POWER PLANT SYSTEM ENGINEERING

Prof. Niranjan Sahoo
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati
Module 3

Lec 3: Combined Power cycle

Dear learners, greetings from IIT Guwahati. We are in the MOOCs course, Power Plant System Engineering, Module 3, Gas Turbines and Combined Power System. So, in the last few lectures, we have given emphasis on different types of gas turbine cycles. And with appropriate modifications the ideal gas cycle which is supposed to be a Brayton cycle gets modified to variety forms, we call them as regeneration, reheat in the turbines, compressor intercooling. So, those modifications helps us in improving the power output and cycle efficiency. So, another significant aspect of this gas turbine cycles is that, in fact, this is the most versatile cycle which can be integrated to any kind of other power generating systems. So, such cycles are known as combined power cycles.

So, in this lectures, we will try to see or emphasize few such combined modes, in which gas turbine cycles can be coupled, so that they form a combined cycle power plants. And towards the end, when you look at the combination of two different concepts like combination of steam with gas, combination of nuclear power plant with gas turbine power plants, there has to be some basic minimum justifications to work them in combined mode.

For such cases, energy and exergy analysis is very vital. So, basically when we are combining them, we are essentially increasing the infrastructure, capital cost and complexity of the systems, but that has to be justified with the need of technical requirement. So, one such thing is that we need to do energy auditing, we also need to do the exergy analysis. So, what does these two concept gives us? It gives the fact that each mode of operations like, either you go for steam turbine mode and gas turbine mode, they will have their individual limitations and individual capability of operating in the operating limits. But when you combine them, there has to be some justifications that cycle efficiency should improve, work output should be improved.

So, such things is possible, if you do a comprehensive energy and exergy analysis. So, in this lecture we will provide a case study in which a gas turbine cycle is combined with a steam power cycle. So, let me start with the first thing, what we have already understood is the idea of combined cycle has grown interest with the need to improve the Brayton cycle efficiency by utilizing waste heat from the exhaust gas. So, this is the entire idea. For that reason, we intentionally make this Brayton cycle to a non-ideal mode by introducing regenerators to improve cycle efficiency, but of course, it does not increase the power output.

And through that mode the optimum pressure ratio for maximum efficiency improves sharply with low value of regeneration, resulting in the reduction of power. So, first thing, it improves the optimum pressure ratio, but it lowers the power. That means, if you look at this particular figure simple cycle and non-ideal cycle, although optimum pressure ratio shifts towards left, but what we see is that after the peak efficiency, the cycle efficiency drops, when you increase the pressure ratio. So, this is the disadvantage of regenerator when integrated with a Brayton cycle to operate in a non-ideal mode. Another requirement is that the simple cycle normally operates in the maximum power situations whereas, the regenerative cycles becomes meaningful when it is operated near cycle efficiency.

That means, when you add complexity to the systems by introducing a regenerator, then we must operate it in the maximum temperature range. Then only the justification of heat exchanger regenerator seems to be appropriate. So, this was the concept what we understood for the gas turbine cycles when they operate in their own individual mode. But what happens that in some situations if you want to improve the efficiency or power of a gas turbine systems, other possible way to do it is that we can integrate with the other power generating unit. So, one of the thermodynamic method is to use large quantity of energy that leaves from the turbine exhaust to generate steam in a steam power plant.

So, normally we say that heat exchanger is one way that gas turbines are operated in non-ideal mode, so that we call them as a heat exchange cycle, but again instead of heat exchanger, we think that the exhaust from the gas turbine can be directly be coupled to provide necessary heat input for a steam power systems. So, that is the benchmark applications when we move from gas turbine cycle operation in individual mode to combined mode. So, if you look at the realistic numbers, what we understood is that the gas turbine power plants use high temperature machines and in this case it is turbine and we look at the maximum temperatures in the range of 1100 to 2000℃. But if you look at similar numbers in steam turbines they normally operate in superheated mode at high pressure in the range 550 to 1000℃.

So, it becomes a natural solutions that the exhaust temperature that comes out from a gas turbine unit is at much higher side. So, that exhaust gas can be used to provide necessary heat input to the steam power systems. Because of this application viewpoint of steam and gas turbine unit operations, it becomes a natural solution for the both units like steam and gas that they can be combined with gas turbines in the hot end and steam turbine in the cold end. So, that we call them as combined cycle power plant. However, such combination has disadvantages, like it increases the complexity and the essence of combining both technology from one power plant is complex.

So, there has to be some synchronization between the gas turbine unit and steam turbine unit. However, the combined cycles have high efficiency over wide range of loads. They are suitable for both base loads and cyclic operation, they have a flexibility with quick starting. So, in case steam turbine does not work, then necessary power can be achieved from gas turbines and in some cases, for a peak load requirement, both the units can work combinedly to cater the load requirement. So, these are some basic advantages.

So, people have looked into different modes of combined cycle operations. So, there are some workable operations what we call as heat recovery boiler systems that can be with or without supplementary firing. Other can be heat recovery boiler with regeneration and feed water heating, then heat recovery boiler with multi-pleasure steam cycle and closed cycle gas turbine with steam cycle feed water heating. In addition to these, there are many other possibilities, but in this lecture we will just demonstrate few concepts of gas turbine cycles which is normally integrated with a steam power unit. So, first we call this as a heat recovery boiler. So, typically heat recovery boiler is normally used for steam turbine unit or other appropriate name is the steam generator.

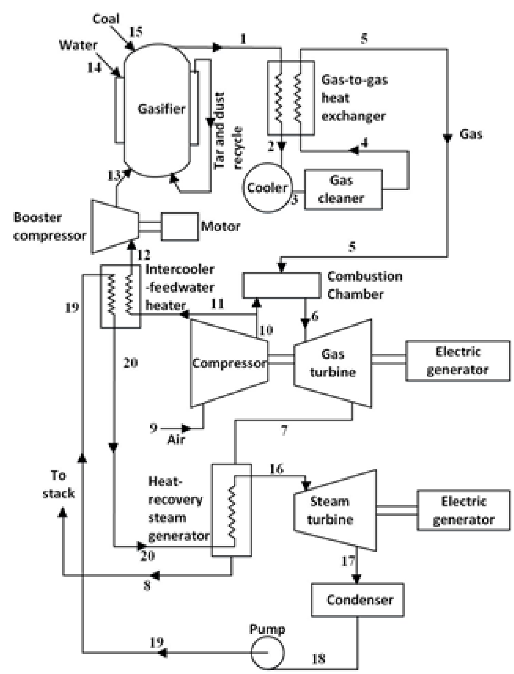
So, what we are looking at here is that, instead of devising an extra boiler or steam generator for steam power systems, we look into another mode of technology and we call it as a heat recovery boiler. So this heat recovery boiler will have same entities which normally a steam turbine unit has, so this heat recovery boiler will have a superheated region, a conventional steam drum or boiler regions, and also economizer regions. So, this is typically a steam generator unit of a steam turbine. We will have the similar features, but how it is needs to be operated? This needs to be powered from the exhaust of the gas turbine unit. Normally exhaust of the gas turbine unit is at very high temperature.

So, that temperature can be utilized at various locations like superheater, boiler or economizer unit to generate steam. So, basically it is a heat exchanger that increases the temperature of the steam. So, instead of adding extra fuel from the coal fired unit or any other boiler unit, we are just get taking it from the gas turbine unit itself. But in some cases we can have an extra or add on supplementary firing unit, where extra fuel can be added. So, these two things will combinedly power the heat recovery boiler unit and this heat recovery boiler unit provides necessary steam to the steam turbine that again expands in the steam turbine.

So, basic idea between these two units is the integration point. So, this part is your gas turbine unit, this is lower part is your steam turbine unit and each one is generating power W_{gas} & W_{steam}. So, combined power can be used to give the necessary power conversion through the generator. Since entire resources comes from the gas turbine units so, the gas turbine units are operated with a very high fuel ratio i.e., 400% of theoretical air. And additionally when efficiency is of prime importance, separate supplementary firing unit is integrated with heat recovery boiler. So, basically these two units are essential addition for a combined cycle mode of operation.

And with similar analogy, we can think of a coal gasifier based combined power cycle. So, there are three basic unit. One is gasifier unit and that gasifier unit normally handles coal. So, these coals can be of low, medium or high calorific value fuels. So, the coal can below grade coal or high grade coal. So, essentially whatever the nature of the coal, we get a gas which is derived from any source of fuel that is gasifier unit.

Second part is the gas turbine unit. So, connecting point between this gas turbine unit and the gasifier unit is the gas to gas heat exchanger and that provides necessary gas to the combustion chamber. And then from this combustion chamber it goes to the gas turbine units. So, this gives the power requirement from the gas turbine unit and exhaust from the gas turbine unit again goes to heat recovery steam generator. This is something similar to heat recovery boiler unit in our previous discussion. So, that gas essentially powers the steam turbine unit, which essentially has super heater unit, re heater unit or economizer unit, all the things are integrated here. So, we get W_{steam} that is the power output from the steam turbine unit. And power production can happen from the gas turbine unit and from the steam turbine unit.

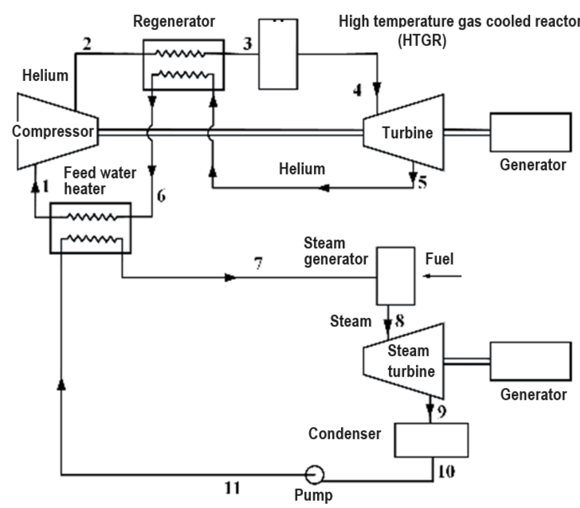


Coal gasifier combined cycle power plant

So, essentially this is a combined cycle mode of operation which integrates coal gasifier unit with a steam and gas turbine system. So, advantage is that we can use synthetic fuel or we can use liquid fuels, we can also use many gas mixture; low/ medium/ high calorific gas. And also attractive utilization is that low calorific gases for electric generation which normal is not possible if it has to be handled by any single unit. So, as a benchmark, here I have given some numbers where a coal gasifier combined cycle power plant operates. This is a realistic picture in which it is told that the temperature and pressure limit for gas turbine unit is 9 bar and 980℃. Steam turbine units operates in the range 20 bar and 480℃ and they have overall efficiency of 35-45%.

The workflow or working fluid flow has been shown in this thermal circuit diagrams. So, it starts at 1 and ends at 20. And till we extract maximum possible energy from the products that goes out from the unit, we can reutilize it at various locations. So, this is the essential objective of this combined cycle power plant mode. This is a very good workable model and it has already been implemented at various locations. So, the extra unit that gets added here is the heat recovery steam generator unit. Another is gas to gas heat exchanger that is the connecting point between the coal gasifier unit and gas turbine unit and the connecting point between gas turbine unit and steam turbine unit is the heat recovery steam generator.

The next application for combined power cycle operation is integration with a nuclear power plant. So, normally when you think about a nuclear power plant, we call this as a reactor. So, location number 3 in the picture is called as a high temperature gas cooled reactor (HTGR). And here we can see a closed gas turbine cycle. So, in this closed gas turbine cycle, the working fluid is helium. So, choice of helium is very natural because it is an inert gas and we are actually integrating with nuclear fuel. So, helium should be the working fluid. Now, here we have this helium turbine and helium compressor. So, this is the complete unit that gets powered and we get the power from the gas turbine unit. Here we do not have exhaust because the helium is getting recirculated in the cycle. But normally the heat exchange happens in a feed water heater, which is allowed from the gas turbine unit to the steam turbine unit. And here if you look at this picture, the gas turbine unit and the steam turbine unit or steam power system are combined through feed water heater. Normally steam power systems use the feed water heater for its applications. So, the necessary energy is being supplied from the

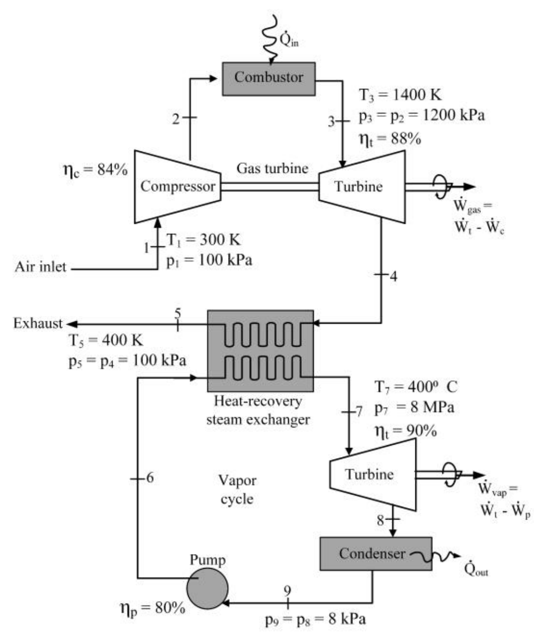


Combined Cycle with Nuclear Gas Turbine and Fossil Fuel Fired Steam Turbine feed water to the steam power unit. So, the combination or connecting point between this gas turbine unit and steam power system is the feed water heater.

Now, some workable numbers what we can see is that we have helium that normally operates at very high temperature i.e., 800℃. So, it can expand and generate the power through gas turbine unit. Then we can couple this to this steam cycle through this feed water heater. So, the heat generated from this HTGR is completely used from the both cycles and heat is rejected (Q_{out}) only in the condenser.

So, that way what we see here, exit point is only one, but all the resources are getting utilized within this combined cycle more. So, this particular arrangement is called as a combined cycle with nuclear gas turbine and fossil fuel based fired steam turbine unit. So, this is all about the versatile ways of applications of gas turbine units which can be integrated to any kind of power generation unit. And now to see the justification for this integration, for thermodynamic operation through combined mode, we also need to revisit some of the basic concept that is why we are you going for such kind of combined mode operation.

Because the combined mode increase the complexity of the system. It also increase the infrastructure cost. So, that analysis has to be justified technically. So, a thermodynamic viewpoint for this power plant system is that we must perform the energy auditing. So, one such energy auditing could be energy analysis and exergy analysis.



So, for that reasons I have given a simple example as a case study. So, here we have a simple gas turbine unit and also a vapor cycle unit or steam power unit. And the coupling point between them is a heat recovery steam exchanger. And each unit is operating with its individual limit and they have their own efficiency that means, isentropic efficiency η_C for the compressor and isentropic efficiency η_t for the condenser. Then the energy that gets added from the fuel is Q_{in} and exhaust that comes out from the turbine is getting utilized in the heat recovery unit.

So, essentially the heat input that comes to the vapor cycle is through exhaust from the turbine. As you can see the peak temperature for gas turbine is 1400K whereas, for steam cycle T_7 that is maximum temperature is 400℃. So, that way we can think that exhaust has sufficient energy to power the vapor cycle. And of course, for this steam cycle also turbine has its own efficiency 90% and they will have a pump efficiency. And finally, when the exhaust goes out to the atmosphere you can see here the pressure is 1000 kPa which is close to atmospheric pressure. Temperature is little bit high that is 400K. If you say 300K is the normal atmospheric temperature then it is 100K more, little bit higher. But that is unavoidable loss due to irreversibility. Now the basic assumption for this simple unit, for our energy and exergy analysis is that we need to do them in component wise for gas cycle and steam cycle. Second thing is that each unit can be analyzed as a control volume operating at steady state with negligible drop in kinetic and potential energy, no pressure drop in the combustion heat recovery systems and condenser. And for gas turbine unit we will use the air standard cycle and for vapor cycle we will think about Rankine cycle unit.

So, for that reasons a case study which is prepared based on this thermodynamic cycles, which has been noted here is that a combined cycle has a net power output of 45 MW, air enters the compressor at certain conditions. So, basically both the units as a combined unit produce 45MW power. The inlet conditions of air for the compressor in the gas turbine unit is 100kPa and maximum pressure is 1200kPa. Isentropic efficiency for compressor and turbine is 84%. Turbine inlet conditions are 1200kPA & 1400K. And the interconnecting unit is the heat recovery steam generator and that finally, discharge necessary heat input to the steam cycle.

So, steam cycle has their own numbers like isentropic efficiency for turbine and pump.

So, our main objective is that with the basic data points, we have to individually calculate the steam cycle unit and gas cycle unit which has been emphasized in our previous lectures. So, normally when you say steam cycles or vapor cycles, we used to look into modified Rankine cycle and necessary steam data can be obtained from the steam tables and based on that we can find out the enthalpies at various locations for the vapor cycle unit. And for gas turbine units, we need to look into air data because we have to assume it as air standard cycle. So, based on this air standard cycle we can think of modified Brayton cycle or in fact, non-ideal Brayton cycle. Of course, it should be a non-ideal Brayton cycle because we have efficiencies into picture. So, with this analysis we can find out the enthalpies at each cardinal point. So, those part I am skipping, but what we essentially require? We require the thermodynamic data points at each locations like 1, 2, 3, and 4 for gas turbine unit and for the steam power unit. So, those numbers I am just noting down here to solve this problem, because we need to find out the mass flow rate of air & steam and net power developed. that is first part because when you operate in a combined mode. Second thing whether that combined cycle is justified or not, for that we need to perform the exergy analysis.

And the exergy that comes into the system is through this combustor. So, exergy entry to the combined system is through this condenser. But exergy lost is in the turbine for the steam turbine, exergy lost in the gas turbine, exergy lost in the heat recovery unit, all these things have to be recalculated. Then we need to perform their exergy balance or the kind of exergy which is lost and with this numbers we can predict whether the justification of steam and gas turbine unit is verified or not. So, to solve this problem the first step is to obtain the data points for steam and gas cycle. So, here I am just noting down the different state points for the gas turbine units and steam turbine units or steam cycle.

So, the data we normally require is the enthalpy points and entropy points. Here we need to know the absolute entropy that is in kJ/kg.K. And this absolute entropy is a function of temperature that we can obtain from any thermodynamics books for air. For steam cycle we have to use steam tables to calculate enthalpy and entropy.

Gas Turbine			Steam cycle		
State	Enthalpy h (kJ/kg)	Absolute entropy s $° = f(T)$ (kJ/kg.K)	State	Enthalpy h (kJ/kg)	Absolute entropy s $° = f(T)$ (kJ/kg.K)
1	300.2	1.702	6	184	0.5975
2	669.8	2.509	7	3138.3	6.3634
3	1515.4	3.362	8	2104.7	6.7282
4	858	2.762	9	173.9	0.5926
5	401	1.992			

So, these data points are obtained by separate analysis for gas turbine and for steam turbine unit. For steam cycle we use steam table, for gas turbine cycle we use the property data for air.

So, having said this we need to perform the first thing that is energy analysis. So, for energy analysis we need to know that how the entire energy comes to the steam power unit. So, for that we have heat recovery steam exchanger or steam generator.

Gas that comes in $= \dot{m}_g$; Steam vapour that enters $= \dot{m}_v$

So, $\dot{m}_g$ your mass from the gas turbine unit and $\dot{m}_v$ is for vapour unit. So, the energy balance equation here says that heat extracted from the gas is fed to the steam unit.

Energy balance; $\dot{m}_g(h_4 - h_5) = \dot{m}_v(h_6 - h_7)$

$$\Rightarrow \frac{\dot{m}_v}{\dot{m}_g} = \frac{(h_4 - h_5)}{(h_6 - h_7)}$$

By putting the data from table, it is found that;

$$\Rightarrow \frac{\dot{m}_v}{\dot{m}_g} = 0.1547$$

So, now what is the power that goes as $\dot{W}_{gas}$?

$\dot{W}_{gas} = \text{Turbine work} - \text{Compressor work}$

$\Rightarrow \dot{W}_{gas} = \dot{m}_g[(h_3 - h_4) - (h_2 - h_1)]$ ------------------ (1)

$\dot{W}_{steam} = \text{Turbine work} - \text{Compressor work}$

$\Rightarrow \dot{W}_{steam} = \dot{m}_v[(h_7 - h_8) - (h_6 - h_9)]$ --------------- (2)

It is given that, $\dot{W}_{gas} + \dot{W}_{steam} = 45000 \text{ kJ/s}$

So, we have two equations now. So, combining equation 1 & 2 let's solve for 2 unknowns that are $\dot{m}_g$ & $\dot{m}_v$.

$$\dot{m}_g = 100.9\frac{\text{kg}}{\text{s}};\ \dot{m}_v = 15.6\frac{\text{kg}}{\text{s}}$$

So, after substituting we can find out

$\dot{W}_{gas} = 29\text{MW};\ \dot{W}_{steam} = 16 \text{ MW}$

Heat that is supplied at the combustor unit, $\dot{Q}_{in} = \dot{m}_g(h_3 - h_2) = 85.3 \text{ MW}$

$$\text{Cycle efficiency}, \eta_{cycle} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{45}{85.3} = 52.8\%$$

So, if you look closely what we can observe here that for only gas turbine unit or steam turbine unit as separate operation, then normally efficiency of gas turbine unit falls in the range of 40% and even for steam unit, it is in the range of 35%. But when you combine them with this given data, a simple analysis will tell you that efficiency is enhanced. Of course, power can be obtained from the both units. So, that way the energy analysis says that combination of steam and gas turbine units is essentially justified.

This is about first law and second law analysis. Then we need to see whether exergy analysis is further justified or not, because that is the essential backbone. This exhaust goes to atmosphere and atmospheric conditions are $p_0 = 1atm; T_0 = 300\text{K}$ P which is also known as the dead state. Now, when you perform this exergy analysis, then the picture will be clearer. So, to do that first thing we need to find out where is the point of entry for exergy entering into the system and where is the points for exergy that goes out, and other thing is that where are the points where exergy is lost. First thing is that exergy entry is to the combustor that is $Exergy_{in}$ and exergy that goes out is $Exergy_{out}$ through this exhaust from the gas turbine.

Other point of $Exergy_{out}$ is from the steam condenser. So, we need to calculate that. Then turbine & pumps operate with their efficiency. So, we say there is a loss of exergy which is not recoverable. So, we need to calculate them one by one first combustor.

Combustor

Increase in the exergy, $\dot{E}_{f3} - \dot{E}_{f2} = \dot{m}_g[(h_3 - h_2) - T_0(s_3 - s_2)]$

So, here we have to recall the expression of exergy keeping surrounding into picture and we need to find out this entropy for the gas with respect to absolute entropy mode.

$$\Rightarrow \dot{E}_{f3} - \dot{E}_{f2} = \dot{m}_g\left[(h_3 - h_2) - T_0\left(s^\circ{}_3 - s^\circ{}_2 - R\ln\frac{p_3}{p_2}\right)\right]$$

As there is no pressure change here. So, the term $\ln\frac{p_3}{p_2} = 0$

$$\Rightarrow \dot{E}_{f3} - \dot{E}_{f2} = 59.5 \text{ MW}$$

Now, exergy that is carried out by exhaust flow.

$$\dot{E}_{f5} - \dot{E}_{f2} = \dot{m}_g\left[(h_5 - h_1) - T_0\left(s^\circ{}_5 - s^\circ{}_1 - R\ln\frac{p_5}{p_1}\right)\right]$$

So, the term $\ln\frac{p_5}{p_1}$ vanishes to 0 because $p_5 = p_1 =$ atmospheric.

$$\Rightarrow \dot{E}_{f5} - \dot{E}_{f1} = 1.4 \text{ MW}$$

Now, ${}^{1.4}/_{59.5} = 2.3\%$

So, this is quite justified, because we are not losing too much exergy. Then we move on to condenser.

$$\dot{E}_{f8} - \dot{E}_{f9} = \dot{m}_v[(h_8 - h_9) - T_0(s_8 - s_9)]$$

$$\Rightarrow \dot{E}_{f8} - \dot{E}_{f9} = 1.4 \text{ MW} \approx 2.3\%$$

Then exergy destruction. So, this happens component wise like air turbine, air compressor, steam turbine, and pump.

Air Turbine, $\quad \text{E}_{\text{gT}} = \dot{m}_g(s_4 - s_3)T_0$

As this is the exergy destruction term, we say exergy destruction for gas turbine

$$\dot{E}_{dgT} = \dot{m}_g T_0[(s°_4 - s°_3) - R \ln\left(\frac{p_4}{p_3}\right)$$

So, here pressure terms cannot be neglected because both ends of turbine will have different pressures.

So, using this we say exergy destruction in the gas turbine, $\dot{E}_{dgT} = 3.42$ MW. So, this number is close to 5.75%.

Similarly, exergy destruction for air compressor.

$$\dot{E}_{dgC} = \dot{m}_g T_0[(s°_2 - s°_1) - R \ln\left(\frac{p_2}{p_1}\right) = 2.8 \text{ MW}$$

So, this turns out to be in the range of 4.7%.

Then exergy destruction for steam turbine.

$$\dot{E}_{dst} = \dot{m}_v T_0(s_8 - s_9) = 1.7 \text{ MW}$$

So, this ratio is close to 2.8%, if you divide by 59.8.

Then exergy destruction for pump.

$$\dot{E}_{dsp} = \dot{m}_v T_0(s_6 - s_9) = 0.02 \text{ MW}$$

So, this number is much less than 1%. So, this means pump have negligible exergy loss.

And for heat recovery steam generator

$$\dot{E}_d = T_0\left[\dot{m}_g(s_5 - s_4) + \dot{m}_v(s_7 - s_6)\right] = 3.7 \text{ MW}$$

It is close to 6.2%. So, what we observed here that wherever the exergy that comes in is from the combustor, it is almost getting utilized and loss at all points is quite minimal which falls in the range of maximum 6%. So, exergy analysis also is quite justified because second law also tells some exergy is always destroyed, we cannot recover it completely. However, for this present problem, exergy analysis justifies the fact that these numbers are quite realistic and based on which we can take an appropriate decision of combining a steam power unit with a gas power unit. So, energy analysis is quite justified because cycle efficiency for combined mode is always higher. Exergy analysis also tells us that the loss of exergy at each component is quite minimal which is close to less than 6%.

Hence combined modes of gas turbine operation is quite possible and with respect to steam unit. So, this is all about the combined power cycle. With this I conclude. Thank you for your attention.