Heat balance of the CFB boiler

Pavel Ruseljuk
Tallinn University of Technology
pavel.ruseljuk@energia.ee

Abstract
Only a fraction of combustion heat is utilized for the generation of steam. This fraction or the thermal efficiency of the boiler is calculated by carrying out a heat balance around the boiler. Boiler efficiency is formed by considering losses relative to ideal products, so for CFB boiler losses must be corrected with heat credit due to heat receiving in sulfatation and heat credit to incomplete decarbonation.

Boiler heat balance then becomes an indicator of energy conversion, from chemical to useful output, relative to a common energy level.

A typical boiler comprises heat exchangers: economizer, evaporator, superheater, reheaters and air preheaters. The economizer preheats the cold water close to its saturation temperature. In the evaporator, the water is heated to saturation and the saturated water turns into saturated steam by absorbing the combustion heat. The saturated steam is superheated by absorbing further heat in the superheater.

Keywords
Heat; loss; flow; boiler; efficiency; temperature; enthalpy; energy; flue gas; furnace; moisture; steam.

Introduction
The combustion heat generated in the furnace is equal to the sum of all heat losses and the enthalpy gain of water/steam in the boiler. The heat balance of a Circulating Fluidized Bed (CFB) boiler is similar to that of any other boiler.

Heat losses are usually expressed as a fraction or percentage of the potential combustion heat. They are expressed in terms of the heat losses associated with the burning coal and its higher heating value (HHV). The following components of the loss are discussed below:

1. Dry flue gas loss through stack
2. Moisture losses (in sorbent, fuels, air)
3. Calcination losses
4. Sulfating credit - it is a negative loss
5. Unburnt carbon loss
6. Convection - radiation loss
7. Sensible heat loss in fly ash and bottom ash
8. Fan credit - it is also a negative loss
9. Unaccounted loss

2 Heat Balance of the Boiler
Boiler efficiency is formed by considering losses relative to ideal products. However, if the outputs (products) from combustion are not ideal, they are then “corrected” through loss terms. For CFB combustion dissociation calcium carbonate or calcium hydride involves endothermic reaction, for which the input of energy is required so for CFB boiler losses must be corrected with heat credit due to heat receiving in sulfatation and heat credit to incomplete decarbonation.

2.1 Dry Flue Gas Heat Loss
When the temperature of the flue gas leaving the stack $T_f$; is higher than the ambient temperature $T_a$; an amount of heat, known as stack heat loss, is lost to the atmosphere. This loss is made up of two components: dry flue gas and moisture in it.

The dry flue gas loss can be calculated by Equation (2.1)

$$L_{stack} = \frac{M_{df}C_f(T_f - T_a)}{HHV}$$

where: $M_{df}$ is the dry flue gas mass per kg fuel burned.

2.2 Loss Due to Moisture in Air
The moisture, leaving the boiler above the ambient temperature, carries with it an amount of heat known as moisture loss. The moisture in the flue gas is made up of three components: moisture from air, coal, and hydrogen. The moisture losses for each of these three components are calculated separately.

Heat loss due to the moisture is relatively high because typical stack temperatures are above the vaporization point of water. Thus, the moisture carries with it the latent heat of vaporization, $Q_{latent}$; which cannot be recovered unless the flue gas is cooled below its vaporization temperature and the superheat, $Q_{SH}$. The moisture loss is defined as Equation (2.2)

$$L_{mo,air} = \frac{M_{d,a} \left[ EACX_m \left( C_m(100 - T_a) + Q_{latent} + Q_{SH} \right) \right]}{HHV}$$

where: $M_{d,a}$ is the stoichiometric amount of dry air required for 1 kg of fuel fired, $X_m$ is the moisture fraction in the air, $EAC$ is the excess air coefficient (1 + excess air fraction), $C_m$ is the specific heat of water, and $Q_{SH}$ is the enthalpy of superheating equal to $C_f (T_f - 100)$. Here, we assume that the saturation temperature of water is 100 °C at stack pressure.
2.3 Moisture Loss from Coal
Coal may contain some moisture, $H_2O$, whose loss can be calculated by Equation (2.3):

$$L_{m,\text{fuel}} = \frac{[H_2O]C_m(100-T_a)+Q_{\text{latent}}+Q_{SH}}{HHV}$$

2.4 Moisture Loss from Burning Hydrogen in Coal
When 2 kg of hydrogen is burned, 18 kg of water is generated. Thus, the moisture loss from the hydrogen content of the fuel, $H$ is calculated by:

$$L_{m,h} = \frac{9[H](100-T_a)+Q_{\text{latent}}+Q_{SH}}{HHV}$$

2.5 Calcination Loss
When the boiler uses limestone to capture sulfur, two additional terms, calcination loss, and sulfation credit are considered in the heat balance. Both limestone and dolomite contain calcium carbonate, magnesium carbonate, and impurities. When exposed to the heat of the CFB furnace, both carbonates calcine to their respective oxides. The reaction is endothermic and absorbs heat from the combustor.

For absorption of the $SO_2$, limestone is fed into the furnace. Limestone is first calcined to CaO through the following reaction:

$$CaCO_3 = CaO + CO_2 - 1830 \frac{kJ}{kg} \text{ of CaCO}_3$$

If the sorbent contains magnesium carbonate, an additional reaction occurs:

$$MgCO_3 = MgO + CO_2 - 1183 \frac{kJ}{kg} \text{ of MgCO}_3$$

The heat loss from calcination can be calculated from the following Equation (2.5):

$$\text{Calc. Loss from CaCO}_3 = \frac{\text{Feed rate of CaCO}_3 \cdot 1830}{\text{Fuel feed rate} \cdot HHV}$$

$$\text{Calc. Loss from MgCO}_3 = \frac{\text{Feed rate of MgCO}_3 \cdot 1183}{\text{Fuel feed rate} \cdot HHV}$$

where: $HHV$ is the higher heating value of the fuel in kJ/kg.

2.6 Sulfation Credit
The calcined limestone (CaO) reacts with sulfur dioxide producing calcium sulfate (CaSO$_4$) according to the following exothermic reaction:

$$SO_2 + CaO + \frac{1}{2}O_2 = CaSO_4 + 15,141 \frac{kJ}{kg}$$

The resulting heat gain from the Equation (2.6):

$$E_{\text{abs}}S \frac{15,141}{HHV}$$

where: $E_{\text{abs}}$ is the fraction of the sulfur content. $S$ converted into CaSO$_4$.

This equation is unaffected by any other source other than the calcium in the coal ash because sulfation from any other source produces the same amount of heat.

2.7 Unburnt Carbon Loss
The unburnt carbon loss, $L_{ubc}$ for CFBs is relatively high, in the range of 5 to 20%, depending upon the rank of coal. Low-rank fuel like lignite would have higher combustion efficiency than the highrank anthracite. The bed ash may typically contain less than 3% unburnt carbon while the fly ash may have a much higher percentage.

2.8 Other Heat Losses
Other heat losses cannot be calculated directly. These losses, which include convective-radiation loss, ash sensitive heat loss, fan credit, and other unaccounted losses.

$$L_{\text{others}} = \text{convective radiation loss } +$$

$$\text{ + ash sensitive heat loss } + \left( \text{fan credit} \right) +$$

$$+ \text{ unaccounted losses}$$

No data on convection–radiation heat loss from fluidized bed boilers is available in the published literature. As the furnace is generally water-cooled, the convective-radiation heat loss through the exterior walls of a typical CFB boiler can be estimated using the graphs provided by the American Boiler Manufacturers Association (Singer, 1991) or ASME Performance test Code PTC-4.1.

3 Boiler Efficiency
Boiler efficiency is defined by the fraction of the total combustion heat released transferred to the water and steam. It is computed by subtracting all types of losses from the potential fuel energy input and then dividing it by the latter. This method is called heat-loss method. Alternately, it could be found directly dividing the enthalpy in the steam produced by the potential energy in the corresponding amount of fuel fired. However, owing to the practical difficulty in measuring, the heat-loss method is more frequently used for efficiency calculations.

The total heat loss is found by adding all the losses from above:

$$L_{\text{total}} = L_{\text{stack}} + L_{\text{m,air}} + L_{\text{m,fuel}} + L_{m,h} + L_m + L_{\text{others}}$$

Using the information above, the boiler efficiency, $\eta$ can be calculated by equation below:

$$\eta = \left(1 - L_{\text{total}}\right) \cdot 100\% \quad (3)$$

In literature so often boiler efficiency is calculated from the equation: $\eta^\text{gr} = 100 - q_2 - q_3 - q_4 - q_5 - q_6$, [%] where: $\eta^\text{gr}$ -the total efficiency of the boiler, %;

$q_2$ - fluegas losses, %;

$q_3$ - losses due to incomplete combustion, %;

$q_4$ - losses due to unburnt matter in flue gas, %;

$q_5$ - radiation losses, %;

$q_6$ - losses due to unburnt matter in slag, %;

245
4 Energy Balance in Dense Circulating Fluidized Bed

The heat balance of the dense bed is a critical aspect of the design of CFB boilers. It determines the operating temperature of the bed. In a CFB, the furnace or bed temperature is controlled within a specified range of about 800 to 900 °C through extraction of heat by heat-absorbing tubes and heat carrying flue gases leaving the bed (Figure 1).

The combustion of fuel is rarely complete in the dense circulating bed. Thus, the combustion heat is partially released in the bed, while some combustibles leave the bed to burn in the freeboard. The heat released in bed $Q_i$ can be found by:

$$Q_i = m_i X_\beta HHV$$  \hspace{1cm} (4)

where: $m_i$ is the fuel feed into the bed, $X_\beta$ is the fraction of combustion taking place in the bed and $HHV$ is the higher heating value of the fuel.

The enthalpy brought into the bed by the primary air $H_i$; depends on the mass of primary air $m_a$; and its preheat, $T_i$:

$$H_i = m_a C_{air}(T_i - T_a)$$  \hspace{1cm} (4.1)

where: $C_{air}$ is the specific heat of air at temperature $T_a$.

The energy brought into the bed by fuel and sorbents $H_f$ includes the heat of the solids as well as the heat of the external moisture carried by them. The surface moisture $M_s$ of a fuel, stacked outside in the open atmosphere, can be substantial at times Equation (4.2):

$$H_f = (m_c + m_s) C_p T_a + (m_f M_f + m_s M_s) H_o$$

where: $C_p$ is the specific heat of solids, $H_o$ is the enthalpy of water at $H_o$; and $M_f$ and $M_s$ are the fractions of moisture in fuel and sorbents, respectively.

**Total heat input** $Q_i + H_i + H_f$  \hspace{1cm} (4.3)

The heat absorbed $Q_i$; by in-bed tubes depends on the bed temperature $T_b$; average tube-wall temperature $T_w$; exposed heat transfer surface area $A_i$; and the (-)h; and is defined by $Q_i = h A_i (T_b - T_w)$.

Heat radiated from bed surface $Q_o$; is a major source of heat loss from the bed and is directly proportional to the bed surface area $A_o$; exposed to the freeboard.

$$Q_r = \sigma e_b A_b \left[ (T_b + 273)^4 - (T_f + 273)^4 \right]$$  \hspace{1cm} (4.4)

where $e_b$ is the effective emissivity of the bed surface, $\sigma$ is the Stefan–Boltzman constant, and $T_f$ is the freeboard temperature.

Heat loss through the bed drain is made up of sensible heat loss due to ash $(m_{ash} X_{ash} C_p T_b)$ and that due to sorbent $(m_{c,s} C_p T_b)$ for boilers with limestone injection.

$$Q_{dr} = (m_{ash} X_{ash} + m_{c,s}) C_p T_b$$  \hspace{1cm} (4.5)

where: $X_{ash}$ is the ash fraction in fuel and $x_a$ is the fraction of the total fuel ash or the spent sorbent present in the bed drain, $m_c$.

The flue gas carries the remaining ash (fly ash). Thus, the total heat loss in flue gas $Q_{fb}$; is made up of the enthalpies of the gas (including water vapor) and the fly ash:

$$Q_{fb} = m_v M_m C_f T_f + m_b M_b H_b + + (1 - x_d) X_{ash} m_c + m_s C_p T_b$$  \hspace{1cm} (4.6)

where: $H_b$ is the enthalpy of steam at $T_b$ and $G_s$ is the amount of flue gas produced per unit mass of fuel burned as Equation (4.7):

**Totalheat leaving the bed** $Q_i + Q_o + Q_r + Q_{fb} + Q_{dr}$

The total heat input is equal to the heat output under a steady state. From Equation 4.3 and Eq. 4.7 we get:

**Total heat entering bed** $=\text{total heat leaving bed}$ $Q_i + H_i + H_f = Q_{fb} + Q_{dr} + Q_r + Q_{sb}$

From this Equation 4.8 one can solve for $T_b$: It is apparent from here that these equations will always yield a positive value of the bed temperature $T_b$; however, small it may be. If it is below the ignition temperature, the fuel will not ignite, but if it is above the softening temperature, the bed will agglomerate. This determines the operating or fuel flexibility limits of a CFB boiler.

5 Heat Balance of Boiler Components

A typical boiler comprises heat exchangers: economizer, evaporator, superheater, reheaters and air preheaters (Fig. 1). The economizer preheats the cold water close to its saturation temperature. In the evaporator, the water is heated to saturation and the saturated water turns into saturated steam by absorbing the combustion heat. In rare exceptions, some evaporation may also be allowed in the economizer. The saturated steam is superheated by absorbing further heat in the superheater.

The primary goal of the thermal design is to determine the heating surface areas of the economizer, evaporator and superheater, which are dictated by their respective heat loads and heattransfer coefficients. Steam conditions specify their heat loads.

The following four parameters of the water/steam are needed to obtain the heat loads or duties of the individual heat exchangers:

1. Steam temperature of the final superheater, $T_{sh, outlet}$
2. Steam pressure of the final superheater $P_{sh, outlet}$
3. Feedwater temperature of the economizer $T_{econ, inlet}$
4. Required steam mass flow rate $G_s$
The superheater heat load is written as:

\[ Q_{\text{sh}} = G_s \left( H_{\text{sh, outlet}} - H_{\text{sh, inlet}} \right) \]  

The calculation procedure could start with the superheater because the pressure of the steam is generally given and the pressure of the water in the economizer can be calculated considering the pressure losses through the heat exchangers in between.

### 5.1 Superheater

The superheater heat load is written as:

\[ Q_{\text{sh}} = G_s \left( H_{\text{sh, outlet}} - H_{\text{sh, inlet}} \right) \]  

The steam enthalpy at the outlet of the superheater is determined by knowing the pressure and temperature of the steam at the outlet of the final superheater. The pressure at the inlet of the economizer can be assumed as the drum pressure plus the hydrostatic head above its inlet and the friction in piping. The temperature at the economizer inlet is the same as the feedwater temperature, and the outlet temperature can be assumed as the temperature at the inlet of the evaporator.

The total heat load of the boiler is found by adding above terms: 

\[ Q_{\text{steam}} = Q_{\text{econ}} + Q_{\text{evap}} + Q_{\text{sh}} \]  

Actual heat load of the boiler will be slightly higher than this because the heat loss due to boiler blowdown, desuperheating has not been considered here.

### 5.2 Evaporator

The pressure at the inlet and outlet of the evaporator can be taken as the drum pressure plus the hydrostatic head and the inlet pressure of the superheater plus the drop across the drum internals, respectively. Temperature at the outlet of the evaporator can be assumed to be the saturated steam temperature at the pressure of \( P_{\text{sh,inlet}} \) plus the drum internal drop. The inlet temperature in the evaporator is expected to be slightly lower due to the mixing of cooler water from the economizer with the saturated water. For rough estimation, it can be taken as 15°C below the saturation temperature \( T_{\text{sat}} \) at drum pressure:

\[ T_{\text{evap,inlet}} = T_{\text{sat}} - 15^\circ C \]  

5.3 Economizer

Pressure at the inlet of the economizer can be calculated by adding economizer pressure drop, \( \Delta P_{\text{econ}} \) to its outlet pressure: 

\[ P_{\text{econ,inlet}} = P_{\text{econ,outlet}} + \Delta P_{\text{econ}} \]  

The economizer heat load is written as:

\[ Q_{\text{econ}} = G_s \left( H_{\text{econ, outlet}} - H_{\text{econ,inlet}} \right) \]  

The pressure at the economizer outlet can be assumed to be the drum pressure plus the hydrostatic head above its inlet and the friction in piping. The temperature at the economizer inlet is the same as the feedwater temperature, and the outlet temperature can be assumed as the temperature at the inlet of the evaporator.

The total heat load of the boiler is found by adding above terms: 

\[ Q_{\text{steam}} = Q_{\text{econ}} + Q_{\text{evap}} + Q_{\text{sh}} \]  

Actual heat load of the boiler will be slightly higher than this because the heat loss due to boiler blowdown, desuperheating has not been considered here.

### 5.4 Total heat from the boiler

Total heat to the steam from the boiler of the boiler:

\[ Q_{\text{Total}} = D_{\text{L}}(i_1 - i_{f,w}) + D_{\text{L}}'(i_3 - i_2) + G_{\text{b,w}}(i_{b,w} - i_{f,w}) + G_{\text{i,w}}(i_3 - i_{i,w}) \] [kJ]

where:

- \( D_{\text{L}} \) - live steam flow to turbine, kg/s;
- \( i_1, i_2, i_3 \) - steam enthalpy to turbine, to re-superheater and to MP (medium pr.) part, kJ/kg;
- \( i_{f,w} \) - feed water enthalpy to boiler, kJ/kg;
- \( D_{\text{L}}' \) - steam flow to re-superheater, kg/s;
- \( G_{\text{b,w}} \) - blowdown water flow from the drum of the boiler, kg/s;
- \( i_{b,w} \) - blowdown water enthalpy, kJ/kg;
- \( G_{\text{i,w}} \) - injection water flow to re-superheater, kg/s;
- \( i_{i,w} \) - injection water enthalpy to re-superheater, kJ/kg;
Table 1. Calculated values of unit 8 of Narva PP with CFB boilers in November 2009.

<table>
<thead>
<tr>
<th>N</th>
<th>Calculated (according actual data) values of unit 8 of Narva PP with CFB boilers in November 2009 Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>unit</td>
</tr>
<tr>
<td><strong>Unit gross electricity production</strong></td>
<td>MWh</td>
</tr>
<tr>
<td><strong>Unit auxiliary power consumption</strong></td>
<td>MWh</td>
</tr>
<tr>
<td>%</td>
<td>9.40</td>
</tr>
<tr>
<td><strong>Unit net electricity production</strong></td>
<td>MWh</td>
</tr>
<tr>
<td>MW</td>
<td>160.9</td>
</tr>
<tr>
<td><strong>Standart fuel consumption</strong></td>
<td>t</td>
</tr>
<tr>
<td><strong>Operating hours</strong></td>
<td>h</td>
</tr>
<tr>
<td><strong>Average turbine capacity</strong></td>
<td>MW</td>
</tr>
<tr>
<td><strong>Boiler gross efficiency</strong></td>
<td>%</td>
</tr>
<tr>
<td><strong>Gross heat rate (production)</strong></td>
<td>kWh/MWh</td>
</tr>
<tr>
<td><strong>Heat Rate (output)</strong></td>
<td>kJ/kWh</td>
</tr>
<tr>
<td><strong>Standart fuel consumption</strong></td>
<td>g/kWh</td>
</tr>
<tr>
<td><strong>Boiler heat production</strong></td>
<td>MWh</td>
</tr>
<tr>
<td><strong>Heat flow for electricity production</strong></td>
<td>MJ/s</td>
</tr>
<tr>
<td><strong>Main steam</strong></td>
<td>kg/s</td>
</tr>
<tr>
<td>t</td>
<td>169 425</td>
</tr>
<tr>
<td><strong>Reheat steam</strong></td>
<td>kg/s</td>
</tr>
<tr>
<td>t</td>
<td>147 351</td>
</tr>
<tr>
<td><strong>Blow down water</strong></td>
<td>kg/s</td>
</tr>
<tr>
<td>t</td>
<td>1 206</td>
</tr>
<tr>
<td><strong>Feed water</strong></td>
<td>kg/s</td>
</tr>
<tr>
<td>t</td>
<td>170 631</td>
</tr>
<tr>
<td><strong>Main steam</strong></td>
<td>°C</td>
</tr>
<tr>
<td><strong>Reheat steam</strong></td>
<td>535</td>
</tr>
<tr>
<td><strong>Cold reheat steam</strong></td>
<td>313</td>
</tr>
<tr>
<td><strong>Feed water at HP heater</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Feed water at boiler inlet</strong></td>
<td>239</td>
</tr>
<tr>
<td><strong>Flue gases</strong></td>
<td>178</td>
</tr>
<tr>
<td><strong>Cold reheat steam</strong></td>
<td>MPa</td>
</tr>
<tr>
<td><strong>Hot reheat steam after boiler</strong></td>
<td>2.00</td>
</tr>
<tr>
<td><strong>Hot reheat steam before turbine</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Feed water</strong></td>
<td>15.70</td>
</tr>
<tr>
<td><strong>Main steam</strong></td>
<td>MJ/kg</td>
</tr>
<tr>
<td><strong>Cold reheat steam</strong></td>
<td>3.051</td>
</tr>
<tr>
<td><strong>Hot reheat steam</strong></td>
<td>3.545</td>
</tr>
<tr>
<td><strong>Feed water</strong></td>
<td>1.032</td>
</tr>
<tr>
<td><strong>Flue gases losses</strong></td>
<td>MW</td>
</tr>
<tr>
<td>MWh</td>
<td>13 933</td>
</tr>
<tr>
<td>%</td>
<td>10.45</td>
</tr>
<tr>
<td><strong>Bottom ash losses</strong></td>
<td>MW</td>
</tr>
<tr>
<td>MWh</td>
<td>1 375</td>
</tr>
<tr>
<td>%</td>
<td>1.03</td>
</tr>
<tr>
<td><strong>Fly ash losses</strong></td>
<td>MW</td>
</tr>
<tr>
<td>MWh</td>
<td>897</td>
</tr>
<tr>
<td>%</td>
<td>0.67</td>
</tr>
<tr>
<td><strong>Radiation and convection losses</strong></td>
<td>MW</td>
</tr>
<tr>
<td>MWh</td>
<td>897</td>
</tr>
<tr>
<td>%</td>
<td>0.67</td>
</tr>
<tr>
<td><strong>Other losses</strong></td>
<td>MW</td>
</tr>
<tr>
<td>MWh</td>
<td>347</td>
</tr>
<tr>
<td>%</td>
<td>0.26</td>
</tr>
<tr>
<td><strong>Heat credit due to heat receiving in sulfatation</strong></td>
<td>MW</td>
</tr>
<tr>
<td>MWh</td>
<td>2 607</td>
</tr>
<tr>
<td>%</td>
<td>1.96</td>
</tr>
<tr>
<td><strong>Heat credit to incomplete decarbonation</strong></td>
<td>MW</td>
</tr>
<tr>
<td>MWh</td>
<td>3 379</td>
</tr>
<tr>
<td>%</td>
<td>2.33</td>
</tr>
</tbody>
</table>
Conclusions

There are several differences in the calculation of boiler efficiency for CFB boiler because an additional loss term is required for the net heat loss or gain from the calcination and sulfitation processes in the bed. The calcination loss is that heat lost in calcining CaCO$_3$ to CaO, an endothermic reaction. The sulfitation heat gain is that from combining the SO$_2$ with O$_2$ and CaO to form CaSO$_4$, an exothermic reaction.

Boiler efficiency, in the broadest sense, is useful energy flow developed from a boiler, relative to the supply of fuel energy. The fuel’s energy content is dependent on the fuel chemistry and how heat was obtained.

References


