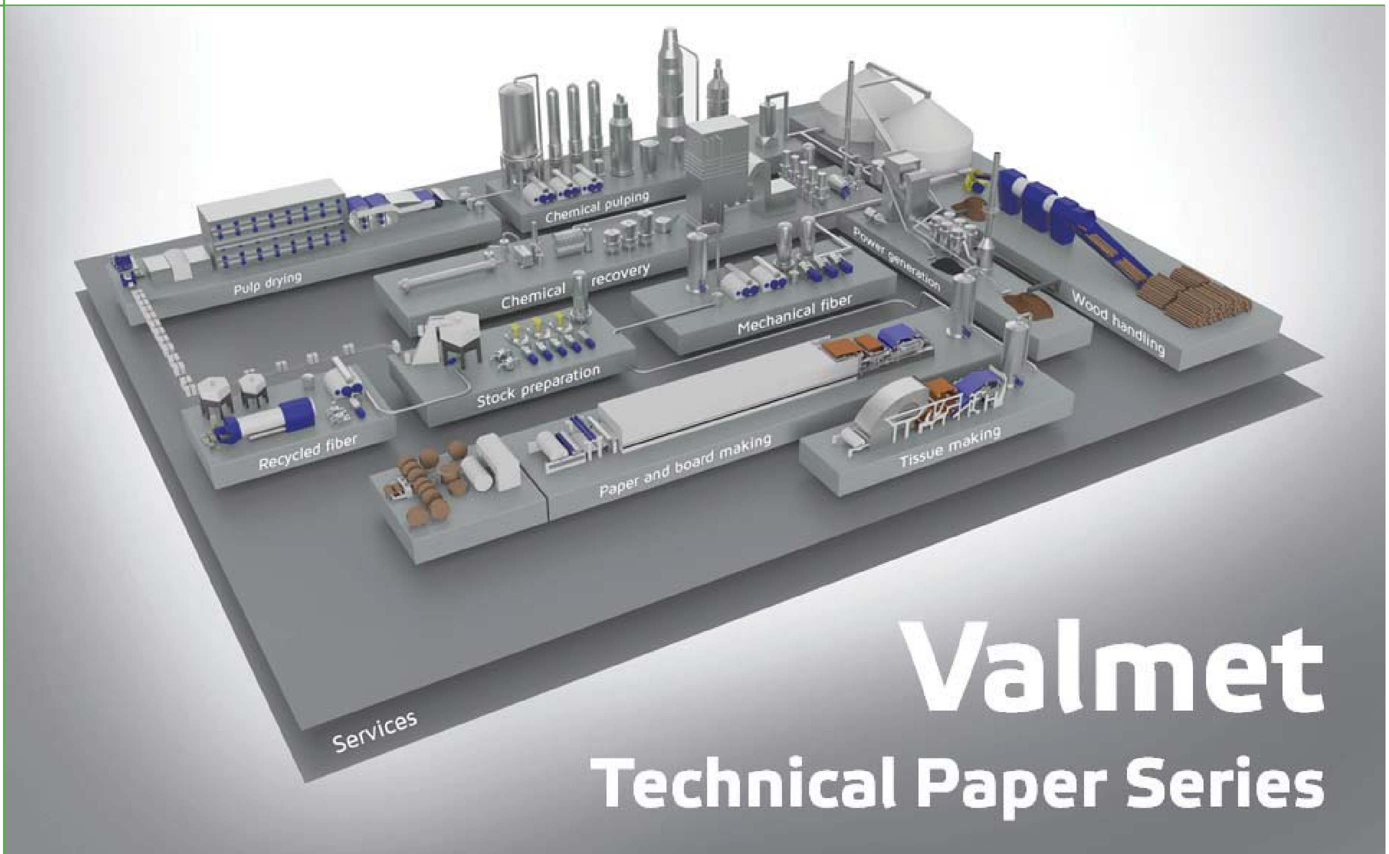

Evaporator and Recovery Boiler Energy Efficiency

Executive Summary

The white paper begins with a brief review of Valmet's Web Academy, which, along with Dynamic Simulator Training, can be used to train operators to fully optimize their existing equipment.

The evaporators / concentrators are the largest energy users in a Kraft pulp mill and represent one of the areas of the mill where significant savings in production costs / additional revenue generation can be achieved. The white paper presents a study which reviews current practices in the design of new evaporators, how these design practices have changed in the past 30 years and how upgrading older evaporators can help the mill achieve most of the benefits associated with the more current practices. Examples of evaporator plant upgrades are reviewed to show benefits that may be achieved.

The white paper concludes with a second study which helps understand what can be done to increase the energy efficiency of an existing recovery boiler and explains how the boiler performance is affected. It also outlines the main focus areas that might need some modifications. Finally, it shows the possible benefits of higher efficiency with two example cases. Mills can benefit from the approaches in these studies by reducing energy usage, increasing mill electricity output and capturing extra annual profit.

WebAcademy

Training employees is an expensive process. With growing reductions in staff, many facilities just don't have the people or the time to train their new operators. Valmet's WebAcademy is an affordable alternative to having someone come in and train your employees. WebAcademy provides systems, equipment and in-depth process knowledge. We offer both generic and fully-customizable training simulators for all of your pulp mill and fluidized bed power plant needs (**Figure 1**). The system is self-paced which allows supervisors to assign courses and because it is available 24/7, it's flexible enough to meet a new operator's schedule. We also offer a Train-the-Trainer option which targets experienced operators and team leaders, allowing them to better train their staff.

Valmet's WebAcademy is an online training product that facilitates individual training programs, individual progress tracking, online tests and exercises that can be accessed at any time. Reporting features and statistics are available for supervisors and HR staff.

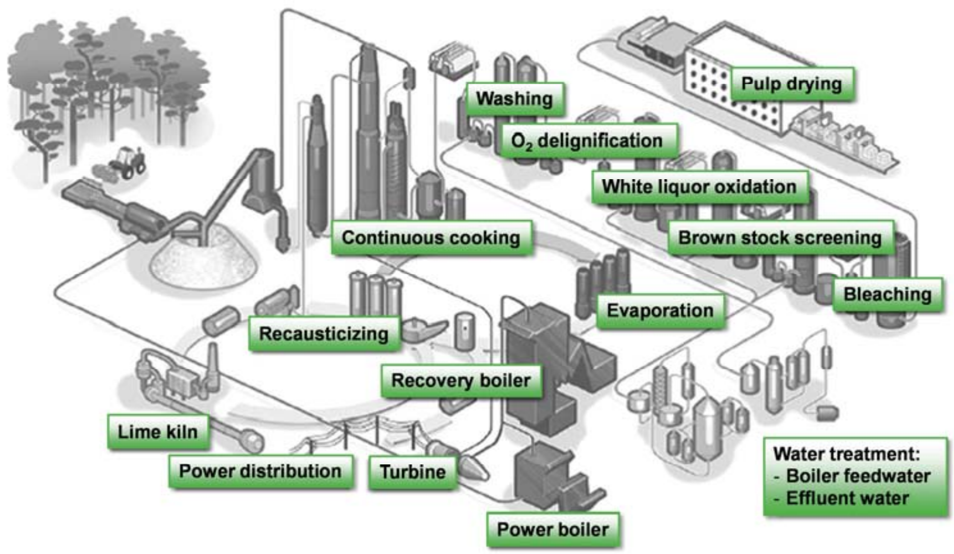

Figure 1. WebAcademy is an affordable alternative to in-person training and available 24/7.

WebAcademy is available in five languages, has more than 300 courses, and offers individual or role-based training programs. Because our program allows you to create personal user accounts, the progress of one operator doesn't interfere with any others. An added benefit of multiple user accounts is the ability to view individual progress tracking to see how well your employees are doing on the given tests and exercises. We also will give you 2 GB of storage on our servers, so you can keep all of your training materials in one central location.

Through an intuitive and educational interface, we explain systems, equipment and in-depth process knowledge, and the effect on production. The idea behind our interactive learning method is that it can be used for not only basic training, but also refresher training, in-depth training, and as a support aid during day-to-day work.

Our courses in pulp, paper, and power focus on many important areas, such as:

- Fuel Handling
- Recovery Boilers and Evaporators
- Fluidized Bed Boilers (BFB/CFB)

- Flue-Gas Cleaning
- Heat-Transfer and Vaporization
- Water Treatment
- Complete Mill Wide Systems

We also have VirtualSite Simulators, such as fully dynamic DCS coupled and stand-alone which uses a replicated DCS display. We will also gladly come to your plant for in-class training.

Still not convinced that WebAcademy is right for you? Contact your Valmet representative or email **WebAcademy@valmet.com** and ask about our free trial account, and let our program speak for itself.

Now let's review the first of two case studies on energy efficiency, which involves changing evaporator trains in existing mills by means of selective upgrades…

Evaporators offer the largest potential for pulp mill savings

The evaporators / concentrators (hereinafter called evaporators) are the largest energy users in a Kraft Pulp Mill. With rising energy cost combined with the potential to sell "green" energy, as electricity produced by steam from the recovery boiler is considered renewable energy, the evaporators also represent one of the areas of the mill where significant savings in production costs / additional revenue generation can be achieved. This paper will review current practices in the design of new evaporators, how these design practices have changed in the past 30 years and how upgrading older evaporators can help the mill achieve most of the benefits associated with the more current practices. Example of evaporator plant upgrades will be reviewed to show benefits that can be achieved.

Modern evaporators

Valmet is one of the largest suppliers of evaporators and chemical recovery boilers (**Figure 2**) for the processing of black liquor in the Pulp & Paper Industry, having supplied evaporators and recovery boilers for several of the large pulp mills built around the world during the last decade. The role of the evaporators (**Figure 3, next page**) in the pulp mill is to evaporate the water content of the weak black liquor leaving the pulp washers to a sufficient concentration to allow firing and combustion of the liquor in the recovery boiler.

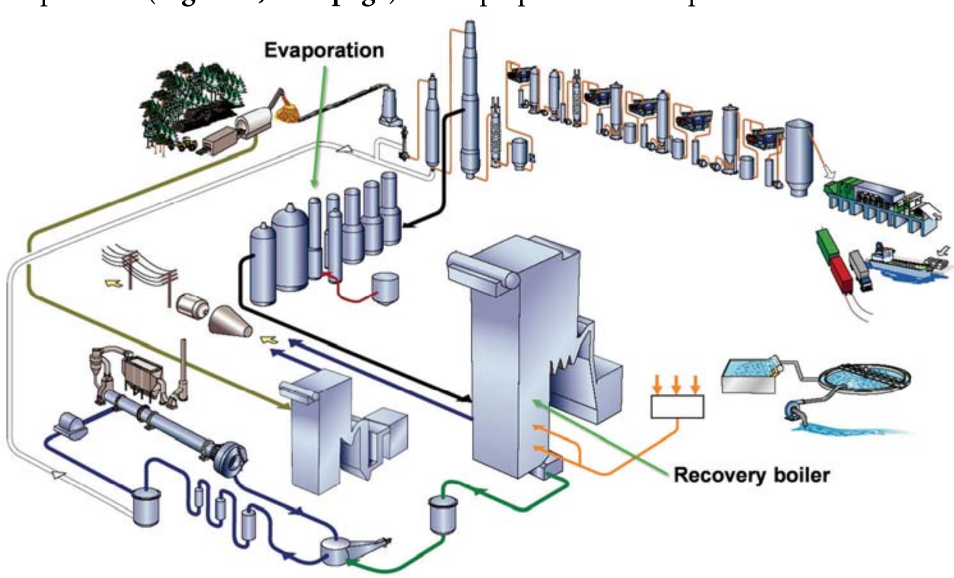

Figure 2. Evaporator plant position in Kraft pulping

To evaporate the large amounts of water contained in the weak black liquor from the pulp washers (15 to 20% solids means

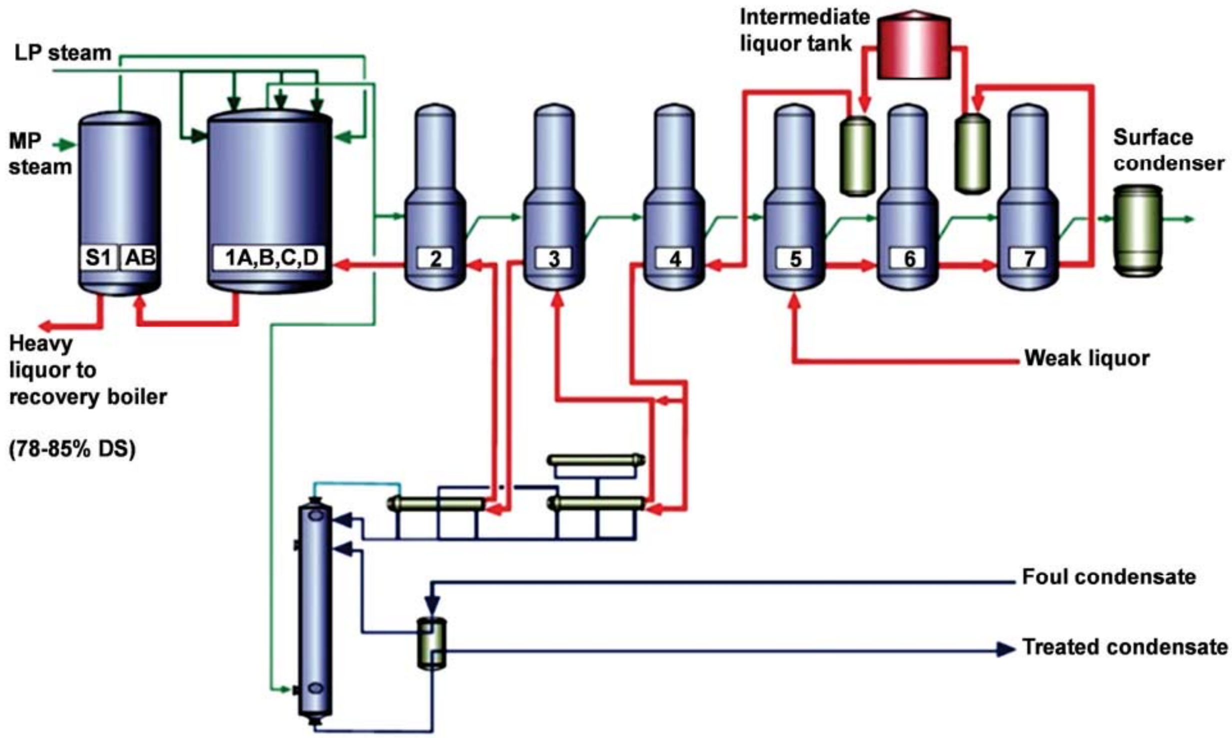

Figure 3. Simplified flow sheet for modern evaporators

that for every ton of solids there is between 4 to 5.7 tons of water in the black liquor), multiple effect evaporators are used.

The principle of operation of the multiple effect evaporator is that live steam is used in the first effect to evaporate water. The vapor from the first effect is then condensed in the second effect to evaporate more water, and so on until the last effect. This is possible as the pressure on the liquor side and the boiling point go down in each successive effect, to end up with the last effect before the surface condenser operating at a significant vacuum.

Concentrator technology has evolved significantly in the last 40 years. The first concentrators for Kraft black liquor to appear on the market 50 years ago where only able to reach product solids concentration in the mid 60% DS. In the late 70's to early 80's, product solids in the low 70% became more common place. In the mid 80's, Valmet pioneered high solids firing in recovery boilers with concentrators capable of producing liquor up to 85% DS. Several benefits come from higher solids firing and will be discussed later in this paper.

The main evaporation technology used in new evaporator plants is falling film evaporation. In falling film evaporation the liquor is recirculated to the top of the vessel where it is distributed and falls as a thin film on the heating surface, as shown in **Figure 4**. Falling film evaporators provide for better heat transfer rate than rising film (also called LTV) evaporators and significantly

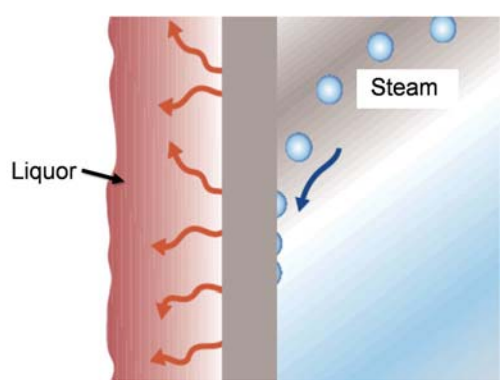

Figure 4. Falling film evaporation

lower power consumption than forced circulation evaporators. Valmet has performed several conversions of LTV vessels to falling film operation (**Figure 5**) to improve evaporation capacity of an existing train without having to replace the existing vessels.

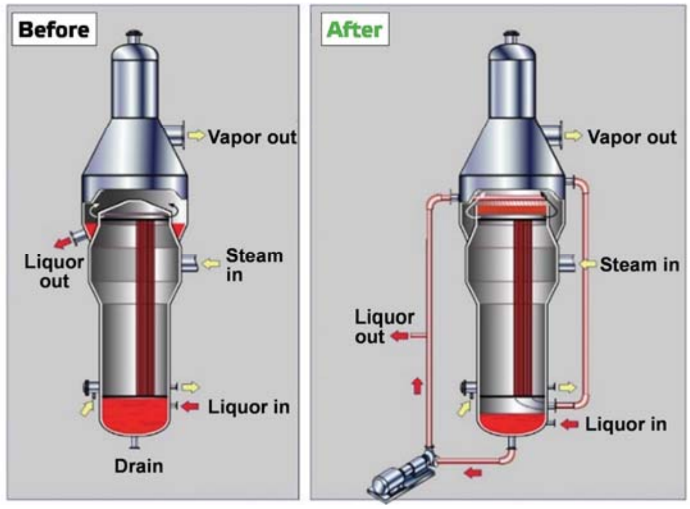

Figure 5. LTV to falling film conversion

Valmet uses mostly two types of falling film evaporator design. The first is a more conventional falling film tube and shell type design where the liquor flows as a thin film on the inside of the tubes (**Figure 6**) and the second is our TUBEL® design where the liquor flows as a thin film on the outside of tube elements (**Figure 7**). The conventional design is used mainly in locations that are not very prone to scaling, such as the higher numbered effects, while the TUBEL® is used more in the critical solids range, typically in the concentrator position.

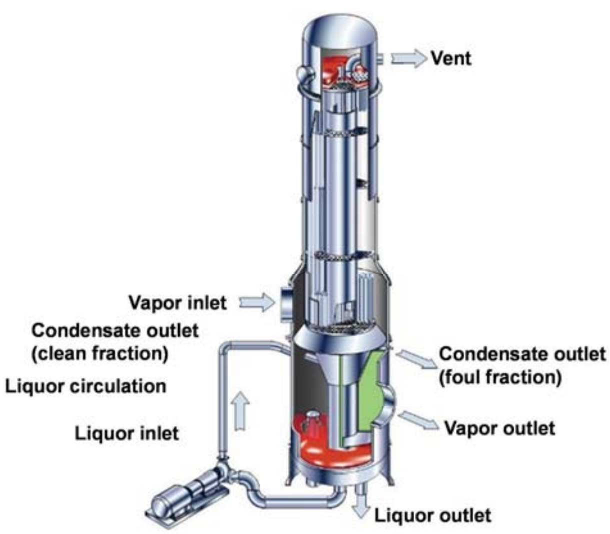

Figure 6. Conventional falling film

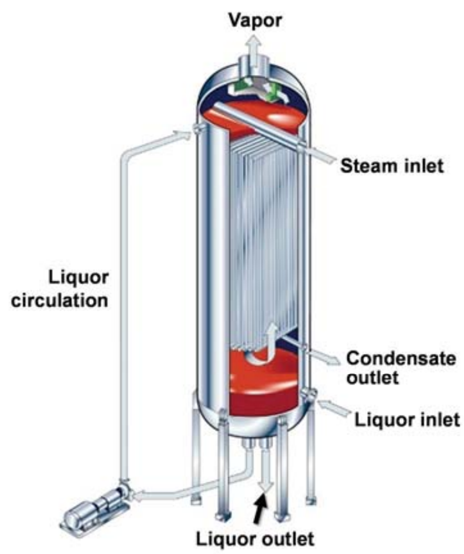

Figure 7. TUBEL® falling film

Critical solids level

The critical solids level in black liquor is the solids level at which sodium salts (typically in the form of Burkeite and Dicarbonate) starts to form crystals [1, 2, 3]. This takes place at the point where the concentration of the salts exceed their solubility limit in the black liquor, typically for liquor in the range of 50 to 55% dry solids. This will vary from mill to mill based on the reduction efficiency in the recovery boiler and the causticizing efficiency, which both impact the dead load of chemicals in the liquor cycle, the ratio of NaOH to NaS in the cooking liquor (sulphidity), type of pulp being produced and non-process elements in the liquor cycle. These crystals will always form once the DS concentration exceeds the critical solids level. A properly designed system will promote the formation of these crystals within the liquor rather than on the heating surfaces. Methods used to insure the liquor does not go through the solubility limit on the heat transfer surface include operating the liquor sump above the critical solids level, feeding the lower solid liquor from the previous effect in the liquor sump, mixing the ash before the concentrators (**Figure 8**) and raising the solids by blending some of the final product liquor with the incoming liquor (sweetening).

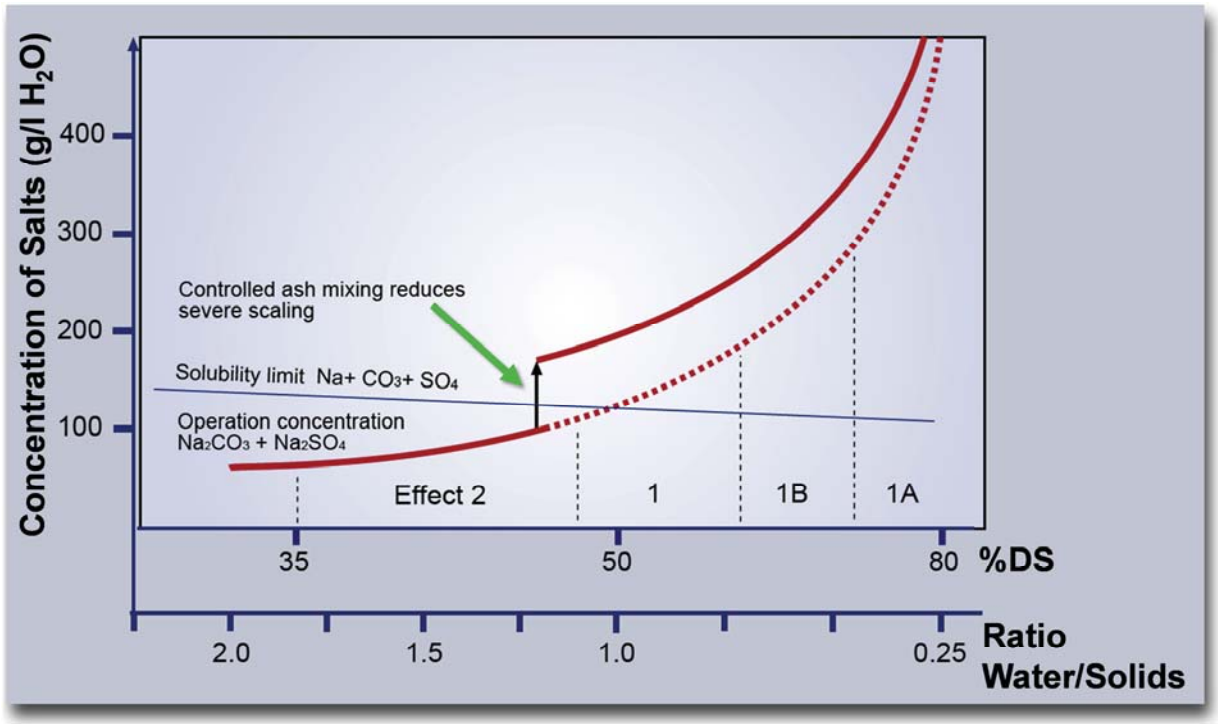

Figure 8. Ash addition prior to final concentration

Thermal efficiency of evaporators

The measure of thermal efficiency of an evaporator train is called the steam economy (unit of water evaporated per unit of steam used) and the steam economy is directly related to the number of thermal effect in the train. Modern evaporators typically have 6 or 7 thermal effects. However, several older evaporators will have only 5 thermal effects and / or will have the concentrators not integrated into the evaporators, significantly reducing the steam economy. **Table 1** shows the impact of the actual number of effects on steam economy for a typical 1000 ton/day pulp mill, based on a typical steam economy of 0.85 per effect.

Mill Production Capacity	1000 t/d	**Weak Liquor**	15%
Recovery Boiler Capacity	2000 t/d of DS	**Product Liquor**	72%
Total Evaporation	440 t/h		
# of Effects	**Steam Economy**	**Steam Consumption t/h**	**Difference t/h**
5	4.25	103.5	-
6	5.10	86.3	17.2
7	5.95	73.9	29.6

Table 1. Steam consumption as a function of the number of thermal effects

The cost of energy will vary greatly based on the type of fuel used for incremental steam production in the mill and the efficiency of the boiler producing the steam. Using a value of $6/GJ and 2.2 GJ/t of steam, based on 350 days of production, the savings with a 6 effect system are in the order of $1.9 million going from 5 effect to 6 effect and of $3.3 million from 5 effect to 7 effect. The payback calculation will be different based on the specific mill conditions. If the mill is self-sufficient in steam from the recovery boiler and while firing only wood waste in the power boiler, then the steam saved can be used to produce additional power.

Product liquor solids and high solids firing

Most North American pulp mills fire liquor in the recovery boiler at dry solids level in the range of 68 to 75%. As mentioned earlier, Valmet pioneered the concept of high solids firing where the dry solids level as fired in the recovery boiler is in the range of 78 - 85% (**Figure 3**). Many benefits come from firing higher solids liquor in a recovery boiler:

- Increased thermal efficiency and steam production as less water needs to be evaporated in the furnace. Every 1% increase in solids typically leads to 0.5% increase in steam production. With the steam economy achieved in multiple effect evaporators, this leads to a net increase in steam generation.
- Less water in the liquor means less flue gas volume for the same amount of solids fired, resulting in lower flue gas velocity and temperature leaving the furnace. This results in less carry over and typically extends the duration between water wash.
- Less liquor drying in the lower furnace leads to higher bed temperatures, producing both better reduction efficiency and lower emissions of SO_2 and TRS.

Condensate segregation and reuse

Additional energy savings can also be achieved by improving the quality of the condensate from the evaporators to make it suitable for reuse in the pulp mill, helping to reduce the water consumption per ton of pulp. The main contaminant in the condensate is methanol and most of the methanol will be released in the initial evaporation of the weak liquor. Various techniques can be used to enrich the concentration of methanol in a smaller volume of foul condensate for treatment while producing a larger volume of cleaner condensate for reuse in recausticizing, pulp washing and bleaching.

Normally modern pulp mills are using secondary condensate in the brown stock washing (unbleached pulp, consumption 4.7 m^3/ADt) and in the recausticizing (~3 - 4 m^3/ADt). Today all possible secondary condensate is reused and none is sent to the effluent treatment. This will reduce the overall water consumption in the mill and also the COD discharge. Normally fresh water is used in the bleach plant, cooling water make-up and other small auxiliary consumption.

In TCF-bleach plants and for dissolving pulp it is beneficial to use washing water with no or very low metal content in the bleach plant. In those processes water can be replaced with clean secondary condensate resulting in reduced bleaching chemical consumption. In addition to water usage reduction, this also leads to energy savings associated with treatment and heating of the fresh water, and reduction of the effluent treatment costs. In modern market pulp mills (South America and Asia) the total raw water consumption is about 22 - 25 m^3/ADt (including cooling water).

Valmet uses various techniques to segregate the condensate into cleaner and fouler fractions. In the higher number effects where tube and shell falling film vessels are used, condensate segregation is accomplished by using a circular baffle to create an outer and inner section on the vapor side as shown in **Figure 9**.

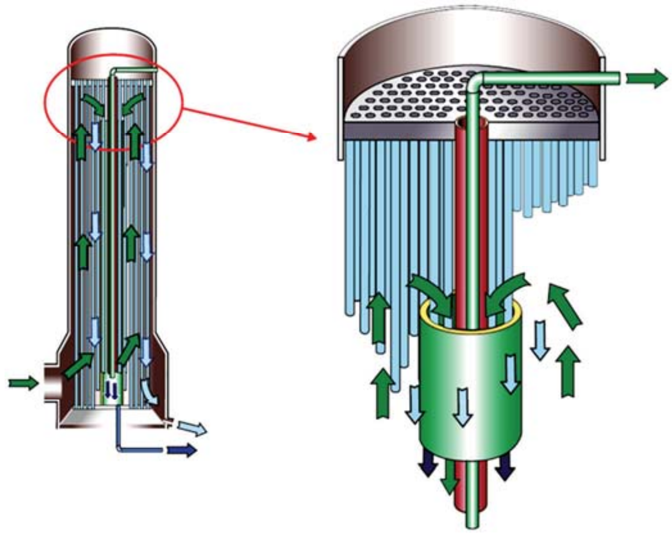

Figure 9. Internal condensate segregation

The vapors from the previous effect are introduced at the bottom on the shell side. As the vapor rises, it goes in counter flow with the condensate forming on the tube providing a stripping effect for the condensate. The vapor enriched in methanol turns and condenses flowing down into the inner section. A large fraction of cleaner condensate is collected at the bottom of the outside section while a smaller fraction of fouler condensate is collected from the inner section. A similar principle can be used in the surface condenser using a two section condenser or two condensers in series as shown in **Figure 10**.

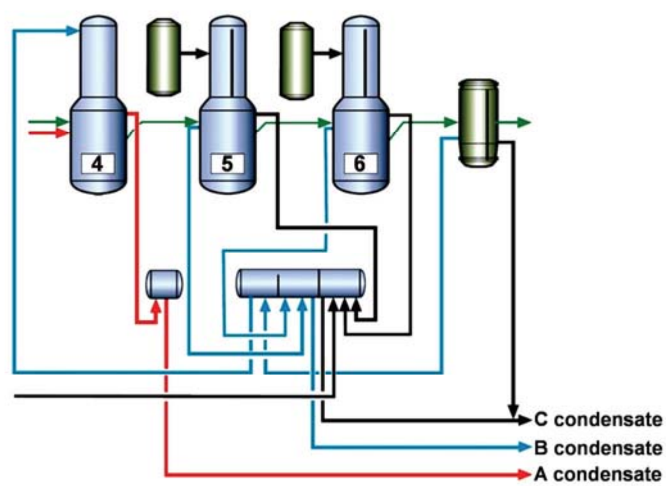

Figure 10. Condensate segregation and ICT

Valmet typically segregates condensate in three fractions; A condensate is the cleanest (<300 mg/l of COD) and is often reused in the bleach plant, B condensate is slightly more contaminated (<800 mg/l of COD) and is typically reused in pulp washers recausticizing while C condensate is the foulest (around 10,000 mg/l of COD) and is typically sent to the condensate stripper or effluent treatment. Typical ratios for the condensate are around 40% for A condensate, 50% for B condensate and 10% for C condensate. In addition to the condensate segregation shown for effect 5 and 6 as well as in the surface condenser, **Figure 10** also shows Valmet's patented Internal Condensate Treatment (ICT) where a portion of the B condensate is pumped back to the top of effect 4, some methanol gets stripped off to produce more A condensate.

Condensate stripper

A large number of mills use a condensate stripper to remove methanol from the evaporator and digester condensates to reduce the load on the effluent treatment plant and control odors. Most of these installations use live steam as a driving force in the stripper to separate the methanol from the condensate. As shown in **Figure 3**, Valmet prefers to integrate the stripper in the evaporators to use vapor from the first effect as the driving force. This prevents the loss of the live steam condensate which would take place with direct steam injection. It also provides the full steam economy of the train instead of the limited economy that would be achieved for a non-integrated stripper. The condensate stripper usually operates at an efficiency of 95% for methanol removal (higher for TRS) and upgrades the C condensate to B condensate quality or better.

Typical arrangement for evaporators in older mills

A quick survey of existing mills in Western Canada shows that the average mill has between 1 to 2 evaporation lines in service and that the average age of the lines is close to 40 years old. Some of these lines have been upgraded and repaired over the years, but not likely upgraded for process improvement or thermal efficiency. With the advent of low-odor boilers and low-odor conversions, concentrators where also added without integration into the evaporator train and therefore operate at a lower thermal efficiency. For example, one mill in Ontario operates a 6 effect LTV evaporator combined with a 2 effect concentrator not integrated into the train. Operating data from the system showed that the total evaporation rate was 370 t/h with a steam consumption of 91 t/h, for an overall economy of just under 4.1, while a 6 effect train should typically be closer to 5.

Case studies

The next part of this paper will give examples of upgrades to evaporator trains and the benefits obtained by the mill, as well as a current study performed by Valmet for a project under development:

Klabin Monte Allegre, Brazil

Valmet completed several retrofits to their evaporator train starting in 1997 with the most recent upgrade taking place in 2013. The sequence of retrofits and the changes to the train are shown in different colors in the simplified flow sheet in **Figure 11**.

The original train was a 5 effect train with LTV vessel supplied in 1978. The first upgrade in 1997 included the addition of new concentrators, stripper and evaporator vessel to increase the total evaporation

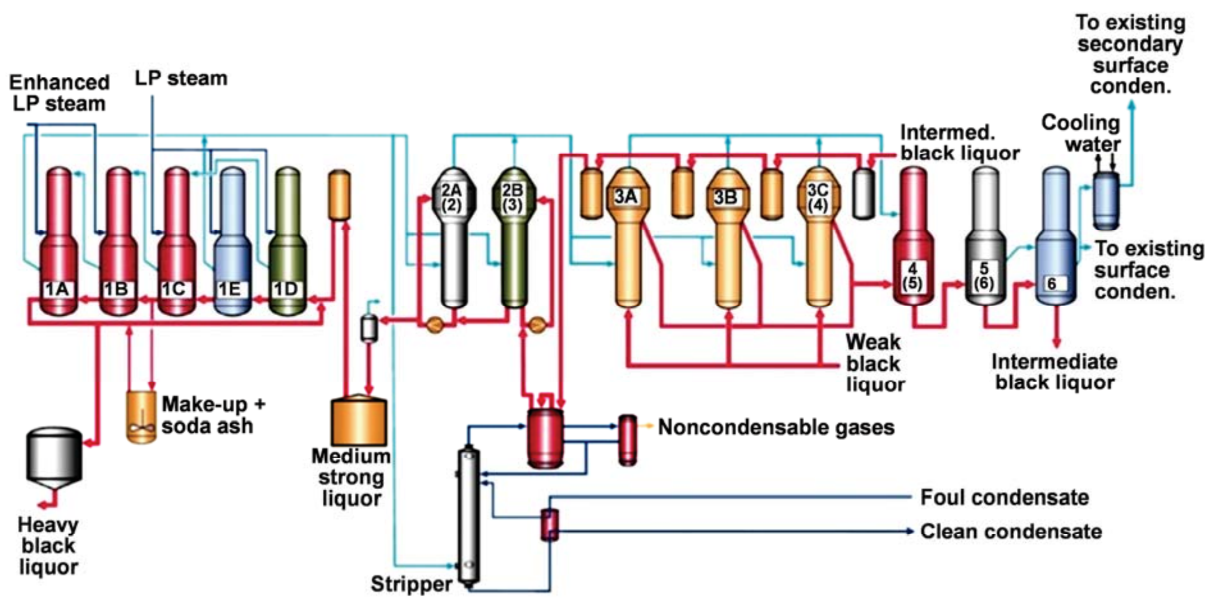

Figure 11. Klabin evaporator simplified flowsheet prior to 2013 upgrade

capacity. Further retrofits were done in 2003, 2005 and 2007 that included additional concentrators and evaporator vessels, an additional surface condenser, the placement in parallel on the vapor side of some of the existing vessels and the conversion of two LTV vessels to falling film. The benefit of this approach was that the evaporator train capacity was able to follow the increase in mill production while reusing the existing assets already in place.

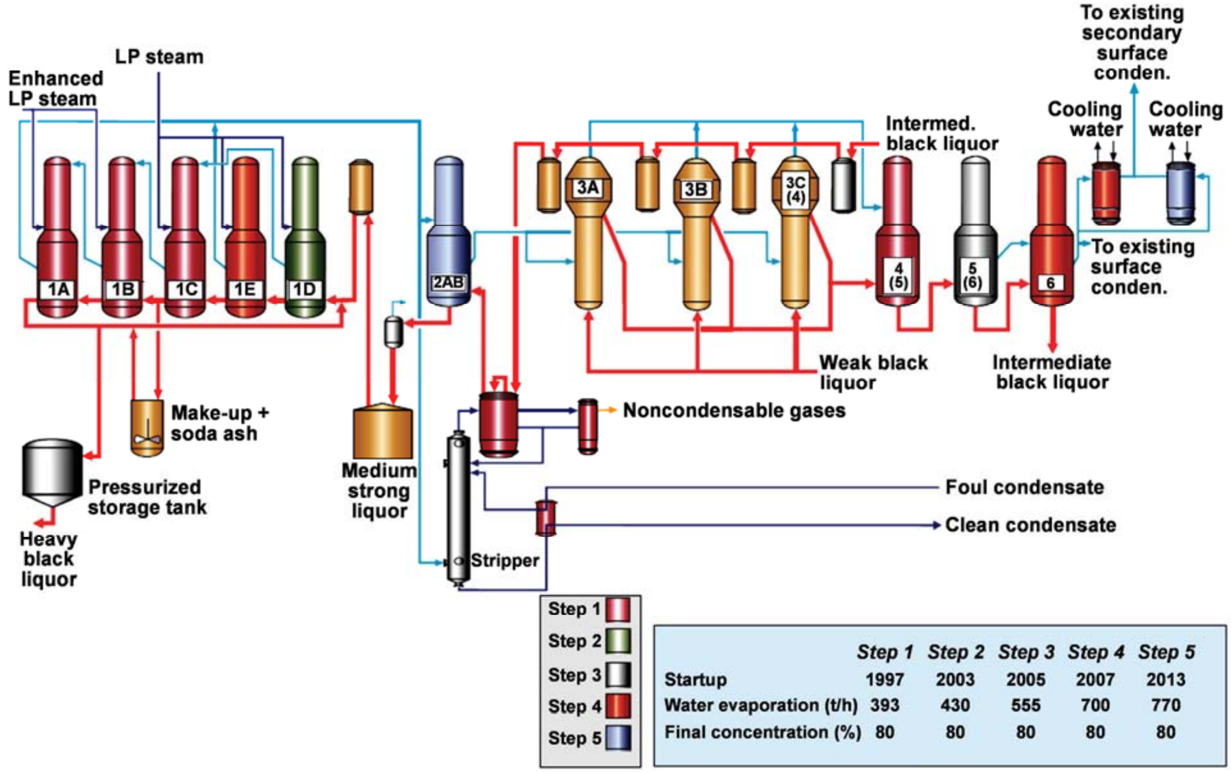

Figure 12. Klabin evaporator simplified flowsheet after 2013 upgrade

A final upgrade in 2013 (**Figure 12**) included the replacement of the 2A and 2B vessels with a single large falling film vessel and of one additional surface condenser in parallel to the existing one. Overall, the train maintains a relatively high thermal efficiency with an evaporation capacity at 770 t/h. The capacity prior to the first retrofit in 1997 was under 200 t/h of evaporation with lower product dry solids.

Cenibra Cellulose, Brazil

Valmet completed two retrofits to their evaporator train in 2003 and 2006. The sequence of retrofits and the changes to the train are shown in different colors in the simplified flow sheet shown in **Figure 13 (next page)**.

The original train consisted of a 6 effect train with LTV vessels. The first upgrade in 2003 consisted in converting three LTV vessels to falling film. The second upgrade included the addition of one concentrator vessel, one conversion of LTV to falling film one new evaporator vessel and a parallel surface condenser. In parallel, Valmet also upgraded the second evaporator train by adding a new concentrator and a new MVR pre-evaporator during the first upgrade and an additional MVR pre-evaporator during the second upgrade.

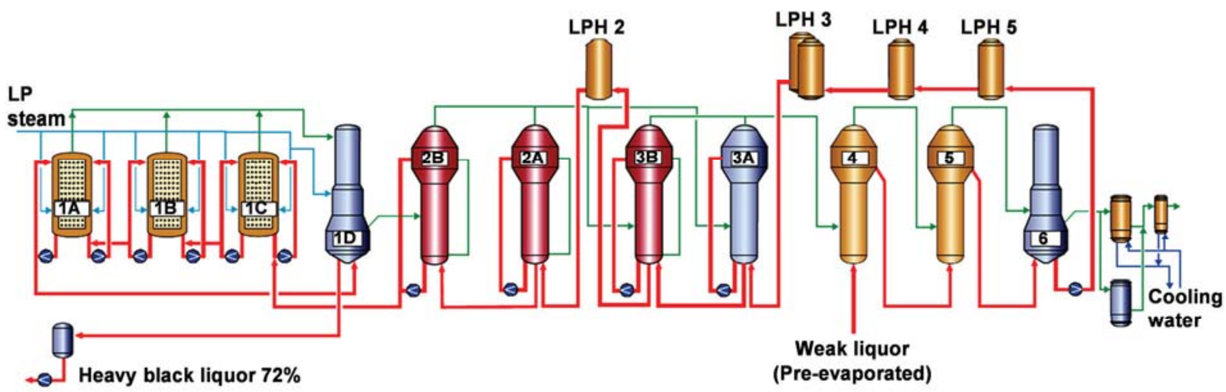

Figure 13. Cenibra evaporator simplified flowsheet

Current Study, Eastern US mill

Valmet has performed a study for a mill located in the Eastern US with the goal of retiring a small evaporator train. Retiring this older train will require increasing the capacity of the second evaporator train to handle the complete evaporation duty of both trains. This upgrade will also include the integration of the current two effect concentrator into the train to increase the overall steam economy. The mill also wishes to increase the overall capacity of the total evaporator plant to provide flexibility.

The study included the collection of operating data for the existing train, the review of the existing vessels and the space available for the addition of new vessels. After the completion of these tasks on site, heat and mass balance calculations were performed for the existing train to confirm the validity of the data. The next step was to determine how to rearrange and modify the existing vessels and what additional vessels would be required to reach the desired capacity.

Currently, the mill processes 58 l/s (900 USGPM) of liquor in one evaporator train and 28.7 l/s (400 USGPM) in the other evaporator train, with weak liquor solids of 15.7%. Both trains are LTV's arranged in a 6 effect configuration and produce liquor that goes in the 50% storage tank. This is followed by a two effect falling film concentrator that raises the solids to 73% for firing in the recovery boiler. Testing of the train showed that the combined steam economy of the concentrator and evaporators in the current arrangement is 4.0 with a total steam consumption of 67.7 t/h (150,000 lb/h).

The revised evaporator configuration would include one additional concentrator vessel with all three concentrator vessels acting as the 1st effect and integrating the concentrator into the evaporator train. The evaporator train would be revised by placing the existing 1st and 2nd effect in parallel as the new 2nd effect and converted to falling film, the existing 3rd and 4th effect will be place in parallel as the new 3rd effect and converted to falling film, the existing 5th and 6th effect would become the new 4th effect, adding two new falling film vessels as the 5th and 6th effect and a new liquor heater in parallel to the 5th effect (**Figure 14, next page**).

With this new configuration, the steam economy becomes greater than 5.6, resulting in steam savings of 19.3 t/h (42,500 lb/h). As part of this upgrade, the evaporation capacity of the evaporators in this new configuration will also be increased by about 7.5% to provide the mill with more flexibility. The new 5th and 6th effect will be able to perform effective condensate segregation, allowing the mill to potentially reuse more condensate in the fiberline and reduce fresh water consumption.

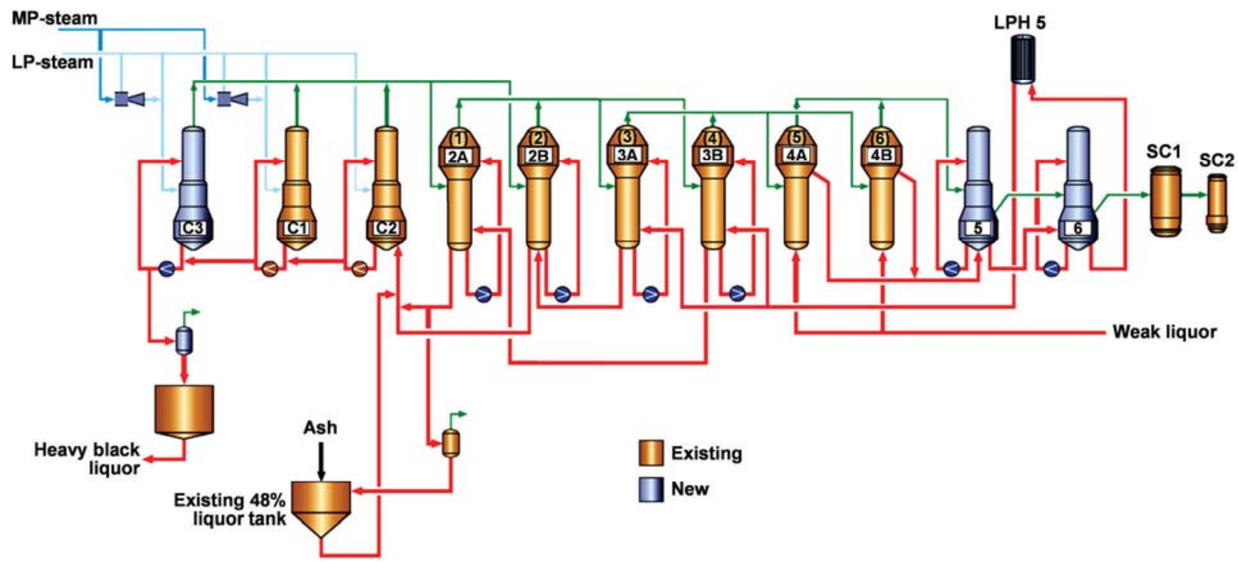

Figure 14. Eastern US mill revised evaporator arrangement

Evaporator conclusions

Evaporators are the largest energy users in a pulp mill. They are also an area that was subject to significant technology improvements in the last 30 years, with the cumulative effect of these improvements resulting in a significant increase in efficiency and reliability of both the evaporators and the complete mill. Modernizing evaporators in an older pulp mill may produce energy savings in the order of 20 - 40% in steam consumption alone, with additional savings if the upgrade also includes better condensate segregation and treatment that allows the mill to reduce fresh water consumption. Additional payback in upgrading evaporators can come from increased availability of the evaporators and higher product solids to the recovery boiler (resulting in more high pressure steam production and other benefits, such as lower emissions, increased capacity and increased reduction efficiency).

Upgrading existing evaporators, provided that they are in reasonable mechanical condition, can be significantly less expensive than replacing them with a completely new train or an additional new parallel train. Upgrades can also be carried out in multiple steps as required to keep up with increases in mill production and can typically be done within the time available during annual maintenance outages if properly planned. ROI on upgrade to evaporators are usually significantly higher than for new trains as they reuse valuable existing assets.

The large number of upgraded evaporators currently in service demonstrates that this is a very viable way for a pulp mill to significantly reduce energy usage and production costs in an existing mill.

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The second case study involves upgrading existing recovery boilers with high power features in order to produce more electricity, thereby producing more income. The boiler is approached section by section…

Improving energy efficiency of existing recovery boilers

Due to the increased global energy demand, increased electricity price, and incentives for renewable energy, it is in many cases profitable to maximize electricity output both from power boilers and from recovery boilers. Another motive for maximizing electricity output from recovery boilers is to decrease fuel input to power boilers. In cases where the saved fuel is fossil fuel, the carbon footprint of the mill can be decreased as well. In recent years, many different electricity efficiency increasing features have been installed on new and existing recovery boilers. In this paper, these recovery boiler-related, so-called high power features are applied to existing recovery boilers. The goal is to show how different kinds of mills with existing recovery boilers benefit from high power features. Some of these features can have certain limitations due to constraints set by the existing boilers, and these limiting factors are also discussed.

In this study, electricity generation of two example cases are calculated with the following high power features: high black liquor dry solids, air preheating, fully pressurized feedwater tank, feedwater preheating, heat recovery from vent gases, heat recovery from flue gases, and high main steam parameters.

This study helps understand what can be done to increase the energy efficiency of an existing recovery boiler and explains how the boiler performance is affected. It also outlines the main focus areas that might need some modifications. Finally, it shows the possible benefits of higher efficiency with two example cases.

High power recovery boilers are becoming more and more common in the pulp mill industry as electricity prices have increased and environmental limits have tightened. Electricity produced by recovery boilers qualifies as green energy in many countries, providing incentives to electricity price, which make high power feature investments profitable. Other interests are in reduction in the use of fossil fuels; with high power recovery boilers it is possible to use less fossil fuel in power boilers located at a pulp mill site.

This paper introduces high power features used in recovery boilers and examines how each feature can be utilized in existing recovery boilers. The effect of each feature on the boiler performance is explained. Boundary conditions and possible boiler modification requirements are also discussed. Finally, two calculation case studies are presented showing the benefit of upgrading an existing recovery boiler with high power features.

High power features

The most common high power features are presented in **Figure 15 (next page)**. Starting from the right side, a typical mixture of demineralized water and turbine condensates are heated in a tube condenser, which uses the heat available in vent gases. After that, the water mixture is heated in a flue gas cooler, where some of the heat left in the flue gases after economizers is recovered. Both of these features decrease the amount of low pressure steam (typically 4 - 6 bar) needed in the feedwater tank.

Then, there are five features that increase main steam flow. If low pressure extraction steam to the feedwater tank is throttled at the control valve, it is possible to increase saturation temperature in the feedwater tank by throttling the extraction steam as little as possible. This kind of configuration is called a

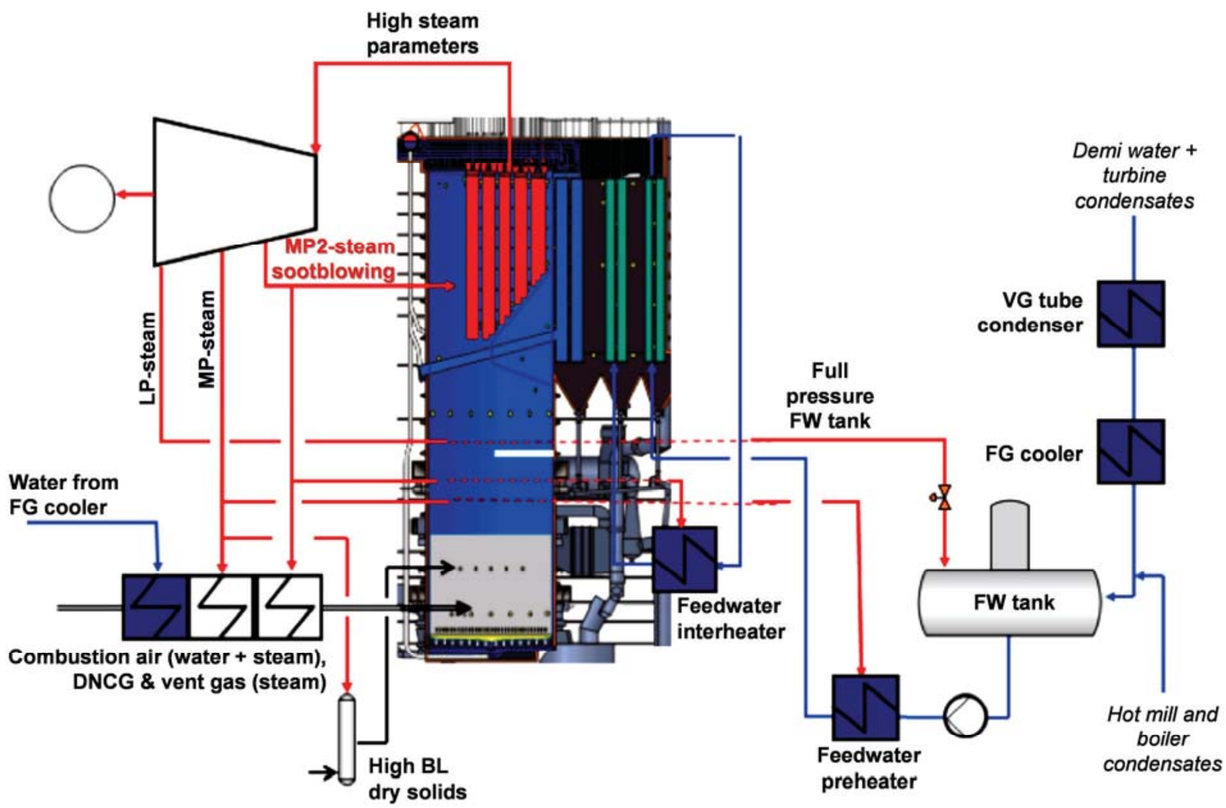

Figure 15. High power features in recovery boilers

fully pressurized feedwater tank. After the feedwater tank, feedwater is preheated in two phases: first with a preheater, and next between the economizers with an interheater. With higher dry solids content, less heat energy is required to evaporate the moisture and more steam is generated. Also, preheating the combustion air leads to an increase in the main steam flow. Low pressure steam consumption can be decreased when the first stage of air preheating is replaced with a heat exchanger using the heat from a flue gas cooler. Finally, electricity generation can be improved by increasing the main steam parameters.

High power features are introduced in more detail in the following sections.

Higher black liquor dry solids

Increasing the black liquor dry solids content has usually been the first step when more efficient electricity production is desired. With higher dry solids content, less water needs to be evaporated in the furnace, leading to higher live steam generation. Of course, more low pressure steam is required in the evaporation plant, and depending on the level of dry solids content and extraction steam pressures, it might also be necessary to use middle pressure steam.

Air preheating

Air and diluted non-condensable gas (DNCG) can be preheated in 1, 2 or 3 stages using turbine extraction steam. In high power applications, 3 stages are typically used, and the first stage steam-air heat exchanger can be replaced with a water-air heat exchanger that gets the heat energy from the flue gases. This kind of feature is called the flue gas cooler system and is explained here in more detail later on.

The aim is to preheat air as high as the extraction steam pressure allows in each stage. Air temperatures can be 200 °C or even higher. Higher air temperature means that heat input to the boiler increases and thus, live steam generation and electricity production increase. At the same time, extraction steam consumption increases, meaning less low pressure steam is left over. Condensing part of the turbine then produces less electricity and has a disadvantage compared to a back-pressure turbine, unless there is a price for this steam, for example, through district heating. The same principle applies with other features that reduce the amount of low pressure steam left over. Overall, air preheating has proven to be very profitable.

Fully pressurized feedwater tank

Some old mills have had a deficiency of low pressure steam for the mill steam consumers. In such cases, operating temperatures in the feedwater tank have been lowered by throttling a control valve in the low pressure steam extraction line. By doing this, less steam is required in the feedwater tank and more low pressure steam is available to the steam consumers in the mill. Improvements in various processes and equipment in the mill have led to more energy efficient applications and less low pressure steam is therefore required. In these kinds of cases, it is very beneficial to throttle the control valve as little as possible so that feedwater temperature is maximized and steam generation increases.

The profitability of a fully pressurized feedwater tank depends on whether there is a condensing or back-pressure turbine and if there is a price for back-pressure steam. With a condensing turbine, use of a fully pressurized feedwater tank is always profitable. The same applies if there is no price for low pressure steam. When there is a price for low pressure steam, then the profitability depends on the price ratio of electricity and low pressure steam. Use of a fully pressurized feedwater tank has typically been very profitable since no additional equipment is required.

Feedwater preheating

There are two types of devices used to heat feedwater: preheaters and interheaters. Preheaters are located before the economizers and typically use middle pressure steam (8-13 bar); whereas interheaters are located between the economizers and typically use more valuable middle pressure 2 steam (25-30 bar). They both increase the feedwater temperature before the steam drum, thus both steam generation and electricity production increase. Depending on the price of electricity, turbine extraction steam pressure levels, and the size of the boiler, the most profitable option could be a combination including both preheater and interheater, or just either one. If just one feedwater heating device is selected, then the choice between preheater and interheater has to be done case by case, as the optimized solution is dependent on many variables.

Heat recovery from dissolving tank vent gases

Heat from vent gases can be recovered with a tube condenser and used to preheat demineralized water or a mixture of demineralized water and turbine condensates, leading to savings in low pressure steam. The amount of heat available depends on the vent gas flow and moisture content. There is also a temperature limit for the water to be heated coming from a certain thermal temperature difference between vent gas and water.

As with a fully pressurized feedwater tank, the profitability of a tube condenser depends on whether or not there is a condensing turbine. With a condensing turbine and reasonable electricity price, payback time for the investment has been quite short and heat recovery from vent gases has proven to be very profitable. If there is a back-pressure turbine, there has to be a high enough price for the low pressure steam in order for the investment to be profitable.

Heat recovery from flue gases

Low pressure steam can be saved by recovering some of the heat in flue gases with a flue gas cooler after the electrostatic precipitators. The heat from flue gases is first transferred to a closed loop water circulation system and then to one of the following:

1. Demineralized water
2. Mixture of demineralized water and turbine condensates
3. Combustion air
4. Dryer used for the drying of biomass

In retrofit projects, the third option is most likely not an economically good solution, since modifications to the existing first air preheating stages are needed.

As with a tube condenser, the profitability of flue gas cooler is also a question of turbine setup and the possible price for low pressure steam.

High main steam parameters

Increasing the main steam temperature (at constant pressure) always increases the electrical output from a turbine generator. A limitation on the main steam temperature is often based on superheater corrosion concerns, which is directly connected to potassium and chloride levels in black liquor. With constant potassium and chloride levels, higher main steam temperatures can be reached if better superheater materials are chosen. Another option is to lower the potassium and chloride contents by treating the recovery boiler electrostatic precipitator (ESP) ash; however, this will result in lower sodium recovery. So, choosing the main steam temperature is basically an optimization between more expensive superheater materials (investment cost) and makeup chemical costs (operating cost) caused by sodium losses in ash treatment.

The main steam pressure needs to be chosen based on the design of steam temperature. With a condensing turbine, the boundary condition is the condensate steam quality (kg steam/kg water-steam mixture). As the main steam temperature increases, condensate steam quality also increases. However, increasing the main steam pressure leads to higher electricity output, but it decreases condensate steam quality. It is beneficial to increase the main steam pressure only to the extent that the condensate steam quality remains the same, unless the condensing turbine is modified and lower condensate steam quality is allowed. With a back-pressure turbine, the main steam pressure needs to be chosen so that low pressure steam is superheated enough to satisfy the requirements of the steam consumers in the pulp mill.

With higher main steam parameters, less main steam is generated, as same amount of heat is transferred from flue gases to steam. However, the increased main steam enthalpy is more advantageous than the impact of the decreased main steam flow; this is because the enthalpy difference over the boiler is much larger than the enthalpy difference over the turbine.

Effect of high power features on boiler performance

The main boiler design parameters that need special attention when increasing the electricity production are presented in detail in this section. Some of the high power features may have an effect on other boiler performance parameters, such as flue gas emissions, particle carryover, etc., but these are excluded in this study.

When introducing high power features to a recovery boiler, the performance of the boiler can change quite drastically, depending on how many features are introduced and how big the difference is between the base and high power case. In the following analyses, a typical boiler with and without high power features is simulated. Process values in the base case, including no features, and a case with high power features are presented in **Table 2**.

	Base	High Power
Dry solids, %	75	85
Primary air temperature, ºC	150	205
Secondary air temperature, ºC	120	205
Tertiary air temperature, ºC	30	205
Diluted non-condensable gas (DNCG) temperature, ºC	120	190
Feedwater temperature from feedwater tank, ºC	118	144
Feedwater temperature after preheater, ºC	-	174
Feedwater temperature after interheater, ºC	-	224
Live steam temperature, ºC	480	500, 515
Live steam pressure, barA	85	97, 107
Turbine condensate + demiwater = mix temperature, ºC	40	40
Mix temperature after vent gas tube condenser, ºC	-	63
Mix temperature after flue gas cooler, ºC	-	77

Table 2. Comparison of base and high power cases

Whether there is a condensing turbine or back-pressure turbine plays a minor role when it comes to boiler performance and, therefore, the following results presented here are based only on condensing turbine calculations for simplicity.

Main steam flow

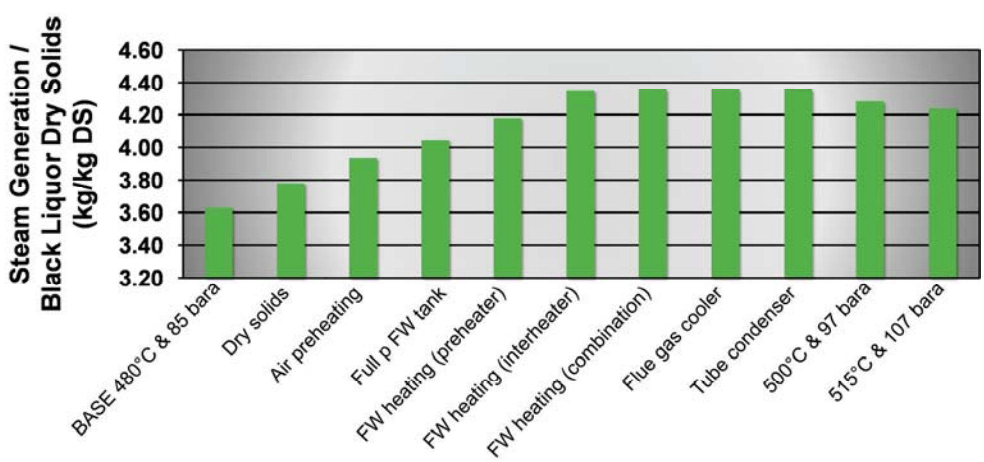

Figure 16. Cumulative effect of high power features on the ratio of steam generation and black liquor dry solids (FW = feedwater).

Figure 16 shows how much steam one kilogram of dry black liquor can produce. The ratio of steam generation and black liquor dry solids depends on, for example, the higher heating value of black liquor and the flue gas exit temperature. But it can be seen in **Figure 16** how much this key figure is cumulatively changed by the addition of high power features.

As discussed previously, there are five features (high dry solids content, air preheating, fully pressurized feedwater tank, preheater, and interheater) that increase steam generation and two features that do not affect steam generation at all. The benefit in the latter cases comes from savings in low pressure steam. Having higher main steam parameters is the only feature that actually decreases steam generation.

When comparing the effect of the preheater and interheaters on steam generation, it can be seen in **Figure 16** that the interheater clearly produces more main steam — and actually as much as with the combination of both feedwater heaters. This is because an interheater does not decrease the efficiency of economizer 1 and it enables a higher increase in feedwater temperature. The drawback is that it consumes more valuable middle pressure 2 steam and, therefore, an interheater is not more profitable in all cases. Electricity production can be increased even more if both feedwater heaters are used, since it enables raising feedwater temperature as high as with an interheater but with lower middle pressure 2 steam consumption.

As an investment combination, this is more expensive of course, and the profitability depends on electricity price and the size of the boiler.

Total boiler steam attemperation

Another parameter that requires consideration when introducing high power features is the total boiler steam attemperation. A certain margin in the total attemperation is required so that the main steam temperature can be maintained and superheater material design temperatures are not exceeded. **Figure 17** illustrates how total steam attemperation cumulatively changes when adding high power features. One needs to bear in mind that in this study the heat transfer surfaces are kept the same. In real cases, additional heat transfer surfaces might be needed.

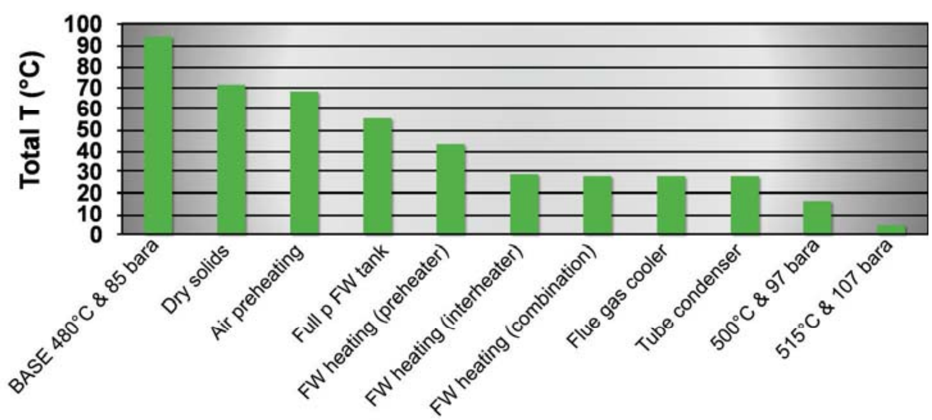

Figure 17. Cumulative effect of high power features on total boiler steam attemperation (FW = feedwater).

The only high power features that do not affect the total steam attemperation are a flue gas cooler and a tube condenser, as these do not affect the main steam flow. Features increasing steam generation reduce the total steam attemperation, as higher steam flow requires more heat energy in order to reach the desired main steam temperature. Even though high steam parameters decrease the main steam flow, they also decrease the steam attemperation. There are actually two reasons for this. First, due to a larger enthalpy difference between the main steam and drum outlet steam, superheaters require more heat energy in order to achieve the same steam attemperation. Reduced steam flow compensates this to some extent, but not enough. Secondly, the average temperature difference between flue gas and steam is smaller and thus heat transfer to the superheater is smaller. For these reasons, steam attemperation falls with high steam parameters.

However, some of the high power features affect the total steam attemperation in ways other than through higher steam flow. When black liquor dry solids content is increased, less water is evaporated in the furnace. As a result, less flue gases are produced and steam attemperation is decreased even more, explaining the big difference between dry solids and BASE cases in **Figure 17**. On the other hand, steam attemperation decreases only a bit when air is preheated, even though main steam flow is considerably increased. The reason is that higher air temperature results in higher flue gas temperature after the furnace, which increases steam attemperation. So, a higher heat input to the furnace compensates for the majority of the reduction in steam attemperation. It can also been seen in **Figure 17** that the interheater decreases steam attemperation almost as much as the combination and clearly more than a preheater due to the difference in main steam flow.

Temperature difference between drum and sweet water condenser/last economizer

Water boiling before the drum is an unwanted phenomenon in recovery boilers due to risk of mechanical failures and, therefore, a minimum temperature difference between the drum and sweet water condenser (SWC, also known as Doležal system) or last economizer is desired. **Figure 18** presents the effect of each high power feature on the temperature difference between the drum and SWC. The temperature difference is smaller if feedwater is preheated or the operation temperature of the feedwater tank is increased. Higher dry solids content and air preheating increase just the feedwater flow without affecting the feedwater temperature, resulting in a larger temperature difference. Even though higher steam parameters decrease the feedwater flow, the temperature difference between the drum and SWC is increased, as the drum pressure and temperature are both higher. A flue gas cooler and tube condenser do not affect the temperature difference.

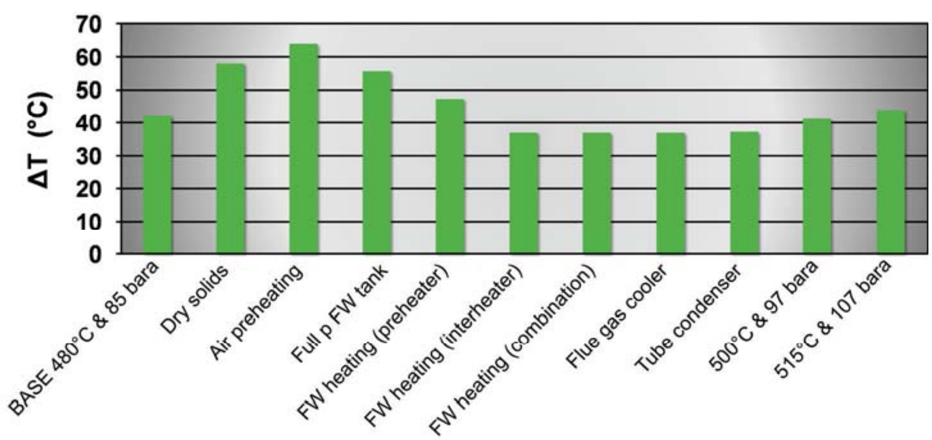

Figure 18. Cumulative effect of high power features on temperature difference between drum and SWC (SWC = sweet water condenser; FW = feedwater).

Flue gas exit temperature

The flue gas temperature after the economizers is increased drastically with some of the high power features, and this needs to be taken into account when evaluating high power recovery boilers. The cumulative effect of high power features on flue gas exit temperature can be seen in **Figure 19 (next page)**.

A fully pressurized feedwater tank and feedwater preheating have the biggest impact on flue gas exit temperature, since they increase the feedwater temperature, resulting in lower economizer efficiencies. **Figure 19** shows that an interheater raises flue gas exit temperature less than a preheater, as it is located between the economizers and only affects the efficiency of economizer 2, whereas a preheater reduces the efficiency of both economizers. High black liquor dry solids and air preheating slightly reduce the flue gas exit temperature, as higher feedwater flow enhances heat transfer in economizers and high black liquor dry solids generate less flue gases. The effect of steam parameters on flue gas temperature is negligible, as feedwater flow is impacted only a little by steam parameters.

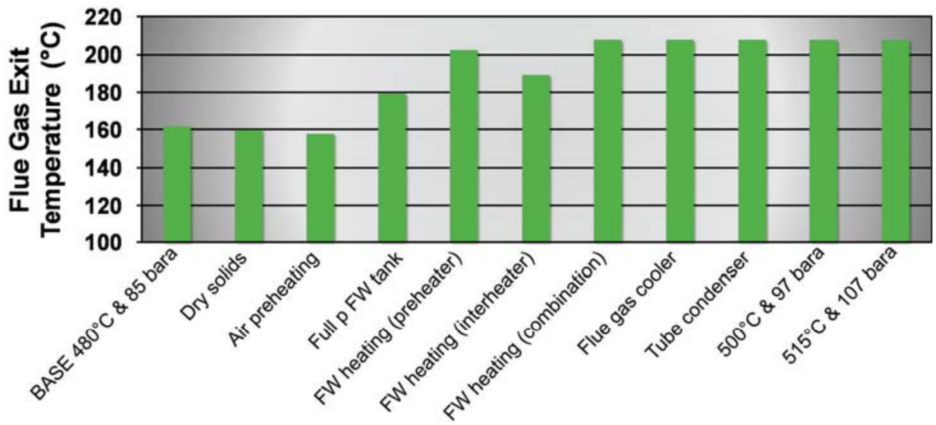

Figure 19. Cumulative effect of high power features on flue gas exit temperature (FW = feedwater).

Sticky area of ash

Stickiness of ash is determined by how much of the ash is in molten state. Ash is considered sticky when the ash melt fraction (wt%) is more than 15% and less than 70%. This melt fraction range is referred to as the sticky area. In order to avoid boiler plugging problems, the location of the sticky area should be before the second pass where side spacing between elements is smaller than in the superheater area. Two ways to improve the situation are to treat ash or add superheater area.

How much of the ash is in molten state depends on the ash temperature and composition. Since the ash composition remains almost constant regardless of the high power features, flue gas temperature is the main parameter affecting the sticky area of ash. The magnitude of the effect on sticky area of each high power feature depends on the size of the difference between the base (existing situation) and high power case. Due to this, only the direction where sticky area moves in superheater area is discussed. However, in general, it can be said that the location of the sticky area does not drastically move and is not a limiting factor in most cases.

Air preheating increases the furnace exit flue gas temperature, also meaning higher temperatures in the superheater area and, thus, the sticky area moves closer to second pass. Higher black liquor dry solids also increase furnace exit flue gas temperature, but on the other hand, flue gas flow is lower, which means the sticky area either remains in the same location or moves slightly closer to second pass. A fully pressurized feedwater tank and feedwater preheating move the sticky area further away from second pass due to enhanced convective heat transfer caused by higher steam flow. However, the effect of increasing feedwater temperature on the sticky area is almost negligible. A flue gas cooler and tube condenser do not affect the location of the sticky area. High steam parameters move the sticky area closer to the second pass, as the average temperature difference between flue gases and steam is lower and, therefore, less heat is transferred to the superheaters. This results in higher flue gas temperatures in the superheater area and moves the sticky area closer to second pass.

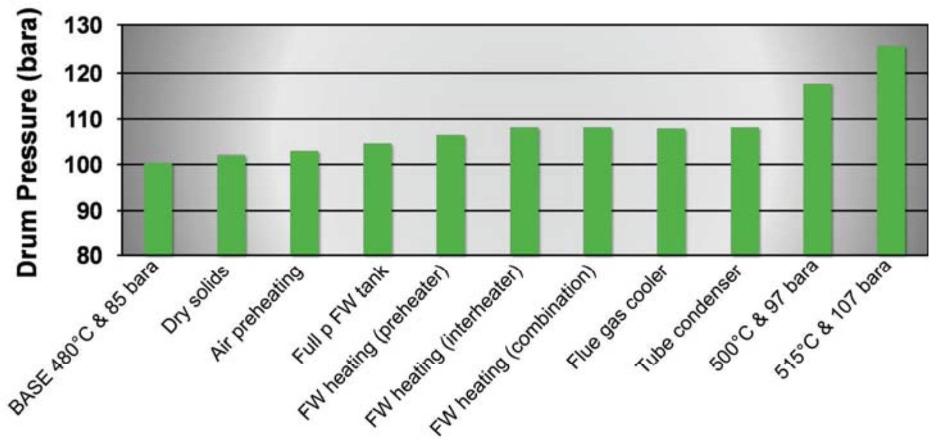

Figure 20. Cumulative effect of high power features on drum pressure (FW = feedwater).

Drum pressure

Drum pressure can be a limitation in some cases when high power features are introduced to a recovery boiler. **Figure 20** illustrates how drum pressure is changed when high power features are introduced. High steam parameters have the most substantial effect on drum pressure, as higher main steam pressure also requires higher drum pressure. A flue gas cooler and tube condenser do not affect the drum pressure, because they do not affect the boiler performance. The five remaining features that increase the main steam flow also increase the drum pressure to a certain extent, due to higher pressure losses in the superheaters.

Limiting factors and required modifications in existing boilers

When improving energy efficiency of existing recovery boilers, one needs to bear in mind the effects high power features have on boiler performance as presented earlier, as these might be limiting factors in certain cases. Through some modifications to the boiler and/or to auxiliary equipment, it might be possible to overcome these limitations, but that also means extra investment costs. In such cases, the profitability needs to be analyzed using case specific input values. Since universally applicable solutions are impossible to formulate, possible targets for modifications are presented in the following sections.

Drum

High power features affect the drum in two ways: higher operation pressure and higher main steam flow.

Drum operation pressure and temperature need to be checked when the drum pressure increases. Small pressure rises should be possible without any modifications, but higher steam parameters most likely result in exceeding the maximum allowable operating pressure and temperature. In such a case, the only solution would be expensive and time consuming, as the drum would probably have to be replaced.

Higher main steam flow results in higher loading of steam drum internals, and it might be necessary to install additional cyclones. Drum pressure also affects the capacity of cyclones, as higher pressure increases steam separation capacity but decreases water separation capacity. Also, changing the secondary steam scrubbers to a bigger size might be necessary.

Turbine

The operation of the turbine supplied from the modified recovery boiler needs to be looked at when the main steam flow is increased. An existing turbine can take only a certain maximum volume flow. High steam parameters actually help increase the steam flow to the turbine, as higher main steam pressure leads to lower specific volume of steam. Since the steam volume flow through the turbine remains constant, higher steam mass flow is possible. If steam parameters remain constant and steam flow is increased, then the turbine capacity needs to be checked. Typically, there is some margin in turbine design, but it has to be checked case by case. A turbine behaves like a common flow resistance when the design steam flow is exceeded; meaning that with higher flow, the pressure drop is higher. As a result, the extraction steam pressure levels become lower. In such a case, it is also possible that steam expansion occurs with lower turbine isentropic efficiency.

Some of the high power features increase or decrease extraction steam flows, so the design of turbine extraction steam bleeds need to be checked. Another issue is that, for example, air preheating and feedwater heating might require new extraction steam pipe lines from the turbine to the heat exchangers. Another alternative is to use the existing bleeds and get smaller benefit in electricity production with less investment cost.

Boiler pressure parts

High power features increase the main steam flow and will affect the boiler water circulation so that the circulation ratio, which is the ratio of total flow and steam flow, decreases as steam flow increases. Modifications in circulation pipes, headers, and downcomers might be necessary and need to be checked case by case.

If the sticky area location becomes an issue, then either more heat transfer surface needs to be installed or an ash treatment system is required. If there is already an ash treatment system, then more ash needs to be treated. If the superheater or furnace screen area is increased, it is necessary to check whether there is room for additional heat surfaces and sootblowers.

The possibility of superheater corrosion also needs to be checked if steam parameters are increased, and may require better superheater materials or ash treatment.

Perhaps the most critical limitation is the boiler design pressure, which is determined by the drum pressure. A certain difference is required between the drum and design pressures in order to ensure correct operation of drum safety valves. Furthermore, the design pressure determines the design of all superheating, evaporating, and preheating surfaces and also circulation pipes, downcomer, and headers, etc. The design pressure cannot be exceeded, and the only solution is to increase the design pressure by replacing the whole boiler; this rarely makes economic sense. Features that increase drum pressure through higher steam generation can be introduced to boilers if enough margin to design pressure can be ensured. Increasing main steam parameters is a more complex issue, as drum pressure increases almost as much as main steam pressure and the correct operation of main steam safety valves also needs to be secured. In other words, the main steam parameters can only be slightly increased, but that would mean that other features increasing the drum pressure most likely cannot be utilized at the same time without exceeding the design pressure. Also, as the investment costs of these features are lower, it is almost certainly not profitable to increase main steam parameters in retrofit projects.

Electrostatic precipitators and flue gas system

The performance of electrostatic precipitators (ESPs) is not so efficient when the inlet flue gas temperature increases, as high flue gas temperature leads to high flue gas volume flow and, therefore, retention time for the particles in the flue gas is shorter and less dust is separated. Also, the mechanical design of ESPs need to be checked when flue gas temperature is increased.

Figure 19 shows how each high power feature affects the flue gas temperature before the ESPs. Higher black liquor dry solids content actually is a benefit, because the flue gas flow is lower and also flue gas temperature is slightly lower. Air preheating is also beneficial to ESP performance due to lower flue gas exit temperature. On the other hand, features increasing feedwater temperature also increase flue gas temperature before the ESP. In these cases, ESP design requires closer analysis. If there is enough margin in dust emission permit levels, then higher flue gas temperature might be acceptable. Otherwise, some modifications to ESP internals, new fields, or a completely new ESP chamber and ducting are required, depending on the case. However, layout issues need to be solved when new fields or ESPs are needed. In many cases, layout is quite compact and the required space might be difficult to find.

Other components requiring closer examination in the ESP area are flue gas fans. Higher feedwater temperature leads to higher flue gas temperature and a bigger pressure drop due to higher flue gas velocity. As a result, the capacities and mechanical design of flue gas fans need to be checked. On the other hand, high dry solids and air preheating are beneficial to the performance of flue gas fans, as they decrease the pressure drop.

If the flue gas cooler is considered when increasing recovery boiler energy efficiency, it is necessary to check whether it is possible from a layout standpoint. As a flue gas cooler does not affect the boiler process, layout together with condensing turbine design are the only issues that need to be considered.

Feedwater system

Sizing of feedwater pumps and motors need to be checked when feedwater flow is increased. One needs to also include the increased feedwater motor electricity consumption in the profitability analysis.

Additionally, water velocity in feedwater piping and in SWC needs to be checked when steam generation is increased in order to avoid any internal erosion of piping.

As a certain temperature difference between the drum and SWC (or last economizer) is required, the amount of heat transferred with feedwater preheaters to feedwater (**Figure 18**) might be limited. Another issue is the location of the preheater and interheater: by default, they are located below economizers but in smaller boilers there might not be enough room for them. One solution is to put them outside the boiler house.

Black liquor firing system

The black liquor firing system may need some modification when black liquor dry solids content is increased. Black liquor becomes more viscous as it contains less water, consequently making it harder to pump. Possible targets for modifications are:

- Black liquor guns
- Piping
- Pumps
- Pressurized black liquor burning system (including pressurized heavy black liquor tank / flash tank / possible indirect black liquor heater for black liquor burning temperature fine tuning)

Special attention to material selection should be considered.

In the evaporation plant, middle pressure steam might be required in addition to low pressure steam, depending on the black liquor dry solids after a retrofit and extraction steam pressure levels. The evaporator plant may also require more heating surface.

Air system

As air is preheated, the volume flow increases. As a consequence, air velocity through the ducts and air ports increases. The velocities at unheated air levels are especially critical, since the potential temperature increase is higher and it is possible that air ports need to be replaced.

Another issue is that the pressure drop in air systems increases as the air preheating stages are increased up to perhaps three, so it is good to confirm the marginal capacity of forced draft fans. Additional steam heating stages also require space and pipe lines from the turbine extractions.

Vent gas system

The vent gas tube condenser is the only high power feature affecting the vent gas system. The tube condenser needs to be added to the existing dissolving tank vent gas system. This requires new piping lines and modifications to the existing ones, but the main challenge is to find enough space, as a tube condenser is a large, vertically installed component. So, the tube condenser faces the same issue as feedwater preheaters: in a small boiler, it might be difficult to fit a tube condenser below the economizers, and in those cases, a tube condenser may need to be located outside the boiler house.

Existing boilers with high power features – calculation examples

As the high power features have now been described in detail, along with their limitations and influence on boiler performance, it is now appropriate to study the benefits in electricity production and extra income. Two examples based on existing mills are shown with the most suitable high power features in those cases. Limiting factors are not taken into account in these analyses so it might not be possible to use all suggested high power features. Nevertheless, the calculation examples present the possible gains of each high power feature.

The following calculations were done with a self-developed tool that is used with Microsoft PowerPoint. A Microsoft Excel spreadsheet runs behind the PowerPoint application, calculating the electricity production based on certain assumptions and correlations. Only some of the boiler parameters are adjustable in the PowerPoint version; a standalone Excel version was also developed that includes more degrees of freedom for adjusting boiler and mill parameters.

The main difference between the two calculation examples is that there is a condensing turbine in the first case, whereas the second case has a back-pressure turbine and is connected to a district heating network.

Case Study #1: Condensing turbine

Figure 21 (next page) shows how generator output is cumulatively changed and the resulting percentage increase in electricity production when compared to the current mill situation (base case). The high power features are assumed to be added to a 3000 TDS/day recovery boiler. Process values of the base case are shown on the left side of **Figure 21**, and values after the modifications are mostly shown on the right side.

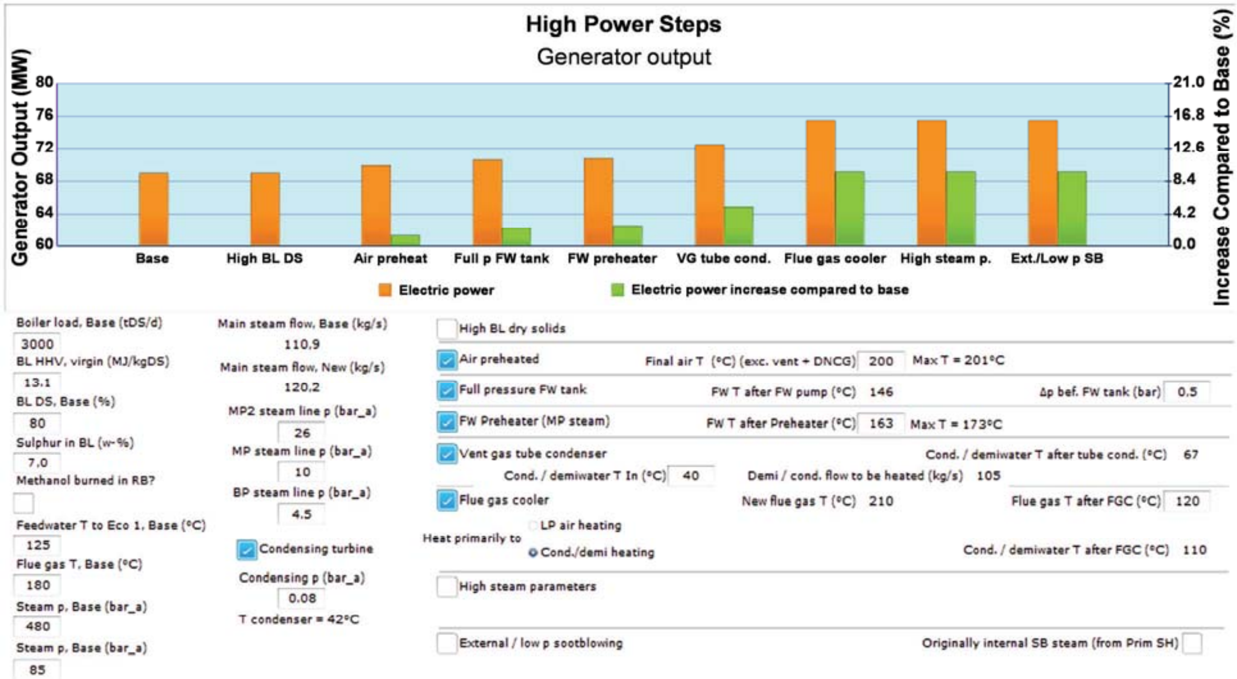

Figure 21. The effect of high power features on electricity production (Case study #1).

In this mill, black liquor dry solids content is already high (80%), so no modifications to the evaporation plant are necessarily needed. The following features were added: air preheating, a fully pressurized feedwater tank, a feedwater preheater, a vent gas tube condenser, and a flue gas cooler. As stated previously, increasing steam parameters is challenging in an existing recovery boiler and most likely not feasible, so these remain untouched.

Air temperatures in the base case are according to **Table 2**, and after adding a new preheating system, air flows in all levels are preheated to 200 °C, giving about 0.9 MW additional electricity. The pressure of the feedwater tank is raised by throttling less in the low pressure extraction steam line so that feedwater temperature after the feedwater tank is increased from 125 °C to 146 °C, resulting in an electricity production increase of 0.6 MW. The feedwater temperature is further increased to 163 °C in a feedwater preheater, which increases electricity output by 0.2 MW. This may not seem significant, but on the other hand, a preheater raises flue gas temperature (**Figure 19**), meaning that more heat from flue gases can be utilized in a flue gas cooler. An interheater might be a better solution and should be studied in a real case. However, with a combination of a preheater and an interheater, the electricity generation would increase even more. Heat is recovered from the vent gases in a tube condenser where a mixture of turbine condensates and demineralized water is heated from 40 °C to 67 °C, giving 1.7 MW of extra electricity. Due to the addition of a preheater and a fully pressurized feedwater tank, flue gas temperature after the economizers has risen from 180 °C to 210 °C and is cooled down to 120 °C in the flue gas cooler, resulting in an additional 3 MW. In total, electricity output is increased by 6.5 MW, which is 9.5% more than the base case.

Figure 22 (next page) illustrates how much extra income is achieved with a given electricity price. In this example, a price of 50 Euro/MWh is used. It can be seen that in this case a tube condenser and a flue gas cooler give the biggest benefit, but one must bear in mind that a flue gas cooler would not be as profitable

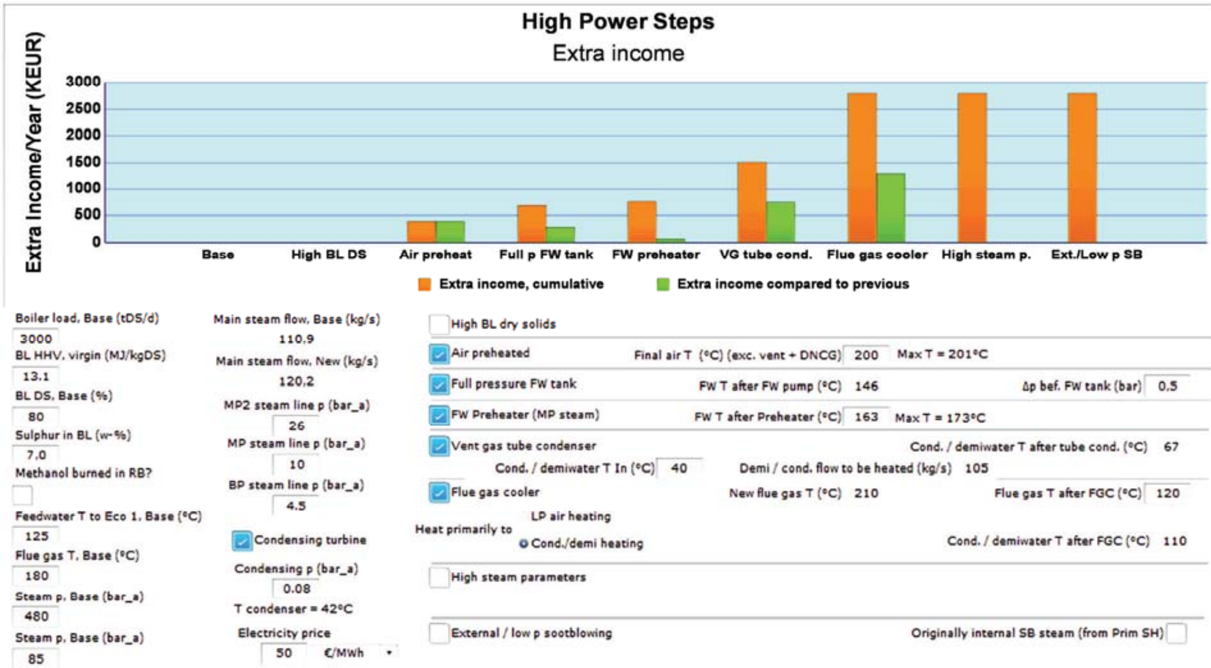

Figure 22. Extra yearly income produced by high power features (Case study #1).

without a fully pressurized feedwater tank and a preheater. Nevertheless, the total extra income in this case would be around 2.8M Euro every year.

Case Study #2: Back-pressure turbine and district heating

The size of the recovery boiler is a bit smaller (2000 TDS/day) in this example, as seen in **Figure 23 (next page)**. The black liquor dry solids content is increased from 72% to 80%, meaning 1.4 MW of additional electricity, whereas air preheating gives 1.0 MW more. Raising the feedwater temperature in two phases from 119 °C to 170 °C with a full pressure feedwater tank and a preheater gives 1.3 MW + 0.8 MW = 2.1 MW. Altogether, electricity production is increased 11.2% compared to the base case, which is 4.5 MW in electrical power. The electricity production with a back-pressure turbine increases more with the high power features than with a condensing turbine, as there is no disadvantage compared to the base case from a reduced amount of low pressure steam.

It is important to notice that the amount of low pressure steam left over is decreased when air preheating, a fully pressurized feedwater tank, and feedwater preheating are introduced to the boiler. This is because the extraction steam consumptions increase more than the main steam flow. The only exception is the high black liquor dry solids feature, which actually increases the amount of low pressure steam left over. In this example, low pressure steam left over is decreased by 2.0 kg/s compared to the base case when high black liquor dry solids, air preheating, a fully pressurized feedwater tank, and a preheater are introduced to the boiler. In this case, low pressure steam is used in district heating and the deficit needs to be taken into account when analyzing the profitability.

As there is no condensing turbine, a tube condenser and flue gas cooler do not generate any extra electricity, but they both reduce the consumption of low pressure steam in the feedwater tank. The tube condenser saves 3.5 kg/s and flue gas cooler saves 5.2 kg/s, meaning that in total 8.7 kg/s (6.7 kg/s compared to base case) more low pressure steam can be utilized in the district heating network.

Figure 23. The effect of high power features on electricity production (Case study #2).

Figure 24 shows the yearly extra income from increased electricity production, which is 1.9M Euro in total. If a tube condenser and flue gas cooler are left out of the scope, a lower low pressure steam amount should be taken into account.

Figure 24. Extra yearly income from increased electricity produced by high power features (Case study #2).

The price of district heat is around 28 Euro/MWh in Tampere, Finland. Assuming that district heating needs 4000 h/year and the average water temperature going to district heating network is 90 °C, the yearly deficit would be around 0.5M Euro. So, the total profit would be 1.4M Euro/year. However, when a tube condenser and flue gas cooler are taken into account, this deficit changes to a surplus of 1.8M Euro/year, with a total extra income of 3.7M Euro/year.

Recovery boiler conclusions

The thermodynamic efficiency of existing pulp mills can be improved by introducing the following high power features to the recovery boiler: higher black liquor dry solids, air preheating, fully pressurized feedwater tank, feedwater preheating, heat recovery from vent gases, heat recovery from flue gases in a flue gas cooler, and higher main steam parameters.

Some of the high power features affect the boiler performance and these impacts need consideration when increasing the thermodynamic efficiency, as they might totally or partially prevent the use of a certain feature. The main parameters affected are the main steam flow, the total boiler attemperation, the temperature difference between the drum and SWC/last economizer, the flue gas exit temperature, the drum pressure, and the sticky area location.

The black liquor firing system needs to be revised when the high solids content is increased. If air preheating with modern air temperatures is considered, it is necessary to check air port velocities and air fan capacities. Features increasing the main steam flow are limited by boiler design pressure, turbine design, boiler total steam attemperation, and drum internals. It is also necessary to check the feedwater system and boiler water circulation. In addition, feedwater preheating is limited by ESP design, and the temperature difference between the drum and SWC.

The vent gas tube condenser and flue gas cooler do not affect the boiler performance, and the main challenges are related to layout issues. Most likely, it is not feasible to increase the main steam parameters in retrofit projects, mainly due to boiler design pressure limitations. High power features also affect the sticky area location, but the overall effect is small.

The type of turbine also plays a big role when choosing high power features. The condensing turbine case is straightforward, but with a back-pressure turbine one must include the changes in low pressure steam flow in economic analysis. When there is a back-pressure turbine, a flue gas cooler and a tube condenser only reduce the low pressure steam consumption but do not increase electricity production. It still might be reasonable to invest in them if there is a high enough price for the low pressure steam.

Using our tool's calculations, it is easy to estimate possible profits when improving electricity production, and payback times can be determined when the installed price of each high power feature is known.

This white paper combines technical information obtained from Valmet personnel and published Valmet articles and papers. The evaporator study was created by Helena Fock, Fredrik Anangen and Raymond Burelle. The recovery boiler study was written by Jarmo Mansikkasalo.

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