed. Further, the possibilities for cooling and condensing the steam further in the moist air should be investigated since this is an important part for the suggested retrofits. Finally a more detailed economic evaluation should be performed with prices equivalent to the actual market price.

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12 APPENDIX

Appendix 1 - Data Katrinefors mill

Appendix 2 - Computer simulated Yankee hood and computer simulated Yankee hood in a scaled model of the Katrinefors mill

Appendix 3 - Calculations

Appendix 4 - Composite curves

Appendix 5 - Stream presentations

Appendix 1 – Katrinefors mill

Machine specification and production data.

Table 29 Machine data on PM35, Katrinefors mill.

MACHINE DATA, PM35	*Value*	*Unit*
Number of press rolls	2	
Yankee dryer data		
Yankee diameter	5500	[mm]
Yankee shell width	3960	[mm]
Design steam pressure	8.6	[bar]
HOOD DATA		
Effective hood area	37.7	[m2]
AIR SYSTEM DATA		
Max design impingement T	520	[Celsius]
Max impingement speed WE/DE	102	[m/s]
AIR SYSTEM BURNERS		
Consumption (from gas flow m) WE/DE	198/198	[kg gas/h]
Power WE/DE	2690/2690	[kW]

Table 30 Production data, Katrinefors mill.

PRODUCTION DATA	*Value*	*Unit*
Yankee speed	1480	[mpm]
Reel speed	1226	[mpm]
Sheet width at Yankee dryer	3.54	[m]
Sheet width at reel	3.54	[m]
Bone dry (BD) production at Yankee	1.69	[kg BD/s]
Evaporation at Yankee	1.98	[kg water/s]
Production at reel	6.54	[ton paper/h]
Yankee dryer steam pressure	4.6	[bar(g)]
Impingement temperature WE/DE	495/494	[Celsius]
Impingement speed WE/DE	103/93	[m/s]

Dimensioned heat exchangers in the system.

Table 31 Dimensioning for the fresh air heat exchanger.

Fresh air HEX	***Unit***	***Wet section***	***Fresh air***
T in	°C	314	25
T out	°C	206	259
x in	kg water/kg dry air	0.533	0.051
x out	kg water/kg dry air	0.533	0.015
Flow	kg/s	3.9	3.5

Table 32 Dimensioning for the fresh water heat exchange; QGV.

Fresh water HEX	***Unit***	***Wet section***	***Water***
T in	°C	206	10
T out	°C	127	40
x in	kg water/kg dry air	0.533	
x out	kg water/kg dry air	0.328	16.6
Flow	kg/s	3.9	2085

Table 33 Dimensioning for the fresh air for the machine hall to prevent condensation.

Ceiling air HEX	***Unit***	***Wet section***	***Air***
Cold winter			
T in	°C	127	-18
T out	°C	86	50
x in	kg water/kg dry air	0.327	0.001
x out	kg water/kg dry air	0.246	0.001
Flow	kg/s	3.9	15
Normal winter			
T in	°C	127	-5
T out	°C	87	54
x in	kg water/kg dry air	0.327	0.001
x out	kg water/kg dry air	0.26	0.001
Flow	kg/s	3.9	15
Summer			
T in	°C	127	20
T out	°C	89	60
x in	kg water/kg dry air	0.327	0.01
x out	kg water/kg dry air	0.287	0.01
Flow	kg/s	3.9	15

Table 34 Dimensioning for the fresh air for the room ventilation,

Ventilation HEX	*Unit*	*Wet section*	*Air*
Cold winter			
T in	°C	86	-18
T out	°C	67	18
x in	kg water/kg dry air	0.246	0.001
x out	kg water/kg dry air	0.161	0.001
Flow	kg/s	3.9	25
Normal winter			
T in	°C	87	-5
T out	°C	70	27
x in	kg water/kg dry air	0.26	0.001
x out	kg water/kg dry air	0.185	0.001
Flow	kg/s	3.9	25
Summer			
T in	°C	Not in use	Not in use
T out	°C	Not in use	Not in use
x in	kg water/kg dry air	Not in use	Not in use
x out	kg water/kg dry air	Not in use	Not in use
Flow	kg/s	Not in use	Not in use

Table 35 Dimensioning for the scrubbers.

Scrubber	Unit	Wet section	White water
Cold winter			
T in	°C	67	30
T out	°C	42	40
x in	kg water/kg dry air	0.161	
x out	kg water/kg dry air	0.056	
Flow	kg/s	3.9	27
Normal winter			
T in	°C	70	30
T out	°C	44	42
x in	kg water/kg dry air	0.185	
x out	kg water/kg dry air	0.016	
Flow	kg/s	3.9	27
Summer			
T in	°C	89	30
T out	°C	50	49
x in	kg water/kg dry air	0.287	
x out	kg water/kg dry air	0.088	
Flow	kg/s	3.9	27

Table 36 Streams in the pinch analysis, Katrinefors mill.

	Short	Flow [kg/s]	T_{start} [°C]	T_{target} [°C]	x_{in}	x_{out}	h_{in} [kJ/kg]	h_{out} [kJ/kg]	Q [kW]	FC_p [kJ/s/°C]
Yankee										
Moist air	MA	5.5[1]	271[1]	58[4]	0.387[1]	0.137[6]	1434[3]	416[3]	5599[3]	26.3[3]
Fresh air	FA	4.4[1]	6[6]	165[2]	0.015[2]	0.015[2]	44[3]	208[3]	715[3]	4. 5[3]
Fresh water QGV	FWQGV	5.0[6]	27[6]	73.1[4]					975[3]	36.2[3]
Ceiling air	AC	15[2]	6[2]	50[2]	0.001[2]	0.001[2]	8.5[3]	52.9[3]	665[3]	15.1[3]
Room ventilation	RV	25[2]	6[2]	20[2]	0.001[2]	0.001[2]	8.5[3]	22.7[3]	353[3]	25.2[3]
Scrubber	WS	33.3[4]	46.3[4]	58.5[4]					1686[3]	139.2[3]
Steam										
Cooling water condenser	CWC	0.677[3]	6.6[2]	59[4]					148[3]	2.8[3]
Steam condenser	STC	0.066[3]	111[5]	111[6]					148[3]	1.3[3]
Steam LPG	STLPG	0.018[3]	111[5]	111[6]					41[3]	0.37[3]
Condensate to KKAB	C-KKAB	1.46[4]	111[5]	10[6]					616[3]	6.1[3]
LPG	LPG	0.091[1]	25[6]	50[3]					41[3]	0.15[3]
Other										
Fresh water white water tank	FW-WT	6.7[4]	6.6[2]	50[6]					1208[3]	27.8[3]
Vacuum pumps	VP	7.2[2]	36.5[3]	10[6]					192[3]	7.2[3]
Wire evacuation	WE	22.4[2]	36.5[3]	10[6]					596[3]	22.5[3]
Waste water	WW	11.8[4]	36.5[3]	10[6]					1305[3]	49.2[3]
De-inking water	DW	41.7[4]	39.5[4]	50[6]					1829[3]	174.1[3]
Hood										
Wet end	WE	13.9[1]	271[1]	371[4]	0.3871[1]	0.3409[1]			1130[1]	
Dry end	DE	15.6[1]	290[1]	328[4]	0.215[1]	0.269[1]			1190[1]	
Yankee										
Steam	ST	1.45[4]	150[4]	150[4]					3384[1]	

1. Values taken from the simulation program developed by Metro Gorizia, Italy.

2. Data taken from the Gorizia machine check-up report, dimensioning data or yearly average.

3. Calculated values.

4. From data provided by Metsä, yearly average value, from the logging system.

5. Data & Diagram .

6. Based on assumptions and estimations.

In the first flash the pressure is reduced with 1 bar and in the second the pressure is reduced to 0,5 bar(g).

Table 37 Data for the flashes.

	Pressure [bar(g)]	Temperature [°C]	h_{liq} [kJ/kg]	h_{vap} [kJ/kg]	Δh_{vap} [kJ/kg]	C_p [kJ/kg/°C]
Flashes						
First flash	3.79[1]	141.79[2]	596.82[2]	2736.31[2]	2139.48[2]	
Second flash	1.5[1]	111.37[2]	467.17[2]	2693.47[2]	2226.3[2]	1.9[2]

1. From data provided by Metsä, yearly average value, from the logging system.

2. Data&Diagram, Energi- och kemitekniska tabeller by Sten-Erik Mörtstedt and Gunnar Hellsten.

Table 38 Steam generated in the second flash.

	Saturated liq inflow [kg/s]	Steam fraction	Steam flow [kg/s]	Liquid flow [kg/s]
Steam flow from the 2nd flash	1.46[2]	0.0582[1]	0.085[1]	1.37[1]

1. Calculated values.

2. From data provided by Metsä, yearly average value, from the logging system.

Table 39 Data for the condenser and evaporator.

	Q [kW]	Flow [kg/s]	Flow [m^3/h]	Δh_{vap} [kJ/kg]
Energy available in steam	189[1]			
Total LPG consumption		0.091[3]		447[2]
Energy for the LPG evaporation	41[3]			
Energy left for the water condenser	149[1]			
Amount of water that can be heated	0.68[1]		2.45[1]	
	Flow [kg/s]			
Steam flow for the LPG evaporation	0.0183[1]			
Steam flow to the condenser	0.0667[1]			
Total flow	0.085[1]			

1. Calculated values.

2. Data & Diagram.

3. Values taken from the simulation program developed by Metro Gorizia, Italy.

For further information on the calculations see Appendix 3.

Appendix 2 – Computer simulated Yankee hood and computer simulated Yankee hood in a scaled model of the Katrinefors mill

Machine specifications and production data.

Table 40 Machine data, computer simulated Yankee hood.

MACHINE DATA, DCT 200TS	***Value***	***Unit***
Yankee dryer data		
Yankee diameter	5500	[mm]
Yankee shell width	5706	[mm]
Design steam pressure	8.5	[bar]
AIR SYSTEM BURNERS		
Consumption (from gas flow m) WE/DE	356/395	[kg gas/h]
Power WE/DE	4662/5189	[kW]

Table 41 Production data, computer simulated Yankee hood.

PRODUCTION DATA	***Value***	***Unit***
Yankee speed	2000	[mpm]
Reel speed	1600	[mpm]
Dryness after the press	39.5	[%]
Dryness at reel	95	[%]
Sheet width at Yankee dryer	3.54	[m]
Sheet width at reel	5.6	[m]
Bone dry (BD) production at Yankee	5.706	[kg BD/s]
Evaporation at Yankee	3.63	[kg water/s]
Production at reel	9.1	[ton paper/h]
Yankee dryer steam pressure	8	[bar(g)]

Table 42 Streams in the pinch analysis for the computer simulated Yankee hood.

	Short	Flow [kg/s]	T_{start} [°C]	T_{target} [°C]	x_{in}	x_{out}	h_{in} [kJ/kg]	h_{out} [kJ/kg]	Q [kW]	FC_p [kJ/s/°C]
Yankee										
Moist air	MA	8.9[1]	343[1]	58[4]	0.515[1]	0.137[5]	1959[3]	416[3]	13754[3]	48.2[3]
Fresh air	FA	7.22[1]	6[2]	200[2]	0.01[2]	0.0[2]	31[3]	230[3]	1435[3]	7.4[3]
Hood										
Wet end	WE	16.2[1]	343[1]	480[4]	0.515[1]	0.419[1]			3804[1]	
Dry end	DE	18.7[1]	340[1]	480[4]	0.3663[1]	0.28[1]			3812[1]	
Yankee										
Steam	ST	3.06[4]	175[4]	175[4]					6207[1]	

1. Values taken from the simulation program developed by Metro Gorizia, Italy.

2. Data taken from the Gorizia machine check-up report, dimensioning data or yearly average.

3. Calculated values.

4. From data provided by Metsä, yearly average value, from the logging system.

5. Based on assumptions and estimations.

Streams in the pinch analysis for the computer simulated Yankee hood in a scaled model of the Katrinefors mill, streams including an asterisk in the stream names have been scaled, i.e. increased with 70 percent.

Table 43 Streams in the pinch analysis, computer simulated Yankee hood in a scaled model of the Katrinefors mill.

	Short	**Flow [kg/s]**	**T_{start} [°C]**	**T_{target} [°C]**	**x_{in}**	**x_{out}**	**h_{in} [kJ/kg]**	**h_{out} [kJ/kg]**	**Q [kW]**	**FC_p [kJ/s/°C]**
Yankee										
Moist air	MA	8.9[1]	343[1]	58[4]	0.515[1]	0.137[6]	1959[3]	416[3]	13754[3]	48.2[3]
Fresh air	FA	7.22[1]	6[6]	200[2]	0.01[2]	0.0[2]	31[3]	230[3]	1435[3]	7.4[3]
Fresh water QGV*	FWQGV	17[6]	10[6]	73.1[4]					4487[3]	71.1[3]
Ceiling air *	AC	25.5[2]	6[2]	50[2]	0.001[2]	0.001[2]	8.5[3]	52.9[3]	1131[3]	25.7[3]
Room ventilation *	RV	42.5[2]	6[2]	20[2]	0.001[2]	0.001[2]	8.5[3]	22.7[3]	600[3]	42.8[3]
Scrubber *	WS	56.67[4]	51[4]	64.5[4]					3206[3]	236.6[3]
Steam										
Cooling water condenser	CWC	3.05[3]	6.6[2]	59[4]					667[3]	12.7[3]
Steam condenser	STC	0.30[3]	111[5]	111[6]					667[3]	6[3]
Steam LPG	STLPG	0.042[3]	111[5]	111[6]					93[3]	0.84[3]
Condensate to KKAB	C-KKAB	2.99[4]	111[5]	10[6]					1267[3]	12.5[3]
LPG	LPG	0.208[1]	25[6]	50[3]					93[3]	0.35[3]
Other										
Fresh water white water tank *	FW-WT	12.7[4]	6.6[2]	50[6]					2295[3]	52.9[3]
Vacuum pumps*	VP	12.2[2]	36.5[3]	10[6]					326[3]	12.3[3]
Wire evacuation *	WE	38[2]	36.5[3]	10[6]					1013[3]	38.2[3]
Waste water*	WW	20[4]	36.5[3]	10[6]					2218[3]	83.7[3]
De-inking water	DW	70.9[4]	39.5[4]	50[6]					3110[3]	296[3]
Hood										
Wet end	WE	16.2[1]	343[1]	480[4]	0.515[1]	0.419[1]			3804[1]	
Dry end	DE	18.7[1]	340[1]	480[4]	0.3663[1]	0.28[1]			3812[1]	
Yankee										
Steam	ST	3.06[4]	175[4]	175[4]					6207[1]	

1. Values taken from the simulation program developed by Metro Gorizia, Italy.

2. Data taken from the Gorizia machine check-up report, dimensioning data or yearly average, scaled.

3. Calculated values.

4. From data provided by Metsä, yearly average value, from the logging system.

5. Data & Diagram

6. Based on assumptions and estimations.

Table 44 Data for the two flashes.

	Pressure [bar(g)]	**Temperature [°C]**	**h_{liq} [kJ/kg]**	**h_{steam} [kJ/kg]**	**Δh_{vap} [kJ/kg]**	**C_p [kJ/kg/°C]**
Flashes						
First flash	8[1]	170.4[2]	721[2]	2769[2]	2048[2]	
Second flash	1.5[1]	111.37[2]	467.17[2]	2693.47[2]	2226.3[2]	1.8897[2]

1. From data provided by Metsä, yearly average value, from the logging system.

2. Data & Diagram.

In the first flash the pressure is reduced with 1 bar and in the second the pressure is reduced to 0,5 bar(g).

Table 45 Steam generated in the second flash.

	Saturated liq, inflow [kg/s]	**Steam fraction**	**Steam flow [kg/s]**	**Liquid flow [kg/s]**
Steam flow from the 2nd flash	3.0[2]	0.114[1]	0.3414[1]	2.653[1]

1. Calculated values.

2. From data provided by Metsä, yearly average value, from the logging system and scaled.

Table 46 Data for the condenser and evaporator.

	Q [kW]	**Flow [kg/s]**	**Flow [m^3/h]**	**Δh_{vap} [kJ/kg]**
Energy available in steam	760[1]			
Total LPG consumption		0.2083[2]		447[3]
Energy for the LPG evaporation	93[2]			
Energy left for the water condenser	667[1]			
Amount of water that can be heated	3.05[1]		11[1]	
	Flow [kg/s]			
Steam flow for the LPG evaporation	0.0418[1]			
Steam flow to the condenser	0.3[1]			
Total flow	0.3414[1]			

1. Calculated values.

2. Values taken from the simulation program developed by Metro Gorizia, Italy.

3. Data & Diagram.

For further information on the calculations see Appendix 3.

Appendix 3 – Calculations

Mollier chart and enthalpy calculations

The moist air present in all three machines has been divided into two parts this because the stream is a mixture of steam and air. When considering this stream as a heat source the air has to initially be cooled down to the dew point before the condensation of the steam can being. The dew point can be either calculated or determined through a so called Mollier chart based on moist air.

From the Mollier chart the wet thermometer temperature is represented as the red line and the moisture content as the blue line. For example a stream which keeps a temperature of 40°C can achieve condensation down to approximately 4% with a relative humidity of 100%, φ =1 in the chart and shown as the green line, and is displayed in the chart with the black . The Mollier chart does not include temperatures above 40°C. But as the temperature of the moist air released to the atmosphere keeps a temperature of 58°C a program named Ångbiblioteket used in Microsoft Office Excel was used to determine the moisture content of the stream at 58°C. This program works in the same way as a Mollier chart.

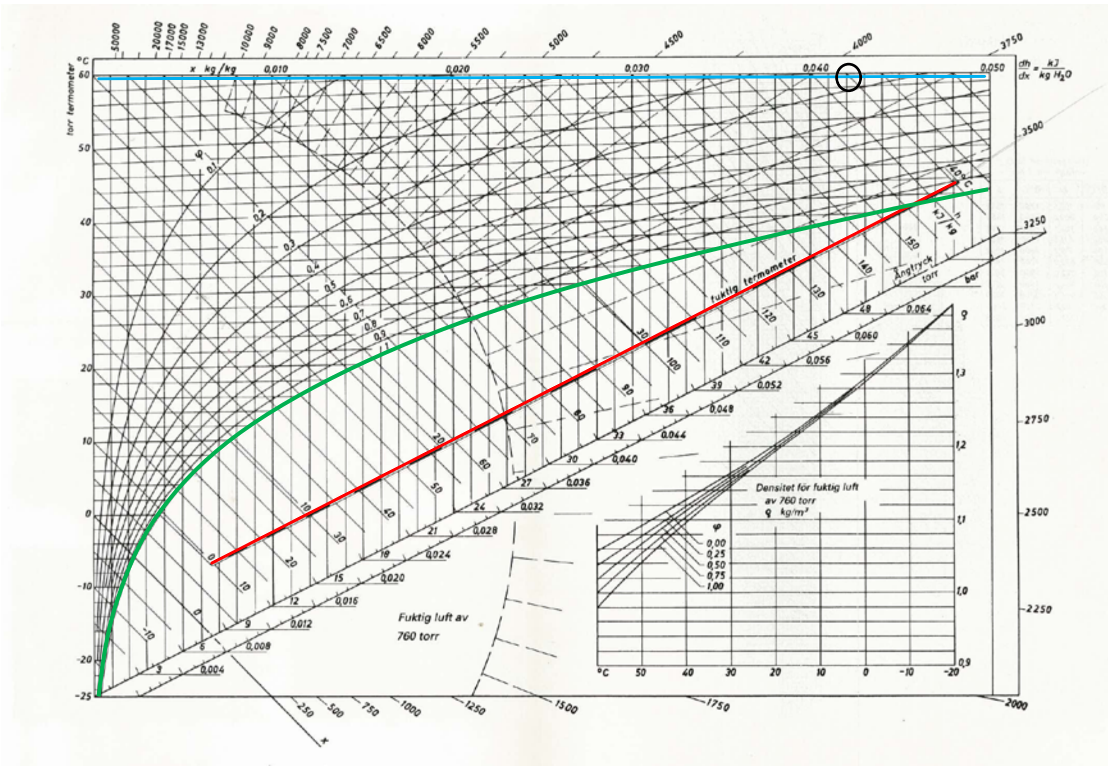

Figure 22 Mollier chart for moist air. (Data & Diagram, 2005)

Since the moist air stream contains both hot air and steam the initial step is to divide the stream into two different parts; one where the hot air is cooled down to the dew point and the other where the steam condenses. In order to determine the enthalpy and then the heat content of the stream the temperature and also the moisture content had to be taken into consideration.

For the Katrinefors mill the temperature of the moist air stream is initially 271°C and with the dew point given at 75°C at a moisture content of 38,7% the air is cooled between these temperatures. The enthalpy difference for this part is calculated from the equation given below.

$$Enthalpy = \left(C_{p,air} \cdot T + x\left(C_{p,water} \cdot T + \Delta h_{vap,water}\right)\right) \qquad \left[\frac{kJ}{kg}\right] \qquad (1)$$

For cooling the air the equation appears as follows, where the moisture content is not changed from the initial state to the final.

$$336{,}8\ kJ/kg = \left(1{,}006 \cdot 271 + 0{,}3871 \cdot (1{,}84 \cdot 271 + 2501)\right) - \left(1{,}006 \cdot 75 + 0{,}3871 \cdot (1{,}84 \cdot 75 + 2501)\right)$$

For the condensation of the steam on the other hand this equation looks different as the steam content is reduced from 38,7% to 5% and the temperature reduced from 75°C to 58°C. The enthalpy difference for the condensation is show below.

$$908{,}3 kJ/kg = \left(1{,}006 \cdot 75 + 0{,}3871 \cdot (1{,}84 \cdot 75 + 2501)\right) - \left(1{,}006 \cdot 58 + 0{,}05 \cdot (1{,}84 \cdot 58 + 2501)\right)$$

The moist air stream has a flow of 5,5 kg per second which gives the total energy content of this stream to 5600kW. This calculation was performed for all three machines.

The energy content, Q, for water streams have been calculated with the following equation.

$$Q = \dot{m} \cdot C_p \cdot \Delta T \qquad [kW]$$

Condenser and evaporator

For the evaporator and condenser certain calculations were necessary due to lack of data. The amount of water heated in the condenser was for example not know neither was the amount of heat required to evaporated the LPG. The stream produced in the second flash is used as the heat source for both these purposes. It was known that the pressure of the condense is reduced down to 0,5 bar(g) in the second flash. With this information and also the input to the flash the amount of steam that is produces can be calculated through the following equation.

$$x = \left[\frac{h_{liq,in} - h_{liq,out}}{h_{vap,ut} - h_{liq,out}}\right]$$

By knowing the flow of the input, this steam fraction is used to calculate the flow of the steam and therefore also the heat content of. Assuming that this stream is completely condensing the heat of evaporation is used.

$$Q = \dot{m} \cdot \Delta h_{vap} \qquad [kW]$$

Further, the amount of LPG needed to produce the hot air is known through the simulation program developed by Metso Gorizia. The amount of heat can then be calculated by knowing the heat of evaporation for LPG; 447 kJ/kg. The remaining heat is used to heat the fresh water entering the condenser and the amount of water is calculated based on this information.

Heat exchangers

The overall heat transfer coefficient was estimated with:

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2}$$

The h-values used are based on the type of fluid passing the heat exchangers and the values used are presented in Section 2.1 and Table 1.

Appendix 4 – composite curves

Katrinefors mill

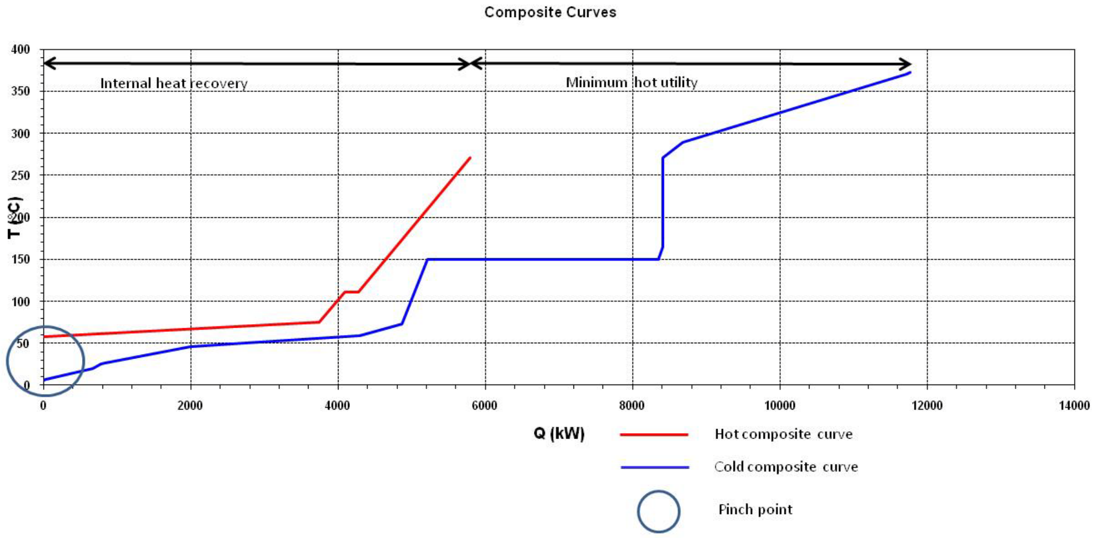

Figure 23 Stream presentation for the original system without wire evacuation, vacuum pumps, waste water and another fresh water stream.

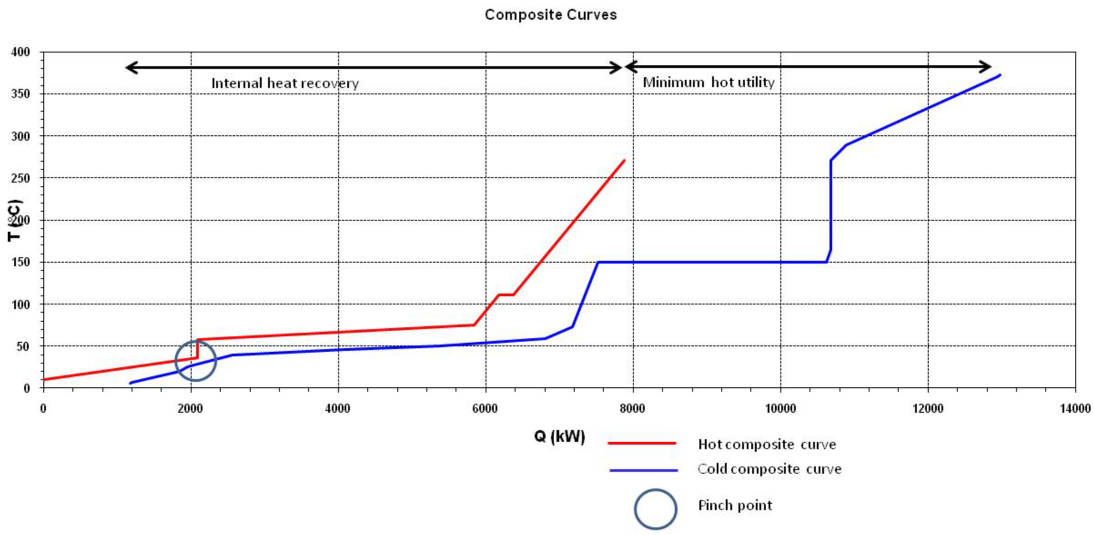

Figure 24 Composite curve for the Katrinefors mill including the wire evacuation, vacuum pumps, waster water and another fresh water stream with the current moisture content of the moist air stream exiting the system.

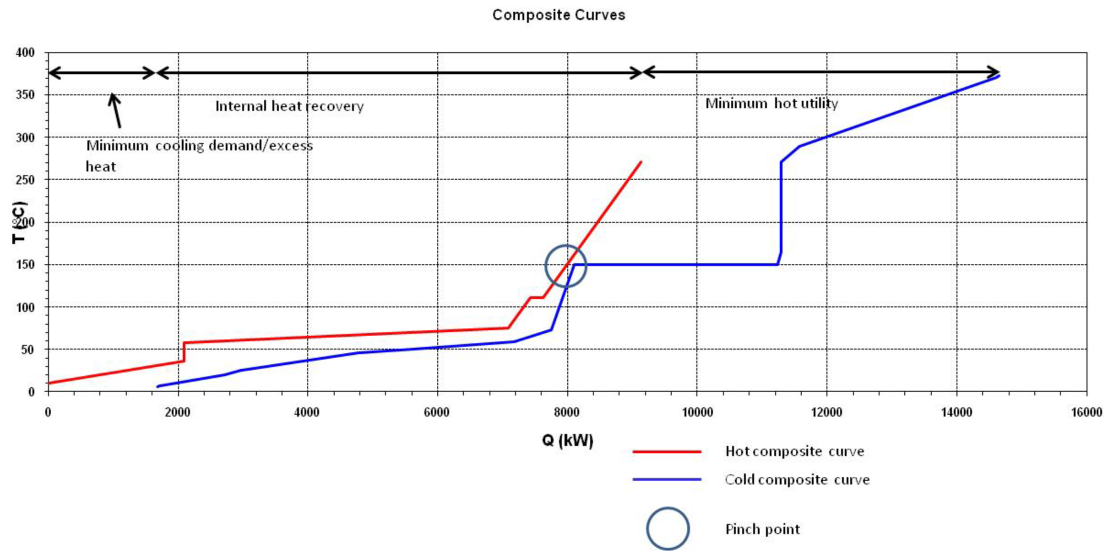

Figure 25 Composite curve for the Katrinefors mill including the wire evacuation, vacuum pumps, waster water and another fresh water stream with a decreased moisture content of the moist air stream exiting the system.

Computer simulated Yankee hood

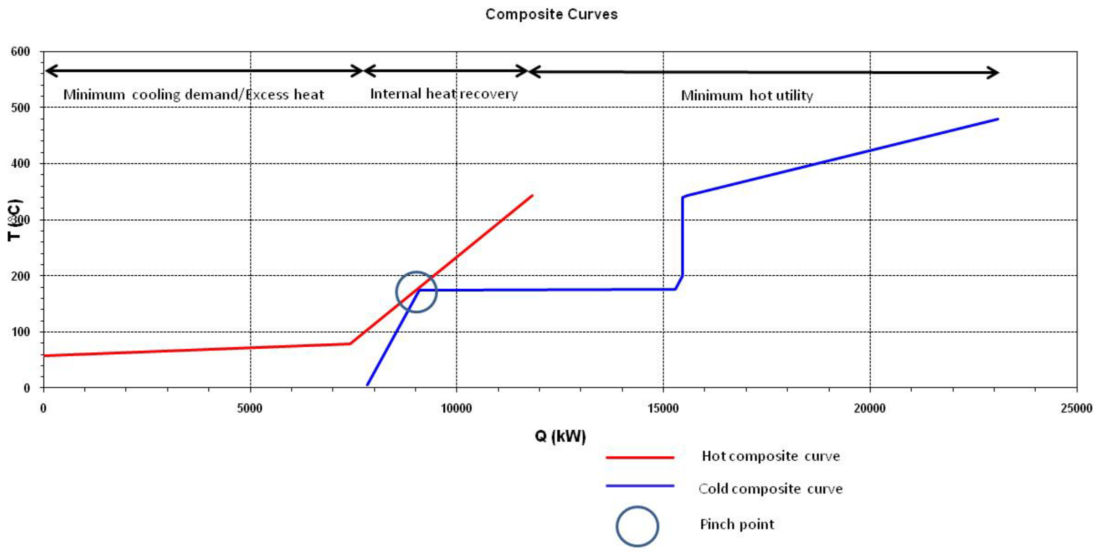

Figure 26 Composite curve for the simulated Yankee hood.

Computer simulated Yankee hood in a scaled model of the Katrinefors mill

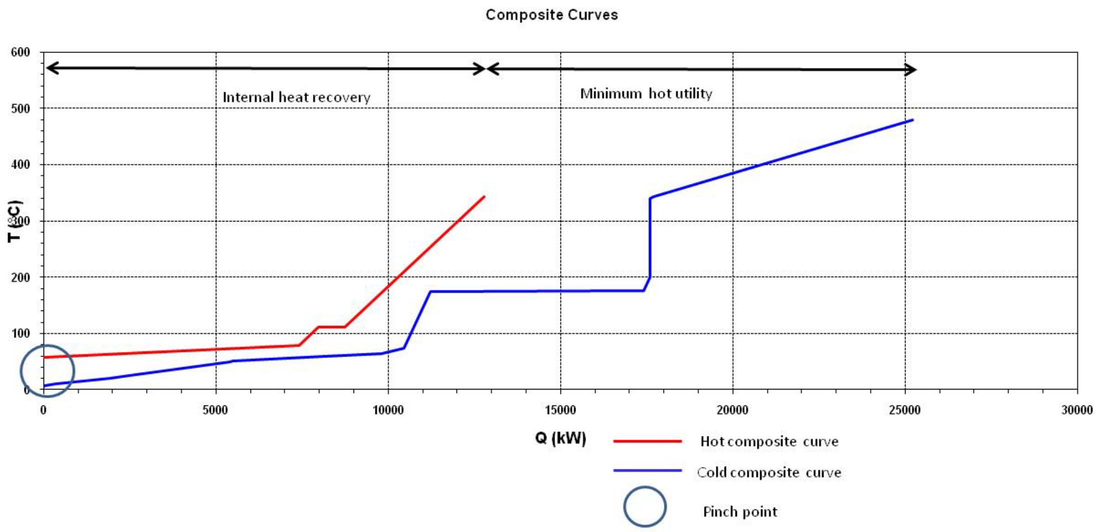

Figure 27 Composite curves for the computer simulated Yankee hood in a scaled model of the Katrinefors mill for the current system.

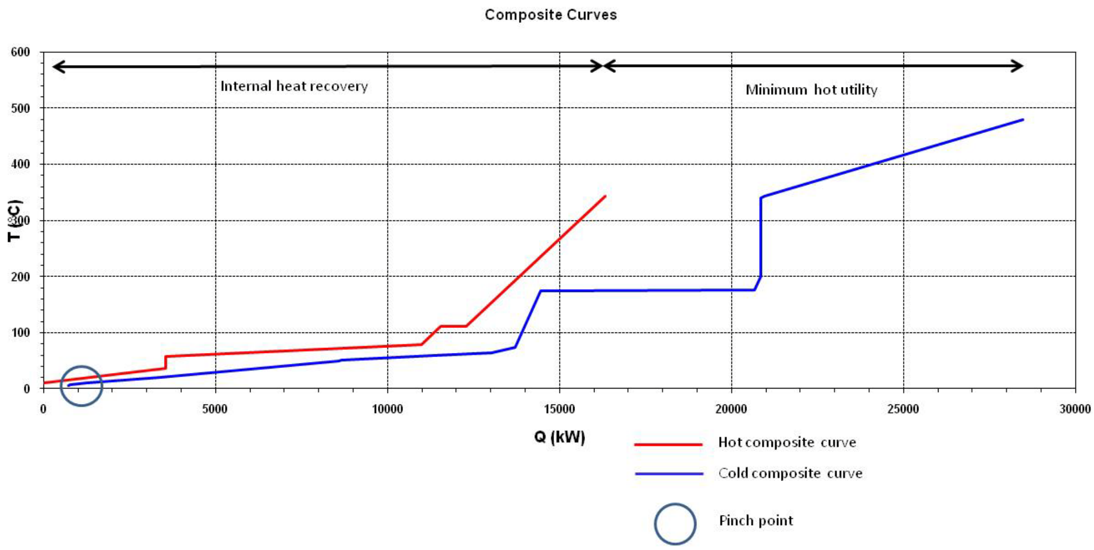

Figure 28 Composite curves for the computer simulated Yankee hood in a scaled model of the Katrinefors mill including the wire evacuation, vacuum pumps, waste water and another fresh water stream.

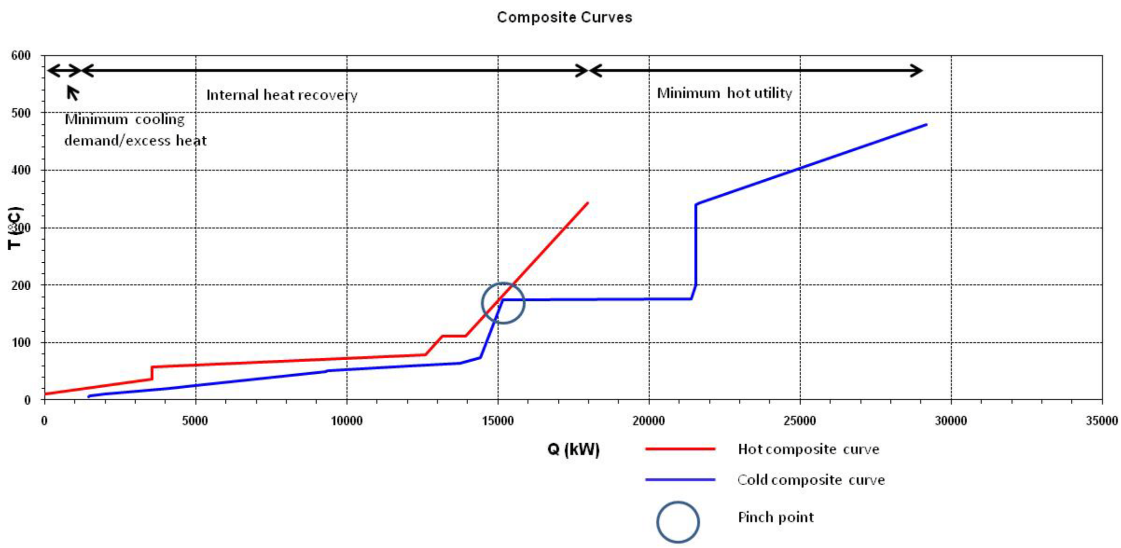

Figure 29 Composite curves for the computer simulated Yankee hood in a scaled model of the Katrinefors mill including the wire evacuation, vacuum pumps, waste water and another fresh water stream with an decreased moisture content in the moist air stream exiting the system.

Appendix 5 – Stream presentations

Stream presentation - Katrinefors mill

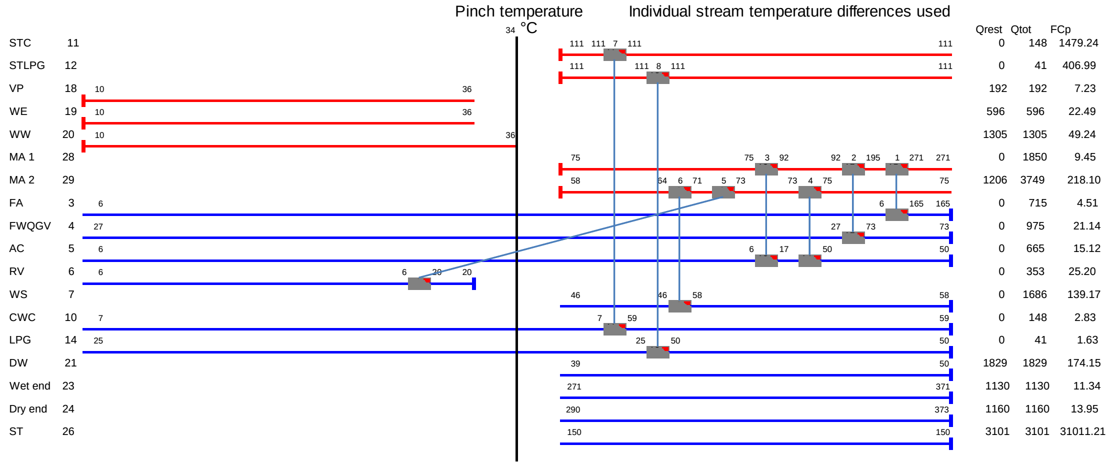

Figure 30 Original stream presentation for the Katrinefors mill.

There are in total seven heat exchangers present in this system, even though eight can be seen in Figure 31, heat exchanger 2 and 3 is considered as one. The reason for this is that the moist air stream has been divided into two streams which were explained in Section 4.4. The two main pinch violations can also be seen in the stream presentation. That is as the moist air stream increases the temperature of the fresh air for the machine hall to prevent condensation and also for the room ventilation.

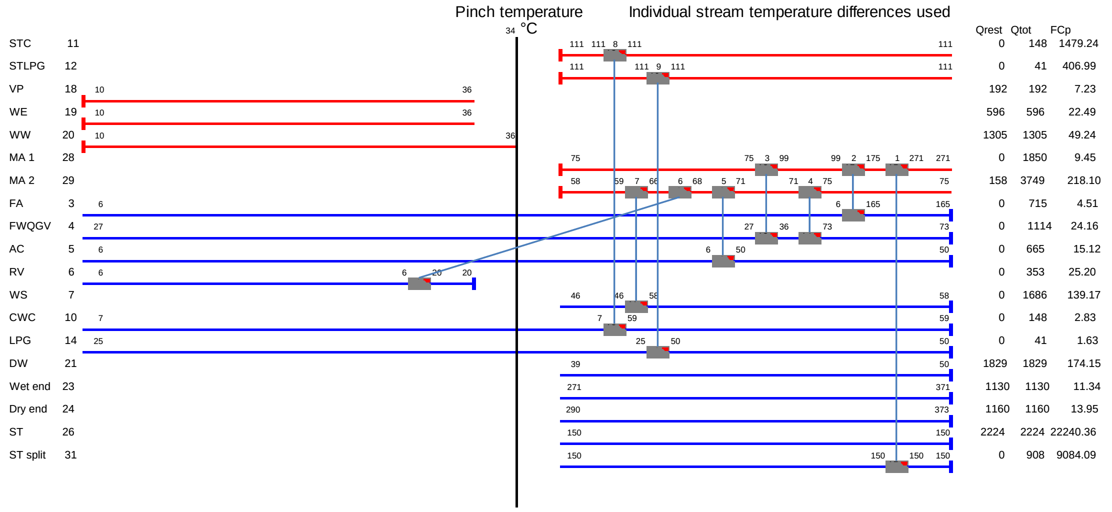

Figure 31 Stream presentation for the suggested retrofit for the present system.

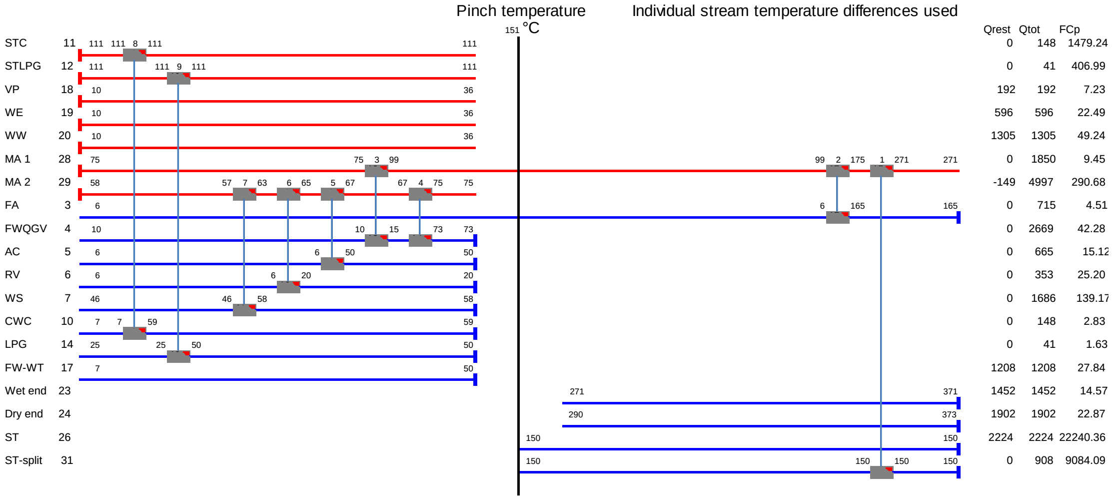

Figure 32 Stream presentation for the suggested retrofit with further cooling and condensing the moisture in the moist air.

Stream presentation – Computer simulated Yankee hood

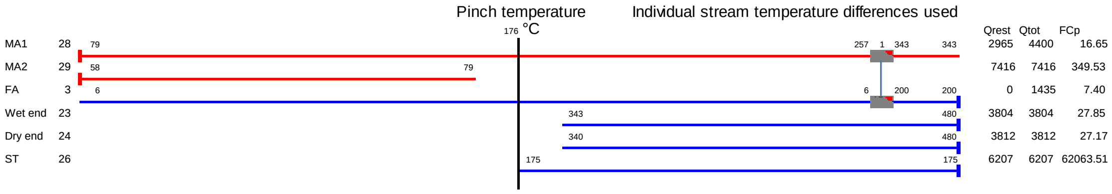

Figure 33 Original stream presentation for the Yankee hood.

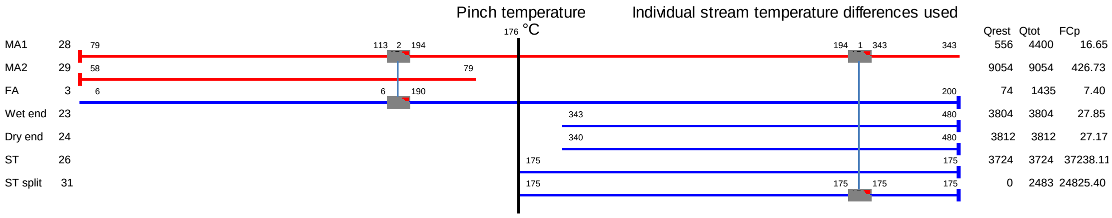

Figure 34 Retrofit suggestion for the Yankee hood.

Stream presentation – Computer simulated Yankee hood in a scaled model of the Katrinefors mill

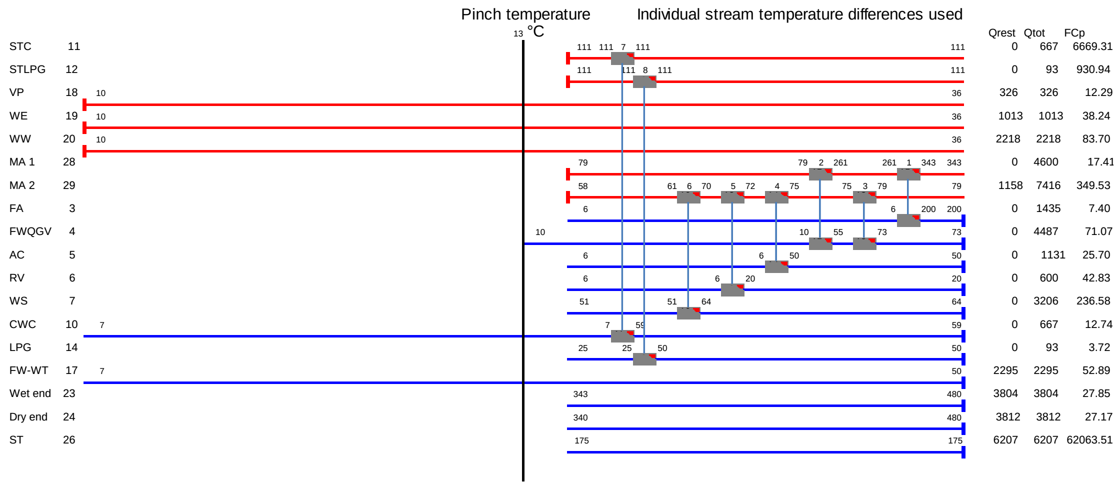

Figure 35 Stream presentation for the computer simulated Yankee hood in a scaled model of the Katrinefors mill.

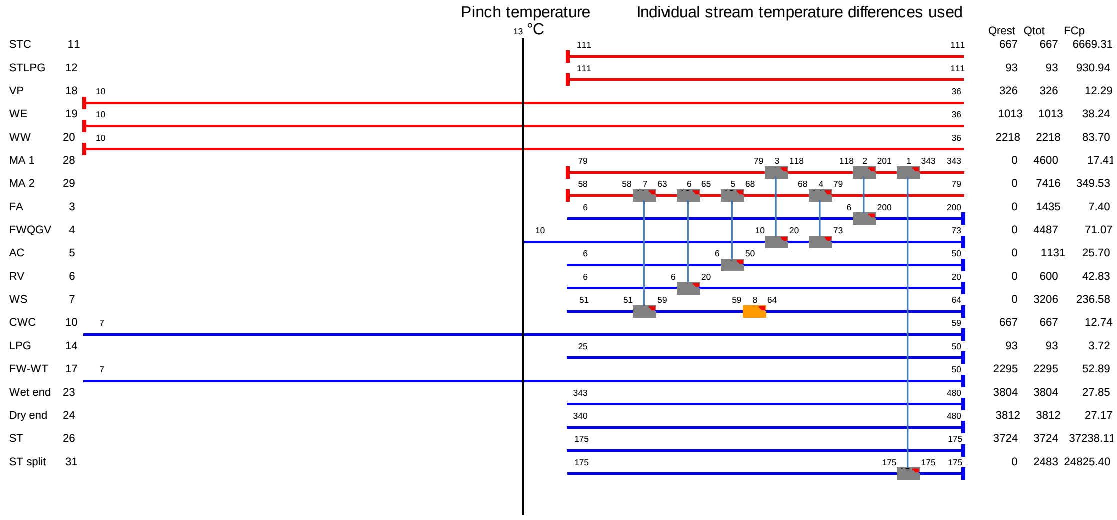

Figure 36 Suggested retrofit for the original system for the computer simulated Yankee hood in a scaled model of the Katrinefors mill.

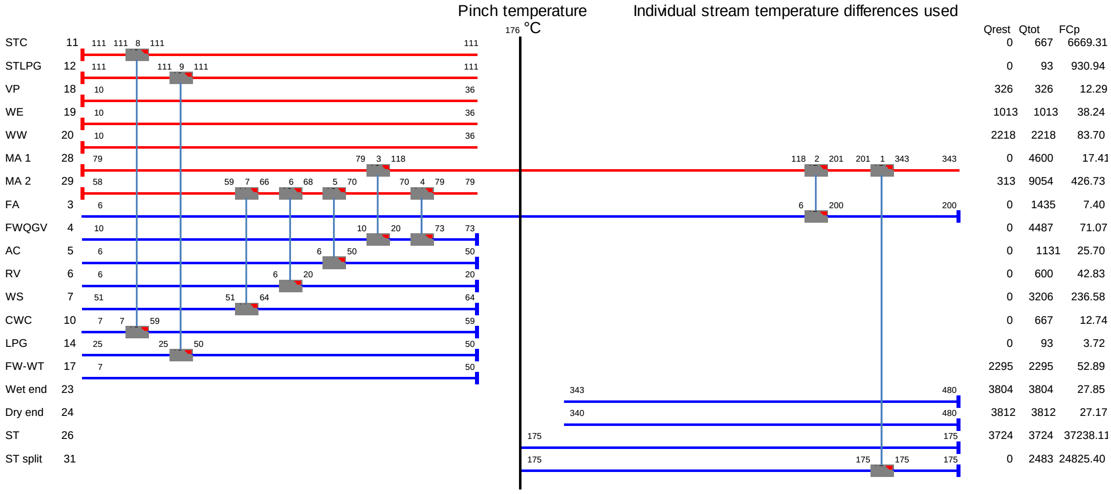

Figure 37 Retrofit for the computer simulated Yankee hood in a scaled model of the Katrinefors mill with an increased condensation.