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Recovery boiler performance calculation – short form

Scope

The calculation procedure described herein provides a relatively simple, standardized method for rating thermal performance of recovery units. The procedure uses an overall energy and mass balance to establish the thermal conversion efficiency--the amount of steam produced relative to the energy expended. It is designed for use only when the main fuel is black liquor from sodium based pulping operations. The following sections address the possible applications, the data required for the calculations, and the calculation procedure itself.

Forms--in both SI and English units - are provided to systemize data acquisition and to carry out the necessary calculations. The calculation is designed as a computer spreadsheet calculation (compatible with Excel 2002 or later), and is available from TAPPI PRESS.

Safety precautions

There are no specific safety precautions relevant to the TIP, although generally accepted safety considerations for recovery boilers and their auxiliary equipment and systems should be observed.

Applications

The primary use of the procedure is to establish an operating efficiency for a recovery boiler. Periodic use of the procedure will allow the monitoring of performance trends. This procedure is not suitable for guarantee performance testing.

The procedure may also be used to roughly estimate the impact of changes to operating variables on overall thermal performance. However, it is limited to fairly small changes in conditions, since the procedure does not account for changes in heat transfer within the recovery unit boundary. The procedure simply uses whatever boundary conditions the user specifies.

Data requirements and collection procedures

The bulk of the inputs to the calculation procedure appear on the first page of the spreadsheet. These inputs are broken down into laboratory and field measurements, and miscellaneous data.

The following procedures are recommended as most suitable for establishing the laboratory and field inputs to the calculation:

Liquor solids

The recommended method for determining the solids content of black liquor is TAPPI Test Method T 650 "Solids Content of Black Liquor." Other devices used by the boiler operator to determine dry solids should be used only when calibrated against the TAPPI method. The solids content of the heavy black liquor (HBL) entering the recovery unit is to be measured at the unit boundary on an ash and salt cake free basis--from storage or from black liquor oxidation. The nozzle liquor solids should be the as-fired solids; this is only used in the liquor heater calculations.

Elemental analysis

The accuracy of the material balance around the recovery unit depends on the accuracy of the liquor elemental analysis. The analysis should include determination of sodium, potassium, sulfur, carbon, hydrogen, oxygen, and chlorine contents. It is recommended that TAPPI T 625 “Analysis of Soda and Sulfate Black Liquor” (withdrawn in 1999), or more current spectrophotometric methods, be used to develop the analysis.

If streams other than salt cake are added to the black liquor after heavy liquor storage or are fired separately in the furnace, the solids content, elemental analysis, and heating value of the liquor must be adjusted to account for these inputs. Appendix A provides a procedure for doing this.

Heating value

The gross heating value of the dry black liquor solids is calculated from the measured heating value of a black liquor sample in a laboratory oxygen bomb calorimeter. In making the calculation, the percent solids of the bomb calorimeter sample must be determined. It is recommended that TAPPI T 650 be used for this purpose.

Smelt analysis

Ideally, a smelt analysis should be performed. Alternatively, the reduction efficiency can be found from analysis of green liquor; however, the calculation of percent reduction should take into account the sulfide and sulfate concentrations in the weak wash to the dissolving tank. The quantity of unburned carbon in the smelt can be estimated from the average dregs solids flow. Typically, 60% to 70% of the dregs are unburned carbon. The “unburned carbon in smelt” input in the procedure is on a pounds of carbon per pound of black liquor solids.

Combustion air and flue gas measurements

The air temperature to the furnace should be the average for all air delivery levels on a mass-weighted basis. On units with externally supplied steam coil air heaters, the downstream temperature is used. On those units which use some internal heat source--flue gas, steam from the steam drum, boiler feedwater, or water from the boiler water circuit -- the air temperature entering the air heater is used. For direct fuel fired air heating, this procedure must be modified.

The O₂, CO and SO₂ in the flue gas should be measured at the economizer exit (or the exit of the generating section if no economizer is used). An “in-duct” measurement should be used to obtain concentration on a wet volume basis. The CO and SO₂ measurements can be neglected; they usually have a small contribution to the heat balance. The flue gas temperature should be measured immediately after the direct-contact evaporator or immediately after the last heat trap (economizer or air heater) on those units without a direct-contact evaporator.

Infiltration air

This is estimated as a percent of the theoretical combustion air. Use 3% for welded wall units and 7% for other units in reasonable repair. This item is used to back calculate the air to the FD fan and air heating.

Sootblowing steam flow

The sootblowing steam flow is used to help establish the total water vapor in the flue gas. It is included since the flue gas parameters, O₂, CO, and SO₂ are on a wet basis, and sootblowing steam is a source of vapor. The soot blowing steam is also included in the heat balance. Specify if the sootblowing steam is external or internal (from the drum or superheater of the boiler being examined) to the recovery boiler. If the sootblowing steam is internal the net steam production will be predicted (total steam minus sootblowing steam). If you wish to get the overall thermal efficiency of the boiler in the case of internal sootblowing then set the internal sootblowing flow to zero.

Boiler steam and water-side enthalpies

The enthalpies of the boiler feedwater, steam drum blowdown, and outlet steam are used to calculate the heat lost in the blowdown and calculate unit steam production. The boiler feedwater enthalpy should be taken as that for saturated water at the economizer water inlet temperature. The steam drum blowdown enthalpy should be taken as that for saturated water at the steam drum pressure. The enthalpy for outlet steam should correspond to the pressure and temperature at the superheater outlet. The spreadsheet will automatically calculate these values.

Specific heats

The following values are used for mean specific heats:

	$\text{kJ/kg} \cdot ^\circ\text{C}$	$\text{Btu/lb} \cdot ^\circ\text{F}$
Air to Furnace:	1.01	0.242
Dry Flue Gas:	1.0	0.24
Moisture:	1.9	0.45
Liquid Water:	4.2	1.0

The following mean specific heats can be used for heavy black liquor if no other data are available:

	$\text{KJ/kg} \cdot ^\circ\text{C}$	$\text{Btu/lb} \cdot ^\circ\text{F}$
50% dry solids:	3.0	0.72
68% dry solids:	2.8	0.67

Radiation heat loss

This loss can be estimated from the following graph. The radiation loss is inversely proportional to load when operating off-rating. The spreadsheet automatically enters the radiation loss based on the entered black liquor flow rate. Note that if the conditions used are significantly less (<70% of unit design capacity) than the design capacity of the boiler then enter a correction using the unaccounted for losses. For example if a 2400 ton/day unit is tested at 1200 tons/day then reduce unaccounted for losses by $(0.30 - 0.22 = 0.08)$.

Radiation Loss vs. Recovery Boiler Capacity (all weights are on a dry solids basis)

Recovery Boiler Capacity	Radiation Loss as % of Total Heat Input
<300 metric tons/day (331 imperial tons/day)	0.5
600 metric tons/day (661 imperial tons/day)	0.4
900 metric tons/day (992 imperial tons/day)	0.35
1200 metric tons/day (1323 imperial tons/day)	0.30
1500 metric tons/day (1654 imperial tons/day)	0.28
1800 metric tons/day (1984 imperial tons/day)	0.26
2100 metric tons/day (2315 imperial tons/day)	0.24
>2400 metric tons/day (2646 imperial tons/day)	0.22

Choose the boiler capacity closest to the boiler being tested.

The fuel heat input rate for a 1000 Btu-Ton/day boiler is 242 MJ/s.

Influence of operating variables

The following table illustrates the typical impacts which some of the key operating variables have on steam generating efficiency. (Relative change here is defined as the difference in efficiency divided by the original efficiency.)

Operating Variable	Relative Change in Efficiency
Stack O_2 rises from 2.8% to 3.8%	-0.5%
Stack SO_2 increases 100 ppm	+0.1%
Stack CO increases 500 ppm	-0.3%
Flue gas temperature 5°C higher	-0.3%
Add 0.01 kg salt cake per kg HBL	-1.1%
Liquor temperature 10°C lower	-0.1%

Operating conditions during data collection

After establishing stable operation under normal operating conditions, the test should be run for four hours with readings taken every half hour. The draft loss in any section of the unit should be normal and the soot blowers operated on a normal cycle. Soap should be shut off or maintained at a rate which is approximately the same during each test. No operational adjustments which could have an adverse effect on emissions should be made before, during, or after the test.

Simplifying assumptions

To facilitate calculation without significant sacrifice in accuracy, the following simplifying assumptions have been adopted in the procedure.

- **Ambient air temperature** is taken to be 298 K (77°F) - the same as the reference temperature for the heat balance.
- **Moisture in air** is taken to be 0.013 kg H₂O per kg dry air. This corresponds to 60% relative humidity at 298 K (77°F)
- **Sensible heat in molten smelt** is assumed to be 1351 kJ/kg (581 Btu/lb) smelt, which corresponds to the heat content of a smelt of 25% sulfidity, 90% reduction, and a temperature of 843 K (1550°F).
- **Ash recycle** is assumed to be 6% on a total solids basis. This is only used in the liquor heating calculations.

Items ignored

- **Liquor pump gland leakage** - The dilution of firing liquor can be considerable with high gland leakage, but it is exceedingly difficult to measure.
- **Fume**-Emission control requirements restrict the amount of fume discharged with the flue gas to very low levels which have a negligible effect on the material balance. Accordingly, it has been ignored in the procedure.
- **Reduced Sulfur Compounds in the Flue Gas** - To significantly affect the heat balance, these compounds would have to be present in environmentally intolerable levels.
- **Uncombusted Hydrogen and Volatile Organics** - The concentrations of these compounds should be negligible when reduced sulfur compounds are properly minimized.

Calculation procedure

Once all necessary data are obtained, the calculation is performed in a step-by-step fashion. First, the liquor solids and water inputs are summed. The water input from steam to the direct liquor heater, if present, is inferred from the before and after liquor heater temperatures. Next, the elemental analysis of the dry solids is adjusted to account for salt cake addition.

All combustion products must be calculated to determine the combustion air quantities. The proportion of nitrogen and moisture in the combustion air is defined by,

$$\text{kmol N}_2 \text{ and Moisture / kmol O}_2 = \frac{1 + \text{Humidity} \left(\frac{28.84}{18} \right)}{.21} - 1$$

at 0.013 kg H₂O/kg dry air - 3.86 kmol N₂ and H₂O/kmol O₂

Since a portion of the "products"- O₂, CO, and SO₂- are known only on a volume concentration, the total molar quantity of flue gas must first be established. The flue gas quantity (in lb-moles) can be reduced to the following relationship.

Lb-moles of Flue Gas =

$$\frac{\left[\frac{4.86}{12} C + \frac{2.92}{2} H + \frac{H_2O}{2} - \frac{3.88}{32} O + .93 \left(\frac{Na}{46} + \frac{K}{78} - \frac{Cl}{71} \right) + \left(6.79 - 7.72 \frac{E_{app}}{100} \right) \frac{S}{32} \right]}{1 - 4.8 \frac{\% O, w.b.}{100}}$$

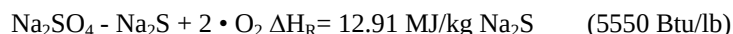
Unburned carbon in smelt and generation of SO₂ and CO also impact the flue gas quantity. However, since their impact on the overall calculation is negligible, they have been ignored in this equation.

With the total flue gas established, the flue gas O₂, CO, and SO₂ can be directly calculated. One by one, the quantity of each combustion product is calculated. All sulfur in the fuel, excepting that contained in the flue gas SO₂, is assumed to be in the smelt in the form of Na₂S or Na₂SO₄. The relative quantities will be in the proportion of the reduction efficiency. All chloride is assumed to leave as NaCl. The sodium left after accounting for those is taken to be Na₂CO₃. All potassium is assumed to leave as K₂CO₃. The carbon not accounted for in the Na₂CO₃, K₂CO₃ and CO is taken to be CO₂ in the flue gas. All hydrogen in the fuel is assumed to leave as water vapor. The oxygen in the combustion air is the total oxygen in combustion products plus the excess in the flue gas minus the oxygen in the fuel.

The combustion air from forced-draft fans is back calculated based on the assumed infiltration air percentage.

The steam generation efficiency is the ratio of heat available for steam to the total heat input into the unit boundary. The heat available for steam is calculated by subtracting the sum of heat losses from the sum of heat inputs. The heat inputs are,

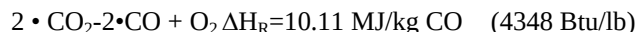
- the fuel heating value,
- the sensible heat content of the liquor and dilution water streams,
- the sensible heat added in liquor heating, and
- the sensible heat in the combustion air. The heat “losses” are,
- the sensible heat in the flue gas,
- the heat required to evaporate the water input and that formed by combustion of hydrogen, 2.442 MJ/kg (1050 Btu/lb),
- the sensible heat in the smelt,
- the heat of reaction to form sodium sulfide.



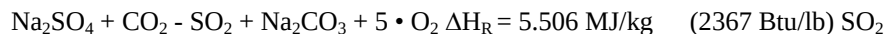
- the heat lost to unburned carbon,



- the heat of reaction to form CO,



- the heat of reaction to form SO₂,



- the heat in the steam drum blowdown water,
- thermal radiation loss, and
- unaccounted for.

Spreadsheet changes

Note that the spreadsheet for this TIP has been extensively modified in order to simplify the entering of data, unit conversions and analysis of the impact of changes in operating parameters. In order to work correctly macros must be enabled in the spreadsheet. Questions regarding the use of the spreadsheet can be sent to standards@tappi.org.

RECOVERY BOILER PERFORMANCE CALCULATION - SI Units

LABORATORY TESTS

Required

INPUTS

Optional

ANALYSIS OF HEAVY BLACK LIQUOR (From Storage or Oxidation System)

1	Sodium, Na	kg/kg solids		{1}
2	Potassium, K	kg/kg solids		{2}
3	Carbon, C	kg/kg solids		{3}
4	Hydrogen, H	kg/kg solids		{4}
5	Sulfur, S	kg/kg solids		{5}
6	Oxygen, O	kg/kg solids		{6}
7	Chlorine, Cl	kg/kg solids		{7}
8	Inerts	kg/kg solids		{8}
Total		1.000		
9	Gross Liquor Heating Value	MJ/kg solids		{9}
10	Solids in Heavy Black Liquor	% solids		{10}

SMELT ANALYSIS

11	Reduction Efficiency $\{Na_2S/(Na_2S + Na_2SO_4) \times 100 \text{ as } Na_2O\}$	%		{11}
12	Unburned Carbon in Smelt (on lbs. per lb HBL basis)	kg/kg solids		{12}

FIELD MEASUREMENTS

COMBUSTION AIR AND FLUE GAS CONDITIONS

13	O ₂ in Flue Gas	% wet vol.		{13}
14	CO in Flue Gas	ppm wet vol.		{14}
15	SO ₂ in Flue Gas	ppm wet vol.		{15}
16	Air Temperature to Furnace (Weighted average mass flow)	K		{16}
17	Exit Gas Temperature Immediately After the Last Heat Trap or DCE	K		{17}

HEAVY BLACK LIQUOR (HBL) INPUT

18	HBL Flow from Storage or Black Liquor Oxidation (BLO)	kg/s		{18}
19	HBL Temperature from Storage or BLO	K		{19}

DILUTION TO DCE

20	Weak Black Liquor Flow (WBL) from Storage	kg/s		{20}
21	Solids in WBL from Storage	%		{21}
22	WBL Temperature from Storage	K		{22}
23	Water Flow	kg/s		{23}
24	Water Temperature	K		{24}

LIQUOR HEATING CONDITIONS

Enter 1 if heater is direct type

25	Solids in Nozzle Liquor	%		{25}
26	Temperature of Nozzle Liquor - Before and After Heater	K		{26}

OTHER DATA

27	Salt Cake Makeup	kg/s		{27}
28	Soot Blowing Steam Flow	kg/s		{28}
29	Feedwater Continuous Blowdown (as % of steam production)	%		{29}



Documents

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