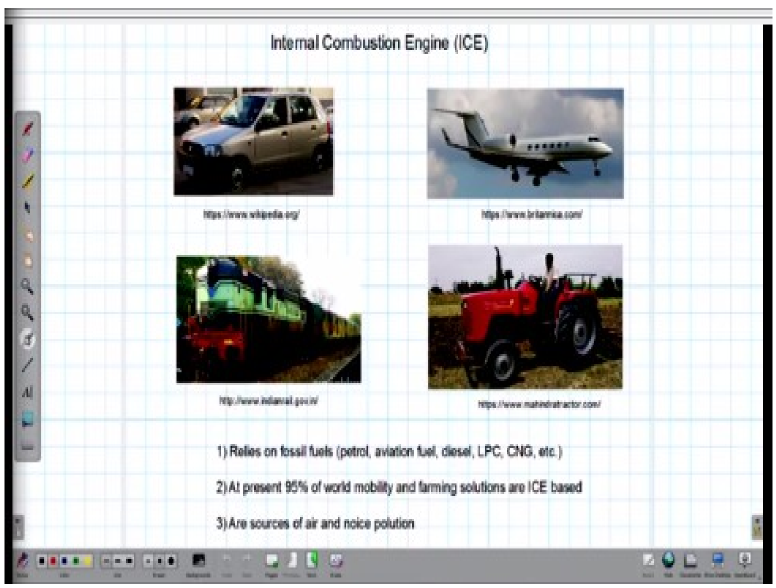
Thermal Physics
Prof. Debamalya Banerjee
Department of Physics
Indian Institute of Technology-Kharagpur

Lecture-43
Topic-The Otto Cycle

Hello and welcome back to another lecture of this NPTEL lecture series on thermal physics. Now in the last few lectures we have been discussing about engines, refrigerators and we have discussed about this ideal reversible engine which is called the Carnot engine. Now for today's lecture we will be focusing on the real life engines which are based on certain thermodynamic rules and we call them the internal combustion engine.

(Refer Slide Time: 00:58)



So, let us look into it in the topic of internal combustion engine. Few examples, our India's favourite car alto, you know the largest selling car in India at present. Any aircraft, a railway diesel locomotive, a farm tractor these are all examples of internal combustion engine. Also apart from that we have motorcycles, scooters even lawnmowers all sorts of small and big machines like for example airlines have a pretty big engine.

Railway locomotive also has a huge engine as compared to that a lawnmower has a really tiny engine few 50 cc or maybe 100 cc, a motorbike also has an 100 cc engine typically. So, all these things are part of this same family of internal combustion engine. Now the internal combustion engine what they does is actually they take some fuel as the input, burn the fuel get some energy from there, convert part of that energy into a work that is movement of the piston and then it releases certain amount of exhaust.

So, at present, so basically it relies on certain type of fuel, now there are many different types of fuel available for an internal combustion engine. For example petrol runs a car, aviation fuel runs aircraft, this railway locomotive and the farm tractor typically are run on diesel of course there are electrically driven electrical locomotives also available. Apart from that we have fuels like LPG and CNG.

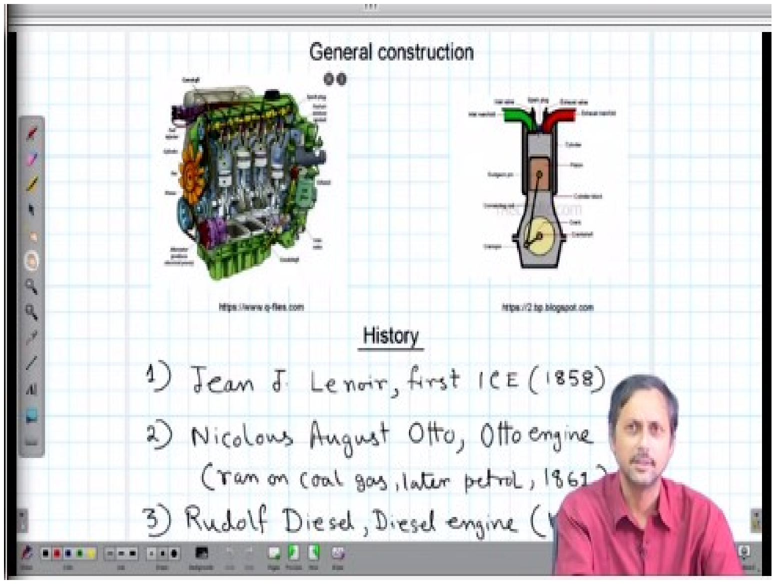
And there are certain non-standard fuels and for example biodiesel, now Indian government is trying to implement biodiesel as a standard fuel, so this type of fuels do exist. Now when we talk about fuels, nowadays the composition of petrol, diesel or aviation fuel LPG, CNG these are all very much standardized. But it was not the case some 100 years back, so we will come back to those in a moment.

At present 95% of world's mobility solution and farming solutions are based on internal combustion engine. Now the rest 5% is electric car, electric vehicles or electric motors which are a fast growing segment. Of course at present we have many projections into picture like for example Indian government has a projection of our aim to convert most of the vehicles into electric by 2030.

But there are certain hurdles set has to be overcome before that can actually be implemented. Now all internal combustion fuel they are sources of air pollution and noise pollution because we cannot have an internal combustion engine that does not exhaust some pollutant gas into atmosphere or that does not make some noise. So, these are very standard features of internal combustion engine.

Of course with improvement in technology and implementation of stricter pollution norms actually have reduced the source, reduce the noise pollution and air pollution to great extent. But still by default every internal combustion engine has to be a source of air and noise pollution.

(Refer Slide Time: 04:45)



Now the general construction of an internal combustion engine, I have taken this four cylinder engine as a very standard there could be number of cylinders in an engine could be varying from single cylinder. For example for a standard motorcycle engine to up to twelve cylinders per engine or even more. So, let us look into the very basic construction of a internal combustion engine. So, apart from all this other connecting wires and all let us focus on this 4 certain piston-like things, these are the cylinders.

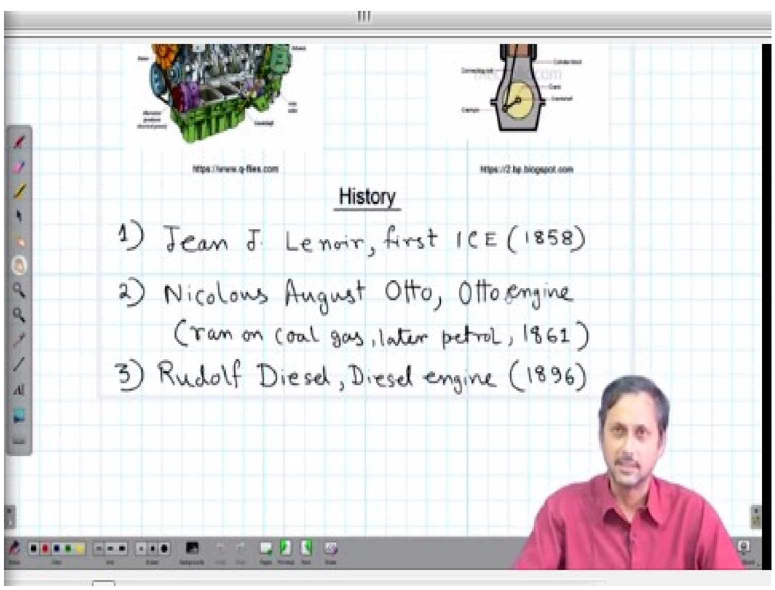
So, these are called the working cylinders and they actually move back and forth and this back and forth movement drives this shaft here, which is called the crankshaft. So, this crankshaft is actually, so this linear movement converts into circular motion and it rotates this crankshaft which eventually gives rise. It gives rotation through certain gearing assembly to the it can rotate the wheels of a car or it can rotate the propeller of a aircraft.

But finally we need rotational motion in order to progress. And strictly speaking the motions inside this cylinder are linear, so these cylinders can move in and out in a straight line. Now the actual engine construction is lot more complicated, we are not go into the details of actual engine operation. What we are going to do is? We are going to focus on what happens inside this piston. So, the work we are talking about is actually the work caused by the linear movement of this piston.

Now if we take one of this 4 cylinder blocks and enlarge it the figure looks something like this. So, inside that typically for every cylinder we have 1 intake manifold, 1 exhaust manifold or intake port, exhaust port and there are valves con controlling these ports. And then there is this piston arrangement which moves inside the cylinder, so this is where the movement happens. And the intake manifold pumps into air fuel mixture inside the combustion chamber, the body of the cylinder is the combustion chamber, the cylinder itself is the combustion chamber.

There is a certain sparking arrangement for a petrol engine, for diesel engine later we will see that the spark plug is not needed, the technology is something different. But typically let us consider there is a spark plug, the ignition takes place and the piston makes an outward movement which makes or, so basically piston makes in and out movement during the motion, during the process and it rotates this crankshaft over here. So, our focus from a pure thermodynamic point of view will be what is happening inside this cylinders block itself? So, let us quickly look into the history of this internal combustion engine.

(Refer Slide Time: 08:03)



The first internal combustion engine was developed by this Belgian-French engineer Jean J. Lenoir that was back in 1858. Now that engine was running on a coal gas or natural gas resource and it had an efficiency of only 2%. Later on within next few years Nicolas Otto, he himself was an engineer, he looked into that engine, he looked into the construction of that engine and thought that he could make further improvement on the efficiency.

And starting from 1861 where he built the first prototype of his patented engine called the auto engine, it went on up till the end of the 19th century and he kept improving his own design in many senses. Now Rudolph Diesel, the word diesel is extremely familiar, diesel is a form of fuel in modern days. But Rudolph Diesel was an engineer who developed his own type of engine which was different in construction by from this auto engine.

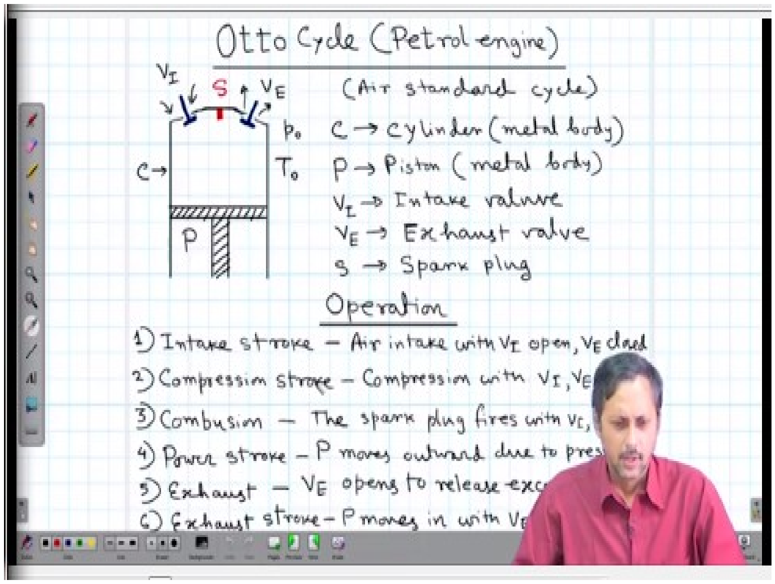
And that the first prototype was built in 1896 although the idea came much some few years back, he wrote a paper where he described his own type of internal combustion engine. But the first prototype was built in 1896 and later on it was found out that diesel engine is very robust, especially for heavy vehicles where the huge load has to be carried even in modern day diesel engine is probably the only option we have.

So, that is why in heavy trucks, in railway locomotives we always have a diesel engine. So, once again this is a lecture on thermodynamics, so we will not go into the details of this development of this engine. What we are going to do now is we will focus on the primary design that was given by Otto and Diesel and there are actually two thermodynamic cycles named after both these inventors.

The Otto cycle is predominantly used for petrol engine even the modern internal combustion petrol engines they rely on the Otto cycle. Although there are certain variations of it or certain different it is not exactly the original design that is still followed nowadays but it is the basic principle remains the same. Later on around 1880 Atkinson came up with his own idea of an Atkinson cycle.

And it turns out to be theoretically more efficient than Otto cycle but frankly speaking Atkinson cycle has never been very popular in real life automotives. Although there are certain car companies or certain special car designed on this Atkinson cycle but they are very few in number.

(Refer Slide Time: 11:08)



So, let us look into the Otto cycle now, what happens inside this? So, what we have here on the left to us is a very basic construction of a cylinder block. So, C is the cylinder, P is the piston, p 0 and T 0 are the temperature and pressure of the outside air, V I is the intake valve, V E is the exhaust valve, S is the spark plug. Now in a basic or in a cycle the following 6 operations are performed by this piston arrangement. Firstly there is an intake stroke, what happens in this intake stroke?

In this intake stroke the piston moves outwards and the intake valve is open. And through intake vault what comes in is the air fuel mixture. Now although it is in real engine what comes in is air fuel mixture, for the purpose of our discussion we will talk about air standard cycles where we will assume that the fuel or air fuel mixture that comes in actually retains the properties of air. Why and what are those properties?

So, basically we will take the gamma value that is C p by C v ratio of pure air which is approximately equal to 1.4. Now in reality what happens is typically for a petrol engine the air to fuel ratio inside in the mixture that comes in is typically 10 is to 1. So, it is not a very bad assumption in any sense. Now after the intake stroke there is a compression stroke, in during the compression stroke both the valves are closed and the piston moves inward. Now when the piston moves inward it will compress the air fuel mixture or in our case pure air into a very small volume, so it is a highly pressurized situation.

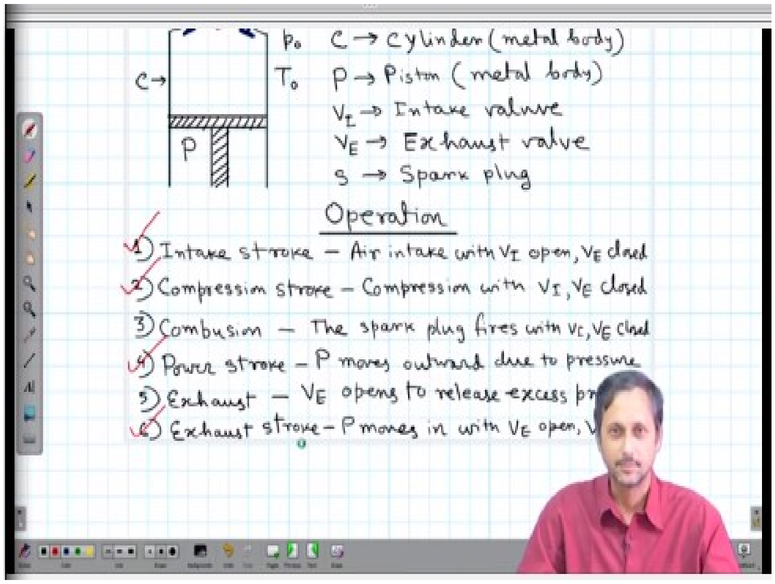
Next the ignition takes place in the spark plug, so in a spark plug there is a positive terminal, there is a negative terminal. And you know every car has a battery or alternator arrangement which will generate power during it is rotation. So, that electric power will go inside this spark plug through some proper electrical wiring and create a spark that is called the ignition. Now that spark will burn all the fuel, this pressurized air fuel mixture.

Then comes the most important part the power stroke. Now this combustion will generate huge amount of energy and the piston will have a kick outside this is called the power stroke. And that is where the actual cylinder actually performs some work. After this power stroke the exhaust valve gets opened and the pressurized air fuel mixture with the pressure inside even after the power stroke the pressure inside this ignition chamber will be more as compared to the outside atmosphere pressure.

And once this valve is open good amount of gas will leave this engine block. Finally there is an exhaust stroke which will move the piston inwards with this particular valve open and this particular valve closed. So, all the extra gases which are still there will exhaust through this exhaust valve and finally will be exhausted by the tail pipe of a car. So, this is once again is a very simple description of this cycle in reality the modern day car the cycles are little more complicated.

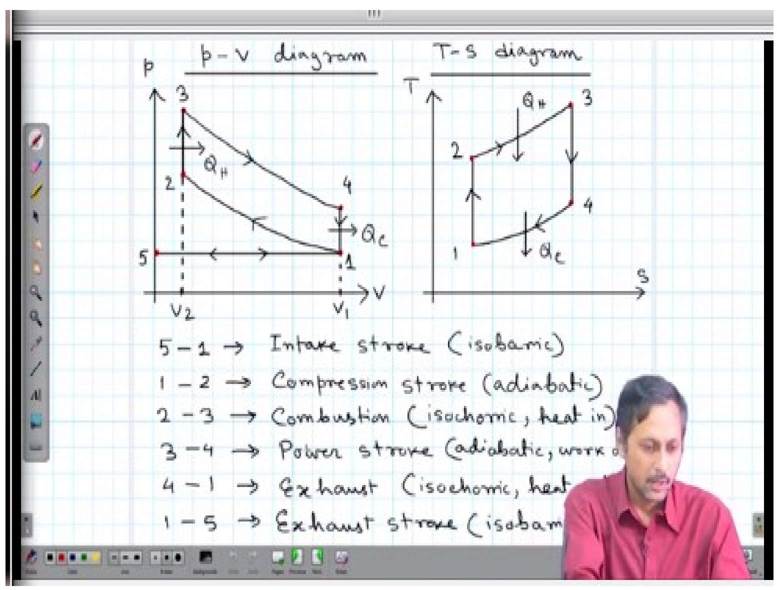
And I never tried to explain how this opening and closing of these valves are performed. So, these are actually there are very complicated timing sequences that is set in order to precisely control such operations. We are not going into this, so we basically talk about this 6 step operation cycle.

(Refer Slide Time: 15:41)



And out of this six there is 1, 2, 3 and 4 strokes that is where the piston actually moves and in two cases during the combustion and the exhaust the piston does not make any movement. So, if we now try to represent this on a pv indicator diagram or a T-S diagram how does it look like.

(Refer Slide Time: 16:07)



So, what do we have here? To our left we have this p-v diagram that is where we have described the Otto cycle and the same diagram or same Otto cycle is represented on a T-S diagram. So, let us look into it in a very close manner. So, we start from the situation 5, state point 5 in where the volume is 0 and the pressure is atmospheric pressure. So, this is actually my p 0 I have not mentioned that, should have mentioned this, this is my p 0. So, p 0 is where the so this is the situation when this piston is all the way up here, so there is only a tiny volume so we can approximately take it as 0.

And this valve gets open, now then 2 things happen. Then the intake stroke starts, so basically the piston starts to move out and simultaneously this valve opens. So, when this valve opens air fuel mixture goes in, so in our case it is pure air that goes in we come to state 1. In here the pressure and temperature is exactly same as the outside pressure and temperature. Well, in real life engine it is not exactly the same but somewhat close.

Then the compression stroke takes place, so 1 to 2 is the compression stroke, so 5 to 1 is the intake stroke which is isobaric in nature, so that happens at constant pressure. Then the compression stroke which is 1 to 2 and this is adiabatic in nature, so this happens in a sudden movement, so that is where there is no heat exchange, it is pure adiabatic in nature. Then the combustion takes place, so the volume does not change but the pressure increases all of a sudden.

Although it is kind of a irreversible process, we have to approximate this with the isochor 2 to 3. So, this is an isochoric process once again and we have to assume that this is a quasi static process although in reality this is definitely an irreversible sudden process. Then the power stroke 3 to 4, and during 2 to 3 the heat Q H enters the cycle, combustion creates the heat. So, that is where the heat Q H comes in. Then the power stroke 3 to 4 and during this step it is an adiabatic and then we have work output from the engine.

So, the work that is performed by the engine during this cycle is the work that is done in this path 3 to 4. Then we have at 4 what happens? The exhaust valve gets opened; the intake valve closes immediately after the intake stroke and then the exhaust valve open at this particular point 4. And because the pressure is high certain amount of gas gets released, so that the pressure comes down to the initial pressure level, the atmospheric pressure level.

We call it the exhaust process which is once again isochoric in nature it happens at constant volume and heat leaves the cycle in this particular sequence. So, we have Q C the heat is rejected, the amount of heat Q C is rejected to the cold reservoir. And finally we have the exhaust stroke, when the engine piston moves once again inside and we go from 1 to 5 in a isobaric manner.

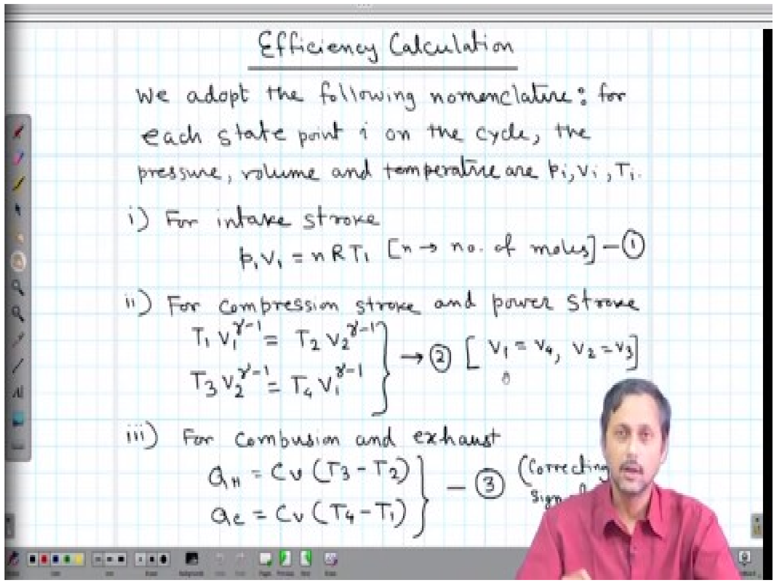
And this is exactly opposite to the intake stroke, so intake stroke is 5 to 1 and exhaust stroke is 1 to 5 that is where all the gases are expelled out of the piston. Now, the same cycle can be represented in a T-S diagram. In a T-S diagram we have 2 adiabatic processes which will be 2 vertical lines 1 to 2 and 3 to 4. And there are 2 isochoric processes one is the 2 to 3 this is the ignition process that is where the heat comes in, so this is one isochoric process.

And the other isochoric process is 4 to 1 in where the heat leaves the engine. Now keep in mind that this is an engine operation, so both the cycles are working in a clockwise direction. This one and this one both working in a clockwise direction as mentioned in the last class, working clockwise is an engine, working anticlockwise is a refrigerator. Now this heat input and heat rejection both are none of these processes are isothermal.

So, frankly speaking it cannot come or the heat cannot come in or heat cannot go to 1 particular reservoir. But in reality in order to make this process quasi static both this isochoric processes quasi static we need to have a series of reservoir at very closely spaced temperatures, so which is practically impossible. So, frankly speaking these two processes are not quasi static at all but for the sake of simplicity we assume them to be quasi static.

And surprisingly the calculations we are going to perform now is basically the calculation of efficiency. The efficiency that will be calculated using this simple relation or simple assumption is somewhat close to the real life efficiency of a petrol engine. So, although is not practically possible but the assumptions do work. So, that is where we have discussed all the processes, please go through it once again if you have any doubts.

(Refer Slide Time: 22:45)



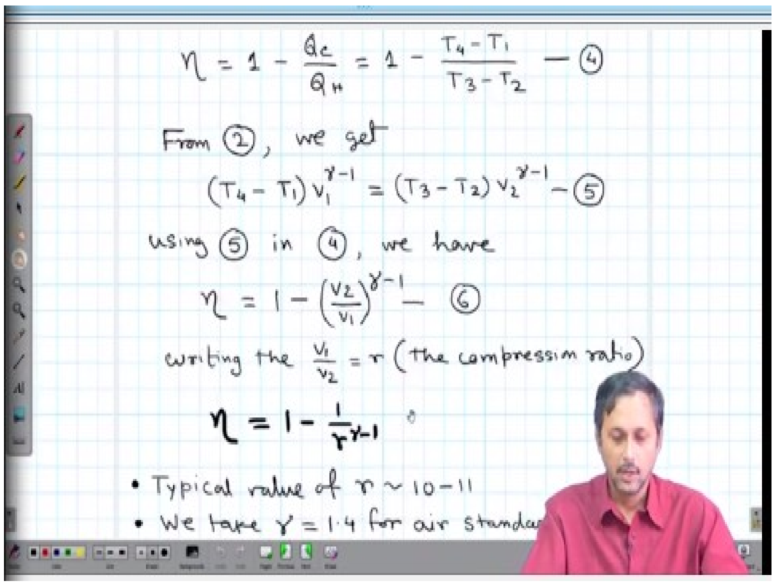
Now let us go to the efficiency calculation. Now, so we basically first we add up this following nomenclature. For the state point i the corresponding pressure volume and temperature is p i, V i and T i. So, going back here for point 5 it will be p 5, T 5 and v 5 but point 5 is not part of the main cycle, so we focus on point 1, 2, 3 and 4. So, for point 1 it will be p 1, V 1, T 1, point 3 will be p 3, V 3, T 3, point 4 will be p 4, V 4, T 4 like that.

So, for the intake stroke, so we compute for the intake stroke we simply have this relation p 1 V 1 is equal to nR T 1, where n is the number of moles. So, this is the intake stroke and we assume p 1 and T 1 is actually p 0 and T 0. So, whatever temperature and pressure the atmospheric air is the same pressure and temperature will be maintained here of course the volume will be V 1. So, we have this simple relation.

Now for the compression stroke and for the power stroke that means from 1 to 2 and 3 to 4 both are adiabatic in nature. So, we have this adiabatic relation T 1 V 1 to the power gamma minus 1 is T 2 V 2 to the power gamma minus 1, T 3 V 2 to the power gamma minus 1 is equal to T 4 V 1 to the power gamma minus 1 because basically V 2 is equal to V 3 and V 4 is equal to V 1. So, that is why we have V 1 here and we have V 2 here, so we call it relation 2. Now for the combustion process and the exhaust process in both cases these are isochoric, we see that these are isochoric.

Now for any isochoric process the relation or the heat generated will be or heat exchange will be Q H C v T 3 minus T 2 that is for Q H and Q C will be C v T 4 minus T 1. And please remember we are not writing it T 1 minus T 4 because we need to correct for the sign of T C. Of course T 1 will be less than T 4, so if we write T 1 minus T 4 Q C will be negative. But in a cyclic process when we want to calculate the efficiency we take both the input heat then the sign of the heat input and the heat output as positive. So, that is why we have to write T 4 minus T 1.

(Refer Slide Time: 25:41)



Now the efficiency will be 1 minus Q C by Q H which is 1 minus T 4 minus T 1 divided by T 3 minus T 2. So, from 2 what do we get? We get T 4, so if we focus on 2 we get T 4 minus T 1 will be, so if we write rather subtract this relation from this relation, the above relation from the below relation we can write T 4 minus T 1 with V 1 to the power gamma minus 1 common will be equal to T 3 minus T 2 times V 2 gamma minus 1 common.

So, that is exactly what we write here and from there we get T 4 - T 1 divided by T 3 minus T 2 will be equal to V 2 by V 1 whole to the power gamma -1. So, eta will be 1 minus V 2 by V 1 to the power gamma minus 1. Now V 2 by V 1 is basically the V 1 and V 2 are the minimum and maximum volume of the cylinder while this actual cycle is going on. Of course the lowest volume is 0 that is where we start from this particular point.

But we are more interested about these volumes through which the cylinder goes through during the actual cycle, actual power stroke and compression stroke. So, we define V 1 by V 2 this ratio as r which is called the compression ratio of a engine and we can write eta is equal to 1 divided by r whole to the power gamma minus 1. So, this is the efficiency of a Otto cycle. Now the typical value of r for a petrol engine is 10 to 11, we can have lower values but it is difficult to increase the value beyond 11.

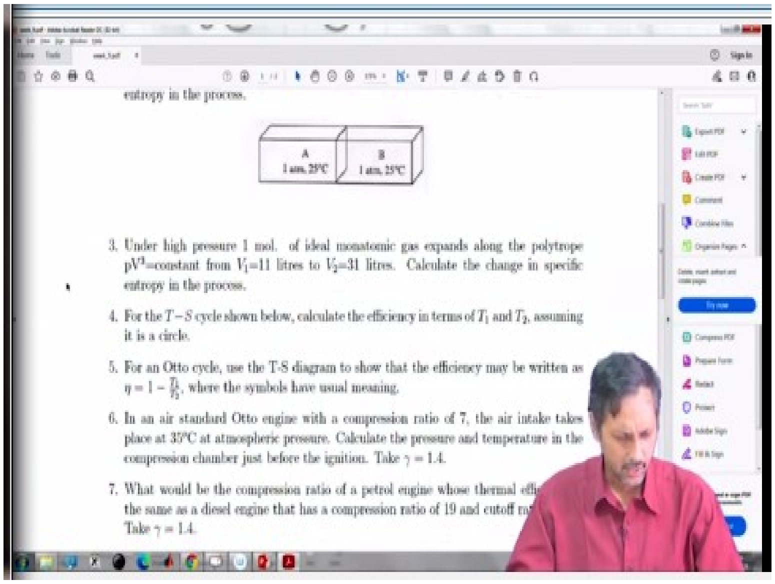
Of course there are certain technical difficulties in order to for doing that, we will discuss that in the next lecture in more details. Modern day direct injection type engines we have a compression ratio of maybe 12, maybe 12.5 but typically we do not see in a traditional petrol powered car, we still do not see more than 11, the compression ratio. And for our calculation if we take gamma = 1.4 because these are air standard cycle.

So, if we put these values here, if we put let us say 10 and gamma is equal to 1.4 we get eta is equal to roughly 0.6, so that means it is a 60% efficiency. Now this looks pretty high on pen and paper but in reality please remember this is the efficiency if we go back this is the efficiency of this cylinder movement only. So, actually this cylinder movement will be transferred into a cyclic movement of the crankshaft and that will go through a series of gears.

Finally it will go to certain joints, certain bearing, axle and finally to the wheel. So, the real life efficiency is lot less as compared to what we get at the cylinder block. But still if we get 60% for modern cars we get an efficiency routinely around 40%, 40% in terms of real life efficiency. How to calculate the real life efficiency? Real life efficiencies are calculated by considering the mileage it gets for a particular fuel.

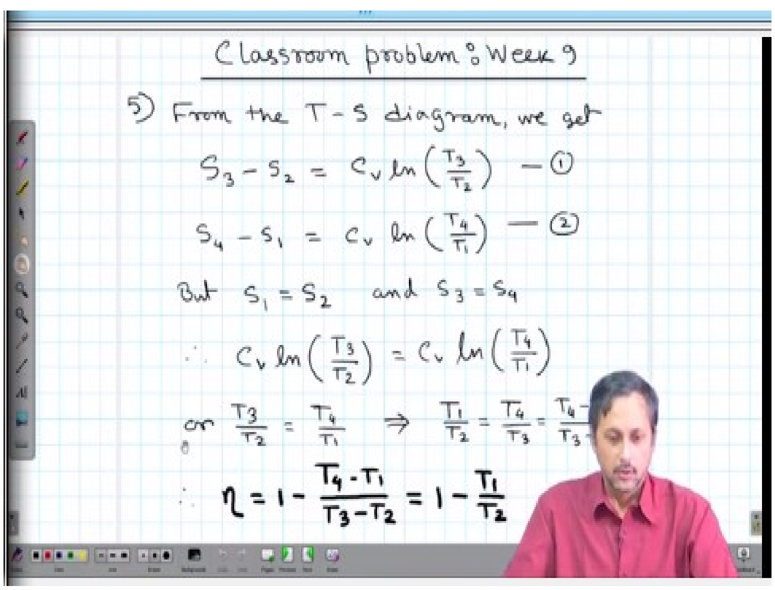
Then we can actually calculate the calorific value of that fuel and convert that into the work done by the car in order to run a certain number of kilometers. So, let us say 1 liter gives a mileage of 12 or 14, let us say 12 kilometers, so car has a certain weight, so we can actually calculate the energy requirement it takes to go to travel 12 kilometers. And then we can also compare it with the calorific value of 1 liter petrol and compute the real life efficiency. So, real life efficiency is typically between 30 and 40, whereas the theoretical efficiencies go up to 60 or even higher.

(Refer Slide Time: 30:25)



So, let us focus on two problems before we end today. So, the 5th problem of this problem set is for Otto cycle, we have to use the T-S diagram to show that the efficiency may be written as eta is equal to 1 minus T 1 by T 2 as well. Where the symbols have their usual meaning? So, T 1 being the temperature of point 1, T 2 being the temperature of point 2, so we have to show that the expression which we have written here that is eta is equal to 1 minus T 4 by T 1 divided by T 3 minus T 2 can be written as 1 minus T 1 by T 2 simply.

(Refer Slide Time: 31:07)

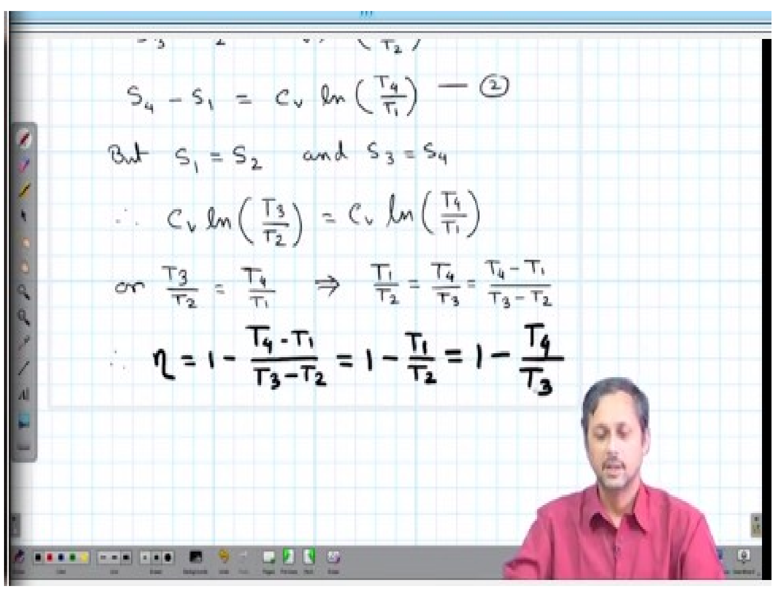


So, from the T-S diagram what do we get? So, from the T-S diagram what we see is we have a process 2 to 3 and process 4 to 1. So, we see S 3 minus S 2 if we just integrate the quantity T ds or if we perform this integration of entropy between point 2 and point 3. So, basically I have not shown you the detailed calculation here but you can write the entropy change for a isochoric process, you can do it yourself.

And just integrate this you will get S 3 minus S 2 is equal to C v ln T 3 by T 2, similarly for point 4 and 1 we will get S 4 - S 1 minus C v ln T 4 by T 1. In both cases these processes are isochoric, so for isochoric process you have to integrate ds is equal to dQ by T. But once again you see these processes are like 3 and 4 and 1 and 2 they are connected by two isentropic processes which are adiabatic, adiabatic is isentropic. So, the entropy of point 1 and point 2 and point 4 and point 3 are equal.

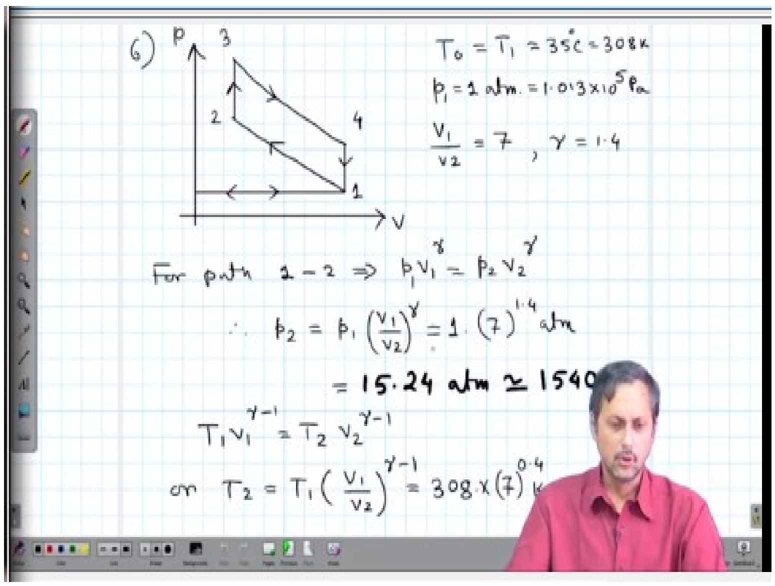
So, that will give us C v, so you see we can write S 3 for S 4 here and we can write S 2 for S 1 here, so both relations are actually identical, so S 3 minus S 2 is equal to S 4 minus S 1, so we can write C v ln T 3 by T 2 is equal to C v ln T 4 by T 1 which gives you T 3 by T 2 is equal to T 4 by T 1. So, that means T 1 by T 2 is equal to T 4 by T 3 and very simple mathematical deduction is T 4 minus T 1 is equal to T 3 minus T 2. Now what is the efficiency expression? eta is equal to 1 minus T 4 minus T 1 divided by T 3 minus T 2 which is equal to 1 minus T 1 by T 2 also equal to 1 minus T 4 by T 3.

(Refer Slide Time: 33:43)



So, this is a very easy proof, all we have to do is we have to do this 2 integrations S 3 to S 2, S 3 minus S 2 and compute S 3 minus S 2 and S 4 minus S 1. So, the next problem which is the last problem for today's lecture, this lecture. In a air standard Otto engine the compression ratio is 7, here the compression ratio is pretty low, the air intake takes place at 35 degree centigrade at atmospheric pressure. Calculate the pressure and temperature in the compression chamber it should be combustion chamber not compression, I will correct it, combustion chamber just before the ignition. Take gamma is equal to 1.4. So, what is given here?

(Refer Slide Time: 34:38)



This is the Otto cycle which I have redrawn once again. So, T 0 which is equal to T 1 is given as 35 degree centigrade that is 308 kelvin, p 1 is the atmospheric pressure which is 1.013 into 10 to the power of 5 Pascal, V 1 by V 2 is given as 7 and gamma is equal to 1.4, so these are the data that is given to us. So, for path 1 to 2 we can write p 1 V 1 to the power gamma is p 2 V 2 to the power gamma.

So, p 2 is equal to p 1 V 1 by V 2 to the power gamma which is 1 times 7 to the power 1 by 4 in terms of atmosphere which is 15.24 atmosphere and if we consider 1 atmosphere is equal to this many Pascals, this is roughly 1 5 4 0 kilopascals. So, it is 1 by 4 0 kilo Pascals, next we have to compute the temperature before ignition. Now where the ignition takes place? Ignition takes place between point 2 and point 3, so we need to compute the temperature at point 2.

So, once again we use the adiabatic relation between point 1 and point 2 and write T 1 V 1 to the power gamma minus 1 is T 2 V 2 to the power gamma minus 1. So, finally that gives you T 2 is equal to T 1 times V 1 by V 2 whole to the power gamma minus 1, V 1 by V 2 is 7. So, 308 into 7 to the power 0.4 Kelvin which is 670.8 Kelvin. So, that is where we stop today for this lecture.

In the next lecture we are going to discuss another very interesting internal combustion cycle that is the diesel cycle. And let me tell you diesel engine is still hugely operational in modern day. And diesel engine has a very specific feature that makes it different from the petrol engine; it does not have a spark plug. So, the combustion is totally pressure driven. So, what are the consequences of that and why diesel engine is the choice of use in for heavy load carrying vehicles? We will see in the next lecture, till then thank you.