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Exercises of "*Fundamentals of Chemical Processes*"

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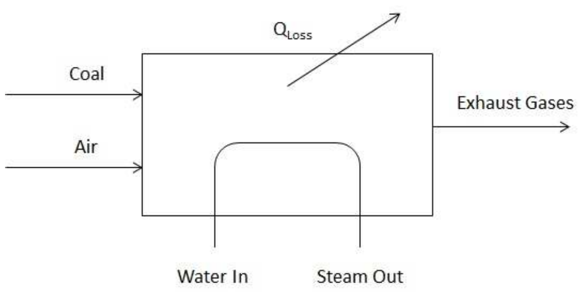
Exercise 2

<u>Analysis of a pulverized coal combustion furnace</u>

In a power plant, a suspension-burning furnace burns pulverized coal particles. The coal has the following composition, in terms of mass fractions on a dry and ash-free basis (ultimate analysis):

C	85.5%
H	5.5%
N	1%
S	1%
O	7%

The coal also contains fractions of humidity and ashes, which amount respectively to 8% and 6% on a total basis (proximate analysis). The pulverized coal enters the furnace at 25°C and 1 bar and is burned with air, at 50°C and with 30% excess, at 1 atm and relative humidity of 25%. The exhaust gases exit the furnace at 150°C. In the steam production section, the incoming liquid water is pumped at 28 bar and 90°C (the effect of pressure on the enthalpy content of water can be neglected) and is converted to saturated steam at 28 bar and 238°C. Assuming that the heat losses amount to 3% of the LHV of the coal, calculate the amount of steam produced per kg of coal and the efficiency of the furnace.



DATA

Coal: T_{IN} = 25°C

Dulong equation for the LHV of coal

$$HHV = 338.7 \cdot C + 1445 \cdot \left(H - \frac{O}{8} \right) + 94.3 \cdot S \; \frac{kJ}{kg}$$

$$LHV = HHV - 25.0 \cdot \left(H_2O + 9 \cdot H \right) \; \frac{kJ}{kg}$$

H_2O = humidity fraction

Air: T_{IN} = 50°C, P = 1atm, R.H. = 25% a 50°C, P_{SAT}^{H2O}(50°C) = 12.349 kPa

Water/Steam: h^{IN}_{H2O} (90°C) = 376.92 kJ/kg_{H2O} h^{OUT}_{H2O} (238°C) = 2804 kJ/kg_{H2O}

Exhaust Gases: T_{OUT} = 150°C, P = 1atm

Specific Heat at constant pressure [J/mol/K]

	C_P (50°C)
Air	29.10
H_2O	33.73

	C_P (150°C)
N_2	29.24
O_2	30.06
CO_2	39.54
H_2O	34.13

Solution

It is convenient to assume 100 kg of total coal as the basis for the material balances. In this way, it is possible to estimate the coal composition with respect to the overall basis. It is important to note that the ultimate analysis is referred to the dry and ash-free (daf) share of coal, while the fractions of humidity and ashes are referred to the overall coal (proximate analysis). The basis of total coal includes the fraction of humidity, the fraction of the ashes and the daf fraction, which represents the 86% of the overall amount, considered humidity and ashes.

$$m_C = 100 kg_{Coal,total} \cdot 0.855 \frac{kg_C}{kg_{C,daf}} \cdot \frac{86}{100} \frac{kg_{C,daf}}{kg_{Coal,total}} = 73.53 kg_C$$

$$m_H = 100 kg_{Coal,total} \cdot 0.055 \frac{kg_H}{kg_{C,daf}} \cdot \frac{86}{100} \frac{kg_{C,daf}}{kg_{Coal,total}} = 4.73 kg_H$$

$$m_O = 100 kg_{Coal,total} \cdot 0.07 \frac{kg_O}{kg_{C,daf}} \cdot \frac{86}{100} \frac{kg_{C,daf}}{kg_{Coal,total}} = 6.02 kg_O$$

$$m_S = 100 kg_{Coal,total} \cdot 0.01 \frac{kg_S}{kg_{C,daf}} \cdot \frac{86}{100} \frac{kg_{C,daf}}{kg_{Coal,total}} = 0.86 kg_S$$

$$m_N = 100 kg_{Coal,total} \cdot 0.01 \frac{kg_N}{kg_{C,daf}} \cdot \frac{86}{100} \frac{kg_{C,daf}}{kg_{Coal,total}} = 0.86 kg_N$$

From these values, the following overall composition is calculated:

Specie	**m_i (kg)**
C	73.53
H	4.73
N	0.86
S	0.86
O	6.02
Ash	6.00
H_2O (humidity)	8.00

Based on the material balances, it is possible to estimate the amount of air necessary for the combustion of the inlet coal feed:

$$\alpha_{st} = 4.31 \cdot \frac{8H + 2.667C + S - O^*}{100} = 4.31 \cdot \frac{8 \cdot 4.73 + 2.667 \cdot 73.53 + 0.86 - 6.02}{100} = 9.861 \quad kg_{\text{Dry Air}} / kg_{Coal,total}$$

$$\alpha = \alpha_{st} \cdot \left(1 + \frac{e\%}{100}\right) = 12.819 \quad kg_{\text{Dry Air}} / kg_{Coal,total}$$

$$n_{\text{Dry Air}} = \frac{12.819}{28.96} \frac{kmol_{\text{Dry Air}}}{kg_{Coal,total}} \cdot 100 kg_{Coal,total} = 44.264 \quad kmol_{air}$$

Given the amount of relative humidity of the inlet air stream, the amount of water fed to the furnace is:

$$x_{H_2O} = \frac{R.H.}{100} \cdot \frac{P_{H_2O}^{sat}(50°C)}{P} = \frac{12.349}{101.325} \cdot 0.25 = 0.03047$$

$$n_{H_2O}^{Humidity} = n_{\text{Dry Air}} \cdot \frac{x_{H_2O}}{1 - x_{H_2O}} = 1.391 \quad kmol_{H_2O}$$

Chosen the coal basis and estimated the amount of air and water vapor entering in the furnace, it is possible to determine the amount and the composition of the outlet exhaust gases:

$$n_{CO_2} = \frac{73.53}{12} = 6.127 \quad kmol_{CO_2}$$

$$n_{H_2O} = 1.391 + \frac{4.73}{2} + 8 \cdot \frac{1}{18} = 4.200 \quad kmol_{H_2O}$$

$$n_{N_2} = 1281.9 kg_{\text{Dry Air}} \cdot \frac{3.31}{4.31} \frac{kg_{N_2}}{kg_{\text{Dry Air}}} \cdot \frac{1}{28.15} \frac{kmol_{N_2}}{kg_{N_2}} + \frac{0.86}{28} kmol_{N_2} = 35.00 \quad kmol_{N_2}$$

$$n_{O_2} = 986.1 kg_{\text{Dry Air}} \cdot \frac{1}{4.31} \frac{kg_{O_2}}{kg_{\text{Dry Air}}} \cdot \frac{1}{32} \frac{kmol_{O_2}}{kg_{O_2}} \cdot 0.3 = 2.145 \quad kmol_{O_2}$$

$$n_{SO_2} = \frac{0.86}{32} = 0.027 \quad kmol_{SO_2}$$

The following composition is obtained for the gas stream exiting the furnace:

Specie	n^{OUT} (kmol)	x%
CO_2	6.128	12.90
H_2O	4.200	8.84
SO_2	0.027	0.06
N_2	35.000	73.68
O_2	2.145	4.52

The outlet flow of SO_2 is much smaller than that of the other gas streams, and therefore it can be neglected in the enthalpy balance. For the same reason, the contribution of the ashes can also neglected in the enthalpy balance. Considering a balance volume that includes the furnace and the steam production system, the enthalpy balance can be written like follows:

$$\sum_{i=1}^{\text{Reactants}} n_i^{IN} \cdot \int_{298K}^{T_{IN}} \overline{C}_{P,i} \cdot dT - \sum_{i=1}^{\text{Products}} n_i^{OUT} \cdot \int_{298K}^{T_{OUT}} \overline{C}_{P,i} \cdot dT - \dot{Q}_{Loss} + \dot{m}_C \cdot LHV_{Coal} = \dot{m}_{H_2O} \cdot \left(\hat{h}_{H_2O}^{out} - \hat{h}_{H_2O}^{in} \right)$$

In the balance, it is important to note that the reference state for the water stream entering in the heat-exchange coil system is different from that of the reacting current. Indeed:

Combustion gases: pressure and temperature at which the fuel $\Delta H°_C$ is known (T_{RIF} = 25°C, P_{RIF} = 1 atm), composition equal to the species entering the furnace.

Water stream: triple point (T_{RIF} = 0.01°C, P_{RIF} = 611.73 Pa), liquid.

It is possible to choose two different reference systems since the two streams (the reacting gases and water in the coils) are segregated from the viewpoint of the material balance. It must also be noted that the reference state of water stull includes the composition (pure water) and the state (liquid), coherently with the points that a reference state has to fulfill. The LHV of the coal can be estimated by application of the Dulong equation:

$$HHV = 338.7 \cdot C + 1445 \cdot \left(H - \frac{O}{8} \right) + 94.3 \cdot S \; = 30733.20 \frac{kJ}{kg_{Coal,total}}$$

$$LHV = HHV - 25.0 \cdot \left(H_2O + 9 \cdot H \right) = 29468.95 \frac{kJ}{kg_{Coal,total}}$$

The heat losses per unit of coal are referred to the LHV of the coal:

$$\hat{Q}_{Loss} = 29468.95 \cdot 0.03 \frac{kJ}{kg_{Coal,total}} = 884.07 \frac{kJ}{kg_{Coal,total}}$$

Considering the reference pressure established by the combustion enthalpy ΔH^0_c (T_{RIF} = 25°C), the calculation of the enthalpy of the gas species reads as follows:

Specie	n_i (kmol)	C_P (50°C)	H_i (kJ)
Aria	44.264	29.10	32202.06
H_2O	1.391	33.73	1172.96
Total			33750.02

The average specific heats at constant pressure at 50°C are given for the inlet streams:

$$n^{in}_{\text{Dry Air}} \cdot \int_{25°C}^{T_{IN}} \overline{C}_{P,\text{Dry Air}} \cdot dT + n^{in}_{H2O} \cdot \int_{25°C}^{T_{IN}} \overline{C}_{P,H_2O} \cdot dT = \left(n^{in}_{\text{Dry Air}} \cdot \overline{C}^{medio}_{P,\text{Dry Air}} + n^{in}_{H_2O} \cdot \overline{C}^{medio}_{P,H_2O}\right) \cdot \left(T_{IN} - 25\right)$$

As well, the enthalpy values of the outlet streams are calculated:

Specie	n_i (kmol)	C_P (150°C)	H_i (kJ)
N_2	35.000	29.24	127925.00
O_2	2.145	30.06	8059.84
CO_2	6.128	39.54	30287.64
H_2O	4.200	34.13	17918.25
Total			184190.73

The enthalpy balance can be solved with reference to the mass of water fed in the steam production system, obtaining:

$$\dot{m}_{H_2O} = 1115.76 \quad kg_{H_2O}$$

$$\frac{\dot{m}_{H_2O}}{\dot{m}_{C,total}} = 11.16 \quad \frac{kg_{H_2O}}{kg_{Coal,total}}$$

The efficiency of the combustion system is calculated as follows:

$$\eta = \frac{\dot{m}_{H_2O} \cdot \left(\hat{h}_{H_2O}^{vap} - \hat{h}_{H_2O}^{liq}\right)}{\dot{m}_{Coal,total} \cdot LHV_{Coal,total}} = 0.919$$

Results obtained assuming 100 kg daf Coal as a the basis

Inlet mass of the species associated to the daf coal basis:

Specie	m_i (kg)
C	85.50
H	5.50
N	1.00
S	1.00
O	7.00
Ash	6.98
H_2O (humidity)	9.30

Mass of the incoming air:

$$\alpha_{st} = 11.466 \quad kg_{aria} / kg_{C,daf}$$

$$\alpha = 14.905 \quad kg_{aria} / kg_{C,daf}$$

$$n_{aria} = 51.470 \quad kmol_{aria}$$

The moles of water vapor entering the system via humidity of the air:

$$n_{H_2O}^{Umidità} = 1.617 \quad kmol_{H_2O}$$

The moles and the composition of the outlet gases are:

Specie	n^{OUT} (kmol)	x%
CO_2	7.125	12.90
H_2O	4.884	8.84
SO_2	0.031	0.06
N_2	40.701	73.68
O_2	2.494	4.52

The HHV and the LHV of the daf coal are:

$$HHV = 338.7 \cdot C + 1445 \cdot \left(H - \frac{O}{8} \right) + 94.3 \cdot S = 35736.28 \frac{kJ}{kg_{C,daf}}$$

$$LHV = HHV - 25.0 \cdot (H_2O + 9 \cdot H) = 34266.22 \frac{kJ}{kg_{C,daf}}$$

The heat losses referred to the LHV of the daf coal amount to:

$$\hat{Q}_{Loss} = 34266.22 \cdot 0.03 \frac{kJ}{kg_{C,daf}} = 1027.99 \frac{kJ}{kg_{C,daf}}$$

The enthalpy of each of the inlet species are:

Specie	n_i (kmol)	C_P (50°C)	H_i (kJ)
Aria	51.470	29.10	37448.37
H_2O	1.617	33.73	1363.82
Total			38812.19

The enthalpy of each of the outlet species are:

Specie	n_i (kmol)	C_P (150°C)	H_i (kJ)
N_2	40.701	29.24	148761.23
O_2	2.494	30.06	9371.27
CO_2	7.125	39.54	35215.31
H_2O	4.884	34.13	20837.62
Total			214185.42

The mass of the steam produced in the heat exchange coils is:

$$\dot{m}_{H_2O} = 1297.22 \quad kg_{H_2O}$$

$$\frac{\dot{m}_{H_2O}}{\dot{m}_{C,daf}} = 12.97 \quad \frac{kg_{H_2O}}{kg_{C,daf}}$$