Fundamentals of Combustion

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Lecture – 08

Stoichiometry – Part 03 – Worked Examples - (Contd..)

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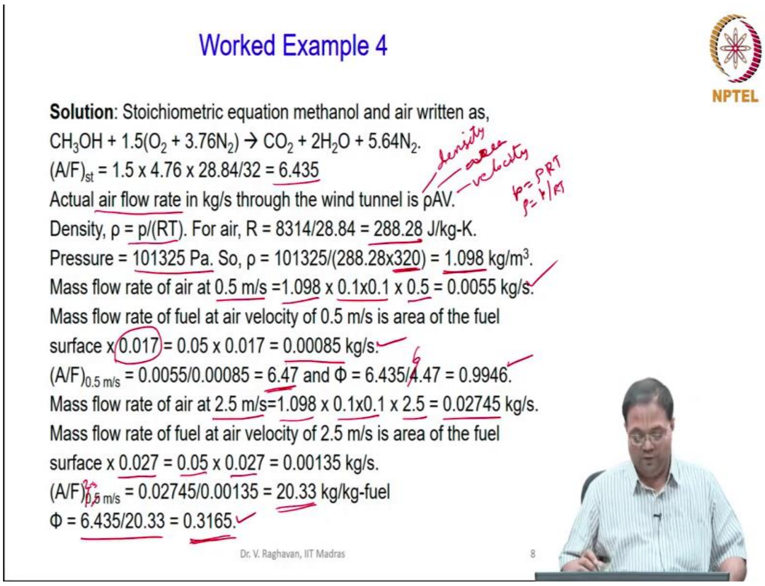

Solution. Methanol equation is written as.

$$CH_3OH + 1.5(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 5.64N_2.$$

CH_3OH plus 1.5 times O_2 plus 3.76 times N_2 gives CO_2 plus 2 H_2O plus 5.64 N_2. You can see that 1.5 is the stoichiometric kilo moles of oxygen supplied.

So, air fuel ratio at stoichiometric condition is 1.5 times 4.76 time 28.84 divided by molecular weight of methanol which is 32. So, that is 6.435, that is the mass of air divided by the mass of the fuel.

$$(A/F)_{st} = 1.5 \times 4.76 \times 28.84/32 = 6.435$$

Actual air flow rate to the wind tunnel is calculated by density times area times velocity, ok. So, this is density, this is area, and this is velocity, ok. Now, ρ density is got by $\rho = p/(RT)$.

So, $p = \rho RT$. Density will be equal to p/RT. Now, for air, R can be found by universal gas constant 8314 divided by molecular weight of the air. So, this will be the R value in J/ kg-K.

What is atmospheric pressure?

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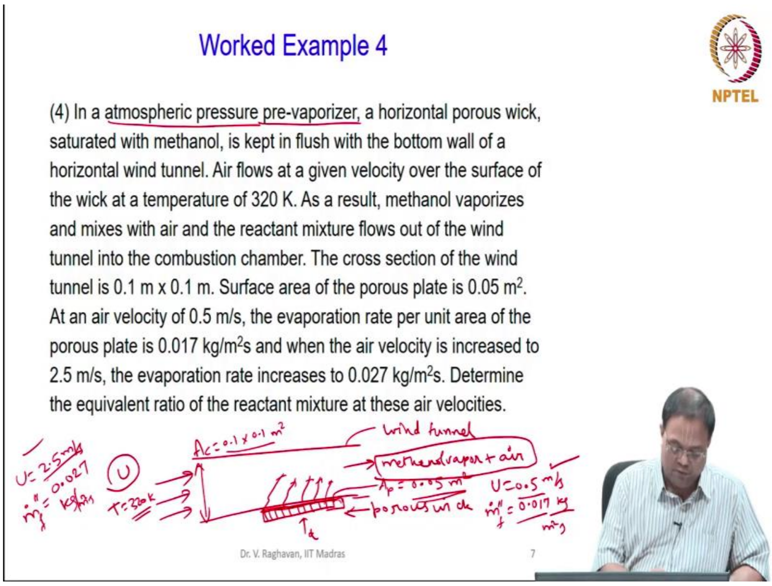

So, we have already given in the problem atmospheric pressure pre vaporizer. So, the pressure remains constant at atmospheric value. One atmosphere equal to 101325 Pascals. So, that is N/m^2.

That will be the value of the pressure. Density of the air which is coming at a temperature of 320. Now, T is 320 Kelvin. So, I have put in Kelvin, so you get 1.098 kg/m^3 as a density of the air flow which is coming into this.

So, mass flow rate of the air, when the velocity is 0.5 m/s is ρ which is 1.098 into area of cross section is 0.1×0.1. Here you have given it is given 0.1×0.1 is area of cross section of the wind tunnel into velocity is 0.5. So, you get the mass flow rate of air as 0.0055 kg/s.

Now, mass flow rate of fuel at air velocity of 0.5 is area of the fuel surface into 0.017 the flux is given, 0.017 kg/m^2s. So, that into meter square will give kg per second. What is the area of cross section of the fuel bed? Area of cross section of the porous bed is given as 0.05 m^2.

So, now you can see that 0.05×0.017. This will be the mass of the fuel. What is air fuel ratio? Actual air fuel ratio is mass of the air 0.0055 divided by the mass of the fuel 0.00085. That is 6.47.

Stoichiometric air-fuel ratio is 6.435. What is the equivalence ratio at the air velocity of 0.5 m/s? This will be 6.435 / 6.47 so, 0.9946. This is correct.

So, its almost equivalence ratio equal to unity. So, at 0.5 m/s when you slowly blow air you will get more evaporation.

Now, the mass flow rate of air is calculated at the velocity of 2.5 m/s. So, density into area of cross section into 2.5 that is 0.02745 kg/s.

Now, what is the mass flow rate of fuel? The flux is given as 0.027 kg/m^2-s for the fuel which is evaporating, that into area of cross section is 0.05. So, that will be 0.00135. Now, air fuel ratio this is again 2.5, 2.5 m/s.

So, that will be 0.02745 / 0.00135 = 20.33 kg / kg fuel. We can see that it is 20.33, very high. The mass of air is very high here, when compared to 1 kg of fuel.

Now, the equivalence ratio here is very low. This is actually lean mixture, fuel lean mixture. When the velocity is 0.5 m/s you get almost stoichiometric mixture leaving the wind tunnel.

When the airflow is increased to 2.5 m/s we do not have much evaporation of the fuel, maybe you have to increase temperature then. So, you get a equivalent ratio of 0.3165.

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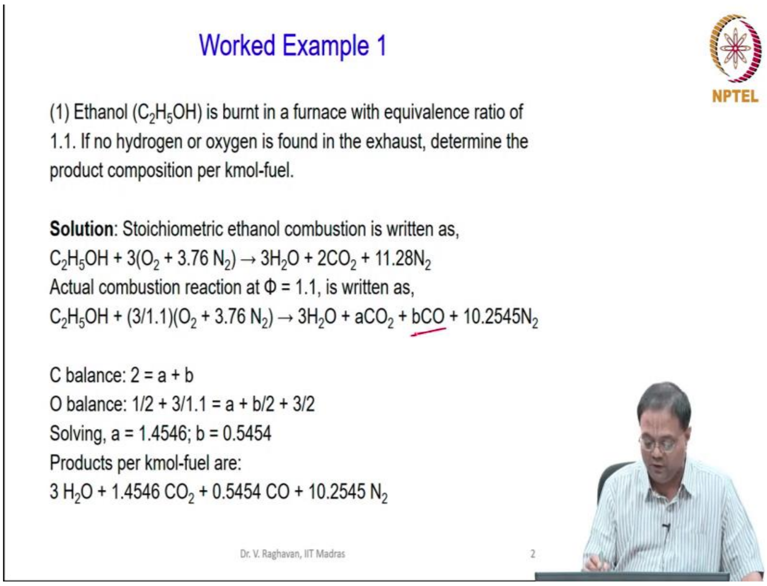

So, first we saw the problem with ethanol in a rich mixture 1.1 equivalence ratio and we saw that the hydrogen fully burns and carbon dioxide is not fully formed. Some amount of CO was present and we got the product composition.

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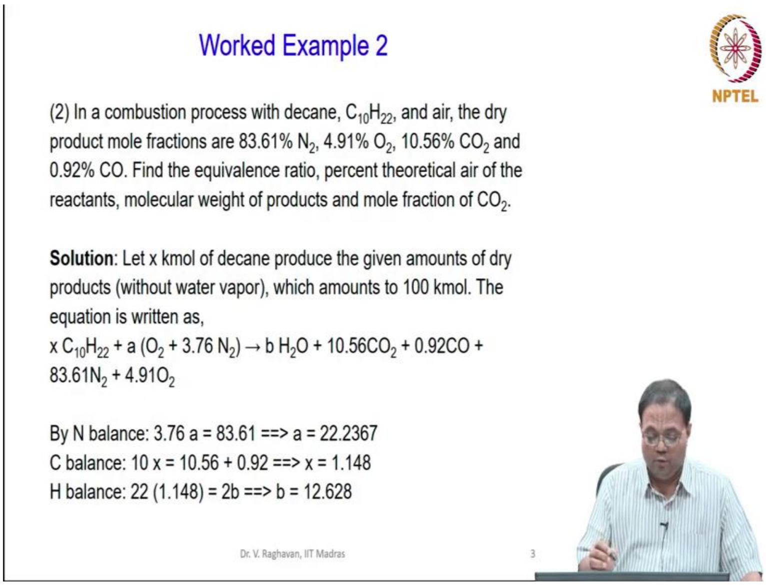

Second problem, we measured the exhaust dry fractions of the products, excluding the water vapour, and when you burn decane we got the product composition basically.

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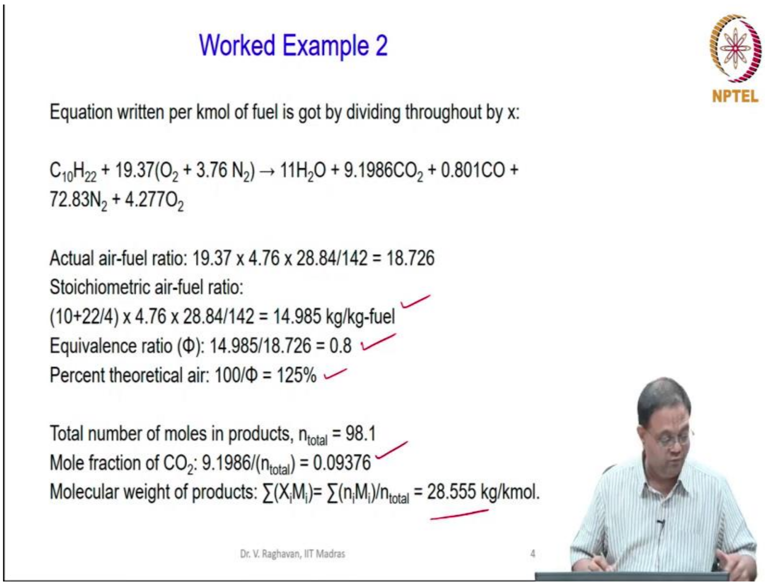

Here, the product composition, the amount of air supplied, the equivalence ratio, and the percentage excess air and we got the molecular weight of products plus the mole fraction of the product, one of the products.

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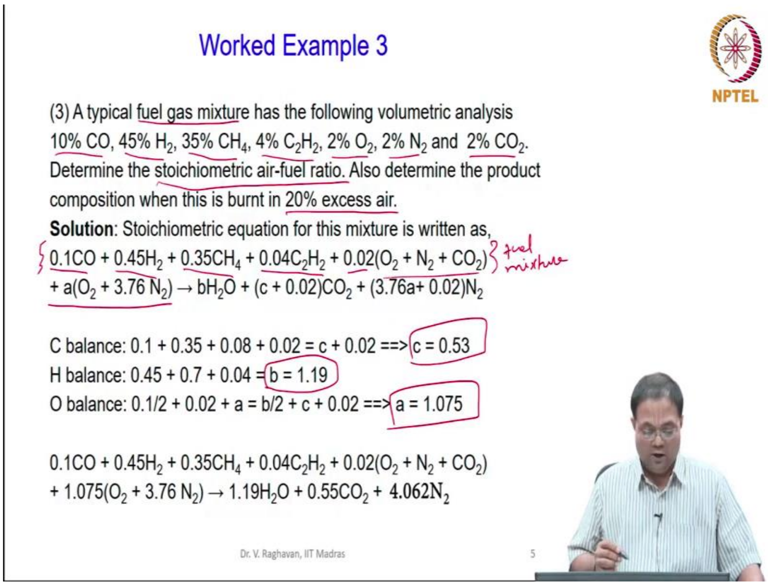

Third problem was a fuel mixture. Gaseous fuel mixture CO, H_2, CH_4, C_2H_2 in some proportions are given. We need to determine the stoichiometric air fuel ratio and a product composition when it is burnt in excess air. That we did here.

Then, the 4th problem is about pre vaporizer where some hot air is fed through a porous bed which is saturated with a liquid fuel and based upon the velocity the evaporation flux increases.

For example, for 0.5 m/s the evaporation flux is 0.017 kg/m^2-s. When it is increased to 2.5, the evaporation flux increases to 0.027 kg/m^2-s. So, we were able to find the equivalence ratio for this.

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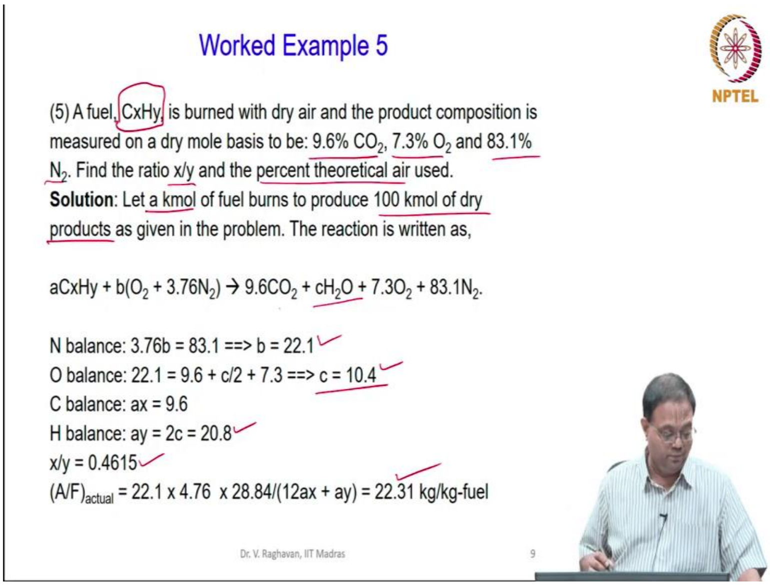

Then, the fifth problem. Now, we do not know the fuel basically. So, the fuel is taken as C_x and H_y. A fuel C_xH_y is burnt with dry air and the product composition is measured on a dry mole basis, ok. So, dry mole basis. Again, we can see that any Orsat apparatus any volumetric analyzer will not take liquid water into it or water vapor into it.

So, water is first filtered out say condensed and liquid water is filtered out and only the the gases are fed into this. So, without water vapor you get 9.6% of CO_2, 7.3% O_2 and rest nitrogen, ok.

Now, we have to determine x / y ratio and the percentage theoretical air used. This is the equation here. We do not know about fuel now.

In the previous case, we got the exhaust gas analyzer where we know the fuel $C_{10}H_{22}$, and we need to find what is the amount of percentage theoretical air. Now, in this case we have to find that, but x / y also we have to find to know what type of hydrocarbon it is.

Now, similar to the previous problem let now ‘a’ kilo mole of fuel burns let us assume that ‘a’ kilo mole of fuel burns to produce 100 kilo moles of dry products, ok.

$$aCxHy + b(O_2 + 3.76N_2) \rightarrow 9.6CO_2 + cH_2O + 7.3O_2 + 83.1N_2.$$

So, $aC_xH_y + b(O_2 + 3.76\ N_2)$ gives 9.6 kilo moles of CO_2 + H_2O (water vapor) I do not know, so ‘c’ times. So, one more unknown I have, plus $7.3O_2 + 83.1\ N_2$.

Now, N balance 3.76 into ‘b’ will give 83.1. So, ‘b’ can be got, ok.

$$\text{N balance: } 3.76b = 83.1 \implies b = 22.1$$

Now, O balance, because ‘b’ is known now, so 22.1 O_2 in left hand side gives 9.6 O_2 in the CO_2 + c /2 O_2 is there in $H_2O + 7.3O_2$, so add them. So, you get the value of c.

$$\text{O balance: } 22.1 = 9.6 + c/2 + 7.3 \implies c = 10.4$$

Now, C balance ax will give you 9.6, but there are two unknowns here. So, we cannot solve anything here. Similarly, H balance ay will give 2c.

$$\text{C balance: } ax = 9.6$$

$$\text{H balance: } ay = 2c = 20.8$$

Now, ‘c’ is known, so we can find that ay value you can find, but not ax. So, there are 3 unknowns now, a, x and y.

But we need to only find the ratio first. So, x / y is nothing, but 0.4615. So, number of C atoms divided by number of H atoms is 0.4615. So, some knowledge of fuel we can get from this particular ratio.

$$(A/F)_{actual} = 22.1 \times 4.76 \times 28.84/(12ax + ay) = 22.31 \text{ kg/kg-fuel}$$

Actual air fuel ratio 22.1. So, 22.1 into number of kilo moles of air is 4.76 into molecular weight of air 28.84 divided by 12(ax + ay).

Why 12 ax? 12 is the C's molecular weight into ax. plus ay H atoms into 1, its molecular weight. So, ax and ay values you know, substitute it and get the value of this. You are supplying 22.31 kg of air per kilogram of fuel.

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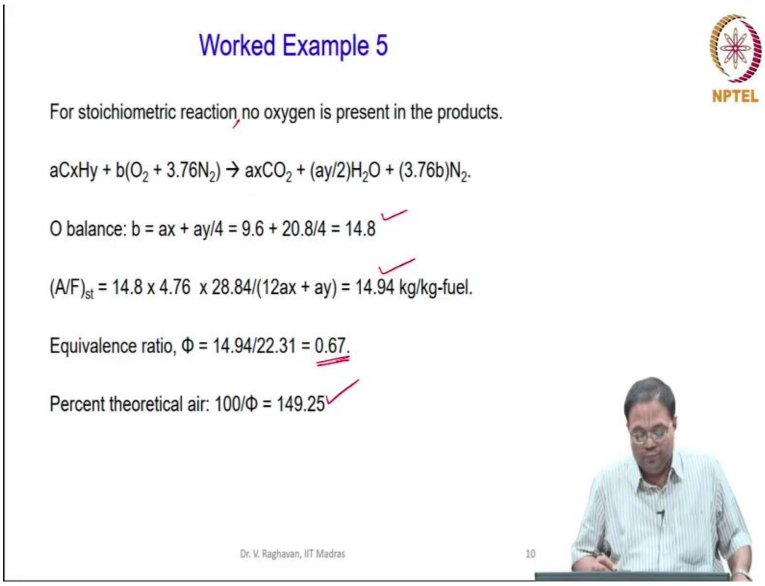

Now, this is the actual reaction where you have excess oxygen in the product. For stoichiometric reaction, no oxygen is present in the products. Again, we can put the same equation.

$$aCxHy + b(O_2 + 3.76N_2) \rightarrow axCO_2 + (ay/2)H_2O + (3.76b)N_2.$$

Please understand I am not trying to write in terms of 1 kilo mole of fuel here, just keeping 'a' kilo moles of fuel, but knocking of the oxygen in the products. So, I write a C_xH_y + b(O_2 + 3.76 N_2) gives ax CO_2 + (ay / 2) H_2O + 3.76b N_2.

Now, oxygen you know that x + y / 4. So, ax + ay / 4 will give you the this. So, you know ax and ay values, that does not change. So, you will get 14.8. From the previous calculation you know what is the value of ax, it is 9.6, value of ay is 20.8. So, ax + ay / 4 will be 14.8.

Now, stoichiometric air fuel ratio is calculated as 14.8 × 4.76 × 28.84 / 12(ax + by) which is 14.94. The equivalence ratio is stoichiometric air fuel ratio divided by actual air fuel ratio this is 0.67. So, it is a lean mixture.

See percentage theoretical air is 100 / Φ that is 149.25. So, this is the problem where you do not know about a fuel, but try to get some information about the fuel just based upon the dry product composition.

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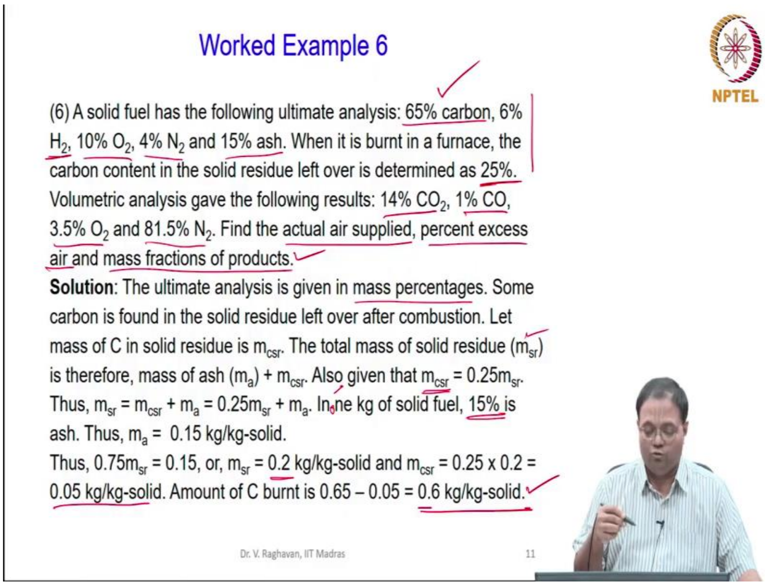

Now, worked example 6. We have dealt with the liquid fuel gaseous fuel etcetera. Now, we will go to a solid fuel, ok. Understanding a solid fuel let us say coal or something which has the following ultimate analysis. Ultimate analysis normally gives the elements which is present in the coal.

It has 65% of carbon. Normally ultimate analysis is given in mass basis. So, 65% of carbon by mass. Then 6% of hydrogen see hydrogen molecule itself is given here in this problem, and 10% of O_2 is given, 4% of N_2 is given, and 15% of ash is given.

This is the actual ultimate analysis what we have got for the solid fuel under consideration.

Now, this is burnt in a furnace. When it is burnt in a furnace the carbon content in the solid residue left over is determined as 25%. When solid fuels with the ash etcetera is burnt some solid residue have to be left out.

But the solid residue should not have any carbon. But unfortunately, in this particular problem it is reported that the solid residue has 25% of carbon in it.

So, solid residue actually speaking only 15% of ash will be a solid residue, out of this 15 percent plus some more carbon is there, so total solid residue has 25% of carbon. That is what the meaning. It is very important to note this.

Now, when this is burnt, we have found two things, one is the solid residue. So, when you take the solid residue and try to see how much carbon in it, they have found that it is 25% of carbon is present in this. Now, how will you do that? Normally you take this solid residue and keep it in the furnace at high temperature for some hours.

Now, say x kilogram or x gram you keep it in the furnace, kept it at a temperature of about 1000 degrees then after a few hours you will see all the carbon converts and nothing will be there. Now, the mass would have reduced to y kilograms or y grams. So, x - y will be the amount of carbon which is present which has burnt away in the furnace.

So, they determine the solid residue left over in that manner and they found 25% of the solid residue is carbon. Volumetric analysis of the gases which has come through the combustion has 14% CO_2, 1% CO, 3.5% O_2, and 81.5% N_2 it is on a dry basis again. Please understand whenever you do exhaust gas analysis, we have to do it on a dry basis and this is what is given here, no H_2O will be present.

Now, what we have to find is the actual air supplied percent excess air and mass fractions of the products. So, this is a problem where solid fluid is involved. Now, first of all we have to determine how much of this carbon has burnt, 25% of the solid residue is carbon, but what is the mass of the solid residue?

When you find the mass of the solid residue produced, then 25 of that is the carbon. So, that carbon which is present will not burn, we have to first exclude that.

Let that mass of carbon in solid residue is called m_{csr}. Total mass of solid residue is m_{sr}.

Now, if all the carbon is burnt the mass of solid residue will be equal to mass of the ash. So, that is surely going to be left as residue only. Here, that ash plus some mass of the carbon is present in the solid residue. We do not know that and we have to estimate it. The total mass of solid residue is m_{sr} mass of the ash plus mass of the carbon in the solid residue will contribute to m_{sr}.

Now, it is given in the problem that m_{csr}, the carbon in the solid residue is 25% of the total mass of the solid residue. Total mass of solid residue is m_{sr} and $0.25 \times m_{sr}$ will be the mass of the carbon in the solid residue.

Now mass balance $m_{sr} = m_{csr} + m_a$, m_{csr} is again written in terms m_{sr}. $m_{csr} = 0.25 \times m_{sr} + m_a$. Now, in 1 kg of solid fuel 15% is ash. So, m_a is 0.15 kg/kg-solid. So, we are going to do everything on per kilogram basis.

So, 0.75 m_{sr} = 0.15 or m_{sr} = 0.2, 0.2 kg/kg-solid. Total solid residue left over is 0.2 kg when 1 kg of solid is burnt. Ash in that is 0.15. So, what is the carbon which is present? It is 0.05.

So, 0.05 kg/kg-solid + 0.15 ash that contributes the total mass of 0.2 of the solid residues which is left over. The amount of carbon burnt is excluding this value. So, 0.65 is the mass fraction of the carbon present minus 0.05. So, 0.6 kg/kg-solid that will be the amount of carbon which is burnt.

Now 60% of carbon burns, 6% of hydrogen burns to produce these things. So, whatever be there, 10% of oxygen is already present in the fuel, apart from that we have to supply for stoichiometric calculations. Anyway, we have got the product so that means, that we have to see the excess air here.

Actual air what is supplied you have to calculate based upon this. So, it is very critical to calculate, since it is given that some amount of carbon is left over it is critical for us to calculate this 0.6. So, 0.05 of the carbon has not been burnt. So,0.65 - 0.05 = 0.6 kg/kg-solid that is the carbon which has burn.

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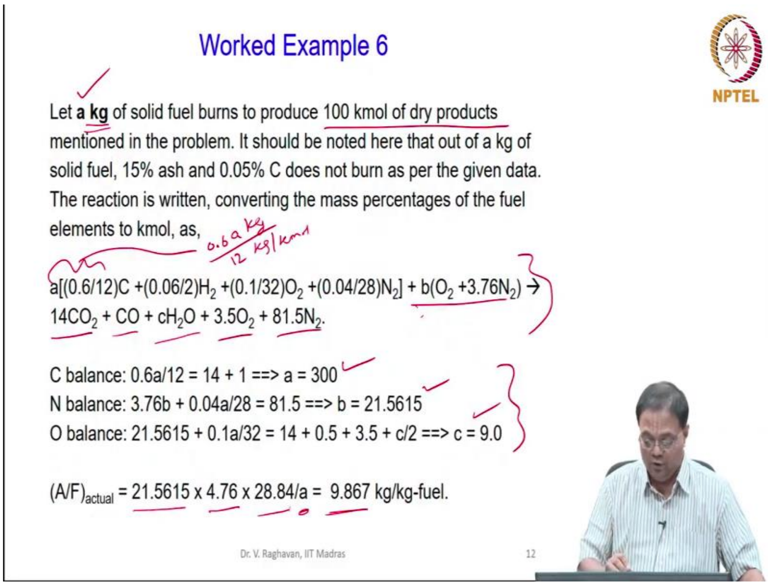

Now, how will you arrive at the equation? Similar to what we have done previously, we have to take some x kg of fuel. So, to produce 100 kilo moles of dry products let us burn a kilogram of 'a' kilogram of solid fuel. So, 'a' kilogram of solid fuel is burnt completely, now carbon in each kg of fuel that is burnt is 0.6 kg.

$$a[(0.6/12)C + (0.06/2)H_2 + (0.1/32)O_2 + (0.04/28)N_2] + b(O_2 + 3.76N_2) \rightarrow$$
$$14CO_2 + CO + cH_2O + 3.5O_2 + 81.5N_2.$$

So, now we write this. Please understand, 'a' is in kilogram here. Now, how will I convert into mole. So, when I say a kilogram of solid burns a × 0.6 kilograms of C burns, and a × 0.06 kilograms of hydrogen burns here. Hydrogen is 6%. So, 0.06 × a, that much kg of hydrogen burns.

Then, oxygen etcetera we will just say this is present. Do not burn, but it is 0.1 × a kg of oxygen participates and 0.04 × a kg of nitrogen participates in the reaction. But this equation is written in molar basis.

So, we have to convert the corresponding masses into kilo mole. So, divide by the molecular weight. When I say 0.6 × a kg of carbon burns, how many kilo moles would have burn? 0.6 × a / 12 kilo moles of carbon would have burnt.

So, this is 0.6a (kg) / 12 (kg / kilo mole). That much moles of C has burnt. Dividing by the corresponding molecular weight, I am converting the mass into moles because this equation is written in molar basis.

So, how many moles of C has burnt? 0.6 × a kg divided by its molecular weight that much moles of C has participated in the reaction. Similarly, 0.06 × a / 2 hydrogen. Similarly, 0.1 × a kg of oxygen divided by 32 kilo moles of oxygen has taken place in reaction. So, this is the fuel mixture.

What is given in the square bracket is the fuel mixture. This is the oxygen mixture. So, b × 4.76 kilo moles of air produces, 14 kilo moles of CO_2, 1 kilo mole of CO. This is dry products I do not know the H_2O, so put 'c' kilo moles of H_2O, 3.5 O_2 these are all given, these are measured quantities. So, only unknown is 'c' in the product side.

$$\text{C balance: } 0.6a/12 = 14 + 1 \implies a = 300$$

Now, I have to determine a, b and c that is all. So, first you do the C balance to get the value of 'a' as 300. So, 300 kg of coal is burnt in which 0.6 × 300 kg of carbon has burnt.

$$\text{N balance: } 3.76b + 0.04a/28 = 81.5 \implies b = 21.5615$$

$$\text{O balance: } 21.5615 + 0.1a/32 = 14 + 0.5 + 3.5 + c/2 \implies c = 9.0$$

So, nitrogen balance will give you the value of 'b' and O balance will give you the value of 'c', that is all. So, once you get the a, b, c values you can now find the air fuel ratio.

$$(A/F)_{actual} = 21.5615 \text{ x } 4.76 \text{ x } 28.84/a = 9.867 \text{ kg/kg-fuel.}$$

So, 'b' is 21.5615; What is the total amount of oxygen supplied? Here, that is what you have to take into account.

So now, 21.5615 kmol is the oxygen supplied. So, for this you have to calculate the actual air fuel ratio. So, 21.5615 × 4.76 × 28.84 / 'a'. Now, mass of the fuel is known, 'a' kg. So, just divided this by 'a'.

That is what we assume to proceed here. So, 9.86 kg / kg-fuel is the air fuel ratio.

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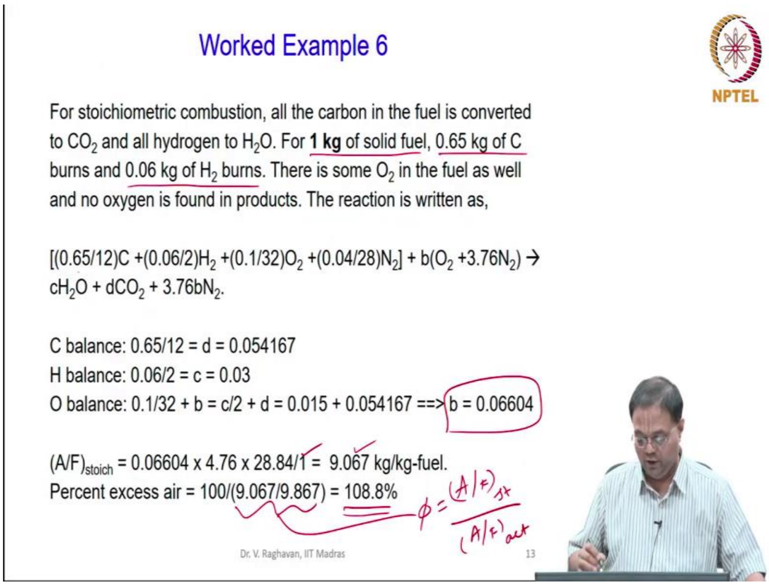

Now, what is asked here is the actual air supplied and percentage excess air; that means, you have to calculate what is the stoichiometric air. For stoichiometric combustion all the carbon in the fuel is converted into CO_2 all hydrogen into H_2O.

Now, please understand when I say stoichiometry, everything is burnt; that means, as compared to the previous problem where some carbon was left in the ash, now in this stoichiometric calculation I assume that also burns; that means, when 1 kg of solid fuel is burnt,0.65 kg of C burns.

I do not leave over anything as a solid residue. Everything burns. Similarly, 0.06 kg of hydrogen burns; this is burnt in the previous case also.

So, now, there is some O_2 in the fuel as well as, so no oxygen found in the products. So, this O_2 also should be consumed along with the additional required oxygen we supply. The required oxygen is supplied based upon the value of the oxygen available in the fuel. Now please see that the reaction is written as,

$$[(0.65/12)C + (0.06/2)H_2 + (0.1/32)O_2 + (0.04/28)N_2] + b(O_2 + 3.76N_2) \rightarrow cH_2O + dCO_2 + 3.76bN_2.$$

0.65 / 12, kg of fuel.

So, ‘a’ is 1, so I put 1 here, 0.65 / 12 C, 0.06 / 2 H_2, 0.1 / 32 O_2, 0.04 / 28 N_2 plus ‘b’ into air give ‘c’ H_2O and ‘d’ CO_2 and 3.76b N_2. So, balance this you get values of ‘b’.

So, now, you find the stoichiometric air fuel ratio. So, 1 kg we have considered. Mass of fuel is one here and the mass of air is this stoichiometric coefficient 0 0.06604 × 4.76

kilo moles of air into molecular weight of air is 28.84. So, it is 9.067. Previously we got 9.867 as the actual air fuel ratio.

So, equivalence ratio, this is Φ. Phi (Φ) is stoichiometric air fuel ratio divided by actual. That is stoichiometric air fuel ratio, 9.067, divided by actual air fuel ratio 9.867. So, excess air will be (100 / Φ) = 108.8.

So, you can see that in a solid fuel its heterogeneous fuel, basically you can see that the ultimate analysis here in the problem gives the compound which is present in this.

Based upon that we have to calculate how it burns. Since the dry products analysis is done and the composition is known, we can find the excess air.

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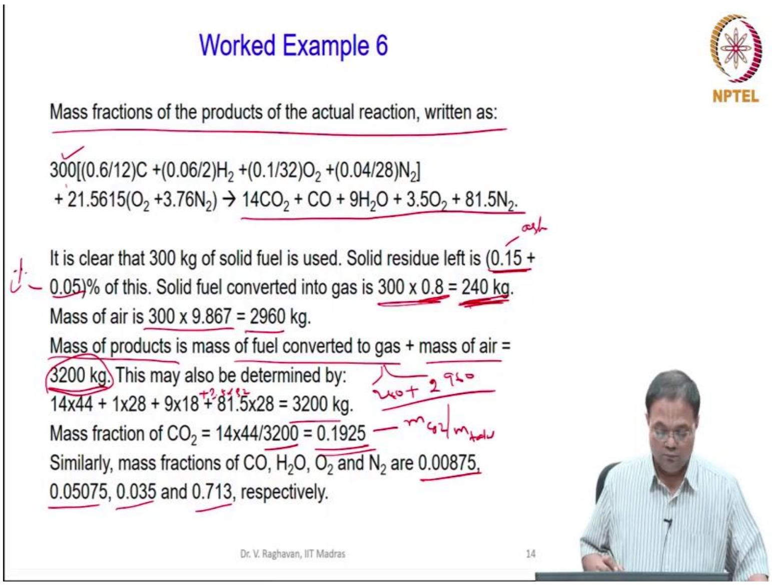

Now, rest is what are the mass fractions of the products in the actual reaction. We have found the actual air supplied. To calculate the percentage excess air, we went back to calculate stoichiometric air and found the percentage excess air. Then what is asked finally is what is the mass fraction of products.

Now, mass fraction of products can be determined as this. So, we have only dry basis hence we have to include H_2O also in that. So, this is the actual composition of products. 300 kgs of fuel is burnt and these are the product which are formed.

Now, please understand that here H_2O is calculated by this. Number of moles of H_2O in the products is 9. It is clear that 300 kg of solid fuel is used. Now, solid residue left is 0.15. So, in the 300 kgs we will contain 15% ash and 5% unburnt carbon. So, 0.15, this is ash percentage and 0.05 is the carbon percentage which is not burnt at all. This is left in the solid residue. Now, solid fuel converted into gas is how much? 20% of the mass, 0.15

+ 0.05, that is 0.2 is not burnt. Rest 80% of the mass is burnt. So, 300 × (80 / 100) = 240 kg burns.

Why I am finding this? Because solid will not be in the gaseous products. When gas goes out, I want to find the total amount of mass in the products. I know what is the mass of the coal supplied that is 300 kgs. But all are not converted into products only 80% of that is converted into products correct.

So, 300 × 80% that is 240 kg of the fuel is converted into products 20% is left as solid residue. So, mass of the fuel burnt is 240 kgs. Mass of the air supplied is 300 into the actual air fuel ratio that is 9.867, which is 2960 kgs. So, when you supply x kg of fuel and y kg of oxidizer products are x + y kgs. Just add it.

So, mass of the products formed is mass of the fuel converted into gas plus mass of the air. Solid residue remains as solid residue. So, 240 + 2960 that is 3200 kgs. So, 3200 kgs of products are formed. I want to find the total mass of the products which is formed that is all.

Now, we can determine the products by this, 14 kilo mole of CO_2 is there. So, 14 × 44 + 1 × 28 + 9 × 18 + 3.5 × 32 + 81.5 × 28, that will also give this. I am just trying to give you a physical understanding of what is happening.

So, out of 300 kgs, 80% burns to form product gases, 20% is left over as residue, so 240 kg of fuel contributes to the gaseous products. Mass of air supplied is only gaseous. So, 2960 kgs of air is supplied, when you add this 3200 kg of product should be formed. That is what is formed.

Now, mass fraction of CO_2 is 14 kilo moles into 44 kg per kilo mole that is the mass of the carbon dioxide divided by; what is total mass of products? 3200. So, this is nothing, but mass of CO_2 divided by total mass, that is 0.129. Similarly, we can determine the mass fractions of CO, H_2O, O_2 and N_2 as 0.00875, 0.05075, 0.035 and 0.713.

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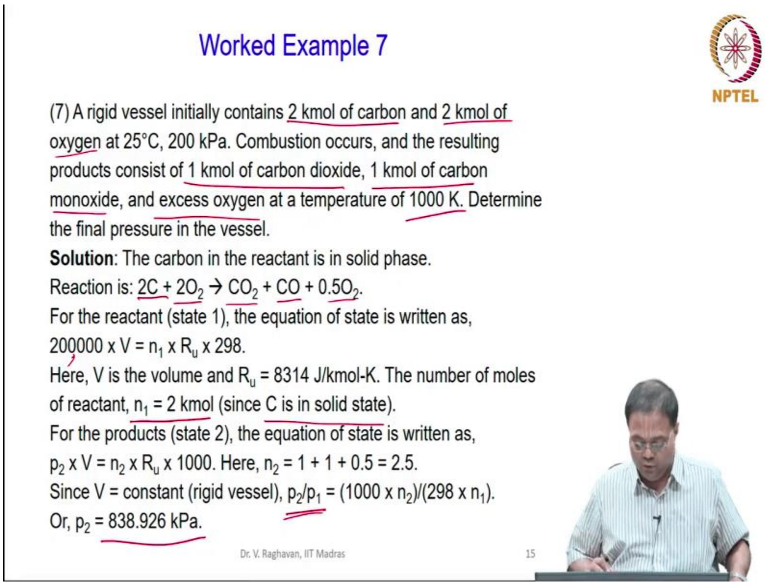

So, this is the last example. Here you can see that a rigid vessel initially contains 2 kilo moles of carbon. Carbon is in solid phase and 2 kilo moles of oxygen at standard temperature of 25^{o}C and, but pressure is 200 kilo Pascals, combustion occurs.

And the resultant products consists of 1 kilo mole of carbon dioxide, 1 kilo mole of carbon monoxide and excess oxygen, whatever be the excess oxygen. But the temperature is now maintained as 1000 Kelvin. So, what is the final pressure? Let us write reaction first.

$$2C + 2O_2 \rightarrow CO_2 + CO + 0.5O_2$$

Carbon is the reactant in the solid phase. So, $2C + 2O_2$, 2 kilo moles each gives CO_2 + CO + 1/2 O_2 by balance. Now, for state 1, we can apply the equation of state. For the state 1 equation of state is written as,

$$200000 \text{ x } V = n_1 \text{ x } R_u \text{ x } 298$$

So, 200000 Pascals × V that vessel has a volume of V gives n_1 number of moles of the reactants × R_u. × 298 Kelvin. So, that is the equation of state for the reactants.

So, V is the volume and R_u is 8314 J/kmol-K, the value is known. So, number of reactant moles is nothing, but the number of gaseous moles in the reactants. C is in solid state, so we should not count that. So, the reactant basically 2 kilo mole of carbon graphite powder or graphite bed is present and 2 kilo moles of oxygen is supplied.

It is like bomb calorimeter; some small amount of carbon is put and oxygen is supplied. When it combusts then you know what is the current value of the carbon.

So, now, 2 kilo mole of oxygen is in gaseous phase, so n_1 is 2. Please understand for solid how can you put that n_1 in the equation of state equation. Equation of state is valid only for the gases. So, n_1 cannot be cannot include the number of moles of solids. So, here we can see that the n_1 will be only that of the oxygen that is 2 kilo moles.

Now, for products equation of state is written as,

$$p_2 \times V = n_2 \times R_u \times 1000$$

I do not know the final pressure p_2. V is same because rigid volume, volume is constant. Then, n_2 is the number of moles which is nothing, but 1 + 1 + 0.5 = 2.5.

Then final temperature 1000 is given. Now, you divide this p_2 / p_1, if you substitute you will get pressure as 838, so it is a good increase in pressure. More than 4 times increase in pressure is got.

So, here we have to understand that when you have a solid reactant in the vessel, in the equation of state you should not apply the number of moles of solid reactants. Anyway, for balancing purpose etcetera that will come into account.