4 Feb 2019
TP

Combustion Technology 2019

Learning Exercise 4 / Model solution

Task 1

a) For propane:

chemical formula C_3H_8

molar mass $M_{C_3H_8} = 44,10$ g/mol

lower heating value $q_{C_3H_8} = 46330 \frac{kJ}{kg}$

Source: G.L. Borman & K.W. Ragland, Combustion Engineering (1998), Table A.1 p. 566.

b) Propane flow rate:

$$\dot{m}_{C_3H_8} = \frac{\phi}{q_{C_3H_8}} = \frac{3500 \text{ kW}}{46330 \frac{kJ}{kg}} = 0.0755 \frac{kg}{s}$$

$$\dot{n}_{C_3H_8} = \frac{\dot{m}_{C_3H_8}}{M_{C_3H_8}} = \frac{0,0755 \frac{kg}{s}}{44,10 \frac{kg}{kmol}} = 0.00171 \frac{kmol}{s}$$

c) Reaction equations

Stoichiometric combustion in pure oxygen:

$$C_3H_8 + 5\,O_2 \rightarrow 3\,CO_2 + 4\,H_2O$$

balance checking

	left-hand side	right-hand side	
C	3	3	ok
H	8	$4 \times 2 = 8$	ok
O	$5 \times 2 = 10$	$3 \times 2 + 4 \times 1 = 10$	ok

Stoichiometric combustion in air:

$$C_3H_8 + 5\left(O_2 + 3.76\,N_2\right) \rightarrow$$

$$\rightarrow 3\,CO_2 + 4\,H_2O + \underbrace{5 \cdot 3.76}_{18.8}\,N_2$$

$$\begin{cases} x_{O_2} = \dfrac{1}{1+3.76} = 0.210 \\[2ex] x_{N_2} = \dfrac{3.76}{1+3.76} = 0.790 \end{cases}$$

in air, for each molecule of O_2, there are 3.76 molecules of N_2

balance checking

	LHS	RHS	
C	3	3	ok
H	8	$4 \times 2 = 8$	ok
O	$5 \times 2 = 10$	$3 \times 2 + 4 \times 1 = 10$	ok
N	$5 \times 3.76 \times 2 = 37.6$	$5 \times 3.76 \times 2 = 37.6$	ok

Combustion in air with air factor λ:

$$C_3H_8 + \lambda \cdot 5 \cdot (O_2 + 3.76\, N_2) \longrightarrow$$

$$\rightarrow 3\,CO_2 + 4\,H_2O + 5(\lambda - 1)\,O_2 + \lambda \cdot 18.8\, N_2$$

balance checking

	LHS	RHS	
C	3	3	ok
H	8	$4 \times 2 = 8$	ok
O	$\lambda \times 5 \times 2 = 10\lambda$	$3 \times 2 + 4 \times 1 + 5 \times \lambda \times 2 - 5 \times 2$ $= 10\lambda$	ok
N	$\lambda \times 5 \times 3.76 \times 2 = 37.6\lambda$	$\lambda \times 18.8 \times 2 = 37.6\lambda$	ok

For future use, we collect the following results:

$$n'_{Air} = \frac{n_{Air}}{n_{Fuel}} = \lambda \cdot 5 \cdot (1 + 3{,}76)$$

$$= 23{,}8 \cdot \lambda$$

$$n'_{WFG} = \frac{n_{WFG}}{n_{Fuel}} = 3 + 4 + 5(\lambda - 1) + \lambda \cdot 18{,}8$$

$$= 23{,}8 \cdot \lambda + 2$$

(WFG = wet flue gas = all components in the flue gas, including water vapor)

$$n'_{DFG} = \frac{n_{DFG}}{n_{Fuel}} = 3 + 5(\lambda - 1) + \lambda \cdot 18{,}8$$

$$= 23{,}8\lambda - 2$$

(DFG = dry flue gas = all components in the flue gas except water vapor)

d) Oxygen mole fraction in DFG:

$$x_{O_2\,DFG} = \frac{n'_{O_2}}{n'_{DFG}} = \frac{5(\lambda - 1)}{23.8\lambda - 2}$$

Solve for λ as a function of $x_{O_2\,DFG}$

$$\Rightarrow (23.8\lambda - 2)\, x_{O_2\,DFG} = 5(\lambda - 1)$$

$$\Rightarrow (23.8\, x_{O_2\,DFG} - 5)\lambda = 2\, x_{O_2\,DFG} - 5$$

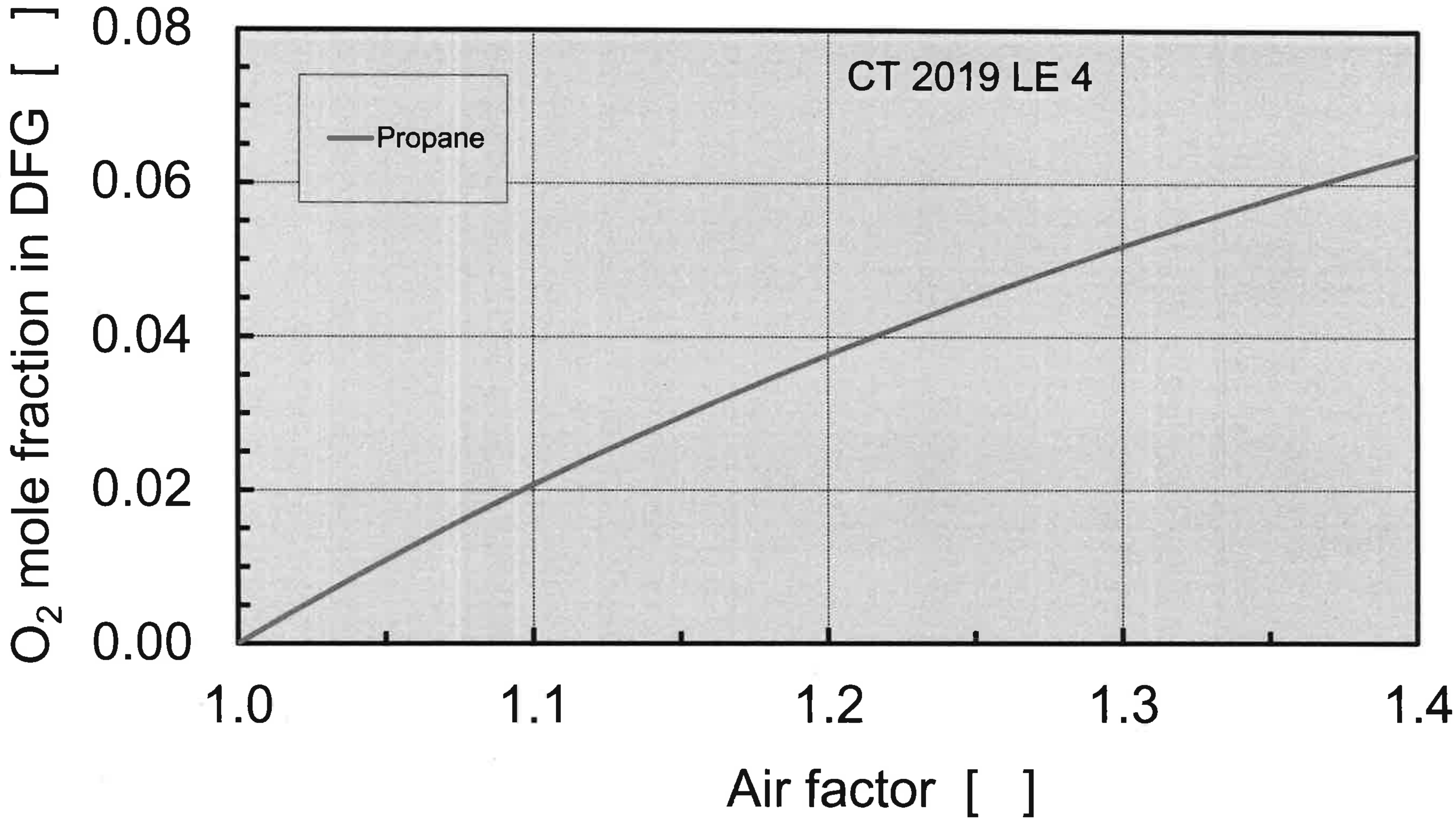
$$\Rightarrow \lambda = \frac{5 - 2\, x_{O_2\,DFG}}{5 - 23.8\, x_{O_2\,DFG}}$$

for $x_{O_2\,DFG} = 0.02$, we obtain

$$\lambda = \frac{5 - 2 \cdot 0.02}{5 - 23.8 \cdot 0.02} = 1.10$$

Plot of $x_{O_2\,DFG}$ as a function of λ is on the next page.

O_2 in dry flue gas vs. air factor



e) For $\lambda = 1,10$, we obtain

$$\dot{n}_{Air} = \dot{n}_{Fuel} \cdot n'_{Air}$$

$$= 0,00171 \frac{kmol}{s} \cdot 23,8 \cdot 1,10$$

$$= 0,0448 \frac{kmol}{s}$$

$$\dot{m}_{Air} = M_{Air} \, \dot{n}_{Air}$$

$$= 29 \frac{kg}{kmol} \cdot 0,0448 \frac{kmol}{s}$$

$$= 1,30 \frac{kg}{s}$$

$$\Big(M_{Air} = x_{O_2} M_{O_2} + x_{N_2} M_{N_2}$$

$$= 0,21 \cdot 32 \frac{kg}{kmol} + 0,79 \cdot 28 \frac{kg}{kmol}$$

$$= 29 \frac{kg}{kmol} \Big)$$

$$\dot{n}_{WFG} = \dot{n}_{Fuel} \, n'_{WFG}$$

$$= 0.00171 \frac{kmol}{s} \cdot (23.8 \cdot 1.10 + 2)$$

$$= 0.0482 \frac{kmol}{s}$$

$$\dot{m}_{WFG} = \dot{m}_{Fuel} + \dot{m}_{Air}$$

$$= 0.0755 \frac{kg}{s} + 1.30 \frac{kg}{s}$$

$$= 1.38 \frac{kg}{s}$$

f) For ethanol:

chemical formula C_2H_6O

molar mass $M_{C_2H_6O} = 46.07 \frac{g}{mol}$

lower heating value $q_{C_2H_6O} = 26803 \frac{kJ}{kg}$

Source: Borman & Ragland

Table A2 p. 567

g) ethanol flow rate:

$$\dot{m}_{C_2H_6O} = \frac{\phi}{q_{C_2H_6O}} = \frac{3500\ kW}{26803\ \frac{kJ}{kg}} = 0.1306\ \frac{kg}{s}$$

$$\dot{n}_{C_2H_6O} = \frac{\dot{m}_{C_2H_6O}}{M_{C_2H_6O}} = \frac{0.1306\ \frac{kg}{s}}{46.07\ \frac{kg}{kmol}} = 0.00283\ \frac{kmol}{s}$$

h) Reaction equations

Stoichiometric combustion in pure oxygen:

$$C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O$$

balance checking

	LHS	RHS	
C	2	2	ok
H	6	3×2 = 6	ok
O	1 + 3×2 = 7	2×2 + 3×1 = 7	ok

Stoichiometric combustion in air:

$$C_2H_6O + 3(O_2 + 3.76\ N_2) \rightarrow$$

$$\rightarrow 2\ CO_2 + 3\ H_2O + \underbrace{3 \cdot 3.76}_{11.28}\ N_2$$

balance checking

	LHS	RHS	
C	2	2	ok
H	6	$3 \times 2 = 6$	ok
O	$1 + 3 \times 2 = 7$	$2 \times 2 + 3 \times 1 = 7$	ok
N	$11.28 \times 2 = 22.56$	$11.28 \times 2 = 22.56$	ok

Combustion in air with air factor λ:

$$C_2H_6O + \lambda \cdot 3 \cdot (O_2 + 3.76\ N_2) \rightarrow$$

$$\rightarrow 2\ CO_2 + 3\ H_2O + 3(\lambda - 1)\ O_2 +$$

$$+ \lambda \cdot 3 \cdot 3.76\ N_2$$

balance checking

	LHS	RHS	
C	2	2	ok
H	6	$3 \times 2 = 6$	ok
O	$1 + \lambda \cdot 3 \cdot 2 = 1 + 6\lambda$	$2 \times 2 + 3 \times 1 + 3(\lambda - 1) \times 2$	
		$= 1 + 6\lambda$	ok
N	$\lambda \cdot 3 \cdot 3.77 \cdot 2 = 22.56\lambda$	$\lambda \cdot 3 \cdot 3.77 \cdot 2 = 22.56\lambda$	ok

For future use:

$$n'_{Air} = \lambda \cdot 3 \cdot (1 + 3.76) = 14.28\,\lambda$$

$$n'_{WFG} = 2 + 3 + 3(\lambda - 1) + \lambda \cdot 3 \cdot 3.76 = 14.28\lambda + 2$$

$$n'_{DFG} = 2 + 3(\lambda - 1) + \lambda \cdot 3 \cdot 3.76 = 14.28\lambda - 1$$

i) Oxygen mole fraction in DFG

$$x_{O_2\,DFG} = \frac{n'_{O_2}}{n'_{DFG}} = \frac{3(\lambda - 1)}{14.28\lambda - 1}$$

(plot see next page)

$$\Rightarrow \lambda = \frac{3 - x_{O_2\,DFG}}{3 - 14.28\, x_{O_2\,DFG}}$$

For $x_{O_2\,DFG} = 0.02$,

$$\lambda = \frac{3 - 0.02}{3 - 14.28 \cdot 0.02} = 1.10$$

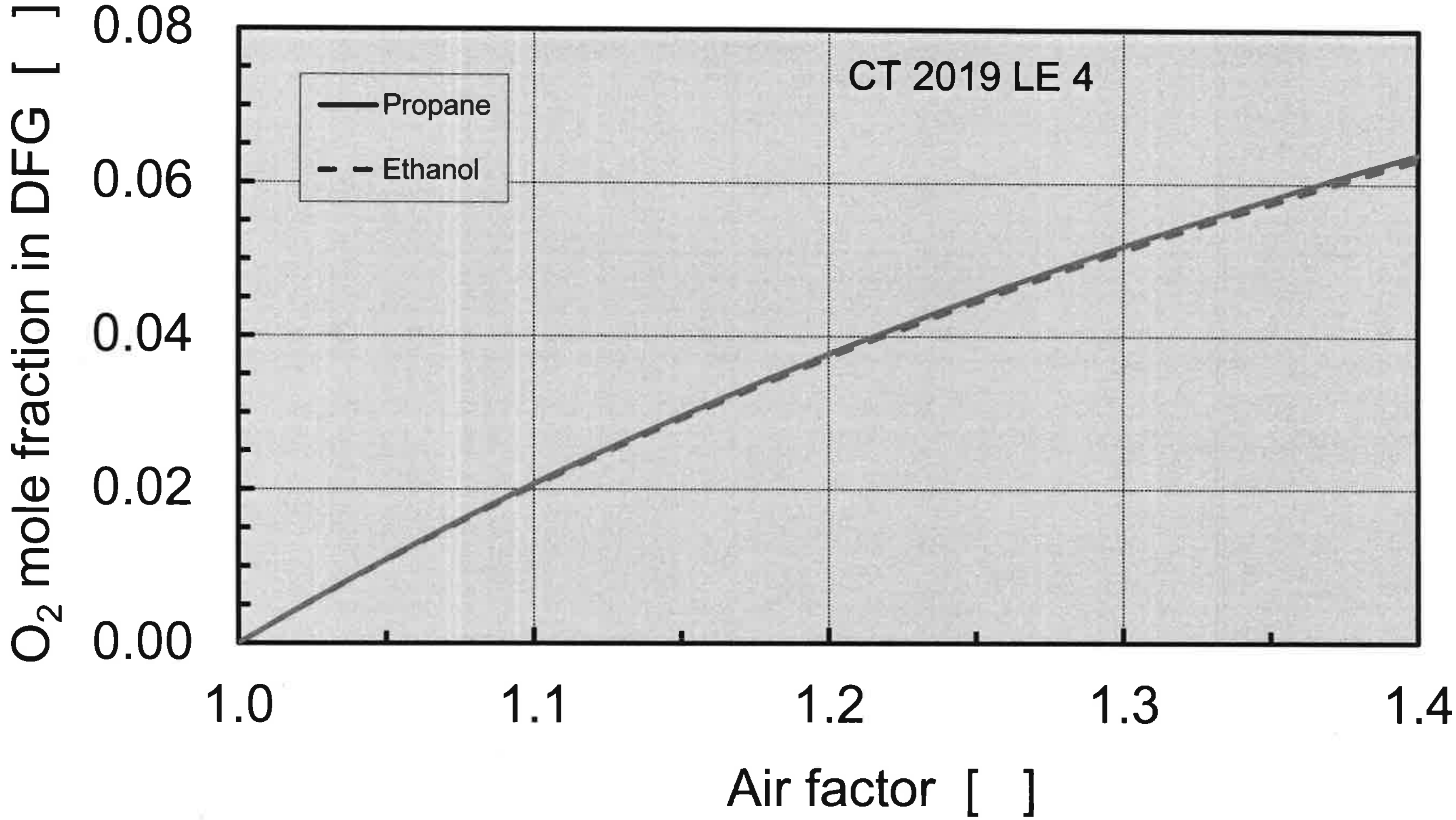
j) For $\lambda = 1.10$, we obtain

$$\dot{n}_{Air} = \dot{n}_{Fuel} \cdot n'_{Air}$$

$$= 0.00283 \frac{\text{kmol}}{\text{s}} \cdot 14.28 \cdot 1.10$$

$$= 0.0444 \frac{\text{kmol}}{\text{s}}$$

O_2 in dry flue gas vs. air factor



$$\dot{m}_{Air} = M_{Air} \cdot \dot{n}_{Air}$$

$$= 29 \frac{kg}{kmol} \cdot 0.0444 \frac{kmol}{s}$$

$$= 1.29 \frac{kg}{s}$$

$$\dot{n}_{WFG} = \dot{n}_{Fuel} \cdot n'_{WFG}$$

$$= 0.00283 \frac{kmol}{s} \cdot (14.28 \cdot 1.10 + 2)$$

$$= 0.0501 \frac{kmol}{s}$$

$$\dot{m}_{WFG} = \dot{m}_{Fuel} + \dot{m}_{Air}$$

$$= 0.1306 \frac{kg}{s} + 1.29 \frac{kg}{s}$$

$$= 1.42 \frac{kg}{s}$$

k) Summary of changes

	Propane	Ethanol	Change
Fuel $[\frac{kg}{s}]$	0,0755	0,1306	+73 %
Air $[\frac{kmol}{s}]$	0,0448	0,0444	− 1 %
Flue gas $[\frac{kmol}{s}]$	0,0482	0,0501	+ 4 %

Fuel flow rate changes considerably. Of course, big changes in the fuel handling equipment and burners will be needed, since a gaseous fuel is substituted with a liquid fuel. However, combustion air flow rate and flue gas flow rate are changed hardly at all, which indicates that the fuel conversion project might be quite feasible. Of course, a lot of things still need to be checked out, e.g. the flame shape and size.

1) It may sound surprising, but for the same amount of fuel energy, the quantities of air and flue gas are almost constants irrespective of fuel composition and heating value. This fact was first noted by Thornton more than 100 years ago and is utilized in, among other things, in many experimental techniques for fire and combustion research and also in the control systems of many steam boilers. The explanation is based on our understanding of the chemical structure of fuel molecules; the energy released during combustion is coming from the creation and disruption of chemical bonds, and since the

technically important fuels consist of similar atoms and bonds, it will not be very important to know what exactly is the chemical composition of the fuel: the quantities of air and flue gas will be approximately proportional to the amount of energy released in combustion.