

20 Feb 2019
TR

Combustion Technology 2019

Learning Exercise 5 / Model solution

Task 1

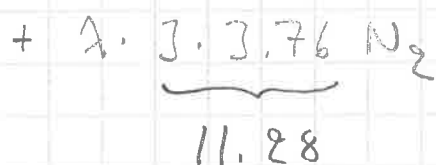
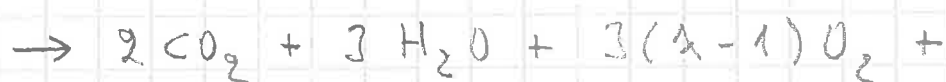
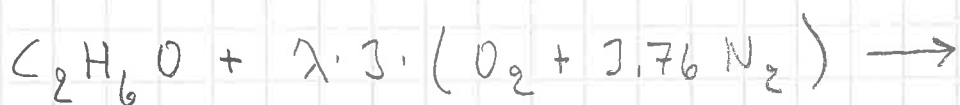
From LE 4:

Ethanol flow rate

$$\dot{m}_{\text{C}_2\text{H}_6\text{O}} = 0.1306 \text{ kg/s}$$

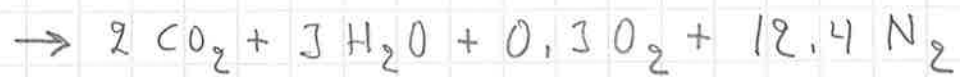
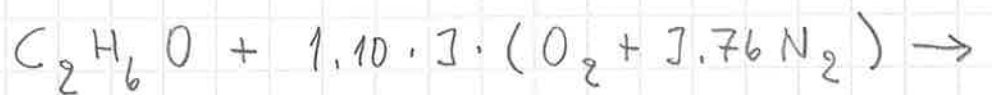
$$\dot{n}_{\text{C}_2\text{H}_6\text{O}} = 0.00283 \text{ kmol/s}$$

Reaction equation for combustion of ethanol in air with an air factor λ :



For $x_{O_2} = 0.02$ in dry flue gas,
 $\lambda = 1.10$ (calculated in LE 4).

Thus, the reaction equation becomes



Checking the results obtained

so far:

$$x_{O_2} = \frac{0.3}{2 + 0.3 + 12.4} = 0.02 \quad OK$$

$$\begin{aligned} n'_{WFG} &= 2 + 3 + 0.3 + 12.4 = 17.7 \\ &= 14.28 \cdot 1.1 + 2 \quad OK \end{aligned}$$

Now the background work has been carried out and we are ready to proceed to part a).

d) Evaluate flue gas loss

Comp.	n' [$\frac{\text{kmol}}{\text{kmol F}}$]	$\dot{n} = \dot{n}_F n'$ [$\frac{\text{kmol}}{\text{s}}$]	H_m [$\frac{\text{MJ}}{\text{kmol}}$]	$\dot{H} = \dot{n} H_m$ [MW]
CO ₂	2	0.00566	4.01	0.0227
H ₂ O	3	0.00849	3.45	0.0293
O ₂	0.3	0.00085	3.03	0.0026
N ₂	12.4	0.03509	2.97	0.1042
Total		0.05009		0.1588

ok, cf. LE4 p. (14) ↗

⇒ Flue gas loss 0.159 MW = 159 kW

Furnace efficiency:

$$\eta = 1 - \frac{\text{Flue gas loss}}{\text{Firing rate}}$$

$$= 1 - \frac{0.159 \text{ MW}}{3.5 \text{ MW}} = 0.955$$

Note: H_m values from Borman & Ragland

App. C pp. 574 - 575. (T = 400 K) (3)

b) For ethanol, LHV = $26.8 \frac{\text{MJ}}{\text{kg}}$

(from LE 4)

$$\begin{aligned} Q_{m,L} &= q_L M \\ &= 26.8 \frac{\text{MJ}}{\text{kg}} \cdot 46.07 \frac{\text{kg}}{\text{kmol}} \\ &= 1235 \frac{\text{MJ}}{\text{kmol}} \end{aligned}$$

In the combustion of 1 kmol of ethanol, 3 kmol of H_2O are generated.

Thus,

$$Q_{m,H} = Q_{m,L} + 3 \cdot Q_{C,H_2O}$$

heat of condensation
of H_2O at 25°C

From steam tables,

$$q_{f,c,H_2O} = 2.44 \frac{\text{MJ}}{\text{kg}} \quad @ \quad 25^\circ\text{C}$$

$$\Rightarrow Q_{c,H_2O} = q_{f,c,H_2O} \cdot M$$

$$= 2.44 \frac{\text{MJ}}{\text{kg}} \cdot 18 \frac{\text{kg}}{\text{kmol}} = 44 \frac{\text{MJ}}{\text{kmol}}$$

(the numerical values for q_{f,c,H_2O} and/or Q_{c,H_2O} can be found in many sources, including BR Ex. 2.3 p. 55)

$$\begin{aligned} \Rightarrow Q_{m,H} &= 1235 \frac{\text{MJ}}{\text{kmol}} + 2.44 \frac{\text{MJ}}{\text{kmol}} \\ &= 1367 \frac{\text{MJ}}{\text{kmol}} \end{aligned}$$

Checking:

$$q_{f,H} = \frac{Q_{m,H}}{M_{C_2H_6O}} = \frac{1367 \frac{\text{MJ}}{\text{kmol}}}{46.07 \frac{\text{kg}}{\text{kmol}}} = 29.7 \frac{\text{MJ}}{\text{kg}}$$

(5)

The calculation is ok
(cf. BR Table A.2 p. 567)

c) Firing rate based on HHV:

$$\begin{aligned}\dot{\Phi}_H &= \dot{n}_F Q_{m,H} \\ &= 0,00283 \frac{\text{kmol}}{\text{s}} \cdot 1367 \frac{\text{MJ}}{\text{kmol}} \\ &= 3,87 \text{ MW}\end{aligned}$$

Now the flue gas loss consists
of two components:

- the sensible enthalpy in flue gas.
This was already computed in a)
and was found to be 0,159 MW
- the enthalpy associated with the
condensation of water vapor.

The enthalpy associated with the condensation of water vapor is

$$\begin{aligned}\dot{Q}_c &= \dot{n}_{\text{H}_2\text{O}} Q_{c, \text{H}_2\text{O}} \\ &= 0.00849 \frac{\text{kmol}}{\text{s}} \cdot 44 \frac{\text{MJ}}{\text{kmol}} \\ &= 0.374 \text{ MW}\end{aligned}$$

Thus, the total flue gas loss is now

$$\begin{aligned}\dot{Q}_{\text{Loss}} &= \dot{Q}_s + \dot{Q}_c = 0.159 \text{ MW} + 0.374 \text{ MW} \\ &= 0.533 \text{ MW}\end{aligned}$$

And the furnace efficiency is

$$\eta = 1 - \frac{0.533 \text{ MW}}{3.87 \text{ MW}} = 0.862$$

Why is it that we get two different results here, one for LHV and one for HHV?

First, note that the useful energy is the same in both cases. Thus,

$$\text{LHV basis: } \phi = 0.95 \cdot 3.5 \text{ MW} = 3.3 \text{ MW}$$

$$\text{HHV basis: } \phi = 0.86 \cdot 3.87 \text{ MW} = 3.3 \text{ MW}$$

The difference is only in how we evaluate the losses.

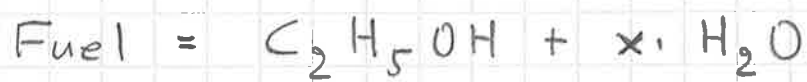
If it is at least theoretically possible to cool down the flue gas to a very low temperature, then we might be able to achieve condensation of water vapor in flue gas to liquid water. In this case it might make sense to use the HHV in calculations. If, on the other hand, 8

the flue gas has to be discharged at a relatively high temperature, then we cannot really achieve condensation of H_2O . In this case the HHV is a purely theoretical concept and it probably makes more sense to use LHV in calculations.

Historically, the traditions in Europe and in the US are different.

In Europe, LHV is mostly used; in the US, HHV is mostly used.

d) The calculation can be carried out in several ways, e.g.,



$$w_{\text{H}_2\text{O}} = \frac{m_{\text{H}_2\text{O}}}{m_{\text{Fuel}}} = \frac{x \cdot M_{\text{H}_2\text{O}}}{M_{\text{C}_2\text{H}_5\text{OH}} + x \cdot M_{\text{H}_2\text{O}}}$$

$$\Rightarrow x_{\text{H}_2\text{O}} = \frac{w_{\text{H}_2\text{O}}}{1 - w_{\text{H}_2\text{O}}} \cdot \frac{M_{\text{C}_2\text{H}_5\text{OH}}}{M_{\text{H}_2\text{O}}}$$

$$= \frac{0.15}{1 - 0.15} \cdot \frac{46 \text{ kg/kmol}}{18 \text{ kg/kmol}}$$

$$= 0.45$$

Heating values / HHV

Initial state

- 1°) 0.85 kg of pure ethanol @ 25°C
- 2°) some amount of air @ 25°C
- 3°) 0.15 kg liquid water @ 25°C

where 1°) + 3°) is the fuel

Final state

- 4°) combustion products of ethanol @ 25°C
(with all H₂O in liquid state)
- 5°) any excess air + N₂ @ 25°C
- 6°) 0.15 kg of liquid water @ 25°C

Here 1°) + 2°) → 4°) + 5°) represents the combustion of 0.85 kg of pure ethanol and 3°) → 6°) represents the "reaction path" of the 0.15 kg of water which was present in the fuel.

For $1^{\circ}) + 2^{\circ}) \rightarrow 4^{\circ}) + 5^{\circ})$, the energy which is released is

$$0.85 \text{ HHV}_{\text{C}_2\text{H}_5\text{OH}} = 0.85 \cdot 29.7 \frac{\text{MJ}}{\text{kg}} = 25.2 \frac{\text{MJ}}{\text{kg}}$$

For $3^{\circ}) \rightarrow 6^{\circ})$, there is no energy release or consumption, since the initial and final states are the same.

Thus, HHV of the fuel is $25.2 \frac{\text{MJ}}{\text{kg}}$

In calculation of LHV, the table for the initial state is the same as for HHV, but the table for the final state is now

7^o) combustion products of ethanol @ 25°C
(with all H₂O in gaseous state)

8^o) any excess air + N₂ @ 25°C

9^o) 0.15 kg of gaseous water @ 25°C

For $1^\circ) + 2^\circ) \rightarrow 7^\circ) + 8^\circ)$,
the energy release is

$$0.85 \text{ LHV}_{\text{C}_2\text{H}_5\text{OH}} = 0.85 \cdot 26.8 \frac{\text{MJ}}{\text{kg}} = 22.8 \frac{\text{MJ}}{\text{kg}}$$

For $3^\circ) \rightarrow 9^\circ)$, the energy
consumption is

$$0.15 q_{\text{C}_2\text{H}_5\text{O}} = 0.15 \cdot 2.44 \frac{\text{MJ}}{\text{kg}} = 0.4 \frac{\text{MJ}}{\text{kg}}$$

$$\Rightarrow \text{LHV} = 22.8 \frac{\text{MJ}}{\text{kg}} - 0.4 \frac{\text{MJ}}{\text{kg}} = 22.4 \frac{\text{MJ}}{\text{kg}}$$

Conclusion: a small amount of
moisture in fuel has only a small
effect on heating values. However,
larger amounts of moisture in the
fuel have a very significant
effect on heating values.

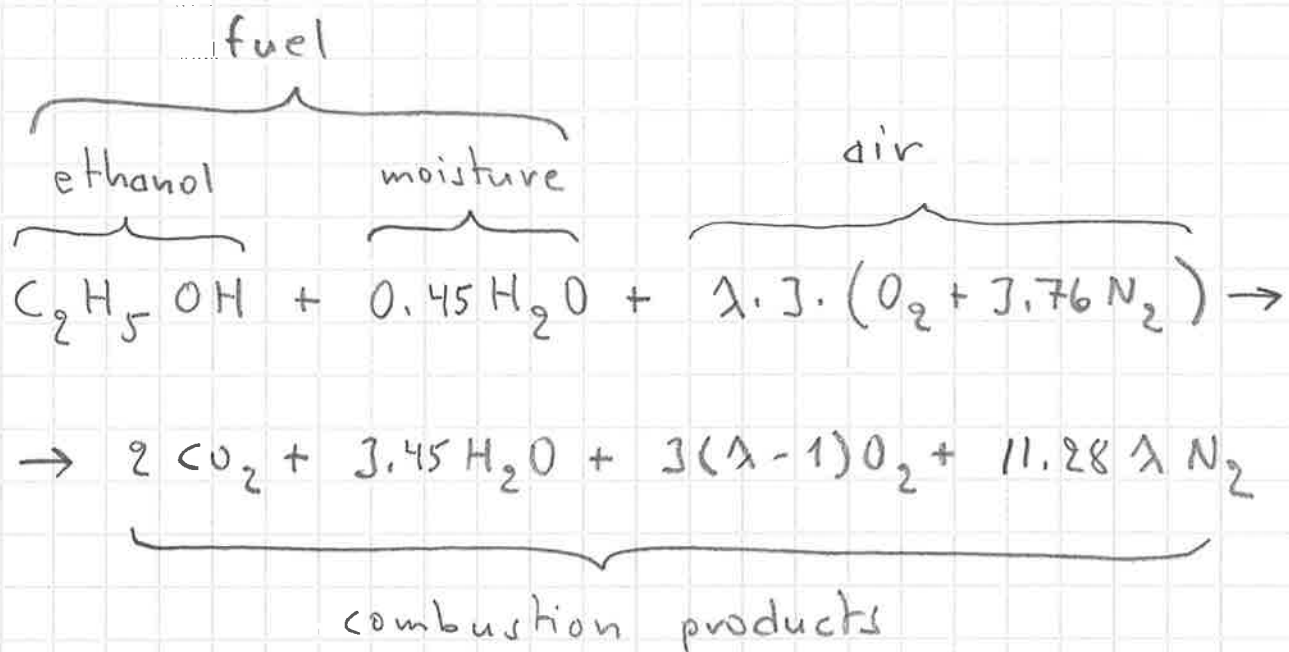
In general, the calculations can be carried out using the following equations:

$$\text{HHV} = (1 - w_M) \text{HHV}_{\text{dry fuel}}$$

$$\text{LHV} = (1 - w_M) \text{LHV}_{\text{dry fuel}} - w_M q_{f, \text{H}_2\text{O}}$$

where HHV and LHV are the higher and lower heating values of the fuel containing a mass fraction w_M of moisture and $\text{HHV}_{\text{dry fuel}}$ and $\text{LHV}_{\text{dry fuel}}$ are the higher and lower heating values of dry fuel.

e) The reaction equation is



$$n'_{\text{Air}} = \frac{n_{\text{Air}}}{n_{\text{C}_2\text{H}_5\text{OH}}} = \lambda \cdot 3 \cdot (1 + 3.76) = 14.28\lambda$$

$$\begin{aligned} n'_{\text{WFG}} &= \frac{n_{\text{WFG}}}{n_{\text{C}_2\text{H}_5\text{OH}}} = 2 + 3.45 + 3(\lambda - 1) + 11.28\lambda \\ &= 14.28\lambda + 2.45 \end{aligned}$$

$$\begin{aligned} n'_{\text{DFG}} &= \frac{n_{\text{DFG}}}{n_{\text{C}_2\text{H}_5\text{OH}}} = 2 + 3(\lambda - 1) + 11.28\lambda \\ &= 14.28\lambda - 1 \end{aligned}$$

In relation to the amount of ethanol, the quantities of air and dry flue gas do not change. The quantity of wet flue gas increases (but only slightly, since the amount of water in the fuel was still quite small)

Oxygen mole fraction in dry flue gas is

$$X_{O_2} = \frac{n_{O_2}}{n_{DFG}} = \frac{3(\lambda - 1)}{14.28\lambda - 1}$$

This exactly the same expression as for combustion of pure ethanol (see p. (12) of LE4 model solution).

Thus, for $X_{O_2} = 0.02$ we obtain

$$\lambda = 1.10.$$

It is good to note that evaluating the value of λ based on analysis of the composition of dry flue gas is a very convenient method, since there is no need to make any adjustments in case the moisture content of the fuel varied.

f) For the mixture:

$$\dot{m}_{\text{Fuel}} = \frac{\phi}{\text{LHV}} = \frac{3.5 \text{ MW}}{22.4 \frac{\text{MJ}}{\text{kg}}} = 0.156 \frac{\text{kg}}{\text{s}}$$

$$\begin{aligned} \dot{m}_{\text{C}_2\text{H}_5\text{OH}} &= 0.85 \dot{m}_{\text{Fuel}} = 0.85 \cdot 0.156 \frac{\text{kg}}{\text{s}} \\ &= 0.133 \frac{\text{kg}}{\text{s}} \end{aligned}$$

$$\begin{aligned} \dot{n}_{\text{C}_2\text{H}_5\text{OH}} &= \frac{\dot{m}_{\text{C}_2\text{H}_5\text{OH}}}{M_{\text{C}_2\text{H}_5\text{OH}}} = \frac{0.133 \text{ kg/s}}{46 \text{ kg/kmol}} \\ &= 0.00289 \frac{\text{kmol}}{\text{s}} \end{aligned}$$

Fuel flow rate increased by 20%, partly because there is now some water mixed with the ethanol and this water is just ballast which is not bringing any energy into the system, but partly also because some energy is actually needed to convert the water from liquid state (in which it arrives to the furnace) into gaseous state (in which it leaves the furnace).

For $\lambda = 1.10$, we obtain

$$\begin{aligned}\dot{n}_{\text{Air}} &= \dot{n}_{\text{C}_2\text{H}_5\text{OH}} \cdot n'_{\text{Air}} \\ &= 0.00289 \frac{\text{kmol}}{\text{s}} \cdot 14.28 \cdot 1.10 \\ &= 0.0454 \frac{\text{kmol}}{\text{s}}\end{aligned}$$

When comparing with the case of firing pure ethanol, the air flow rate increased by 2%.

$$\begin{aligned}\dot{n}_{WFG} &= \dot{n}_{C_2H_5OH} \cdot n'_{WFG} \\ &= 0.00289 \frac{\text{kmol}}{\text{s}} \cdot (14.28 \cdot 1.10 + 2.45) \\ &= 0.0525 \frac{\text{kmol}}{\text{s}}\end{aligned}$$

When comparing with the case of firing pure ethanol, the wet flue gas flow rate increased by 5%.

$$\left(\begin{array}{l} \text{From LE 4: } \dot{n}_{Air} = 0.0444 \frac{\text{kmol}}{\text{s}} \\ \dot{n}_{WFG} = 0.0501 \frac{\text{kmol}}{\text{s}} \end{array} \right)$$

Evaluate flue gas loss:

Comp.	n' [$\frac{\text{kmol}}{\text{kmol E}}$]	$\dot{n} = \dot{n}_E n'$ [$\frac{\text{kmol}}{\text{s}}$]	H_m [$\frac{\text{MJ}}{\text{kmol}}$]	$\dot{H} = \dot{n} H_m$ [MW]
CO ₂	2	0.00578	4.01	0.0232
H ₂ O	3.45	0.00997	3.45	0.0344
O ₂	0.3	0.00087	3.03	0.0026
N ₂	12.4	0.03584	2.97	0.1064
		<hr/>		<hr/>
ok, cf. p. (19) →		0.05246		0.1666

⇒ Flue gas loss is 0.167 MW = 167 kW

Furnace efficiency:

$$\eta = 1 - \frac{0.167 \text{ MW}}{3.5 \text{ MW}} = 0.952$$

Some of the fuel energy had to be spent in evaporating the moisture in the fuel and this led to a decrease in furnace efficiency. The amount

of moisture in the fuel was still quite small and consequently the decrease in efficiency was not very significant. If the calculation had been based on HHV, the decrease in efficiency would have been much bigger.