Applied Thermodynamics
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Module - 04
Gas Turbine Engines
Lecture - 03
Gas Turbine Performance Cycle-II

Dear learners greetings from IIT Guwahati. We are in the MOOCS course Applied Thermodynamics Module 4 Gas Turbine Engines.

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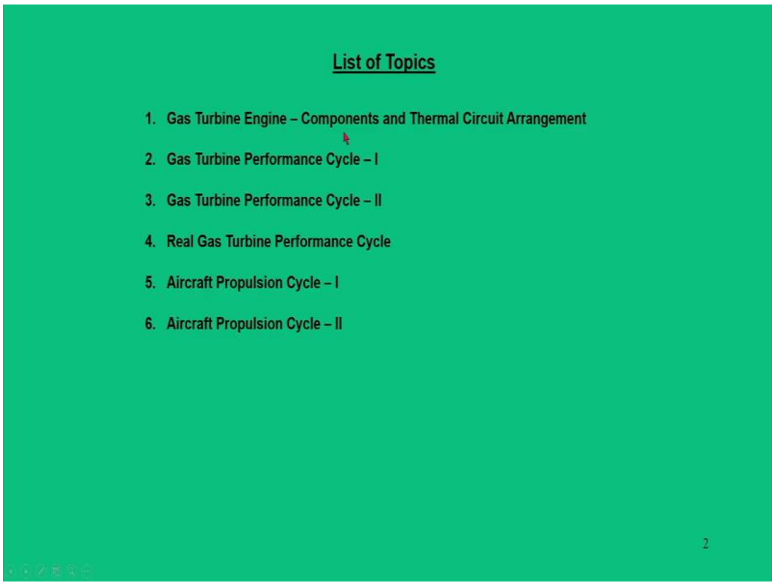

So, in previous lectures, we analyzed the gas turbine engine components, thermal circuits, gas turbine performance cycle part I. Now, we are going to discuss about gas turbine performance cycle part II. Here, we will mainly discuss about the modifications of basic cycles in order to improve the performance. So, you are in the lecture number 3.

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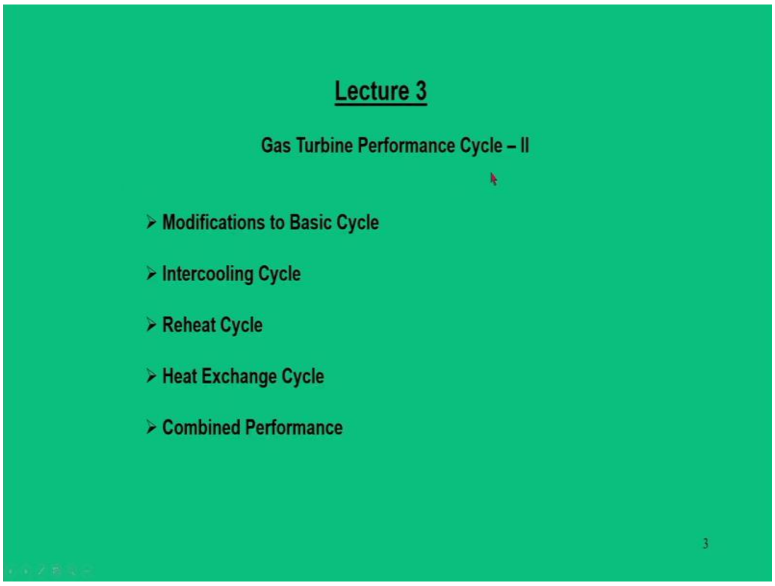

So, under this lecture following topics will be discussed that is modifications to basic cycles. First we will discuss about intercooling cycle, we will discuss about a reheat cycle. And, these two cycles are introduced in the basic cycles with a main intention to increase the work ratio or work output.

Other one, which we discussed about this it is heat exchange cycle, so, this is also a part of this basic cycle, but this particular cycle can be also integrated with intercooled and reheat cycle so that it will also ensure the efficiency. So, meaning that reheat with heat exchange or intercooling has the potential to improve the power output as well as the cycle efficiency.

And, that three things comes under the combined performance.

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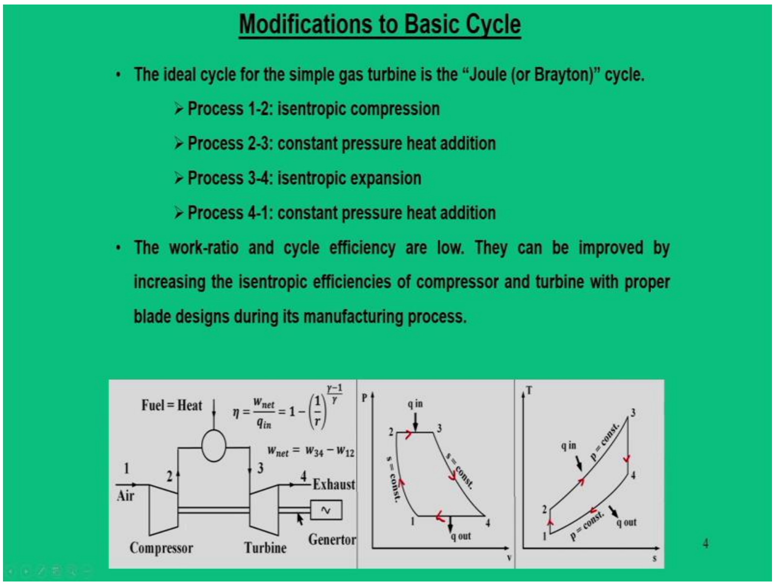

Just to give you brief introduction about the basic cycles with what we discussed. The simple gas turbine or Brayton cycle has 1-2 isentropic process, 2-3 constant pressure process where heat is added, 3-4 isentropic expansion process in the turbine and 4-1 constant pressure heat rejection process.

Now, similarly we show it in the Pv diagrams as well as in the T-s diagram. And, for this basic cycle we defined the efficiency as a function of pressure ratio and the gamma. And, also we find the net work output from this cycle and these two are the main factor for analysis.

So, what we observed is that the work ratio and cycle efficiency are very low in the basic cycles. They can be improved by increasing the isentropic efficiency of the compressor and turbine with proper blade design in the manufacturing process. So, basically first thing is that we have to make the thermodynamic process in the compressor and turbine to follow more and more isentropic nature.

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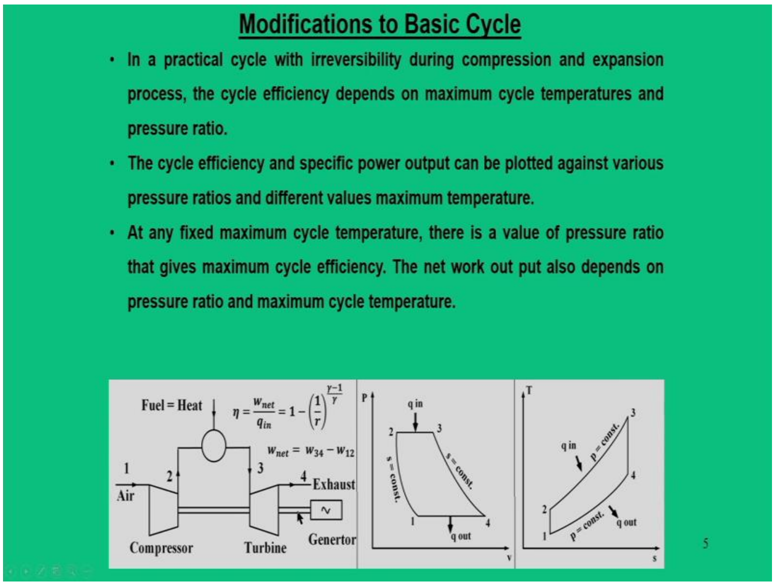

But, that has also limitations because the practical cycles are associated with irreversibility and second issue is that the upper limit of the cycle temperature is fixed based on the materials used in the turbine blades.

And, of course, in the compressor side there is a limiting case that we cannot go beyond certain pressure ratio, because handling will be difficult. And, while we are going for very high pressure ratio within a single compressor, then it becomes non isentropic in nature. So, these are the some of the issues that needs to be attended so that we get a better cycle efficiency and work power output.

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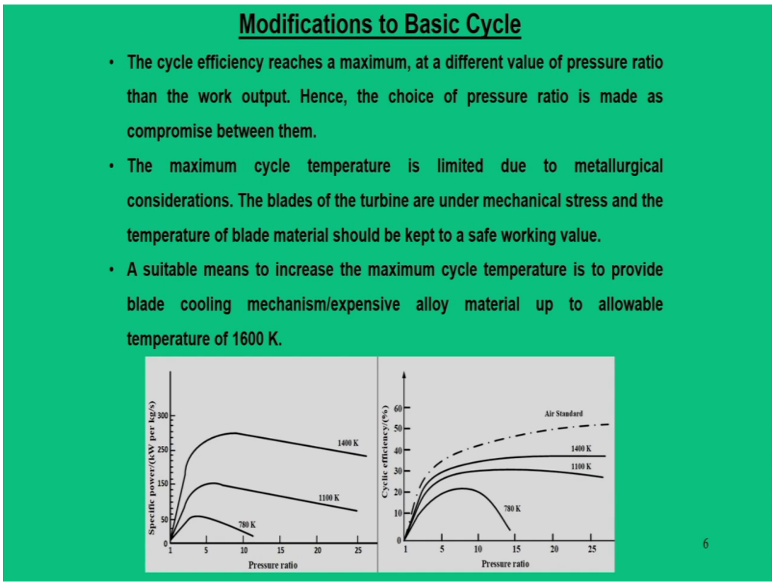

And, then another topic of interest which we discussed in the last class is that the specific power or power output and cycle efficiency, they are functions of pressure ratio as well as the temperature ratio.

So, when you are increasing the pressure ratio; obviously, cycle efficiency increases beyond some point and it comes down. But, at the same time when you increase the temperature ratio, we can have a prolonged cycle efficiency for a wide range of pressure ratio.

And, these are the some of the things that there are some limiting temperature and pressure ratio range within which a gas turbine cycle needs to be operated. And, this has been proven that the cycle efficiency as well as work output are related to temperature ratio as well as the pressure ratio. And, for a given power output or for given applications the temperature and pressure ratio is fixed for a particular application.

Now, having said this let us see that, how we can improve the performance. So, considering the temperature ratio and pressure ratio as the vital parameters, we have to see that how we can adopt certain methodology in which we can improve the performance.

So, by improving performance means we mean two things first thing power output needs to be increased, second thing is that cycle efficiency needs to be also increased. But, as far as the cycle efficiency is concerned, because the gas turbine engines many a times we are merely concerned with work ratio. Because, power output requirement are fixed by the user, having that work ratio with us then you have to see what cycle efficiency we are going to get.

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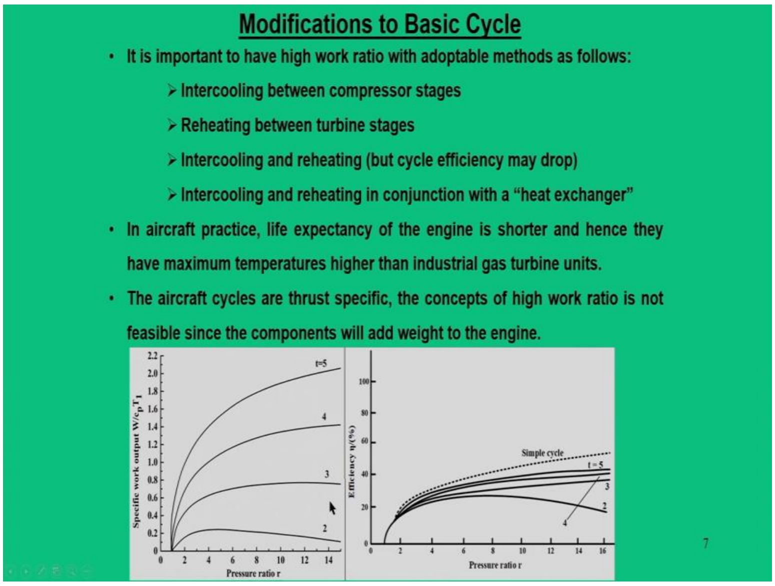

So, for that reasons, there are some adoptable or possible methods that are introduced, first thing is a intercooling between compressor stages, and reheating between turbine stages. So, these two are things that basically to increase the work ratio that is we need to either increase the work output from the turbine side. So, that can be done by through reheating, other way is that you can reduce the compressor work. So, that can be done through intercooling.

So, these two things will give you higher work ratio. But, at the same time if you are very concerned about the efficiency, then we have to think about intercooling and reheating combination with a heat exchanger.

But, when you adopt this third method that intercooling and as well as reheating, so, in both the cases we are going to get the work output high. But, the cycle efficiency we cannot guarantee, it may drop. To increase the cycle efficiency, if you are very concerned with that, then this intercooling and reheating should be adopted with a heat exchanger cycle. So, these four things are basically very vital for the design of a gas turbine power plant.

And, this is mainly used when we have a shaft power cycle, but in aircraft practice we expect the thrust. So, life expectancy of the engine is shorter, hence the maximum temperature is higher in the industrial gas turbine unit. So, your main intention is the high temperature.

And, there since thrust is main concern, concept of high work ratio is not feasible; since you are not concerned with high work ratio. So, intercooling reheating concept is not part of the aircraft cycles. So, their aspect is something different that we will see later.

So, these two plots which we have shown in our last class that how a specific work output and efficiency varies with pressure ratio as well as the temperature ratio.

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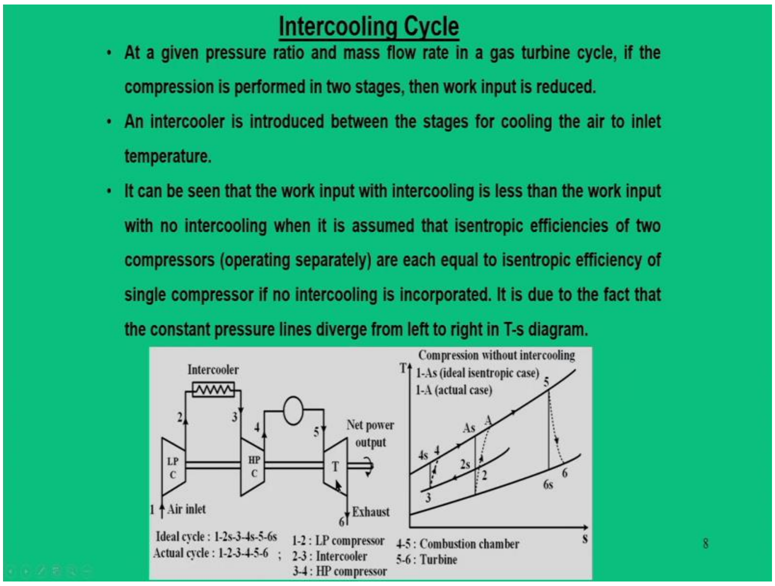

Now, let us start with the first modification that is what we call as a intercooling cycle. So, it has been shown in thermodynamics, that when you make this compression process in a quasi static manner we will consume less work. So, in that sense instead of going for a single stage compression. a intercooling method is adopted.

So, in that way when we are doing this compression is performed in multiple stages, two or more stages, the work input will be reduced. So, for that an intercooling is introduced. Now, what does this intercooling does? This brings down the temperature of air to the inlet temperatures.

So, it can be shown that work input with intercooling is less than the work input with no intercooling. So when it is assumed isentropic efficiency between two compressors; each is equal to isentropic efficiency of a single compressor if no intercooling is adopted.

So, it means that, if you are using the intercooling methods and assume same isentropic compressor for each, then, with this intercooling method your work input will be reduced when you go for a multi stage intercooling or two or more compressors.

And, this is mainly because if you recall this T-s diagram. So, in the beginning part T-s diagram, the width between the pressure ratio is less and it diverges as and when the pressure ratio increases. So, it means that when you are in the compression side this difference is smaller, but in the expansion side this difference is larger.

So, that is basically by looking at the trend of the diagram and taking the advantage of this T-s diagram, we used to use the concept of intercooling and reheating. Now, let us see that how an intercooling cycle operates.

So, here what has been given is that here we have two compressors; low pressure compressor, high pressure compressor. And, they are coupled with the turbines and entire power comes from the turbine for both the compressors.

And, there is an intercooler between 2 to 3. So, the ideal cycle goes in the sense that, if the cycle starts with 1, if it is a ideal isentropic cycle then it will have 1-As-5-6s. If, it is an non isentropic cycle without intercooler, it will be 1-A-5-6. So, this would have been the case when it is a simple cycle.

Now, with intercooling what does it do that, after the first stage of compressions; that means, at 2 or 2s the cycle temperature is again brought back to the original temperature. And, then further second stage compression starts; so, this process now becomes 1-2-3-4.

And, had the process mean isentropic it would have been 1-2s in the first compression or 3-4s in the second compressor. And, finally, the circuit goes like this. So, this is how the T-s diagram explains the intercooling arrangement or circuit arrangement.

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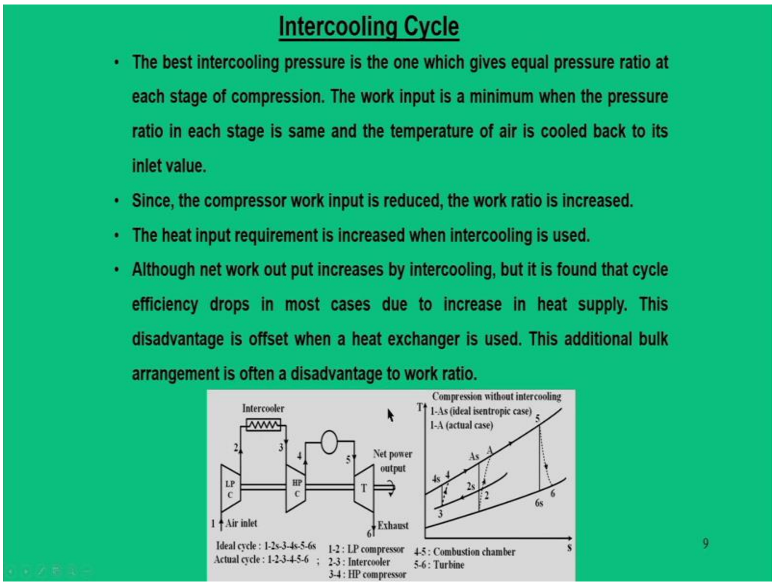

Now, there are some other factors that plays when we will deal with the compressor; in the last module, we will find out that the best intercooling pressure is the one which gives the equal pressure ratio at each stage of the compression.

So, the work output is a minimum when the pressure ratio at each stage is same; that means the pressure ratio in each stage remains same. If you have n number of stages, the pressure ratio in each stages should be equal in each stage. Then only we call this as a perfect intercooling.

Since, the compressor and work input is reduced work ratio is increased, the heat input requirement is increased when the intercooling is used. So, this is another drawback of for intercooling that your input heat requirement is increased, because you need an another intercooling circuit.

Although the net work output increases by intercooling, but it is found that cycle efficiency drops in the most of the cases due to increased heat supply. Because, we need some kind of circuit, that takes out this heat from the compressed air. So, we need an intercooler circuit; so, that means, you need another additional device that must take this heat. And, of course, in many a times if the intercooling arrangement becomes bulky and it becomes a disadvantage in terms of work ratio.

So, these are the some drawbacks, but intercooling is one of the options to reduce the compressor work.

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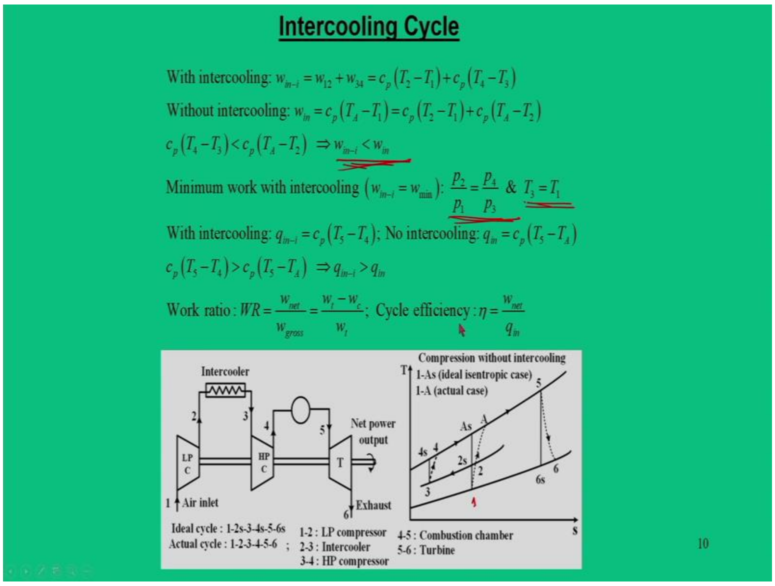

Now, let us see that how an intercooling cycle mathematically proves that work ratio is increased and cycle efficiency drops. So, we can see the circuit with an intercooling circuit, the work input would be $w_{in-i} = w_{12} + w_{34}$; that means, these are the two circuits that consumes work.

With intercooling: $w_{in-i} = w_{12} + w_{34} = c_p\left(T_2 - T_1\right) + c_p\left(T_4 - T_3\right)$

Without intercooling: $w_{in} = c_p\left(T_A - T_1\right) = c_p\left(T_2 - T_1\right) + c_p\left(T_A - T_2\right)$

$c_p\left(T_4 - T_3\right) < c_p\left(T_A - T_2\right) \Rightarrow w_{in-i} < w_{in}$

So, from by analyzing these two expressions, one can clearly say that with intercooling, the work input is less. And, this minimum work with intercooling is possible when the pressure ratio in each stage are equal.

So, when the pressure ratio in each stage is equal; that means, after each stage of heat compression, the temperature must be brought back to its original temperature; that means, $\frac{p_2}{p_1} = \frac{p_4}{p_3}$ & $T_3 = T_1$. So, an ideal circuit would be that after the first stage of compression, the temperature should be brought back to its original temperature.

Now, let us see with intercooling what happens to heat.

$$\text{With intercooling: } q_{in-i} = c_p\left(T_5 - T_4\right); \text{ No intercooling: } q_{in} = c_p\left(T_5 - T_A\right)$$
$$c_p\left(T_5 - T_4\right) > c_p\left(T_5 - T_A\right) \Rightarrow q_{in-i} > q_{in}$$

And one can clearly say that with intercooling the heat input is increased.

So, when heat input is increased and now what will happen is finally, obviously, the compression work is reduced. So, work ratio is increased because you are not touching the turbine work. But, in other side of the story is that the cycle efficiency there is a chance that it may reduce with since q in is increased, cycle efficiency may likely drop out. Of course, all depends on the value of w_{net}. And, in most of the situations the cycle efficiency generally drops.

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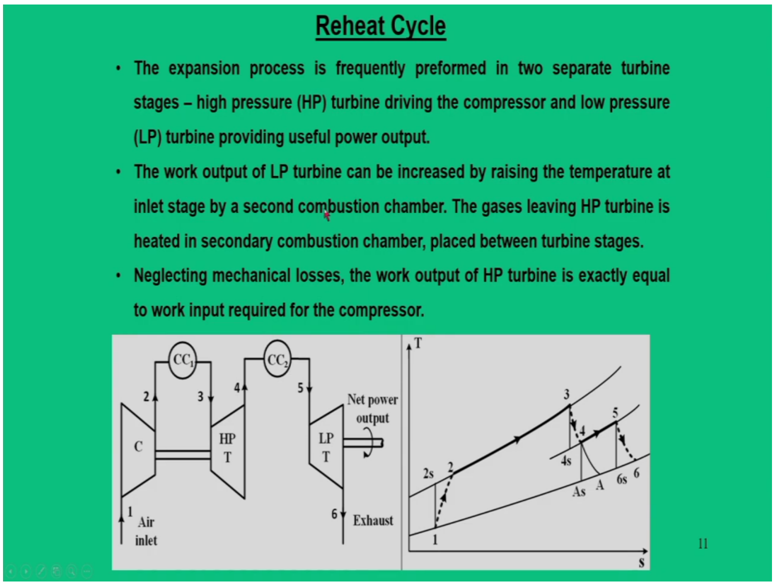

Now, let us see what happens to the reheat cycle. So, this is completely opposite phenomena. So, in opposite phenomena what happens is that do not touch anything about the compressor, you think about what way best you can do to increase the power output from the turbine. So, for that reason the turbine stages are divided. So, one is called as high pressure stage, other is the low pressure stage. So, this high pressure turbine now drives the compressor and the low pressure turbine is now separate that gives the power output.

Now, if you look at this thermodynamic T-s diagrams. So, the compression process 1-2s or 1-2 remains as it is, but in the expansion process, it is now goes in the two stage that is from 3 to 4 in the high pressure turbine expansion. And, then again reheated that is 4 to 5 through another combustion chamber, again 5 to 6 is another expansion in the low pressure turbine.

So, the process now becomes 1, 2, 3, 4, 5 and 6. And, had this process been a complete single stage expansion, then the process would have come from 3 to A. Again, when you do the reheating; the reheating has to takes place till the maximum temperature.

So, the reheat process is complete when T_3 becomes T_5. Normally reheating takes place till it we get the upper limit of the temperature that is typically T_3.

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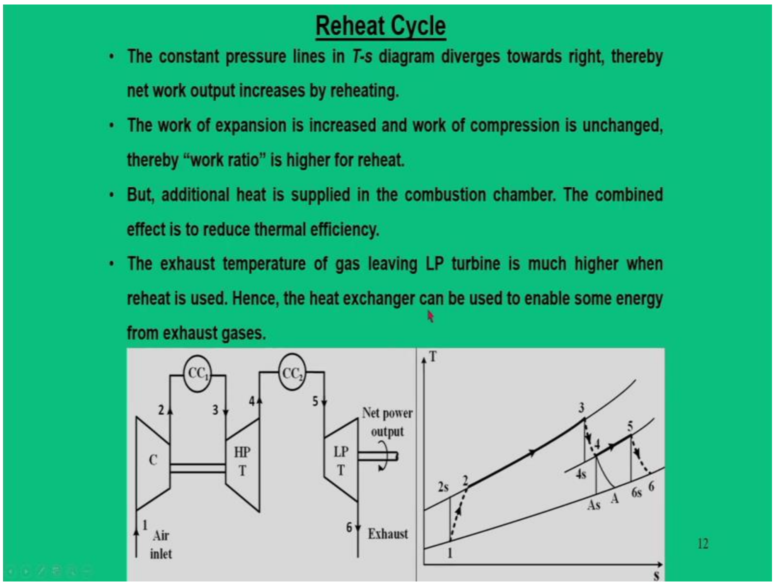

And, in the process of this reheating what we get the expansion work is increased, but since the compression work remains unchanged. So, the work ratio is always higher, but the additional heat is supplied in the combustion chamber. So, the combined effect is to reduce the thermal efficiency.

The exhaust temperature of the gas leaving the LP turbine is higher when the reheat is used. So, hence the heat exchanger can be used to enable some energy from the exhaust gas. So, when you are doing reheating; obviously, we are going to go for very high temperature. And, finally, when the exhaust goes out instead of releasing it to the atmosphere then we have to tap that heat.

So, normally to tap that heat we require a heat exchanger, but that is a separate aspect we will discuss about that part later, that how we can manage in a better way taking the exhaust from the turbine. So, that is a separate aspect.

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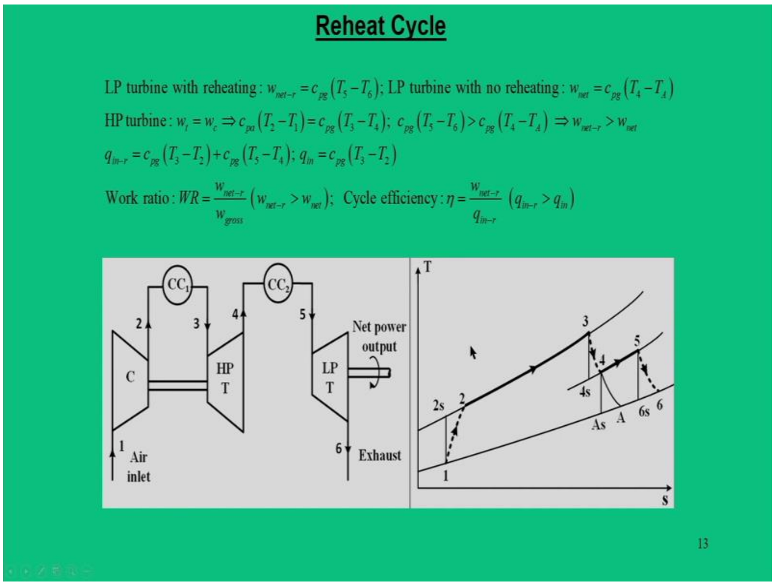

Now, let us see that how reheat improves the work ratio and what happens to cycle efficiency? So, this phenomena is something a reverse phenomena. So, let us think about low pressure turbine with reheating. So, here the power output has two parts; one is the actual power that we get from low pressure turbine and the high pressure turbine normally drives the compressor.

So; that means, HP turbine work is equal to compressor work. And, this can be written as $w_t = w_c \Rightarrow c_{pa}(T_2 - T_1) = c_{pg}(T_3 - T_4)$. So, here you will see that when you look at the compressor side it is mainly air. Now, when you say turbine side it is the hot gas. So, that is what cp_g has been written. So, it is a hot gas, because we have already fuel and air mixture. Now, if you can look at this particular figure, let us start with LP turbine;

$$\text{LP turbine with reheating}: w_{net-r} = c_{pg}(T_5 - T_6);\ \text{LP turbine with no reheating}: w_{net} = c_{pg}(T_4 - T_A)$$

Now, similarly for HP turbine we can get the compression work, but finally, what this what it matters is the net work due to reheat. And, this we can find out had the process been without reheating and with reheating in a LP turbine. So, it can clearly say that this particular number $c_{pg}\left(T_5 - T_6\right) > c_{pg}\left(T_4 - T_A\right) \Rightarrow w_{net-r} > w_{net}$.

And, in this process of reheating how much extra heat we are going toward? So, this can be given because from 4 to 5 it is going again. So, in this 4 to 5 process we are adding extra heat in the combustion chamber 2. So, that is the reason we can say the extra heat that gets added is $c_{pg}\left(T_5 - T_4\right)$. And, how much heat we are going to supply without reheat then it would have been $c_{pg}\left(T_3 - T_2\right)$.

And, in this way we can clearly say that through this reheating process your turbine net work is higher and cycle efficiency drops. Because with reheat we are adding extra heat. And, since q_{in} becomes higher so, cycle efficiency drops. So, this is the disadvantage of reheat cycle.

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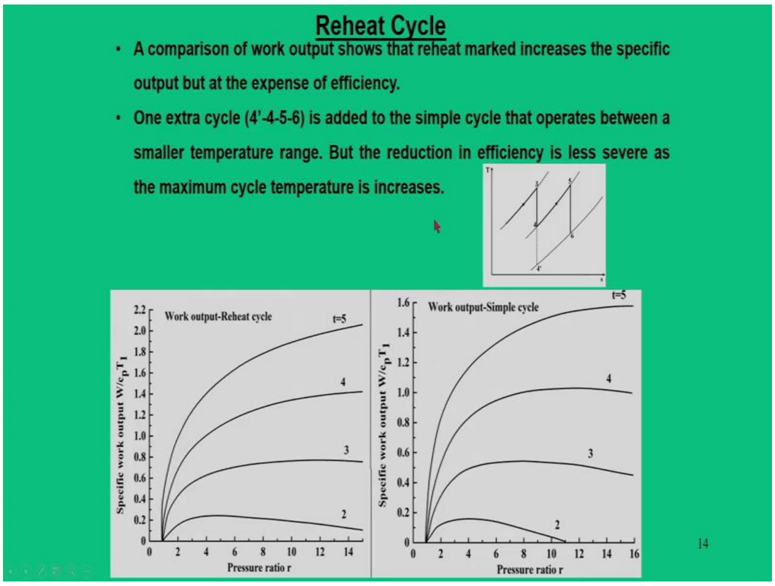

And, some extra philosophy we can say that with reheating, in the T-s diagram, area under T-s diagram is extra heat additions. Now, in that case if the extra heat added in the cycle becomes 4-5-6-4`. So, this particular extra heat since gets added because of this reason cycle efficiency drops.

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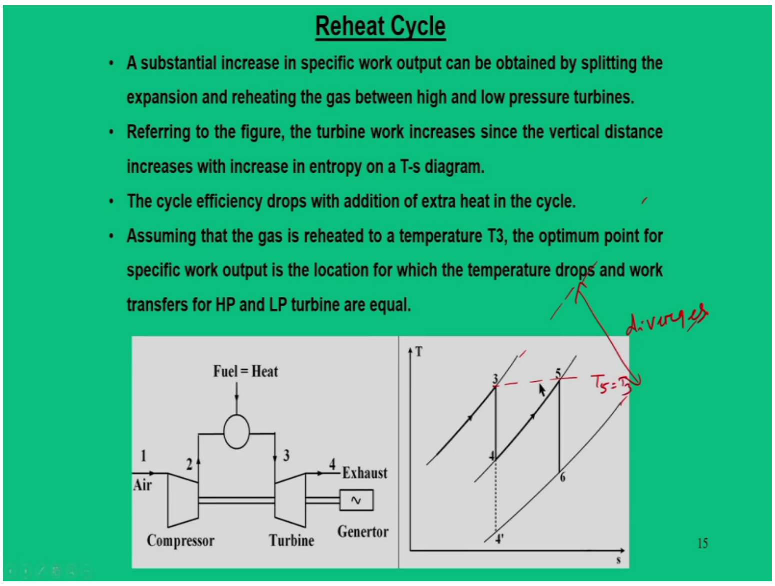

So, this is again another way of representing the things and some better inferences that we can draw that substantial increase in this specific workout can be obtained by splitting the expansion and reheating of the gas between high and low pressure turbines. So, because of this turbine work increases since the vertical distance increases, with increase in the entropy in a T-s diagram. Because this particular gap, as you go further in the T-s diagram, this part diverges.

Since this part diverges; so, we can say that turbine work increases, because the vertical work increases. The cycle efficiency drops with addition of extra heat in the cycle and assuming that gas is reheated and this reheating process is optimum, when this T_5 and T_3 are equal; that means, reheating has to take place to the peak temperature.

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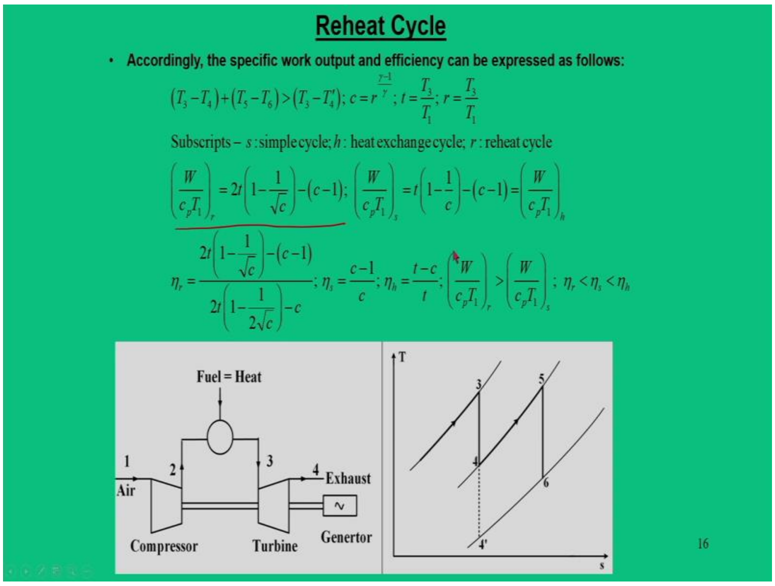

And, work transfers for HP and LP turbines are equal. And, the another way of representing the cycle efficiency the way we represented for basic cycle and heat exchange cycle, we can also calculate for a reheat cycle. What can be the expression for non dimensional work in terms of pressure and temperature ratio?

So, those aspects you can see that the non dimensional work can be represented in this manner $\left(\frac{W}{c_pT_1}\right)_r=2t\left(1-\frac{1}{\sqrt{c}}\right)-(c-1)$. And, with reheat the cycle efficiency can be expressed in terms of temperature ratio and pressure ratio. $\eta_r=\frac{2t\left(1-\frac{1}{\sqrt{c}}\right)-(c-1)}{2t\left(1-\frac{1}{2\sqrt{c}}\right)-c}$

So, it can be shown that for a reheat cycle, efficiency is the least and for the heat exchange cycle efficiency is the highest, by looking at these expressions. Similarly, for a reheat cycle $\left(\frac{W}{c_pT_1}\right)_r>\left(\frac{W}{c_pT_1}\right)_s$. So, this has been shown mathematically that in a reheat cycle the specific work output is higher, but the efficiency drops.

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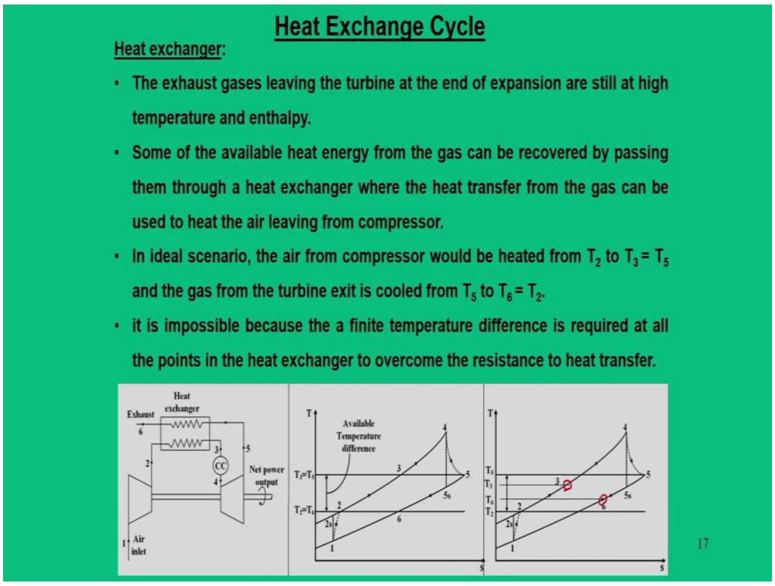

Now, we have already discussed some details about heat exchange cycle, but here the heat exchange cycle is analyzed with a context that, the heat exchanger has to be a integral part when you are talking about reheat or intercooling.

Now let us see that when you introduce a heat exchange cycle; the ideal location of heat exchanger would be that from turbine outlet and till the exhaust and similarly from the compressor outlet to the combustion chamber.

So, in that process we are going to tap the extra heat that is available in the exhaust gas and that can be utilized to pre heat the air, when it leaves from the compressor. So, in an ideal scenario the air compressor would be heated from T_2 to T_3, it can be a maximum of T_5, and gas from the turbine exit is cooled from T_5 to T_6 which has a upper limit could be T_2.

So, if you look at this particular figure this is an ideal scenario, temperature available is the difference that is $T_3 - T_2$ or $T_5 - T_6$, but actually in an actual cycle, heating cannot go up to the point 5 we will land up at the point 3 and while heating and while the exhaust gas instead of getting cooled to temperature T2 it stops at point 6.

So, the location of 3 and 6 is the location where it is within the available temperature difference between T2 and T5. So, that is the reason we say that ideal location of heat exchanger with an intention is to tap the heat from the exhaust of the turbine.

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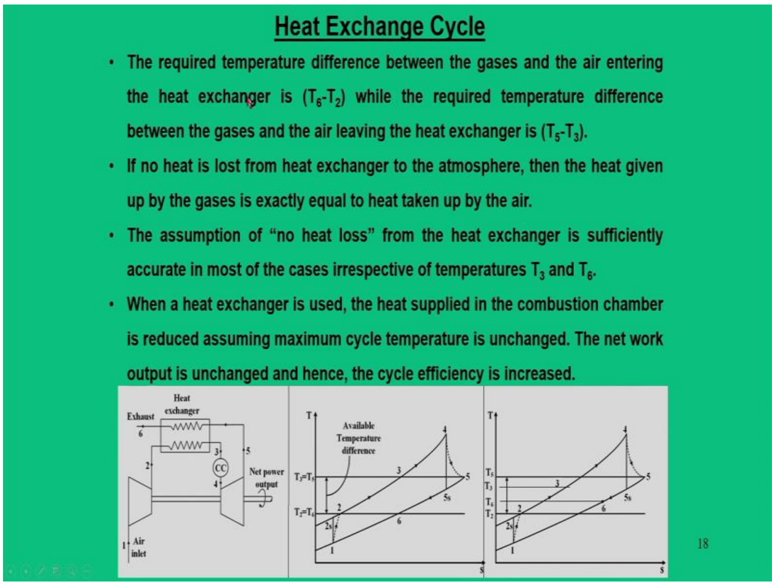

Some of the other inferences that can be drawn here, that required temperature difference between the gases and air entering the heat exchanger is T6 minus T2, while the required temperature difference of the gases and the air leaving the heat exchanger is T5 minus T3. So, the heat is lost from the heat exchanger to the atmosphere, then the heat given by the gas is exactly equal to the heat taken up by the air.

So, the assumption of "no heat loss" from the heat exchanger is sufficiently accurate in the most of the cases irrespective of the temperature T3 and T6.

So, finally, when a heat exchanger is used, heat supplied in the combustion chamber is reduced assuming maximum cycle temperature is unchanged. So, the net work output remains unchanged, but the cycle efficiency is increased.

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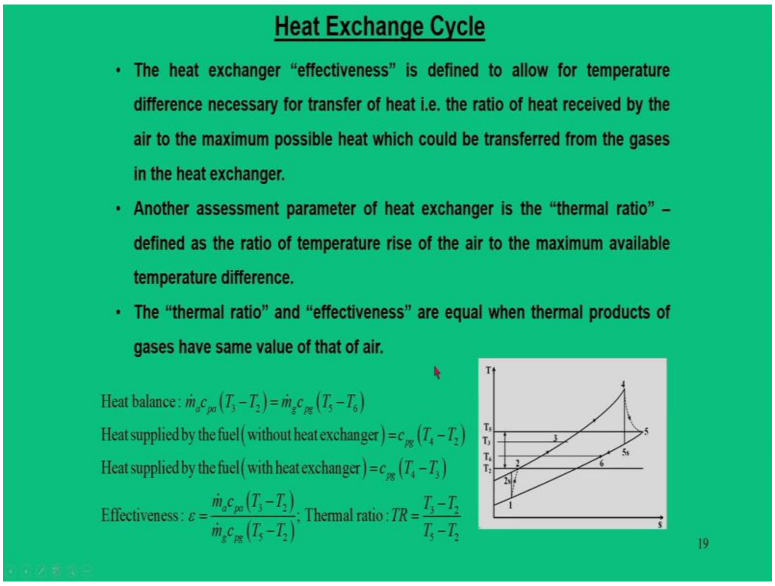

And, to get some mathematical assessment, we define a parameter called as a heat exchanger "effectiveness". And, it is defined to allow the temperature difference necessary for heat transfer or transfer of heat that is ratio of heat received by the air to the maximum possible heat which could be transferred from the gases in the heat exchanger.

That means, we have available temperature difference, with that available temperature difference we have certain quantity of maximum transfer possible. But, due to our variety of regions we are not going to tap the exact quantity of heat. So, to have certain kind of estimation we define this heat effectiveness.

So, a simple heat balance equation can be used that is $\dot{m}_a c_{pa}(T_3 - T_2) = \dot{m}_g c_{pg}(T_5 - T_6)$. Here, we can see that when we are looking at the turbine side we are representing at the gas term $\dot{m}_g c_{pg}$ that is specific heat of the gas. And, when we are looking at the compressor side we look only for the air.

And, ideally when we say there is no fuel supplied, then this number $\dot{m}_a$ and $\dot{m}_g$ has no meaning. And, in that context there are two parameters are defined one is effectiveness which is nothing but the ratio of between these two that is $\varepsilon = \frac{\dot{m}_a c_{pa}(T_3 - T_2)}{\dot{m}_g c_{pg}(T_5 - T_2)}$.

And, in some other situations to make the analysis simplifier, we defined a parameter called as thermal ratio. $TR = \frac{T_3 - T_2}{T_5 - T_2}$ .Thermal ratio means, if you take that ratio $\frac{\dot{m}_a c_{pa}}{\dot{m}_g c_{pg}}$; if, this ratio is unity or close to unity, then instead of writing in fact, effectiveness we simply write it as a thermal ratio. So, the thermal ratio and effectiveness are equal, when the thermal products of the gases have same value with that of air.

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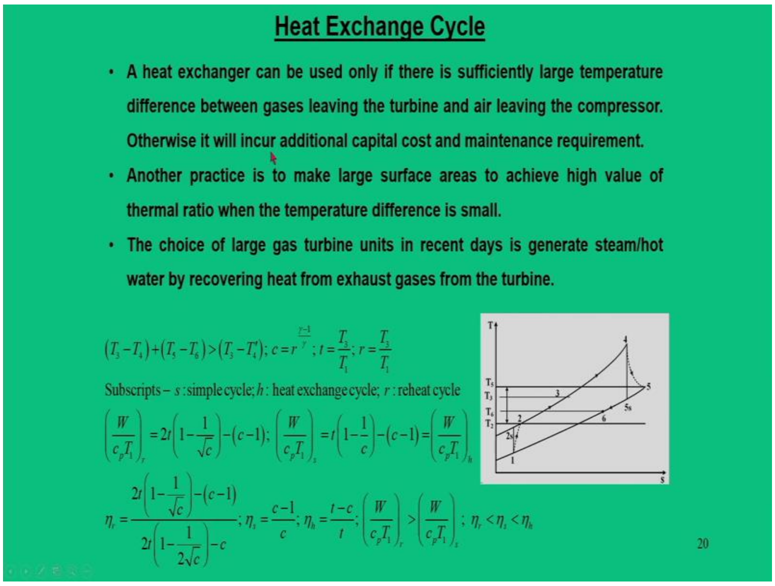

So, it is also possible to say that how heat exchanger cycle improve the cycle efficiency. So, a typical T-s diagram is drawn here. So, from this we can say that for a heat exchange cycle that is efficiency is defined by $\eta_h = \frac{t - c}{t}$ and by putting this we can say, this particular relations holds good $\eta_r < \eta_s < \eta_h$, that is for a heat exchange cycle the efficiency is always higher. Of course, we are not touching the work output.

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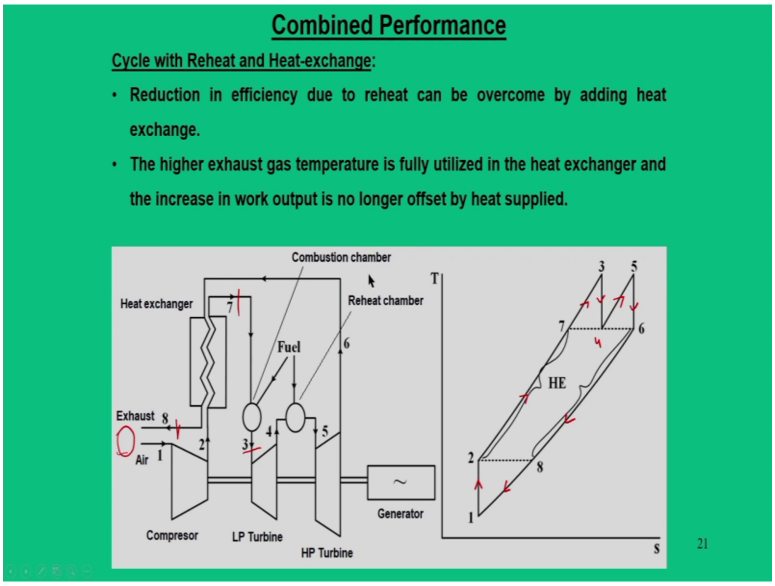

Now, to give some kind of introduction to combined performance, of course the circuit becomes too complicated when involved so many components. So, another situation could be a cycle could be with reheat and heat exchange.

So, reheat means we will have a low pressure turbine, and high pressure turbines. So, these two turbines can be part of that and then a heat exchanger could be another part, that will have basically one primary unit will have a combustion chamber, secondary addition of heat would be a reheat chamber. And, completes thermodynamic cycles could be 1,2, then with reheating 2 to 7, and from 7 to 3 through the combustion chamber.

Then, 3 to 4 that is in the low pressure turbine that is expansion, then 4 to 5 in the reheat chamber and 5 to 6 in the expansion in the second turbine, and 6 to 8 that goes till the exhaust. And, from 8 to 1, it is something like this particular loop where it is actually open, but here it is closed in the sense that the exhaust goes to the atmosphere and from the atmosphere we get the fresh air.

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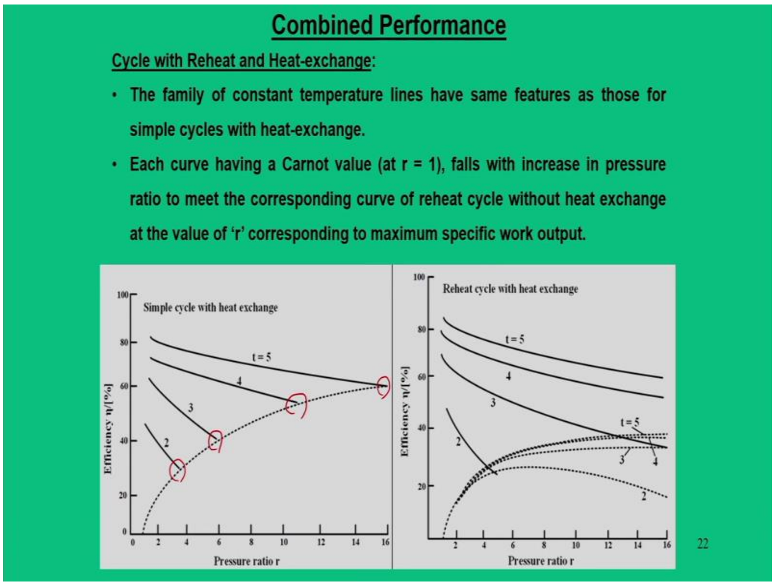

Now, in another way we can represent the cycle with reheat and heat exchange in terms of efficiency and pressure ratio. So, when you say a simple cycle with heat exchange. So, as I mentioned in my previous lecture.

See, if you have only simple cycle we can drop this dotted line curve and here the efficiency is a function of pressure ratio. And, when you look at this particular curves, these curves shows that your efficiency is a function of temperature ratio as well as the pressure ratio.

Now, these two points merge or intersect some location and those points are treated as the optimum things. Now, with this reheat concept, if you look at this, with reheat the basic curves is also going to change for different temperature ratio. And, side by side with reheat and heat exchange cycles, what we can say with a very high temperature reheat cycle, we can achieve a large pressure ratio.

So, this is the very basic philosophy and of course, this circuit becomes too complicated, but just to give that such a cycle is also thermodynamically possible.

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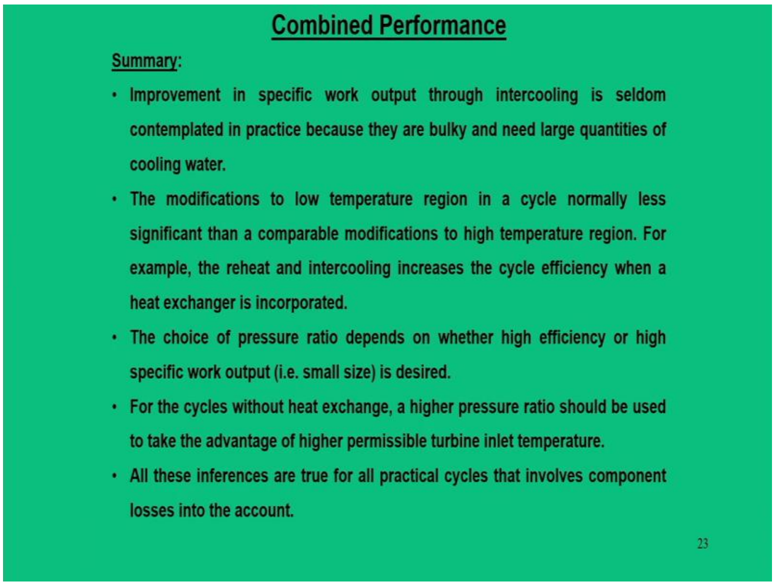

And, finally, I can summarize whatever we have as a combined performance. So, we have discussed so many ways that a circuit can be modified with an intention for work output or efficiency. So, if you want to summarize as an user what we should do.

So, the first thing is that improvement in the specific work output through intercooling is normally not recommended. Because they are bulky they need large quantities of cool cooling water in a typical gas turbine plant, although thermodynamically it is one of the very viable option to reduce the compressor work.

Modifications to low temperature region in a cycle normally less significant, normally what happens is that compressor is typically low temperature zone or in the cycle the region of gas is in the low temperature regime when it is in the compressor side. And, gas is at high temperature regime when it is at turbine side.

So, people do not make any alteration in the low pressure region; that means, intercooling unnecessarily we are going to give. Because when you deal with the low pressure of course, it does not have a work capacity or sufficient heat capacity so, there is no point in doing significant modification. So, always for modifications are treated only in the high temperature region of the cycle. So, that is what reheat is a better approach than intercooling.

Now, reheating with intercooling increases the cycle efficiency. Now, anyway we are going to go reheat and then we have to go for intercooling, increases the cycle efficiency when a heat exchanger is incorporated. That means, a actual gas turbine cycle that involves reheat and intercooling must use a heat exchanger.

But, there are some situations where the choice of pressure ratio is a very vital and it depends on whether the high efficiency or high work output is required. That means, if you want a very work output means you require a small size, when high specific work means you need large size unit. So, depending on the pressure ratio we can make a judgment.

For cycles without heat exchange higher pressure ratio should be used, when there is a no heat exchange cycle is there. So, higher pressure ratios should be used to take the advantage of higher permissible turbine inlet temperature. So, all these significant summary can be used for the gas turbine cycle and it is used for all practical cycles.

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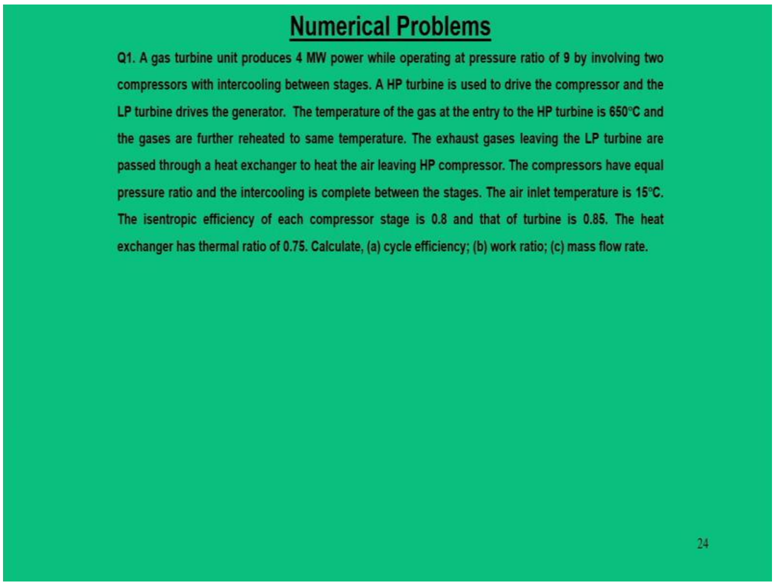

So, this is all about the performance of gas turbine cycle. Now, we will try to solve a problem.

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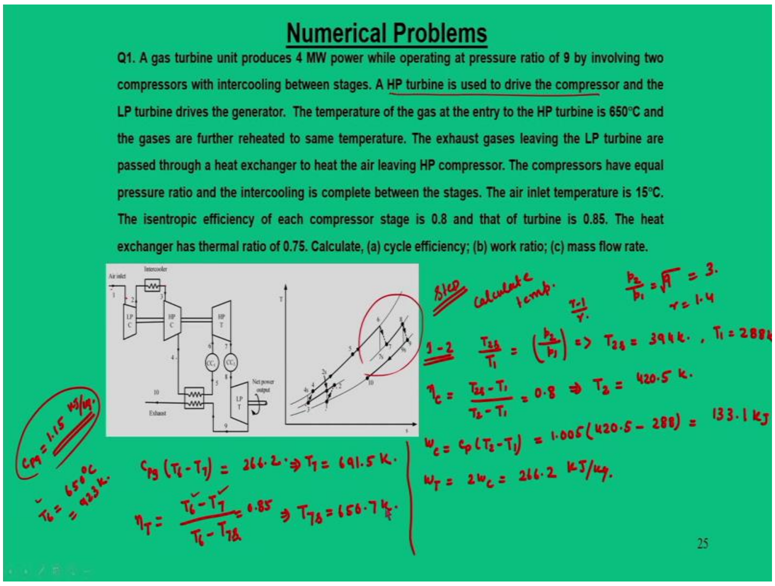

So, the problem goes like this that a gas turbine unit produces 4 MW power, while operating at pressure ratio of 9 and it involves two compressors with intercooling in between stage.

So, let us see the circuit first. So, first we have to draw the circuit; that means, it is a two compressor with an intercooling in between. And, the HP turbine is used to drive the compressor and LP turbine is used to drive the generator that means, it is going to produce the power.

So, LP turbine and HP turbine shafts are different, because one produces the power other drives the compressor. The temperature of the gas entry to the HP turbine is 650°C and the gases are further reheated to the same temperature. The exhaust gases leaving the turbine are passed through an heat exchanger.

So; obviously, when the exhaust gases has to pass through, it has to have a heat exchanger here. The compressors have equal pressure ratio and intercooling is perfect. So, it is a perfect intercooling system; that means, pressure ratio in stage should be equal.

The air inlet temperature is 15°C, the isentropic efficiency of the compressor are given and turbines are given. And for heat exchanger the thermal ratio is given; that means, we do not bother about the heat capacity of gases as well as the air. So, finally, what we are going to get is cycle efficiency work ratio and mass flow rate. So, these are the numbers we are interested. So, let us see, how we are going to solve it.

To solve the first step is to calculate temperatures. And, if you look at the T-s diagrams one can draw the process in the T-s diagram for the entire circuit in that manner. So, the process goes from 1, 2, 3, 4, 5, 6, 7, 8, 9.

So, we will go step by step so, the process 1 to 2. So, you can for the process 1 to 2 we can write down the compression stage. So, you can write down the relation this isentropic compression

$$\frac{T_{2s}}{T_1}=\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}};\frac{p_2}{p_1}=\sqrt{9}=3\Rightarrow T_{2s}=394\text{K}$$
$$\eta_c=\frac{T_{2s}-T_1}{T_2-T_1}=0.8\Rightarrow T_2=420.5\text{K}\qquad .$$
$$w_c=c_p\left(T_2-T_1\right)=133.1\text{kJ/kg}$$

So, what we have given is that high pressure turbine drives the compressors. So, basically there are two compressors. So, turbine work would be two times the compressor work. So, you can get the turbine work $w_t=2w_c=266.2\text{kJ/kg}$.

So, when you say turbine work we get, then we will let us come back to this part of the cycle turbine side.

$$c_{pg}\left(T_6-T_7\right)=266.2;c_{pg}=1.15\text{kJ/kg}\Rightarrow T_7=691.5\text{K}$$
$$\eta_t=\frac{T_6-T_7}{T_6-T_{7s}}\Rightarrow T_{7s}=650.7\text{K}$$

$$\text{pressure ratio}=\frac{p_6}{p_7}=\left(\frac{T_6}{T_{7s}}\right)^{\frac{\gamma}{\gamma-1}};\gamma=1.33(\text{hot gas})\Rightarrow\frac{p_6}{p_7}=4.09$$

$$\Rightarrow\frac{p_8}{p_9}=\frac{9}{4.09}=2.2;\frac{T_8}{T_{9s}}=\left(\frac{p_8}{p_9}\right)^{\frac{\gamma-1}{\gamma}}\Rightarrow T_{9s}=762.8K(\because T_8=T_6)$$

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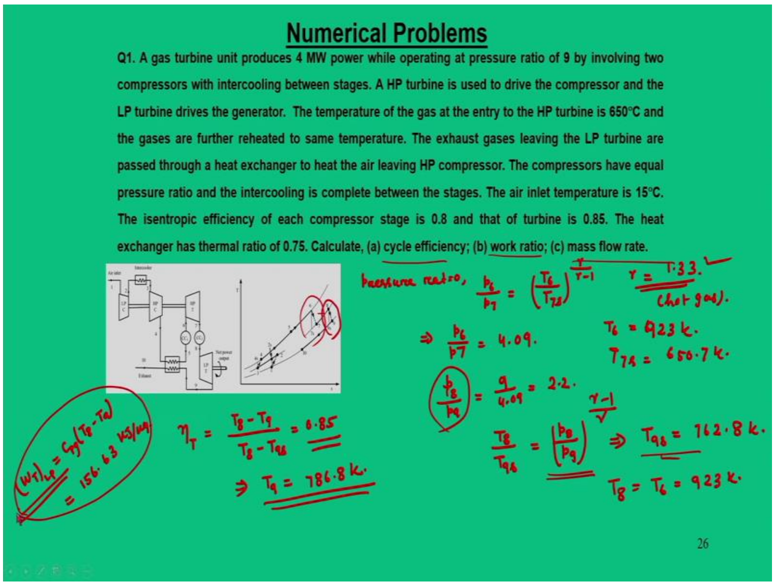

$$\eta_t = \frac{T_8 - T_9}{T_8 - T_{9s}} = 0.85 \Rightarrow T_9 = 786.8\text{K}$$

Now, let us now talk about these particular answers which we are looking at the cycle efficiency work ratio and mass flow rate.

So, for low pressure turbine, that we can write $w_{T,LP} = c_{pg}\left(T_8 - T_9\right) = 156.43\text{kJ/kg}$

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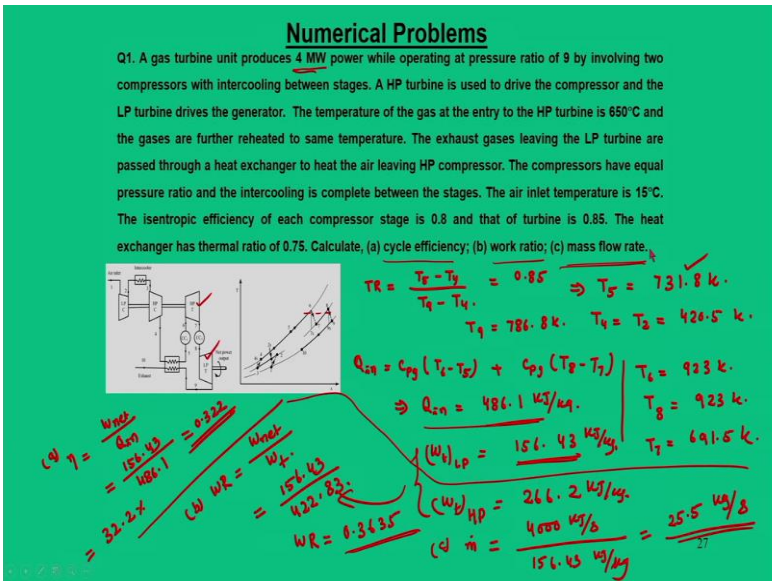

Then, we have to recall this thermal ratio TR.

$$TR = \frac{T_5 - T_4}{T_9 - T_4} = 0.85 \Rightarrow T_5 = 731.8\text{K}$$

$$Q_{in} = c_{pg}\left(T_6 - T_5\right) + c_{pg}\left(T_8 - T_7\right) = 486.1\text{kJ/kg}$$

$$\eta = \frac{w_{net}}{Q_{in}} = \frac{156.43}{486.1} = 0.322 = 32.2\%$$

$$WR = \frac{w_{net}}{w_T} = \frac{156.43}{156.43 + 266.2} = 0.3635$$

$$\dot{m} = \frac{4000\text{kJ/kg}}{156.43\text{kJ/kg}} = 25.5\text{kg/s}$$

So, of course, if you look at this particular problem, the problem is very big, but the simplified way of analyzing it is to draw the T-s diagram, calculate the cardinal temperatures, then use this expression how much heat is getting added. So, accordingly the overall sense we can get the cycle efficiency, work ratio and mass flow rate.

So, with this I conclude this particular part that is gas turbine performance cycle Part B.

Thank you for your attention.