of heat involved in SI units.

SOLVED PROBLEMS

Note the following points before solving the problem :

(1) Minimum O_2 required = Theoretical O_2 required–Excess O_2 present in the fuel.

(2) Minimum O_2 required should be calculated on the basis of complete combustion. If the combustion products contain CO and O_2, then excess O_2 is found by subtracting the amount of O_2 required to burn CO to CO_2.

(3) The weight of dry flue gases formed should be calculated by balancing the carbon in the fuel and carbon in the flue gases.

(4) All gaseous fuels generally contain CO_2 and N_2 therefore these gases should be added to the dry flue gases produced by the combustion of gaseous fuel to find the total dry flue gases formed per m^3 of gaseous fuel.

(5) The Orsat apparatus always gives the analysis of dry flue gases.

(6) The heat carried away by the steam in the combustion of fuel should be calculated by finding the partial pressure of steam in the exhaust gases if sufficient data is given, otherwise partial pressure of the steam should be assumed as 0.07 bar and specific heat of steam is to be taken as 2.1 kJ/kg K.

(*a*) For finding the steam and air supply in gas producer plant ; the following two equations should be used

$$2C + O_2 = 2CO + \text{Heat}$$

$$H_2O + C = H_2 + CO + \text{Heat}$$

The heats in the above equations should be calculated from fundamentals according to the given data.

The following Equations are Used for Solving the Problems

(1) $$\text{H.C.V.} = \frac{1}{100}\left[35000\,C + 143000\left(H - \frac{O}{8}\right) + 9160\,S\right] \text{kJ/kg}$$

(2) $$\text{L.C.V.} = \left[\text{H.C.V.} - \frac{9H}{100} \times 2460\right] \text{kJ/kg}$$

(3) $$m_{o2} = \frac{1}{100}\left[\frac{8}{3}C + 8\left(H - \frac{O}{8}\right) + S\right]$$

kg of O_2/kg of fuel for complete combustion.

$$m_a = \frac{1}{23}\left[\frac{8}{3}C + 8\left(H - \frac{O}{8}\right) + S\right] \text{ kg of air/kg of fuel for complete combustion.}$$

(4) $$m_a = \frac{1}{33}\left[\frac{NC}{C_1 + C_2}\right] \text{ kg of air supplied/kg of fuel.}$$

The above formula should not be used when the fuel contains nitrogen.

(5) $$m_g = \frac{C\Sigma X}{12(C_1 + C_2)} \text{ kg of dry flue gases/kg of fuel}$$

where $$\Sigma X = \frac{1}{100}[28C_1 + 44C_2 + 28N + 32O]$$

(6) $$V_{o2} = \frac{1}{100}\left[\frac{H}{2} + \frac{CO}{2} + 2CH_4 + 3C_2H_4\right] \text{ m}^3 \text{ of } O_2/\text{m}^3$$

of gas for complete combustion.

(7) $$V_1 = \frac{OV}{21 - O} \text{ volume of excess air/m}^3 \text{ of gaseous fuel.}$$

where V is the volume of dry products per m^3 of gaseous fuel burned and O is the volume of oxygen in exhaust.

(8) Percentage of C burning to $CO_2 = \frac{C_2}{C_1 + C_2} \times 100.$

(9) Percentage of C burning to $CO = \frac{C_1}{C_1 + C_2} \times 100.$

(10) Excess air supplied $= \frac{4C}{69}\left(\frac{2O - C_1}{C_1 + C_2}\right)$ kg/kg of fuel.

(11) $$\text{H.C.V.} = \left(\frac{m_w + m_c}{m_f}\right).\theta - m_{af} \times \text{C.V.}$$ (Bomb calorimeter)

(12) $$\text{H.C.V.} = \frac{m_w(\Delta T)_w}{V_g} \text{ (gas calorimeter)}$$

where $$V_g = V_g' \times \frac{273}{T_g} \times \frac{1}{760}\left(h_b + \frac{h_w}{13.6}\right)$$

Problem 12.1. *A coal has the following composition by mass :*
$C = 90\%$, $H_2 = 3\%$, $S = 1\%$, $O_2 = 2\%$, $N_2 = 2\%$ and remaining is ash. Find the H.C.V. and L.C.V. of the fuel.

Solution.

$$\text{H.C.V.} = \frac{1}{100}\left[35000\ C + 143000\left(H - \frac{O}{8}\right) + 9160\ S\right]$$

$$= \frac{1}{100}\left[35000 \times 90 + 143000\left(3 - \frac{2}{8}\right) + 9160 \times 1\right]$$

$$= 31500 + 3932.5 + 91.6 = 35524 \text{ kJ/kg}$$

$$\text{L.C.V.} = \text{H.C.V.} - \frac{9H}{100} \times 2460$$

$$= 35524 - \frac{9 \times 3}{100} \times 2460 = 34860 \text{ kJ/kg of fuel.}$$

Problem 12.2. *The following observations were made during the test for finding the lower calorific value of a solid fuel with the help of Bomb calorimeter.*

Mass of fuel in crucible = 0.78 gram, Mass of fuse wire = 0.02 gram. C.V. of fuse wire = 6500 kJ/kg.

Mass of water in the calorimeter = 1.88 kg

Water equivalent of calorimeter = 0.37 kg.

Observed temperature rise = 2.98°C.

Cooling correction = 0.02°C.

Assume the fuel contains 90% of carbon, 4% of hydrogen, the rest being ash.

Solution. Heat developed by the combustion of fuel + heat developed by the burning of fuse wire = Heat carried by cooling water + Heat contained in the calorimeter.

Corrected temperature rise = 2.98 + 0.02 = 3°C.

$$\therefore \quad m_f \times \text{H.C.V.} + m_{wf} + \text{C.V. of wire} = C_{pw}\,(m_w + m_c) \times \theta$$

$$\frac{0.78}{1000} \times \text{H.C.V.} + \frac{0.02}{1000} \times 6500 = 4.2\,(1.88 + 0.37) \times 3$$

$$0.78\ \text{H.C.V.} + 130 = 4200\,(2.25) \times 3$$

$$\therefore \quad \text{H.C.V.} = \frac{4200 \times 6.75 - 130}{0.78} = 36180 \text{ kJ/kg.}$$

Problem 12.3. *The following observations were made during the test for finding the calorific value of a gaseous fuel with the help of Boys gas calorimeter.*

Gas burned = 60 litres, Gas pressure = 4 cm of water above atmospheric pressure, Barometer reading = 750 m.m. of Hg. Temperature of the gas = 30°C.

Water circulated through the calorimeter = 20 kg.

Rise in temperature of water = 10°C. Condensate collected during the test = 60 grams.

Find the H.C.V. and L.C.V. of the gas at 0°C and 760 mm of Hg pressure.

Solution. The volume of gas used at 0°C and 760 mm of Hg is calculated using

$$V_g = V_g' \times \frac{273}{T_g} \times \frac{1}{76}\left(h_b + \frac{h_w}{13.6}\right)$$

$$= 60 \times \frac{273}{30 + 273} \times \frac{1}{76}\left(75 + \frac{4}{13.6}\right) = 60 \times \frac{273}{303} \times \frac{75.294}{76}$$

$$= 53.5 \text{ litres} = 0.0535 \text{ m}^3$$

$$\text{H.C.V.} = \frac{C_{pw}\, m_w (\Delta T)}{V_g} = \frac{4.2 \times 20 \times 10}{0.0535} = 15708 \text{ kJ/m}^3 \text{ at N.T.P.}$$

$$\text{Condensate formed per m}^3 \text{ of gas used at N.T.P.} = \frac{60}{1000} \times \frac{1}{0.0535} = 1.12 \text{ kg}$$

$$\text{L.C.V.} = \text{H.C.V.} - \text{Heat carried away by water vapour}$$
$$= 15708 - 1.12 \times 2460 = 15708 - 5755 = 12953 \text{ kJ/m}^3.$$

Problem 12.4. *The percentage composition by mass of a solid fuel used in a boiler is given below :* $C = 90\%$, $H_2 = 3.5\%$; $O_2 = 3\%$, $N_2 = 1\%$, $S = 1\%$ *and the remainder being ash.*

(a) Find the mass of air required per kg of fuel for complete combustion and mass analysis of the dry products of combustion.

(b) If 50% excess air is supplied in actual combustion, determine the volumetric analysis of the products and also the mass of flue gas per kg of fuel

Solution.

Constituent	Mass per kg of fuel	Mass of O_2 required for complete combustion	Mass of products formed		
			N_2	CO_2	SO_2
C	0.9	$0.9 \times \frac{8}{3} = 2.4$		$0.9 \times \frac{11}{3} = 3.3$	
H_2	0.035	$0.035 \times 8 = 0.28$			
S	0.01	$0.01 \times 1 = 0.01$			$0.01 \times 2 = 0.02$
Total		= 2.69		= 3.3	= 0.02
O_2	0.03	= 0.03			
N_2	0.01		0.01		

Total oxygen required for complete combustion

$$= 2.69 - 0.03 = 2.66 \text{ kg/kg of fuel}$$

$\therefore$ Air required $= 2.66 \times \frac{100}{23} = 11.58$ kg/kg of fuel

Dry products after combustion of one kg of fuel

$CO_2 = 3.3$ kg ; $SO_2 = 0.02$ kg

N_2 = Coming from the air supplied + from the fuel itself.

$$= 11.58 \times \frac{77}{100} + 0.01 = 8.92 \text{ kg}$$

Total dry products formed per kg of fuel = $CO_2 + SO_2 + N_2 = 3.3 + 0.02 + 8.92 = 12.24$ kg

The mass analysis of the dry product is given as

$$N_2 = \frac{8.92}{12.24} \times 100 = 72.86\%, \quad CO_2 = \frac{3.3}{12.24} \times 100 = 26.97\%, \quad SO_2 = \frac{0.02}{12.24} \times 100 = 0.164\%$$

(*b*) If 50% excess air is supplied, then the products of combustion are as

$CO_2 = 3.3$ kg ; $SO_2 = 0.02$ kg

Nitrogen comes from complete air supplied and the nitrogen from the fuel itself

$$= 11.58 \times 1.5 \times \frac{77}{100} + 0.01 = 13.36 \text{ kg}$$

Oxygen comes from only excess air supplied $= 11.58 \times \frac{1}{2} \times \frac{23}{100} = 1.33$ kg

Total dry products formed per kg of fuel

$$= CO_2 + SO_2 + N_2 + O_2 = 3.3 + 0.02 + 13.36 + 1.33 = 18.01 \text{ kg}$$

The mass analysis of dry product is given as $N_2 = \frac{13.36}{18.01} \times 100 = 74.19\%$

$$CO_2 = \frac{3.3}{18.01} \times 100 = 18.3\%, \quad O_2 = \frac{1.33}{18.01} \times 100 = 7.4\%, \quad SO_2 = \frac{0.02}{18.01} \times 100 = 0.11\%.$$

The mass analysis of the flue gas can be converted into volume analysis as follows :

Constituent	Percentage by mass (a)	Molecular Weight (b)	Proportional volume $(c) = \frac{a}{b}$	Percentage by volume $(d) = \frac{c}{\Sigma c} \times 100$
CO_2	18.30	44	0.415	12.60
SO_2	0.11	64	0.00172	0.05
O_2	7.40	32	0.231	7.00
N_2	74.19	28	2.65	80.35
Total	100.00		$\Sigma_c = 3.29772$	100.00

Problem 12.5. *A hydro-carbon fuel contains 86% carbon and 13% hydrogen by mass and the remainder is incombustible material. 25 kg of air is supplied per kg of fuel. Determine the dry and wet volumetric analysis of the exhaust gases.*

Assuming the vapour formed to be a perfect gas and total pressure of the exhaust gas as 1.03 bar, find the partial pressure of the vapour in the exhaust gas and the heat carried by the exhaust gas and steam per kg of fuel burned, if the temperature of the exhaust gas is 420°C and the room temperature is 20°C.

Take C_v (for dry gases) = 1 kJ/kg-k and C_v (steam) = 2.1 kJ/kg. K.

Solution. The oxygen required for complete combustion of one kg of fuel

$$= 0.86 \times \frac{32}{12} + 0.13 \times \frac{32}{4} = 2.28 + 1.04 = 3.32 \text{ kg}$$

∴ Air reqiured per kg fuel for complete combustion $= 3.32 \times \frac{100}{23} = 14.45$ kg

∴ Excess air supplied per kg of fuel = 25 – 14.45 = 10.55 kg

The products of combustion per kg of fuel are

$$CO_2 = 0.86 \times \frac{44}{12} = 3.16 \text{ kg}, \quad H_2O = 0.13 \times 9 = 1.17 \text{ kg}$$

N_2 (from the air supplied) = 25 × 0.77 = 19.25 kg.

O_2 (from excess air) = 10.55 × 0.23 = 2.42 kg

The mass analysis of the exhaust gases can be converted into volumetric analysis as follows.

Constituent	Wet Products				Dry products	
	Kg per kg of fuel (a)	Molecular weight (b)	Proportional volume (c) = a/b	Percentage volume $(d) = \frac{C}{\Sigma C} \times 100$	Proportional volume $(e) = \frac{a}{b}$	Percentage volume $(f) = \frac{e \times 100}{\Sigma e}$
CO_2	3.16	44	0.0718	8.00	0.0718	8.60
O_2	2.42	32	0.0756	8.43	0.0756	9.06
N_2	19.25	28	0.6880	76.33	0.688	82.34
H_2O	1.17	18	0.0680	7.25	—	—
Total			$\Sigma C = 0.9004$	100	$\Sigma e = 0.8353$	100

Partial pressure of H_2O vapour in wet product = Total pressure $\times \dfrac{H_2O}{\Sigma C}$

$$= 1.03 \times \frac{0.068}{0.9004} = 0.0746 \text{ bar.}$$

Mass of the dry-exhaust gases formed per kg of fuel = 3.16 + 2.42 + 19.25 = 24.83 kg

∴ Heat carried away by the dry exhaust gases per kg of fuel burned

$$= 24.83 \times 1\ (420 - 20) = 9932 \text{ kJ}$$

Heat carried away by the steam per kg of fuel

$$= 1.17\ [h_s + C_v(T_{sup} - T_s) - C_{pw}\ (20)]$$

The values of h_s (Total heat of dry saturated steam) and T_s (saturation temperature at the partial pressure of steam in exhaust at 0.0746 bar) are taken from steam table.

∴ Heat carried by steam formed per kg of fuel burned

$$= 1.17\ [2576 + 1\ (420 - 40) - 4.2 \times 20] = 3358 \text{ kJ/kg of fuel.}$$

Heat carried away by the wet exhaust gases per kg of fuel burned

$$= 9932 + 3358 = 13290 \text{ kJ.}$$