MODERN METHOD TO DETERMINE RECOVERY BOILER EFFICIENCY

Authors*:   Esa K. Vakkilainen[1]
             Pekka Ahtila[2]

Keywords: Acceptance test, black liquor, boiler efficiency, energy balance, recovery boiler

ABSTRACT

Recovery boiler mass and energy balances are needed for the performance testing of recovery boilers, mill energy wide control systems, and in calculating the air emission data. Typically, recovery boiler balances are mainly based on 1996 TAPPI publication "Performance Test Procedure: Sodium Base Recovery Units", the use of which is problematic in Europe because of its view that the losses from the recovery of process chemicals are counted when determining the recovery boiler steam generation efficiency. A low efficiency leads to taxation and legislative problems in some European countries. There is a newly accepted European standard for steam generator acceptance tests: EN 12952-15:2003 "Water-tube boilers and auxiliary installations - Part 15: Acceptance tests". This paper examines how the standard could be applied to recovery boilers to find out the net efficiency which is shown to be approximately the same as for other biomass boilers, not 10% lower. A new and more accurate method to calculate losses from convection and conduction is discussed. In addition, a suggestion on how to handle borate autocausticization in the recovery boiler furnace is made.

INTRODUCTION

Recovery boiler mass and energy balances are needed for the performance testing of recovery boilers, mill energy wide control systems and in calculating the air emission data. There is no suitable procedure for modern recovery boilers. Current recovery boiler balances are mainly based on 1996 TAPPI publication "Performance Test Procedure: Sodium Base Recovery Units" [1] the use of which is problematic in Europe because of US units and its view that the losses from the recovery of process chemicals are counted when determining the recovery boiler steam generation efficiency. General steam generator balances have been based on the outdated DIN 1942 "Acceptance Test on Steam Generators" [2], which fails to mention recovery boilers.

There is a newly accepted European standard for steam generator acceptance tests: EN 12952-15:2003 "Water-tube boilers and auxiliary installations - Part 15: Acceptance tests" [3]. This paper examines how the standard can be applied to recovery boilers. Because this standard does not give answers to kraft recovery boiler specific questions, some additional definitions have been made to e.g. calculate some heat losses. Borate autocausticization in the recovery boiler furnace has been included. This type of operation takes currently place in some Scandinavian mills. The balances are thus based on the as-fired liquor flow and as-fired liquor dry solids. The mass and energy balances are made for the unit mass flow of the as-fired liquor.

BALANCE CALCULATIONS

Recovery boiler mass and energy balances have been presented by Gullichsen [4], Clement *et al.* [5], Adams and Frederick [6], and Vakkilainen [7]. The conventions used to express the heat used in the reduction and the heat losses as smelt are for every author similar to the Tappi standard [1] that covers exclusively the recovery boiler mass and energy balance calculation.

Boiler efficiency

The boiler efficiency is a measure of the goodness of the chosen process and equipment to transfer the combustion heat to the heat in steam. For the best solid fuel boilers, the boiler efficiency is 86 … 90% [8]. Oil and natural gas fired boilers can achieve 90 … 94% efficiency. The boiler efficiency can be defined as the ratio of the useful heat output to the total energy input.

$$\eta = \frac{Q_{abs}}{Q_{in}} \qquad 1$$

where η is the boiler efficiency
         Q_{abs} is the useful heat absorbed (heat transferred to steam)
         Q_{in} is the heat and energy input into the boiler

*Authors' references:

1. Lappeenranta University of Technology, P.O. Box. 20, FI-53581 Lappeenranta, Finland
2. Aalto University, P.O. Box 4100, FIN-02015, Espoo, Finland
   E-mails: esa.vakkilainen@lut.fi , pekka.ahtila@aalto.fi

Corresponding author: Esa K. Vakkilainen - E-mail: esa.vakkilainen@lut.fi

To determine the efficiency of a boiler, a system must be defined and the energy flows that cross the system boundaries must be resolved. System boundaries should be chosen so that it is possible to define all the energy and mass flows in and out with sufficient accuracy. In practice, many minor flows are usually neglected. When determining the boiler efficiency, all internal reactions and recirculations can be neglected. The determination of boiler efficiency can be done with only flows through the system boundaries.

In a simple boiler process, the fuel and the required amount of combustion air are fed into the boiler. The fuel reacts with the oxygen in the boiler and the flue gas is drawn out. The released heat is captured to the water pumped into the boiler which transforms it to the steam that flows from the boiler.

It is clear that the system boundaries can be drawn in many ways. For example, the boiler house might form a convenient system boundary. It has been pointed out that the losses and heat input caused by fans, blowers and pumps should not affect the boiler efficiency. On the other hand, forced circulation pumps, flue gas recirculation fans and other internal process devices should be taken into account because they play a role when the boiler efficiencies between different types of boilers are compared. Therefore, the system boundary for the boiler efficiency loosely includes some but not all the equipment inside the boiler house.

A system boundary for the boiler efficiency measurement is determined in an equivalent way to the definition in EN 12952-15. **Figure 1** shows a typical system boundary for a recovery boiler. All flow values are recorded when the flow crosses the system boundary.
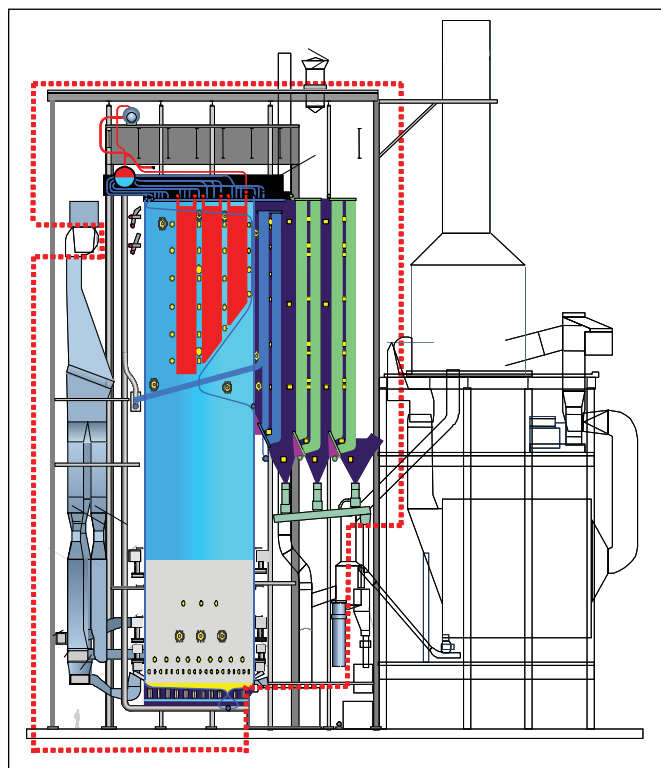

Figure 1. Typical system boundaries for a recovery boiler

Comments for system boundary definition

Most of the important subsystems are inside the system boundary: black liquor preheating and the associated equipment that increase the heat input and all the equipment starting from the first heat transfer surface, air preheater, including all the steam and water heat exchangers that cool the flue gas as they remove heat from flue gas and transfer it to steam/water. If forced circulation pumps are used, they are inside the system boundary.

Many important subsystems are outside the system boundary. Black liquor handling, storing and feeding equipment affect only the incoming black liquor properties. Air fans and air ducts affect the entering air temperature. Smelt handling and dissolving tank occur after the smelt exits the recovery boiler. Flue gas cleaning equipment affects the flue gas after it exits the boiler. A possible fan for flue gas affects the flue gas after it exits the boiler. The control system, instrumentation and electrification do not loose heat to the steam/water system.

MATERIAL AND ENERGY BALANCE

The control of combustion requires air flow that matches the fuel flow. The amount of air required to burn a mass unit of black liquor depends mainly on the water content and the heating value of the fuel. It is only the organics in black liquor that combust. A black liquor heating value increase, **Figure 2**, means that more air is needed for the combustion. Figures like Figure 2 can be used to estimate the required air flow for the dimensioning of the fans. More importantly, they should be used to estimate the possible range of air flows. A recovery boiler should be able to handle not only the design black liquor, but a range of typical black liquors. Normally, the actual design and performance estimation is done using the actual black liquor elemental composition.

Typical biofuels consist of carbon, hydrogen, nitrogen, sulfur, and oxygen. Black liquor contains also a high amount of ash; sodium, potassium and chloride compounds. It is often impossible to define the individual chemical compounds that form the fuel. The stoichiometric air demand can be calculated assuming that the fuel can be divided into three fractions: i) organic portion, which combusts fully, ii) reactive inorganic portion, which reacts to predefined end products, iii) inactive portion, which passes through the combustion system unchanged.

The basis for material calculations is typically one mass unit of black liquor. If mass balance values for one mass unit are known, it is easy to formulate the mass balance for a known load by multiplying all values with a single factor.

Flue gas flow

The black liquor flue gas production depends on the black liquor heating value. For a simple analysis, the estimation based on the predetermined mass ratio of flue gas to air can be done. The accurate flue gas flow can be calculated from a simple mass balance, if air flow, black liquor flow and smelt flow are known. When calculating real recovery boiler air and flue gas flows, the leakage should be taken into account. Air flow through air fans is less than the calculated
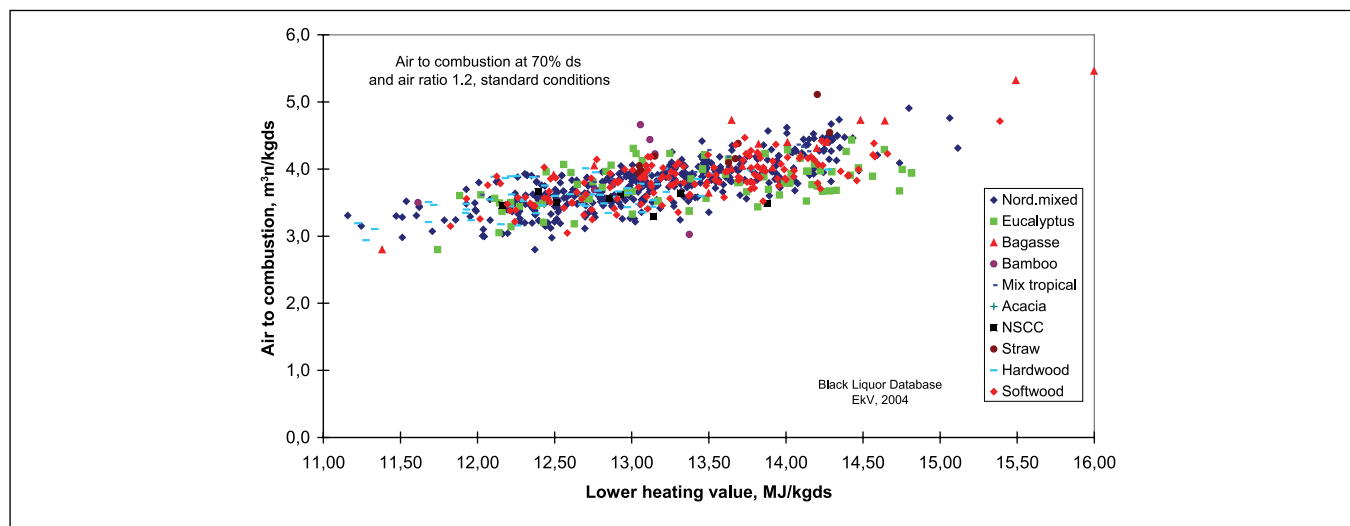
Figure 2. Black liquor air demand as a function of the lower heating value

as some of the air is infiltration air through various openings. The flue gas flow at stack can be significantly higher than through the economizers because of the same reason.

Useful heat output

The useful heat output includes all the heats to all of the steam flows. This value depends on the boiler type and the boundaries with which the boiler efficiency is calculated. Normally, the useful heat output can be defined as

$$Q_{abs} = Q_{ms} + Q_{rh} + Q_{bd} \qquad 2$$

where Q_{ms} is the heat transferred to main steam

Q_{rh} is the heat transferred to reheat steam

Q_{bd} is the heat transferred to blow down

The steam used to heat air or sootblowing are not taken into account.

Heat and energy input

The energy input consists of two components. One is proportional to the fuel flow, and the other does not depend on the fuel flow. The energy flows that depend on the fuel flow are:

- Chemical energy in the main fuel, H_u (heat of combustion)
- Chemical energy in the auxiliary fuels, H_u (heat of combustion)
- Energy included in the fuel preheating, Q_f
- Energy included in the air preheating, Q_a

Examples of energy flows that are somewhat independent of the fuel flow are shaft powers of the flue gas and air fans, shaft powers of circulation pumps, and the energy input by flue gas recirculation fan. It is customary to treat the useful heat input as a difference of input and output values. This means that the useful heat is the difference between the enthalpies of output flows and input flows. Therefore, it is logical that many energy flows are not considered as input flows. Such input flows include the heat in the feedwater, the heat in the desuperheating water flow and the heat in the incoming steam flow to the reheater.

Problems in determining efficiency with the direct method

Acceptance standard EN 12952-15:2003 "Water-tube boilers and auxiliary installations - Part 15: Acceptance tests" states that the efficiency can be calculated with a direct method. When mass flows, specific heat values and temperatures are known, the heat input with preheated air and fuel can be calculated using e.g. the following simplified formula

$$\eta = \frac{Q_{ms} + Q_{rh} + Q_{bd}}{H_u * m_f + Q_f + Q_a + \sum P} \qquad 3$$

or with the states of the flows as

$$\eta = \frac{m_{ms} * (h_{ms} - h_{fw}) + m_{rh} * (h_{rh,out} - h_{rh,in}) + m_{bd} * (h_{bd} - h_{fw})}{H_u * m_f + m_f * (h_{f,out} - h_{f,in}) + m_a * (h_{a,out} - h_{a,in}) + \sum P} \qquad 4$$

where:

H_u is the heating value of fuel

m_f is the fuel mass flow

Q_f is the heat transferred to preheated fuel

Q_a is the heat transferred to preheated air

SP   is the sum of mechanical end electrical energy input flows

m_{ms} is the main steam mass flow

m_{rh} is the reheat steam mass flow

m_{bd} is the blow down mass flow

m_a is the air mass flow

h_{ms} is the enthalpy of main steam

h_{fw} is the enthalpy of feedwater steam

h_{bd} is the enthalpy of blowdown

$h_{rh,out}$ is the outlet enthalpy of reheat steam

$h_{rh,in}$ is the inlet enthalpy of reheat steam

$h_{f,out}$ is the outlet enthalpy of fuel

$h_{f,in}$ is the inlet enthalpy of fuel

$h_{a,out}$ is the outlet enthalpy of air

h_{ain} is the inlet enthalpy of air

The above presented formula is a very simple formula. It ignores most of the energy flows that cross the boundary. We note that at least the following streams, typical for the recovery boiler, have not been accounted for: NCG-flows, methanol, turpentine flows, condensate, leakage air, sootblowing, other electricity flows, flows to and from flue gas cleaning, atomizing steam, auxiliary fuels, and HVAC streams.

It can be argued that these streams are minor and do not affect the calculation. It is difficult to assess their effect *a priori* without measuring them. Thus, the need to measure many flows is one of the main problems in the direct efficiency measurement. Another problem arises from the theory of mathematical uncertainty associated with the measurements. As each and every stream needs to be measured, the error in the efficiency becomes quickly very large. Therefore, the direct method is very seldom used in practice.

Determining efficiency with the indirect method

The recovery boiler efficiency is determined always using the indirect method. The efficiency equation can be arranged as

$$\eta = 1 - \frac{Q_{in} - Q_{abs}}{Q_{in}} \qquad 5$$

and even further as

$$\eta = 1 - \sum \frac{Q_{loss,i}}{Q_{in}} \qquad 6$$

where $Q_{loss,i}$ is the i:th heat lost

The main losses in a recovery boiler steam generator are: the heat lost with the flue gases, the losses of unburned combustible fuel, the sensible heat in the smelt flow (ashes), and the radiation and conduction losses. Most of these losses can be estimated to a greater accuracy than the actual flows. The indirect method, therefore, gives a higher accuracy when estimating the efficiency of the steam generator.

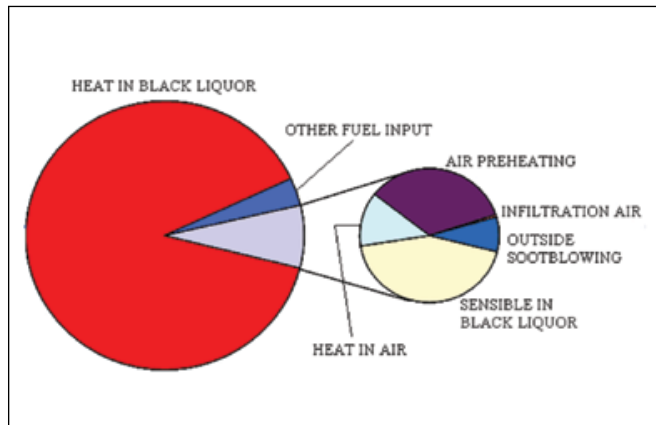As one can see from **Figure 3**, most of the heat input comes from

Figure 3. Example heat inputs to a recovery boiler

the heat that can be released in the combustion of black liquor. Other large sources are the sensible heats in black liquor and air preheating.

Useful heat

The useful heat can be calculated by subtracting the sum of heat losses from the total heat input. The useful heat is the heat than can be used to generate steam and the heat that is used in reduction and autocausticizing reactions.

Figure 4 shows how the total heat input is used. Most of the heat input is converted to steam. Reduction reactions are responsible for almost half of the rest. Autocausticizing with borate takes quite little heat. The biggest actual losses are the heat lost with wet flue gases and the sensible heat in smelt.
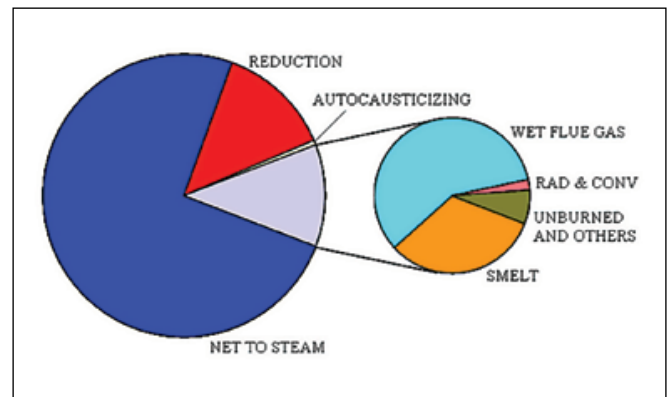

Figure 4. Example heat outputs of a recovery boiler

Heat for reduction

A recovery boiler recovers heat from the combustion of organics in the black liquor. In addition, it converts inorganic materials from their oxidized state to the reduced state. All this is useful work and consumes usually about 10% of the heat input. It should be taken into account in the recovery boiler net efficiency.

$$\eta = 1 - \sum \frac{Q_{loss,i}}{Q_{in}} + \frac{Q_{dR}}{Q_{in}} \qquad 7$$

where Q_{dR} is the sum of heats to reduction

Example: In a 4000 tds/d recovery boiler burning softwood black liquor at 85% dry solids, the heat used in the reduction is 1818,7 kJ/kgds, the losses are 3382,9 kJ/kg, and the heat input based on LHV is 1375,6 kJ/kgds. Calculate the recovery boiler efficiency based on the heat in the incoming fuel

$$\eta_{LHV} = 1 - \frac{\text{Losses}}{\text{Input}} - \frac{\text{Reduction}}{\text{Input}} = 1 - \frac{3382,9}{13375,6} + \frac{1818,7}{13375,6} = 88,3\% \quad 8$$

The steam generation efficiency is

$$\eta_{LHV2} = \frac{\text{Net to steam}}{\text{Input}} = \frac{9992,6}{13375,6} = 74.7\% \qquad 9$$

A modern recovery boiler is well in the range of the efficiencies of other biofuel boilers.

RECOVERY BOILER SPECIFIC QUESTIONS IN BALANCE

Using European standard EN 12952-15:2003 "Water-tube boilers and auxiliary installations - Part 15: Acceptance tests" for recovery boiler balances, one needs to define some specific details: how to take into account NCG (DNCG and CNCG), the dissolving tank vent gases, the methanol and turpentine, and the ash pickup with evaporator liquor, and determine the radiation and convection losses.

DNCG combustion in the balance

The combustion of dilute non condensable gases (HVLC) in recovery boilers should be treated like introducing wet additional air, if not otherwise agreed upon. If DNCG burning is allowed, their sulphur content needs to be very low. These gases do not typically contain combustibles. The error in the efficiency is small.

CNCG combustion in the balance

The combustion of concentrated non condensable gases (LVHC) in recovery boilers should be treated like burning auxiliary fuel. In the performance test, the heating value and the analysis in the contract corrected to actual conditions (water content) can be used.

Dissolving tank vent gas combustion in the balance

The combustion of dissolving tank vent gas in recovery boilers should be treated like combustion of dilute non condensable gases. Heating value for dissolving tank vent gas is zero, and the analysis is a mixture of water vapor and dry air.

Methanol and turpentine combustion in the balance

The combustion of methanol and turpentine in recovery boilers should be treated like burning auxiliary fuel. In the performance test, the heating value and the analysis corrected to actual conditions (water content) can be used.

Ash pickup with evaporator liquor

The way boiler and ESP ash is mixed to the black liquor does not matter. The mixing tank is placed outside the boiler balance boundary. This way it does not matter for the boiler balance whether it has a modern ash pickup with evaporator liquor or a traditional ash mixing to incoming liquor. The ash from recovery boiler increases with the boiler load and black liquor dry solids. **Figure 5** represents an estimate for ash flows from a modern recovery boiler. As the ash flow is notoriously difficult to measure, a figure of this kind can be agreed to show the ash flow during the balance case. Dust flow in Figure 5 is represented by the following equations

$$q_{ESP} = 0.3509*ds-(2800-HHRR)/1000*5.6158-6.865 \pm 3 \quad 10$$
$$q_{ECO} = 0.1*ds-4 \pm 2 \quad 11$$
$$q_{BB} = 1 \pm 1 \quad 12$$

where

q_{ESP} is the dust flow to electrostatic precipitator divided by dry flue gas flow at 3% O_2, g/m^3n, dry

q_{ECO} is the dust flow from economizer hoppers divided by dry flue gas flow at 3% O_2, g/m^3n, dry

q_{BB} is the dust flow from boiler bank hopper divided by dry flue gas flow at 3% O_2, g/m^3n, dry

ds   is the as-fired black liquor dry solids, %

HHRR   is the heart heat release rate, kJ/m^2

$$HHRR = LHV*MCR/A_{bottom} \quad 13$$

where

LHV   is the as-fired black liquor dry solids lower heating value, kJ/kgds

MCR   is the as-fired black liquor dry solids flow, kgds/s

A_{bottom} is the recovery boiler furnace bottom area, m^2

Sensible heat in black liquor

It is recommended that no separate determination of the sensible heat of black liquor is done for the performance test. In the performance test, the contract value corrected to actual conditions
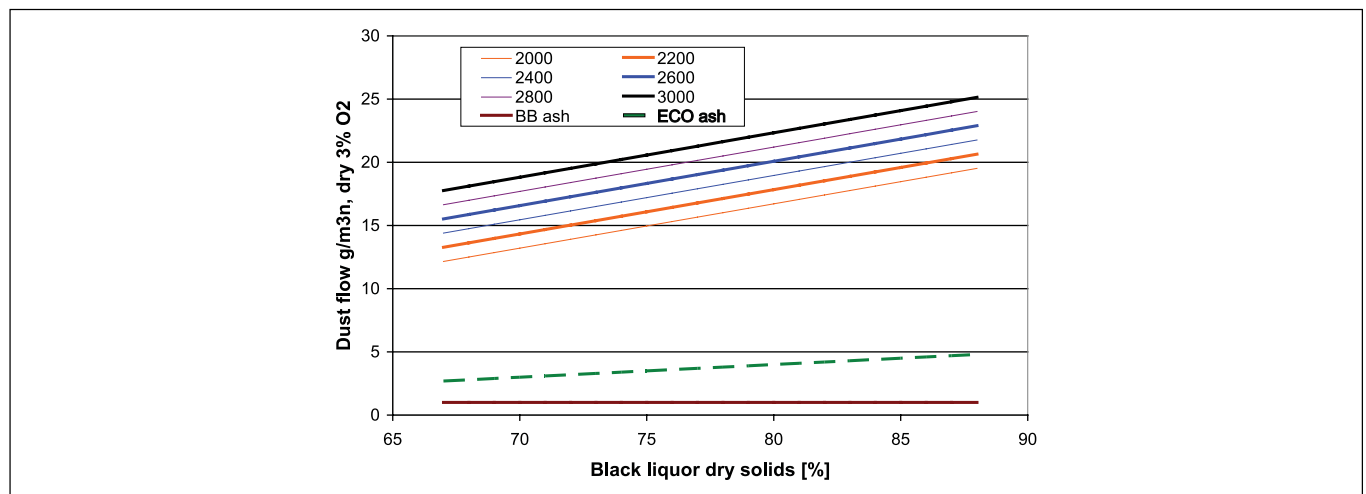

Figure 5. Effect of black liquor dry solids to dust flows; BB ash is the lowest line, ECO ash next higher line, ESP ash the upper lines at different HHRR

(dry solids, temperature) can be used. If the contract has no specified values, then a value from reliable literature [9] can be used.

Heat lost with the flue gases

The biggest heat loss from a steam generator is the heat lost with the exiting flue gas. The flue gas loss depends on the final flue gas temperature and the amount of flue gases. Thus, the higher the air ratio the higher the flue gas losses. The flue gases should leave the boiler at a temperature as low as possible to minimize the flue gas losses. Usually, either economics, equipment or corrosion issues limit the flue gas temperature between 150ºC and 200ºC.

Losses in the unburned combustibles

The fuels fired into the boiler will not combust totally. Thermodynamics limits the combustion process to some finite value. This means e.g. that there is always some CO, H_2 and other hydrocarbons present in the flue gases. When burning biofuels, some carbon tends to remain unburned. This means that some carbon remains in the ash. Carbon in the ashes captured from the flue gases is mixed with black liquor. This means that no losses occur. Usually the carbon content in modern recovery boilers is extremely low. Some unburned carbon exits with the smelt. The heat lost with this stream is very low.

Losses of sensible heat of smelt

To know the loss in the sensible heat of smelt, the temperature, flow and enthalpy must be determined. The enthalpy of different smelt components (e.g. Na_2S) can be expressed with the following equation:

$$h_c = h_m + c_p(T_{smelt} - T_{ref})$$ (14)

where
h_c is the specific enthalpy of component, J/kg
h_m is the specific enthalpy of melting for component, J/kg
c_p is the specific heat capacity of component, J/kg ºC
T_{smelt} is the smelt temperature, ºC
T_{ref} is the reference temperature, ºC

The enthalpy for a smelt with a given composition can then be calculated as

$$H_{SMELT} = \sum_{i=1}^{n} m_i h_{c,i}$$ (15)

where
H_{smelt} is the enthalpy of smelt, J
m_i is the mass of component i, kg
$h_{c,i}$ is the specific enthalpy of component i, J/kg

Specific heats of melting and specific heat capacities for typical smelt compounds can be found in literature [9, 10].

Borate

There are some mills in Scandinavia that use borate autocausticization [11]. Borate compounds can be treated similarly to sulfur compounds.

Loss in electrostatic precipitator ash

The heat loss in ash is usually small enough that even high inaccuracies in the ash loss determination usually have a negligible effect on the accuracy of overall efficiency.

RADIATION AND CONVECTION HEAT LOSSES

There are some losses from the hot boiler walls to the surroundings. Part of this energy increases the incoming air temperature. The amount of heat recovery does not affect the boiler efficiency but affects the amount of heat needed for air preheat. Radiation and convection heat losses do not depend on the boiler load. Radiation and convection heat losses from the recovery boiler are hard to measure because there are many flows in and out to the space surrounding the boiler proper inside the recovery boiler building. The radiation and convection heat loss can be estimated through equation 16. The coefficient 0.0257 is between coal (0.022) and lignite (0.0315) boiler values [11]. This equation with Tappi loss function is presented graphically in **Figure 6**.

$$\Phi_{RC} = 0.0257 * \Phi_s^{0.7}$$ (16)

where Φ_{RC} is the radiation and convection heat loss, MW
        Φ_s is the useful heat output at MCR load, MW

Most of the heat loss is from pipes (50%). Ducts and tanks account for only a minor portion (10%). The furnace accounts for roughly between fourth and fifth part (22%). Almost as large portion as furnace of heat losses comes from the electrical equipment (18%) [12]. The losses calculated from equation 16, the losses from Tappi and the measured losses are compared in **Table 1**. As can be seen, the Tappi loss function is not valid for boilers above 3500 tds/d.
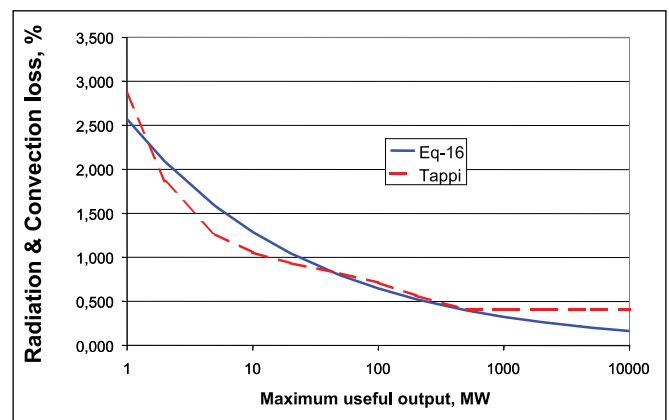

Figure 6. Radiation and convection losses: Equation 16, Tappi standard

Table 1. Calculated heat losses compared to measured heat losses from Finnish recovery boilers [10]

Boiler	Capacity tds/d	Calculated heat loss		Tappi loss	Measured kW
		kJ/kgds	kW	kJ/kgds	
Sunila SK11	1000	63.3	734	72.9	870
Kaukopää, SK6	3000	45.6	1582	44.6	1590
Rauma, SK3	3200	44.7	1655	43.3	1600
Kaukas, SK3	3350	44.1	1709	42.6	2000

BLACK LIQUOR HEATING VALUE AND ANALYSIS

The determination of the black liquor heating value and the elemental analysis is typically done at an accredited laboratory. The analyzed heating value is always the higher heating value. In the literature, one sees also often the effective heating value in which the loss by heat of reduction has been subtracted from the lower heating value [4, 6, 9]. The black liquor higher and lower heating values in dry black liquor are related with the known equation

$$LHV = HHV - 2.443 * (M_{H2O} / M_{H2}) * H \qquad 17$$

where   H   is the hydrogen mass fraction in black liquor
   M_i is the mole weight of i, kg/kmol

Black liquor hydrogen to carbon ratio is practically constant and the black liquor higher heating value is a function of carbon content. Therefore, with a very good accuracy, the lower heating value of black liquor dry solids can be presented as a function of the higher heating value

$$LHV = 0.96454 * HHV - 0.25335 \pm 0.05 \qquad 18$$

Typically, the lower heating value of dry black liquor is about 0.7 MJ/kgds less than the higher heating value. It should be noted that, generally, the anal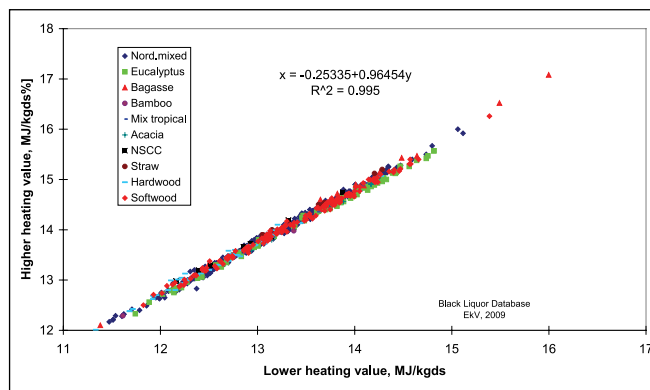ysis accuracy of heating value is about 0.1 MJ/kgds. The correlation shown in equation 18 is valid for all kinds of black liquors, **Figure 7**.

Figure 7. Black liquor higher heating value as function of lower heating value

ERROR ANALYSIS

Errors associated with the measuring equipment and analysis methods will affect the result of the performance test. All used measuring equipment should be calibrated before the performance test. If the result of an individual measurement has not been subjected to a closer error analysis, the error in the efficiency can be assumed to be according to **Table 2**.

Table 2. Error in efficiency caused by error in measurement

Measured property	Error		Efficiency
	%	Unit	%
Temperature at nose (pyrometer)	±5	±50°C	-
Temperature before bb (calibrated probe)	±5	±30°C	-
Temperature before bb (net, calibrated probe)	±2	±12°C	-
Temperature after eco (calibrated probe)	±2	±3°C	0.2
Temperature after eco (net, calibrated probe)	±0.5	±1°C	0.05
Air temperature (calibrated probe)	±0.5	±0.2°C	0.00
Black liquor HV (KCL)	±0.6	±0.1 MJ/kgds	1.0
Carbon in black liquor (LECO)	±1.4	±0.5%-unit	0.05
Hydrogen in black liquor (LECO)	±0.2	±0.01%-unit	0.03
Sulfur in black liquor (KCL)	±5	±0.2%-unit	0.6
Reduction (1 sample, KCL)	±1	±1.0%	0.1
Reduction (10 samples average, KCL)	±0.2	±0.2%	0.03
Dry-solids (calibrated refractometer)	±2.5	±2%	0.7
Dry-solids (1 sample, KCL)	±0.5	±0.4%	0.1
NOx (calibrated mill measurement 0-200)	±3	±6 ppm	-
NOx (outside accredited firm)	±3	±2 ppm	-
SO_2 (calibrated mill measurement 0-500)	±3	±15 ppm	-
SO_2 (outside accredited firm)	±3	±2 ppm	-

DISCUSSION

A method to calculate the recovery boiler efficiency based on the lower heating value has been presented. Calculating recovery boiler efficiency based on EN 12952-15:2003 "Water-tube boilers and auxiliary installations - Part 15: Acceptance tests" can be done if the recovery boiler specific questions are accounted for. The recovery boiler efficiency is similar to the efficiency of other biomass boilers if the process work that goes into reducing reactions is taken into account.

The use of this analysis for other types of boilers than modern kraft recovery boilers needs careful consideration. Without changes, its application to other types of boilers is not possible. Modifications are needed to accommodate NSSC boilers, magnesium and calcium based recovery units, boilers with direct contact evaporators, and gasification of black liquor. One of the biggest differences to earlier procedures is that this work includes all the applicable flows to furnace. Typical additional flows to the furnace are: the combustion of weak non condensable gases (DNCG or HVLC NCG), the combustion of strong non condensable gases (CNCG or LVHC NCG), the combustion of dissolving tank vent gases, and the combustion of methanol and turpentine. In addition to the above, with black liquor other streams are burned, makeup, waste acids, biosludge and soap.

Because the balances are based on the as-fired liquor, all the streams added to the virgin black liquor are automatically included. It is recommended that the maximum allowable flows for each stream during the performance testing are defined. Typically changes in these additional streams cannot be accepted during the performance testing. It is recommended that the testing is done with all typical additional flows on. Such flows are waste acids from the chemical manufacture and biosludge. Similarly, all individual flows to the furnace, like DNCG, CNCG and dissolving tank vent gases, should be operated during the performance testing.

Acknowledgements

REFERENCES

1. *Performance test procedure: sodium base recovery units*, 1996, CA Report No. 84041601, March 1996, Tappi Press, 54 p. ISBN 0-89852338.

2. *DIN 1942, 'Acceptance Testing of Steam Generators'* Deutsches Institut Fur Normung E.V. (German National Standard), 01-Feb-1994, 50 p.

3. *EN 12952-15:2003. Water-tube boilers and auxiliary installations - Part 15: Acceptance tests. No. 97/23/EC 2003,* CEN European Committee for Standardization, 89 p.

4. Gullichsen, Johan, 1968b, *Heat values of pulping spent liquors.* Preprints of the Symposium on Recovery of Pulping Chemicals, Helsinki, The Finnish Pulp and Paper research Institute and Ekono, pp. 85 - 100.

5. Clement, J. L., Coulter, J. H. and Duda, S., 1963, *B&W Kraft recovery unit performance calculations.* Tappi, Vol. 46, No. 2, p. 153.

6. Adams, Terry N., Frederick, Wm. James, Grace, Thomas M., Hupa, Mikko, Iisa, Kristiina, Jones, Andrew K., Tran, Honghi, 1997, *Kraft recovery boilers.* AF&PA, TAPPI PRESS, Atlanta, 381 p. ISBN 0-9625985-9-3.

7. Vakkilainen, Esa, 2000, *Recovery boiler. Chapter 13 in Chemical Pulping, Book 6,* series editors Johan Gullichsen and Carl-Johan Fogelholm, Finnish Paper Engineers' Association and TAPPI. ISBN 952-5216-06-3.

8. European Commission, Integrated Pollution Prevention and Control (IPPC), Reference Document on Best Available Techniques for Large Combustion Plants. 2006, European Integrated Pollution Prevention and Control Bureau, July 2006, 618 p.

9. Vakkilainen, Esa, 2000, *Chemicals recovery. Chapter 11 in Chemical Pulping, Book 6,* series editors Johan Gullichsen and Carl-Johan Fogelholm, Finnish Paper Engineers' Association and TAPPI. ISBN 952-5216-06-3.

10. Chase, M.W., Jr., 1998, NIST-JANAF *Themochemical Tables, Fourth Edition, J. Phys. Chem. Ref. Data*, Monograph 9, 1998, 1-1951

11. Björk, Maria, Sjögren, Tomas, Lundin, Tommy, Rickards, Helen and Kochesfahani, Saied, 2005, *Partial borate autocausticizing trial increases capacity at Swedish mill.* Tappi Journal, Vol. 84, No. 4, April 2001, pp. 15 - 19 p.

12. Ahtila, Pekka, 1997, Optimization of recovery boiler plant air systems by new design method and process integration. Acta polytechnica Scandinavica. Me. Mechanical engineering series; 127, Finnish Academy of Technology, 137 p. ISBN 952-5148-34-3

13. Vakkilainen, Esa K., 2006, *Recovery boiler performance testing - Material and energy balance.* Finnish Recovery Boiler Committee, Report 5/2006 4.12.2006, 55 p.