

# Recovery boiler history and future

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## INTRODUCTION

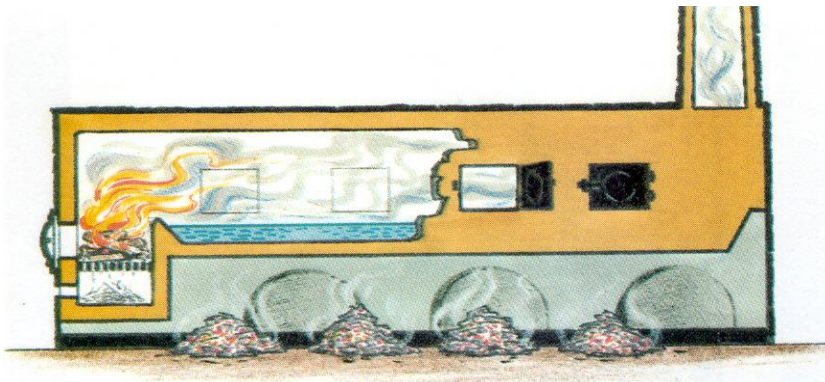
Recovery boilers are built all over the world. The roots of recovery technology are longer than the roots of recovery boilers. But it wasn't until the invention of recovery boilers before the Second World War that the pulping technology was revolutionized. This led to long development of essentially the same type of equipment, culminating into units that are largest biofuel boilers in the world.

Early recovery technology concentrated on chemical recovery as chemicals cost money and if one could recycle these chemicals then the profitability of pulp manufacture would improve. For pulp mills the significance of electricity generation from the recovery boiler was for long secondary. The most important design criterion for the recovery boiler was a high availability. The electricity generation in recovery boiler process can be increased by elevated main steam pressure and temperature or by higher black liquor dry solids as well as improving its steam cycle. This has been done in the modern Scandinavian units.

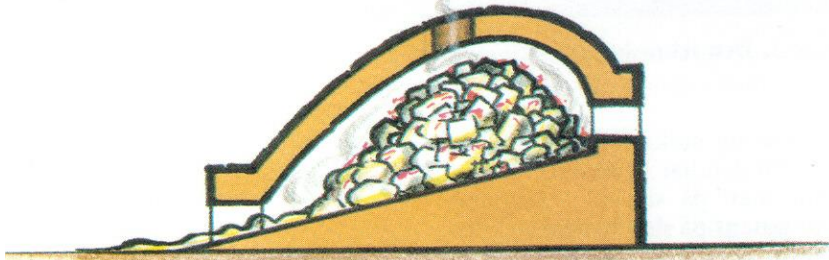
## EARLY RECOVERY TECHNOLOGY

Early recovery technology concentrated on chemical recovery (Deeley and Kirkby, 1967). Chemicals cost money and it was easy to discover that recycling these chemicals would improve the profitability of pulp manufacture (Vakkilainen, 2005).

Recovery of pulping chemicals could be based to French chemist Nicholas LeBlanc's process for producing soda at reducing furnace. A flame oven was hand filled with black liquor, Figure 1. Then the black liquor was dried with flue gases from burning wood. The dried black liquor was then scraped to floor, collected and sent to separate smelt pot, Figure 2, for reduction and burning the remaining organics (Rydholm, 1965). Recovery of chemicals with this type of system was inefficient. Chemicals recovery hardly exceeded 60 % (Whitney, 1968).

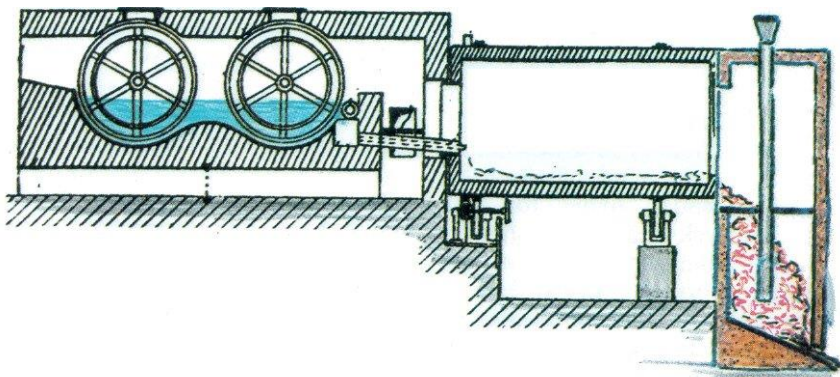


**Figure 1.** Early flame oven from late 1800's (Edling, 1981).



**Figure 2.** Early smelt pot from late 1800's (Edling, 1981).

Hand operated recovery grew more complicated with additional heat recovery surfaces. Pre-evaporation and scrubbing in a rotary device was invented by Adolph W. Waern (Combustion Engineering, 1949). The direct contact evaporator improved the heat economy of the recovery system. The hand feeding operation was soon replaced by rotating oven, Figure 3.



**Figure 3.** Rotating oven from 1890, liquor in at 20 % ds (Edling, 1981).

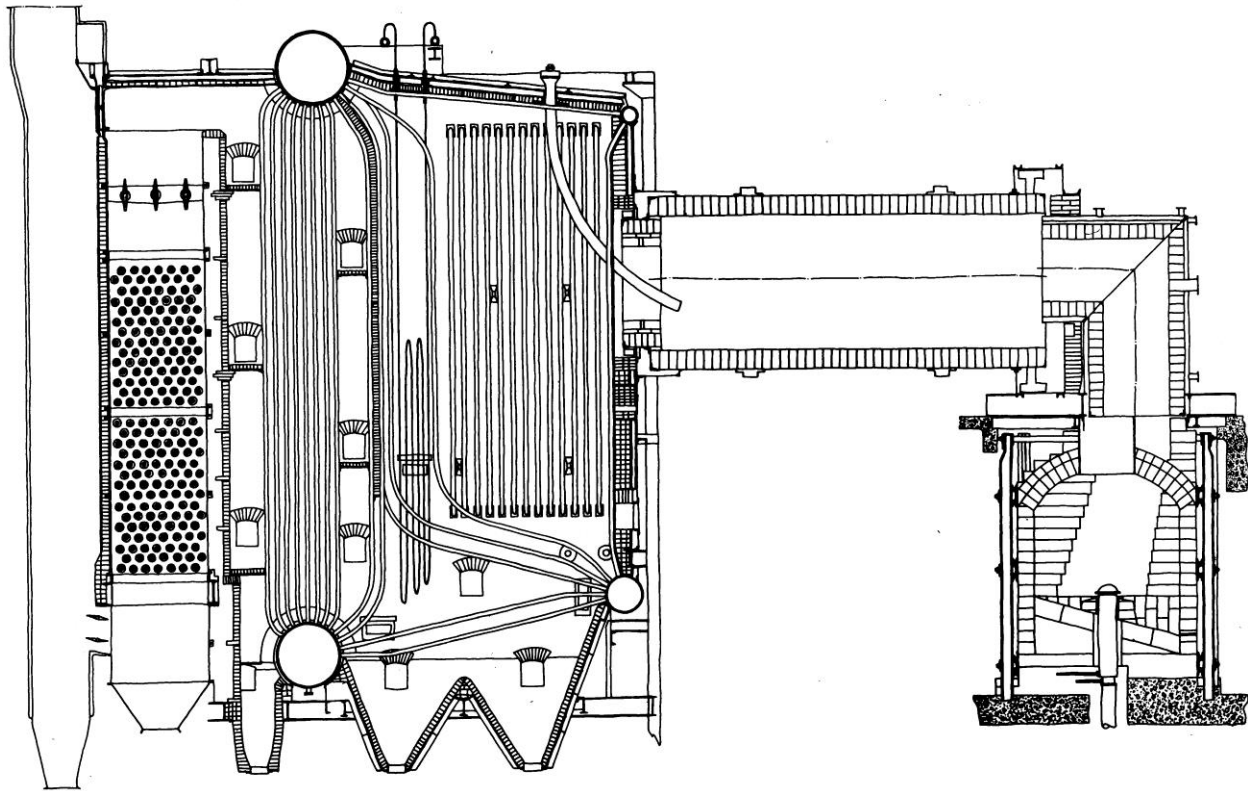
Use of rotary oven improved the heat economy. Then it was a small step to introduce heat recovery equipment as was done with other types of boilers at that time. In 1912 the S-S system (Sundblad-Sandberg) was taken online at Skutskär. In it liquor was sprayed into rotary furnace at 50 % ds. The evaporation took place in a four stage evaporator. The heat was recovered with vertical tube boiler.

Tampella was among the first manufacturers to build S-S type furnaces, Figure 4. Preventing unnecessary air flow through sealing arrangement between rotary drum and fixed parts was one of the major operating problems. The combustion was often conducted at very high air ratio leading to inefficient energy use. One could generate 3000... 4000 kg of 3.0 MPa steam for each ton of pulp (Roschier, 1952).

The main recovery equipment itself remained unchanged, but details were improved on. Smelt dissolving tank was introduced, final smelting was improved on and capacities grew. The use of refractory and rotating oven tended to limit the recovery capacity to 70 ... 75 tds/d (Sebbas *et al.*, 1983). Rotary part lengths were 7 ... 10 m and diameter about 1.5 m (Swartz and MacDonald, 1962).

The boilers parts were improved on. In 1930 seven LaMont type forced circulation units were built. The use of rotary furnaces pinnacle in Murray-Waern type units which were successfully built around the world. In these the rotary precombustion was combined with totally water-cooled furnace with lower part refractory lined. The Murray-Waern recovery units were popular until the fifties.

An epitome of inventiveness of that age was the Godell recovery unit at Stevens Point Wisconsin in 1940's. There the liquor was completely dried in a chamber after the boiler (Edling, 1983). But that unit and most of those other alternative systems were hard to operate and did not achieve high availability.



**Figure 4.** Early Tampella rotary furnace from about 1925 (Tampella).

### First recovery boilers

The modern recovery boiler has a few strong ideas that have remained unchanged until today. It was the first recovery equipment type where all processes occurred in a single vessel. The drying, combustion and subsequent reactions of black liquor all occur inside a cooled furnace. This is the main idea in Tomlinson's work. Secondly, the combustion is aided by spraying the black liquor into small droplets. Controlling process by changing spray proved easy. Stationary spraying was used in early rotary furnaces and with some success adapted to stationary furnace by H. K. Moore (Toivanen, 2012). Thirdly one can control the charbed by having primary air level at charbed surface and more levels above. Multiple level air system was introduced by C. L. Wagner.

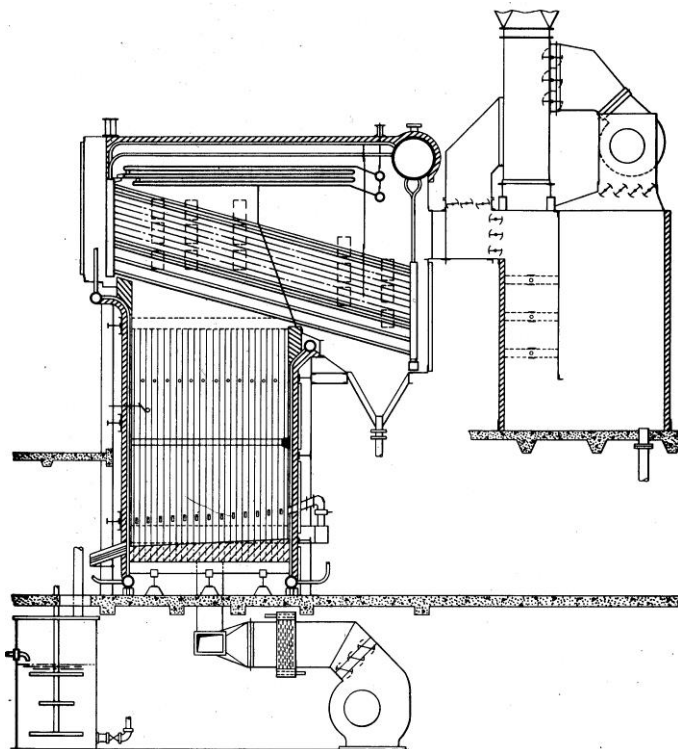
Recovery boiler also improved the smelt removal. It is removed directly from the furnace through smelt spouts into a dissolving tank. Some of the first recovery units employed the use of Cottrell's electrostatic precipitator for dust recovery.

After several attempts and learning from co-operation with Wagner when they built a stationary recovery furnace at the soda pulp mill of Howard Smith Paper Mills Ltd., in Cornwall, Ontario, Tomlinson built and put into service his first experimental stationary furnace with a heat recovery boiler in 1929 (Steam, 1992). This was soon followed by the world's first recovery boiler unit with completely water cooled furnace at Windsor Mills which started operation on June 27, 1934 (Tomlinson, 1975). After reverberatory and rotating furnaces the recovery boiler was on its way (Jones, 2004). Recovery boiler had two substantial benefits. One could build more easily larger recovery boilers than rotating furnaces. The second was energy efficiency.

In Finland Oulu Mills invested in the first five 120 tds/d recovery boilers in 1937. They followed in the footsteps of Husum 1936 and Skutskär 1937 which both had invested in similar recovery boilers. Kotka mills meanwhile invested in rotating furnaces. When the energy efficiency of recovery boiler and rotating furnace was investigated it was found that recovery boiler could produce 5000 ... 5300 kg/ADt steam when rotating furnace could produce only

4500 kg/ADt. The most modern boilers produce 4500 kg/ADt (Fernandez, 2001; Antônio, 2011). The early recovery boilers had net efficiency of about 70 % (LHV).

The second early pioneer, Combustion Engineering based its recovery boiler design on the pioneering work of William M. Cary, who in 1926 designed three furnaces to operate with direct liquor spraying and on work by Adolph W. Waern and his recovery units. The first CE recovery unit, looks a lot like a modern recovery boiler.



**Figure 5.** First Tomlinson kraft recovery boiler with water cooled furnace from Babcock&Wilcox in 1934. Note spray tower using weak black liquor before the ID fan.

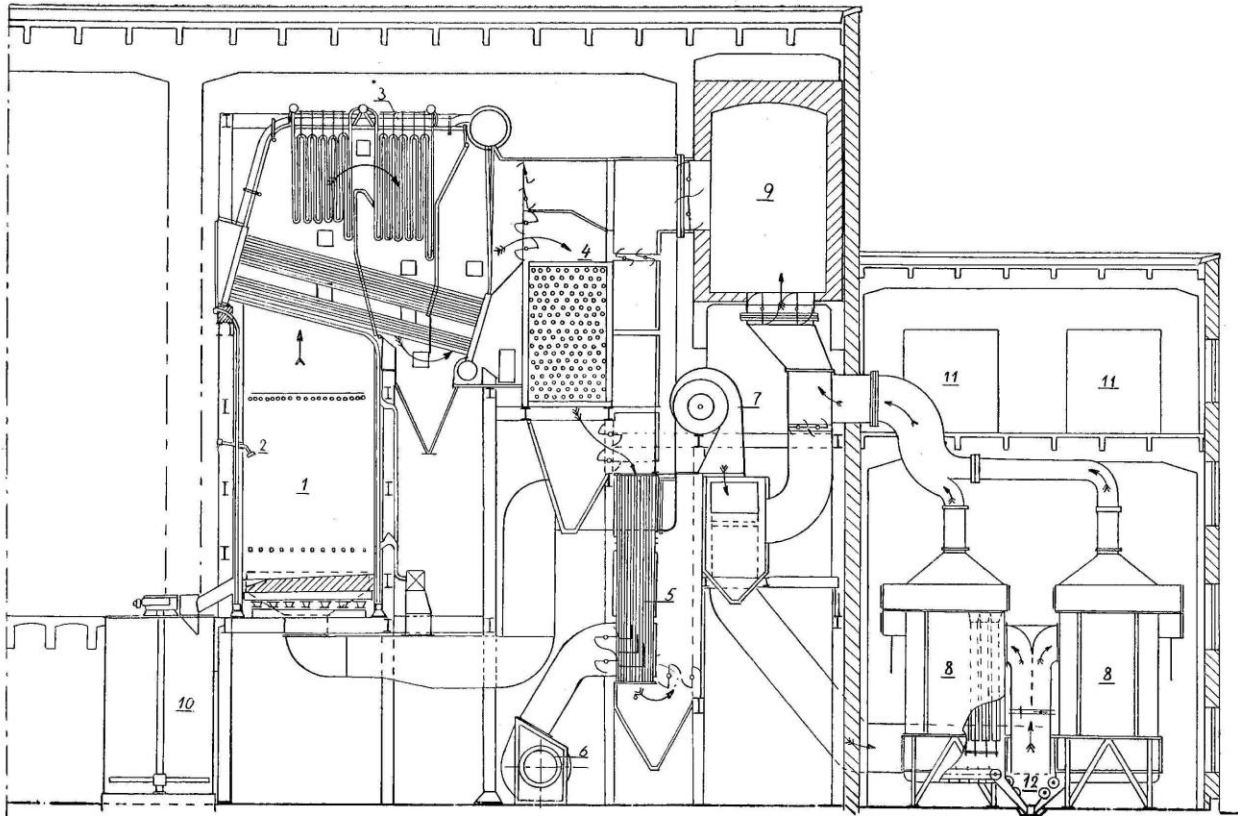
Recovery boiler were soon licensed and produced in Scandinavia and Japan. These boilers were built by local manufacturers from drawings and with instructions from licensors. One of the early Scandinavian Tomlinson units employed a 8.0 m high furnace that had 2, 8\*4, 1 m furnace bottom which expanded to 4, 0\*4, 1 m at superheater entrance (Pettersson, 1983). This unit stopped production for every weekend. In the beginning economizers had to be water washed twice every day, but after installation of shot sootblowing in the late 1940s the economizers could be cleaned at the regular weekend stop.

The construction utilized was very successful. One of the early Scandinavian boilers 160 t/day at Korsnäs, operated still almost 50 years later (Sanquist, 1987). Edling states in 1937 that more than 20 units had already been built of which 10 in Scandinavia.

### **Development of recovery boiler technology**

Spread of kraft recovery boilers was fast as functioning chemical recovery gave kraft pulping an economic edge over sulfite pulping (Boniface, 1985). They had about 20% better energy efficiency as more than 5000 kg of 3.0 MPa steam for each ton of pulp could be generated (Roschier, 1952, Alava, 1955). The first recovery boilers had horizontal evaporator surface followed with superheaters and more evaporation, Figure 1-13. These boilers resembled the state-of-the-art boilers of some 30 years earlier. This trend has continued until today. It is easy to understand that when any stop will cost a lot of money the adopted technology tends to be conservative. Conservatism meant that e.g. the new Oulu Oy, 100 000 t/a sulphate mill installed four Tomlinson boilers when it started operating in 1937 (Oulu, 1937).

The first recovery boilers had severe problems with fouling (Deeley and Kirkby, 1967, Roschier, 1952). Tube spacing wide enough for normal operation of a coal fired boiler had to be wider for recovery boilers. This gave satisfactory performance of about a week before a water wash. Mechanical steam operated sootblowers were also quickly adopted, Figure 6. To control chemical losses and lower the cost of purchased chemicals electrostatic precipitators were added. Lowering dust losses in flue gases has more than 60 years of practice. One should also note the use of electrostatic precipitators in an early Finnish recovery boiler (Roshier, 1952). The air levels in recovery boilers soon standardized to two. The primary air level was placed at the char bed level and the secondary above the liquor guns.



**Figure 6.** Early Finnish recovery boiler (Roshier, 1952).

In the first tens of years the furnace lining was often of refractory brick or refractory on cast blocks. The flow of smelt on the walls causes extensive replacement and soon designs that eliminated the use of refractory were developed. The standard then became the tangent furnace wall. Membrane wall use became widespread in the 60's.

B&W favored use typically a single black liquor gun at front wall. In larger units additional gun was placed on back wall (Tomlinson and Richter, 1969). They preferred a significant part of the liquor to be sprayed to walls for drying. Boiler bottom was in angle causing smelt to flow quickly out. Hardly any space was reserved for smelt layer in the furnace. Thus this kind of furnace is named sloping bottom type. Final black liquor evaporation was often carried in a direct contact evaporator of venturi scrubber or cyclone evaporator type. The highest practical black liquor solids was 60 ... 65 % depending on black liquor properties. Use of wall spraying was promoted by B&W and its licensees Götaverken and Babcock Hitachi. B&W adopted three level air in the late 1960s.

Early on the CE design stressed use of multiple guns in all walls (Tomlinson and Richter, 1969). Boiler bottom was flat with space for smelt layer on top of the whole floor. Thus this kind of furnace is named decanting floor type. Final black liquor evaporation was carried in a direct contact evaporator of cascade evaporator type. The basic aims of recovery boiler design could soon be summarized as; highest possible recovery of chemicals, high efficiency,

high utilization of the calorific values in black liquor and highest safety of operation (Hochmuth, 1953). CE stucked for a long time with a two level air system that had corner fired secondary. They used similar system in PCF-boilers.

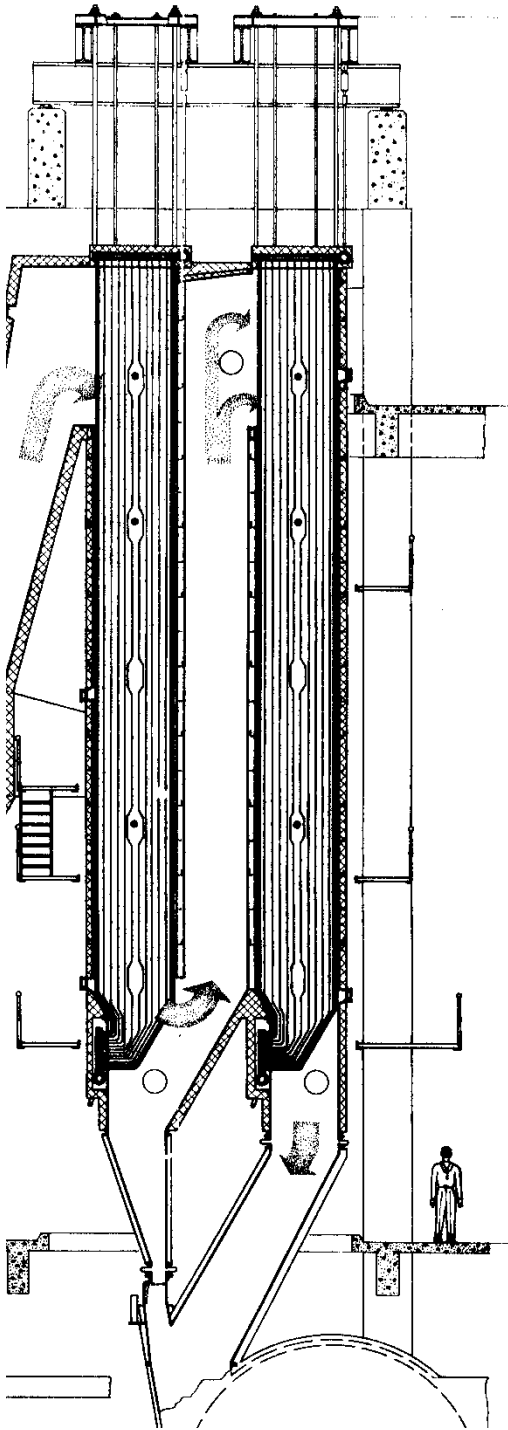
There are some early examples of single drum recovery boilers. Both B&W and Ahlstrom delivered a single drum boiler in the late 1950's. The first modern single drum recovery boiler was delivered in 1984 by Götaverken to Leaf River at Hattiesburg, Mississippi. The boiler size was 1966 tds/d. By 1990 all manufacturers started providing single drum boilers. Excluding very small boilers, all modern boilers are now of single drum design.

There are several advantages in a single drum boiler. Single drum construction eliminates the possibility of water leakage to furnace as it is placed outside the furnace. There are significantly less holes in a drum wall. Therefore it can be built thinner. Thinner wall of drum allows faster startup and stop-down. The gas flow to the boiler bank is smoother and heating surface arrangement is simple. The erection period is shorter because of large block construction. There is no rolled tube work. Enhanced and steady water circulation by separated and unheated down-comers. The largest advantage is that single drum boilers can be made larger. Tube stiffness limits cross flow two drum arrangement to about 2300 tds/d size (Steam, 1992). Vertical flow two drum constructions have suffered from plugging because of vibration stiffeners.

First recovery units had brick lined lower furnace with straight tubes forming cooling section behind bricks. This design persisted until the 1960's. Some of these units are still operating today. Another design provided corrosion protection of furnace tubes with studs and refractory. Some manufacturers use studs even today, but the need of stud replacement has led to decline in stud use. From late fifties onwards the membrane wall design took over, first with carbon steel walls. Tangent tube design was replaced with membrane design. The drawbacks of tangent design were the difficulties in inspecting welds and doing maintenance work

First furnace walls were of carbon steel. With increasing design pressure there were several corrosion problems in lower furnace. The advantage of chrome containing alloys as wall corrosion inhibitor was discovered as an answer to high pressure boiler sulfidation corrosion (Moberg, 1974). In 1972 Tampella delivered first totally compound tube recovery boiler furnace to ASSI Lövholmen mill in Piteå, Sweden. By 1982 there were 30 recovery boilers with AISI 304 compound tube bottoms in Scandinavia (Westerberg, 1983). Use of composite tubing in United States started only in 1981.

Sanicro 38 is a widespread material that offers improved corrosion protection for lower furnace. The first lower furnace made from Sanicro38 was delivered by Valmet. They used Sanicro38 in the lower furnace up to primary ports in 1994 for their Rauma recovery boiler.



**Figure 7.** One of the first long-flow economizers, Sunila (Moberg, 1967).

Earlier the recovery boilers had horizontal tube economizers. They plugged fast and had to be water washed at intervals of 1- 4 weeks (Rissanen, 1965). It was not until the early 1960 that installing vertical economizers started. In economizers of vertical flow design the gas flows downwards and water counter currently upwards (Hyöty, 1994). In a period of few years the current long flow economizer design emerged, Figure 7 (Moberg, 1967). Vertical economizer design spread fast in Scandinavia where by mid 1970's more than a half of the recovery boilers had long flow economizers without direct contact evaporator (Environmental, 1976).

In competition to purely vertical, the three pass designs featured gas flow which was forced crosswise the economizer tubes to improve heat transfer.

There have been several rounds of economizer header designs. In a typical old design each economizer tube is connected to a common large header. As maximum number of tube rows that fit to this type header is about 8 ... 10. The larger economizers must have front and back headers. This design has the disadvantage of having a header in the gas flow. The header can corrode and the welded joints tend to receive thermal stress. Modern economizers have flat horizontal headers.

### **High dry solids**

Dry solids at as fired black liquor was between 60 and 65 % in Sweden in the beginning of 1960's (Jönsson, 1961). In the beginning of 1950's the typical as fired black liquor concentration was 50 % (Vegeby, 1961). The final concentration was often done with cascade or cyclone evaporator. In practice the as fired dry solids could remain dangerously low before refractometers started to be applied in late 1960's and early 1970's (Hellström, 1970). The only reasons seen for higher dry solids were the energy economy and increase of bottom loading (Vegeby, 1961). One advantage noted was that partial load capability improved with higher dry solids. Increasing black liquor dry solids from 60 % to 68 % enabled running recovery boiler without auxiliary fuel firing at 65% of rated MCR (Rissanen, 1965). At 60 % dry solids hardly any partial load could be run.

In 1980's the first high dry solids' units started their coming on line. Extensive tests of effect of increasing dry solids from 72 % to 84 % were run at Metsä-Botnia Kemi and Rosenlew, Pori (Finland) recovery boilers (Hyöty and Ojala, 1987). They noticed that above 75 % dry solids the SO<sub>2</sub> and H<sub>2</sub>S emissions were practically zero. Also reduction increased more than one percentage point. Other benefits listed were, that steam generation and boiler controllability increased. High dry solids require that ESP ash is mixed to the black liquor with 62 ... 65 % liquor. Higher retention time also improves the stability of resulting black liquor.

### **Improving air systems**

Air system development continues and has been continuing as long as recovery boilers existed (Vakkilainen, 1996). As soon as the target set for the air system has been met other new targets are given. Currently, the new air systems have achieved low NO<sub>x</sub>, but are still working on with lowering the fouling.

The first generation air system in the 1940's and 1950's consisted of a two level arrangement; primary air for maintaining reduction zone and secondary air below the liquor guns for final oxidation (Llinares and Chapman, 1989). The recovery boiler size was 100 ... 300 tds/d and black liquor concentration 45 ... 55 %. Frequently to sustain combustion auxiliary fuel needed to be fired. Primary air was 60 ... 70 % of total air with secondary the rest. In all levels openings were small and design velocities were 40 ... 45 m/s. Both air levels were operated at 150 °C. Liquor gun or guns were oscillating. Main problems were high carryover, plugging and low reduction. But the main target, burning of black liquor could be done.

The second generation air system targeted high reduction. In 1954 CE moved their secondary air from about 1 m below the liquor guns to about 2 m above them (Llinares and Chapman, 1989). The air ratios and temperatures remained the same, but to increase mixing 50 m/s secondary air velocities were used. CE changed their frontwall/backwall secondary to tangential firing at that time. In tangential air system the air nozzles are in the furnace corners. The preferred method is to create a swirl of almost the total furnace width. In large units the swirl caused left and right imbalance. This kind of air system with increased dry solids managed to increase lower furnace temperatures and achieve reasonable reduction. B&W had already adopted the three level air by then.

At first the airport openings were made by bending one tube away from the opening sideways and making room for this by bending another tube back. Airport width was about tube spacing and large plate areas were needed to make airport gas tight. In 1978 CE began experiments with two level primary air. Upper primary was designed to about 20 % of total air with velocity up to 60 m/s. Total air split remained the same. The aim was to increase hearth temperatures.

Third generation air system was the three level air. In Finland the use of three level air with primary and secondary below the liquor guns started about 1980. At the same time stationary firing gained ground. Use of about 50 % secondary seemed to give hot and stable lower furnace (Westerberg, 1983). Higher black liquor solids 65 ... 70 % started to be in use. Hotter lower furnace and improved reduction were reported. With three level air feed and higher dry solids the sulfur emissions could be kept in place.



Fourth generation air systems are the multilevel air and the vertical air. As black liquor dry solids to the recovery boiler have increased, achieving low sulfur emissions is not anymore the target of the air system. Instead low NO<sub>x</sub> and low carryover are the new targets.

**Table 7.** Development of air systems.

Air system	Main target	But also should
1st generation	Stable burning of black liquor	
2nd generation	high reduction	Burn liquor
3rd generation	decrease sulfur emissions	Burn black liquor, high reduction
4th generation	low NO <sub>x</sub>	Burn black liquor, high reduction and low sulfur emission
5th generation	decrease superheater and boiler bank fouling	Burn black liquor, high reduction, low emissions

The three level air system was a significant improvement, but better results were required. Use of CFD models offered a new insight of air system workings. The first to develop air system with additional air levels was Valmet (Tampella) with their 1990 multilevel secondary air in Kemi, Finland, which was later adapted to a string of large recovery boilers (Mannola and Burel, 1995). Valmet also patented the four level air system, where additional air level is added above the tertiary air level. This enables significant NO<sub>x</sub> reduction.

Meanwhile Andritz adopted vertical air where primary level is arranged conventionally. Rest of the air ports are placed on interlacing 2/3 or 3/4 arrangement. Vertical air was invented by Erik Uppstu (1995). His idea is to turn traditional vertical mixing to horizontal mixing. Closely spaced jets will form a flat plane. In traditional boilers this plane has been formed by secondary air. By placing the planes to 2/3 or 3/4 arrangement improved mixing results. Vertical air has a potential to reduce NO<sub>x</sub> as staging air helps in decreasing emissions (Forssén *et al.*, 2000).

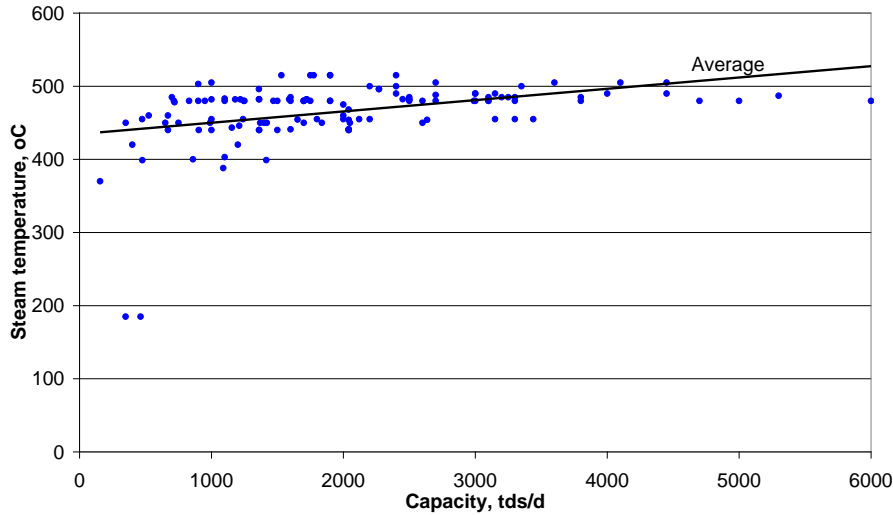
### High temperature and pressure recovery boiler

Development of recovery boiler main steam pressure and temperature was rapid in the beginning, Figures 1-18. By 1955, not even 20 years from birth of recovery boiler highest steam pressures were 10.0 MPa and 480 °C (Vakkilainen *et al.*, 2004). The typical pressures and temperatures then backed downward somewhat due to safety (McCarthy, 1968). By 1980 there were about 700 recovery boilers in the world (Westerbeg, 1983). In Japan, because of high electricity prices, more than ten high temperature and pressure recovery boilers are in use (Tsuchiya *et al.*, 2002). The biggest one is the 2700 tds/d, 10.3 MPa and 505 °C recovery boiler at Iwakuni mill (Ohtomo, 2000).

New large recovery boilers seem to favor high main steam temperatures and pressures (Vakkilainen, 2004). These increase the amount of backpressure electricity.

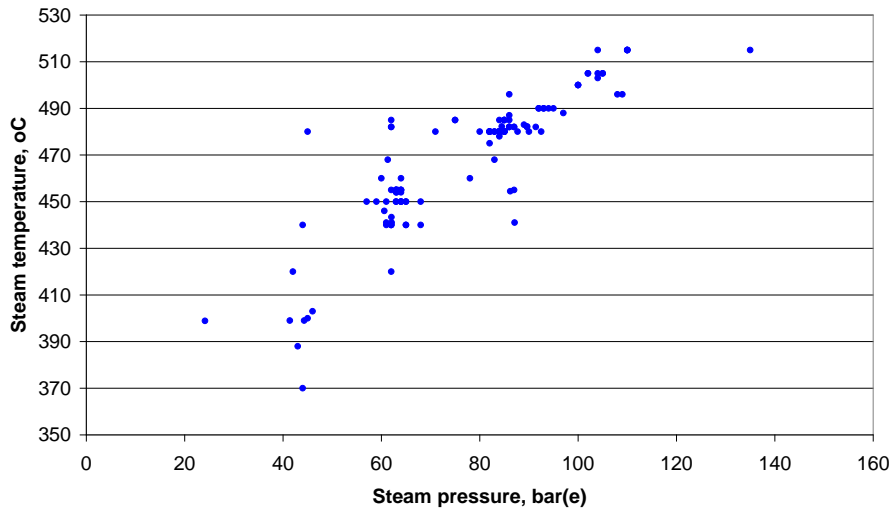
### Main steam temperature

Maximizing electricity generation is driving increases in the main steam pressures and temperatures. The maximum steam temperature can be limited by the ash properties. The first melting curve at the superheater front should be taken into account. Increasing mill closure with high chlorine and potassium decreases the melting temperatures. The overall mill heat balance should be used to optimize the feed water and flue gas temperatures.



**Figure 8.** Main steam temperature as a function of recovery boiler capacity.

The main steam temperature of recent recovery boilers is shown in Figure 8 as a function of MCR capacity of that boiler. The average steam temperature increases with size. Small boilers tend to have lower pressures to reduce specific cost. There are many boilers with main steam parameters higher than 500 °C. Most of them are in Japan.



**Figure 9.** Main steam temperature as a function of recovery boiler main steam pressure.

### **FUTURE HIGH ENERGY EFFICIENCY RECOVERY BOILER**

The increase of power generation in a pulp mill is result of larger recovery boilers being built (Haaga, 2014). The widely adopted industry practice of rising the black liquor dry solid content and main steam parameters will change the recovery boiler to sellable energy generator (Heinola, 2014). The rise of main steam parameters after superheaters from 90 bar/490°C to 100 bar/505°C increases generated power 2%. When increasing steam parameters and increasing black liquor dry solid content from 75% to 82% the generated power increases by more than 6%.

Often neglected way to increase generated power is the low-pressure preheating of turbine condensate and demineralized water to 100°C by turbine condensing section bleeds. This increased generated power by some 3% due to reduction of low-pressure steam extraction for water heating in feed water tank.

The rise of feed water temperature from 115°C to 140°C was the next attempt to increase power generation. It requires only small investments. It did not increase the generated power due to the higher flue gas losses. The high-pressure preheating of feed water to 180°C has even worse effect on generated power due to the heat losses of the flue gases. The solution is to increase the economizer surface areas or to add a heat. The flue gas heat recovery devices have high investment costs, but they are still highly recommendable. Using flue gas heat recovery devices with other alternatives can increase their effect significantly. The combination of combustion air / demineralized water heating and feed water preheating has the best result increase of generated power. The gain is because use of extraction steam can be reduced. These combinations have short payback periods in slightly more than one year.

The coupling using high-pressure preheating and combustion air heating means significantly increased generated power. This combination reduces high-pressure steam extraction significantly. Adding high-pressure preheating increases investment about 1 M€ and has a negative payback period.

The combustion air heating to 190°C increases generated power due to higher steam flow. The investment cost of an additional steam/air unit and modernization of power generation equipment is 1 M€. Payback period is in our case a few months. The energy improvement's efficiency can be increased through combinations with alternatives of feed water heating and flue gas heat recovery. These combinations reduce payback period to 11-13 months due to increase of generated power.

The combination of all energy improvements can increase generated power more than 15%. This requires an additional investment of more than 11 M€ but gives payback period of approximately one year depending on flue gas recovery application used.

Hence, the total optimization of pulp mill can increase generated power up to 23 MW with a payback period of the additional investment being 13 months. When calculating at a net sale price rate of 50 €/MWh it will create an additional profit of 10 M€/year from additional power sales.

There are some other opportunities for increasing the power output of the mill. One is of course designing the mill for lowest possible process heat consumption, thus freeing steam for condensing power. Preheating of boiler feed water between the economizer stages is possible, thus increasing the mass flow of steam through the turbine is another way. Many mills already use part of the methods mentioned above:

The Wisaforest Andritz recovery boiler started-up in 2004 in Pietarsaari, Finland (Nordbäck, Kaj, 2004) and Kymi Valmet recovery boiler started-up in 2008 in Kouvola, Finland (Tikka, Matti, 2008) have steam parameters of 102 bar/505 °C. They fire 82-85 % DS (w.o. ash) black liquor, use turbine bleed steam for sootblowing and heat combustion air to high temperature. Both the plants have Siemens extraction back-pressure turbines having many bleeds at different pressure levels and extraction for medium pressure steam.

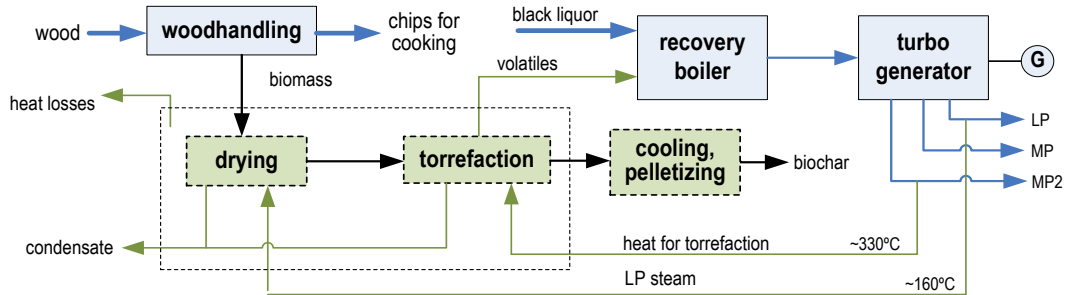
In Joutseno pulp mill the ABB extraction condensing turbine started-up in 1998 has a low-pressure pre-heater between the turbine condenser and the feed water tank (Vakkilainen, Esa *et al.*, 1999). The Östrand Andritz recovery boiler started-up in 2006 has steam parameter of 105 bar / 515 °C and uses flue gas heat recovery systems (Westberg, Åke, 2007) (Jakobsson, Mats *et al.*, 2007). The Värö Andritz recovery boiler started-up in 2003 was retrofitted in 2009 with extra feed water pre-heaters, additional superheater stage, enlarged economizer and a flue gas cooler. The Orion pulp mill in Fray Bentos, Uruguay involves many above mentioned energy efficiency items (Kiuru, Jukka, 2008). It fires 80 % dry solids eucalyptus black liquor in Andritz recovery boiler with steam parameters of 93-105bar / 495-505 °C. It has one 60 MW Siemens extraction back-pressure turbine and one 75 MW extraction condensing turbine. Now new mills will have a high efficiency recovery boiler which can generate in the order of 260 kg/s of steam. If a large single cylinder extraction condensing turbine is used then an output of more than 216 MW of electricity can be achieved.

## CONCLUSIONS

The energy efficiency of recovery boiler process can be improved by

- New modes of operation such as improvement of skills and motivation of personnel, energy audits, enhanced process integration of existing processes and industrial plants (secondary heat), collecting of reliable process information (monitoring and control) and decreasing sootblowing steam usage

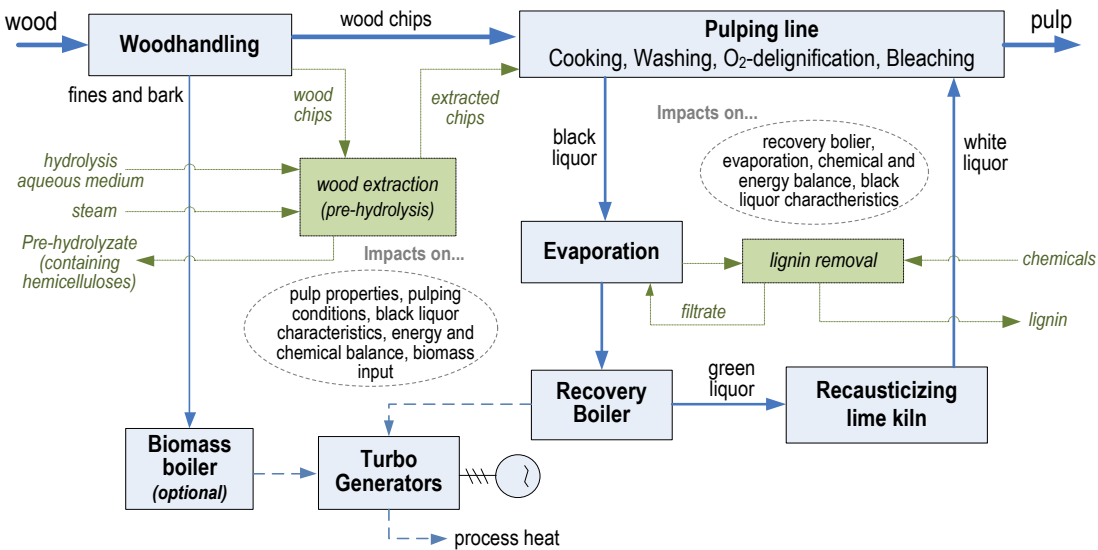
- New technology such as higher steam pressure and temperature, higher firing liquor dry solids and adopting electricity increasing features known from general boiler technology (increased feed water temperature, increased air preheating, flue gas heat recovery,
- New processes such as additional firing (e.g. bark or chips) and combining torrefaction or bio-oil production with recovery boiler



**Figure 10.** Torrefaction process integrated to kraft recovery.

Figure 10 shows recovery boiler integrated with torrefaction (Hamaguchi *et al.*, 2013b). If we can adopt our recovery operation to produce additional sellable products such as biochar, then changes are to be expected.

The recovery boiler operation will be affected by changes in pulping process such as lignin recovery and hemicellulose removal, figure 11 (Hamaguchi *et al.*, 2013a ).



**Figure 11.** Lignin removal and pre-hydrolysis: main impacts on the kraft process.

Modern kraft recovery boiler has evolved from chemical recycler to energy generator to providing sellable power. With next ten years even more radical changes are expected.

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