ENE 302 – Energy Conversion Processes II

WEEK 3: FOSSIL FUELS

PROBLEM SETS

Problem 1: Proximate analysis of a coal was carried out by taking three samples as follows:

a) First sample is taken in 25 ml silica crucible of 16.3256 g and weighed as 17.1348 g. It is heated at 105 ^{o}C in a hot air oven till constant weight is obtained. Its weight is 17.1239 g.
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b) Second sample is taken in another 25 ml silica crucible of 17.0826 g and weighed as 17.9301 g. It is heated at 800 ^{o}C in a muffle furnace till all the coal in it completely burns. Its weight is 17.3846 g.

c) Third sample is taken in a 18.5364 g silica volatile matter crucible and weighed as 19.3579 g. This is kept in a muffle furnace at 925 ^{o}C for 7minutes and then weighed as 19.1603 g.

Calculate
i) Percent moisture
ii) Percent mineral matter
iii) Percent coal substance

Solution 1:

(i) Weight of the coal sample=17.1348−16.3256=0.8092 g

Weight of the moisture=17.1348−17.1239=0.0109 g

% Moisture=M=0.01090/0.8092×100=1.35%

(ii) Weight of the coal sample=17.9301−17.0826=0.8475 g

Weight of the ash=17.3846−17.0826=0.3020 g

% Ash=A=0.3020/0.8475×100=35.63%

(iii) Weight of the coal sample=19.3579−18.5364=0.8215 g

Weight of volatile matter and moisture=19.3579−19.1603=0.1976 g

Since fresh sample is used

% Volatile matter+Moisture=0.1976/0.8215×100=24.05%

% Volatile matter=V=24.05−01.35=22.70%

% Fixed carbon=100−(01.35+22.70+35.63)=40.32%

% Mineral matter=1.1Ash=1.1×35.63=39.19%

% Volatile matter from coal substance=% Volatile matter−0.1%Ash

% Volatile matter from coal substance=%22.70−0.1×35.63=19.14%

% Coal substance=% Fixed carbon+% Volatile matter from coal substance
=40.32+19.14=59.46%

Problem 2:

A coal has 2.34% moisture, 23.45% volatile matter and 45.67% ash. Calculate ash% on dry basis, volatile matter on d.a.f basis and fixed carbon on d.m.m.f basis.

Solution 2:

% Fixed carbon$=100-2.34-23.45-45.67=28.54\%$

Proximate Analysis of Coal
$M=02.34\%$
$V=23.45\%$
$A=45.67\%$
$FC=28.54\%$

% Ash on dry basis$=A/100-M\times100=45.67/100-02.34\times100=46.76\%$

% Volatile matter on d.a.f
basis$=V/100-M-A\times100=23.45/100-02.34-45.67\times100=45.10\%$

% Fixed carbon on d.m.m.f basis$=FC/100-M-1.1A\times100$
% Fixed carbon on d.m.m.f basis $=28.54/100-02.34-1.1\times45.67\times100=60.18\%$

Alternately, fixed carbon can also be calculated through volatile matter

% Volatile matter on d.m.m.f basis$=V-0.1A/100-M-1.1A\times100$

Volatile matter on d.m.m.f basis
$=23.45-0.1\times45.67/100-02.34-1.1\times45.67\times100=39.82\%$

% Fixed carbon on d.m.m.f basis$=100-39.82=60.18\%$

Problem 3:

A gaseous fuel contains 75 % v/v (volume percent) methane (CH_4), 15.0 % n-buthane (n-C_4H_{10}), 5.0 % iso-buthane (iso-C_4H_{10}), and 5.0 % N_2 (noncombustible).

a) Calculate the higher heating value **(HHV)** and the lower heating value **(LHV)** of this fuel in **kJ/mol**, using heats of combustion in related table.

b) Calculate the higher heating value (HHV) and the lower heating value (LHV) of the fuel in **kJ/kg.**

Solution 3:

a) Using Enthalpy Tables

Methane

$\boldsymbol{CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(v)}}$,

$\Delta\widehat{H}_c^o = -890.36\ kJ/mol, \quad HHV = 890.36\ kJ/mol$

$HHV = LHV + n\widehat{H}_v(H_2O, 25^oC),$

$890.36 = LHV + 2 * 44.01 \rightarrow LHV = 802.34\ kJmol\ CH_4$

n-butane

$\boldsymbol{C_4H_{10(g)} + 13/2O_{2(g)} \rightarrow 4CO_{2(g)} + 5H_2O_{(v)},}$

$\Delta\widehat{H}_c^o = -2878.5\ kJ/mol, \quad HHV = 2878.5\ kJ/mol$

$HHV = LHV + n\widehat{H}_v(H_2O, 25^oC),$

$2878.5 = LHV + 5 * 44.01 \rightarrow LHV = 2658.45\ kJmol\ C_4H_{10}$

iso-butane

$\boldsymbol{C_4H_{10(g)} + 13/2O_{2(g)} \rightarrow 4CO_{2(g)} + 5H_2O_{(v)},}$

$\Delta\widehat{H}_c^o = -2868.8\ kJ/mol, \quad HHV = 2868.8\ kJ/mol$

$HHV = LHV + n\widehat{H}_v(H_2O, 25^oC),$

$2868.8 = LHV + 5 * 44.01 \rightarrow LHV = 2648.75\ kJmol\ C_3H_8$

$$HHV_{gas\,fuel} = \sum x_i(HHV)_i = 0.75 * 890.36 + 0.15 * 2878.5 + 0.05 * 2868.8$$
$$= \mathbf{1242.98\ kJ/mol}$$

$$LHV_{gas\,fuel} = \sum x_i(LHV)_i = 0.75 * 802.34 + 0.15 * 2658.45 + 0.05 * 2648.75$$
$$= \mathbf{1132.96\ kJ/mol}$$

b) <u>volume percent = mol percent</u>

For 1 mol gasous fuel;

$$\left[\overbrace{(0.75\ mol\ CH_4)\left(16.04\frac{g}{mol}\right)}^{CH_4} + \overbrace{(0.15 * 58.12)}^{n-C_4H_{10}} + \overbrace{(0.05 * 58.12)}^{iso-C_4H_{10}} + \overbrace{(0.05 * 58.12)}^{N_2}\right]$$
$$= 25.055\ g = \mathbf{0.025\ kg}$$

$$HHV \rightarrow 1242.98\frac{kJ}{mol}x\frac{1\ mol}{0.025\ kg} = \mathbf{49719.2\ \frac{kJ}{kg}}$$

$$LHV \rightarrow 1132.96\frac{kJ}{mol}x\frac{1\ mol}{0.025\ kg} = \mathbf{45318.4\ \frac{kJ}{kg}}$$

Problem 4:

A gas (fuel) contains 80.0 wt % propane (C_3H_8), 15.0 wt % n-butane (C_4H_{10}) and 5.0 wt % water.

- **a.** Calculate the molar composition of this gas (fuel) on both a wet and a dry basis and the ratio (mol H_2O/mol dry gas).
- **b.** If 100 kg/h of this fuel is to be burned with 30 % excess air, what is the required air feed rate (kmol/h)?

Atomic weight(s): C: 12, H: 1, O: 16

Solution 4 :

(a) Basis: 100 g fuel

Species of the fuel	mass (g)	MW (g/mol)	n (mol)	mole % (wet basis)	mole % (dry basis)
C_3H_8	80	44	1.818	77.26	87.57
C_4H_{10}	15	58	0.258	10.97	12.43
H_2O	5	18	0.277	11.77	
Total	100		2.353	100	100

$$ratio = \frac{H_2O, mol}{totalmoles, dry} = \frac{0.277}{(2.353 - 0.277)} = \frac{0.277}{2.076} = 0.133 \frac{mol\ H_2O}{mol\ \ dry\ \ fuel}$$

Solution (b)

$C_3H_8 + 5O_2 \longrightarrow 3CO_2 + 4H_2O$

$C_4H_{10} + 13/2O_2 \longrightarrow 4CO_2 + 5H_2O$

Calculation of theoretical O_2:

For C_3H_8 $$\frac{100\ kg\ \ fuel}{h} x \frac{80\ kg\ C_3H_8}{100\ kg\ \ fuel} x \frac{1\ kmol\ C_3H_8}{44\ kg\ C_3H_8} x \frac{5\ kmol\ O_2}{1\ kmol\ C_3H_8} = 9.09\ kmol\ O_2 / h$$

For C_4H_{10} $$\frac{100\ kg\ \ fuel}{h} x \frac{15\ kg\ C_4H_{10}}{100\ kg\ \ fuel} x \frac{1\ kmol\ C_4H_{10}}{58\ kg\ C_4H_{10}} x \frac{6.5\ kmol\ O_2}{1\ kmol\ C_4H_{10}} = 1.68\ kmol\ O_2 / h$$

Total O_2: 9.09+1.68=10.77 kmol O_2/h

Required air feed rate

$$\frac{10.77\ kmol\ O_2}{h} x \frac{100\ kmol\ air}{21\ kmol\ O_2} = 51.286\ kmol\ \frac{air}{h}$$

51.286x1.30=66.67 kmol air/h

or

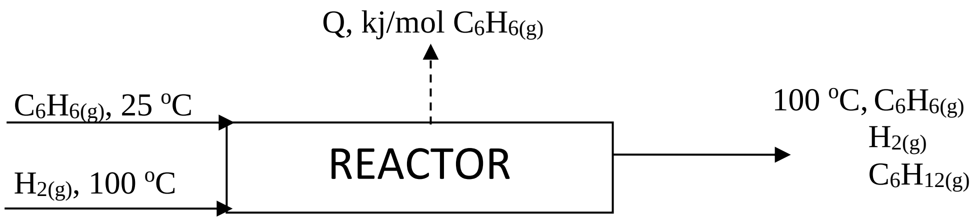
$$\frac{10.77\ kmol\ O_2}{h} x \frac{100\ kmol\ air}{21\ kmol\ O_2} x \frac{130\ kmol\ air\ (30\%)}{100\ kmol\ air} = 66.67\ \frac{kmol\ air}{h}$$

Problem 5:

A gas (fuel) contains 100 % Benzene gas (C_6H_6) reacts with hydrogen (H_2) to produce cyclohexane (C_6H_{12}).

$$C_6H_6(g) + 3\ H_2(g) \rightarrow C_6H_{12}(g), \quad \Delta Hr = -206\ kj/mol\ C_6H_6$$

Conversion of $C_6H_6(g)$ is 60 %. 5 mol of $H_2(g)$ enters the reactor at 100 °C, 1 atm. 2 mol of $C_6H_6(g)$ enters the reactor at 25 °C, 1 atm. Product gas stream leaves the reactor at 70 °C, 1atm. The flowchart is given below. Determine the amount of heat (Q) that should be removed from the reactor.



<u>Mass balance:</u>

Basis: 2 mol benzene & 5 mol hydrogen in feed stream

Molecule	In	Out	Reacted
C_6H_6	2	0.8	1.2
H_2	5	1.4	3.6
C_6H_{12}	0	1.2	-

Fractional conversion of Benzene = 0.6 → 2 mol C_6H_6 × 0.6 = 1.2 mol C_6H_6 reacted

→ 2 – 1.2 = **0.8 mol C_6H_6 out**

1 mol C_6H_6 → 3 mol H_2 reacts →→ 1.2 mol C_6H_6 → 3.6 mol H_2 reacts

→ 5 – 3.6 = **1.4 mol H_2 out**.

1 mol C_6H_6 → 1 mol C_6H_{12} produced →→ 1.2 mol C_6H_6 → **1.2 mol C_6H_{12} produced**

Energy balance:

Molecule	n_{in}	H_{in}	n_{out}	H_{ouy}
C_6H_6	2	0(T_{ref})	0.8	H_2
H_2	5	H_1	1.4	H_3
C_6H_{12}	0	-	1.2	H_4

H_1

In Table B.8 → H_2 (100 °C) = 7.96 kj/mol

H_2

C_6H_6 (70 °C) = $\int_{25}^{70}(74.06 \times 10^{-3} + 32.95 \times 10^{-5}T)dT$ (Table B-2)

= 4.028 kj/mol

H_3

H_2 (70 °C) = $\int_{25}^{70}(28.84 \times 10^{-3} + 0.00765 \times 10^{-5}T)dT$ (Table B-2)

= 1.289 kj/mol

H_4

C_6H_{12} (70 °C) = $\int_{25}^{70}(94.14 \times 10^{-3} + 49.62 \times 10^{-5}T)dT$ (Table B-2)

= 5.295 kj/mol

$$\Delta H = Q$$

$$\Delta H = \xi \times \Delta H_r + \sum_{out} n_i H_i - \sum_{in} n_i H_i$$

$$\xi = \frac{n_{C6H6}, reacted}{|\gamma_{C6H6}|} = \frac{1.2}{1} = 1.2$$

$\Delta H = (1.2) \times (-206) + [(0.8 \times 4.028) + (1.4 \times 1.289) + (1.2) \times (5.295)\} - (5 \times 7.96))$
= -275.6 kj

Problem 6:

Compare the thermal efficiency ηth of a subcritical, supercritical, and ultra-super-critical steam power plants operating on the Rankine cycle under the following conditions:

Case 1: live steam conditions
p1=180 bars and t1=550°C (subcritical power plant)

Case 2: live steam conditions
p1=300 bars and t1=600°C (supercritical power plant)

Case 3: live steam conditions
p1=350 bars and t1=750°C (ultra-supercritical power plant)

Condenser pressure is 0.04 bar. The work of feed pump may be ignored.

Solution 6:

From water/steam table, enthalpy of condensate at 0.04 bar is

h3=121.4 kJ/ kg.

<u>Case 1</u>

Subcritical cycle:

P_1=180 bars, T_1=550°C.

From h – s diagram, enthalpies of live and exhaust steam, respectively, are

h_1=3425 kJ/kg, and h_2=1935 kJ / kg.

With feed pump work wp=0, the cycle thermal efficiency is given by;

$\eta th=(h_1–h_2)/(h_1–h_3) =(3425 – 1935)/(3425 – 121.4) = 0.454$.

Case 2

Supercritical cycle:

P_1=300 bars, T_1=600°C.

Enthalpies of live and exhaust steam, respectively, are

h_1=3450 kJ/kg, h_2=1885 kJ/kg. Hence,

$\eta_{th}=(3450 - 1885)/(3450 - 121.4)=0.47$.

Case 3

Ultra-supercritical cycle:

P_1=350 bars, T_1=750°C.

Enthalpies of live and exhaust steam, respectively, are

h_1=3850 kJ/kg, h_2=1980 kJ/kg. Hence,

$\eta_{th}=(3850 - 1980)/(3850 - 121.4)=0.50$.

Compared to the subcritical power plant (Case 1), the efficiency η_{th} of supercritical power plant (Case 2) is higher by $(0.47/0.454 - 1) \times 100=3.55\%$, and η_{th} of the ultra-supercritical power plant (Case 3) is higher by $(0.5/0.454 - 1) \times 100=10.5\%$, respectively.

Problem 7:

A single-reheat subcritical steam power plant (refer to Figure 3.5) is operating under the following conditions:

- Plant electric power output P_{el}=600MW
- Live steam condition:P_1=180 bars and T_1=550°C
- Reheat steam condition: P_2=20 bars and T_3=560°C
- Turbine isentropic efficiency η_{it}=0.92
- Condenser pressure P_3=0.04 bar
- Fuel lower heating value LHV =29 MJ/kg

Calculate (a) plant heat addition and rejection rates, (b) plant thermal efficiency, (c) plant heat rate, and (d) plant steam and fuel rates. Ignore work of the feed pump.

Solution 7:

Enthalpies of steam and condensate (h–s diagram,)

- Live steam at 180 bars/550°C, enthalpy h_1= 3475 kJ/kg
- HP turbine exhaust steam at 20 bars, enthalpy $h_{2}s$= 2825 kJ/kg
- Reheat steam at 20 bars/560°C, enthalpy h_3= 3600 kJ/kg
- LP turbine exhaust steam, enthalpy $h_{4}s$= 2285 kJ/kg
- Condensate (saturated water) at 0.04 bar h_5= 121.4 kJ/ kg

Actual enthalpy of HP and LP turbine exhaust steam, respectively

$h_2=h_1-(h1-h2s) \times \eta it = 3475 - (3475 - 2825)\times 0.92 = 2877$ kJ/kg

$h_4=h_3-(h3-h4s) \times \eta it = 3600 - (3600 - 2285)\times 0.92 = 2390$ kJ/kg

Plant thermal efficiency and heat rate (with wp=0)

$\eta th = wnet/qin = [(h_1-h_2)+(h_3-h_4)]/[(h_1-h_5)+(h3-h2)] =$

$[(3475 - 2877)+(3600-2390)]/[(3475-121.4)+(3600 - 2877)] = 0.4435$

$HR=3600/\eta th=3600/0.4435=8117$ kJ / kWh

Plant rate of heat addition

$Qin = Pel/\eta th = 600/0.4435=1352.9$ MJ/s

Plant steam rate $ms = Qin/[(h_1-h_5)+(h_3-h_2)] =$
$1,352,900/[(3475-121.4)+(3600 - 2877)] = 331.87$ kg/s = 1194.7 t/h

Plant fuel rate $mf = Qin/LHV=1352.9/29=46.7$ kg/s = 167.9 t/h

Problem 8:

An advanced steam power plant is operating under the following conditions:
- Plant electric power output Pel=1200 MW
- Fuel: bituminous coal with LHV of 30 MJ/kg
- Plant net overall efficiency ηnet is 45%
- Wet flue gas volume per kg fuel Vg=9.85 m3/kg

Calculate (i) the plant net heat rate HR, (ii) the hourly fuel consumption rate of the plant mf, (iii) the plant-specific fuel consumption SFC, and (iv) the hourly flue gas flow rate Vg,h.

Solution 8:

Plant net heat rate HR =3600/ηnet = 3600/0.45 = 8000kJ/kWh

Plant hourly fuel consumption rate mf = Pel/(LHV ηnet) = 1200/(30×0.45) = 88.89kg/s =320 t/h

Plant-specific fuel consumption SFC = 3600 mf/Pel = 3600 s/h×88.89kg/s/1.2×106 kW = 0.267 kg/kWh

Hourly flue gas flow rate Vg,h = Vg × SFC × Pel
= 9.85m3/kg×0.267 kg/kWh × 1.2 × 106kW = 3.152×106 m3/h

References:

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