LANDMARK UNIVERSITY, OMU-ARAN

LECTURE NOTE: 3
COLLEGE: COLLEGE OF SCIENCE AND ENGINEERING
DEPARTMENT: MECHANICAL ENGINEERING
PROGRAMME:
ENGR. ALIYU, S.J

*Course code: MCE 311*
*Course title:* **Applied Thermodynamics**
Credit unit: *3 UNITS*. Course status: *compulsory*

1. *The following is the volumetric analysis of the dry exhaust from an internal combustion engine:*
*$CO_2$ = 8.9%; CO = 8.2%; $H_2$ = 4.3%; $CH_4$ = 0.5% and $N_2$ = 78.1%. If the fuel used is octane ($C_8H_{18}$) determine air-fuel ratio on mass basis:*
(*i*) *By a carbon balance*. (*ii*) *By a hydrogen-oxygen balance*.

**Solution.** (*i*) As per analysis of dry products, the combustion equation is written as

$$aC_8H_{18} + 78.1N_2 + 78.1\left(\frac{21}{79}\right)O_2 \rightarrow 8.9CO_2 + 8.2CO + 4.3H_4 + 0.5CH_4 + 78.1N_2 + xH_2O$$

Carbon balance: 8a = 8.9 + 8.2 + 0.5 = 17.6 i.e, a = 2.2

Hydrogen balance: 18a = 4.3 x 2 + 0.5 x 4 + 2x

or 18 × 2.2 = 8.6 + 2 + 2*x i.e.*, *x* = 14.5

***Oxygen balance***: 2*b* = 8.9 × 2 + 8.2 + *x*
or 2*b* = 17.8 + 8.2 + 14.5 *i.e.*, *b* = 20.25

$$\therefore Air - fuel\ (A/F)ratio = \frac{(20.25\ x\ 32) + (20.25)\frac{79}{21}x\ 28}{2.2(8\ x\ 12 + 1\ x\ 18)} = \frac{2781}{250.8}\ 11.09\ Ans.$$

2. *The exhaust from an engine running on benzole was measured with the help of Orsat apparatus. Orsat analysis showed a $CO_2$ content of 12%, but no CO. Assuming that the remainder of the exhaust contains only oxygen and nitrogen, calculate the air-fuel ratio of the engine.*
*The ultimate analysis of benzole is C = 88% and $H_2$ = 12%.*

**Solution.** 1 kg of fuel, consisting of 0.88 kg C and 0.12 kg $H_2$, can be written as 0.88/2 moles C and 0.12/2 moles $H_2$. Therefore, considering 1 mole of *dry exhaust gas* (D.E.G.) we can write the combustion equation as follows:

$$X\left(\frac{0.88}{12}C + \frac{0.12}{2}H_2\right) + YO_2 + \frac{79}{21}YN_2 \rightarrow 0.12CO_2 + aO_2 + (0.88 - a)N_2 + bH_2O$$

$$\left[\begin{array}{c}\text{Let the D. E. G. contain moles of } O_2\text{ . The moles of } CO_2 \text{ in 1 mole of D. E. G. are 0.12. Therefore the D. E. G.} \\ \text{contains } (1 - a - 0.12) = (0.88 - a)moles\ of\ N_2\end{array}\right]$$

Where, *X* = Mass of fuel per mole D.E.G.,

$Y$ = Moles of $O_2$ per mole D.E.G.,
$a$ = Moles of *excess* $O_2$ per mole D.E.G., and
$b$ = Moles of $H_2O$ per mole D.E.G.
Now,
$Carbon\ balance: \frac{0.88}{12}X = 0.12,\ \therefore X = 1.636$
**Hydrogen balance:** $0.06X = b \therefore b = 0.06 \times 1.636 = 0.098$
***Oxygen balance*:** $2Y = 2 \times 0.12 + 2a + b$
or $2Y = 0.24 + 2a + 0.098 \therefore Y = 0.169 + a$
$Nitrogen\ balance: \frac{79}{21}Y = (0.88 - a),\ \therefore Y = 0.234 - 0.266a$
Equating the expressions for $Y$ gives

$$0.234 - 0.266a = 0.169 + a \therefore a = 0.0513$$

*i.e.,* $Y = 0.169 + 0.0513 = 0.2203$
$\therefore$ $O_2$ supplied = 0.2203 × 32 kg/mole D.E.G.
i.e, $Air\ supplied = \frac{0.2203\ x\ 32}{0.233} = 30.26\ kg/mole\ D.E.G$
Since $X$ = 1.636, then, the fuel supplied per mole D.E.G. is 1.636 kg
$\therefore\ A/F\ ratio = \frac{30.26}{1.636} = 18.5/1\ (Ans)$

3. *The analysis of the dry exhaust from an internal combustion engine is as follows:*

*Carbon dioxide ($CO_2$) = 15 per cent* *Carbon monoxide (CO) = 3 per cent*
*Methane ($CH_4$) = 3 per cent* *Hydrogen ($H_2$) = 1 per cent*
*Oxygen ($O_2$) = 2 per cent* *Nitrogen ($N_2$) = 76 per cent*

*Calculate the proportions by mass of carbon to hydrogen in the fuel, assuming it to be a pure hydrocarbon.*

**Solution.** Let 1 kg of fuel contain $x$ kg of carbon (C) and $y$ kg hydrogen ($H_2$). Then considering 1 mole of D.E.G. and introducing $X$ and $Y$, we can write

$$X\left(\frac{xC}{12} + \frac{y}{2}H_2\right) + YO_2 + \frac{79}{21}YN_2 \rightarrow 0.15CO_2 + 0.03CO + 0.03CH_4 + 0.01H_2 + 0.02O_2 + aH_2O + 0.76N_2$$

Then,

$Nitrogen\ balance: \frac{79}{21}Y = 0.76,\ \therefore Y = 0.202$
$Oxygen\ balance: Y = 0.15 + \frac{0.03}{2} + 0.02 + \frac{a}{2}$ or,

$$0.202 = 0.15 + \frac{0.03}{2} + 0.02 + \frac{a}{2} \therefore a = 0.034$$

$Carbon\ balance: \frac{Xx}{12} = 0.15 + 0.03 + 0.03 \therefore Xx = 2.52 \quad \ldots\ldots i$
$Hydrogen\ balance: \frac{Xy}{2} = 2\ x\ 0.03 + 0.01 + a = 0.06 + 0.01 + 0.034 \therefore Xy = 0.208 \quad \ldots\ldots ii$
Dividing equations (*i*) and (*ii*), we get
$\frac{Xx}{Xy} = \frac{2.52}{0.208} \quad or \quad \frac{x}{y}\ 12.1$
$\therefore Ratio\ of\ C\ to\ H_2\ in\ fuel = \frac{x}{y} = \frac{12.1}{1}$ Ans.

4. *Methane ($CH_4$) is burned with atmospheric air. The analysis of the products on a 'dry' basis is as follows:*

*$CO_2$ = 10.00%, $O_2$ = 2.37%, CO = 0.53%, $N_2$ = 87.10%.*
(*i*) *Determine the combustion equation ;* (*ii*) *Calculate the air-fuel ratio ;*
(*iii*) *Percent theoretical air*.

**Solution.** (*i*) **Combustion equation:**

From the analysis of the products, the following equation can be written, keeping in mind that this analysis is on a *dry basis*.

$x\ CH_4 + y\ O_2 + z\ N_2 \rightarrow 10.0\ CO_2 + 0.53\ CO + 2.37\ O_2 + a\ H_2O + 87.1\ N_2$

To determine all the unknown co-efficients let us find balance for each of the elements.

***Nitrogen balance*:** $z = 87.1$

Since all the nitrogen comes from the air,

$\frac{z}{y} = \frac{79}{21}; y = \frac{87.1}{79/21} = 23.16$

***Carbon balance*:** $x = 10.00 + 0.53 = 10.53$

***Hydrogen balance*:** $a = 2x = 2 \times 10.53 = 21.06$

***Oxygen balance*.** All the unknown co-efficients have been solved for, and in this case the oxygen balance provides a check on the accuracy. Thus, $y$ can also be determined by an oxygen balance

$y = 10.0 + \frac{0.53}{2} + 2.37 + \frac{21.06}{2} = 23.16$

Substituting these values for $x, y, z$ and $a$, we have,

$10.53\ CH_4 + 23.16\ O_2 + 87.1\ N_2 \rightarrow 10.0\ CO_2 + 0.53\ CO + 2.37\ O_2 + 21.06\ H_2O + 87.1\ N_2$

Dividing both sides by 10.53, we get the **combustion equation** per mole of fuel,

$\mathbf{CH_4 + 2.2\ O_2 + 8.27\ N_2 \rightarrow 0.95\ CO_2 + 0.05\ CO + 2H_2O + 0.225\ O_2 + 8.27\ N_2}$. **(Ans.)**

(*ii*) **Air-fuel ratio A/F:**

The air-fuel ratio on a *mole basis* is

2.2 + 8.27 = **10.47 moles air/mole fuel. (Ans.)**

The air-fuel ratio on a *mass basis* is found by introducing the molecular weights

$A/F = \frac{10.47\ x\ 28.97}{12+1\ x\ 4} = 18.96\ kg\ \ air/kg\ fuel$. Ans.

The theoretical air-fuel ratio is found by writing the combustion equation for theoretical air,

$CH_4 + 2O_2 + 2\left(\frac{79}{21}\right)N_2 \ \rightarrow\ CO_2 + 2H_2O +\ (2)\left(\frac{79}{21}\right)N_2$

$A/F_{theor} = \frac{\left[2 + (2)\left(\frac{79}{21}\right)\right]28.97}{12+1\ x\ 4} = 17.24\ \ kg\ air/kg\ fuel$ Ans.

(*iii*) **Percent theoretical air:**

$\textbf{Percent theoretical air} = \frac{\mathbf{18.96}}{\mathbf{17.24}}\ \boldsymbol{x}\ \mathbf{100 = 110}\%$. Ans.

5. *The following is the analysis (by weight) of a chemical fuel:*
*Carbon = 60 per cent; Hydrogen = 20 per cent; Oxygen = 5 per cent; Sulphur = 5 per cent and Nitrogen = 10 per cent*.
*Find the stoichiometric amount of air required for complete combustion of this fuel*.

**Solution.** On the basis of 100 kg fuel let us assume an equivalent formula of the form:

$C_aH_bO_cN_dS_e$

From the given analysis by weight, we can write

$12a = 60$ or $a = 5$
$1b = 20$ or $b = 20$
$16c = 5$ or $c = 0.3125$
$14d = 10$ or $d = 0.7143$
$32e = 5$ or $e = 0.1562$

Then the formula of the fuel can be written as

$$C_5H_20O_{0.3125}N_{0.7143}S_{0.1562}$$

The combustion equation is

$$C_5H_{20}O_{0.3125}N_{0.7143}S_{0.1562} + xO_2 + x\left(\frac{79}{21}\right)N_2 \rightarrow pCO_2 + qH_2O + rSO_2 + sN_2$$

Then,

***Carbon balance*:** $5 = p \therefore p = 5$

***Hydrogen balance*:** $20 = 2q \therefore q = 10$

***Sulphur balance*:** $0.1562 = r \therefore r = 0.1562$

***Oxygen balance*:** $0.3125 + 2x = (2p + q + 2r)$

i.e, $x = p + \frac{q}{2} + r - \frac{0.3125}{2} = 5 + \frac{10}{2} + 0.1562 - \frac{0.3125}{2} = 9.99$

$Nitrogen\ balance$: $0.7143 + 2x \times \frac{79}{21} = 2s \quad \therefore s = \frac{0.7143}{2} + x \times \frac{79}{21} = \frac{0.7143}{2} + 9.99 \times \frac{79}{21} = 37.94$

Hence the combustion equation is written as follows:

$$C_5H_{20}O_{0.3125}N_{0.7143}S_{0.1562} + 9.99O_2 + 9.99\left(\frac{79}{21}\right)N_2 \rightarrow 5CO_2 + 10H_2O + 0.1562SO_2 + 37.94N_2$$

$$\therefore Stoichiometric\ air\ required = \frac{9.92 \times 32 + 9.99\left(\frac{79}{21}\right) \times 28}{100} = 13.7\ kg/kg\ of\ fuel$$ Ans.

6. *A sample of fuel has the following percentage composition by weight:*

*Carbon = 84 per cent* *Hydrogen = 10 per cent*
*Oxygen = 3.5 per cent* *Nitrogen = 1.5 per cent*
*Ash = 1 per cent*

(*i*) *Determine the stoichiometric air-fuel ratio by mass.*

(*ii*) *If 20 per cent excess air is supplied, find the percentage composition of dry flue gases by volume.*

**Solution.** (*i*) **Stoichiometric air fuel ratio:**

On the basis of 100 kg of fuel let us assume an equivalent formula of the form: $C_aH_bO_cN_d$

From the given analysis by weight, we can write

$12a = 84$ *i.e.*, $a = 7$
$1b = 10$ *i.e.*, $b = 10$
$16c = 3.5$ *i.e.*, $c = 0.218$
$14d = 1.5$ *i.e.*, $d = 0.107$

The formula of fuel is

$$C_7H_{10}O_{0.218}N_{0.107}$$

The combustion equation is written as

$$C_7H_{10}O_{0.318}N_{0.107} + xO_2 + x\left(\frac{79}{21}\right)N_2 \rightarrow pCO_2 + qH_2O + rN_2$$

Then,

***Carbon balance*:** $7 = p$ *i.e.*, $p = 7$

***Hydrogen balance*:** $10 = 2q$ *i.e.*, $q = 5$

***Oxygen balance*:** $0.218 + 2x = (2p + q)$

or $0.218 + 2x = 2 \times 7 + 5$ *i.e.*, $x = 9.39$

$Nitrogen\ balance: 0.107 + 2x \times \frac{79}{21} = 2r\ \ or, 0.107 + 2 \times 9.39 \times \frac{79}{21}\ \ 2r, i.e, r = 35.4$

Hence the combustion equation becomes

$C_7H_{10}O_{0.318}N_{0.107} + 9.39O_2 + 9.39\left(\frac{79}{21}\right)N_2 \rightarrow 7CO_2 + 5H_2O + 35.4N_2$

$\therefore Stoichiometric\ air\ required = \frac{9.39 \times 32 + 9.39\left(\frac{79}{21}\right) \times 28}{100} = 12.89\ \ kg/kg\ of\ fuel$ . Ans.

(*ii*) **Percentage composition of dry flue gases by volume with 20 per cent excess air:**

If 20 per cent excess air is used, the combustion equation becomes

$C_7H_{10}O_{0.318}N_{0.107} + (1.2)9.39O_2 + (1.2)9.39\left(\frac{79}{21}\right)N_2 \rightarrow 7CO_2 + 5H_2O + (1.2)(9.39)O_2 + (1.2)(35.4)N_2$

Total number of moles of dry products of combustion

$n = 7 + (0.2)(9.39) + (1.2)(35.4)$

$= 7 + 1.878 + 42.48 = 51.358$

$\therefore$ **Percentage composition of dry flue gases by volume is as follows:**

$\boldsymbol{CO_2 = \frac{7}{51.358} \times 100 = 13.63\%. Ans.}$

$\boldsymbol{O_2 = \frac{1.878}{51.358} \times 100 = 3.66\%. Ans.}$

$\boldsymbol{N_2 = \frac{42.48}{51.358} \times 100 = 82.71\%. Ans.}$

# SOLUTIONS TO ASSIGNMENT.

c. The percentage composition of sample of liquid fuel by weight is, C = 84.8 per cent, and $H_2$ = 15.2 per cent. Calculate (i) the weight of air needed for the combustion of 1 kg of fuel; (ii) the volumetric composition of the products of combustion if 15 per cent excess air is supplied.

SOLUTION.

| Element, wt. (kg) | $O_2$ used (kg) | Dry products (kg) |
|---|---|---|
| C = 0.848 | $0.848\ x\ \frac{8}{3} = 2.261$ | $\frac{0.848\ x\ 11}{3} = 3.109\ (CO_2)$ |
| $H_2$ = 0.152 | 0.152 × 8 = 1.216 | |
| Total | $O_2$ = 3.477 | |

**(i) Minimum weight of air needed for combustion**

$= \frac{3.477\ x\ 100}{23} = 15.11\ kg$ Ans.

Excess air supplied $= \frac{1511\ x\ 15}{100} = 2.266\ kg$

Wt. of oxygen in excess air $= \frac{2.266\ x\ 23}{100} = 0.521\ kg$

Total air supplied for combustion = Minimum air + Excess air

= 15.11 + 2.266 = 17.376 kg

$\therefore$ Wt. of nitrogen ($N_2$) in flue gases $= \frac{17.376\ x\ 77}{100}\ 13.38\ kg$

(*ii*) To get **volumetric composition of the product of combustion** let us use tabular method.

| *Name of gas* | *Weight (x)* | *Molecular weight (y)* | *Proportional volume (z)* = $\frac{(x)}{(y)}$ | *Percentage volume* = $\frac{(z)}{\Sigma(z)} \times 100$ |
|---|---|---|---|---|
| $CO_2$ | 3.109 | 44 | 0.0707 | 12.51 per cent. **(Ans.)** |
| $O_2$ | 0.521 | 32 | 0.0163 | 2.89 per cent. **(Ans.)** |
| $N_2$ | 13.38 | 28 | 0.4780 | 84.60 per cent. **(Ans.)** |
| | | | $\Sigma z = 0.5650$ | |

2. A cold storage vessel has its outer flat surfaces insulated with three layers of lagging. The innermost layer is 270 mm thick, the centre layer is 60 mm thick and the outer layer is 370mm thick. The thermal conductivities of the lagging materials are 0.12, 0.1 and 0.2 W/mK respectively. A temperature sensor embedded half-way through the centre lagging indicates a temperature of 1°C.
Calculate the temperature of the outer surface of the cold storage vessel when the outer surface temperature of the outer layer of lagging is 20°C.
Solution.
Figure 1 shows the wall.
This problem demonstrates working through part of the wall only.

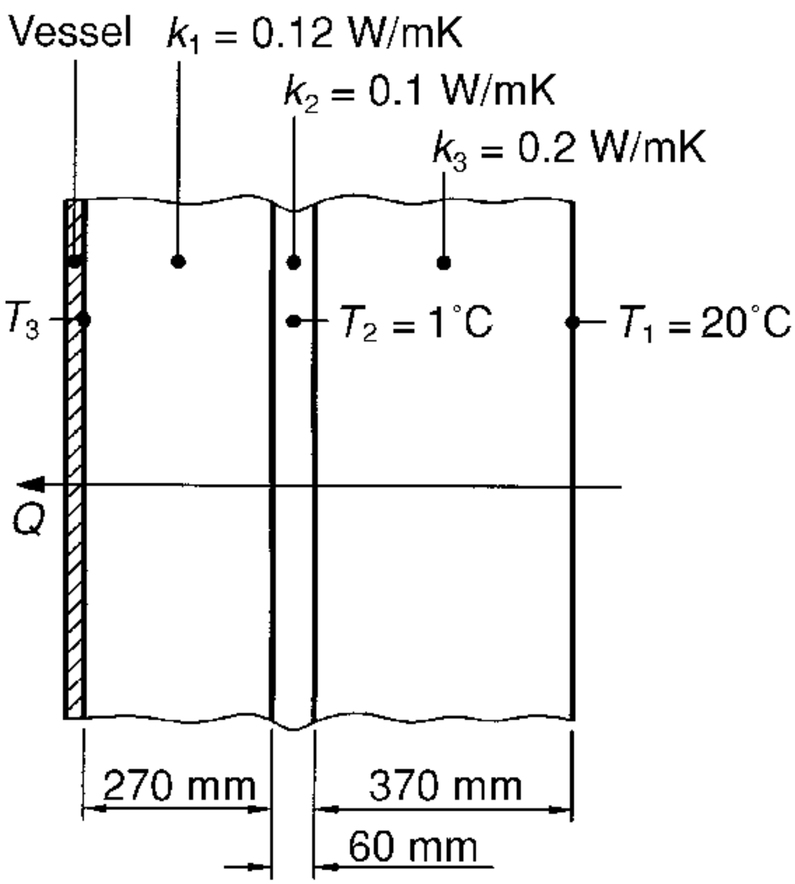

**Figure 1**

Working from the midpoint of the inner layer, and calling this temperature $T_2$,

$$T_1 - T_2 = \frac{Q}{A.t}\left(\frac{s_1}{k_1} + \frac{s_2}{k_2}\right)$$

$$20 - 1 = \frac{Q}{1\ x}\left(\frac{0.37}{0.2} + \frac{0.03}{0.1}\right)$$

$Q$ = 8.84W

Remember that $Q$ is the same through all sections of the wall.

Working from the centre to the inner surface,

$$T_2 - T_3 = \frac{Q}{A.t}\left(\frac{s_1}{k_1} + \frac{s_2}{k_2}\right)$$

$$1 - T_3 = 8.84\left(\frac{0.03}{0.1} + \frac{0.27}{0.12}\right)$$

$1 - T_3 = 8.84(2.55)$,

$T_3 = -21.54$°C

Key point

Always make temperature differences positive.

3. A motorist equips his automobile tyres with a relief-type valve so that the pressure inside the tyre will never exceed 220 kPa (gauge). He starts the trip with a pressure of 200 kPa (gauge) and a temperature of 23$^o$C in the tyres. During the long drive the temperature of the air in the tyres reaches 83$^o$C. Each tyre contains 0.11 kg of air. Determine:

a) the mass of air escaping each tyre,

b) the pressure of the air inside the tyre when the temperature returns to 23$^o$C.

SOLUTION

a) $P_1V_1 = m_1RT_1$

$$m_1 = \frac{P_1V_1}{RT_1} = \frac{200\ x\ 10^3\ x\ V_1}{287\ x\ (273+23)} = 0.11kg$$

$$V_1 = \frac{0.11\ x\ 287\ x\ 296}{200\ x\ 10^3} = 0.04672\ m^3$$

$V_1 = V_2$ = constant

$P_2V_2 = m_2\ RT_2$

220 x 103 x 0.04672 = m2 x 287 x (273 + 83)

$\therefore m_2$ = 0.1006 kg

$\therefore dm = m_1 - m_2$ = 0.11 - 0.1006 = 0.0094 kg

b) $V_3 = V_2 = V_1$ and $m_3 = m_2$

$$P_3 = \frac{m.R.T_3}{V_4} = \frac{0.1006\ x\ 287\ x\ 296}{0.04672} = 183\ kPa$$