The Heat Balance and Efficiency of Steam Boilers

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The efficient utilization of fuel in steam boilers is primarily determined by the following three factors:

- Complete combustion of the fuel in the furnace
- Deep cooling of the combustion products during their passage through heating surfaces.
- Minimization of heat losses to the environment.
Heat absorbed by working fluid in boiler:

- Heat content of superheated steam from boiler
- Heat content of reheated steam from boiler
- Heat content of boiler blow-down water
<table>
<thead>
<tr>
<th><strong>HEAT BALANCE IN STEAM GENERATOR</strong></th>
</tr>
</thead>
</table>

**INPUT**
- Heat in Fuel
- Heat in atomising steam
- Sensible heat in fuel
  - Pulveriser or crusher power
  - Boiler Circulating pump power
  - Primary air fan power
  - Recirculating gas fan power
  - Heat supplied by moisture in entering air

**OUTPUT**
- Heat in reheat steam out
- Heat in desuperheater water
- Heat in feedwater

**Boundary envelope**
- Heat in Final superheater steam
- Heat in blowdown water
- Heat in reheat steam in

**LOSSES**
- Unburnt carbon in ash
- Heat in dry gas
- Moisture in fuel
- Moisture from burning hydrogen
- Moisture in air
- Heat in atomising steam
- Unburnt gases
- Radiation and convection
- Sensible heat in slag
- Heat in mill rejects
- Sootblowing

Reference: PTC; 4.1
Efficiency

\[ \text{Input} = \text{Heat input} \]
\[ \text{Output} = \text{Input} - \text{losses} \]

\[ \text{Efficiency} = \frac{\text{Input}}{\text{Output}} \]
The Heat balance Equation

The distribution of the heat supplied to the boiler as useful heat and lost heat is the basis for compiling the heat balance of a steam boiler.
The Heat Balance Equation

\[ Q = Q_1 + (Q_2 + Q_3 + Q_4 + Q_5 + Q_6) \]

where:

- \( Q \) = available heat of burnt fuel
- \( Q_1 \) = heat absorbed by working fluid
- \( Q_2 \) to \( Q_6 \) = heat losses

Dividing both sides by \( Q \) and expressing as a percentage we get:

\[ 100 = q_1 + (q_2 + q_3 + q_4 + q_5 + q_6) \]
Methods of determining Boiler Gross efficiency

- Direct method
- Inverse balance method
The direct method

- Uses the heat balance equation
- Measures $Q$ and $Q_1$
- Method is insufficiently inaccurate
- Accurate measurements of certain parameters like mass flow rate of steam and fuel, heating value of fuel etc is not possible
- Not a preferred method
The inverse balance method

- Uses the equation
  \[ \text{Efficiency} = 100 - (q2 + q3 + q4 + q5 + q6) \]
- Determines the sum of heat losses
- Is more accurate method since the sum of the heat losses roughly constitutes 10% of \( Q1 \).
- All the items can be reliably measured
- Is the SOLE method used for determining efficiency
# Heat Losses in Steam Boilers

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>% as relative loss of Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste Gases</td>
<td>$q_1$</td>
<td>4 - 7</td>
</tr>
<tr>
<td>Incomplete combustion</td>
<td>$q_2$</td>
<td>0 - 0.5</td>
</tr>
<tr>
<td>Unburnt Carbon</td>
<td>$q_3$</td>
<td>0.5 - 5</td>
</tr>
<tr>
<td>Cooling through lining</td>
<td>$q_4$</td>
<td>0.2 - 1</td>
</tr>
<tr>
<td>Pysical heat of removed slag</td>
<td>$q_5$</td>
<td>0 - 3</td>
</tr>
<tr>
<td>Sum of heat losses</td>
<td></td>
<td>6 - 12</td>
</tr>
</tbody>
</table>
Chart depicting heat losses

- Waste gases
- Incomplete combustion
- Unburnt carbon
- Cooling through lining
- Physical heat of removed slag
Analysis of Heat losses in Steam Boilers
Dry Flue gas loss

- Is the largest component of heat loss.
- It depends on the absolute difference between the enthalpy of waste gases and the enthalpy of cold air supplied.
- The enthalpy of waste gases depends on the exit temperature of waste gases and its volume.
Dry Flue gas loss

- It is the heat lost to the atmosphere by the dry component of flue gas
- Also referred as stack loss
- Carbon and sulphur in coal burn to form the dry component of flue gas
- Carbon can burn to form either CO or CO2
Components of Dry Flue gas

- Carbon- Dioxide
- Carbon Monoxide
- Residual oxygen
- Nitrogen
- Sulphur Dioxide – can be neglected for Indian coals
Seigert Formula for estimation of Dry Flue gas loss

\[ \% \text{ loss} = K (T - t) \]

% CO2

K is a constant whose value are taken as:
For anthracite: 0.68
For Bituminous coal: 0.63
For coke: 0.70
Wet flue gas loss

- Wet products of combustion are obtained from the following components in fuel:
  - Moisture
  - Hydrogen – Burns to form water vapour
    - 1 Kg of hydrogen burn to form 9 Kg of moisture
  - The heat lost with the mass of the water vapour along with flue gas to the atmosphere is known as wet flue gas loss
Sensible Heat of water vapour

- This is the amount of sensible heat absorbed by moisture in coal.
- It is calculated by:

\[ \text{(Wet FG loss} - (\text{GCV} - \text{NCV})) \text{ KJ/Kg fuel} \]
Moisture in combustion air

- This is the amount of heat absorbed by the moisture present in cold air.
- However, this loss is very small and is normally not calculated.
Heat loss with waste gases

- By reducing the temperature of waste gases by 22 degree cent it is possible to increase boiler efficiency by 1%.
- The exit temperature of waste gases depends on feed water temperature at economizer inlet and and cold air temperature at air heater inlet.
- The exit temperature depends on the moisture content of fuel used. A higher moisture content results in increase of heat loss for the same heating surface due to higher volume of combustion.
Heat loss with waste gases

- A cost economic approach is taken for determining the design optimal flue gas exit temperature.
- One of the main considerations in limiting the FGET is the low temperature acid corrosion in air preheaters. The waste gas temperature is generally kept within 140-160 deg cent to prevent acid condensation.
Reasons for high FGET

- Improper soot blowing
- Deposition on furnace wall tubes
- Low feed water inlet temperature
- Low temperature at air heater inlet
- High moisture content of fuel
- High excess air ratio
- High air infiltration
Clean Tube
1200°C

Soot
300°C
Limiting Metal Temp of 450°C

Scale

Both side deposits

200M Kcal/hr/m²
150M Kcal/hr/m²
155M Kcal/hr/m²
120M Kcal/hr/m²

Typical Heat transfer and temperature drop across furnace tube
Heat loss with unburnt carbon

- In the combustion of solid fuels, unburnt coke particles are carried off from the combustion chamber by flue gases.
- During the short time they are present in the high temperature zone of the flame, these particles evolve volatile matter but remain partially unburnt.
- Under normal operating conditions, these unburnt carbon loss may range from 0.5% to 5%
- More the VM of fuel less is the heat loss.
Heat loss with unburnt carbon

- This loss can be divided into:
  - Carry over loss
  - Loss with slag or bottom ash

- The carry over loss is much predominant over the loss with slag.

- The carry over loss is determined by the carbon content in Fly ash samples collected from ESP hoppers.

- The slag loss is determined by the carbon content in bottom ash samples.
Heat loss with unburnt carbon

The carry over loss depends on:
- Excess air ratio
- The VM of coal used

The slag loss depends on:
- Improper fineness of pulverized fuel from mills
Heat loss by Incomplete combustion

The products of combustion contain gaseous combustible substances such as CO, H2 or CH4.

Their afterburning beyond the boiler furnace is practically impossible since the temperature of gases and concentrations of combustible components and oxygen are too low.
Heat loss by Incomplete combustion

- The heat that may be produced by afterburning these components constitutes the heat loss due to incomplete combustion.
- This item of heat loss is mainly determined by the concentration of CO and to a lesser extent H2 in flue gas.
- However analysis for incomplete combustion should always be done for all components of flue gas since even a slight quantity of CH4 may have a noticeable effect.
Heat loss by Incomplete combustion

- Heat loss due to incomplete combustion substantially depends on excess air ratio and boiler load conditions.
- Theoretically, thorough intermixing of fuel and oxygen ensures that this heat loss may take place only for $K < 1$.
- Under real conditions, incomplete combustion cannot take place at critical excess air ratio which is usually 1.02 – 1.03.
Heat loss by Incomplete combustion

- With reduced load conditions, the exit rate of fuel and air through the burners decreases causing improper mixing which results in increase in heat loss.
- Also the temperature of the combustion zone decreases with reduced load causing an increase in incomplete combustion.
Unaccounted losses

- Radiation loss
- Loss due to unburnt volatile hydrocarbons
- Loss due to combination of carbon and water-vapour
- Mill rejection
- Physical heat carried by bottom and fly-ash
Heat Loss by Radiation

Since the temperature of the boiler linings and casings are higher than the surroundings, they give up heat to the environment.

Higher is the temperature of the linings and casings higher is this heat loss.

In general the boiler casings should be insulated in such a way that the average temperature of the casings is not more than 55 degree cent.
## Typical summary of Radiation and Unaccounted losses

<table>
<thead>
<tr>
<th>Boiler Rating</th>
<th>Approximate Range in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>020</td>
<td>0.6 - 1.7</td>
</tr>
<tr>
<td>050</td>
<td>0.38 - 1.2</td>
</tr>
<tr>
<td>060</td>
<td>0.35 - 1.15</td>
</tr>
<tr>
<td>100</td>
<td>0.3 - 1.0</td>
</tr>
<tr>
<td>200</td>
<td>0.25 - 0.93</td>
</tr>
<tr>
<td>500</td>
<td>0.2 - 0.88</td>
</tr>
</tbody>
</table>
Heat Loss by Cooling

- In rough calculations, the heat flux from the boiler surfaces to the surroundings is taken at an average level of 200 – 300 W/m².
- With increasing boiler power, the absolute and relative heat loss q5% becomes lower as the total heat release and the volume of combustion products increase more quickly than the area of exposed boiler surfaces.
Heat loss with physical heat of slag

- The slag removed from the bottom of a boiler furnace has rather high temperature and possesses a significant amount of heat.
- This heat is transferred to cooling water in the slag bath and is lost irreversibly.
- In dry bottom furnaces the temperature of slag is 600 - 700 deg cent.
- In slagging bottom furnaces the temperature of flowing slag is 1400 - 1600 degree cent.
Heat loss with physical heat of slag depends on:

- Total ash content of fuel
- Fraction of ash removed as slag from furnace
- Enthalpy of slag
- Method of removal of slag from furnace.
Theoretical Air

- It is the quantity of air required by a fuel which will provide just sufficient oxygen for complete oxidation of the combustible components present in the fuel.

- It is also known as the stoichometric air requirement.
Quantity of theoretical air

The theoretical air is calculated from the Ultimate analysis of fuel by the formula:

\[ 4.31 \times \left[ \frac{8}{3}C - 8\left( H - \frac{O}{8} \right) - S \right] \text{Kg/Kg of fuel} \]

- The value within the bracket denotes the quantity of oxygen reqd.
- The factor 4.31 gives the amount of air required to supply this oxygen
Excess Air

- The actual amount of air required for complete burning of a fuel is always more than the theoretical air.
- This additional quantity of air required over the theoretical air is known as excess air.
- Present designs allow for 20% excess air for coal fired boilers.

THE SUM OF THEORETICAL AIR AND EXCESS AIR IS THE TOTAL AIR REQUIREMENT FOR A BOILER
Reasons for excess air

- To overcome the uncertainties in the fuel-air mixing process
- To ensure intimate mixing of fuel and oxygen at point of injection
- To account for errors in ultimate analysis of fuel
Quantity of excess air

Excess air =

\[(\text{O}_2 \ % \times 100) / (21 - \text{O}_2 \ %)\]

OR

\[(\text{CO}_2 \ % (\text{max}) \times 100) / \text{CO}_2 \ % - 100\]
Conclusion

- The quantity of excess air adversely affects boiler efficiency.
- The quantity of excess air needs to be optimized for achieving maximum efficiency of boiler.
Monitoring of excess air

- By residual carbon dioxide in flue gas
- By residual oxygen in flue gas

- By residual carbon-monoxide in flue gas
Optimisation of Total Air

• Unburnt gas (primarily CO) is formed just a little higher than the optimum CO2
• Measurement of CO is a better method of determining optimum air quantity
• Oxygen measurement in flue gas can be misleading due to air ingress
• Modern combustion control utilizes CO measurement in addition to Oxygen measurement
Graph Depicting variation of Oxygen with Carbon Monoxide in Flue gas

Saturation

Air Deficient

Air Rich

Ideal Operating Point

ppm vol CO at ID fan discharge

% Oxygen in Flue gas

1 2 3 4 5 6 7 8 At ID Discharge

1 At AH Inlet
Effect of mill operation on CO breakpoint for a 500 MW PF boiler

- 6 Mills equally loaded
- 6 Mills unequally loaded
- 5 Mills equally loaded

ppm vol CO at ID fan discharge

% Oxygen in Flue gas at Air Heater Inlet
Trend of Boiler Gases with variations in excess air

- CO2 %
- O2 %
- SO2 ppm

Excess Air %age

-20 -10 0 10 20
Thank You