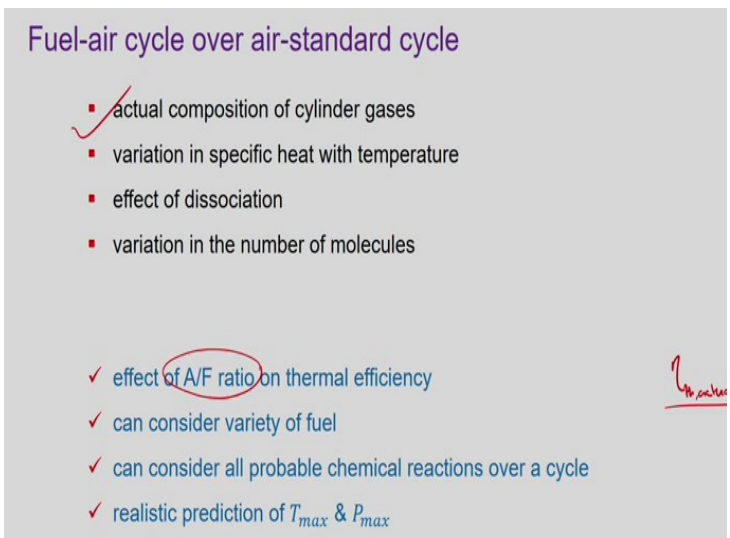
**Applied Thermodynamics for Engineers**
**Dipankar N. Basu**
**Department of Mechanical Engineering**
**Indian Institute of Technology – Guwahati**

**Lecture – 15**
**Numerical Exercise on Fuel-Air Cycles**

Hello friends welcome back to the second lecture of our week number 5 where we are talking about the real cycles for reciprocating engines. In the previous week we have talked about the ideal cycle i.e., the air standard cycles or gas power cycles. Primarily the Otto cycle which is the ideal cycle for 4-stroke SI engines or SI engines in general. And the diesel cycle which is ideal cycle for CI engines that we have discussed along with a few others also.

And now this week we are talking about the way we can add different practical factors into the analysis of those cycles. And in connection with that in the previous lecture we have talked about the fuel-air cycle.

**(Refer Slide Time: 01:12)**




Fuel-air cycle is you can say is an improvement over the air standard cycles where out of several possible limitations or assumptions incorporated into the air standard cycle. Some of them are lifted primarily the fuel air cycle adds these four factors into the air standard cycle and accordingly tries to modify the cycle diagrams. And therefore, attempts to provide a more realistic prediction about the system performance.

So, these four factors are at the actual composition of the cylinder gases thereby allowing the possibility of taking care of different kinds of fuels and reactions. Then the variation in specific heat with temperature, specific heat can vary strongly with temperature. It generally follows a linear relationship to a temperature of about 1000 or 1500 K and a quadratic relation afterwards. The effect of dissociation at very high temperature, dissociation is an endothermic reaction.

So, the presence of dissociation can affect the final temperature of the system and also the total work production and finally we have also talked about the variation in the number of molecules. So, these are the four factors which we add over the air standard cycle to get the fuel air cycle. And individual effect of each of these factors we have discussed in the previous lecture. So, now we know that the fuel-air cycle allows us to consider several factors over the air standard cycle.

Like in case of air standard cycle we generally can understand the effect of only a single performance parameter of the system which is the compression ratio. But the air-fuel ratio or fuel-air ratio is another extremely important parameter for any real engine analysis. And in air standard cycle we considered the working medium to be only air thereby eliminating any kind of chemical reactions.

So, there is no way we can consider something like an air fuel ratio. But fuel-air cycle allows us to consider the actual composition of cylinder gases and thereby we can analyze the effect of the air fuel ratio or the equivalence ratio on the thermal efficiency of the engine and also the other performance parameters. We can also consider a variety of fuel again the same factor as we are considering the actual composition of cylinder gaseous.

So, various kinds of fuels can definitely be considered whereas there is no concept of fuel at all in the air standard cycle. Then we can also consider all possible kinds of chemical reactions both exothermic and endothermic reactions like in case of dissociation. And thereby even if we are talking about a blend of ways that can be considered all possible kind of reactions, the pre-combustion chemical reactions post combustion chemical reactions, the dissociation reactions, all can be incorporated during the cycle analysis. Then we can get a much more realistic prediction of the maximum pressure and temperature of the cycle and also the cycle efficiency and work output. These parameters are very important because our design of the engine the structural design depends on the maximum level of pressure and temperature that we have to withstand of the cylinder has to withstand.

And therefore, it is very important to get a more realistic estimate about their values. Similarly, we can get a more realistic prediction about the output power and efficiency, like we have mentioned in the previous lecture, that the failure efficiency can be quite close to the actual cycle efficiency. In fact, it is a common observation that the actual thermal efficiency for a real reciprocating engine can be about 80 to 90 % of the thermal efficiency predicted following the fuel-air cycle.

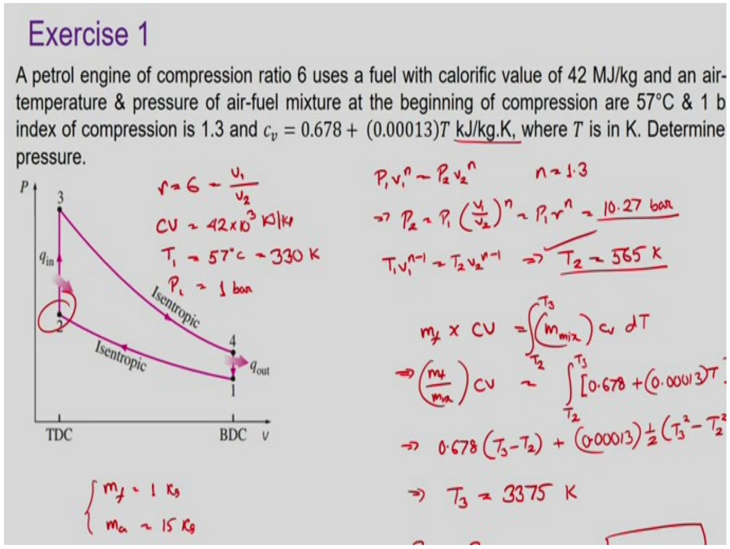
But the thermal efficiency related by the fuel-air circle can be significantly lower than what can be predicted following an air standard cycle. And therefore, it is extremely important to understand the fuel air cycle and corresponding performance parameter. The thermal efficiency created by the fuel-air cycle maximum output power that we can get, maximum pressure and temperatures etc.

Because in case of an actual cycle the parameters can be quite close to the one predicted by the fuel-air cycle. So, today we are not going to discuss about any new concept rather, in this lecture we are going to solve a few numerical examples just to see how we can incorporate the fuel-air consideration into the analysis of practical engines. So, I repeat today we are not going to talk about any new concepts the in the next lecture which is the third one for this particular week we shall be talking about the valve timing diagram and different actual losses present in the real engine which are also not considered in the fuel air cycle, which actually leads to this 0.1 to 0.2 or 10 to 20 % loss of efficiency in the actual case compared to the fuel-air cycle. That we shall be discussing in the next lecture. Let us concentrate on a few numerical problems.

And here I would also like to mention that till the previous week I have primarily followed the standard books of thermodynamics like the book of Cengal and Boles or the book of Van Wylen and Sonntag. But in this particular week I am following books on IC engines primarily the book of IC engines by Dr. V Ganesan of IIT Madras. Also, there is a very popular book on IC engine written by Sharma and Mathur, I am primarily following these two books.

And in fact, the problems that I am going to solve here those are also generally example problems taken from those books only.

**(Refer Slide Time: 06:46)**




So, the first one that I am talking about a petrol engine with a compression ratio of 6 it is using a fuel as the calorific value of 42 MJ/kg. Now this term calorific value that never came into picture in air standard cycle, but in a real fuel analysis we have to consider the heating value or calorific value of the fuel. And we have an air fuel ratio of 15, this 15 or 15:1 both formats can be considered general or quite often we generally neglect that second part and write it as 15. But it actually refers to 15:1.

The temperature and also this air fuel ratio always talks about mass, never volume. So, it is for every 1 kg of fuel we have to consider 15 kg of air and air means a mixture of oxygen and nitrogen. The temperature and pressure of an air fuel mixture at the beginning of compression are given as 57 $^0$C and 1 bar respectively. And the index of compression is 1.3.

Now in air standard cycle we consider all the processes to be reversible in nature and the compression and expansion processes are considered to be reversible adiabatic, therefore isentropic. And therefore, the index of compression and expansion was always the ratio of specific heats primarily 1.4 for diatomic gases. But here we are talking about an index of 1.3 which can be quite close to what we get in practice.

And $c_v$ is given as a function of temperature where $T$ is in Kelvin. So, you have to determine the maximum cycle pressure. So, let us see what we can use here. This is the standard cycle diagram the air standard cycle diagram. So, using this diagram let us summarize the given information. We have a compression ratio of 6 which is talking about the ratio of these two volumes $v_1$ and $v_2$ this definition remains same this is geometric parameter so it does not depend on which kind of cycle we are following.

$$r = 6 = \frac{v_1}{v_2}$$

Then we have got a calorific value, CV = $42 \times 10^6$ J/kg

and we have an air fuel ratio 15. Temperature and pressure of air fuel mix at the beginning of compression. So, we have $T_1$ that is at the beginning of compression to be equal to 57 $^0$C. So, it is mandatory to convert it to Kelvin. So, therefore we can easily convert this to Kelvin to be equal to 330 K.

$T_1 = 57\ ^0\text{C} = 330$ K

And similarly, pressure is given as 1 bar, pressure you can convert to Pascal or mega Pascal or kilo Pascal.

$P_1 = 1$ bar

So, you can keep in bar because it does not matter that much. But temperature has to be in Kelvin scale. And also, the index of compression is given, so the compression process actually follows a relation:

$$P_1 v_1^n = P_2 v_2^n$$

with this $n = 1.3$

So, from there we can say that your

$$P_2 = P_1 \left(\frac{v_1}{v_2}\right)^n = P_1 r^n$$

and we know all the values so putting the numbers we are getting

$$P_2 = 10.27\ bar$$

I have already pre-calculated the numbers so I am just putting the numbers directly. And correspondingly the temperature $T_2$, here it is given that specific it is a function of temperature and that we have to consider during the combustion process, in order to understand the maximum cycle pressure. So, $T_2$ again we can directly consider using the index of compression because we know for any polytropic process

$$T_1 v_1^{n-1} = T_2 v_2^{n-1}$$

putting this we generally get

$$T_2 = 565 \text{ K}$$

in this particular case.

So, we have the state at the end of compression it is given to us. Now we have to analyze the combustion process. So, let us consider the air fuel ratio. Air fuel ratio is given as 15, so if we consider the:

$$\text{mass of fuel, } m_f = 1 \text{ kg}$$

then corresponding

$$\text{mass of air, } m_a = 15 \text{ kg}$$

And therefore

$$\text{mass of mixture, } m_{mix} = 16 \text{ kg}$$

So, for every kg of fuel we have to believe the 16 kg of mixture which needs to be heated up during the combustion process. So, if we talk about this combustion process, if we write an energy balance then total amount of energy released during combustion will be how much? That will be equal to mass of fuel into the calorific value of the fuel near the total amount of energy released. And which is the medium that is receiving this energy that is not fuel rather that is fuel and air together. So, fuel air together this mixture that is the one that is receiving this energy so instead of writing fuel plus air, here we can also write this as mass of the mixture multiplied by the specific heat multiplied by the change in temperature which is, let us say the change in temperature d$T$ in the combustion process and this will be integrated over temperature point temperature at point 2 to temperature at point 3.

$$m_f CV = \int_{T_2}^{T_3} (m_{mix}) c_v \, dT$$

So, we can say:

$$\left(\frac{m_f}{m_{mix}}\right) CV = \int_{T_2}^{T_3} [0.678 + (0.00013)T] \, dT$$

And so if we perform this integration then what we are going to get is

$$0.678(T_3 - T_2) + (0.00013)\left(\frac{1}{2}\right)\left(T_3^2 - T_2^2\right) = \left(\frac{1}{2}\right) \times 42 \times 10^3$$

Here one thing we have to be careful the unit of $c_v$ is given as kJ/kg. So, the calorific value it is better to convert it to kilo Joule. So, if you put this you are getting

$T_3 = 3375$ K

Another approach of solving the same problem is instead integrating it assume an average $C_p$ which can be the corresponding temperature at $(T_2 + T_3)/2$ and then take it out of the integration but probably this is a much better approach.

You are doing because this is simple function here $C_p$ is a very simple function of temperature; we can integrate this one very easily. So, now we have temperature at point 3, and therefore how we can get the maximum pressure? Because you know 2-3 is a constant volume process, even in case of fuel air cycle also. So, therefore

$$\frac{P_3}{T_3} = \frac{P_2}{T_2}$$

$P_2$ and $T_2$ I have calculated earlier and this we have just obtained from there,

$$P_3 = 61.35 \text{ bar}$$

which is the final answer that we are looking for 61.35 bar is the maximum pressure for this cycle.

Where in fact we have considered only the fuel-air ratio and the variation of specific heat with temperature. These two factors are considered accordingly, we are getting this particular expression for this maximum pressure this particular magnitude. If we solve the same problem assuming a constant value of $C_v$, let us say we take

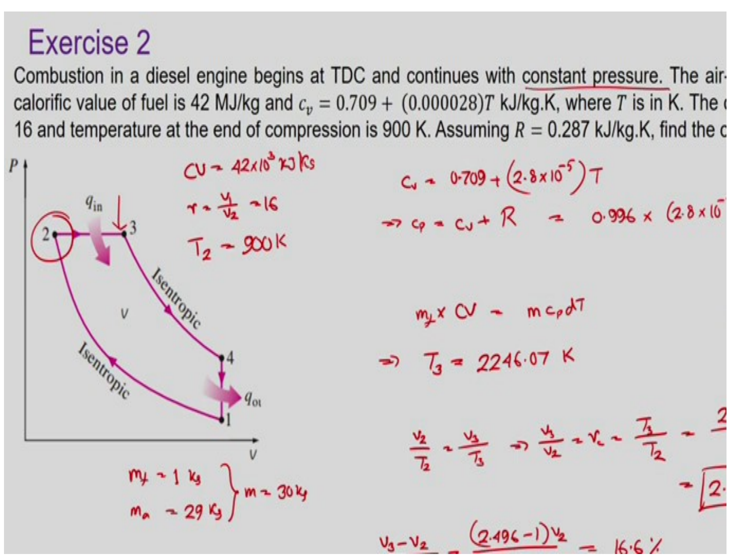
$C_v = 0.717$ kJ/kgK

which is the $C_v$ for air under normal atmospheric condition. Then you would have got this

$P_3 = 76.81$ bar

you can see how the difference from ideal cycle would have predicted a maximum pressure of 76.8 bar which in case of fuel-air cycle is coming down to 61.35 bar, there is significant reduction in pressure which will affect the design quite significantly.

**(Refer Slide Time: 16:00)**



Let us move to the second problem, where we are dealing the diesel cycle. So, here the combustion is in the diesel cycle is beginning at top dead center which is a standard and it is continuing the constant pressure, air fuel ratio is 29. So, let us have a diesel cycle so this is a standard diesel cycle $Pv$ diagram. Here air fuel ratio is 29 calorific value of the fuel is 42 MJ/kg. So,

CV = $42 \times 10^3$ kJ/kg

CV again is a function of temperature slightly different function, but again a linear function of temperature. Compression ratio is given so

$$r = \frac{v_1}{v_2} = 16$$

Temperature at the end of compression is 900 Kelvin. Look it is end of compression on beginning of compression. So, we have which point we are talking about end of compression means point 2, so

$T_2 = 900$ K

the value of R is also given you have to find the cut-off ratio.

Now CV is given as:

$$C_v = 0.709 + (2.8 \times 10^{-5})T$$

then here we are talking about the diesel cycle where the combustion is taking place at constant pressure. So, $C_p$ is more important and $C_p$ we know will be equal to:

$$C_p = C_v + R$$

so it will be equal to:

$$= 0.996 + (2.8 \times 10^{-5})T\ kJ/kgK$$

Now next part of the problem is quite simple, again the air fuel ratio is given as 29. So, if we take

$$\text{mass of fuel, } m_f = 1 \text{ kg}$$

$$\text{mass of air, } m_{air} = 29 \text{ kg}$$

$$\text{total mass, } m = 30 \text{ kg}$$

So, during the combustion process we have the total amount of energy released per kg of fuel will be equal to the calorific value only we are talking about 1 kg of fuel that is equal to 1 into calorific value just look at what we have done in the previous problem.

Where also we have considered the mass of fuel into calorific value and mass of will was equal to 1 same here okay let me be consistent with that particular notation.

$$m_f \times CV = mc_p \, dT$$

So, if you put it your final temperature for after at the end of combustion processes,

$$T_3 = 2246.07 \text{ K}$$

But our objective is not to get the maximum temperature or the temperature the end of combustion, rather we have to get the cut-off ratio. And what is your definition of cut-off ratio? Our definition of cut-off ratio $r_c$ is

$$r_c = \frac{v_3}{v_2}$$

So, we have to get somehow a relation between this $v_3$ and $v_2$ look at the combustion process again it is at constant pressure.

$$\frac{v_2}{T_2} = \frac{v_3}{T_3}$$

that is

$$\frac{v_3}{v_2} = r_c = \frac{T_3}{T_2}$$

and

$$T_3 = 2246.07 \text{ K}$$

$$2_3 = 900 \text{ K}$$

So, your cut-off ratio is:

$$r_c = \frac{2246.07}{900}$$

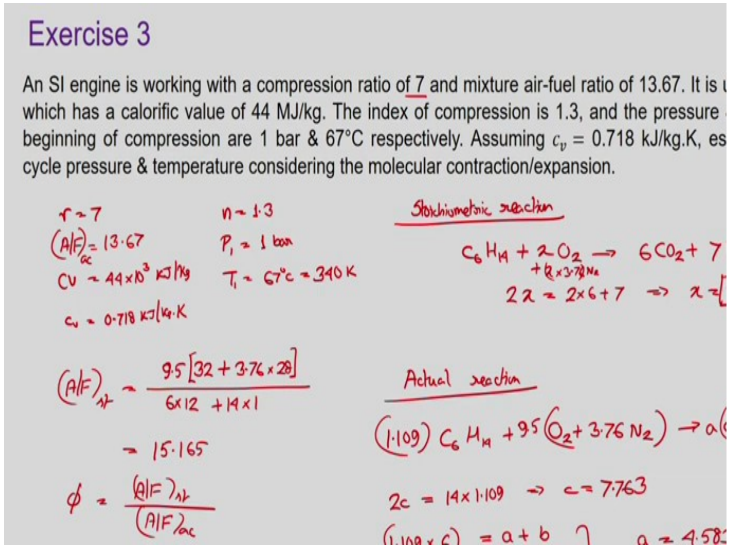
this is the cut-off ratio that we are looking for. If it is desired that instead of writing the cut-off ratio represent the same result that when combustion finishes as a percentage of the stroke, how we can do this?

We have solved one similar problem or we use similar terminology in the previous week. Here we are looking to get the change in volume as a percentage of the total stroke volume which is:

$$\frac{v_3 - v_2}{v_2 - v_1} = \frac{(2.496 - 1)v_2}{(16 - 1)v_2} = 16.6 \ \%$$

which is the same result represented in different way. Cut-off ratio is 2.496 and the cut-off takes place at 16.6% of the stroke which refers to a volume at this point of the change in volume during the combustion process. So, we have solved now two example problems, one for SI engine another for Diesel engine where we have considered the variation of specific heat with temperature and also you have considered the actual chemical composition or I should say we have considered the air fuel ratio and calorific value.

**(Refer Slide Time: 21:42)**




Let us now consider another problem where you have to deal with the chemical reaction itself. It is quite longish problem statements please go through it carefully. We are talking about a SI engine it is working the compression ratio of 7. So, let us let us list in the information compression we say,

$$r = 7$$

$$A/F = 13.67$$

it is using hexane as the fuel which has a calorific value of 44 mega Joule per kg. So,

$$CV = 44 \times 10^3 \text{ kJ/kg}$$

index of compression, n = 1.3

I have not put any diagram there I am using the general notation for any SI engine. So, n is 1.3 pressure and temperature the beginning of compression are given so

$$P_1 = 1 \text{ bar}$$

$$T_1 = 67\ ^0\text{C} = 340 \text{ K}$$

So, we have the state points given okay it is also given that

$$c_v = 0.718 \text{ kJ/kgK}$$

here our objective being to analyze the combustion process we are not considering specific heat variation we are keeping it as constant. So, that we can deal with each of the factors individually. Now it is given that the problem working fluid is hexane. So, we have to consider the true conversion of hexane and get the corresponding stoichiometric reaction.

So, let us first write the stoichiometric reaction. For a stoichiometric reaction, your working fluid is hexane. Hexane means $C_6 H_{14}$ because it generally follows a relation $C_n H_{2n+2}$ from there hexane is $C_6 H_{14}$. So, $C_6 H_{14}$ is the fuel plus some oxygen:

$$C_6 H_{14} + O_2 \rightarrow CO_2 + H_2O$$

How many moles of oxygen required? That we do not know that will lead to these two stoichiometric reactions, there will be perfect combustion nothing will be left out. So, it will form $CO_2$ and $H_2O$ and again no oxygen also will be remaining. We need to have just exactly the same quantity of oxygen or minimum quantity of oxygen required to have complete combustion. So, just now balance the number of molecules, so we shall be having a six on this side and we shall be having how many? 7 $H_2O$. So, what will be your x? Your x, so we can write:

$$2x = 2 \times 6 + 7$$

So

$$x = 9.5$$

So 9.5 moles of oxygen will be required to have a complete combustion for this. Therefore, stoichiometric air fuel ratio that we have to identify. Here the air fuel ratio that is given that is the actual air fuel ratio, and how much will be your stoichiometric air fuel ratio? Stoichiometric air fuel ratio will be the mass of air required to have complete combustion, a minimum amount of air required to have complete combustion divided by the mass of fuel. So, how much moles are required here? 9.5.

And what is the mass of 1 mole of oxygen it can be written as 32 and you have to remember for every mole of oxygen 3.76 mole of nitrogen also comes into picture. So, 3.76 multiplied by 28 because in this chemical reaction which we have not written actually we have here $x$ multiplied by 3.76 multiplied by left on this side, similarly that comes as $3.76x$ of multiplied by that comes out as it is. So, this nitrogen also has to be considered because we are not getting oxygen to fuel ratio rather or air to fuel ratio. So, we have air on the numerator in the denominator what we have hexane. So, we have 6 multiplied by 12 for carbon plus 14 multiplied by air 1 for hydrogen which gives us actual air fuel ratio to be equal to 15.165.
This can be mathematically calculated as:

$$\frac{9.5[32 + 3.76 \times 28]}{6 \times 12 + 14 \times 1} = 15.165$$

So, your equivalence ratio is stoichiometric air fuel ratio by actual air fuel ratio so that is:

$$\phi = \frac{(A/_F)_{st}}{(A/_F)_{ac}} = \frac{15.165}{13.67} = 1.109$$

which refers to a rich mixture that is, we do not have sufficient quantity of oxygen rather we are supplying only less amount of oxygen then exactly required.

So, now you can write the actual reaction. Actual reaction we have:

$C_6H_{14} + (O_2 + 3.76\ N_2) \rightarrow CO_2 + CO + H_2O$ + nitrogen will be left out for this.

Now we have to consider this actual equivalence ratio. So, if we keep this 9.5 here then how much of fuel you are supplying? you know if your objective was to have a stoichiometric reaction for every 9.4 moles of oxygen we have to supply 1 mole of fuel.

But here we are supplying additional amount of fuel, so we are going to put it here 1.109, because this is the additional amount of fuel that we are supplying into this. So, let us put as *a, b* and *c* for each of them these are all unknown and on this side.

$$(1.109)\ C_6H_{14} + 9.5\ (O_2 + 3.76\ N_2) \rightarrow a(CO_2) + b(CO) + c(H_2O) + (3.76 \times 9.5)\ N_2$$

So, we have to solve this to get the values of *a, b* and *c*. Let us take *c* first, so balancing the number of hydrogen molecules or hydrogen atoms we have:

$$2c = 14 \times 1.109$$

$$c = 7.763$$

Now we write for carbon, so we have:

$$(1.109 \times 6) = a + b$$

Similarly, if we balance the oxygen we have:

$$(9.5 \times 2) = 2a + b$$

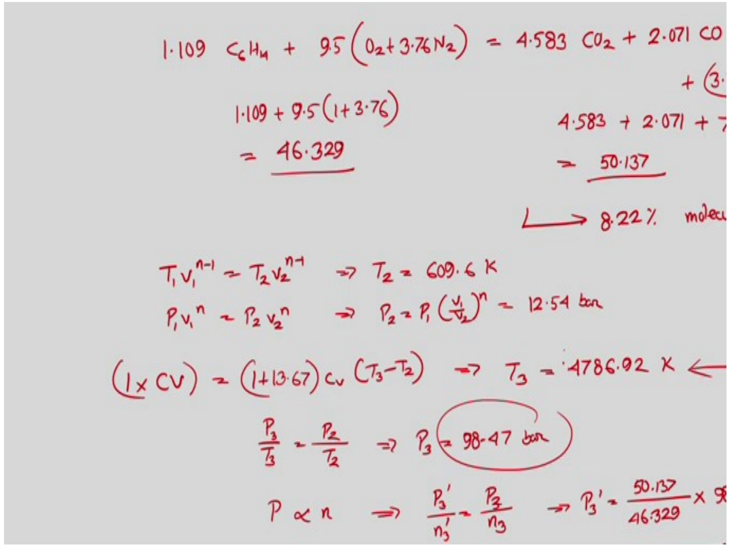
So, if it balances these two, we are going to have

$$a = 4.583$$

$$b = 2.071$$

So, we have got the values of this *a*, *b* and *c*.

**(Refer Slide Time: 29:39)**




Let me write the actual reaction once more. So, what we have now:

$$1.109C_6H_{14} + 9.5\ (O_2+3.67) = 4.583\ CO_2 + 2.071\ CO + 7.763\ H_2O + (3.71 \times 9.5)\ N_2$$

I am just going back to the problem statement what we are looking to find. You have to estimate the maximum cycle pressure and temperature considering the molecular contraction and expansion.

Molecular contraction or expansion talks about what? You have used this term in the previous lecture. There is a change in the number of moles during the chemical reaction and look at here, what we are having? On the left-hand side i.e., before the chemical reaction how many numbers of moles you have? If you add this, we have a total of:

$$1.109 + 9.5\ (1 + 3.76) = 46.329 \text{ number of moles before chemical reaction.}$$

And after chemical reaction we have:

$$4.583 + 2.071 + 7.763 + (3.776 \times 9.5) = 50.137$$

that means we are having an 8.22% molecular expansion i.e., number of moles has increased, so there is an expansion at the molecular level. And we know that pressure is proportional to the number of moles. As a number of moles has increased because of this chemical reaction, then the final pressure also should increase.

Now we have to calculate the final pressure neglecting the chemical this molecular reaction or expansion first and then we have to get this into account. So, to get in this into picture, let us quickly do it. We know that

$$T_1 v_1^{n-1} = T_2 v_2^{n-1}$$

which gives us $T_2$ because the even information you had in $P_1$ and $T_1$ given here. If you put it so

$T_1 = 609.6$ K

Similarly, if we get this and also the $R$ is given here, this is the $R$ so from there we have

$$P_1 v_1^n = P_2 v_2^n$$

which gives us the pressure at the beginning of combustion process to be equal to in fact I have $P_2$ we can calculate from here:

$$P_2 = P_1 \left(\frac{v_1}{v_2}\right)^n$$

I do not have the value of $P_2$ because that is not required for the next step of calculation but you can calculate as per your interest.

Now we have to consider the chemical reaction we know the air fuel ratio to be equal to actual air fuel ratio and calorific value both are given. So, if you consider for every 1 kg of fuel multiplied by the calorific value, we have to deal with 1 plus the air fuel ratio is 13. 67 so 1 + 13.67 this much mass of mixture multiplied by $c_v$ multiplied by $T_3 - T_2$, $c_v$ is also given.

$$1 \times CV = (1 + 13.67)\, Cv\, (T_3 - T_2)$$

So, putting this we are getting

$$T_3 = 4786.92 \text{ K}$$

it is an extremely high temperature.

As the molecular expansion does not have any role on the final temperature, but it affects only the pressure so this is also going to be the final temperature or the maximum temperature. This is not going to get affected by this molecular expansion. Now if there is no molecular expansion, then what will be your final pressure that you can easily calculate because

$$\frac{P_3}{T_3} = \frac{P_2}{T_2}$$

$$P_2 = 12.54 \text{ bar}$$

from here we get

$$P_3 = 98.47 \text{ bar}$$

But this is excluding the effect of molecular expansion, and if we take the molecular expansion into consideration then you know pressure is proportional to the number of moles. So, from there

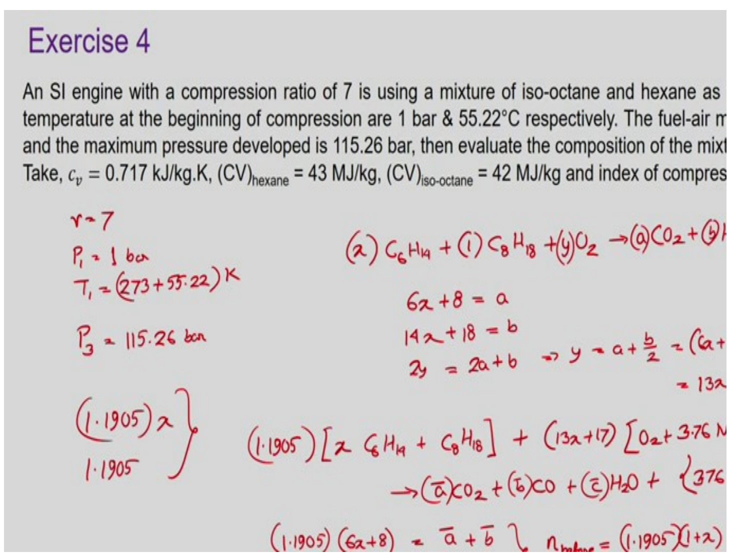
$$\frac{P_3{}'}{n_3{}'} = \frac{P_3}{n_3}$$

where $n_3$ refers to the number of molecules had there been no expansion that is this where a and $P_3$ is the corresponding pressure which is this value. And $n_3$' refers to the number of molecules because of the expansion which is this number. So, we get

$$P_3' = \frac{50.137}{46.329} \times 98.47 = 106.56\ bar$$

this is the final value that we are looking for. So, the temperature remains unaffected the maximum temperature because of this molecule expansion. But there is a noticeable change in this final pressure because there is about 8.2% molecular expansion because of the chemical reaction. So, this way we can consider the real characteristic of the fuel and the real chemical reaction. Of course, we have considered a single step chemical reaction but we could have added more chemical reactions also for this. So, I hope this is this has given you an ample idea about how to deal with the actual fuel composition in case of a fuel air cycle.

**(Refer Slide Time: 36:41)**




Just to round it off we shall be solving a final problem, which is again quite similar but here look at what we what is the difference here. Here we have an assigned in the compression ratio of 7. So, we have

$$r = 7$$

and it is using a mixture of isooctane and hexane not one fuel rather we are talking about two fuels. The pressure and temperature the beginning of compressions is given. So,

$$P_1 = 1 \text{ bar}$$

$$T_1 = 55.22\ ^0\text{C} = (273 + 55.22)\text{ K}$$

I shall only be giving you the description instead of solving everything step by step. The fuel air mixture is 19.05% reach and the maximum pressure developed is 115.26 bar. So, your

$$P_3 = 115.26 \text{ bar}$$

this is the true pressure or true value of the maximum pressure which takes care of the molecular expansion into consideration. So, we have to consider the chemical reaction also. We have to evaluate the composition of the mixture that is we know that the; it is working with a mixture of iso-octane and octane and hexane. We have to find this mixture composition their ratio in terms of mole or in terms of mass. Other information given are CV calorific value of both the fuels and the index of compression to be 1.31.

So, let us try to solve this problem by starting with the chemical reaction. And for that we need to assume some mixture composition. So, what will be the chemical reaction? Chemical formula for hexane and isooctane hexane you have already used which is $C_6H_{14}$ and isooctane is $C_8H_{18}$.

Let us assume for every mole of isooctane we have $x$ moles of hexane to be taken into consideration. So, for every mole of isooctane we have $x$ moles of hexane in the fuel mixture. So, adding oxygen we are trying to form the stoichiometric reaction and therefore we are not writing nitrogen. Let us say we have $y$ $O_2$ to be dealing with. So, if it is a true reaction so we shall be having $CO_2$ and $H_2O$ only on the product side plus nitrogen which you have not written here.

$$(x)\ C_6H_{14} + (1)\ C_8H_{18} + (y)\ O_2 \rightarrow (a)\ CO_2 + (b)\ H_2O$$

Let us say we have $a$ amount of $CO_2$ and $b$ amount of $H_2O$. So if we balance the number of carbons say,

$$6x + 8 = a$$

Then similarly if we write balanced the hydrogen, we have,

$$14x + 18 = b$$

And if we balance the oxygen then

$$2y = 2a + \text{b}$$

that is

$$y = a + b/2$$

and putting the expression for $a$ and $b$ in terms of $x$, we have

$$= (6x + 8) + ½(14x + 18) = 13x + 17$$

So, $y$ is this much, so this many moles of oxygen that we shall be requiring for solving or for having a stoichiometric chemical reaction. Now, it is given in the problem that your mixture is 19.05 % rich. So, what does that mean? Mixture 19.05% rich means the chemical composition that is provided, if we provide exactly this quantity of oxygen then the amount of hexane is provided is 19.05 % more than $x$ that is it has been provided to be $1.1905x$ and isooctane has been provided to be 1.1905.

So, if we write the chemical reaction now considering these two factors, then we can write:

$$(0.1905)\ [x\ C_6H_{14} + C_8H_{18}] + (13x + 17)\ [O_2 + 3.76\ N_2]$$

$$\rightarrow$$

$$(\underline{a})\ CO_2 + (\underline{b})\ CO + (\underline{c})\ H_2O + [3.76(13.x + 17)]\ N_2$$

that leads to the formation of certain amount of $CO_2$ plus certain amount of CO plus certain amount of $H_2O$. Remember we are providing a rich mixture so the fuel does not have sufficient amount of oxygen. So, there will be incomplete combustion leading to the production of this CO plus nitrogen the amount of nitrogen we know it will always be 3.76 times of whatever you have provided 13.x + 17 this much of in nitrogen. So, to balance this again let us write this as $\underline{a}$, this is $\underline{b}$, and this is $\underline{c}$.

Then we have to get the balance again so if we equate the number of carbon molecules. Then we can write from the left-hand side we have:

$$1.1905\ (6x + 8) = \underline{a} + \underline{b}$$

Similarly, if we balance the number of hydrogen just following the same procedure that we have done for the stoichiometric one:

$$1.1905\ (14x + 18) = \underline{c}$$

So, we have balanced this reaction. From this reaction we can calculate the number of moles or the molecular expansion in a way. How can we do this? Because we already have everything written in terms of $x$ like $\underline{a}$ and $\underline{b}$ is given in terms of $x$, $\underline{c}$ is also given in terms of $x$ from there we can calculate the total number of molecules that is present or total number of moles rather before reaction and after reaction. Like number of moles before:

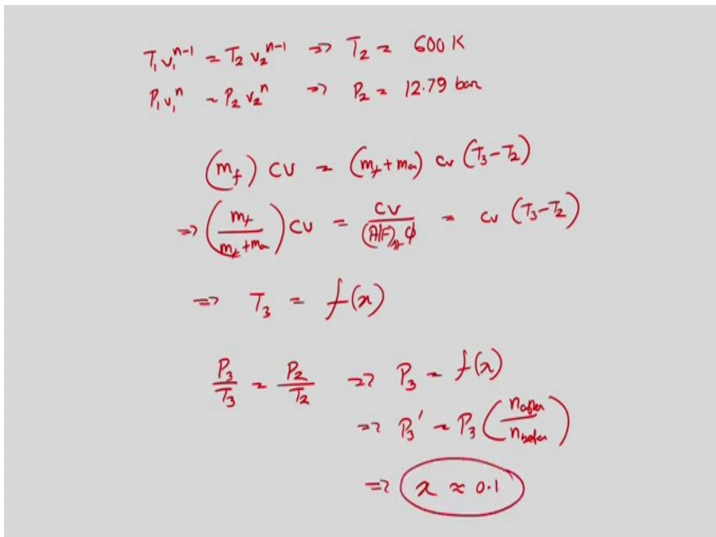
$$n_{before} = (1.1905)\ (1 + x) + (13x + 17)\ (1 + 3.76)$$

So, we can simplify this these are number of moles present before chemical reaction similarly number of moles present after chemical reaction how much that will be? Already we have got <u>a</u> and <u>b</u> so that and also we have got <u>c</u>. So from that we have:

$$n_{after} = (1.1905)\ (6x + 8 + 14x + 18) + 3.76(13x + 17)$$

So, we have the ratio of these two in terms of $x$, which is going to give you the molecular expansion. Now we have to get this see the maximum pressure is given as 115.26 bar which actually takes into account the difference between these two.

**(Refer Slide Time: 45:20)**




So, we have $P_1$ and $T_1$ given to you so we can follow in the previous a previous procedure can calculate

$$T_1 v_1^{n-1} = T_2 v_2^{n-1}$$

that is

$$T_2 = 600 \text{ K}$$

$$P_1 v_1^n = P_2 v_2^n$$

from this case

$$P_2 = 12.79 \text{ bar}$$

So, total of heat added given the combustion process will lead to the calculation of $T_3$. So from there we can calculate:

$$(m_f) CV = (m_f + m_a)\ Cv\ (T_3 - T_2)$$

Your fuel air ratio we can get a write in terms of the equivalence ratio or we can write in terms of the air fuel stoichiometric and $\phi$. I am writing this way so that you can you will be able to calculate the value of $\phi$ and put it here and this should be equal to in the $C_v\ (T_3 - T_2)$ and now air fuel ratio is available with you in terms of $x$.

$$\left(\frac{m_f}{m_f + m_a}\right) CV = \frac{CV}{({}^{A}/_{F})_{st}\phi} = Cv\,(T_3 - T_2)$$

So, from here we are going to get

$$T_3 = \mathrm{f}(x)$$

And now during the chemical reaction what kind of cycle you are talking about? Here we are talking about an SI engine for during where the volume remains constant pressure varies. So, we know that

$$\frac{P_3}{T_3} = \frac{P_2}{T_2}$$

which is going to give you an expression for

$$P_3 = \mathrm{f}(x)$$

Now this $P_3$ is the one which does not take into consideration the molecular expansion. If we want to get the molecular expansion then we have to get $P_3$' which is:

$$P_3{}' = P_3 \frac{n_{after}}{n_{before}}$$

And $P_3$'is the one that is given to you. So, if you solve this you are going to get the value of *x*. In this case I give you the approximate number:

$$x \approx 0.1$$

This is the answer that we are looking for. That means the mixture composition is:

$$(0.1)\ C_6H_{14} + C_8H_{18}$$

this is the mixture composition. If we want, we can also express this one as a mass ratio because we can easily calculate the mass of both these two components.

So, this is a really complicated problem I have not solved it step, I have shown all the stage but I have not solved given all the intermediate numbers and leaving it to you. Please try to solve it on your own. This is quite similar to the way we do the combustion analysis of course specific heat is considered as a constant here. We could have considered that as a function of temperature as well but that would have led to a very complicated integration.

So I would like to stop here itself for the day, because today we have ran out of time and also there is no point going for any further discussion. Today we have solved quite a few numerical problems for two specific heats to discuss that way of calculating the performance of reciprocating engines taking into consideration the fuel air considerations. In the next lecture which is going to be the last of this week, we shall be talking about the actual losses that can be present in the reciprocating engine which we have to consider along with the fuel air consideration to predict the actual performance.

Till then go through this lecture, try to solve each of these problems on your own and you can also refer to the textbooks that I have mentioned, where you may find some more problems for your practice purpose. Thank you.