THE EFFICIENT OPERATION OF BOILERS
What are we trying to do?

\[ \text{C} + \text{O}_2 = \text{CO}_2 + \text{heat} \]

Unfortunately

\[ \text{N}_2_{\text{cold}} = \text{N}_2_{\text{hot}} \]

\[ 2\text{H}_2 + \text{O}_2 = 2\text{H}_2\text{O} \]

\[ \text{S} + \text{O}_2 = \text{SO}_2 \]
In order to minimise the $\text{N}_2$ we need to minimise the air to the boiler.

Unfortunately

When we do that, we cannot burn all the fuel.

So where does that leave us?
Excess air versus flue gas analysis.
## Typical Excess Air (1 of 3)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Boiler/furnace type</th>
<th>Excess air (% by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulverised coal</td>
<td>Completely water-cooled furnace</td>
<td>15 - 20</td>
</tr>
<tr>
<td></td>
<td>Partially water-cooled</td>
<td>15 - 40</td>
</tr>
<tr>
<td>Crushed coal</td>
<td>Cyclone furnace</td>
<td>10 - 15</td>
</tr>
<tr>
<td>Coal</td>
<td>Spreader stoker</td>
<td>30 - 60</td>
</tr>
<tr>
<td></td>
<td>Water-cooled vibrating-grate</td>
<td>30 - 60</td>
</tr>
<tr>
<td></td>
<td>Chain grate and travelling grate</td>
<td>15 - 50</td>
</tr>
<tr>
<td></td>
<td>Underfeed stoker</td>
<td>20 - 50</td>
</tr>
</tbody>
</table>
### Typical Excess Air (2 of 3)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Boiler/furnace type</th>
<th>Excess air (% by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Oil</td>
<td>Oil burners</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Acid sludge</td>
<td>Cone &amp; flat flame burners</td>
<td>10 - 15</td>
</tr>
<tr>
<td>Natural, coke oven &amp; refinery gas</td>
<td>Register burners</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Blast furnace gas</td>
<td>Inner tube nozzle type burners</td>
<td>15 - 18</td>
</tr>
<tr>
<td>Multi-fuel burners</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multi-fuel burners</td>
<td>7 - 12</td>
</tr>
</tbody>
</table>
## Typical Excess Air (3 of 3)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Boiler/furnace type</th>
<th>Excess air (% by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>Dutch oven</td>
<td>20 - 25</td>
</tr>
<tr>
<td>Bagasse</td>
<td>All furnaces</td>
<td>25 - 35</td>
</tr>
<tr>
<td>Black liquor</td>
<td>Recovery furnace</td>
<td>5 - 7</td>
</tr>
</tbody>
</table>
Control of combustion is vitally important to ensure efficient combustion.

But how do you do that?

Answer: Exhaust or flue gas monitoring
Typical flue gas analysers

$O_2$, $CO_2$, $NO_x$, $CO$
Next problem: Hot surfaces radiate heat

Message: Check the insulation on your boiler and on steam lines
Next problem: Some fuels contain moisture
This moisture has to be heated and leaves the stack as superheated gas.

Message: Check your fuel storage area
Next problem: Dirty surfaces = bad heat transfer

Message: Keep surfaces clean
Next problem: Not all the combustible gases burn in the boiler

- Some volatile hydrocarbons will not combust due to time, temperature and mixture constraints
- Carbon monoxide (CO) is combustible but may not burn.

Message: Control combustion carefully
We can summarise these losses as follows:

1. Energy loss due to unburned fuel
2. Energy loss in the heated exhaust/flue gas
3. Energy loss due to moisture in the fuel
4. Energy loss due to incomplete combustion
5. Radiation and other losses

It is necessary to quantify these losses in order to establish the efficiency of a boiler.
Boiler Efficiency Tests

It is possible to establish the efficiency in two different ways:

1. *The Direct Method* where one compares the energy supplied in the fuel with energy transferred to the water to convert it to steam.

2. *The Indirect Method* where the efficiency is the difference between the energy in the fuel and the losses.
Fuel Analysis

In order to establish the energy content of the fuel, it is necessary to have three chemical analyses carried out.

1. *The Proximate Analysis*
   - *Moisture content*
   - *Volatile matter*
   - *Ash*
   - *Fixed carbon*
2. The Ultimate Analysis

- The sample is first dried
- Carbon
- Hydrogen
- Sulphur
- Nitrogen
- Ash
- Oxygen
3. The Calorific Value (CV)

This is the energy released by a fuel when it is completely burned and when the products of combustion are cooled to the original fuel temperature.

The hydrogen content of a fuel has an effect on the CV in the following way.

\[ 2 \text{H}_2 + \text{O}_2 = 2 \text{H}_2\text{O} \]

Considering molecular weights:

\[ 4 + 32 = 36 \]

i.e. 1 kg of H\(_2\) will generate 9 kg of H\(_2\)O
The water generated can leave the system as a liquid (*the Higher Calorific Value*) or as a vapour (*the Lower Calorific Value*)

\[
\text{Higher CV} = \text{Gross CV} \\
\text{Lower CV} = \text{Net CV}
\]

By convention, the *gross calorific value* is used for boiler efficiency calculations.
The Direct Method

Energy input = Coal flow rate X GCV

Energy output = Steam flow x heat gain

Efficiency = Energy Output / Energy Input

The accurate measurement of steam flow at high pressures and temperatures is difficult. It is thus more common to measure the flow of water to the boiler.
Disadvantages of the Direct Method

1. Direct method gives no indication as to the cause of inefficiency.

2. Direct method requires the measurement of:
   - Coal flow
   - Feedwater flow
   - Feedwater temperature
   - Steam temperature
   - Steam pressure

3. For accurate measurements, special test instrumentation will have to be installed.
The Indirect Method

Energy losses are established.

The losses are conveniently related to the amount of fuel burnt (i.e. kilojoules of losses per kilogram of fuel used).

or

ne the energy supplied (i.e. losses as a percentage of the energy content of the fuel).
Energy loss due to unburned carbon

If we know the mass of the ash remaining after combustion, and the amount of carbon contained in the ash, we can determine the unburned energy loss.

Carbon loss = \text{mass}_{\text{ash}} \times \text{carbon content}_{\text{ash}} \times \text{CV}_{\text{carbon}}

Note: In order to determine the carbon content of the ash, a sample will have to be sent for chemical analysis.
Energy losses in the gas leaving the boiler

Gas loss = mass_{gas} \times \text{specific heat}_{gas} \times \text{temperature rise}_{gas}

From the above equation, it is clear that the magnitude of this loss is directly proportional to the mass of gas in the exhaust and the temperature rise of the gas between inlet to and exhaust from the boiler.

In other words, too much excess air increases losses and high exhaust temperatures also increase losses.
**Energy loss due to moisture in the fuel**

Fuel moisture loss = \( \text{mass}_{H_2O} \times \text{heat gain}_{H_2O} \)

The heat gain of the moisture is the energy required to bring it from ambient conditions to the exhaust stack temperature. This includes:

- the sensible heat to bring it to boiling point
- the latent heat to evaporate the water
- the energy required to superheat the steam to the exhaust temperature.
Energy loss due to the formation of hydrogen

The combustion of hydrogen and air results in water being formed. When this water leaves the system at the exhaust temperature, it carries with it the energy that could have been recovered were the water to have been allowed to cool to ambient temperature.

$$\text{Hydrogen loss} = 9 \times \text{mass}_{H_2} \times \text{heat gain}_{H_2O}$$

Remember that 1kg $H_2$ generates 9 kg $H_2O$, and hence we use the heat gain of the water produced.
Energy loss due to incomplete combustion

Although a whole range of combustible gases could be found, especially in older boilers, it is normal only to consider carbon monoxide (CO), since this can be conveniently measured.

\[ \text{CO loss} = \text{CO generated per kg of fuel} \times CV_{\text{CO}} \]

In an efficiently operated boiler, the CO loss should be very small.
Energy loss due to superheating vapour in the combustion air

This is a very small loss, and is only included for completeness.

Knowing both the wet and dry bulb temperatures and with the aid of a psychrometric chart, it is possible to determine the moisture content of the combustion air.
Energy loss due to superheating vapour in the combustion air

Air vapour loss\(_{\text{kg dry air}}\) = mass of \(\text{H}_2\text{O}\) per kg dry air \(\times\) specific heat\(_{\text{H}_2\text{O}}\) \(\times\) temp. gain across the boiler

This tells us the loss per kg of dry air, but we still need to determine how much dry air is used per kg of fuel.

This is done using a mass balance:

\[
\text{mass fuel} + \text{mass air} = \text{mass dry flue gas} + \text{moisture} + \text{ash}
\]

Or \[
\text{mass air} = \text{mass (dry flue gas} + \text{moisture} + \text{ash})
\]

Air vapour loss\(_{\text{kg of dry air}}\) = mass air \(\times\) air vapour loss\(_{\text{kg of dry air}}\)
Radiation and unaccounted losses

Radiation and unaccounted boiler losses. Lower curve for radiation only is based on data in the American power test code. The unaccounted losses are primarily due to moisture in the combustion air and sensible heat in the refuse. They could be larger particularly if unburnt gases are present but not detected.
## A boiler heat balance

<table>
<thead>
<tr>
<th>Description</th>
<th>kJ/kg</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Unburned carbon in ash</td>
<td>626.8</td>
<td>2.29</td>
</tr>
<tr>
<td>2. Dry flue gas</td>
<td>1154.0</td>
<td>4.22</td>
</tr>
<tr>
<td>3. Moisture in the fuel</td>
<td>197.2</td>
<td>0.72</td>
</tr>
<tr>
<td>4. Moisture from hydrogen</td>
<td>946.4</td>
<td>3.46</td>
</tr>
<tr>
<td>5. Incomplete combustion</td>
<td>391.1</td>
<td>1.43</td>
</tr>
<tr>
<td>6. Moisture in the combustion air</td>
<td>31.03</td>
<td>0.11</td>
</tr>
<tr>
<td>7. Radiation and unaccounted losses</td>
<td>273.2</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Total losses</strong></td>
<td>3619.7</td>
<td>13.23</td>
</tr>
<tr>
<td><strong>Boiler efficiency</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{Boiler efficiency} = (100% - \text{losses})$</td>
<td></td>
<td>86.77%</td>
</tr>
</tbody>
</table>
Advantages of the indirect method

1. It is possible to identify the cause of inefficiency
2. No specialist instrumentation is required.
3. Only requires measurement of the following:
   - Carbon content of the ash
   - Flue gas analysis
   - Flue gas outlet temperature
   - Ambient temperature
4. Note that it is not necessary to measure either fuel or water flows.
Boiler Efficiency – A Check-List

- Maintain efficient combustion
- Maintain good water treatment
- Repair water and steam leaks
- Recover heat from flue gas and boiler blowdown
- Ensure good operational control
- Attempt to match boilers to heat demand
- Use flue gas dampers where appropriate
- Make sure boiler and steam distribution system is insulated
Boiler Efficiency – A Check-List continued

- Blowdown boilers only when necessary
- Recover as much condensate as possible
- Insulate oil tanks and keep steam or electric heating to a minimum
An Example of the Indirect Method of Boiler Efficiency Determination

### Ultimate analysis of coal

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon content</td>
<td>60%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>5%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>7%</td>
</tr>
<tr>
<td>Ash</td>
<td>17%</td>
</tr>
<tr>
<td>Sulphur</td>
<td>2%</td>
</tr>
<tr>
<td>Moisture</td>
<td>9%</td>
</tr>
</tbody>
</table>

Gross Calorific Value: 26 MJ/kg
Measured values

Carbon in ash    15%
Air inlet temperature  30°C
Flue gas exit temperature  150°C
Air moisture content  0.018 kg/ kg dry air

Flue gas analysis

CO₂  15%   CO  1%
O₂   4%
## Solution to Indirect Boiler Efficiency Calculation

<table>
<thead>
<tr>
<th>Loss due to:</th>
<th>(kJ/kg)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Unburned carbon</td>
<td>862.0</td>
<td>3.32</td>
</tr>
<tr>
<td>2. Dry flue gas</td>
<td>1117.74</td>
<td>4.30</td>
</tr>
<tr>
<td>3. Moisture in fuel</td>
<td>238.6</td>
<td>0.92</td>
</tr>
<tr>
<td>4. Moisture from $\text{H}_2$</td>
<td>1193.0</td>
<td>4.59</td>
</tr>
<tr>
<td>5. Incomplete combustion</td>
<td>860.9</td>
<td>3.30</td>
</tr>
<tr>
<td>6. Moisture in air</td>
<td>39.0</td>
<td>0.15</td>
</tr>
<tr>
<td>7. Radiation &amp; unaccounted</td>
<td>130.0</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Total losses</strong></td>
<td>4441.2</td>
<td>17.08</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{Efficiency} = 100 - \text{losses} = $</td>
<td>82.92</td>
<td></td>
</tr>
</tbody>
</table>