Thermal Physics

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Lecture-44
Topic-The Diesel Cycle

Hello and welcome back to another lecture on this NPTEL lecture series on thermal physics. Now for today's lecture we will be discussing Diesel cycle, in the previous class we have talked about the general formation of internal combustion engine, general construction of an internal combustion engine. And we talked specifically about the petrol engine where Otto cycle is used. So, even in the modern engines the cycle which we have discussed in the last class is not exactly what it is followed in a modern engine.

But the basic principle remains the same; of course the modern technologies are lot more complicated. So, in effect and we have seen that for a compression ratio of roughly 10, so we get an efficiency of the order of 60%. But as I have already said the real life efficiency is a lot less because we are talking about efficiency of the cylinder itself. Now there will be many mechanical parts between the cylinder and the wheel, so the real life efficiencies less. So, now let us look into the another major type of internal combustion engine that is the diesel engine which follows a Diesel cycle. So, let us look into this.

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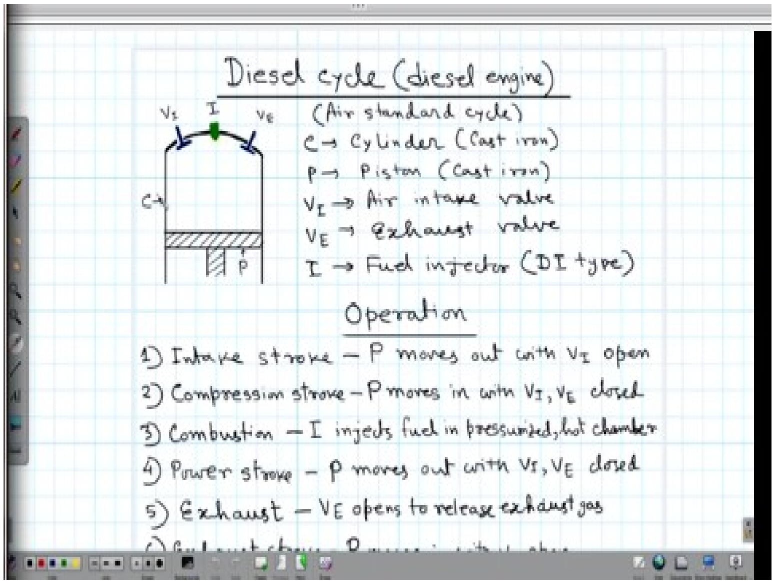

So, this is the schematic diagram of a cylinder block or a cylinder, cross section of a cylinder in a typical Diesel cycle. Of course I have only drawn the minimal components as before; there will be many more mechanical components in between this design. So, the basic difference between a petrol cylinder or petrol engine and a diesel engine being that, here you remember in a petrol engine this there is an input valve here, there is an exhaust valve here and there is a spark plug here.

So, instead of spark plug in a diesel engine what do we have is a fuel injector I. Now unlike in petrol engine where air fuel mixture is injected inside and compressed. In a diesel engine what is compressed is pure air and at the very last phase of compression this injector is used in order to spray like spray the diesel fuel at a very high pressure. And because already the temperature is high inside this combustion chamber because of this initial compression, the air itself is hot, this diesel will burn out which will give us the required power input.

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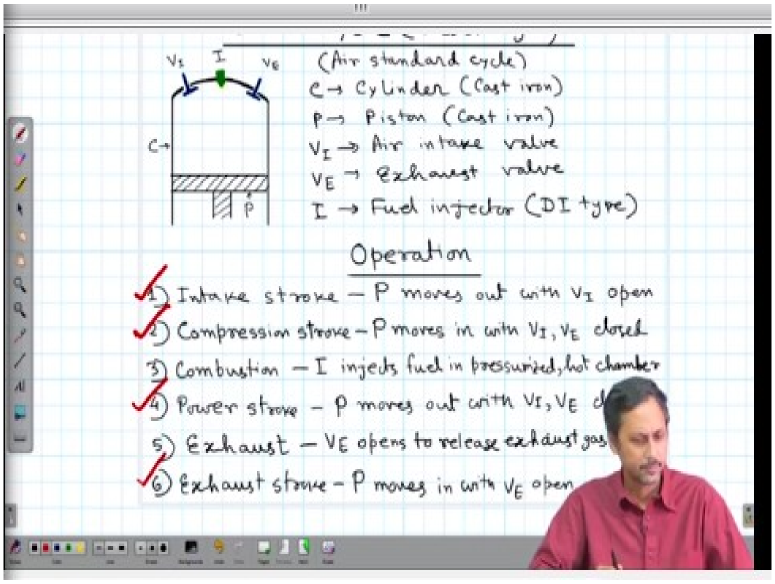

Now let us quickly look into this operation cycle. First there will be an intake stroke in which the piston P moves in and moves out with the valve V I open. So, that is where all the only air will be sucked in, then this valve will get closed, once again we are not talking about the mechanism which makes these valves open and close. But we are assuming that this is happening somehow. So, and of course you have to keep in mind that a good amount of energy goes into that also, all these operations draws energy from the engine itself.

So, although we are calculating the pure efficiency in terms of the engine operation, there are a lot many things inside a modern vehicle apart from the engine. So, engine also has it is mechanical component, then inside the engine, we have music system, we have air conditioner, everything is run on the power of the engine itself. So, they everything affects the real life efficiency.

So, after this input stroke is complete, then we have both the valves closed and the piston starts to move in, so this is called the compression stroke. And unlike this petrol engine once again, where air fuel mixture is compressed where in diesel engine it is compressing pure air. So it has certain advantages and disadvantages. Then comes the combustion part, at the peak of this compression process, injector injects fuel and because the air itself is very hot inside the compressed air.

Because when we compress air, we are working against or work working on it. So, this will enhance the internal energy, the temperature will go up. And as the fuel comes inside this hot chamber, it will burn out. But unlike petrol engine where the combustion process or ignition process takes place at constant volume, here it takes place at constant pressure. So, what happens?

During the combustion also the piston starts moving outwards, piston will go down once again and at the end of combustion or during the combustion process the pressure inside this combustion chamber will remain invariant. Now after the combustion comes the power stroke, by the way if the first compression stroke is a adiabatic stroke, the intake stroke is a isobaric stroke, we will come back to that in the next page.

And once again the power stroke will be an adiabatic stroke and then at the end of power stroke, the exhaust valve will be opened and the exhaust gas will start leaving the cylinder. So, this is called the exhaust process which is once again an isochoric process, the volume does not change. And finally the exhaust stroke when the piston will move all the way up to the minimal value of top of the cylinder and all the gases will be expelled from inside the cylinder.

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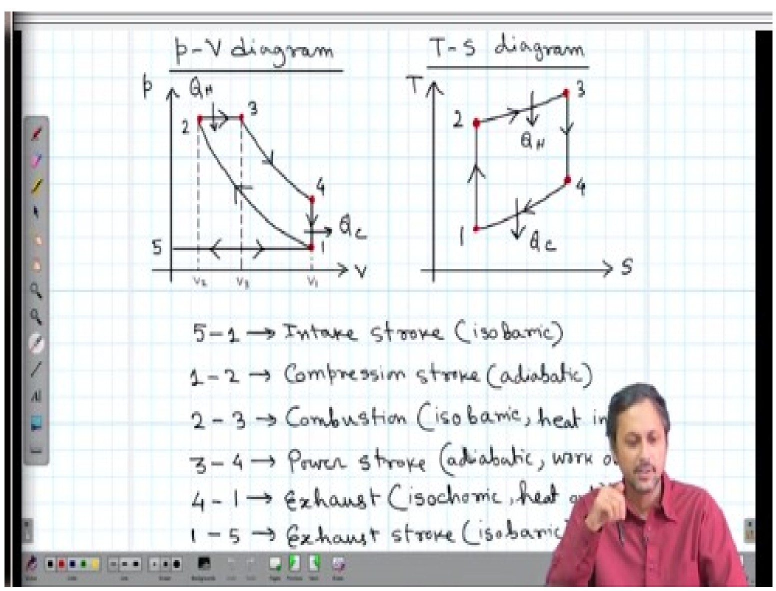

So, if I represent this process in a p-v diagram and T-S diagram, it looks something like this. So, once again there are 5 points, I forgot to mark the 5th point here, yeah, so, this is the 5th state point. So, we start from 5 to 1, this is my intake stroke, 1 to 2 is the adiabatic compression stroke, 2 to 3 is the combustion process which is isobaric in nature. So, the pressure remains constant but the volume changes.

Once again we assume that this is a quasi static process, in reality it is not because sudden combustion of fuel which takes place inside few milliseconds cannot be a reversible quasi static process but we assume it is. So, then comes the power stroke 3 to 4 which is an adiabatic and 4 to 1 which is the stroke, it is the exhaust process which is isochoric happening at a constant volume and then the exhaust stroke comes in.

So, once again we have out of these 6 stages we have 1 stroke, 2 strokes, 3 and 4 strokes, so this is also a 4 stroke cycle. So, like petrol engine which we have discussed in the last class, it is also 4 stroke engine, petrol engine also is a 4 stroke engine diesel engine also is a 4 stroke engine, correct. And corresponding T-S diagram very simple we have two adiabatic processes which will be represented by two vertical lines these are isentropic processes.

And these will be connected by 1 isobaric process 1 isochoric process. Once again the isobaric process will have smaller slope as compared to the isochoric process because C p is greater than C v for any system. And for our efficiency calculation, we will be assuming air standard cycle where air will be treated like an ideal gas. Here actually air is a better assumption as compared to petrol engine.

Because in principle, the initial phase is pure air, the initial compression is pure air; fuel comes in only at this point. So, this is where the heat input takes place and this exhaust where the heat output takes place and the power stroke where the effective work is done by the system. So, in order to compute the efficiency we assume all these processes are reversible process or rather quasi static process which is once again is only an assumption.

But let us go ahead and do the efficiency calculation. So, for efficiency calculation, so we start we focus primarily on this cycle 1, 2, 3, 4, 1 to 5 or 5 to 1 although it is part of the cycle, we do not consider it is part of the process, we do not consider this as a part of this effective cycle.

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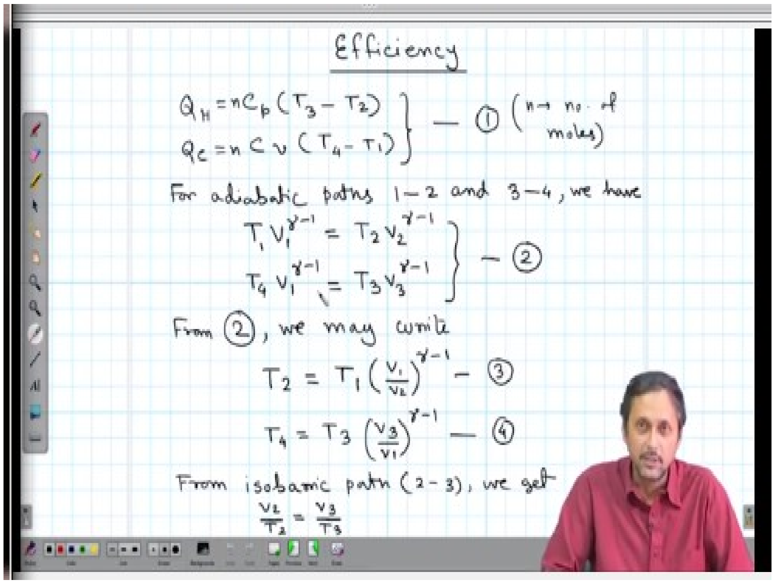

So, Q H is n C p T 3 minus T 2 that is here. So, once again T 1 has pressure volume temperature as p 1, V 1, T 1, T 3 has a pressure volume temperature as p 3, V 3, T 3 like this. So, we just follow the exact same nomenclature and the first process where the heat comes in is isobaric. So, we have C p times T 3 minus T 2, the exhaust processes isochoric So, we have C v times T 4 minus T 1 once again we correct for the sign of QC which in our usual convention is negative, so we correct for that.

So, this is our expression for Q H and Q C. So, we focus on the adiabatic paths 1 to 2 and 3 to 4. So, that means this part and this part here and we get T 1 V 1 to the power gamma minus 1 is equal to T 2 V 2 to the power gamma minus 1, T 4 V 1 to the power gamma minus 1 because V 1 and the volume at point 1 and point 4 that means V 1 and V 4 are identical. Here by the way 2 and 3 are not identical, we have 3 volumes to deal with V 1, V 2 and V 3.

So, we have this one the second relation is T 4 V 1 to the power gamma minus 1 is equal to T 3 V 3 to the power gamma minus 1. And from 2 what we can do is? We can write T 2 in terms of T 1 and T 4 in terms of T 3. Now, considered the process 2 to 3, so from 2 to 3 we have a isobaric process. So, for this isobaric process V 2 by T 2 is equal to V 3 by T 3 because we are assuming air is an ideal gas which once again is a assumption.

So, there is a relation between V 3 and T 3. So, what we are trying to do here? Let me tell you the efficiency will be the ratio of these 2 numbers, 1 minus ratio of these 2 numbers. So, we want and please remember here finally what we have to get is, we have to get this in terms of the ratio in terms of volumes. So, in order to do that the standard trick is express everything in terms of T 1. Or we can take any temperature; T 1 is probably the most convenient one.

So, if we can express T 3, T 2 and T 4 in terms of T 1 the life becomes easier. So, T 2 we immediately see that T 2 is equal to T 1 V 1 by V 2 whole to the power gamma minus 1, T 4 is equal to T 3 V 3 V 1 whole to the power gamma - 1. Now this isobaric process 2 to 3, from this isobaric process we can establish a relation between T 2 and T 3.

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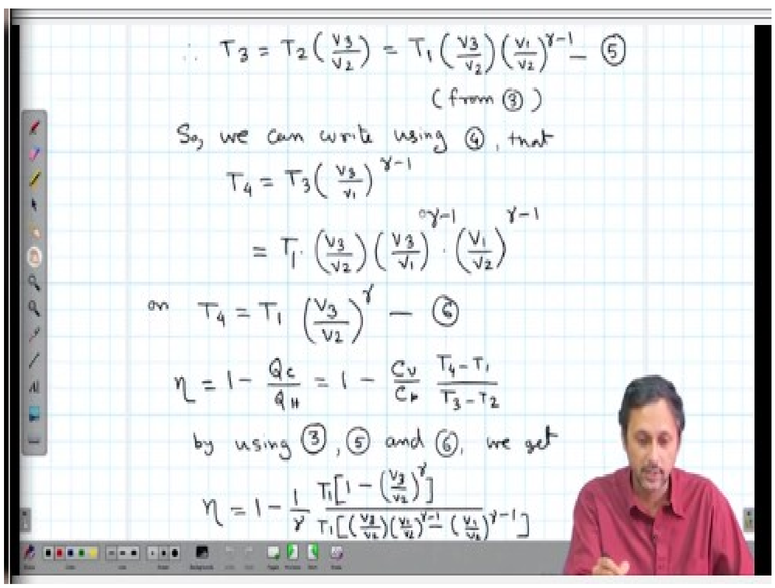

So, if we do that, we get T 3 is equal to T 2 times V 3 by V 2, once again T 2 is equal to T 1 times this quantity. So, we can use this and write T 3 is equal to T 1 times V 3 by V 2 times V 1 by V 2 whole to the power gamma minus 1, let us call it relation 5. And for T 4, see T 4 is equal to T 3 times V 3 V 1 to the power gamma minus 1. So, we can substitute for T 3 with T 1 V 3 by V 2 V 1 by V 2 whole to the power gamma minus 1. Simplify, and we get T 4 is equal to T 1 V 3 V 2 whole to the power gamma.

So, from relation 6, 5 and 4 we have, not 4 actually 3, so we have T 3 and T 4 in terms of T 1. And of course there were ratios V 1, V 2, V 3, these volumes are present. So, putting everything together the efficiency which is 1 minus Q c by Q H is equal to 1 minus C p by C v by C p T 4 minus T 1 divided by T 3 by T 2. Now C v by C p is 1 over gamma and now I express T 4 in terms of T 1, T 3, T 2 all in terms of T 1.

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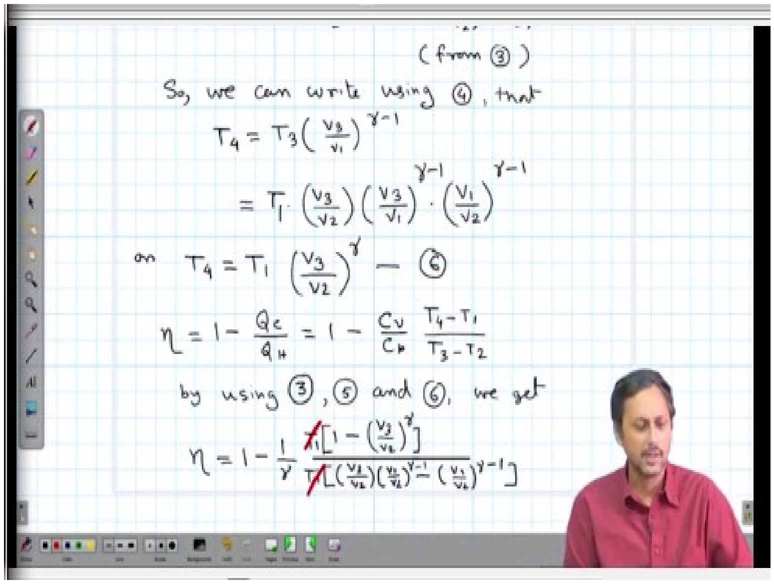

So, we get this expression from which T 1 and T 1 cancels out nicely which leaves us with.

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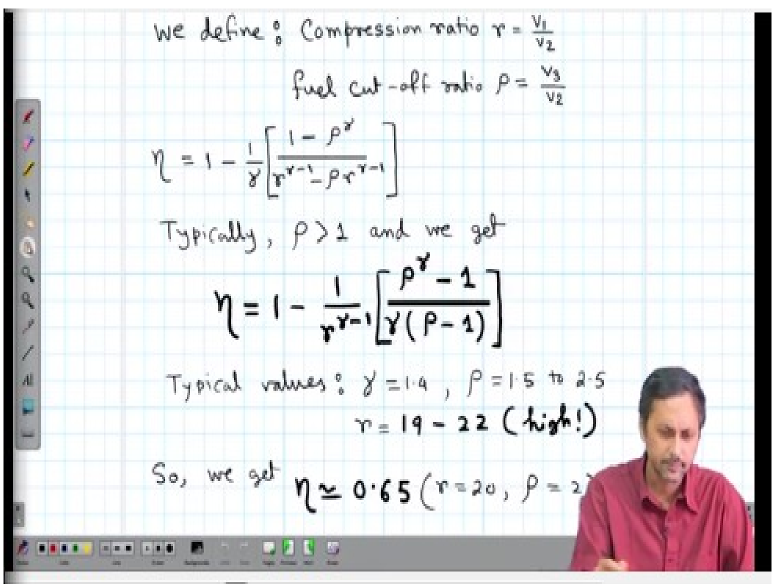

And we now define 2 ratios one is the compression ratio which is V 1 by V 2, there is the maximum to minimum volume, ratio of maximum volume divided by the minimum volume of the cylinder during this working cycle. And then there is the fuel cut-off ratio we call it rho which is defined by V 3 by V 2. So, basically this is the ratio of the volumes before, just before and after the combustion process.

So, this ratio is called and please remember during this entire process the fuel is spread in. So, fuel cut-off ratio means, V 3 is the volume at which the fuel is cut-off, the combustion process ends and the power stroke begins. So, this V 3 by V 2 we call it the fuel cut-off ratio and call it rho. So, eta becomes in terms of if we simplify slightly we finally get eta is equal to 1 over r to the power gamma minus 1 whole multiplied by rho to the power gamma minus 1 gamma times rho minus 1.

Now unfortunately this relation is not as simple as the one we get for the Otto cycle, which where we have only one variable r and gamma is a constant. Here we have two variables rho and r and the relation is slightly complicated, but anyway at the end it is purely algebra. And if we put gamma is equal to 1.4 typical values of low is between 1.5 to 2.5. Whereas, typical value for r is 19 to 22 which is high.

Now we have to keep in mind that a diesel engine, the petrol engine has certain limitations. First of all there is a spark plug which has a finite length, so it cannot be compressed till the very end of the cylinder. But apart from that there is also a limitation because for petrol engine, the cylinder essentially sucks in the air fuel mixture. So, if we start compressing it at some point and petrol has a slightly lower flush point as compared to diesel.

So, if the temperature increases, if the compression is too high, then before the sparking the ignition will take over and it has certain disadvantages. So, it has certain disadvantages, so that is why the compression ratio in a petrol engine. So, this phenomena which I have discussed here is called a knocking in terms of automobile engineering. For petrol engine, the ignition is precisely controlled by the spark, whereas for the diesel engine, it happens over a relatively longer period of time and that leads to higher vibration.

So, both has different applications, we will come back to that. Anyway, so this ratio of 19 to 22 which is standard for a standard diesel engine, some high performance diesel engines even have higher values which can never be reached in a petrol engine. Petrol engine is typically 10 to 11 more or less is the maximum. Anyway, so if we put in r is equal to 20 and rho is equal to 2 and take gamma is equal to 1.4 we get eta is equal to 0.65 which is, okay, I should not really compare the efficiency in this way. Because here we have two parameters the compression ratio is high and all. But for the last example we took was for a petrol engine it was like between we got 2 examples 50 and 60 I think, in the range of range between 50 and 60, whereas it is slightly on the higher side.

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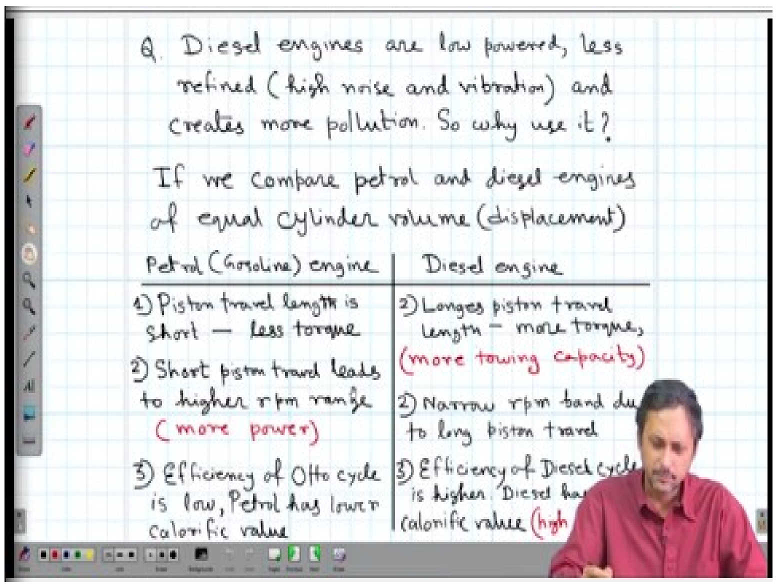

Now let me ask you a question you must have had travelled or seen a diesel car. Now a diesel car, it has you know diesel car typically has low power or diesel engines typically has low power and it has less refinement. So, it will vibrate mode, it will make more noise and finally a diesel car will pollute more, it will have more pollution. But still we see, so many of diesel cars around us, like diesel vehicles I should not call it car because sometimes we have for example locomotives or heavy trucks are always diesel.

So, why we choose diesel? So, just to get to the answer is not that simple, but I will try to summarize it for you because as a student or before I went into this details of this one I always had this curiosity. So, why should I choose diesel car or a petrol car or petrol vehicle? What are the parameters should I look for? So, if we compare the 2 engines, it is difficult to compare because typically diesel engine and petrol engines are very different in construction and in many ways.

So, but let us assume that we have in a given car model we have options of having both petrol engine and diesel engine and they are more or less comparable in size. So, rather we say that the displacement or engine capacity, the displacement is essentially the piston volume if we go back here the effective volume of the piston, the maximum effective volume. So, what we call V 1 in this diagram is called the displacement for an engine.

So, a displacement for a cylinder and if a engine has 4 cylinders we add 4 displacements and get the final value of the displacement of the engine. So, just to give you an example, if we have a 1200 cc 4 cylinder engine. So, in general we can assume that each cylinder has a displacement of 300 cc. So, if we have let us say 2 1200 cc motors, one is driven by petrol, one is driven by diesel if we compare.

So, the compression ratio in a diesel engine is more as we have seen already, there is a reason for it. It can be compressed because it is compressing pure air as compared to air fuel mixture in a petrol engine. Now because of that the travel length is longer, now because of this long travel length, it will generate more torque as compared to a petrol engine. So, petrol engine will give less torque and a long piston travel in a diesel engine will gives more torque. Now why torque is important? Let us quickly go back to the diagram of we have shown you in the last class.

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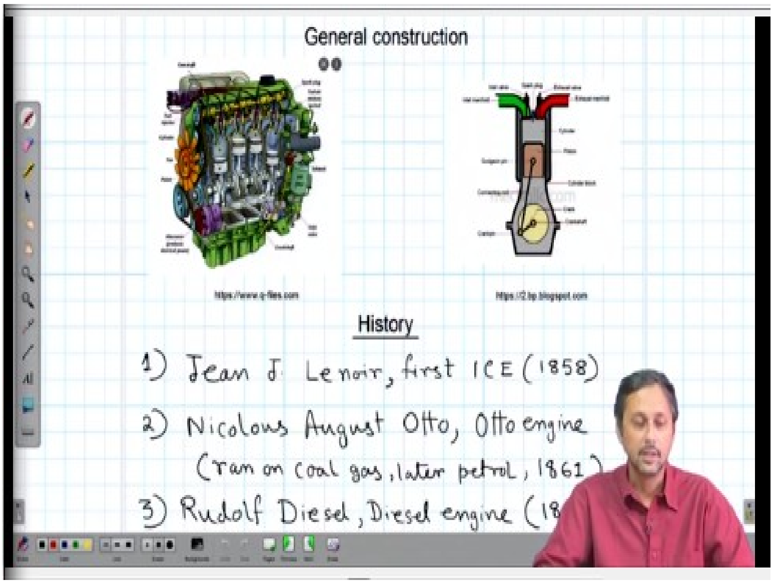

You see finally this piston will move this crankshaft. So, if the travel length is more this mechanical energy or the linear energy is essentially converted into linear motion converted into a circular motion that is what the torque comes into action. More the travel length is more torque it will generate on the crankshaft. So, why this torque is useful? This torque is useful when it comes to towing.

Try to imagine a huge truck it is taking maybe 30 tons of load, a petrol engine probably will not be able to let us say it has a huge engine it has a 5 litre or 7 litre engines. A 7 litre petrol engine will probably not be able to pull that much of weight that effortlessly as compared to a diesel truck, so that is where diesel is chosen. Now petrol engine has more power, it has a wide rpm band because of the short travel range it can go back and forth in a frequent manner.

So, the typical rpm range of a petrol engine is larger as compared to a diesel engine. Just to give you an idea for a standard petrol engine in a normal passenger vehicle small car, it can go up to 6000 rpm, 6000 revolutions per minute. But for a diesel car, it generally does not go beyond 5000 rpm, actually at 4500 rpm itself the power starts to degrade. So, petrol engine is chosen where more power is needed, diesel engine is chosen where more towing capacity is needed.

Also, the efficiency of an Otto cycle is low as compared to efficiency of a Diesel cycle, so that gives you high mileage. There are actually two things, first of all the efficiency of the cycle itself and secondly the fuel petrol has a lower calorific value per litre. So, typical values for petrol is 32 to 34 mega joules per litre. So, if we burn 1 litre of petrol we might get 33 kilo mega joules of energy, whereas the value is 36 to 37 for diesel.

So, typically if we compare the energy contained inside 1 litre of petrol and 1 litre of diesel, for 1 litre of diesel it is more. And also the Diesel cycle is thermodynamically more efficient as compared to an Otto cycle. So, combined together what we get is a more or higher mileage for a diesel vehicle, for comparable size of course. If we have 2 1200 cc 1 petrol cars, 1 diesel car identical model the diesel car will generally gives better mileage.

So, these are the points we have to keep in mind when comparing petrol car and diesel car. Although the diesel car produces more vibration, makes more noise, pollutes more, we still have high mileage and more towing capacity as compared to a petrol car.

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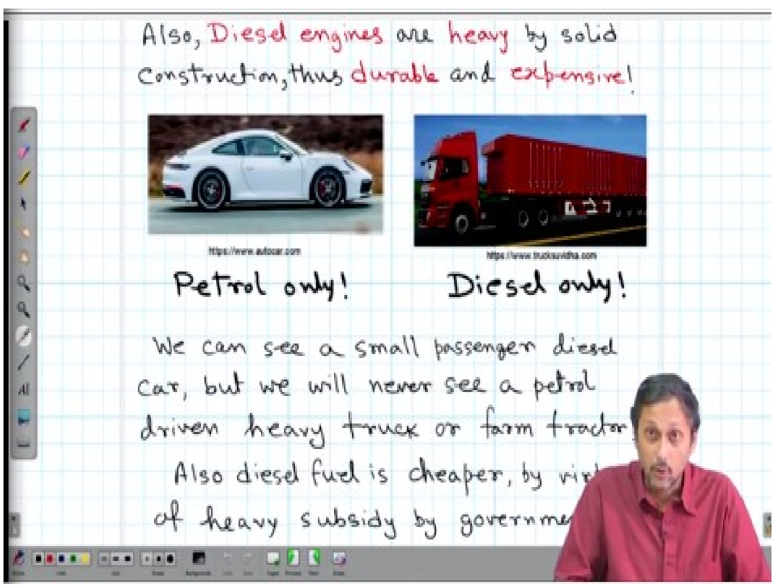

And also please remember that a diesel engine is heavy by construction because the entire combustion process is based on what we call compression, pure compression there is no spark involved. Diesel engine is typically made of cast iron metal basically cast iron whereas an aluminum block is used in a typical petrol car which makes a equivalent model diesel car some 100 to 200 kilograms heavier as compared to a petrol car.

Also it becomes more expensive; the typical diesel car for equivalent model is typically 50,000 to 1 lakh rupees costlier as compared to a petrol car. So, basically what we have understood from this discussion is petrol cars are typically performance oriented, it gives you more power, but diesel car are more about utility, you have high mileage, heavy load user design. So, the typical use just to give you an idea, let us say a Porsche's sports car is always a petrol, we cannot have a sports car in a diesel version because diesel engine will not give that much of power that is required for a typical sports car.

Whereas, a heavy truck, a multi axle heavy truck which can carry up 230 or 30, 40 or 50 tons of load cannot be a petrol vehicle, it is always has to be a diesel vehicle. But still sometimes small passenger vehicles are preferred; some people preferred diesel engines because of the high mileage and of course the durability because the diesel engines are made of solid steel or solid cast iron.

A diesel car which has ran about 2 lakhs kilometer probably have no wear and tear in the engine. Whereas, a petrol car which has ran for 2 lakhs kilometer probably needs it is like, has reached the end of it is life cycle, so that is why. And also keep in mind that not only the high mileage but the diesel as a fuel is cheaper as compared to petrol went to very high subsidy by the government.

This subsidy is given primarily because the diesel is the choice for farming equipment and transport equipment where transport vehicles where the public life depend on these things. So, that is why there is a heavy subsidy on diesel but please remember diesel the production cost of diesel fuel is more as compared to equivalent amount of petrol fuel, keep this in mind.

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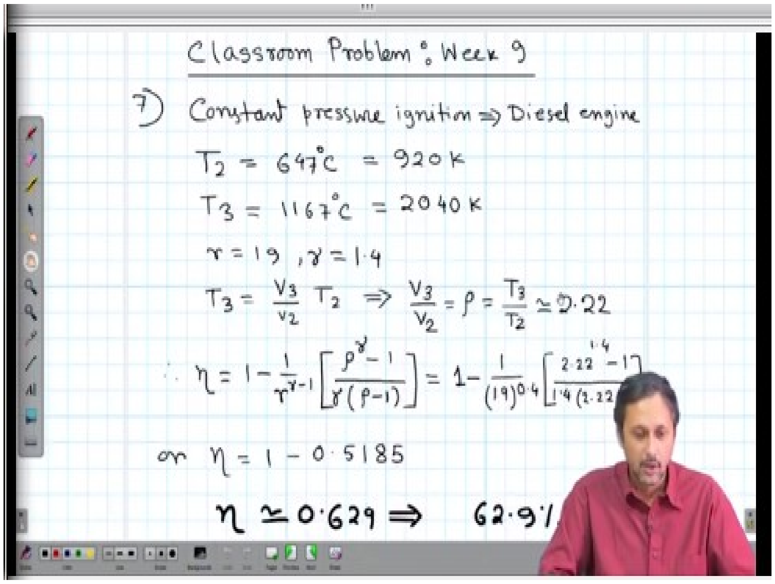

So, let us move to the classroom problems with this discussion.

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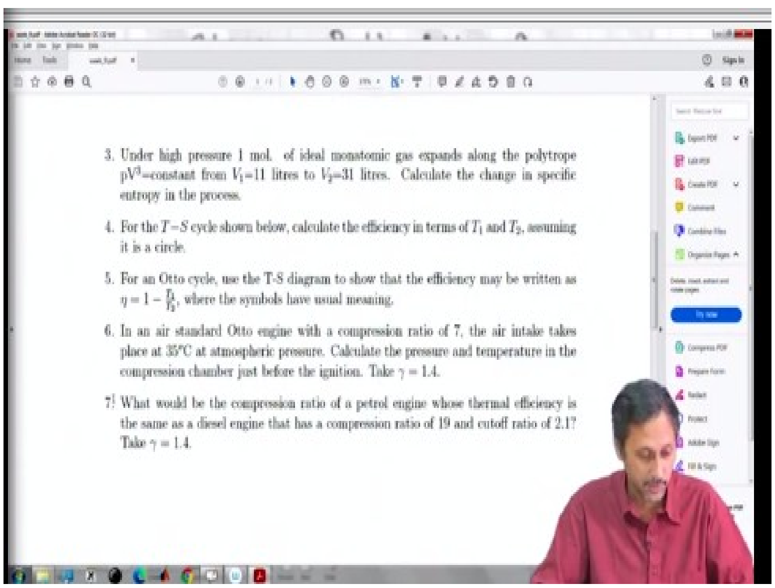

So, unfortunately I forgot to bring the updated this one, updated question paper. I have the second problem which we are going to discuss that in the modified set will be problem number 8, problem number 7 in the modified set is a slightly different problem which says, I can give you the statement which says in a constant pressure ignition type internal combustion engine, the temperature just before and after ignition is 647 degrees centigrade and 1167 degree Centigrades. Find out the efficiency of that engine.

Now when it says constant pressure ignition type that means we are talking about a diesel engine. Because just to give you a quick recap, this is where the ignition takes place, so it is a constant pressure, petrol engine is a constant volume ignition type. So, we have T 2, so basically T 2 and T 3 are given which is 920 Kelvin and 2040 Kelvin. Also r is given the compression ratio is 19, gamma is equal to 1.4.

So, now what we have to do is we have to find out the value of rho, now rho is what? Rho is V 3 by V 2, now T 3 by T 2 is equal to V 3 by 2 because T by V is equal to constant for a constant pressure situation. Given that we are talking about ideal gas, of course which is only an approximation. So, we get V 3 by V 2 is equal to rho is equal to T 3 by T 2 which is 2.22. So, if we plug in 2.22 as rho is equal to 19 for r and gamma is equal to 1.4. So, we get eta is equal to putting all these numbers, we get 0.629 which means 62.9% efficiency.

Just to give you a hint, the idea that real life efficiency of a diesel engine can go up to 40 to 45%. Whereas, for real life efficiency of a petrol engine can go up to may be 35% but typically between 25 to around 30, 32%. So, diesel engine in considering everything, so this 62.3 or let us say 63%, of course is the efficiency the thermodynamic efficiency. And right now I am talking about real life efficiency which is much less, but still it will be more for a diesel car as compared to a petrol car.

Now the last problem for today which is actually problem number 8 in the modified set but it is 7 here. What would be the compression ratio of a petrol engine whose thermal efficiency is the same as a diesel engine that has a compression ratio of 19 and the cut-off ratio of 2.1? So, compression ratio is 19, cut-off ratio is 2.1 and gamma is equal to 1.4. Now, just from the previous problem, we have seen when there is a compression ratio of 19 and cut-off ratio of 2.22, we get 62.3%.

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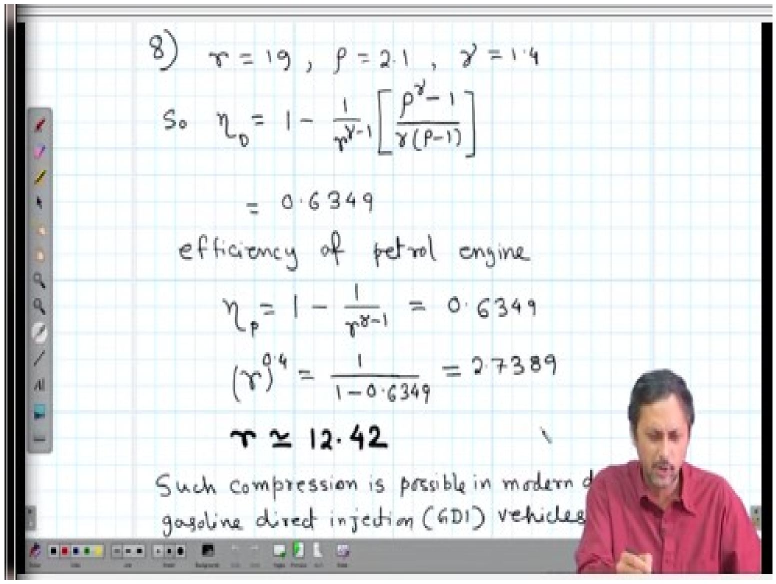

So, the value I have not calculated it explicitly here, it will be slightly higher, it will be 63.5% roughly, so 0.6349. Now if we need to have this efficiency in a petrol engine, we need to put this formula n P, so eta D is equal to this. So, eta P is equal to 1 by r to the power gamma minus 1 which is 0.6349, so we get r is equal to 12.42. Which once again is a very, I mean it is high for a conventional petrol engine but let me once again tell you that there are gasoline direct injection type of car engines which are called the GDI engines.

Which is relatively modern technology not very new, it is there a news from late 90s actually or early 90s actually. But at present this technology is new to the Indian market, slowly and slowly it is being introduced to India now. And this GDI engines can have the technology is somewhat similar to diesel. So, there the compression ratio can go up to 12 or 13%. Anyway, so that is where we stop today.

And today we have discussed primarily about diesel engine. And although this course has nothing to do with automobile engineering, I thought I will give you some basic overview of a petrol driven car and a diesel driven car. I thought I think I have managed to do that. So, in the next lecture, which will be the last lecture for this week, we will be talking about little more theoretical aspects related to entropy, till then goodbye.