Thermal Engineering Basic and Applied

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Lecture - 62
Gas Turbine Units and Thermodynamic Cycles

Very good afternoon. I welcome you all to the session of Thermal Engineering Basic and Applied and today we shall discuss about gas turbine units and to analyze the performance of gas turbine units we shall discuss about another thermodynamic cycle and that is the Brayton cycle. In the last few classes in particular during our discussion of steam power module we have discussed about the vapour power cycle.

And the sole purpose was essentially to produce power. Now for the gas turbine units again we need to discuss about gas power cycle and the objective is to produce power, but if you try to understand vapour power cycle and gas power cycle only the difference is the working fluid. In a vapour power cycle we have discussed about the power generation, power production using a working fluid that is steam or steam water mixture.

But here for the gas turbine units power will be produced through several processes and those processes will be executed in several units and the working fluid is gas. So, for the gas power cycle, you know, Brayton cycle is the air standard cycle. I would like to discuss again that whether we have discussed about steam power cycle or we have discussed about the gas power cycle like Otto cycle, diesel cycle.

In all those cycles essentially we had to map or compare the processes with an air standard cycle, for example, you know for the gas power cycle that we have discussed about the Otto cycle, diesel cycle. So, basically air standard cycles are used to analyze the performance of a petrol engine of a diesel engine or the Otto cycle and diesel cycle, but for the vapour power cycle you know that it is not the gas rather it is a pure substance.

So, we had to analyze the performance of a steam power plant using another thermodynamic cycle that is the Rankine cycle. So, today we shall discuss about you know gas turbine units and let us start our discussion with the classification of the gas turbine units.

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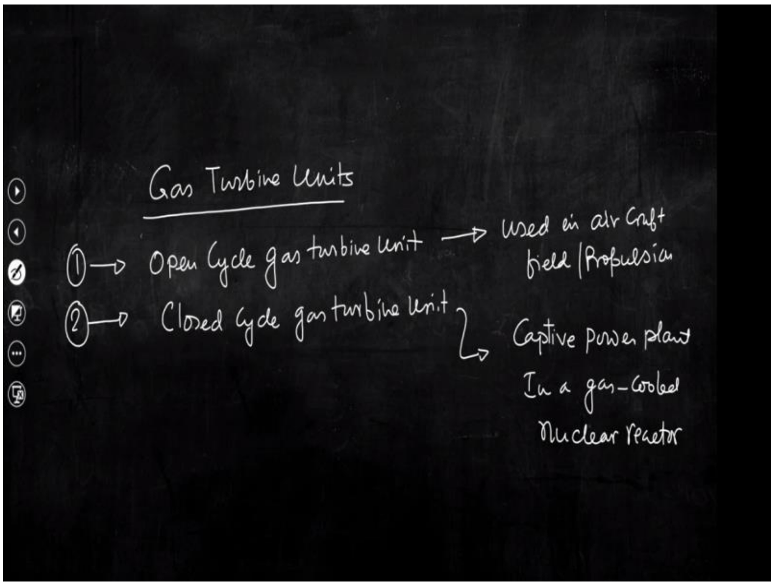

So, there are 2 broad classes of gas turbine unit. First one is open cycle gas turbine unit and second category is closed cycle gas turbine unit. So, these are the two different classifications of the gas turbine units. Now we shall be discussing about both open cycle and closed cycle units with schematic depiction. I would like to mention here like Otto cycle is used to compare the performance of a petrol engine.

Diesel cycle is used to compare the performance of a diesel engine, Rankine cycle or modified ranking cycle is used to compare the performance of steam power plant. Similarly, open cycle gas turbine unit to be precise the air standard cycle Brayton cycle. So, this air standard cycle is used to measur or you know compare the performance of the gas turbine units.

So, what are the applications of these gas turbine units? Applications are you know aircraft field, propulsion and also captive power plant. Typically, you know that for a gas cooled nuclear reactor a small gas turbine unit is used. Open cycle gas turbine units are used mostly in aircraft field and propulsions. So, closed cycle gas turbine unit is typically used in captive power plant in particular in a gas cooled nuclear reactor.

Basically you know that energy which is produced due to nuclear fisher reaction that energy is absorbed or taken by the gas and that gas is again allowed to expand in a turbine and we try to obtain work output.

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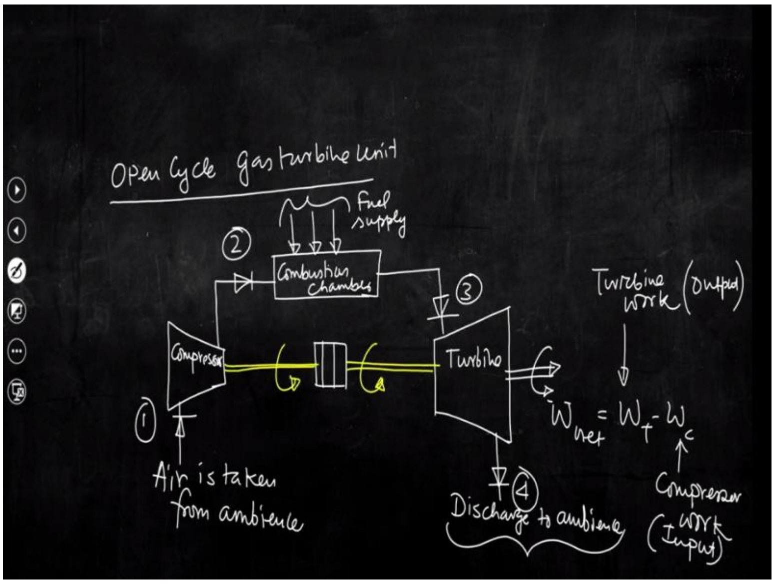

So, now let us discuss about the open cycle gas turbine unit through schematic depiction. So, this is the compressor, air is drawn into the compressor and you know that compressor is used to increase the pressure. So, essentially air will be compressed and pressure will be increased, temperature also will increase, but the most important part is to increase the pressure of the working fluid.

So, air is taken from the ambience and that compressed air is now taken into this combustion chamber wherein fuel is sprayed, and so basically compressed air is allowed to pass through the combustion chamber wherein fuel is sprayed and combustion will occur. It is because of this combustion, you know, combustion reaction to be precise, the pressure of this working fluid will increase further. temperature of the working fluid will increase further.

So, essentially the working fluid that comes out from this combustion chamber is now taken into this turbine and finally so this is state point 3 and this is state point 4 and this is the turbine and we will be getting W, work output. So, basically try to understand ambient air will be taken into this compression, air will be compressed and at the exit of the compressor air is having high pressure temperature is also higher than its inlet temperature of course.

That air will be now taken into this combustion chamber wherein fuel will be sprayed. It is because of this combustion reaction temperature and pressure will be increased further of the working fluid and that working fluid is further taken into this turbine wherein the working fluid is allowed to expand and we obtain work output. Now question is to run this compressor we need to feed some amount of energy in the form of work.

So, compressor shaft is connected to the shaft of this turbine, when turbine is producing work I should say a significant part of that output work would be absorbed by this compressor for its operation. Now, essentially the work that we will be getting from the turbine that is W net equal to Wturbine - Wcompressor.

So, turbine work that would be available at this shaft of this turbine is $W_T - W_C$. So, this is basically turbine work and Wc is the compressor work. So, this compressor work is input and turbine work is output. So, had we not connected this shaft of this compressor with this shaft of the turbine we could have obtained turbine work that is W_T, but what we can see from this you know schematic depiction is that a significant part of this turbine work will be absorbed by the compressor for its operation.

Hence, we will be getting network output and that is $W_T - W_C$ and Wc is basically the amount of work that we need to feed to this compressor. So, this is basically open cycle. Now why it is open cycle you try to understand, we are taking the working fluid from the ambience and finally the working fluid is again discharge into the ambience at the exit of the turbine. So, this is discharge to ambience.

So, this is called open cycle because working fluid is not further taken back to this compressor, had we tried to recycle back this discharge that is the working fluid that comes out from the turbine into this compressor then the cycle would be the closed cycle gas turbine unit. So, not only this there are a few aspects that we shall be discussing in the context of closed cycle gas turbine unit, but this is the case.

I would like to tell you a few important points pertaining to this unit that is open cycle gas turbine unit. See in the combustion chamber in real case high pressure and temperature is also high, air will be supplied into this combustion chamber and then fuel will be sprayed therein. So, combustion reaction will occur. Now, when combustion reaction will occur or combustion will occur we will be getting products of combustion.

And the products of combustion are certainly different from the reactants. Now the effect being a gradual decrease in the chemical energy of the fuel when you are supplying fuel so basically the fuel is having chemical energy. So, the effect is being if we allow not to have any heat transfer from the combustion chamber into the surroundings then the sole effect would be a gradual decrease in the chemical energy of the fuel.

And simultaneous increase of the enthalpy of the working fluid. So, in real case it is because of this combustion with a reduction of the chemical energy of the fuel, enthalpy of the working fluid will be increased, but to simplify the entire combustion process that would be used to you know quantify the mathematical form of the efficiency of the gas turbine cycle, it is assumed that equivalent amount of energy in the form of heat that would be generated because of this combustion will be now transferred to the working fluid.

And that energy as if is, coming out or being liberated by the combustion reaction. So, this is basically an important thing. Another important thing is, that the closed cycle gas turbine units cannot be compared with the constant pressure cycle because try to understand here we are again further discharging the working fluid to the ambience. So, it is not a constant pressure cycle.

Second thing you know when you would like to match the processes what are those processes? Compression of the air, then combustion that is basically equivalent amount of heat addition and finally expansion of the working fluid in the turbine. So, the combustion process as I said few minutes back can be mimicked by an equivalent amount of heat addition to the working fluid at a constant pressure.

The question is here the working fluid is air or gas? Now the specific heat of the gas will vary because it is function of temperature as well. So, we have to assume that when the working fluid is getting compressed in a compressor or it is getting expanded in a turbine, we can you know certainly consider an average value of Cp and also gamma to measure the performance or to measure the processes those are there in a compressor or turbine.

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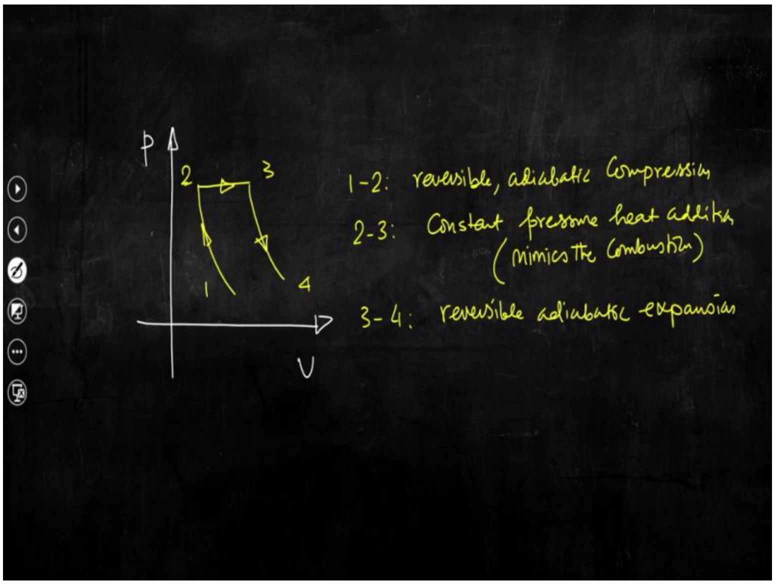

Another thing is in an open cycle gas turbine units if we try to now map the processes in P-v diagram, so we can see compression process that is 1 to 2 that process can be mimicked by an isentropic process that is reversible adiabatic process. It is very difficult to achieve that process in real applications, but we can assume that the process is reversible adiabatic, isentropic process.

And that process is represented in this P-v plane by this 1 to 2 that is $pv^{\gamma} = C,$ if we try to analyze the performance using different air standard equation. So, now then process 2 to 3 that is at constant pressure heat addition and finally so this is 4 that is expansion process. So, basically, you know, 1 to 2 reversible adiabatic compression, 2 to 3 constant pressure heat addition that is essentially mimics the combustion process and 3 to 4 reversible adiabatic expansion.

So, now this is an open cycle so we did not connect the state point 4 and 1 though condition of the working fluid at state point 1 is the ambient air and when the working fluid comes out from the turbine it is discharged into the ambience, so the state point would be you know ambient condition. Now temperature will certainly be higher than the ambient air, but we are directly discharging into the ambience.

So, this is the open cycle. Now question is, as I said that open cycle gas turbine units are used mostly in the aircraft fields. One important drawback is air is directly taken from the ambience so that air will be now allowed to pass through compressor then turbine. Air that will be drawn into the compressor from the ambience. It is very likely that foreign particles will also enter with the airstream.

And those foreign particles will now rather will interact with the turbine blades as well as compressor, you know, rotor of the compressor. So, what will happen that those particles may create problematic issues essentially for the turbine blades and also the compressor in a rotor. So, we need to ensure that air that should be drawn into the compressor should be properly screened to eliminate those foreign particles.

So high quality filters are needed, but if we somehow can recycle back the air that comes out or gas that comes out from the turbine into the compressor again certainly you have to release certain amount of heat. As I said you the state point 4 though that gas or air is discharge to this ambience, but that state point 4 is not exactly equal to state point 1 thermodynamically.

Certainly pressure and temperature of the working fluid at state point 4 is higher than the state point 1. So, next is that if we try to reuse the gas that comes out from the turbine that means if you like to recycle back that working fluid perhaps you know that contamination due to foreign particle of the incoming airstream can be avoided or can be prevented.

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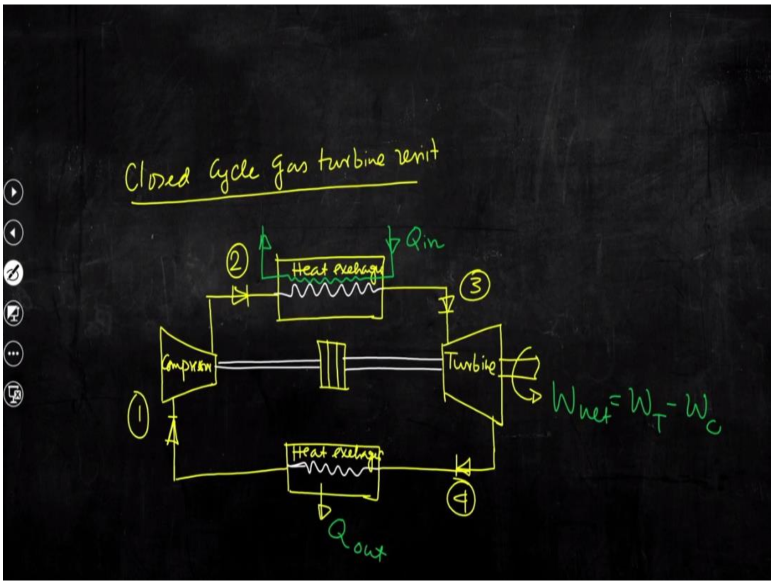

So, now we shall be discussing about closed cycle gas turbine unit. See basically we need to close this. So, the gas that comes out from the turbine will be recycled back to the compressor through certain process. So, if we try to draw the schematic. So, this is the schematic depiction of a closed cycle gas turbine unit. So, this is the turbine, this is basically heat exchanger, this is also heat exchanger and this is the compressor.

So, again the shaft of this compressor is connected to this shaft of this turbine. A significant part of this turbine work output will be utilized to run this compressor. Here it is not the combustion chamber rather it is a heat exchanger. So, few minutes back I said that the closed cycle gas turbine units are used in skeptic power plant or in a gas cool nuclear reactor.

So, what will happen if I try to draw here maybe there will be another circuit through which high temperature working fluid stream will be allowed to pass and in the primary circuit the working fluid will absorb that heat and that upon receiving that heat or energy to be precise working fluid temperature pressure will increase essentially we are trying to mimic the entire combustion process by this heat exchanger unit.

And the remaining process is similar, then the working fluid will enter into this turbine and again it will expand then Wnet will be produced that is Wturbine - Wcompressor and here we need to reject certain amount of heat. So, this is Qout and here as if we are supplying certain amount of Qin. So, upon receiving this amount of energy in the form of heat the thermodynamic state of the working fluid will change and then at state point 3 the working fluid will be having high pressure temperature, it will expand in the turbine and instead of directly discharging the working fluid into the ambience now what is done here that working fluid is again taken through another heat exchanger wherein that working fluid releases certain amount of energy to another stream and then that working fluid is again further taken to this compressor and cycle is getting completed.

So, this is basically closed cycle gas turbine unit. Now question is also I could have discussed another important aspect which is valid for both closed cycle as well as open cycle, you know what do we expect that if W_C is a significant part of this W_T then certainly efficiency of the plant will be less rather very less. So, this is one important factor. Second thing is, that though we will map the processes by reversible adiabatic process.

What are those processes compression process and the expansion process in the turbine, expansion of the gas in the turbine. So, in real case these two processes will certainly have high degree of irreversibility and accounting for that irreversibility, you know, actual efficiency of the turbine unit will certainly be less. So, that means the work output that we are expecting for a given design condition the actual work output by the turbine should be very much less than this W_T.

We are assuming that this work will be produced if we consider the process to be an isentropic process, reversible adiabatic, but as I said in real case this process will encounter high degree of irreversibility and accounting for that this W_T should be even less than the predicted value by using this isentropic process. Similarly, here I had written that W_C is the work input to this compressor.

Now if this is the amount of work needed by assuming the process is reversible adiabatic in the compressor. So then the actual work that we need to supply to the compressor accounting for the irreversible losses should be more than this. So, essentially what we can understand the W net will be reduced. So W_T should be even less W_C will be more and the gross effect would be reduction in Wnet and Wnet becomes so less that self sustaining of this unit becomes an problematic issue.

So, while we will be considering the process either in a compressor or in this turbine, we have to assume that process or processes are not reversible adiabatic

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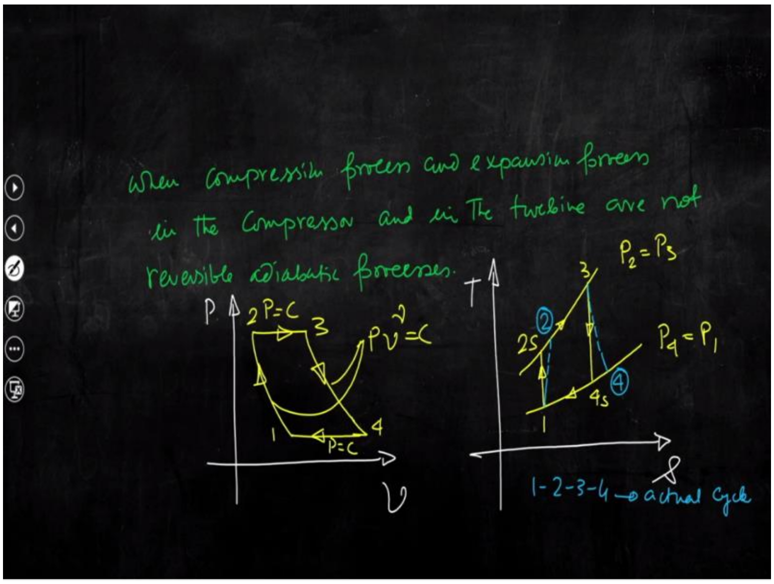

So, now let us discuss about when compression process and expansion process in the compressor and in the turbine are not reversible adiabatic processes. So, now let us try to discuss about this particular aspect here now. So, what we can do we can again map the processes in another plane that is $T - s$ plane and we also can map the processes in $p - v$ plane. As I said for the open cycle gas turbine unit.

So, this 4 to 1 that process is a new process for this closed cycle gas turbine unit because if we try to recall the p-v diagram for the open cycle gas turbine unit we can see that, these two points are not connected because there is no process, but now we are having another process that is represented in p-v or T-s plane by a constant pressure heat rejection.

This is a constant pressure heat addition not only at constant pressure in reality, in real application there is basically combustion will be there and it is because of this combustion we are trying to discuss here using a simplified schematic diagram. So the combustion process is mimicked here by an equivalent amount of energy addition at a constant pressure and constant Cp.

So, here also we are assuming that the amount of heat that is added to this working fluid in the primary circuit is at constant pressure and Cp essentially because in a combustion process as I said you that Cp of the gas will change in the combustion chamber. So, it is advisable to consider average value of Cp and gamma, of course Cp in the combustion chamber again, Cp and gamma inside the compressor and turbine.

So, here also the process is represented by a constant pressure heat rejection process and that is shown here 4 to 1. Now, if we try to draw the T-s diagram. So, these two processes are basically you know this is you know $p_2 = p_3$ and it is $p_4 = p_1$ because this process is at a constant pressure. So, now this is the process 1 to 2s.

So, this is isentropic compression 1 to 2s, $pv^\gamma = C$ and this is P equal to constant. So, this is isentropic process and also again there will be isentropic expansion. So, this is 3 and this is 4s. So, if we try to calculate or if you try to represent the compression process by reversible adiabatic compression and reversible adiabatic expansion of the working fluid inside the turbine.

Then we can represent these two processes by this 1 to 2s and then 3 to 4s these two lines at constant entropy. Now question is as I said that these two processes certainly will deviate from the reversible adiabatic processes rather some degree of irreversibility will be there and if we try to then represent you know the actual process then actual process should be like this. So, this is 2.

Similarly entropy it can be shown by using you know second Tds equation that entropy in the expanses expansion process. So, basically if we consider the expansion process from 3 to 4 then in the direction of flow or forward flow direction, entropy will increase and the actual process should be like this. So, this is 4.

So, now 1, 2, 3, 4 this is the actual process. Now accounting for the losses due to irreversibility we can define two important efficiencies. One is isentropic efficiency of the compressor and isentropic efficiency of the turbine. Now, what is this?

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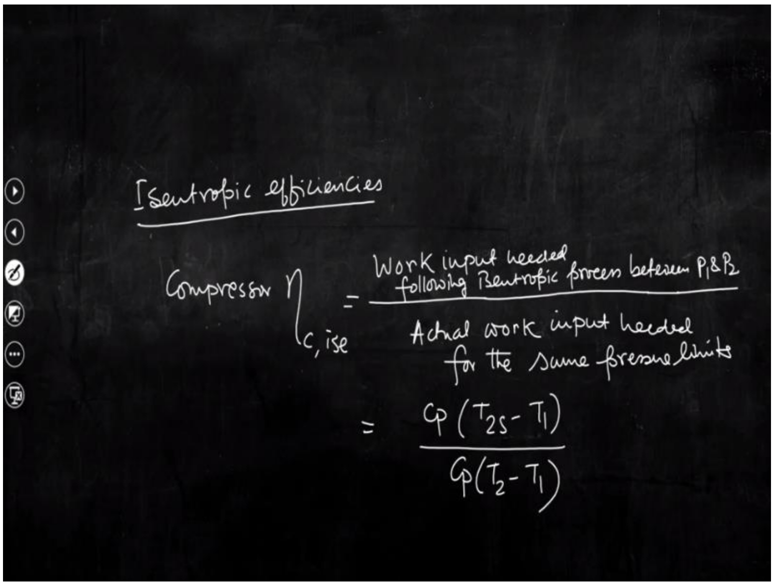

So, see compressor is basically not a wok producing device. It is a device which consume work. So, this is a work absorbing device. So, if I try to define what would be the definition of this isentropic efficiency of the compressor. So, actual work needed to be supplied to the compressor should be greater than the work needed to run the compressor following isentropic process.

So, efficiency can be defined as the ratio of work input needed following isentropic process between P_1 and P_2 that is two pressure limits to the actual work input needed for this same pressure limit. That means the work input needed to run the compressor following the isentropic process between two pressure limits that is P_1 and P_2 and actual work input.

$$\eta_{c,iso} = C_p(T_{2s} - T_1)/C_p(T_2 - T_1)$$

You can understand certainly the actual work needed to be supplied to the compressor should be higher than the work needed following the isentropic expansion. Hence isentropic efficiency of the compressor will certainly be less than the predicted value using the isentropic process. So, this is basically, the isentropic efficiency of the compressor.

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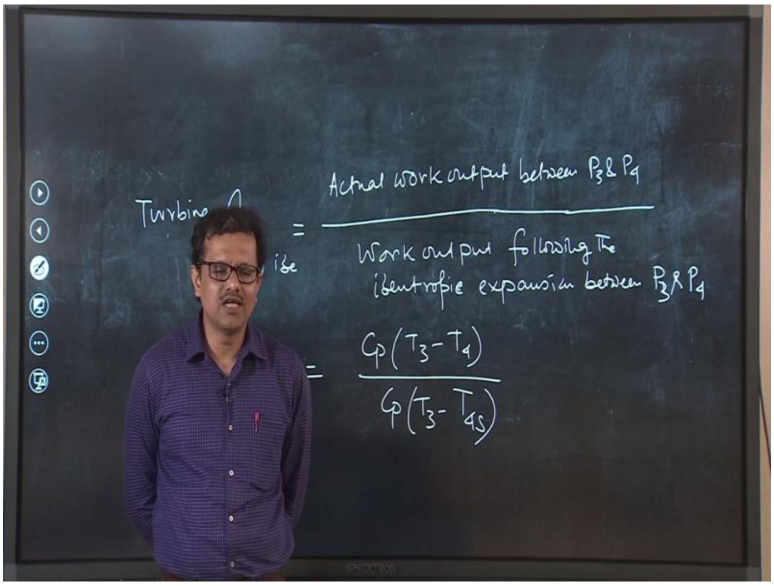

Similarly, isentropic efficiency for the turbine you can understand easily, turbine is basically you know work producing device. So, what, would be the definition? Now in a turbine we are getting work output. So, actual work output should be less than the predicted one following the isentropic expansion. So, the efficiency definition can go as that actual work output between P3 and P4 to the work output following the isentropic expansion between P3 and P4.

$$\eta_{T,iso} = C_p(T_3 - T_4)/C_p(T_3 - T_{4s})$$

So, this is the mathematical expression of the isentropic expansion of the turbine. So, we could write isentropic efficiency of both compressor and turbine. Now let us quickly take an effort to derive the cycle efficiency. We had seen that we can have the mathematical quantification of the cycle efficiency.

We also can quantify the cycle efficiency knowing the efficiency of all units like compressor then certainly the combustion efficiency and then the turbine efficiency. If you try to recall in the context of a steam power cycle, we could establish that the overall efficiency like the efficiency of the boiler multiplied with the efficiency of the turbine then multiplied to the efficiency of the condenser.

And then with the pump. So, basically if we can figure out the efficiency of all these components and then the overall efficiency will be multiplication of these efficiencies. So, now as I said you that the Brayton cycle is basically the air standard cycle for the gas turbine unit, In other word I can tell you that when you try to mathematically quantify the thermal performance, thermal efficiency then we need to compare all the processes by using an air standard cycle. And that cycle for this particular power producing unit be precise gas turbine unit is the Brayton cycle.

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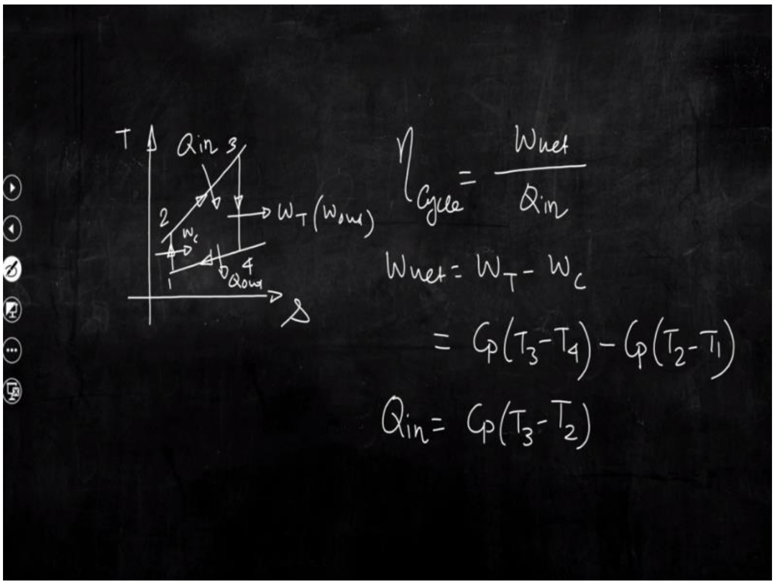

So, if we just again redraw the T s diagram. So, again we shall try to quantify the efficiency assuming that the compression process and expansion process these two processes are reversible adiabatic. So, here this is basically W turbine or W out. This is basically Wc, this is basically Qin and this is Qout. So, what is the efficiency?

Thermal efficiency or efficiency of this cycle is W_{net}/Q_{in} that we have studied in our basic thermodynamic course. So, what is Wnet? If we go back to the either close cycle unit or if even for the open cycle unit. This is $W_T - W_C$ that is the turbine work which is produced minus the part of that work that is fed to the compressor for its operation.

So, you can see from this T s diagram that $W_T = C_p(T_3 - T_4)$. In real application it would be, correct if we can consider the average value of Cp and gamma because this process 3 to 4 and 1 to 2 these two processes mathematically be represented by the relation $pv^{\gamma} = C$.

And this gamma should be taken average because in the expansion and compression process gamma will change. Particularly in the compression process Cp and gamma will certainly be changed. Why? In the real application if we go back to the open cycle gas turbine unit, We are supplying fuel and combustion reaction has taken place and it is because of this particular factor gamma and Cp will change and so it is advisable to consider average value of Cp and gamma when we will be calculating properties at the exit of the turbine using air standard equation that is $pv^{\gamma} = C$. So, compressor work is $W_C = C_p(T_2 - T_1)$.

As I said that here we are not going to consider the actual processes rather we are going to consider the isentropic processes for the compression and turbine processes. So, $Q_{in} = C_p(T_3 - T_2)$ that is the heat addition.

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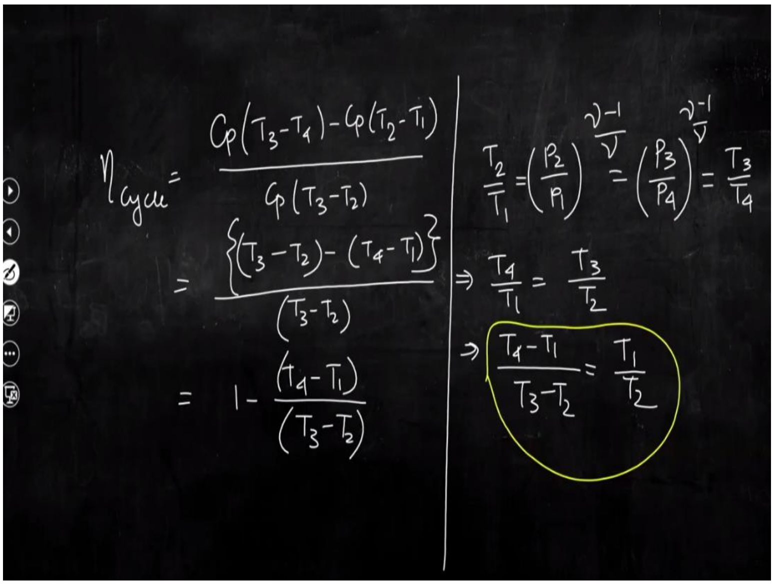

So, if we now write the cycle efficiency then we can write

$$\eta_{cycle} = \frac{\left(C_p(T_3 - T_4) - C_p(T_2 - T_1)\right)}{C_p(T_3 - T_2)} = \frac{\left((T_3 - T_4) - (T_2 - T_1)\right)}{(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

So, this is the mathematical expression of the cycle efficiency of the gas turbine unit. So, now we can again rewrite this process that this is essentially a reversible adiabatic compression. And that is represented by this process $pv^{\gamma} = C$. So, that means we can write what would be the rise in temperature due to the compression process? If you try to recall I have mentioned that after compression certainly pressure of the air will be higher, but temperature also will increase.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4} \to \frac{T_4}{T_1} = \frac{T_3}{T_2} \to \frac{T_4 - T_1}{T_3 - T_2} = \frac{T_1}{T_2}$$

So, this is what we had obtained using air standard equation.

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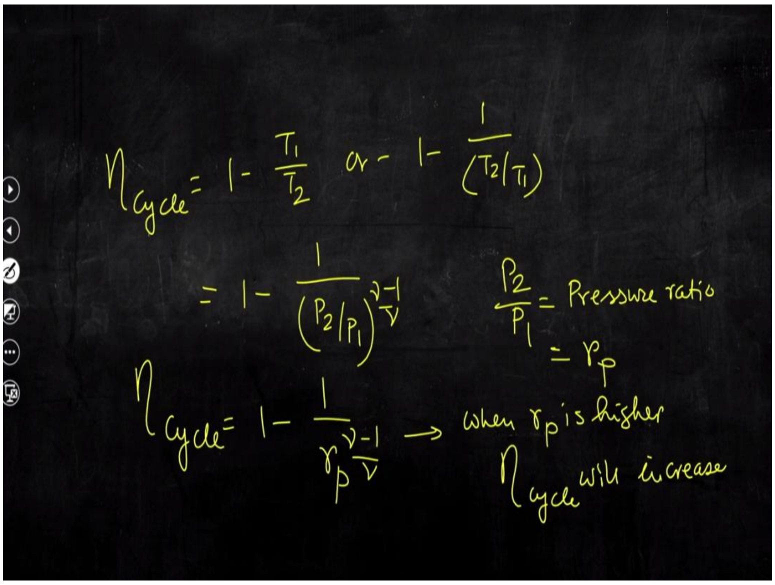

So, what we can write again then cycle efficiency

$$\eta_{cycle} = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{\frac{T_2}{T_1}} = 1 - \frac{1}{\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}}$$

So, you can understand P2 that is the pressure of the working fluid at the exit of the compressor and P1 is the pressure of the working fluid at the inlet of the compressor. So, this $\frac{p_2}{p_1}$ that is called pressure ratio and is represented by r_p.

$$\eta_{cycle} = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}}$$

What you can understand from this expression is that if we somehow increase the pressure ratio that means if we can compress the air. If we can compress the air to the higher extent, then efficiency of the cycle will be more. So, that means higher the compression ratio higher will be the efficiency of the gas turbine unit or cycle efficiency. So, this is basically the expression. So, now question is we also can write this a mathematical efficiency, like this.

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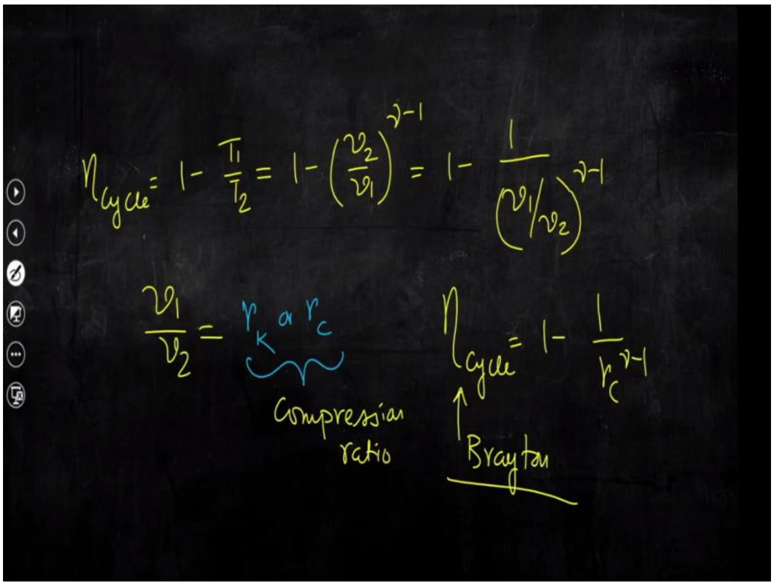

$$\eta_{cycle} = 1 - \frac{T_1}{T_2} = \eta_{cycle} = 1 - \left(\frac{v_2}{v_1}\right)^{\gamma-1} = 1 - \frac{1}{\left(\frac{v_1}{v_2}\right)^{\gamma-1}}$$

So, if we go back to the P-v diagram so basically, and at the end of the compression process volume has reduced.

And it is because of this reduction in volume we could increase the pressure from P1 to P2 and the ratio of $\frac{v_1}{v_2}$ if you try to recall we have discussed in the context of Otto cycle is known as the compression ratio that means we could compress the air or any other working substance and it is because of this compression we could increase the pressure of the working fluid also temperature will increase.

As I said you that pressure increase is more than the increase in temperature. So, here we can write that $\frac{v_1}{v_2} = r_k \; or \; r_c$. So, this is known as compression ratio. So, we also can write $\eta_{cycle} = 1 - \frac{1}{(r_c)^{\gamma-1}}$. So, for the same compression ratio if the compression ratio is same efficiency of the Brayton cycle will be equal to the efficiency of the Otto cycle. So, to summarize today's discussion we have discussed about the gas turbine unit, we have classified the gas turbine units and then we have discussed about the operation of both open cycle gas turbine units then we could define the isentropic efficiency of both compressor and turbines.

And finally we could establish the cycle efficiency and then we have expressed the cycle efficiency both in terms of pressure ratio and the compression ratio. So, with this I stop here today and we shall continue our discussion in the next class. Thank you.