### Sustainable Power Generation MJ2405

### TUTORIAL on Boiler Efficiency calculations



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## **Energy losses in a typical steam boiler**

**Energy in various forms would leak out from all parts of the boiler.** Here we would still disregard mass losses or pressure losses.





# Major types of energy loss

The most important types of energy losses in a steam boiler:



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- Thermal losses with the high temperature of flue gas in the stack released to the atmosphere (after all heat exchangers).
- Thermal losses with ash being discarded from the boiler both as bottom ash and flyash.
- Chemical losses with unburned solid fuel particles (soot) in the ash.
- Chemical losses with unburned gaseous compounds mostly CO
- Thermal losses with heat radiation from boiler walls to surroundings.



# Defining the boiler efficiency

Can be done in two ways – direct and indirect:

#### Direct efficiency calculation:

Energy transferred to steam versus Energy contained in the fuel

#### Problems:

Both steam flow and fuel mass flow can often be very difficult to measure precisely!

#### Indirect efficiency calculation:

Measuring all major losses and subtracting them from unity.

#### Advantages:

It is often easier, cheaper and more precise to measure the loss parameters rather than the steam and fuel flows.

Major losses can be defined by temperature and chemical composition measurements, comparatively easy.

Sometimes the indirect method is the only applicable option for assessment of old boilers or at partial load conditions.



### Indirect estimation of boiler efficiency

$$\mathbf{n}_{\text{boiler}} = 1 - L_{\text{th}(\text{gas})} - L_{\text{chem}(\text{gas})} - L_{\text{th}(\text{ash})} - L_{\text{chem}(\text{ash})} - L_{\text{radiation}}$$



KTH Industrial Engineering and Management These losses can be easily estimated as fractions (per unit fuel energy) and defined by temperature values, specific heat capacity values, and chemical parameters.

Giving handy names to the above types of losses, and writing the equation in %:

$$\mathbf{\eta}_{\mathbf{b}} = 100 - L_{\text{stack}} - L_{\text{CO}} - L_{\text{ash}} - L_{\text{soot}} - L_{\text{rad}}$$
 [%]



# **Estimation of the losses**

**L**<sub>stack</sub> → hot flue gas released in the stack → =  $\Sigma(c_p^*\Delta T)$  for the entire mixture of gas species at the measured stack temperature

 $L_{CO}$  → energy contained in the unburned CO measured in flue gas (LHV<sub>CO</sub> = 12.634 MJ/m<sub>n</sub><sup>3</sup>)

 $L_{ash} \rightarrow$  thermal value of residual ashes (total rejected ash after boiler) assumingly at the measured stack temperature

 $L_{soot} \rightarrow$  energy contained in the unburned carbon, measured in the total residual ash (exit ash); (LHV<sub>c</sub> = 30 MJ/kg)

 $L_{rad} \rightarrow$  either given or measured or taken from diagrams





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# Thermal loss in the stack

 $L_{stack} \rightarrow$  thermal energy contained in the flue gas if cooled down to a chosen reference temperature, representing an enthalpy difference.



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Let's choose normal conditions (0 °C, 1 atm) as a reference point. The pressure does not change and plays no role for the gas enthalpy. We need to know the change of temperature ( $\Delta$ T) and the function of specific heat Cp as it also changes with temperature. For exercise 4:  $\Delta$ T = 170 K

The flue gas is a mixture of different gas species.  $\Delta T$  is the same for all of them. For exercise 4 – we know exactly the flue gas composition (in volume parts) after solving the combustion process in exercise 1.

Cp is different for each gas in the mixture and can be found in various tabulated sources or diagrams. *As an example - see next slides and follow the relevant diagrams in the third help-file*.



### Specific heat of common gases: diatomic species



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# Specific heat of common gases: average values for diatomic species

*For example:* A reading at 500 C for air (*luft*) gives the average  $c_p$  value for air between 0 °C and 500 °C, which is ~ 30.2 kJ/kmolK



## Specific heat of common gases: tri- and multi-atomic species



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# Specific heat of common gases: average values for tri- & multi-atomic species

11

*For example:* A reading at 500 C for CO<sub>2</sub> gives the average  $c_p$  value for CO<sub>2</sub> between 0 °C and 500 °C, which is ~ 45 kJ/kmolK



# Enthalpy of a gas mixture

For the specific case of exercise 4:

The LHV of the fuel and the composition of the flue gas after combustion are already found, see the solved combustion table for exercise 1.



KTH Industrial Engineering and Management Each gas component supplies a part of the flue gas thermal loss as: ([x] *in mol*<sub>x</sub>/kg<sub>fuel</sub> \*  $c_{p(x)average at 170^{\circ}C}$  *in J/molK* \*  $\Delta T$  *in K*) / LHV<sub>fuel(wet)</sub> *in J/kg<sub>fuel</sub>* 

We know the [x] mols of H<sub>2</sub>O, CO<sub>2</sub>, N<sub>2</sub>, SO<sub>2</sub>, O<sub>2</sub> in the total flue gas from the combustion solution.

$$\mathbf{L_{stack}} = \frac{40.92 \times 34 \times 170 + 9.61 \times 39.5 \times 170 + 50.86 \times 29.2 \times 170 + 0.322 \times 42.5 \times 170 + 3.1 \times 29.8 \times 170}{2860000} = 0.19984 = -20\%$$

#### Observation:

Using a very wet fuel, producing large volumes of flue gas and releasing it at a comparatively high temperature in the stack, incurs a very high thermal loss for the boiler. That's why biomass-fired boilers would always cool down the flue gases as much as possible, preferably below 100°C.



## **Chemical energy loss with unburned CO**

 $L_{CO} \rightarrow$  mass flow of CO multiplied with LHV<sub>CO</sub>

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But in the given exercise the CO was measured per dry flue gas, therefore we first find the dry flue gas in  $m_n^3/kg_{fuel}$ . This wouldn't be necessary if the measurements were reported per total (wet) flue gas.

 $\mathbf{L_{CO}} = \frac{1.431 \times 390 \times 0.000001 \times 12.634}{2.86} = 0.00247 = -0.25\%$ 

#### Observation:

The loss of energy with the heating value of unburned CO is low, if a reasonably small amount of CO exists in the flue gas. Here we disregarded the fact that any presence of CO would change the thermal properties of the flue gas, as this factor is far smaller and certainly neglectable.



# Chemical energy loss with unburned solid carbon particles

Unburned carbon (soot) is entrained in both the bottom ash and in the flyash. Soot may contain also other elements or impurities, its energy value is somewhat lower than that of pure carbon and can be approximated to roughly 30 MJ/kg.



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Soot amount in the total exiting (residual) ash is measured and reported in %. The incoming ash in the boiler (with the fuel) is known, while the actual amount of residual (outgoing) ash is unknown. For the data in exercise 4:

$$Ash_{in} = 0.141 \ kg/kg_{fuel} \quad ; \quad Soot = 0.05*Ash_{out} \quad ; \quad Ash_{out} = \frac{Ash_{in}}{1 - 0.05} = \frac{0.141}{0.95} = 0.14842$$
$$L_{soot} = \frac{0.05*0.14842*30}{2.86} = 0.07784 = -7.8 \ \%$$

#### Observation:

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The loss of energy with the heating value of unburned carbon (soot particles) is large if the fuel has low energy content and high ash content. Here we disregarded the fact that if carbon doesn't burn entirely, the flue gas composition would change (less  $CO_2$  and more remaining  $O_2$ ), but this factor is neglectable in relation to the chemical energy of the unburned carbon.



# Thermal energy loss with hot ashes

 $L_{ash} \rightarrow$  thermal value of residual ashes (total rejected ash after boiler) assumingly at the measured stack temperature

The  $\Delta T$  for the ash can, for the sake of simplicity, be taken as the difference between the measured flue gas temperature and the chosen reference point at normal conditions. If there is lots of flyash (often the case in a typical biomass boiler) this assumption holds well.

The specific heat of different types of ashes can vary anywhere between 0.4 to 1 kJ/kg.K. A good approximation is to use the  $c_p$  of sand or cement:  $c_p = \sim 0.9$  kJ/kg.K, remaining mostly independent of temperature.

$$\mathbf{L_{ash}} = \frac{Ash_{out} * c_p * \Delta T}{LHV_{fuel}} = \frac{0.14842 * 0.9 * 170}{2860} = 0.00794 = -0.8\%$$

#### **Observation:**

The heat lost with ashes is not so important even for fuels with high ash content. However, if the actual temperature of ash disposal is much higher, the loss value will quickly increase.





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# **Radiation or Convection Losses**

The heat emitted from boiler walls to the ambient surroundings via radiation or convection depends on the wall insulation and on the size & type of the boiler. More intense combustion of good fuels in a compact boiler would provide for lower radiation loss. Using bad and wet fuels would mean large volume flows and bulky boilers, hence relatively larger radiation losses.

The radiation loss can be given as percentage, or estimated from empirical diagrams as a function of boiler size and fuel type. The example in the next slide shows one old German-language diagram, still very relevant today. The diagram means to tell that the radiative loss needs to be assessed as a variable parameter, whose relative effect grows if a boiler is only partially loaded.

For exercise 4, the radiation loss is readily given as 0.5 %,  $L_{rad} = 0.5\%$ 



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#### Radiation Loss Factors

Nominal boiler load in MW

#### **Final result for exercise 4**



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$$\mathbf{\eta}_{\mathbf{b}} = 100 - L_{\text{stack}} - L_{\text{CO}} - L_{\text{ash}} - L_{\text{soot}} - L_{\text{rad}}$$
[%]

$$\mathbf{\eta}_{\mathbf{b}} = 100 - 20 - 0.25 - 0.8 - 7.8 - 0.5 = 70.7 [\%]$$

