Engineering Thermodynamics
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Lecture – 16
Laws of Thermodynamics:
Introduction to Carnot Cycle.

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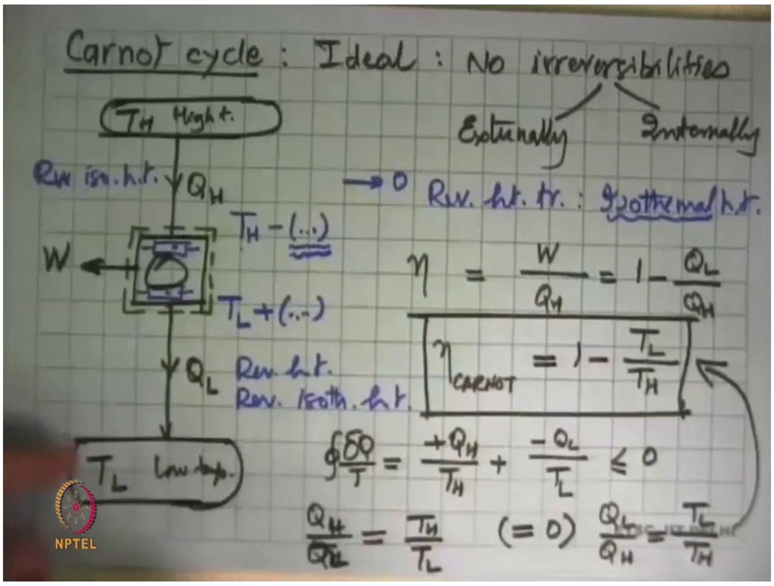

This cycle you already probably you have come across this called the Carnot cycle. This would be what you may call the ideal cycle; this is a cycle it will be the best possible cycle if there are no irreversiblities internally or externally. So, let us look at first at the heat engine and say that this is the cycle and its takes energy from a reservoir at temperature T H and a quantum of heat which is Q H and dumps Q L into the low temperature reservoir and the difference of these is W.

So, the 1st law is obeyed by this system that that we are say from that. And we say what is the highest possible efficiency that we can get from this. And that tells us that there has to be a relation. Firstly, there should be no irreversibilities no reversibilities inside the system so, there could be a pipe flow, there could be a turbine, there could be a compressor, there could be a cylinder piston arrangement whatever is there inside there should be no irreversibility inside this.

The second thing is, this heat transfer this is going to be the cause of external irreversibility; that means, when this heat you have been transferred it will do. So, to some device in this system and we are saying is that this heat transfer should be reversible to. For that to happened the temperature of the substance here should be T H minus a very very very very small amount so, that we have reversible heat transfer and second with this heat transfer is taking place, the system is undergoing some process there the temperature here should be T L plus a very very very small amount over there.

And that is leading us to a the idea that for heat transfer to be reversible, that temperature difference should be very very small and say this is approaching 0, this temperature is almost equal to this temperature and we say this is reversible heat transfer. As in the temperatures were same we can say that this is reversible or isothermal heat transfer to a some little bit fine in that how can a heat transfer take place if it is a isothermal process; isothermal means there is no heat transfer, but heat transfer means there is energy transfer.

So, because that this is now only an approximation that we are doing, that the temperature difference take place over an infinitesimally small difference that is all. So, this has to be reversible heat transfer process same thing here. Reversible isothermal we can both together reversible isothermal heat transfer and this is also reversible isothermal. So, if all these conditions are met, then we look at the efficiency of the Carnot cycle the cycle efficiency, this will be as before W upon Q H which was 1 minus Q L upon Q H and we can go through a involve derivation and show that the maximum possible efficiency which is the Carnot efficiency this is 1 minus T L upon TH.

Or we looked at in another way we apply Clausius inequality on this then what happens is, it is telling us that cyclic integral of delta Q by T, this is Q H is positive divided by T H plus Q L is minus Q L heat out of the system divided by T L less than or equal to 0 and so, the Clausius inequality is telling us that if this were to be equal to 0, then Q L Q H upon T H should be equal to T H, T L upon TL. So, in case this equality is 0 and we can see that this leads to this that sorry this is Q; Q L upon Q H is equal to T L upon T H then we got this expression.

So, what I had just stated we have actually prove it very simply by employing Clausius inequality and we note the fact that the most ideal cycle is going to be a reversible cycle so, we put this equal to 0 and going to have. Now the Qs and Ts in this are the system Qs and Ts the temperatures here, but because this was isothermally transfer the fluid here the working substance here is at T H very very slightly less and here at T L very slightly more than T L that we are approximating both as T H and T L which is why we got this now.

So, we got a very important expression which tells us that the maximum possible efficiency you can get is determined by the temperature of your high temperature reservoir and by the low temperature reservoir. It is independent of what type of a cycle you make, how many stages you make, what working substance you have, how small it is, how big it is one of that matters only these 2 temperatures tell you what is the maximum symbol efficiency that you can get.

So let us play with some numbers on this, in fact, no what are all numbers are you looking at. So, we say that look in the real world when I have to make electricity which is what your work is, I have to have a high temperature source and I have to have a low temperature reservoir.

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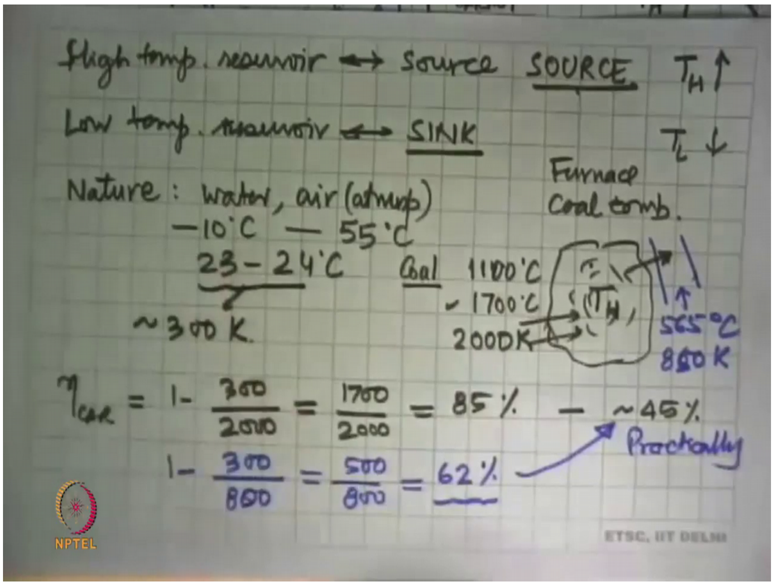

So, we need to figure out two things; a high temperature reservoir that we shall call a source and a low temperature reservoir which we will call sink. So, those two things are there and we want to work with what is around us. So, we say that what is that sink that is around me and you have either in nature, you have either the water in the oceans or air in the atmosphere. They are the only two things we have naturally occurring. One can argue that well I will reduce my temperature of the sink by putting a refrigeration plant, well yes you will put that plant, but when trying to reduce the temperature you will consume a lot more energy and that way although your efficiency of the cycle heat engine went up a little bit to overall efficiency is high.

So, that is not a very impractical solution and we say well what type of temperatures do we have around us and we say look in winters, there are some parts of India where temperatures are minus 10 minus 20 minus 40 degree Celsius and in summers we get temperatures of the order of 55 degree Celsius in some parts of the country. And water which depends on the if you have looking at the ocean you have temperature which are raising of the order of 23-24 degree Celsius, so, that is a type of sink temperatures that we have.

And this expression tells us that to get highest efficiency, T L should be as low as possible, T H should be as high as possible. So, which say that where should I locate my thermal power plant, the answer will be go to the place which is very cold and that probably meet the C R chain glacier that is way to far off getting any material over there is the challenge putting it to whether is the big difficulty and then even if you make electricity there how are you going to get it out. So, all of this make it in impossible although scientifically it is possible technically it is impossible so, we do not do it.

And so, we put it somewhere and the power plant I just showed you the picture that is at y z. And y z takes water from the ocean at 23 24 degree Celsius and it is the coal fired power plant. So, the source is sort of a furnace in which we are all the time continuously burning coal. So, what you are doing is, we created a big space in which we are continuously keep firing coal and air, it keeps burning and as the heat is transferred to the water we keep firing more and more coal, so, this temperature remains elevated at temperature T H.

Same thing we do if we have firing oil in a boiler to produce steam and the maximum temperature we can get in this case is of the order of say about 1100 degree Celsius somewhere over there. If you burn very good quality coal you could get 16 1700 degree Celsius. So, which means that if you burn very high quality coal which we do not have in our country, what we have is very low quality coal we (Refer Time: 12:15) ash in it even if I get good quality coal we get a source temperature of about 2000 Kelvin.

And the sink temperature of the order of 300 Kelvin and now we put it back in that three method and what is the best efficiency I can get? Then we get that for this temperatures, the Carnot cycle efficiency becomes 1 minus 300 upon 2000 which is equal to 1700 by 2000 which is 85 percent, a much high efficiency we will be very happy to get that. In the real world (Refer Time: 13:14) you saw would be lucky to get to 45 percent. So, this is what is theoretically possible, this is what is actually there, all our electricity comes from plants whose thermodynamic efficiency is of this order.

But now we look at another way to analyze this problem because here we assume that the furnace temperature was 2000 Kelvin and to the water temperature that it produce was also 2000 Kelvin which is what we assumed in the Carnot cycle. So, that is what remain in the case, because at this transfers heat to the water going in the maximum water temperature we have there is 565 degree Celsius. So, this we can say is of the order of 800 8 let us say 850 K I am approximating it.

And in this case the efficiency you know becomes 1 minus 300 upon say 800 and that is 500 by 800 which is about 62 percent. So, we sacrifice something because we could not general operate the power plant whose steam temperature was 565 degree Celsius then that little we can do with the ambient. So, we say that the best I could get is 62 in fact, this 300 will also be slightly more its about 310 315 320 that refinement one can do later on that is not an issue, but its of the order of like 60 62 percent. So, with 60 62 percent possible theoretically practically 45 percent is what we get. So, what it tells us is that, in this system whatever energy we took from here some of it came out as power some went over here.

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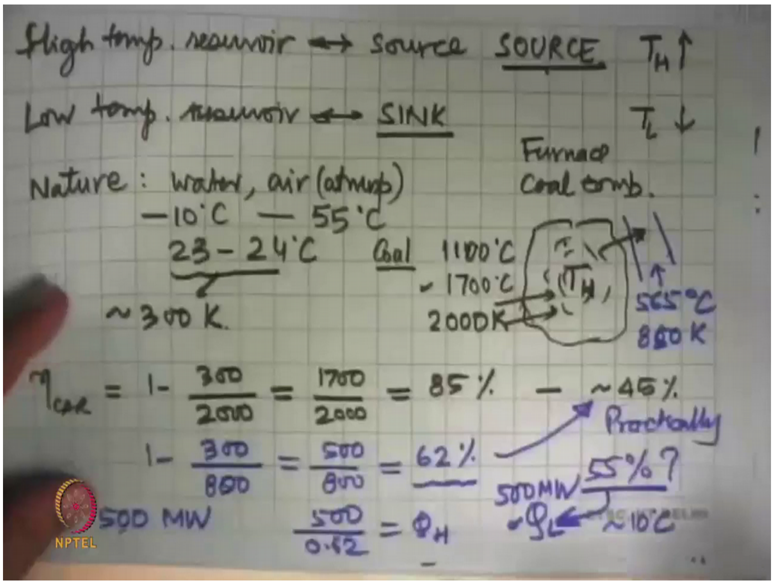

And in this particular case if the work output was say 500 megawatts, gross met then it tells us that this is only 62 percent of what we put in. So, in reality we are putting 500 divided by 0.62 this is how much Q H is there and the difference of these 2 is Q L; that means, in this case instead of 45 percent coming out; 45 percent came out of the electricity, there we did the 55 percent remaining go and that went as Q L.

It was dumped into the atmosphere and how we did that? We just took lots and lots of water from the ocean, condense the steam, the water temperature goes by about 10 degree Celsius and we threw this water back into the ocean or we dip that with water and we cool the water in air so, that heat was transferred to the air. So, if this was 500 megawatt electrical output we are dumping of the order of 500 megawatts into the atmosphere after burning 1000 megawatts from the fuel. That is what the total energy balance looks like that is the huge amount of energy which we dump into the sink and we have to do it, because that is what the 2nd law of thermodynamics is telling us ok.

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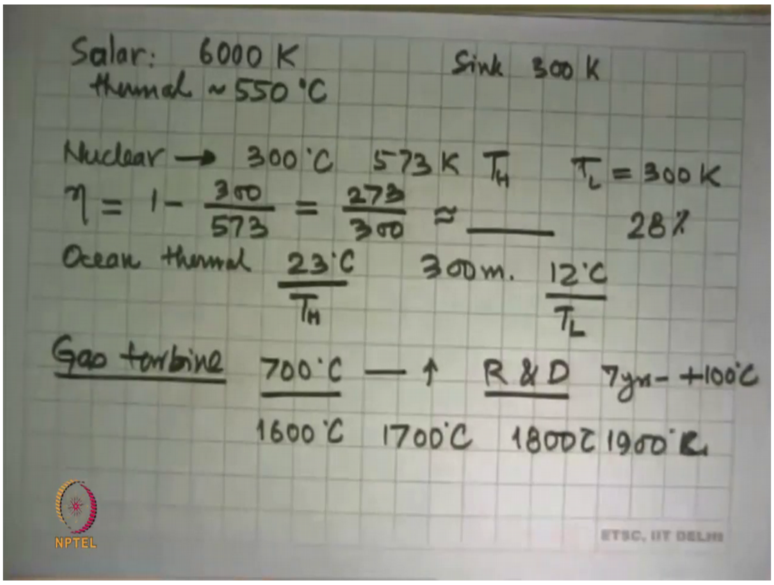

So, we let us take some other example now, there are lot of talk of solar energy now. So, somewhere we know is at 6000 Kelvin and the atmosphere is at 300 Kelvin then clearly this ratio tells you that we can get great cycle efficiency by going to 6000 Kelvin. But that means, that your working substance also has to go to 6000 Kelvin and that is not possible because neither we have a substance nor a metal or a material which can withstand 6000 Kelvin, so, we work at much lower temperatures.

So, solar thermal what one ends of doing with some of the pictures which I had showed you in first module, where you concentrate the solar rays on to a point and heated the steam there we got temperature is much like the solar the fossil fuel power plant, steam temperature of the order of 550 degree Celsius, sink again 300 Kelvin or near about. And the efficiency of solar thermal power plant in the best case is comparable to the efficiency of a coal fired power plant. If this temperature were to be lower the steam were to be generated at 300 degree Celsius efficiency would further come down.

In the nuclear power plant, the reactor that we have efficient type of reactors they produce steam at about 300 320 degree Celsius. So, that is 573 Kelvin and that is your T H and you are dumping back T L is (Refer Time: 19:00) 300 Kelvin. So, if you look at the ratio now the thermodynamic efficiency will be 1 minus 300 Kelvin upon 573. So, this is 273 upon 300 and so, this is about less than 50 percent no sorry T L is 300 K, this is 573 and this is 273 this is of the order of this comes for to be a very large number there no wait there is something missing here.

The efficiency of a nuclear power plant is of the order of 28 percent you know temperatures are much lower and we can also look at the idea of ocean thermal, where the sea surface temperature is 23 degree Celsius and at 300 meters depth the temperature is like 12 degree Celsius. So, theoretically it is possible that this is used as T H this is used as T L and we can see what type of efficiencies we can get very very small efficiencies is what we get here.

So, that is the idea of what sort of numbers we are dealing with here. So, that is all coming out from what the Carnot cycle was we will take one more example then we will stop and that is the gas turbine. When the first gas turbines were made in the 1950s, the maximum temperature in the turbine was of the order of 700 degree Celsius and efficiencies were very very low. And then they realized that if you can keep take this up the engine should become more and more efficient and this has been the big driving force of much of R and D in aircraft engine design, it still continuing and in every 7 years or so, this temperature goes up by 100 degree Celsius.

So, today we have engines which are 1600 degree Celsius already there 1700 degree Celsius which are also be marketed and research is going on to take it to 1800 1900 and 2000 Kelvin sorry Celsius. So, what is its a lot of effort very large research teams work on this, but the whole idea of doing that research is that what we have just learnt in the Carnot cycles, that we want the efficiency of this system to go up. So, although we are not directly everyday working with the Carnot efficiency and doing this calculation, this is the basic driving force for all of research that is happening here and what is also happening on fossil fuel power plants, that is were 565 the idea is to take it to 710 degree Celsius.

When we do that our efficiency goes up of the same power output, we need to burn less fossil fuel because of that the carbon footprint is less we make the power plant little more ecofriendly. And so, climate change is now little issue where efficiency is the we looked that very seriously and thing which were not done for 20 30 40 years are now being done here where in aircraft engines this is always been a trend and still continuing there are some questions here. So, let me take those first why Carnot cycle is irreversible no sorry

Carnot cycle is the only thing where everything is irreversible I said no irreversiblities so, ideal means this is reversible. So, there are no internal boxes of any type in the Carnot cycle that is why it is the most efficient cycle.

Why is it not possible practically? Practically it is just not possible simply because first if you want to do heat transfer over a very small temperature difference, you need very very huge machines that is not feasible economically; in the engineering becomes very difficult and no matter what you do friction will always be there. So, that is going to be an irreversibility that is there in the real world, when a fluid moves in a pipe there is the pressure drop that is because of frictional drop. So, you cannot ever get rid of all these with sources of irreversibilities.

Processes have finite rates of change, so, they are irreversible. So, we just cannot get rid of that there is no hope ok. So, there is a question that was come up what is a Carnot cycle ok? So, let us take that up now. So, I have been saying there is a Carnot cycle. So, we have seen that this Carnot cycle has a at least 2 processes ok.

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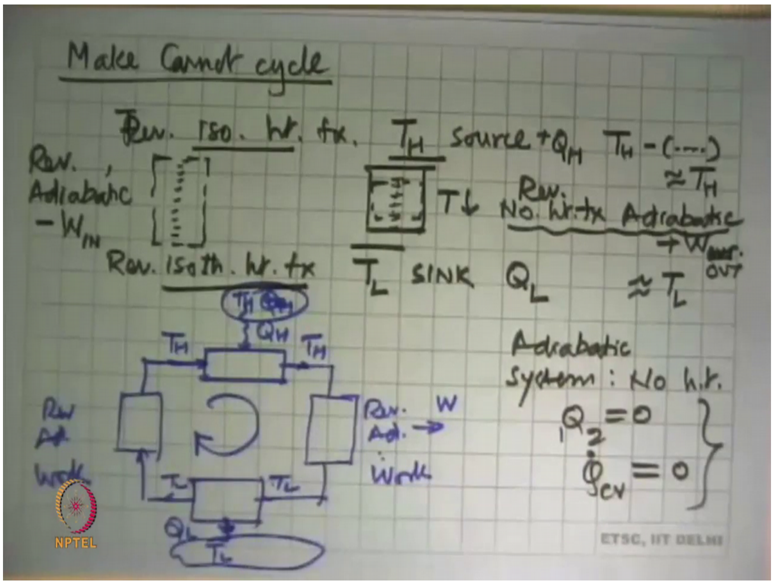

How to make a Carnot cycle? So, there has to be 2 processes first there is a reversible isothermal heat transfer from the source this is one process. And this during this process the working substance temperature is just slightly less than this practically equal to T H; that means, during this process the temperature of the working substance cannot change.

Then, we said that there has to be a second process here, which is this heat transfer so, we have here reversible isothermal heat transfer. So, this is plus Q H with as T L temperature sink and dumping some heat Q L and the temperature of the working substance when it does this is almost equal to T L. Two processes are required and now we want to complete the cycle, the fluid in this state is at T H fluid in this state is at T L, we just cannot have this directly go into this because, then you will have something you are hot fluid mixing with the cold fluid it immediately becomes irreversible not possible.

So, what do we have to do? We have to take the fluid from this state to this state and do something with this. There has to be some other process. Now we already put a restriction that the fluid not exchange heat with either T H or with T L, it cannot exchange heat with any third reservoir. The moment the fluid starts doing something and its temperature starts coming down in this. So, this process has to be a process where its temperature keeps coming down and at any point when its temperature is decreasing, it cannot be in touch with this and it cannot be in touch with this because we have finite temperature difference between them that will cause irreversible heat transfer.

So, that is not allowed, which means that as this temperature is coming down there should be no heat transfer. So, this has to be my adiabatic process, as it is during this adiabatic process that you get a work output. So, this is a plus W process we can put it that way. So, we heated it got it a T H and then we did an adiabatic process with it in which we got workout and the fluid came down to a lower temperature which is T L.

Now, it dumps heat into the sink and it s temperature still remain T L so, it has done this heat transfer. So, this is a third process that we have added no heat transfer adiabatic work output and we need now one more process that we will take it from here to there. And to do that we will put a another process and argue the same way that we have do this process in such a way that as the fluid goes through this its temperature should keep going up that is number 1. Number 2 it should not be in contact with either that sink or it in contact with the source that will neglect irreversible hear transfer.

So, as it goes through this, again this has to be a adiabatic process and here we have to do work on the system. So, we will say W my plus W we call this out, this will be in. Adiabatic means that the system does not have any heat transfer with the surroundings. So, Q 1 2 would be 0 if it would have cylinder piston management or Q dot c v will be 0 if it is the flow system. So, we need two more processes which are adiabatic and we said that the Carnot cycle everything has to be reversible, so, this has to be a reversible adiabatic process and this also has to be a reversible adiabatic process.

So, now we can put the essential elements of the Carnot cycle reservoir that we take the working substance in whichever that close system or open system, where in one process it comes in contact with the high temperature reservoir and gets energy Q H it goes in at temperature T H and comes out at temperature T H. Then we put it through a process which is reversible adiabatic process where you get work out then we have a process where it comes in contact with the low temperature sink, where it dumps heat Q L is output.

Temperature of the fluid remains at T L and then we have another reversible adiabatic process, in which its temperature rises from T L to T H without heat transfer. So, this is temperature drop without heat transfer this is temperature rise without heat transfer, so, that needs only work transfers are possible.

So, those are the four process we want, a reversible isothermal heat transfer, reversible adiabatic process, reversible isothermal heat transfer, reversible adiabatic work. Those four processes if you can get together we will make a Carnot cycle and to see how that will happen, we will go little beyond this and now come across with the definition of what is entropy.

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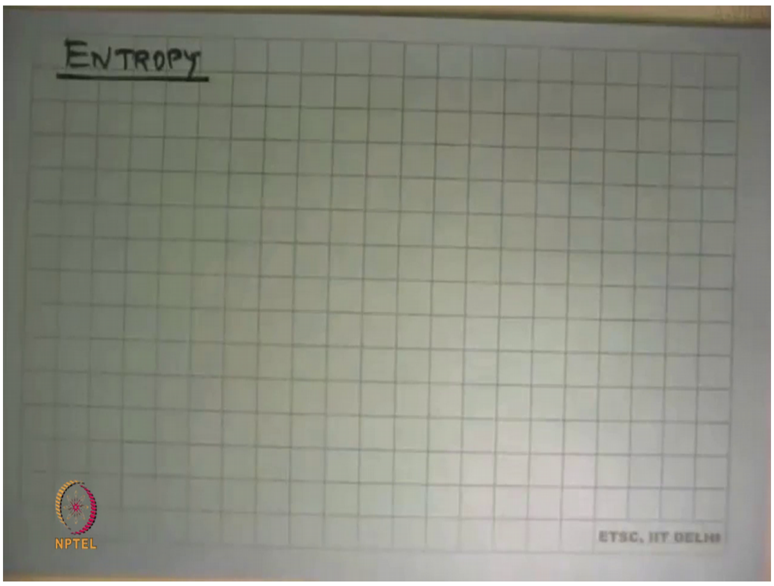

And that will tell us how the cycle has to be made there is a question. Here is the overall efficiency of engine more than 50 percent we were questioned where I do not know what engine one is looking at because thermal power plants internal combustion engines are all engines, well designed diesel engines operating at steady state will have the efficiencies of the order of 45 to 48 percent.

Petrol engines are much more and remember this whole discussion about efficiency that we have talked about is only valid if you have steady state. If the engine is not in steady state we cannot talk about its efficiency and unfortunately that is the reality on the road when you drive a vehicle, your engine is never in steady state always ok. Coming back to the question can we have efficiency of 50 percent, well yes now we have we can say the heat engine, which is a combined cycle power plant we will come to that a little later were you burn fuel in a gas turbine get a very high temperature there.

Then use that exhaust to generate steam and then run a steam turbine, that you are talking of processes that get us a 60 percent efficiency and there is a research going on to take it up to 66 percent efficiency. So, burning a fossil fuel oil or gas not coal, they have the highest efficiency possible in a combined cycle power plant which people are talking of getting about 66 68 percent that is possible.

So, there is also a heat engine although it may be a very big huge building thermodynamically, that is a heat engine because we are putting in fuel and getting heat and dumping it to the atmosphere and the remaining is coming outer over.