Indian Institute of Technology Kanpur

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Course Title
Engineering Thermodynamics

Lecture – 32
Gas Power Cycles 2

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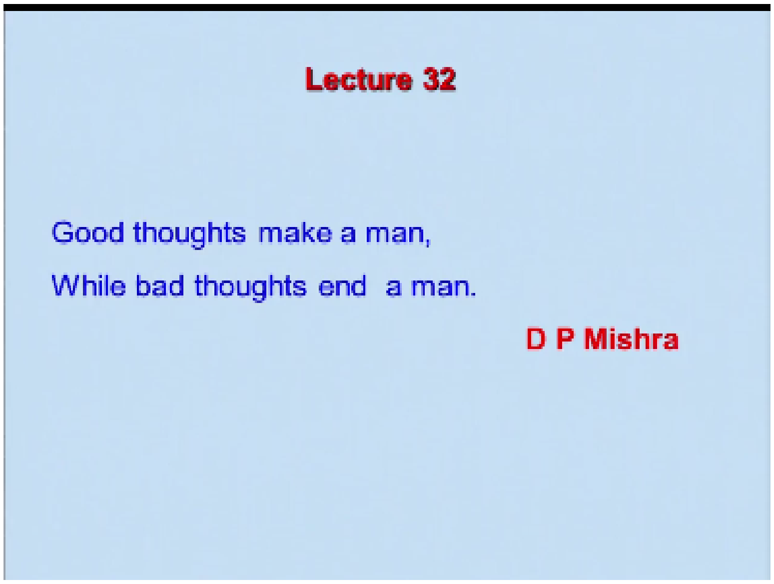

Lecture 32

Good thoughts make a man,
While bad thoughts end a man.

D P Mishra

So let us start this lecture with a thought process that is which is important for human life what you call man is a thinking animal right. So good thoughts makes a man well bad thoughts end a man. So one has to be careful about his own thoughts what are coming to you. And let us now go back to our discussion on thermodynamics, and in the last lecture we discuss basically the gas power cycles in that we looked at the example of auto cycle what we call a spark ignition engine also, because spark ignition engine is modeled using the auto cycle.

And also it is known as gasoline engine not only the SI engine or the spark ignition engine but also the gasoline engine. But if you look at this gasoline engine is being used basically for the small powers and then as we are discussed that its limitation is the lower compression ratio as a result the efficiency will be you can think of lower. And inert to enhance this efficiency and utilizing the problems faced by that that the problem faced by that is the auto ignition right which will be leading to the uncontrolled compassion.

So we will be now discussing an engine which utilizes that concept and develop engine that is the diesel engine.

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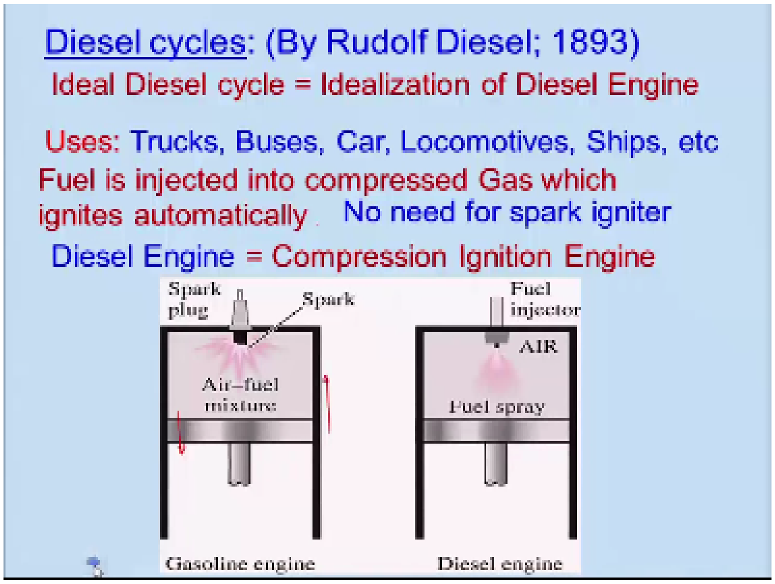

Diesel cycles: (By Rudolf Diesel; 1893)

Ideal Diesel cycle = Idealization of Diesel Engine

Uses: Trucks, Buses, Car, Locomotives, Ships, etc

Fuel is injected into compressed Gas which ignites automatically. No need for spark igniter

Diesel Engine = Compression Ignition Engine

So we will be discussing about basically ideal diesel cycle which is based on the air standard assumptions what we had done for the auto cycle those assumptions will be valid for this ideal diesel cycle and diesel Rudolf diesel is the person who devised this cycle and also he conducted experiments in 1893 who really did not use diesel for his experiments he used vegetable oils for that okay, what we use today known as biodiesel okay you might be aware biodiesel is a very big thing nowadays.

But it is their history goes back to the Rudolf diesel in 1893. So and generally this is being used very much for the trucks, buses, car, locomotive ships and several places like you are even if you go to the rural area we do pump the water in the field right for cultivation purposes and that uses the diesel engine. And beside this for the temporary power kind of thing what you call the genset generator kind of generating electricity we do use the diesel.

But however the gasoline engine is restricted to very small power like your car or your automobiles and sorry bike a kind of things that is being used. So and in this case what is being done is the fuel is injected into compressed air which ignites automatically right, there is no need for any spark ignition engine, but in this case if you look at that concept the problem which was faced by the auto engine that is the auto ignition being exploited here to the advantage which was a disadvantage for the auto engine that is being used as advantages in this engine right.

As a result we need not to have a spark igniters in case of a gasoline engine we need a spark igniter to initiate the combustion and diesel engine is also known as compression ignition engine right the auto engine or the gasoline engine we call it basically spark ignition engine and here we call it as a compression ignition engine some place you may find CI engine right. And just to explain it this thing let me just look at what is happening difference between the gasoline.

In the gasoline engine both the fuel and air mixtures enter into the engine during the suction stroke, but in case of diesel engine only air enters into the engine during suction stroke you got the difference now. And then in the compression in the gasoline engine both the fuel and air mixture are compressed when the piston moves up it get compressed and then it will be spark will come and again the piston will move down and that is of course shown here in this diagram was known as the power stroke okay.

But in case of diesel engine that air is compressed not the fuel-air mixture as in the case of gasoline engine. And then when it what you call compressed and the pressure will be increasing so also the temperature. And then the fuel is injected using basically spray it is the liquid fuel directly injected right. And there will be droplet is a quite a complex phenomena spray will be there will be small droplet, larger droplets and then they will be mixing in between and then it will ignite off because the temperature is much higher than the auto ignition temperature.

Let me emphasize again earlier the auto ignition is a problem, but here it is a solution for igniting the mixture kind of. As a result like you can use the higher compression ratio in this case of course you will have to pay a penalty you might have observed whenever you are going in a truck and other things that noise level is higher and even diesel car has come up that noise level and vibration also higher.

So therefore the life of a diesel engine is less as compared to what you call gasoline engine that is why the diesel engine should be made heavy little bit to observe the what you call vibration created by the engine.

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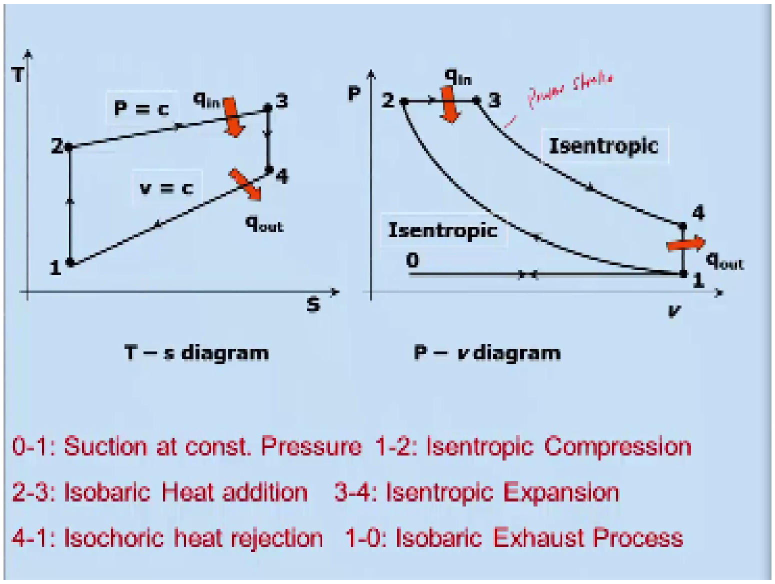

0-1: Suction at const. Pressure 1-2: Isentropic Compression

2-3: Isobaric Heat addition 3-4: Isentropic Expansion

4-1: Isochoric heat rejection 1-0: Isobaric Exhaust Process

So what we will be doing, we will be doing the similar cases like what we have done for the auto cycle that is 0 to 1 is a suction without any pressure change which is an idealization and 1 to 2 is your compression isentropic compression, and 2 to 3 is your heat addition at a constant pressure keep in mind this is a constant pressure heat addition right. And in case of auto cycle the heat addition is constant volume heat addition are you getting the point.

So this is a very important point it should keep in mind after that of course it is same from state 3 to 4 isentropic expansion and this is basically power stroke, because the power by the engine is being produced during this expansion process only. And 4 to 1 is your constant volume heat rejection during the section of course 1 to 2 will be constant pressure exist kind of thing which is idealizes and this is the ideal cycle keep in mind that we are using ideal for the simplicity.

And if you look at in TS diagram right it looks like that I have not considered the 0 to 1 as a process in the TS diagram and 1 to 2 your isentropic compression and 2 to 3 is your constant pressure heat addition and 3 to 4 is your isentropic expansion, of course 4 to 1 is your heat rejection right. So this is the process and we are going to analyze that.

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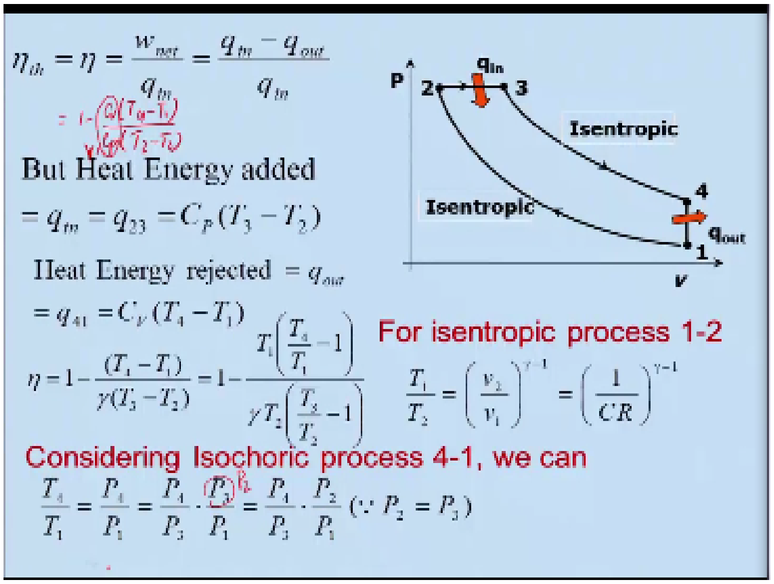

$$\eta_{th} = \eta = \frac{w_{net}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}}$$

$$= 1 - \frac{C_v(T_4 - T_1)}{\gamma C_v(T_3 - T_2)}$$

But Heat Energy added

$$= q_{in} = q_{23} = C_p(T_3 - T_2)$$

Heat Energy rejected $= q_{out}$

$$= q_{41} = C_V(T_4 - T_1)$$

$$\eta = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{\gamma T_2\left(\frac{T_3}{T_2} - 1\right)}$$

For isentropic process 1-2

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \left(\frac{1}{CR}\right)^{\gamma-1}$$

Considering Isochoric process 4-1, we can

$$\frac{T_4}{T_1} = \frac{P_4}{P_1} = \frac{P_4}{P_3} \cdot \frac{\overset{P_2}{P_3}}{P_1} = \frac{P_4}{P_3} \cdot \frac{P_2}{P_1} \; (\because P_2 = P_3)$$

And we will do the similar way and here again we will be considering the control mass system not the control volume of course keep in mind that you can also use the control volume and do that but you will have to do it carefully okay, you do not think that only the control mass system can be utilized you can use that, but one has to take care of it. Any problem seminary problem can be solved either by the control volume or the control mass, but in one case it will be simpler other case it would be little complex that is all.

Here we are taking the control mass system, because it will be simpler one okay. So the thermal efficiency is basically equal to the net work done divided by the Qin and net work done we know that Q_{in} - Q_{out} right that is a net work done. And / the queue in will give me the thermal efficiency and we are always interested to find an expression for the thermal efficiency and also the work done.

So the heat energy added is basically Qin = Q23 x Cp (T_3-T_2) right and heat energy rejected is Q_{out} and which is Q Cv x T_4 - T_1 right. If you look at this heat added is basically constant pressure heat addition. So therefore the Cp will come into picture is it is the change in enthalpy basically constant pressure process you know very well that is E direction is nothing but change in enthalpy, enthalpy is no CP x ΔT that is the thing and it is a heat rejection and you put the things is basically 1-T_4-T_1/ γ because Cp Cv if you look at into T_3 – T_1.

So if you look at you can do it here itself that is 1 - that is Q_{out}, Q_{out} is nothing but your Cv T_4-T_1/Cp T_3-T_2 so Cp Cv you know this one is nothing but your γ. Cp/Cv is your γ okay, so Cp/Cv, so if I take this out like T_1 here then I will get T_4/T_1-1 and in similarly in the denominator like if I take T_2 out it will be T_3/T_1 -1 in this bracket. So what we will do we know that this T_1/T_2 right we know this what is that right we have all is done in the auto cycle, we can relate this between this state 1 to state 2 this is isentropic compression we can basically convert that into the compression ratio right.

So we have already done that T_1/T_2 is nothing but 1/CR that is a compression of power to the γ-1 and considering the isochoric process for 1 we can get basically T_4/T_1 is nothing but you P_4/P_1 and I can write down P_4/P_3xP_3/P_1 and if you look at constant heat addition therefore we can say that P3 constant pressure heat addition right constant pressure heat addition there for P_2=P_3 so therefore I can write down P_3 in place of P_3 I can write on P_2 here.

And if you look at this P_4/P_3 is basically nothing but relate the isentropic expansion and P_2/P_1 is isentropic compression process.

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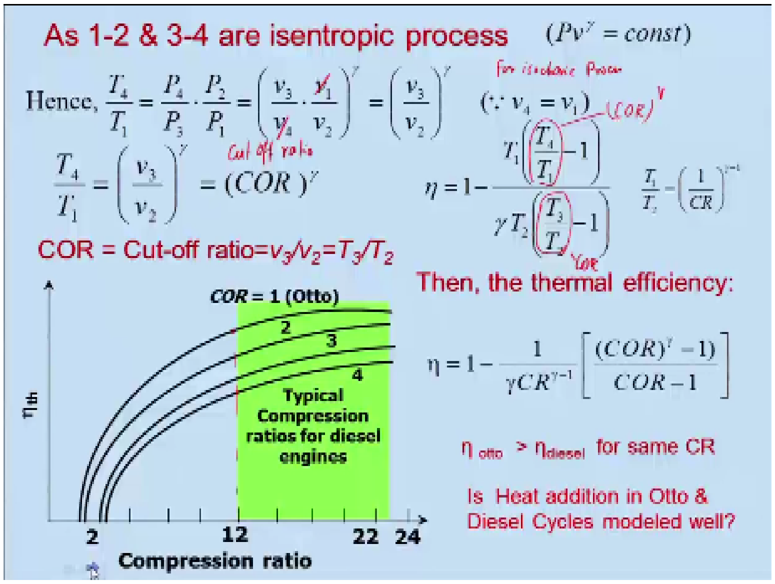

As 1-2 & 3-4 are isentropic process $(Pv^{\gamma} = const)$

for isochoric Process

$$\text{Hence, } \frac{T_4}{T_1} = \frac{P_4}{P_3}\cdot\frac{P_2}{P_1} = \left(\frac{v_3}{\cancel{v_4}}\cdot\frac{\cancel{v_1}}{v_2}\right)^{\gamma} = \left(\frac{v_3}{v_2}\right)^{\gamma} \quad (\because v_4 = v_1)$$

Cut off ratio

$$\frac{T_4}{T_1} = \left(\frac{v_3}{v_2}\right)^{\gamma} = (COR)^{\gamma}$$

COR = Cut-off ratio=$v_3/v_2=T_3/T_2$

$$\eta = 1 - \frac{T_1\left(\boxed{\frac{T_4}{T_1}} - 1\right)}{\gamma T_2\left(\boxed{\frac{T_3}{T_2}} - 1\right)} \qquad \frac{T_1}{T_2} = \left(\frac{1}{CR}\right)^{\gamma-1}$$

$(COR)^{\gamma}$

COR

Then, the thermal efficiency:

$$\eta = 1 - \frac{1}{\gamma CR^{\gamma-1}}\left[\frac{(COR)^{\gamma} - 1)}{COR - 1}\right]$$

$\eta_{otto} > \eta_{diesel}$ for same CR

Is Heat addition in Otto & Diesel Cycles modeled well?

So you can relate that thing and then do that. So we know that for this both the isentropic process the Pv^{γ} is constant. So therefore we can write down T_4/T_1=P_4/P_3 x P_2/P_1 we have already seen that and P_4/P_3 for a isentropic process is nothing but V_3/V_4^{γ} and P_2/P_1 is nothing but V_1 by V_2^{γ} and for what you call constant volume heat rejection right. So therefore this $V_4=V_1$ for isochoric process right. So therefore, this V_1 will be cancelled it out and you will get T_4/T_1 is nothing but V_3/V_2^{γ}.

So these we call it is basically cut off ratio this is what we call cut up ratio COR it is basically being cut off and then like because you are going to ads process between the state 2 to 3 what you do you add the heat basically add the fuel for the combustion at the heat. So therefore after that it is being cut off like therefore it is known as cut off ratio. So now cut off ratio is like is equal to $V_3/V_3=T_3/T_2$ that we have seen and the thermal efficiency we can look at this ratio is basically if you look at T_1/T_4 is nothing but your COR^{γ} is not it.

And we will have to see T_3/T_2 what is this one this portion is nothing but your COR, and already we know this T_1/T_2 so therefore you know we can explain this thermal efficiency as basically thermal efficiency is equal to $1/\ \gamma\ CR^{\gamma-1}xCOR^{\gamma-1}/COR-1$. So if you look at now the thermal efficiency is function of not only the compression ratio, but also the cut off ratio apart from the γ that means one more variable has come into picture for a diesel engine right.

So we can look at how it is varying we can take various what you call cut off ratios and then vary the CR for a particular γ right. And if I take these things cut off ratio of 1, 2, 3, 4 you can see the thermal efficiency is basically decreasing right for a particular pressure ratio whatever pressure is if I take this 1 pressure ratio compression ratio of 12 you can see this COR is 1 is higher thermal efficiency as compared to the COR cut off ratio of 4 right for a particular compression ratio.

And of course it is the similar in nature that a water cycle in the beginning it will be having higher slope at it decreases for a particular you know curve and the typical compression ratio for a diesel engine varies from 1 to 2 so that you can get a very higher thermal efficiencies and when this cutter pressure is equal to 1 this is the Otto cycle okay and if it is across different than one.

Will be a diesel cycle kind of thing depending upon that and keep in mind that generally a what you call Otto cycle operates over what you call around 8, 8 to 10 something people use even kind of things not beyond really 1 to 2 but this engine start from beyond when right so therefore one can say that as I told for the same compression ratio Otto cycle is greater than the diesel cycle right then question arises is heat addition in Otto cycle and digital model well if you look at in the case of Otto cycle what we have model we are model it basically as a constant volume heat addition.

Right that means what it will be very fast process right because volume would not be changing if you look at the engine is moving right all the time it will be piston will be moving right you are saying instantly it will become compression taking place and the diesel cycle if you look at it is a constant pressure process you know like right the pressure is remaining constant right so which is not really the true model if you look at both the cases is not possible so we will look at that.

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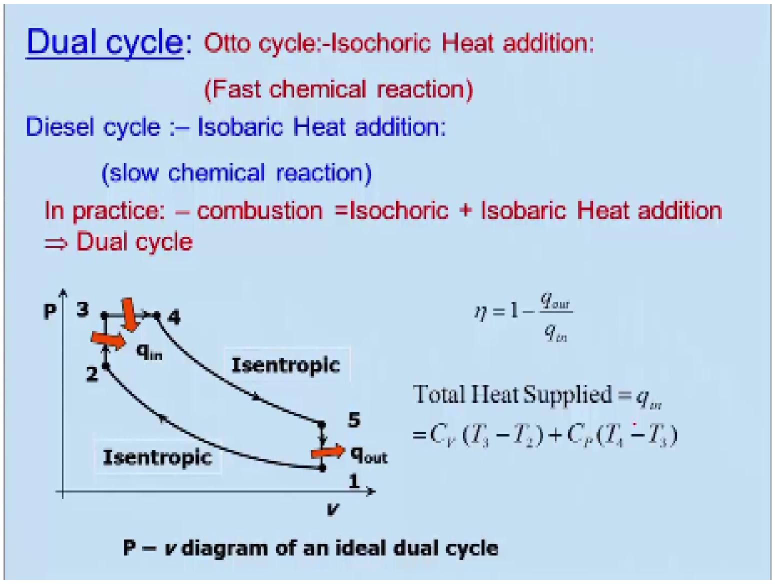

Dual cycle: Otto cycle:-Isochoric Heat addition:

(Fast chemical reaction)

Diesel cycle :– Isobaric Heat addition:

(slow chemical reaction)

In practice: – combustion =Isochoric + Isobaric Heat addition

⇒ Dual cycle

$$\eta = 1 - \frac{q_{out}}{q_{in}}$$

$$\text{Total Heat Supplied} = q_{in}$$
$$= C_V(T_3 - T_2) + C_P(T_4 - T_3)$$

P – v diagram of an ideal dual cycle

In the Otto cycle as I told the isochoric heat engines is a first chemical reaction should occur instantaneously wrong within the fraction of second wife action is a nanosecond it will be doing like that you can think of which is impossible similarly the isobaric redirection we should be slow chemical reaction will be occurring so that pressure would not go upright pressure will be remaining constant during combustion which is not possible you know because heat being added the pressure will go up in a constant volume kind of thing.

So therefore both the thing is not right so what we will do we will have to can model basically combustion as a both combination of isochoric and isobaric heat addition if you do it may meet the actual cycle to some extent and that we call it as a dual cycle right where the constant heat you know constant volume heat addition and constant pressure heat addition can take place so the cycle will be looking like that if you look at 1 to 2 compression isentropic compression will be same but and 4 to 1.

Isentropic expansion it is the same as the either the Otto on the diesel cycle and constant volume heat rejection all are same only the difference is that here we are saying it is a combination of 2 to 3 that is the isochoric heat addition and three to four is a constant pressure heat addition that is the difference what we are saying it basically any engine will be combination of that we are saying and that is the dual cycle and the thermal efficiency if you look at we can write find it out vesicle 1 - q out by q in and that is the you know constant heat addition between station 2 to 3.

Constant volume heat addition that is C_V 3 - T_2 and constant pressure heat addition that is C_PT_4 - T_3 right this is the thing what will be of course the q out will be constant volume heat rejection so if you look at.

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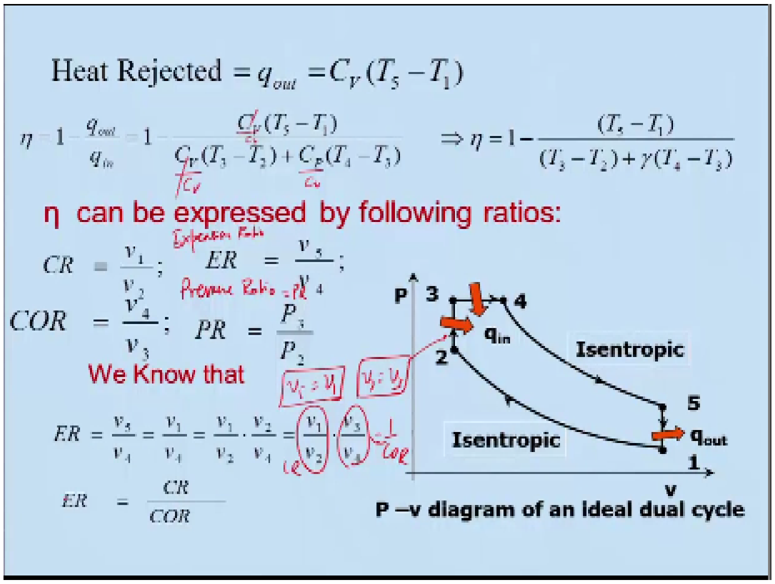

Heat Rejected $= q_{out} = C_V(T_5 - T_1)$

$$\eta = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{\cancel{C_V}(T_5 - T_1)}{\underset{\div C_V}{C_V}(T_3 - T_2) + \underset{C_V}{C_P}(T_4 - T_3)} \Rightarrow \eta = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)}$$

η can be expressed by following ratios:

$CR = \frac{v_1}{v_2}$; $\overset{\text{Expansion Ratio}}{ER} = \frac{v_5}{v_4}$;

Pressure Ratio = PR

$COR = \frac{v_4}{v_3}$; $PR = \frac{P_3}{P_2}$

We Know that

$\boxed{v_5 = v_1}$ $\boxed{v_2 = v_3}$

$$ER = \frac{v_5}{v_4} = \frac{v_1}{v_4} = \frac{v_1}{v_2} \cdot \frac{v_2}{v_4} = \underset{CR}{\frac{v_1}{v_2}} \cdot \frac{v_3}{v_4} = \frac{1}{COR}$$

$$ER = \frac{CR}{COR}$$

P –v diagram of an ideal dual cycle

Now if I substitute this heat rejection you know constant volume that is C_VT_5 - T_1 and here right and the this is the constant volume heat addition and constant pressure heat addition so it is a little complex you know like because there several temperature comes into picture T_1 T_2 T_3T_4 T_5 you know all are coming the this thing and we will have to look at how we can express in terms of certain you know parameters like you what you call compression ratio cutoff ratios kind of thing.

So that we can vary those parameters and find out what is happening and I so if you divide this thing you know by basically $C_{V,}$ C_V we hear this will cancel it down as C_P by C_V is nothing but γ right and we can express in terms of values less you already we have defined the what you call compression ratio V_1 / V_2 and cut up ratio V_4 / V_3 we have already defined and we are defining another ratio expansion ratio ER right this is I call it expansion ratio V_5 / V_4 right and pressure ratio.

This is pressure ratio is equal to PR P_3 / P_2 okay so we will be doing a little you know algebra to express this thermal efficiency of various things so we know that ER that is expansion ratio is basically V_5 / V_4 and I can write down basically V_5 is equal to V_1 here right V_5 is equal to V_1 because of isochoric heat rejection so therefore I can write down in place of V_5 $V_{1,}$ V_1 / V_4 and I can also write down V_1 / V_2 into V_2 / V_4 and V_2 is nothing but your V3 isochoric heat addition right so therefore this is the process if you look at so therefore I can write down basically V_1 by V_2 into V_3/ V_4 and we know that this is V_1 by V_2 is nothing but your CR s or no so this is your C_R and V_4 by B3 is nothing but 1by what you call COR so ER is equal to CR/ COR right.

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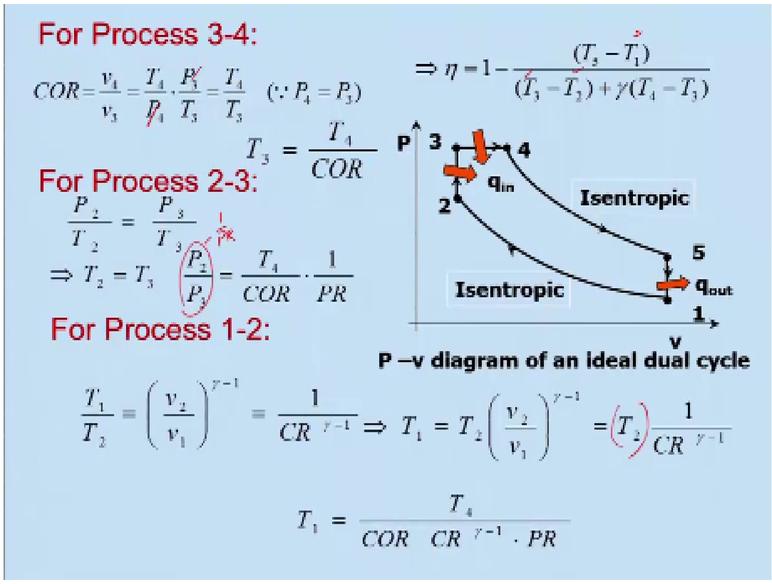

For Process 3-4:

$$COR = \frac{v_4}{v_3} = \frac{T_4}{\cancel{P_4}} \cdot \frac{\cancel{P_3}}{T_3} = \frac{T_4}{T_3} \quad (\because P_4 = P_3)$$

$$\Rightarrow \eta = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)}$$

$$T_3 = \frac{T_4}{COR}$$

For Process 2-3:

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

$$\Rightarrow T_2 = T_3 \left(\frac{P_2}{P_3}\right) \overset{\frac{1}{PR}}{} = \frac{T_4}{COR} \cdot \frac{1}{PR}$$

For Process 1-2:

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \frac{1}{CR^{\gamma-1}} \Rightarrow T_1 = T_2 \left(\frac{v_2}{v_1}\right)^{\gamma-1} = (T_2)\frac{1}{CR^{\gamma-1}}$$

$$T_1 = \frac{T_4}{COR \quad CR^{\gamma-1} \cdot PR}$$

P –v diagram of an ideal dual cycle

And if you look at the cut off ratio that is V_4 by V_3 is equal to T_4 by T_5 in 2P3 / T_3 and we know that T_4 is equal to P_3 for a constant pressure heat addition so therefore that begins you know this will cancel it out so therefore that becomes T_4 by T_3 and therefore we can you know what you call express the T_3 in terms of T_4 by COR because now we are expressing this thing and keep in mind that what we will be doing all these temperature we will be expressing in terms of T_4.

Right in terms of T_4 so for the process 23 is nothing but P_2 / T_2 is equal T_3 / T_3 because a constant volume heat addition you know between the state 2 to 3 so therefore we can write down T_2 is equal to P_3 into P_2 / P_3 and already we note that t3 right that is your T4 COR and this is this one is nothing but 1 by P are by definition pressure ratio right so therefore we are now getting you know T2we are getting right in terms of T_4 similarly for the process 1 to 2 we can get T_1 / T_2 is nothing but V_2 / V_1 power to γ - 1 is nothing but 1 over COR γ - 1 right that we have already done for the both the vertical for the Otto cycle right.

And that is nothing but basically T_1 is equal to T_2 into V_2 by VR I am like then you can express this T_1 in terms of compression ratio and if you look at the T1 right because already we have calculated here T_2, T_2 is nothing but your T_4 by COR into one more P or you just substitute these values here in place of this you know and you will get you are expressing T_1in terms of T_4 and cut off ratio compression ratio and PR right basically what I am trying to do expressing all the things here you know in terms of T_4 right so T_1 is.

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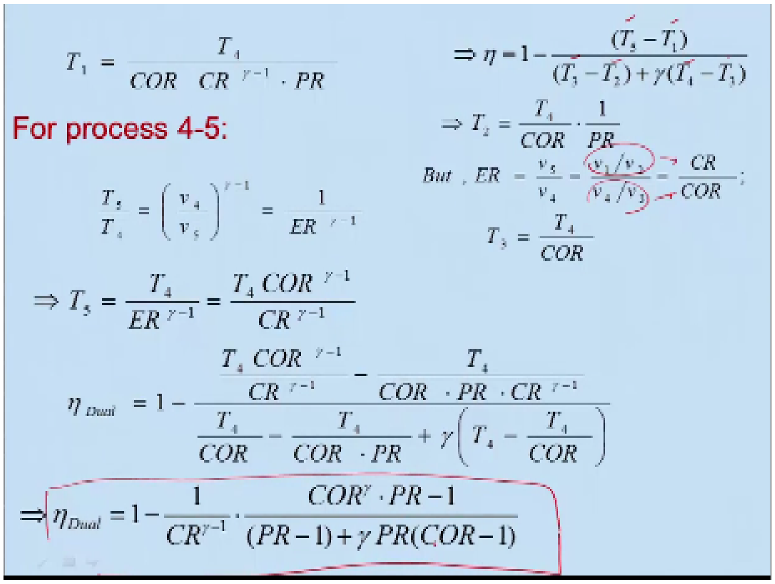

$$T_1 = \frac{T_4}{COR \; CR^{\gamma-1} \cdot PR}$$

For process 4-5:

$$\frac{T_5}{T_4} = \left(\frac{v_4}{v_5}\right)^{\gamma-1} = \frac{1}{ER^{\gamma-1}}$$

$$\Rightarrow T_5 = \frac{T_4}{ER^{\gamma-1}} = \frac{T_4 \, COR^{\gamma-1}}{CR^{\gamma-1}}$$

$$\Rightarrow \eta = 1 - \frac{(\acute{T_5} - \acute{T_1})}{(T_3 - \acute{T_2}) + \gamma(\acute{T_4} - T_3)}$$

$$\Rightarrow T_2 = \frac{T_4}{COR} \cdot \frac{1}{PR}$$

$$But\,,\; ER = \frac{v_5}{v_4} = \frac{v_1/v_2}{v_4/v_3} = \frac{CR}{COR};$$

$$T_3 = \frac{T_4}{COR}$$

$$\eta_{Dual} = 1 - \frac{\dfrac{T_4\,COR^{\gamma-1}}{CR^{\gamma-1}} - \dfrac{T_4}{COR \cdot PR \cdot CR^{\gamma-1}}}{\dfrac{T_4}{COR} - \dfrac{T_4}{COR \cdot PR} + \gamma\left(T_4 - \dfrac{T_4}{COR}\right)}$$

$$\Rightarrow \boxed{\eta_{Dual} = 1 - \frac{1}{CR^{\gamma-1}} \cdot \frac{COR^{\gamma} \cdot PR - 1}{(PR-1) + \gamma\, PR(COR-1)}}$$

Already we have done that I am like you know so for the process 45 I can get T_5 / T_4 right is equal to V_4 by V_5 power to the γ - 1already we have defined this is ER γ – 1 and we know that ER is equal to basically V_5 x V_4 and if you look at I can say that V_5 is what is V_5, V_5 is equal to V1 right is not it because that is the your constant volume heat addition so therefore V_1 + / V_2 I can say and V_4 / V_3 and V_2 / V $_3$ is same for the constant volume heat addition right so that is nothing but you what you can see our this is by definition and V_4 /V_3.

Is nothing but your COR are so therefore I can express the T_5 in terms of $_{T4}$ power to are nothing but to you this thing for ER is equal to COR / CR CUR there for you know you can put this values here again we are expressing T5 in terms of T4 and other ratios and already I think we got this T_3 is equal to P_4 by CR and T_2 already we got that T_4 x COR into 1/ PR so if we substitute these values you know what you call T_5 here right and T_1 already we know right T_1 is here right and T_3 and all those things we have expressed if you express that thing here right.

And simplified you can get basically is equal to one minus one over COR power to the γ - 1 in 2 COR that is cut off ratio power to the γ PR pressure ratio - 1divided by the PR -1 + γPR into COR - 1 in this bracket so if you look at in this process we have reduced one variable right which we had defined that is expansion ratio is not coming in this expression so therefore if you look at apart from the CR and cut off ratio and γ there is another variable which has come into picture in case of dual cycle that is the pressure ratio right so one can do that and then you know express it kind of things so we will be I mean like you know you can see that this will be trying to mimic the actual cycle to some extent not real x you know to the greater extent but however it is better than this.

This is known as a dual cycle and keep in mind that the second law of efficiency you know efficiency second law efficiency is basically equal to the dual cycle by the Carnot cycle this is your corner cycle efficiency you know corner cycle efficiency this will be not only true for the dual cycle it will be true for the Otto cycle diesel cycle and other cycles as well are you getting a point so you please keep in mind that and that will be helpful to know how much we can extend the thermal efficiency if it is less than the what you call second library.

If it is equal then you cannot go and that will be that means that will be the reversible engine okay so that will be very important one has to look at whenever you are doing cycle analysis one can also look at the second law of efficiency of the cycle and now what we will be doing we will be looking at another cycle.

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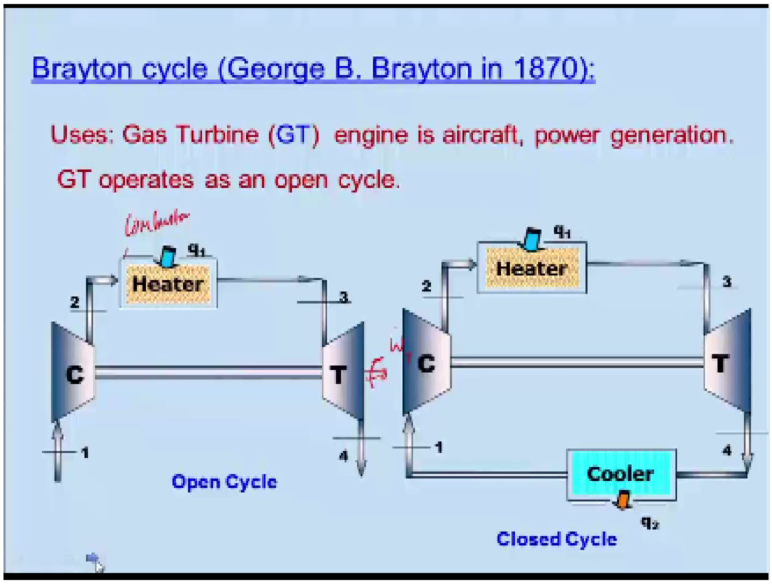

Brayton cycle (George B. Brayton in 1870):

Uses: Gas Turbine (GT) engine is aircraft, power generation.

GT operates as an open cycle.

Which is basically used for the what you call gas turbine engine and then it is known as the Brayton cycle and George be Britain found out that thing in 1870 if you look at all the cycles are in similar all the engines are under very narrow band you know periods in the history and all are developed simultaneously like you are during our independence you know time like era lot of great people come up in this country and who have got independence but after that there is a lull right so before that also there is a large.

So that is a kind of things what happened during that resin against period you know we call and it basically this gas turbine engines you know find application aircraft power generation even the Sheep like you know for propelling a sieve big ships and other thing and the gas turbine generally operate as an open cycle right and if you look at it is having a component of a compressor like it is similar way you will have to compress the air or the gas in air from state 1 to the two.

And then there will be some combustion you know combustor will be there this is basically a combustors which will be modeling it as a heater because we will be doing air standard you know analysis and then it will be expanded in a turbine which will give me the work right if you look at this will give me the work right and this work also supplied to the compressor because the work from the turbine will be you know supplied to the compressor because the work from the turbine will be you know supplied to the compressor so that it can go because you will have to supply walk to the compression. But what will be modeling it as basically a closed cycle although it operation the open cycle right.

We will be saying that look the reheat rejection you know will be taking place a cooler and so that it will be closed and will be modeling it as a closed cycle right and a standard cycle that means in the combustor is replaced by a heater as if you know combustor is external and keep in mind this is known as also a internal combustion combustor is a part of the engine. But in this case we are saying look it is away it is giving only the heat to for this our analysis.

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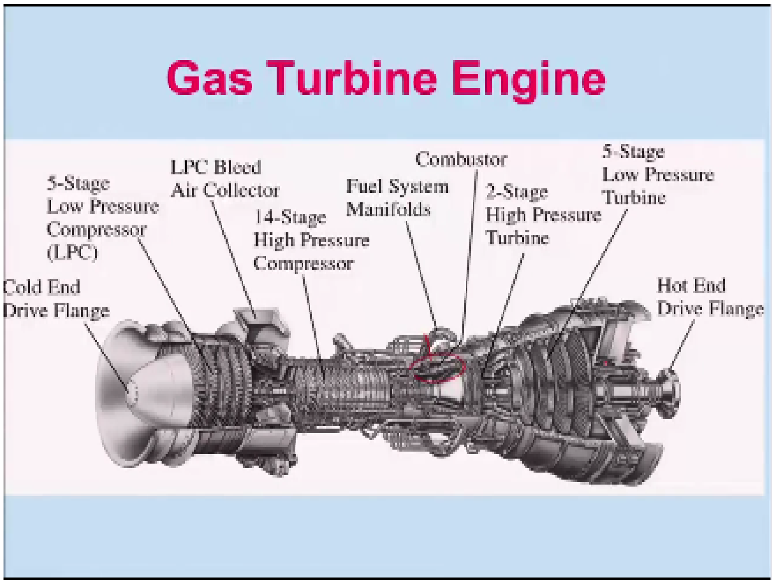

Gas Turbine Engine

So I have already shown you this picture again I am putting it so if you look at this is your you know what you call compressors of course there will be a low-pressure compress or high pressure compressor is in you it is a compressor and this is your combustion chamber is a very tiny one you know if you look at this is your combustion chamber and then it is expanded in the turbine these are all turbines you know and you will get the of course in this engine in like you can get the power and then a particular this engine is mean for the getting the thrust and it is gas has to be expanded in a nozzle, okay.

So in case of power generation you need not to have a turbine all expansion will be taking place in a term as a you need not to have a nozzle all the expansion will be taking place in a cortical turbine so that you can get what them. So as you know from here the air will be entering in this place and then it will be you know all will be burnt over in the combustor and it will be expanded in turbine it will going out you know the product gases right. And if this is basically an open cycle one can think of but we are modeling it as a closed cycle.

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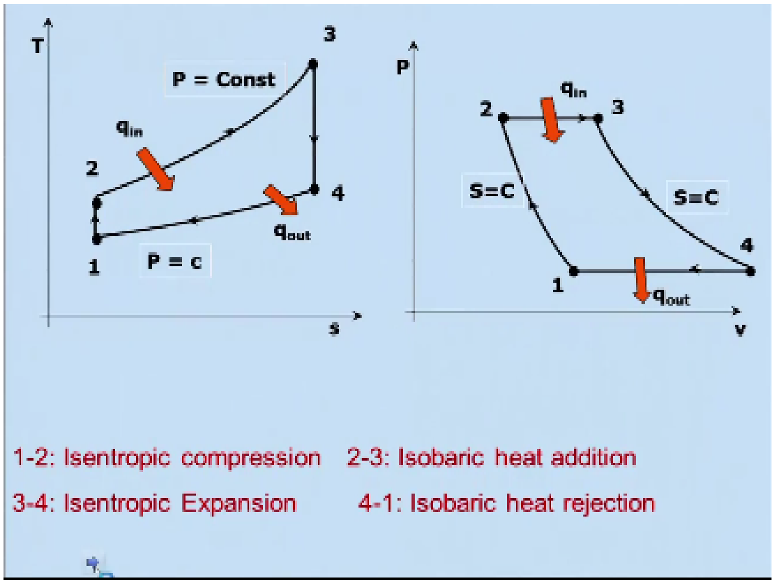

1-2: Isentropic compression 2-3: Isobaric heat addition

3-4: Isentropic Expansion 4-1: Isobaric heat rejection

So let us look at the processes I am in like processor one to two in T_S diagram this is a isentropic compression right, entropy would not be changing and 2 to 3 is your constant pressure heat addition it is similar to that of your what you call diesel engine and 3 to 4 your isentropic expansion and 4 to 1 is your constant pressure heat rejection okay, in case of diesel engine or auto engine the heat rejection is constant volume.

But in this case constant pressure heat addition and constant pressure heat rejection that is the difference. So you can see that thing in the process in the P_V diagram you know which is very clear that heat addition in this case is the constant pressure and heat rejection is the again in the constant pressure unlike the diesel and auto cycle that heat rejection.

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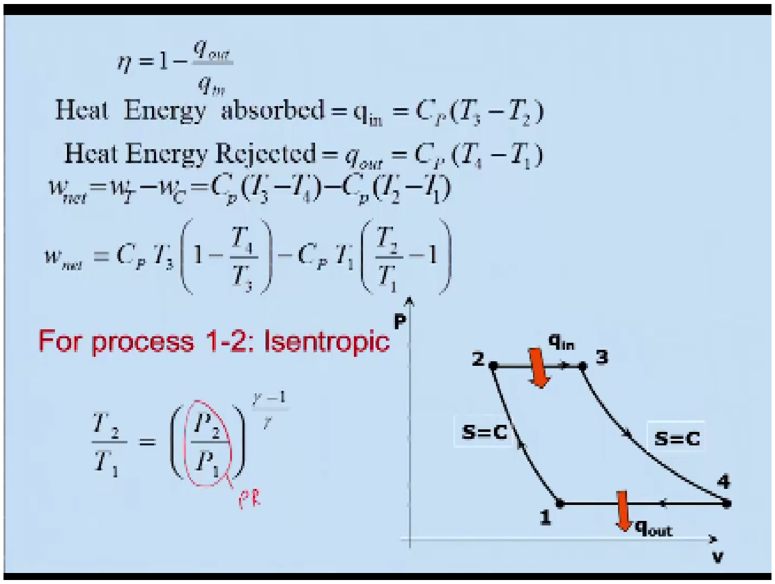

$$\eta = 1 - \frac{q_{out}}{q_{in}}$$

Heat Energy absorbed = $q_{in} = C_P(T_3 - T_2)$

Heat Energy Rejected = $q_{out} = C_P(T_4 - T_1)$

$$w_{net} = w_T - w_C = C_p(T_3 - T_4) - C_p(T_2 - T_1)$$

$$w_{net} = C_P T_3\left(1 - \frac{T_4}{T_3}\right) - C_P T_1\left(\frac{T_2}{T_1} - 1\right)$$

For process 1-2: Isentropic

$$\frac{T_2}{T_1} = \left(\boxed{\frac{P_2}{P_1}}\right)^{\frac{\gamma-1}{\gamma}}$$

PR

So we will be looking at the again thermal efficiency that is equal to $1-q_{out}/q_{in}$ and in this case the heat energy observe is basically change in enthalpy. Now in this case what you will be using will you be using control mass system volume system what is the natural one you can use both as a matter of fact, what will be natural one natural one will be control volume system, okay. So therefore the q_{in} is basically change in enthalpy right that is nothing but $C_pT_3-T_1$ keep in mind.

That we are considering the C_P as a constant is not a function of temperature but in real situation it is not it will be function of temperature, okay. But in ideal cycle or air standard cycle is like that so heat energy rejected is nothing but q_{out} that is $C_PT_4-T_1$here right, and then we can get the network done is basically the turbine work minus the compressor work right, so you know that is turbine work $C_pT_3-T_4$ and compressor works $C_p(T_2-T_1)$ this process you know this is your compressor.

So the network you know will be basically see C_pT_3 I can take out then I will get $1-T_4/T_3$ similarly in the compressor part I can take T_1 out that will be then in the bracket it will be T_2/T_1-1 right, and for isentropic process 1, 2 we know $T_2/T_1^{\gamma-1/\gamma}$ and this ratio what we call is basically compression ratio you can say that this is the compression ratio what we call and we called based on the pressure so I will be defining this as a PR, okay. And that is different in case of auto engine, auto engine basically based on the volume in this case based on the pressure that is the difference okay.

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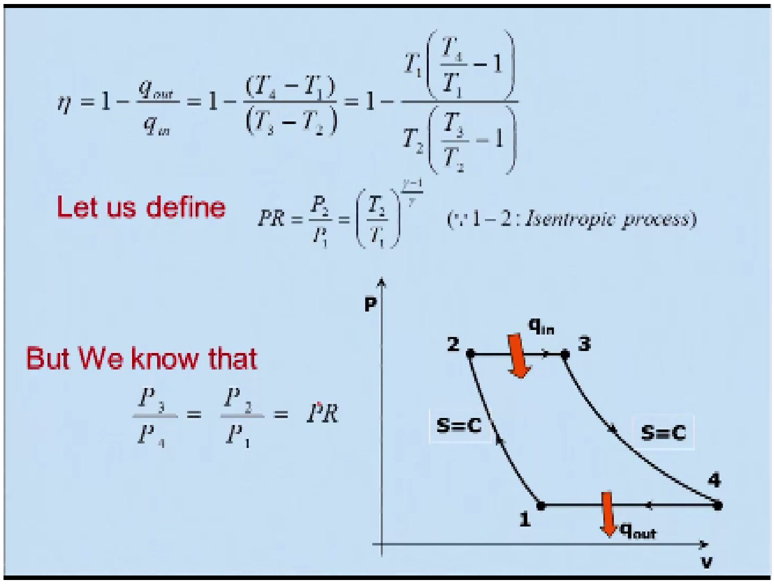

$$\eta = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$$

Let us define $PR = \frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma-1}{\gamma}}$ $(\because 1-2: \textit{Isentropic process})$

But We know that

$$\frac{P_3}{P_4} = \frac{P_2}{P_1} = PR$$

So let us as we told that it is the PR I am defining for isentropic process and that is true for also the expansion process. So therefore we know P_3/P_4 that during the expansion process is nothing but you are what you call pressure ratio and P_2 by P_1 also during the compression process between state 1 to the state 2 is also known as the pressure ratio keep in mind the pressure is you always defined from the higher pressure to the lower pressure that we have defined for both the compression and expansion.

So therefore we can write down the $T_3/T_4^{\gamma/\gamma\text{-}1}=T_2/T_1^{\gamma/\gamma\text{-}1}$ so therefore we can write down that what you call $T_3/T_4=T_2/T_1$.

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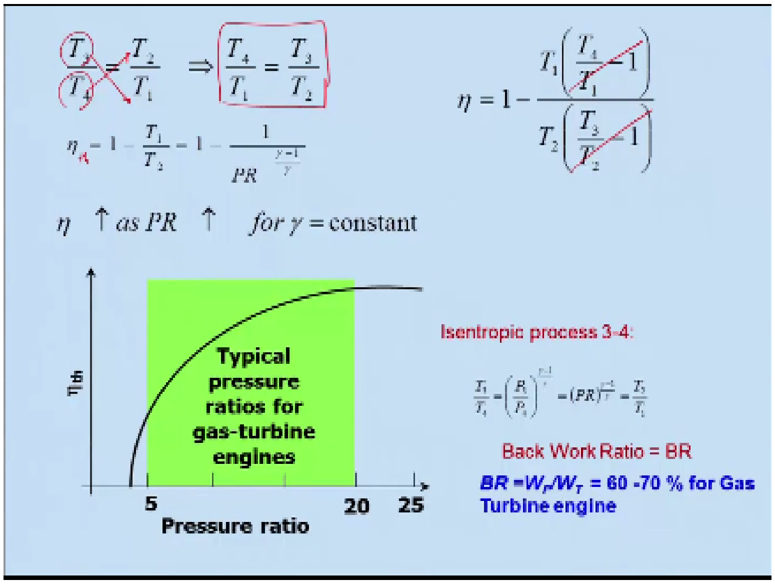

$$\frac{T_3}{T_4} = \frac{T_2}{T_1} \Rightarrow \boxed{\frac{T_4}{T_1} = \frac{T_3}{T_2}}$$

$$\eta = 1 - \frac{T_1\left(\cancel{\frac{T_4}{T_1}-1}\right)}{T_2\left(\cancel{\frac{T_3}{T_2}-1}\right)}$$

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{PR^{\frac{\gamma-1}{\gamma}}}$$

$\eta \uparrow as\ PR \uparrow$ $for\ \gamma = \text{constant}$

Isentropic process 3-4:

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = (PR)^{\frac{\gamma-1}{\gamma}} = \frac{T_2}{T_1}$$

Back Work Ratio = BR

$BR = W_P/W_T$ = 60 -70 % for Gas Turbine engine

And we can write down that is nothing but your what you call you know I can take this what you call temperature over here and the temperature T_3 to this side then I will get $T_4/T_1=T_3/T_1$ so we know that T_3/T_4 right is equal to $P_3/P_4=PR^{\gamma-1/\gamma}$ which is nothing but by T_2/T_1 right, so therefore we can write down you know like this expression if you look at T_4/T_1-1 it can be canceled it out T_3/T_2-1as this is the case right.

So it is simplifies it says that the thermal efficiency is basically equal to 1-1/PRγ-1/γ this is similar to that what we got for the auto cycle right, similar it not same. So therefore for a particular γ PR will go up the thermal efficiency will be going up it will be increasing and if you look at the typical pressure ratio for this is something 5 to 20 even people are using the pressure ratio of something 35 to 40 nowadays people are using very.

But as you go on then you know turbine inlet temperature will be very high because you are using higher compression ratio and then there will be limitation of the article material and heat additions kind of things and but very important thing what do I would like to draw your attention that you know back work ratio in this case you know is very high right, if you look at the something the 60 to 70% of the turbine work is utilized for pumping the gas you know in this case. Whereas for what you call steam power plant we have seen something 1 to 2% is negligibly small you know power is being utilized for pumping purposes so therefore that you should even kind is basically guzzling that compressor is guzzling lot of power.

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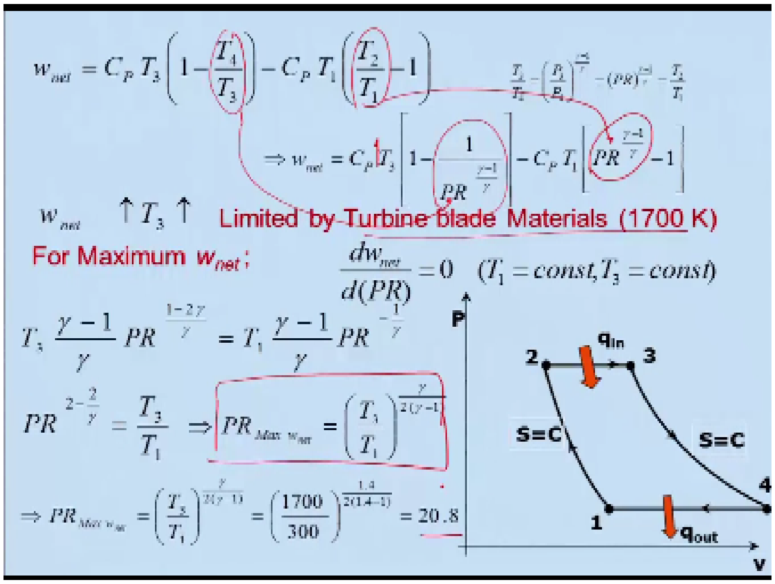

$$w_{net} = C_P T_3 \left(1 - \frac{T_4}{T_3}\right) - C_P T_1 \left(\frac{T_2}{T_1} - 1\right)$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = (PR)^{\frac{\gamma-1}{\gamma}} = \frac{T_2}{T_1}$$

$$\Rightarrow w_{net} = C_P T_3 \left[1 - \frac{1}{PR^{\frac{\gamma-1}{\gamma}}}\right] - C_P T_1 \left[PR^{\frac{\gamma-1}{\gamma}} - 1\right]$$

w_{net} ↑ T_3 ↑ Limited by Turbine blade Materials (1700 K)

For Maximum w_{net}: $\frac{dw_{net}}{d(PR)} = 0 \quad (T_1 = const, T_3 = const)$

$$T_3 \frac{\gamma - 1}{\gamma} PR^{\frac{1-2\gamma}{\gamma}} = T_1 \frac{\gamma - 1}{\gamma} PR^{-\frac{1}{\gamma}}$$

$$PR^{2-\frac{2}{\gamma}} = \frac{T_3}{T_1} \Rightarrow \boxed{PR_{Max\ w_{net}} = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}}}$$

$$\Rightarrow PR_{Max\ w_{net}} = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}} = \left(\frac{1700}{300}\right)^{\frac{1.4}{2(1.4-1)}} = 20.8$$

So we look at the question arises you know what will be the pressure ratio we should use so that maximize the work output and for that we have already derived this expression and we can also express that in terms of pressure ratio right because we note T_3/T_4= pressure ratio however to the γ-1=T_2/T_1 this we have already derived so then I can write down this expression in terms of you know T_4/T_3 if you look at this is nothing at $1/PR^{\gamma-1/\gamma}$ right this portion so this portion is nothing but that right.

And a similar way we can also find out basically you know T_2/T_1 this one is equal to this portion right and then what we will do we will have to find out what is the maximum pressure one can get so that my network output will be you know maximum that means what is the pressure ratio I should use so that I can maximize my work so what I will have to do I will have to basically you know differentiate this expression with respect to pressure ratio and that is equal to 0 right we can do that.

And so for maximum as I told that will have to do this you know work network with respect to the pressure ratio that is a 0 of course you can keep the temperature T_1 constant and T_3 is basically T_3 is constant you can consider so if you do that you will get this expression and it right and you will get this $PR^{2-2/\gamma}=2T_3/T_1$ and so that we will get an expression that maximum pressure ratio what you can do is basically $T_3/T_1^{\gamma/2\gamma-1}$ and as I told that if I increase this T_3 here if you look at this T_3 will be higher than natural the work input work net will be higher because if this T_3 is higher for the rest of the things then naturally work network output will be higher.

But however there is a limitation of the you know limitation of increasing this temperature because the turbine inlet material turbine material you know is the problem because the turbine will be subjected to what you call not only the thermal stress but also the centrifugal stress so therefore if I say this turbine material is basically limited to1700 K then you know we can find out what will be the pressure ratio for this example if i put this is 1700K right, and 300 you will get I can get maximum you know pressure we can operate the pressure ratio at 20.8 forgetting the maximum work output.

By this we can optimize you know like find out what is the pressure ratio one can operate and if I am getting a lower you know turbine Inlet temperature the natural oiler to go for lower pressure if I increase this one to the higher you know like values for the with the advent of better material then naturally I can go for the higher pressure ratio. So what I am saying by using this simple cycle you can really play around and find out ways and means of doing the what you color enhancing the thermal efficiency.

As I told earlier that in case of vapor power cycle right that you can regenerate you can you know kind of things so here also you can do the regenerative kind of things you can recall you can compressor work you can reduce because here in gas turbine engine the problem is the compressor is guzzling the power is taking all the power out so therefore you can cool it you know during the compression there is known as inter cooling you can do that so that you can reduce the work input to the compressor and as a result you can increase the network output and then thermal efficiency of course will be increasing.

There are several ways and means which is not a part of your course but I am just trying to give you a flavor there is a lot of scope for improving the what you call performance of the engine by using simple cycles of course there will be realistic cycles in this case one can think of what you call using the isentropic efficiency what we had done earlier right, we are you some isentropic efficiency right for the compressor and expansion by that we can also analyze the real cycles not only for the Brayton cycle but also for the what you call auto cycle, diesel cycle other things okay. So with this I will stop over here and then next class we will be looking at refrigeration cycles, thank you.

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