Thermal Engineering Basic and Applied
Prof: Pranab K Mondal
Department of Mechanical Engineering
Indian Institute of Technology – Guwahati

Lecture - 65
Gas Turbine Unit: Combined Cycle

Very good morning I welcome you all to the session of Thermal Engineering Basic and Applied and today we shall discuss about gas turbine unit those run using a combined cycle concept. So, in the last class you know we have talked about the multi staging and we had discussed the need of multi stage compression and also we had seen that for the multi stage compression intercooling is a must.

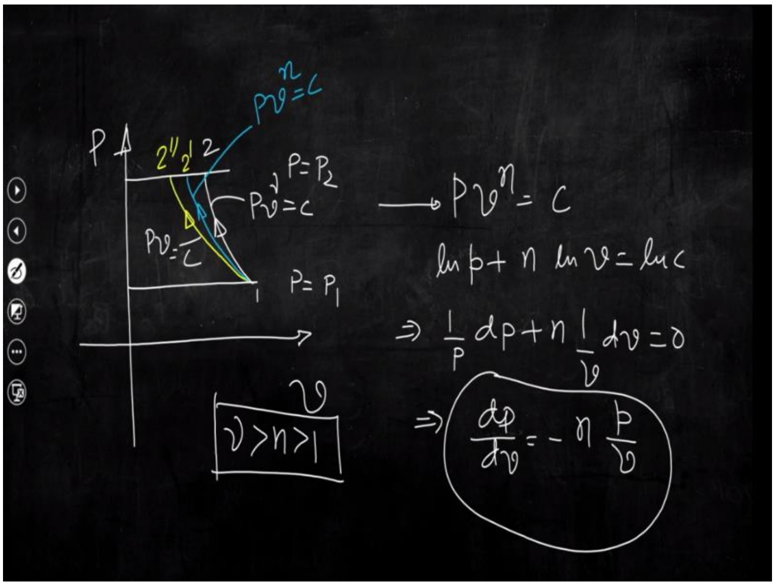
And we had seen that in a multi stage compression with intercooling we could save certain amount of work to run the compressor and it is intuitively expected that saved work will certainly increase the cycle efficiency. So, today we shall discuss that again from the perspective of the process diagram and if we map all those processes in a T-s plane. Now for the recapitulations what we have discussed that air which is drawn into the compressor that air is compressed.

Now we need to run gas turbine units having certain pressure ratio, just by looking at the mathematical expression of the cycle efficiency, we can easily understand that with increasing pressure ratio efficiency will increase and if we need to achieve a higher pressure ratio it is also doable by using a single stage compression, but as we have discussed that if we consider single stage compression certainly we can build that pressure.

But at the exit of the compressor temperature rise will be so high that rise in temperature which is associated with the rise in pressure will lead to the damage of several mechanical components of the compressor not only that you know when that gas temperature or temperature of any other working fluid increases and if you need to go for multi staging of course we need to go for intercooling because it is easier to compress high density cool air than the hot air.

So, multi staging essentially an important aspect of the compression process wherein we need to compress at a high pressure and such a pressure will lead to an increase in temperature and that temperature may be vulnerable to several mechanical components and we need to go for multi staging.

(Refer Slide Time: 04:13)



So, for the brief recapitulation if we consider that $pv^n = C$ for the compression process this is generic reversible poly tropic process. So, if we now just do some calculation

$$\ln p + n \ln v = \ln C$$

$$\frac{1}{p}dp + n\frac{1}{v}dv = 0$$

$$\frac{dp}{dv} = -n\frac{p}{v}$$

So, what we could draw in the last class that if we try to draw several processes in this Pv plane and if we need to raise the pressure from P1 to P2, then we can see that this is $pv^n = C$. So, this is 1 to 2 and then we also can have another one process where n equal to 1.

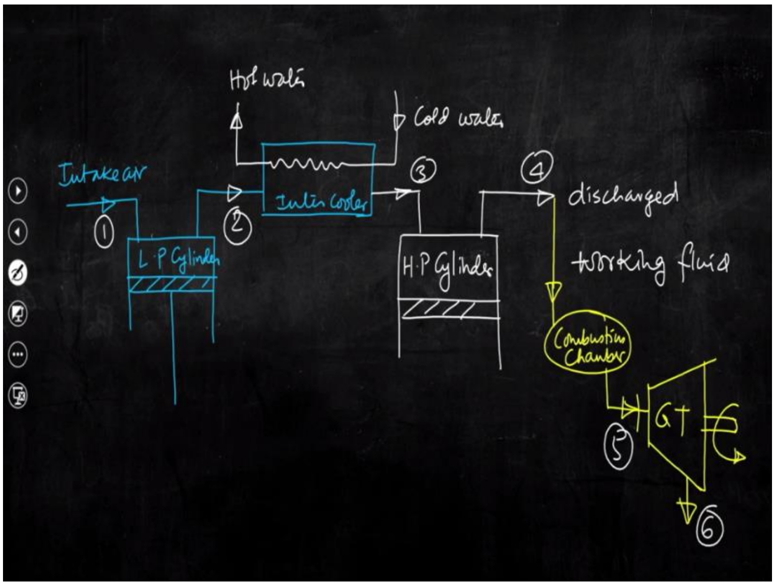
So, this is the process 1-2 then $1 - 2'$ and $1 - 2''$. So, that means here if we consider $\gamma > n > 1$ if this is the sequence then we can understand this is basically $pv^\gamma = C$, this equal to Pv is equal to constant and certainly this is $pv^n = C$. So, what we can understand if $\gamma > n >$, then in this Pv plane whatever you know processes we could map we can easily say that reversible adiabatic compression that is $pv^\gamma = C$ is steeper than the reversible isothermal compression. Hence, work input to the compressor if the compression process follows reversible adiabatic one then it would be high.

And the minimum work would be needed for the reversible isothermal compression, but we have discussed that compression of any working fluid whether it is air or any other gas say helium if we need to compress it. So, compression process if we need to consider reversible isothermal one then this is not of that much use we have discussed because in this type of compression we can only increase pressure.

But temperature will remain more or less constant. So, this is what we can see that without going into much more mathematical analysis just by using this and mapping all the processes in this Pv plane we can see that reversible adiabatic compression is steeper than the reversible isothermal one. Hence if we hatch the area under the process line in Pv plane it would be much for the reversible adiabatic one.

Now, what we would like to discuss today that in the last class we have discussed about intercooling.

(Refer Slide Time: 08:27)

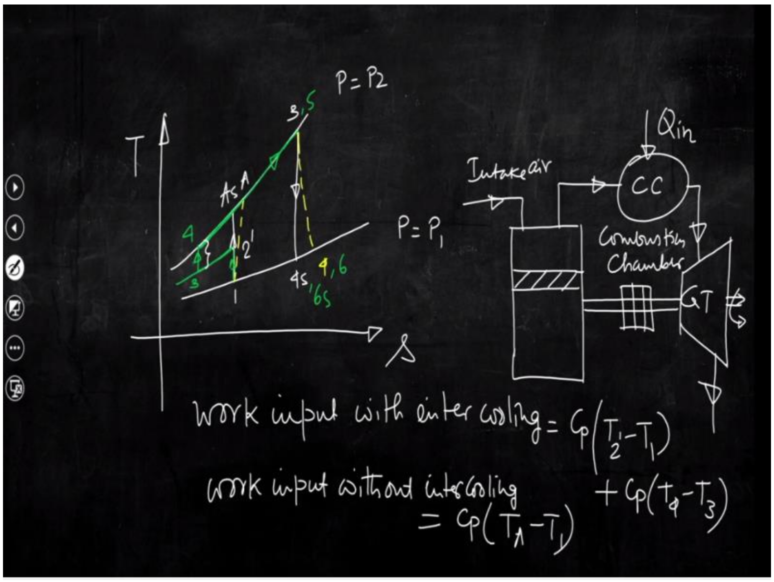


And we had seen that so this is the first cylinder or LP cylinder, low pressure cylinder that air is coming. So, this is intake air and that is again taken to this is intercooler and from intercooler we are again taking the working fluid to another cylinder that is high pressure cylinder. HP stands for high pressure LP stands for low pressure and finally that compressed air will be discharged.

Now this intercooler now if you try to draw here that discharges again taken to the combustion chamber and from there it is again taken to the gas turbine. So, a case would have been like this. We are taking intake air to the low pressure cylinder then we are taking that compressed air to this intercooler, from intercooler again essentially what we are doing we are reducing the temperature of the air before it enters into the second stage compression.

And finally the discharged working fluid is taken to this combustion chamber or working fluid is discharged into this combustion chamber wherein again by addition of heat, pressure and temperature increases and then it expands in the gas turbine and we are getting work output and finally this should be the final discharge. Now what is important here to discuss that we could discuss in the last class that by mapping the processes in Pv plane, we had seen that we can save certain amount of work input. Now if we try to you know discuss the processes using a T-s plane then it will help us to understand even though we can save certain amount of work input still the efficiency using this intercooling unit reduces and why it is reduced we shall try to now understand.

(Refer Slide Time: 11:58)



So, if we try to plot the processes in T-s plane. So, this is $p = p_1$ this is $p = p_2$, a common process would be that this is the isentropic compression 1 to 2 s then again this is 3, this is 4 s and if we now consider that some degree of irreversibility will be there in both the compression and expansion process. So, this is actual one, but say we are taking the air in this chamber and that compressed air is taken to this CC that is combustion chamber.

We are supplying certain amount of Q in and that is again taken to this and finally discharge. So, now this is gas turbine and this is CC stands for combustion chamber. Now a case would be like this that we are using single stage compression, but still we would like to develop the same pressure that is pressure ratio is same. We are taking intake air in the compressor single stage compression going to the combustion chamber.

Again we are having some amount of heat addition to this working fluid and finally you are taking that working fluid having high pressure high temperature into this gas turbine unit and working fluid will expand and we will be getting certain amount of work. Of course to run this compressor you know shaft is connected that is what we had seen.

So, if this compressor is now connected to the gas turbine instead what we are doing here we are considering one intercooling unit we are having two different stages of compression low pressure stage and intercooling and a high pressure stage, finally to the combustion chamber and going to the gas turbine. The sole purpose is not to increase the temperature of working fluid substantially which would be there if we consider single stage compression.

And hence we can reduce the problems or we can eliminate several problems those will be there with the single stage compression. We have discussed all those then for a single stress compression volumetric efficiency will be less. COP will be less, work input will be more and degree of irreversibility will be more in this case for this single stage compression.

So, what we are doing over here compression of the air using this intercooler or intercooling unit. So, this is cold water and this is hot water. Now, if we try to map the processes here in this Ts plane then you can see certainly in the low pressure stage turbine pressure will increase.

So, 1 to 2 will be there, but you know this is low pressure cylinder, so compression ratio would be less. So, what we can do we can assume that now what will happen if this compression will be there up to an intermediate pressure and we really do not know, let us assume this is the intermediate pressure. So, now this is the amount of rise in pressure in the low pressure stage compressor.

Then what we are doing if we go back to the previous slide, rising pressure of the working fluid we are taking inside the intercooler. So, temperature will reduce and the reduction in temperature will be at constant pressure. So, this would be say 3, because 2 to 3 that is reduction in temperature of the working fluid.

And hat heat will be taken away by the cold water that is supplied to the intercooler, then again 3 to 4 would be rise in pressure. So, that means we are trying to rise pressure from P1 to P2 and now again that pressure will be developed in a high pressure stage unit 3 to 4 that you see from this schematic diagram.

And then finally 4 to 5 that is the heat addition at constant pressure in the combustion chamber. We are assuming that pressure rise of the working fluid at the end of the second stage of compression is equal to the rise in pressure by the single stress compressor. So, you can see that we could develop pressure from P1 to P2 by using these two different stages.

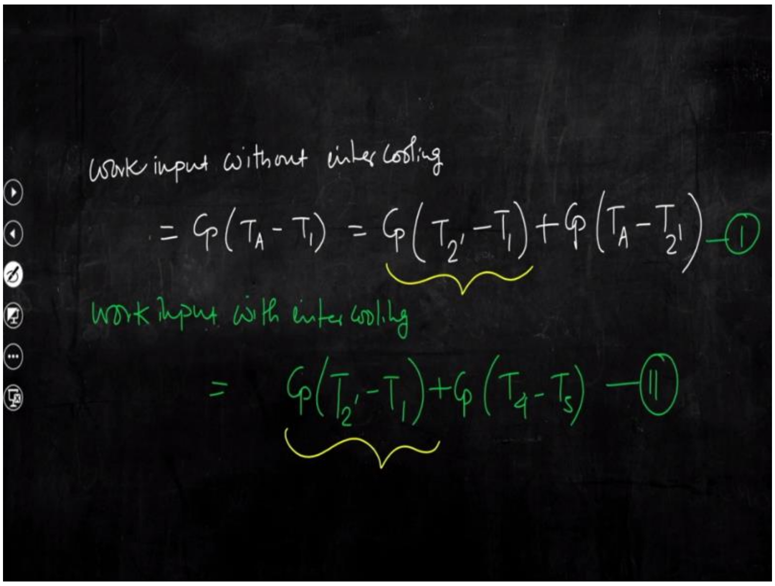
We started from here then up to this intermediate pressure, then again cooling and then finally rising in temperature. So, as if again we are adding certain amount of energy to the working fluid by burning fuel and we are able to supply equal amount of energy and then it is again coming to that point and finally expanding in the turbine.

So, what we can see from this particular depiction, what is the work input.

$$\text{Work input with inetrcooling: } C_p(T_{2'} - T_1) + C_p(T_4 - T_3)$$

$$\text{Work input without inetrcooling: } C_p(T_A - T_1)$$

(Refer Slide Time: 21:42)

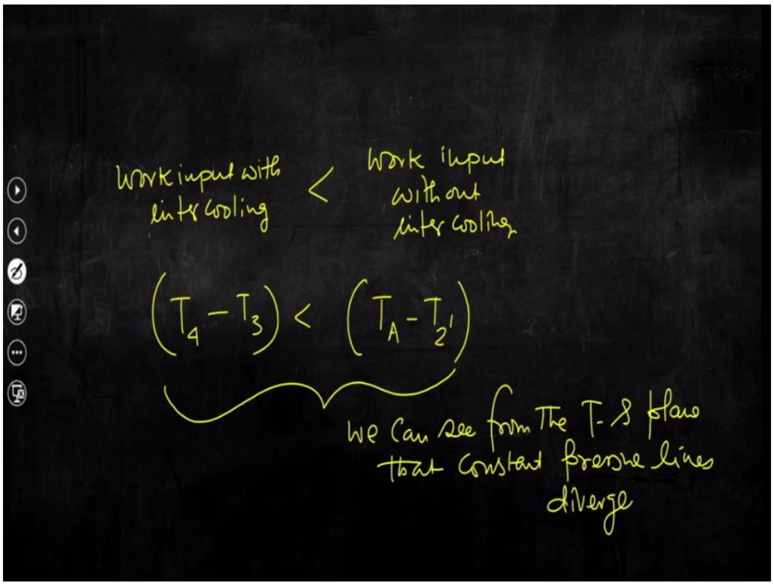


$$\text{Work input without inetrcooling: } C_p(T_A - T_1) = C_p(T_{2'} - T_1) + C_p(T_A - T_{2'})$$

So, this is with intercooling and this is without intercooling, but the objective is to get equal pressure ratio and we are also trying to supply the amount of heat for which if we consider single stage compression then heat addition will be $T_3 – T_A$ or $T_3 – T_{As}$ that is depending on the actual or ideal cycle or with intercooling it should be $T_3 – T_4$.

Now, if we compare these two equation, then certainly following our previous discussion that work input needed following reversible adiabatic compression but using an intercooling unit is less than the work that would be required for the reversible adiabatic compression, but using a single stage compression no intercooling effect.

(Refer Slide Time: 25:02)



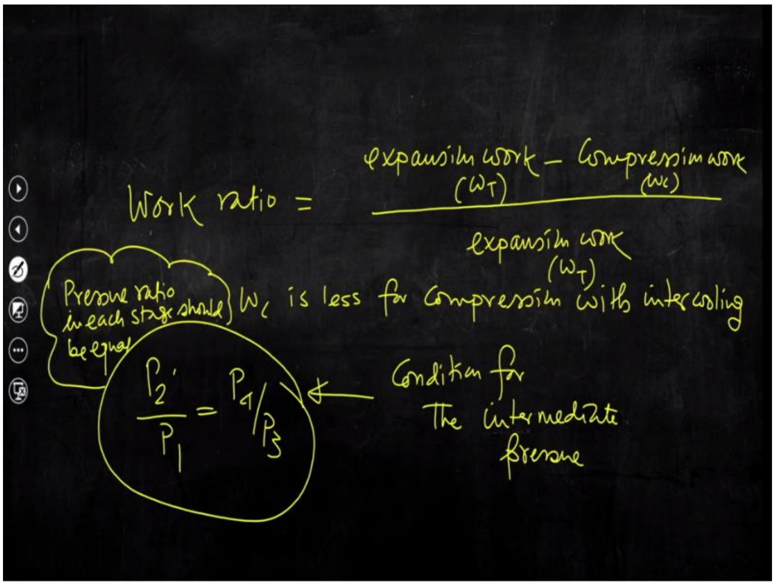
So, we can write that work input with intercooling should be less than work input without intercooling provided $T_4 - T_3 < T_A - T_{2'}$. If we look at this T-s plane you can see that we have drawn two constant pressure lines here and we can see this lines diverge as we move from left to right and hence it is easily understandable that $T_A - T_{2'}$ is certainly greater than $T_4 - T_3$.

So, we can see from the T-s plane that constant pressure lines diverge as we move from left to right, so this is true and hence whatever we could establish in the last class from the Pv plane that saved amount due to intercooling is also getting justified from this analysis from by mapping the processes in a T-s plane.

Now, if we assume that efficiencies of both compressions, we are having compression in the low pressure cylinder and high pressure cylinder, so isentropic efficiencies of these two compressors operating separately are each is equal to the isentropic efficiency of the single stage compression.

So that means using an intercooling unit what we are doing we are essentially allowing air to be compressed following two different stages and if we assume that the isentropic efficiency of both compressors though they are working separately and if they are is equal to the isentropic efficiency of the single stage compressor then this is true. Now question is what would be the work ratio.

(Refer Slide Time: 29:26)



Work ratio is defined as the expansion work that is the positive work - compression work divided by know expansion work.

$$Work\ Ratio = \frac{W_T - W_C}{W_T}$$

Now Wc is less for compression with intercooling. Hence, work ratio will be more for the gas turbine unit having multi stage compression.

Question is although we can ensure that the work ratio will be high but still efficiency of the gas turbine units having multi stage compression is less. Why it is so we know efficiency is equal to net work output by the heat addition. Again if we look at this T-s plane what is the amount of heat addition needed if we consider single stage compression that is $T_3 – T_A$ if it is actual cycle or $T_3 – T_{As}$ if it is ideal cycle.

But now heat addition which we need to supply to the combustion chamber to get equal amount of work output in that case the heat addition should be $T_3 - T_4$ certainly this is higher than $T_3 - T_A$ or $T_3 - T_{As}$. So, this extra amount of heat addition that should be there because of this intercooling effect will reduce the cycle efficiency even after achieving higher work ratio.

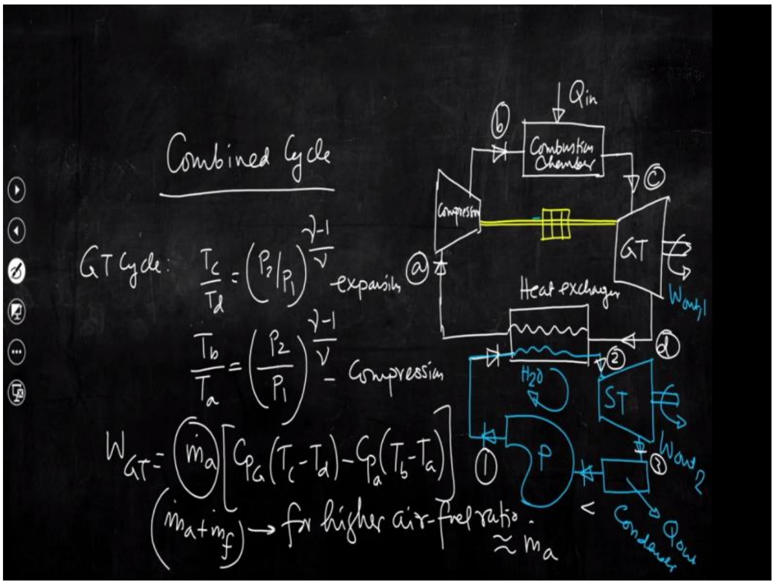
So, rather increase in heat addition that should be needed to run the unit having multi stage compression with intercooling should be such that after having higher work ratio, the overall or gross impact is cycle efficiency reduces not only that as we have discussed for the intercooling unit we need to supply water or any other coolant and for that again you need to have mechanical components.

So, installation of those mechanical components as well as maintenance will eventually increase the total cost associated with this unit and hence even though intercooling effect increases work ratio, but the gross impact is the reduction in thermal efficiency. I also would like to discuss another important issue that what should be the intermediate pressure at which this intercooling effect will be performed.

So, this is very important that when you are talking about multi stage compression, pressure ratio in each stage should be equal. So, intermediate pressure will be selected in such a way that for a multi stage compression pressure ratio in each stage should be equal.

$$\frac{p_{2'}}{p_1} = \frac{p_4}{p_3}$$

(Refer Slide Time: 35:08)



Now let us now discuss about the combined cycle plant. We all know that gas turbine units are largely used in aircraft field and propulsion, but still if you recall we had discussed about the use of closed cycle gas turbine units and typically closed cycle gas turbine units are used in captive power plant, gas cooled nuclear reactor and sole purpose is to supply certain amount of energy as and when demand increases and this gas turbine plants are known as picking unit to supply certain amount of energy when demand increases.

Now question is there are several disadvantages of gas turbine units, what are those? Large compression ratio, high exhaust loss, high degree of irreversibility associated with both compression, expansion process, then low cycle efficiency that we have discussed. Even after increasing work ratio it is not possible to increase cycle efficiency.

So, accounting for all these problematic issues, there are certain applications wherein gas turbine units are used, but still there are several advantages as well because less installation cost and installation time and also this gas turbine units respond quickly to the change in demand or load and we can start quickly, you also can stop this unit quickly. So, now question is despite having a few disadvantages features still there are some advantages.

And accounting for these advantages feature are new concept that is the use of combined cycle. If we consider this is the compressor, then we are having combustion chamber, we are supplying certain amount of Qin, we are supplying certain amount of heat. So, basically in this unit we are having heat addition to the working fluid.

So, this is heat exchanger and here we can see there are 2 cycles, one is known as topping cycle another is bottoming cycle. So. we had seen that in a gas turbine unit we have high exhaust losses, had we not used the gas that comes out from the turbine to this heat exchange, it would not have been possible to utilize that heat. Essentially, what we are doing is we are taking the gas that comes out from the gas turbine after doing certain amount of work to this heat exchanger wherein that gas which is having high temperature is taken away by this stream that is water. So, here we are having steam cycle and gas cycle.

So, it is because of this high exhaust loss gas turbine units are having low cycle efficiency. Now the idea behind this combined cycle is to utilize the heat or energy which will otherwise will be rejected to the ambience and utilizing that energy we can run the steam cycle or steam power unit and we can run another steam turbine. So, we have discussed about steam power cycle and we have seen that boiler will be there.

But here there is no boiler, but the amount of energy that will be released by the gas that comes out from the gas turbine in this heat exchanger to the working fluid that is the water that water will be converted into steam and it will again taken to the steam turbine wherein the working fluid will expand. So, water will be converted into steam that steam will expand now in the steam turbine and will be getting work output.

So, here we are getting $W_{out,1}$ we are getting $W_{out,2}$. So, if we can run this unit perhaps we are getting work output from the gas turbine, work output from the steam turbine though certain amount of work that would be needed to be supplied to compressor. So, this is the common shaft. So, idea is to use two different cycles and you know 2 cyclic power plants are coupled in series to produce network output.

So, idea is to utilize the heat to run this bottoming cycle and that is the H_2O cycle. So, topping cycle is gas cycle, bottoming cycle is H_2O cycle and by running these two cycles we can get the power and as I said you closed cycle gas turbine units are known as picking units and the picking units are used to supply certain amount of energy when demand increases.

So, now we can see that there are two different cycles.

Gas turbine Cycle:

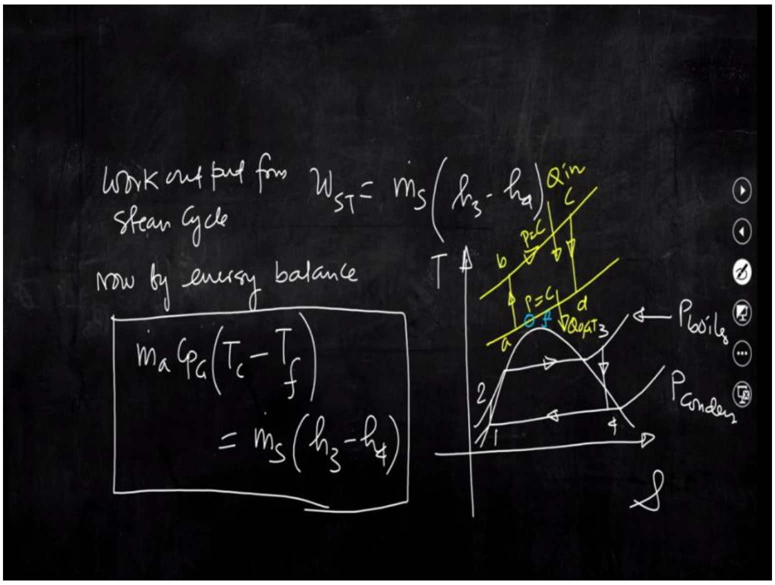
$$\frac{T_c}{T_d} = \left({}^{p_2}/_{p_1}\right)^{\frac{\gamma-1}{\gamma}} \ (Expansion)$$

$$\frac{T_b}{T_a} = \left({}^{p_2}/_{p_1}\right)^{\frac{\gamma-1}{\gamma}} \ (Compression)$$

$$W_{GT} = \dot{m}_a\left[C_{p,G}(Tc - T_d) - C_{p,a}(T_b - T_a)\right]$$

So, as I said gamma for compression may not be equal to gamma for expansion because we are adding certain amount of fuel here in real applications and hence gamma and Cp will change. We are assuming gamma may not be equal this Cpg and Cpa are not equal because those are different and we are assuming mass flow rate of air only because essentially when will be getting work output we need to consider mass flow rate of fuel as well. So, ideally this should be $\dot{m}_a + \dot{m}_f$, but for higher air fuel ratio it is more or less $\dot{m}_a$ because fuel is very less. Now what about steam turbine work output?

(Refer Slide Time: 47:38)



Then work output from steam turbine cycle is mass flow rate of steam into enthalpy drop, $W_{ST} = \dot{m}_s(h_3 - h_4)$. So, now we need to go for energy balance. For energy balance, we have to draw the T-s diagram. So, this is P condenser and this is P boiler.

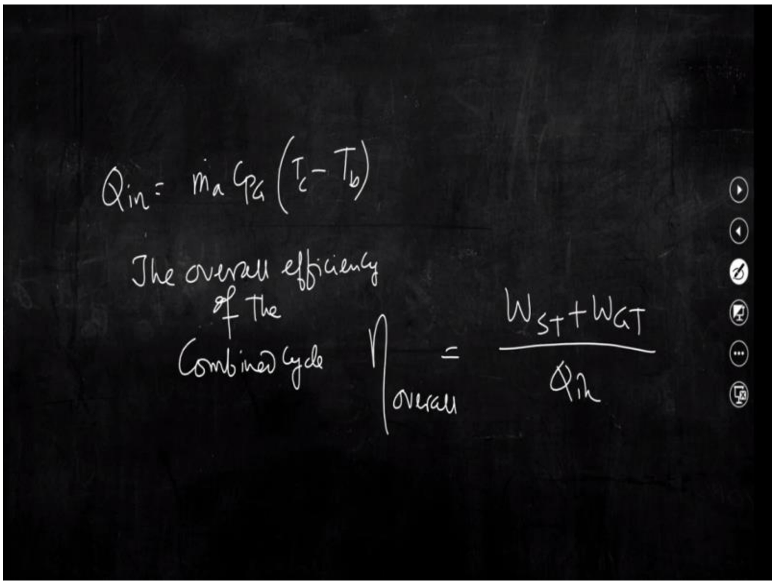
So, this is steam power cycle that we had discussed many times before. Now there is a topping cycle and that cycle is in the T-s plane is like this. Now you can see that amount of energy released by the gas will be taken by the water and it will be converted into steam. So, if we now do the energy balance what we can write? Now by energy balance we can write so basically amount of energy that we need to supply to run the gas turbine unit.

So, basically the amount of energy available with the working fluid before it enters into the gas turbine and finally flowing gas is producing certain amount of work here and then remaining energy is transferred to the bottoming cycle that is the H_2O cycle.

$$\dot{m}_a C_{p,a}(T_c - T_f) = \dot{m}_s(h_3 - h_4)$$

So, now then this is the expression we can write from the energy balance. So, part of that energy is producing gas turbine work, remaining part of this energy is utilized to producing steam turbine work.

(Refer Slide Time: 52:13)



$$Q_{in} = \dot{m}_a C_{p,a}(T_c - T_b)$$

$$\eta_{overall} = \frac{W_{ST} + W_{GT}}{Q_{in}}$$

So, we could write the expression of the overall efficiency and that is the total work output from both cycles divided by the total energy added to the system. So, now the advantage of this combined cycle is high overall efficiency, low water requirement and then low environmental impact. So, though closed cycle gas turbine units are not used frequently for power generation.

But closed cycle gas turbine units are connected in series with the steam power cycle to to supply certain amount of load when demand increases, but despite having several disadvantages feature of the closed cycle gas turbine unit still when that unit is now connected in series with the steam turbine unit we can have a few advantages like high overall efficiency, low environmental impact and low water requirement.

So with this I stop here today and we shall continue our discussion in the next class. Thank you.