WinGEMS modelling and pinch analysis of a paper machine for utility reduction

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SUMMARY

A multi-ply paper machine process model was developed using WinGEMS and the stream data produced was used to conduct a pinch analysis. The product stream was excluded from the analysis and the composite curves display the enthalpy contained only in the inputs and outputs to the various sections of the paper machine. The pinch point for the overall paper machine was 55.9°C while the minimum hot utility target was 170 MW. Occurrences of cross pinch heat transfer were identified and discussed. Heat recovery options for heating of the fresh water showers, using waste heat streams were investigated. Steam savings of over 14 MW could be achieved by recovering heat from two waste streams that currently go directly to drain with no heat recovery taking place. The use of pinch analysis for utilities targeting under non-continuous conditions was examined. Finally, the feasibility of integrating non-conventional technologies, such as heat storage, is discussed.

KEY WORDS
Pinch Analysis, Process Simulation, Energy Efficiency, WinGEMS

INTRODUCTION

As a major energy user the pulp and paper industry faces a number of issues regarding energy use, energy security, and energy costs. Superimposed are concerns over greenhouse gas emissions and subsequent emissions trading regimes or carbon taxes. Although the industry has a relatively low CO_2 intensity due to the heavy reliance on bioenergy in the form of wood waste and black liquor, integrated mills are often net importers of electricity from the grid and fossil fuel in the form of natural gas or coal. As a result they face increasing energy costs due to rising fuel and electricity prices, in addition to increases due to carbon trading and the like. Furthermore, it is expected that feed material prices will increase due to the improved returns from alternate land use for dairying or energy cropping for biofuel production.

The utilisation of existing technological solutions and the development of new ones are vital for the pulp and paper industry to improve specific energy consumption and help decouple profitability from energy costs. The competitiveness of mills will be improved over the long term by focusing on energy efficiency and conservation. Process heat integration is a successful field of engineering and formal methodologies such as process simulation and pinch analysis have been developed and applied to the pulp and paper industry with proven and useful results (*1*,*2*). Process integration projects aim to reduce utilities use (therefore fuel savings) or to eliminate constraints on capacity and production rates (*3*). As the cost of energy continues to increase, heat recovery and process improvement projects that have previously not been economically feasible will be re-examined. Improved heat recovery via increased heat exchange has been identified as an economic energy efficiency investment for pulp and paper mills (*4*).

A WinGEMS (Windows General Energy and Material balance System) process model of a hypothetical multi-ply paper machine was developed (*5*). Stream data was able to be ascertained using the WinGEMS process model. This stream data was then used in a pinch analysis. Heat recovery opportunities were identified as a result of the pinch analysis. This paper reports the findings of the pinch analysis and discusses some specific opportunities for heat recovery that were identified. Limitations of traditional pinch techniques are also discussed, specifically concerning the non-continuous nature of paper production.

Pinch Analysis and Process Simulation

Pinch analysis was developed as a process integration tool during the 1970's and has since been successfully applied to numerous industrial processes. Significant energy savings and enhanced process integration has been achieved by applying the various analysis techniques. The basic pinch analysis method is presented in Kemp (*6*) and Smith (*7*). Estimates of theoretical savings identified using pinch analysis in the pulp and paper industry range from ~20 to ~40% depending on the mill type and process, while practical savings range from between ~10 to ~28% (*1*).

Reliable and accurate stream data extraction is essential for a high-quality pinch study. This process can be a laborious and time consuming one and can comprise up to around 75% of the analysis budget (*1*). Despite the dependability of any pinch study relying on the quality of the input data (i.e. stream data), there is a dearth of information in the literature regarding systematic methodologies for stream data extraction and handling methods. Appropriate extraction and handling techniques will vary depending on the constraints and the aims of the individual project.

Mass and energy balances are often based on inaccurate or incomplete data sets. Even when all data is available, process fluctuations due to situations such as fouling or variable inputs cause the operating conditions to vary. This leads to significant overall inaccuracies that must be interpreted and carefully dealt with in order to make the balances useful. The enormity of the data collection task should not be underestimated, and will generally include data obtained from each of the following sources:

- Process Flow Diagrams;
- Piping & Instrument Diagrams;
- Process simulations;
- Control system measurements;
- Manual measurements;
- Operating manuals;
- Design specifications.

The information required to complete a pinch analysis study can be extracted

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from the process flow sheet and accompanying mass and energy balance. The minimum required information consists of the temperature, heating load (enthalpy), and CP (mass flow rate x heating capacity) for each stream. The data extraction phase is critical as it directly affects all the results arising from the overall pinch analysis.

Process simulation tools such as WinGEMS can provide valuable assistance during the data extraction stage of any pinch study. Furthermore a robust process model can help identify constraints and opportunities that could otherwise be overlooked. Process simulation also provides a convenient method for assessing the affect of process changes and to assist in identifying potential unforeseen consequences of proposed modifications (*8*). As most modern paper machines are required to produce several grades of paper or board, simulation can help identify variations in utilities profile with changes in grade or production rate (*9*). A robust process model on its own is a valuable tool to the papermaker or plant engineer even when no pinch study is being undertaken.

Traditional pinch analysis has focused on continuous processes and as a consequence methods to consider non-continuous, batch, and variable rate processes have not been developed to a satisfactory standard (*10*). Early work on batch processes employed a "pseudo-continuous" approach called the Time Average Model (TAM) that simply averages the heat flows over the entire duration of the operating period. Although this approach simplifies the analysis only a small proportion of the predicted savings are realised in practice. A more sophisticated approach was developed by Kemp & MacDonald called the Time Slice Model (TSM), which used time intervals to produce a series of time dependant heat cascades that provided targets for the amount of heat exchange and heat transfer (*6*). All pinch studies on paper machines have assumed steady state operation despite the fact that the utilities usage and stream conditions will vary with the productions of different grades. For example it is known that steam usage will vary significantly with sheet basis weight.

The concept of using pinch techniques to perform what is termed a total site analysis has been popular over the past decade. Total site analysis attempts to highlight interactions between the several individual plants on site (i.e. between the pulp mill, bleach plant, paper machine, etc). Although this is important, the authors have found that much detail can be lost when performing a total site analysis, and care must be taken. For example, a recent study of an integrated pulp and paper mill only included one stream from the paper machine and one stream from the pulp dryer in the entire analysis. Many heat recovery opportunities that existed within the paper mill were not identified due to the lack of detail in the total site analysis and by ignoring a number of significant process streams. Furthermore, practical implications such as geographic location within the mill may exclude heat exchange opportunities, which may not be considered in the total site analysis. Finally, variable production rates are also neglected as steady state operation is assumed in almost all pinch studies.

Data Collection & WinGEMS

The mass and energy balance for this case study is based on the results of a WinGEMS model that was created for a hypothetical multi-ply paper machine. Inputs to the model were based on typical values for a paper machine of this type. WinGEMS is a modular program designed to solve mass and energy balance equations. Mass and energy balance calculations are grouped together in modules known as blocks. There are many different blocks that may be used for simulation of various aspects of the pulp and paper making process. A simulation is constructed by arranging blocks and streams to create a diagram of the process. Blocks model unit operations while streams model process input and output flows. As more data is collected further calculations can be performed and the process can be modelled in greater detail. A schematic of the simplified paper machine model is illustrated in Figure 1.

A number of assumptions were made during the construction of the WinGEMS model to simplify the process. These assumptions should only have a very marginal effect on the resulting mass and energy balance. The input data used for this study was representative for a paper machine of this type. Cleaner and screen reject streams were considered to be minimal, whilst stock temperatures and consistencies were assumed to be typical.

As with all modelling strategies there are a number of limitations that the user needs to be aware of in order to successfully construct a valid process model. The model does not account for all fibre losses within the system, and does not estimate the heat losses occurring throughout the process. Despite these limitations a valuable model was constructed that gave a consistent mass and energy balance of the entire paper machine and associated streams.

Assumptions and Limitations of Pinch Analysis

The composite curves derived as part of the pinch analysis have been constructed using a minimum temperature difference (ΔT_{min}) of 10ºC as a driving force for heat transfer to occur. It has been assumed that all liquid streams involved in the pinch analysis can be cooled to a temperature of 25ºC, while heat recovery from air

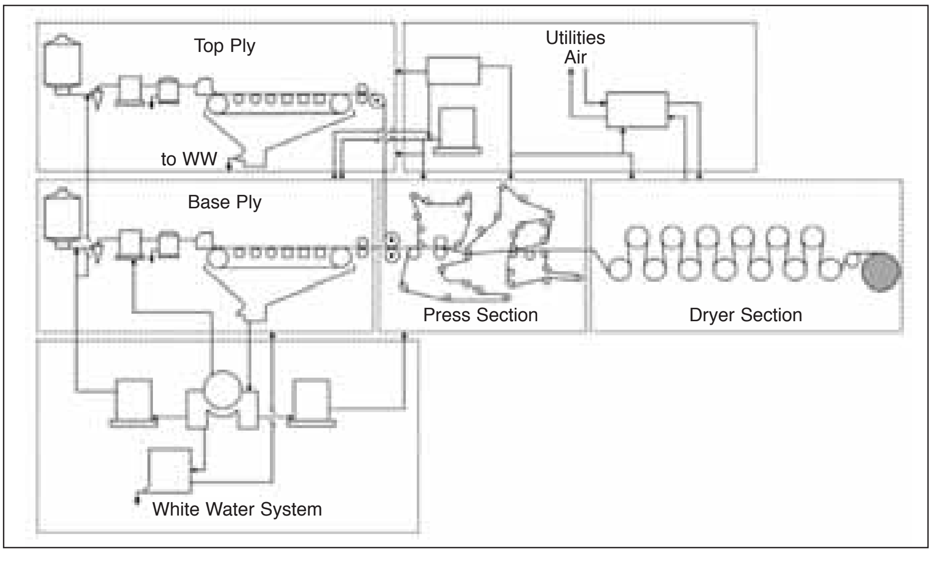

Fig. 1 Schematic of the simplified WinGEMS paper machine process model and detailed section of the dryer section from the model.

streams below 80ºC has been deemed unrealistic. An 80ºC limit for air streams only affects the dryer and utilities sections of the paper machine and is a conservative assumption. All enthalpy values use a reference point of 0ºC.

The coldest water streams entering the plant are at a temperature of 11.5ºC. This means that the 25ºC lower cooling limit for liquid streams results in a temperature difference of 13.5ºC for the utilities section, greater than the 10ºC limit used for the rest of the paper machine. It also results in a slightly higher temperature difference for the overall site. This implies that further opportunities may exist to exchange heat between waste streams and the cold water beyond those displayed on the overall composite curve.

An assumption was made that direct steam injection throughout the process could not be replaced by an equivalent amount of hot water. An approximation method was used on a number of these process streams to simplify the heat transfer during the condensing of steam. The condensing process could be modelled in greater detail by splitting the latent and sensible heat portions of the streams and compiling them separately. No heat or mass losses were considered during the pinch analysis process.

The modelling of a paper machine using traditional pinch analysis techniques provides difficulties due to the nature of paper production. The fibre consistency of the main process stream is vital and must remain within stringent limits at various points throughout the production cycle. Therefore heat recovery possibilities that would impact on the consistency are immediately made redundant.

To avoid generating numerous unfeasible heat recovery options a non-traditional form of data extraction was utilised for the pinch analysis study. Instead of examining all changes to the main process stream, the only data extracted from the mass balance is the stream data for the "other" flows currently occurring within the paper machine. This resulted in composite curves that display the enthalpy contained in the inputs and outputs from each section. While this method will eliminate any possibilities that would impact on the properties of the main process stream, it may also omit the full extent of some opportunities. For example, the options to replace a steam flow with hot water may not be highlighted. However, once the pinch point for the process is known, any cases of cross pinch heat transfer can be identified.

Another difficulty involved with carrying out a pinch analysis study on a paper machine is the common existence of direct recycle streams. Ignoring minor heat losses these recycle streams result in heat transfer with temperature differences approaching 0ºC; a lot less than the stipulated minimum temperature of 10ºC. Results of the pinch analysis, especially those from the white water system, where recycle is common will need to be carefully interpreted.

RESULTS AND DISCUSSION

Top Ply & Base Ply Sections

The composite curves for the top ply and the base ply are shown in Figure 2 and Figure 3 respectively. Figure 2 shows that the top ply system operates mainly in the region of 20 to 60ºC, other than a small input of steam. Removing the steam spike at the end shows the inputs and outputs are very similar, with the outputs having a slightly greater enthalpy due to the net amount of heated water removed from the process. The composite curves for the base ply show very similar results to those of the top ply as expected. It should be noted that the magnitude of the demand is an order of magnitude higher for the base ply than the top ply, due to the greater number of streams in the base ply section and their much larger flow rates.

Press & Dryer Sections

The outputs curve for the press section, shown in Figure 4, demonstrates that over 25 MW of heat is removed from this part of the paper machine. A significant portion of the inputs are at a temperature greater than the hottest outputs, however the overlapping region in the curves highlights possibilities for increased heat transfer in this region.

The composite curves for the dryer section, shown in Figure 5, indicate a number of high temperature streams are present. As the output curve virtually fully overlaps the input curve a large amount of heat recovery should be possible from the waste streams leaving this section of the paper machine.

White Water Section

The two curves for the white water section in Figure 6 are identical which shows that these streams are fully recycled within the process. They are displayed with a temperature difference of 10ºC, however in reality they are directly recycled and could be shown virtually overlapping each other.

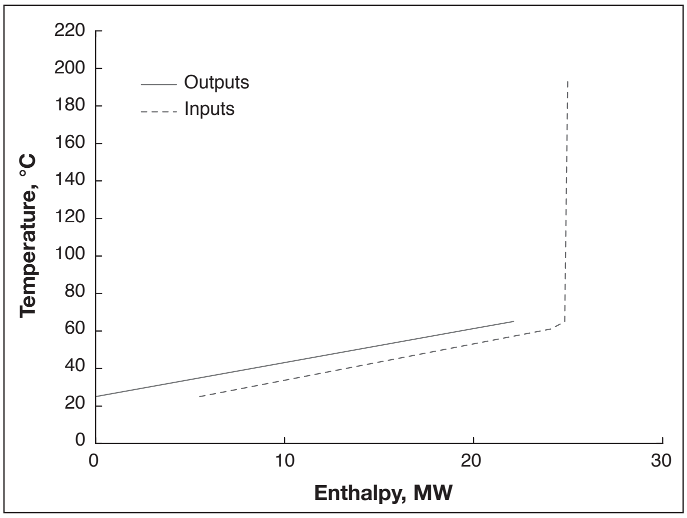

Fig. 2 Composite curves for the top ply system.

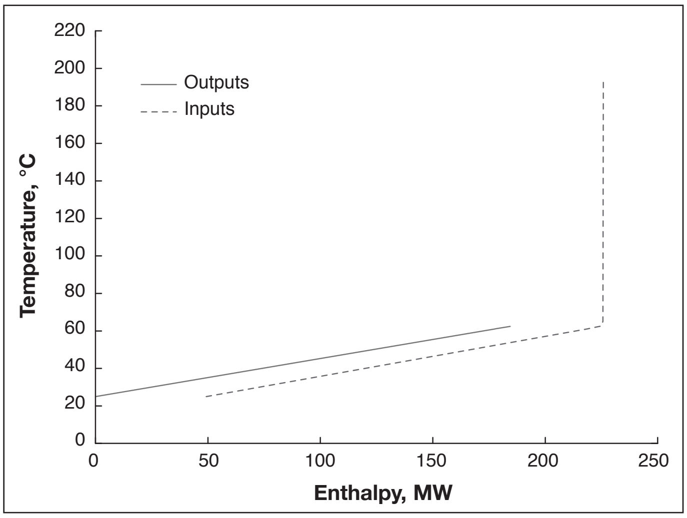

Fig. 3 Composite curves for the base ply system.

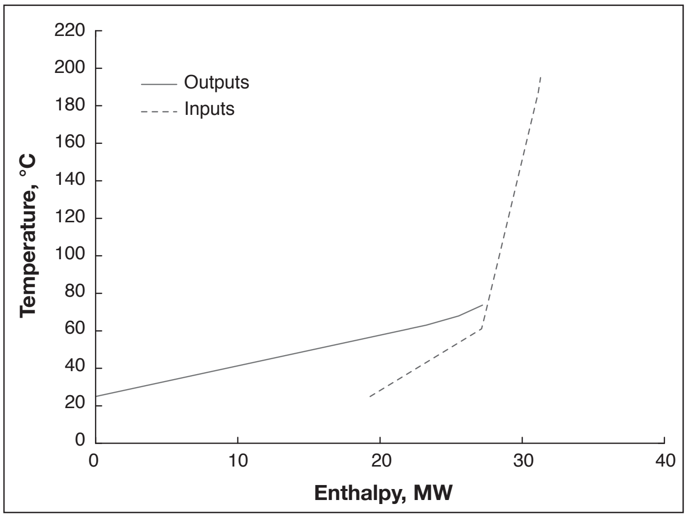

Fig. 4 Composite curves for the press section.

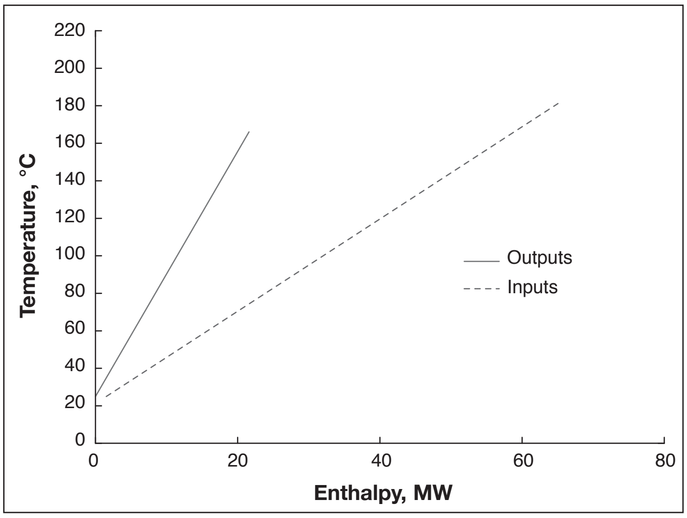

Fig. 5 Composite curves for the dryer section.

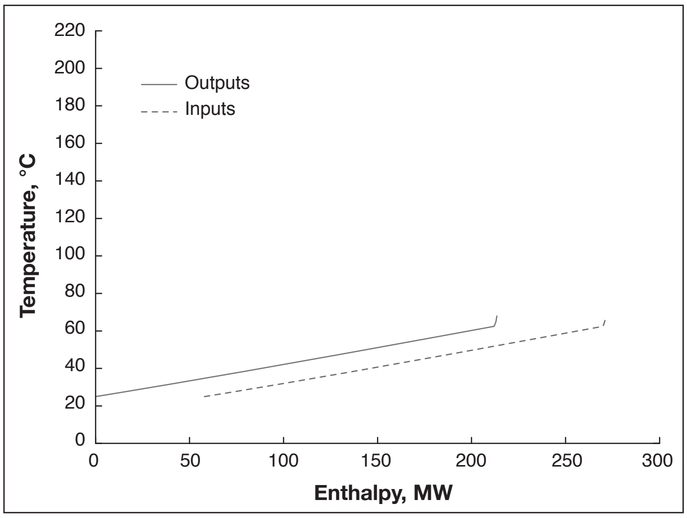

Fig. 6 Composite curves for the white water system.

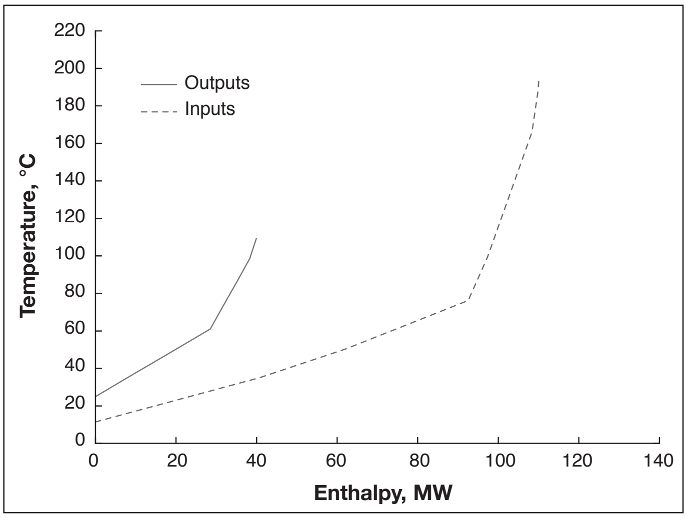

Fig. 7 Composite curves for the utilities.

Utilities Section

The input streams to the utilities section contain over 110 MW of enthalpy as demonstrated in Figure 7. The overlapping region with the output curve would suggest that close to 40 MW of this energy could theoretically be recovered. Of significance, is the fact that over half of the enthalpy in the input streams is at a temperature level of 45ºC or lower.

Overall Paper Machine

The overall composite curves are formed by combining each of the six sections previously displayed, and removing the double occurrence of streams that are both an input to one region and an output to another. The difference between the end points of the curves shows that the theoretical net amount of heating utility required by the paper machine is 170 MW. Assuming a minimum temperature difference for heat transfer of 10ºC, all enthalpy from the output streams could be theoretically recovered.

Grand Composite Curve

The grand composite curve plots the heat flow through the process against temperature. It can be generated from the overall composite curves by subtracting the total outputs curve from the total inputs curve for each point on the temperature range. The pinch temperature for the process is the point where the curve touches the y-axis, while the top and bottom end points indicate the hot and cold utility targets respectively.

The pinch point for the overall paper machine is 55.9ºC. This is midway between the input and output curves at vertically their closest point to touching, as shown by the overall composite curves in Figure 8. The temperature gap between the input and output curves is 10.5ºC, which corresponds to an input pinch temperature of 50.6ºC and an output pinch temperature of 61.2ºC. The pinch point is clearly highlighted on the grand composite curve as the point where the curve meets the y-axis in Figure 9. This implies that the heating of all cold streams should be possible up to this temperature level without the use of utility streams.

The upper portion of the grand composite curve extends to just over 200ºC, and reaches an enthalpy value of 170 MW. This is the minimum target for overall hot utility usage. The grand composite curve also shows the temperature levels at which this utility needs to be supplied. The graph shows that 100 MW of this heat is required only at a temperature of 70ºC, while only 45 MW is required above 100ºC.

Below the pinch point, the curve extends out to approximately 40 MW at a temperature level of approximately 20ºC before pointing back towards the y-axis. The graph heads back to the y-axis due to

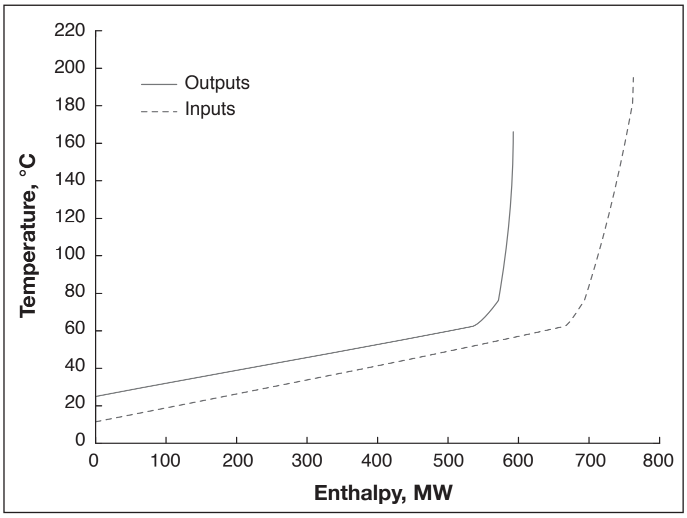

Fig. 8 Composite curve for the overall paper machine.

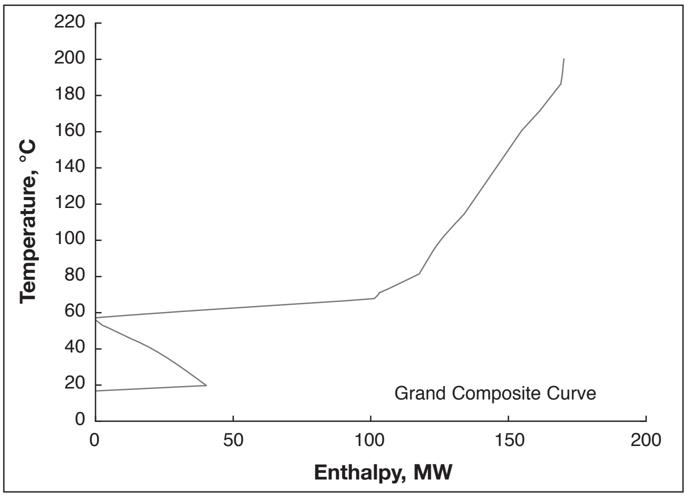

Fig. 9 Grand composite curve for the overall paper machine.

two assumptions, firstly heat can only be recovered from output streams down to 25ºC. Secondly, cooling of effluent streams is ignored as it occurs in waste treatment outside of the paper machine. Without these assumptions the grand composite curve would not head back towards the y-axis. Instead a target temperature level and enthalpy for the amount of cold utility would be found by analysing the lower end point of the grand composite curve.

Cross pinch heat transfer

Based on the assumptions made during the pinch analysis, the overall process has a hot utility target of 170 MW and no need for cold utility. Note that plenty of cold water is required by the process, however it is generally used for dilution and not to carry out a specific cooling task. Therefore, the obvious place to look for energy savings is to find situations where the amount of hot utility used can be reduced.

The grand composite curve also showed that the pinch point was located at 55.9ºC, so any utility streams above this temperature should not be used to heat streams below the pinch point. Situations where this does occur are referred to as cross pinch heat transfer, and immediately lead to a greater utility usage than the target amount. When an amount of heat from hot utility is used below the pinch, it is additional to the utility target that must still be supplied to satisfy the above-pinch enthalpy imbalance. This extra heat that has been transferred to below the pinch must also be removed from the system through the use of additional cold utility. Therefore to achieve the minimum utility targets no heat should be transferred across the pinch point.

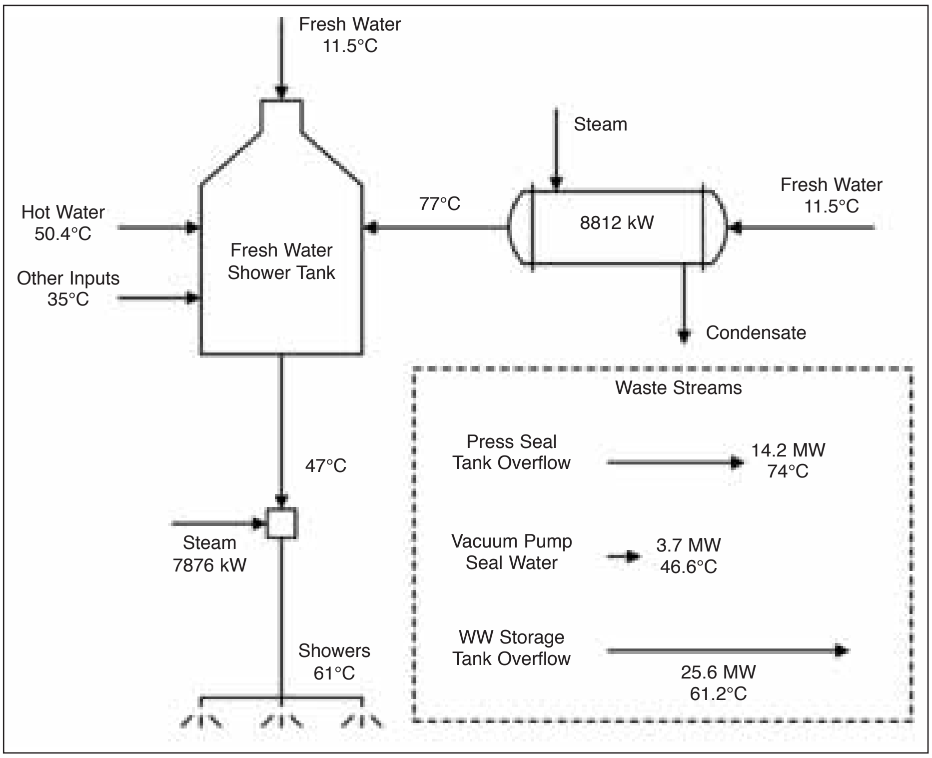

Fig. 10 Current fresh water heating arrangement and possible waste streams for heat recovery.

Currently the heating of the water for the fresh water showers takes place via direct heat transfer (8.8 MW) and direct steam injection (7.9 MW) as illustrated in Figure 10. Heating of the fresh water from 11.5°C to 77°C and then mixing this stream with other inputs is extremely inefficient from an exergetic stand point. Furthermore heat is being exchanged in both cases across the pinch temperature of 55.9°C. There are also numerous waste heat streams available that are currently not being utilised to any extent. The temperature and magnitude of three of these streams are also indicated in Figure 10. Both the press seal water and the white water overflow contain small amounts of fibre however the consistency of both of these streams is around 0.02% and 0.005% respectively.

A proposed heat exchanger network that utilises two of the waste heat streams identified previously is illustrated in Figure 11. The two water streams represent over 50% of the flow and therefore are treated as a single stream in any consideration of recovery options. The ΔT_{min} for heat transfer was set at 10°C. White water overflow at around 62°C can be used to heat all of the fresh water from

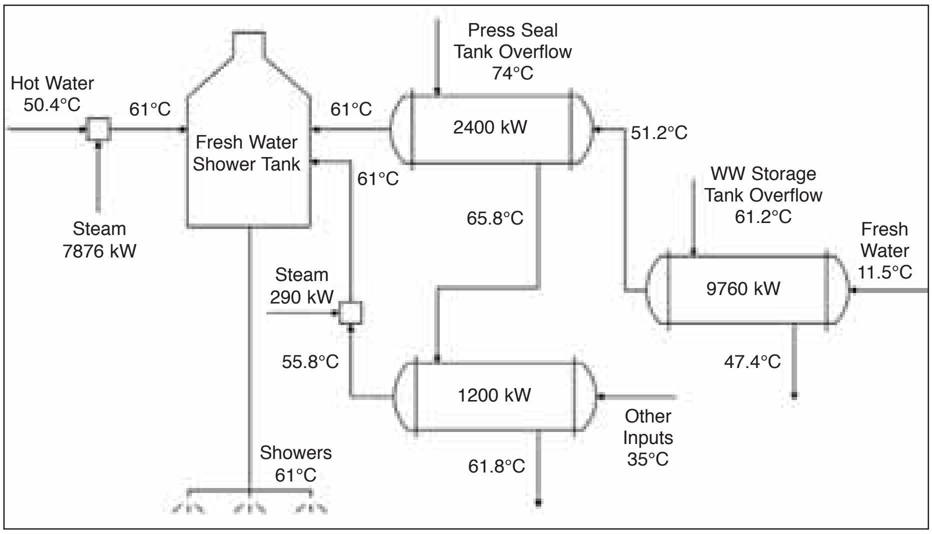

Fig. 11 A possible heat exchanger network for fresh water shower water heating and heat recovery.

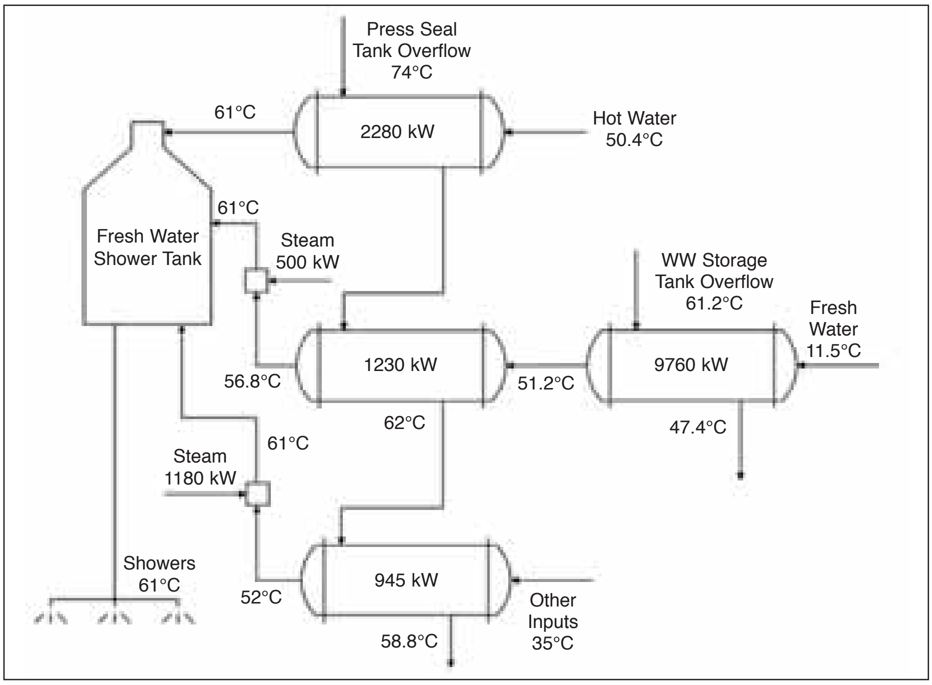

Fig. 12 An alternative heat exchanger network with an extra heat exchanger unit.

11.5°C to just over 51°C. This stream can then be heated further to the required temperature of 61°C by using the press seal water, which is available at 72°C. These two waste streams can therefore provide over 12 MW of heating to the fresh water without the use of steam.

More heat can be recovered from the press seal water (now at 65.8°C), which can be used to heat the other inputs stream from 35°C to 55.8°C. Direct steam injection can then be used to finish heating this stream to the desired temperature. Due to the 10°C ΔT_{min} criteria set previously no further heat can be recovered from the press seal water stream and therefore the h ot water stream at 50°C must be heated via direct steam injection. The total steam demand for this system is just under 2.6 MW and is a saving of around 14 MW compared to the current system with no heat recovery (Fig. 10).

The heat exchanger network described above is only an illustrative example as this could be optimised further for greater heat recovery if the ΔT_{min} criterion is relaxed further. Other possibilities exist that recover more heat and use less steam if other heat exchanger units are considered while still retaining a ΔT_{min} of 10°C. Another possible heat exchanger network with one extra unit is shown in Figure 12. This network reduces the steam demand a further 890 kW but includes an extra heat exchanger unit. The site does not have a steam surplus and so therefore any steam savings are valuable as they will reduce the amount of steam that needs to be produced at the marginal price.

The air system is another area that could be examined for opportunities for waste heat recovery however this is not considered in this paper.

Non-continuous data

As previously mentioned, paper machines very rarely operate under steady state conditions for long periods of time. This is due to factors such as multiple product grades and the occurrence of breaks. The non-continuous nature of the process makes it more complicated to analyse, however heat transfer opportunities can still be extremely beneficial. In order for the proposed process modification to be successful, all streams must be present and operating under the expected conditions. If this is not the case then utility streams will still be required to provide the necessary heating or cooling duty. The production of different paper grades can also significantly affect the utility demands; however there has been little research from a process integration and heat exchanger network design aspect (*9*).

Assuming the existing utility links remain in place, then during time periods when the required energy from direct heat transfer is unavailable the plant can still meet the demand by using utility. When the energy in the output streams is greater than the demand they can still be sent to drain as is currently the case. There may also be an opportunity to utilise the extra energy elsewhere within the paper machine, or in another plant on site. In the case of hot water, another plant may even have a direct demand for its use instead of using it for heat transfer (*9*). When investigating heat transfer between plants the non-continuous operation of the overall plants must also be considered, however including total-site analysis in the investigation can lead to significantly greater savings.

Heat Storage

Due to the non-continuous nature of a paper machine there will be occasions when it is simply not possible to utilise all available energy using direct heat transfer. Instead of wasting the energy it may be possible to use heat storage to allow the energy to be used for a future demand. The viability of heat storage is heavily dependant on the capacity of storage required and the length of time until the heat will be used.

To evaluate opportunities involving heat storage a further parameter, time, must be added to the data extraction phase. This allows the pinch analysis of the stream data to take in to account the transient nature of some flow rates and temperatures. This added complexity multiplies the time required to complete the analysis, making it essential that software is implemented to complete the task (*10*).

CONCLUSIONS

Process simulation and pinch analysis are powerful tools for investigating improved process integration opportunities. An industry specific simulation tool such as WinGEMS aids in the data extraction stage when conducting a pinch analysis study. Traditional pinch analysis techniques can be successfully adapted for use on a paper machine so as to exclude the product stream (i.e. the paper sheet) from the analysis. The overall pinch temperature for the paper machine was 55.9°C, the minimum hot utility target was 170 MW, and 14 MW of steam savings could be achieved through recovering heat from the press seal water overflow and white water overflow streams. Due to the non-continuous nature of the paper machine, however, the availability of the waste streams needs to be accounted for when assessing possible heat recovery opportunities. Heat storage also becomes an important consideration when the non-continuous nature of the paper machine is considered in the pinch analysis.

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