Applied Thermodynamics for Engineers
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Lecture – 24
Combined Gas-Steam Power Plant

Hello everyone. Welcome to week number 8. Over previous 4 weeks we have talked about different kinds of power producing cycles. Like in the fourth module we have talked about the gas power cycles, which are the operating cycles or driving cycles for the reciprocating type internal combustion engines. Whereas in the previous two weeks we have talked about the gas power cycle for rotary type of external combustion engines and also the vapour power cycles.

Under the gas power cycles for the reciprocating engines or for internal combustion engines we have talked about in detail about the Otto, Diesel and Dual cycles, we have also talked about the Stirling and Ericsson cycles though they are more relevant to rotary kind of devices. We have talked about the Brayton cycle in detail, which is the operating cycle or the ideal cycle for the rotary type of gas power cycles. That is also a kind of external combustion engine.

And in the previous week we have talked about the vapour power cycle in the form of the Rankine cycle, which is the ideal cycle for the steam driven external combustion engines or I should say the phase change based external combustion engines. So, in all these cases we have started with the ideal cycles, then we talked about several additional factors like a possible kind of irregularities or abnormalities that can be present in the system in the form of irreversiblities in the turbines, pumps and compressors. We have talked about the possible pressure drop in heat exchange devices, like the boilers, heat exchangers etc. We have also talked about particularly in conjunction with the gas power cycles for internal combustion engines where combustion plays a very important role, the possible factors like the time loss and different other kinds of practical losses.

So, we are in a good position to understand the working principle for different kinds of power producing cycles. And if you follow the lectures properly sure that by now, you know all the different kinds of power producing cycles that are being used in industries. But all the cycles that we have discussed are standalone cycles. Like the Rankine cycle is a standalone cycle, of course we can have reheating and regeneration, the feedwater heater etc. But still the basic cycle is a Rankine cycle which operates between some maximum temperature, which you can find the exit of the boiler and the minimum temperature which commonly you find the condenser and that is it. It acts as a standalone cycle. Similarly, the Brayton cycle or the earlier Otto and Diesel cycle that we have talked about those are also standalone cycles operating between one maximum temperature and minimum temperature.

But, there will be several situations where such standalone options may not be the most potent one or maybe if we instead of going for standalone, if we go for some kind of combination of cycles, we may be able to harness much more. And that is where the concept of combined cycles and also cogeneration comes into picture. The combined cycle affects the combination of several power producing cycles, two or more number of power producing cycles in a suitable way, so that we get a combined efficiency higher than the individual efficiencies for the cycles. And cogeneration refers to simultaneous production of power and some other quantity. Like, in the previous lecture or I should say in the last lecture of your previous week, I have mentioned about two alternate versions of the turbines. There was one pass out turbine. What was the objective of pass out turbine? The objective was to extract bled steam somewhere from the turbine and supply to some process.

Similarly, we also have done a back pressure turbine, where there was no condenser rather the steam that is coming out of the turbine that is been supplied to some process. So, what we are getting from there? We are getting power output definitely from the turbine plus the steam that is coming out of the turbine or has been extracted from the turbine that is being used in some process as well.

So, that kind of things where we are getting electricity by the rotation of the turbine shaft and also thermal energy in the form of the extracted steam, we call cogeneration. So the idea of cogeneration is to achieve something extra apart from the conventional electrical power output and the idea of combined cycle is to combine several cycles together to enhance the efficiency.

And these two generally goes hand in hand as we shall we seeing shortly. And I would also like to add that this week our lecture may be slightly less in content, of course previous two weeks we had a quiet extensive coverage of the gas power cycles for gas turbines and also the ideal vapour power cycles for the steam turbines. So, you deserve little bit of break. So, I have decided to go a little bit light on this particular week where, we shall mostly be discussing about the basic principles of the combined cycle and also the cogeneration and subsequently a few applications of possible combine cycles that we shall be talking about without going to too much detail of this. Now, in the previous lecture again, the last lecture of our model number 7 you are introduced to this particular cycle where we have two Rankine cycles in combination which are called the binary vapour cycles.

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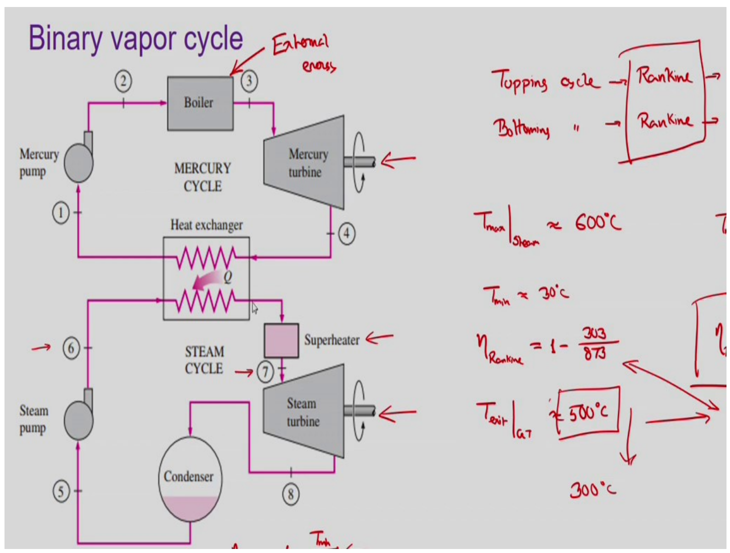

The term binary of course refers to two and by now you already know that we have a topping cycle. Let me write this side detail utilisation of the space. We have topping cycle which is of course a Rankine cycle and working with mercury as the working medium.

And then we have a bottoming cycle which is again another Rankine cycle and working with steam or water as the working medium. And where is overlap between the two? The overlap is here in heat exchanger. The condenser for the topping cycle is also acting as the boiler for the bottoming cycle. That is the amount of heat rejected by the topping cycle has been supplied to the bottoming cycle to increase its enthalpy of the working medium from the state 6 to the turbine into this state of 7.

There may be optional super heater, of course, but generally the condenser of the topping cycle is coupled or clubbed with the boiler of the bottoming cycle. And this type combination is what we refer as the combined cycle. Of course, in the previous lecture we have talked in somewhat detail about the advantages and disadvantages of the cycle while mercury has a very favourable critical pressure and temperature. But mercury is toxic and expensive which are generally makes this particular combination too costly to be considered in practice. And therefore, though it was in decent amount of used in 1920's and 30's, but over a last few years you hardly find a combination like this.

But the working principle that is we have one topping cycle and one bottoming cycle and their clubbed such that the condenser of the topping cycle is acting as a boiler for the bottoming cycle is the working principle for any kind of combined cycle. And that is always a good proposition, provided we have a decent combination of the two cycles. Like the combination that I am showing here, here, both of them are Rankine cycle in nature. But it has been observed in practice such kind of Rankine-Rankine combination that is a binary vapour cycle concept may not be very economical, just like this particular one shown here. Rather it will be much more convenient where we are going to stick to the Rankine cycle as the bottoming cycle, but we are going to replace the topping cycle with something else may be a gas turbine or a Brayton cycle. Like, you have already discussed about both Brayton cycle and Rankine cycle.

We have solved several numerals also and probably one thing you must have noticed there that the working temperature level for the Brayton cycle is significantly higher compared to the Rankine cycle. The Rankine cycle the highest temperature of steam that you get that hardly is in the range of 550 to 600 ^{0}C where it is quite common in the Brayton cycle that the maximum temperature will be 1400 ^{0}C or even more.

So, if we talk about these values, the maximum temperature that we get in case of Rankine cycle or let me write the steam-based cycle that is generally in the range of 600 ^{0}C. However, the maximum temperature that we get in case of the Brayton cycle that is the gas based cycle will be in excess of 1400 ^{0}C and turbo propeller kind of engines it can be in excess of 1500 ^{0}C. So, there is definitely a significant difference in the maximum temperature. And we also know that the efficiency of any Carnot cycle is given as:

$$\eta_{th} = 1 - \frac{T_{min}}{T_{max}}$$

Though neither the Brayton cycles nor the Rankine cycle are a perfectly reversible cycle, they are only internally reversible in nature and hence none of them can attain the Carnot efficiency. However, we can get a decent indication by saying this front.

We know that to increase the efficiency of a power producing cycle you need to have higher for highest possible T_{max} and lowest possible T_{min}. Now if we keep the T_{min} the same then if we compare now the Brayton and Rankine cycle, definitely the Brayton cycle is going to score more. It is going to be much higher efficiency because the T_{max} is substantially higher. Let us fix up the T_{min} to be something like 30 ^{0}C.

Then for the Rankine cycle, the maximum possible efficiency will be equal to the corresponding Carnot cycle efficiency or I should say the efficiency of a Carnot cycle working between is 30 ^{0}C and 600 ^{0}C that will be:

$$\eta_{Rankine} = 1 - \frac{303}{873}$$

Whereas the maximum possible efficiency of the corresponding Brayton cycle will be:

$$\eta_{Brayton} = 1 - \frac{303}{1673}$$

where

303 is the lowest temperature is 30 ^{0}C in Kelvin and highest temperatures 1400 ^{0}C which is 1673 K. Which one is greater? Definitely this one is significantly larger for this. And hence we can expect a Brayton cycle to produce significantly larger efficiency compared to the Rankine cycle. But that may not be the case in practice because the lowest temperature that we are talking about it is not possible to have that same for both Rankine and Brayton cycle. In fact the hot exhaust gas that leaves a Brayton cycle can be at a very high temperature.

Even, the temperature of the gas that is leaving the gas turbine plant, exit temperature of a gas turbine plant can well be around 500 ^{0}C or even higher or which is quite close to the maximum temperature Rankine cycle can reach and accordingly its efficiency suffers. So the practical efficiency for the Brayton cycle then will only be:

$$= 1 - \frac{773}{1673}$$

which definitely is a significant reduction compared to this particular value.

And of course, I do not have the number because I am generating this temperature values quite randomly. But now you can calculate these two and there may not be any significant advantage for getting the Brayton cycle in terms of the efficiency. Then what to do? Firstly both are giving quiet similar level of efficiency despite the Brayton cycle working at high temperature and secondly, the exit temperature that you are getting from the gas turbine is very very high for it to be released to the surrounding. Your surrounding may be only around 30 ^{0}C and now you are releasing a gas of temperature 500 or 600 ^{0}C to that, that is significant amount of thermal pollution. We can definitely go for regeneration which will reduce this temperature and after regeneration the temperature may still be in the range of 300 ^{0}C which is still quite high. So, what can be the option? Then the option is that this exit gas that is coming out of the gas turbine we can use that as the source of energy for the steam production in the boiler. The gas temperature is definitely much higher it is in the range of 500 ^{0}C or even higher and so it is very much possible if we can carefully control the flow rate of the mass flow rate of the gas and the mass flow rate of the steam, then we can easily use this exhaust of the energy or the remainder of the energy in this gas for increasing the temperature of the steam to something quite close this 500 ^{0}C. And hence we can easily go for such kind of combination. Look at this, though there are two power cycles and there are two turbines, this is the mercury turbine and this is the steam turbine. But still we have only one boiler where we have to supply external energy. This is the one we are supplying external energy. For the bottoming cycle we do not need any external source because the heat rejected by the topping cycle is the one that is being getting absorbed in the bottoming cycle, but we are getting power output from both of them.

So, if we can use or channelize this exit gas coming out of the gas turbine plant to the steam boiler, so that we can convert the liquid water coming from the pump to the saturated vapour state or even possible to be superheated vapour state, there we can easily run steam turbine plant without needing any additional source of energy. And that is the idea of this combined cycle for this.

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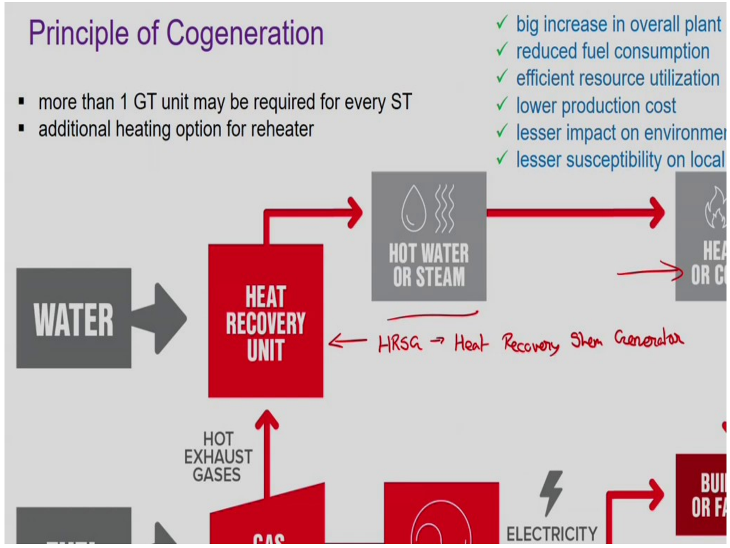

And this is what I am talking about. Here we have a gas turbine plant where we are having some fuel. A fuel is being supplied to the gas turbine and accordingly you have already learned about the gas turbine plant. So, a supply of the fuel in the combustor of the gas turbine, compressed air is coming from the compressor and reacts in the combustion chamber to produce very high temperature combustion gases which finally goes through the gas turbine and produces electrical energy. But the hot exhaust gas that is coming out of this gas turbine plant, that is supplied to something on the heat recovery unit to produce steam. Often we call this HRSG which is called Heat Recovery Steam Generator. Here to generate the steam in this unit, we are not adding an external energy rather we are recovering the waste heat available in hot exhaust gases. That is why it is also called sometimes the waste heat boiler. So, the hot exhaust gases are used in this heat recovery unit, liquid water is supplied to that. This is the boiler of the Rankine cycle; liquid water is coming from the pump at the boiler pressure and it is converted to steam that hot water or steam we can use for subsequently whatever purpose that we are interested. If the temperature is lower, the output you are getting will be only liquid water but at high temperature. That can be used for some specific purposes, for drinking purposes, for cooking, for several kind of pharmaceutical and other kind of industries, where we need hot water. If you are getting steam, again, the steam may also can be used for chemical industries and several kind of processing industries. And if the steam temperature is sufficiently high then you can direct the steam to a steam turbine as well, for further production of power.

So, this is the idea of cogeneration and in the form of combined cycle. You have to be very clear now, what you are referring as a combined cycle. When the one that is shown that is more in a cogeneration mode where we are getting electricity only from the gas turbine plant and from the heat recovery unit, from other plant vehicle getting hot water or steam. However, history of this getting this hot water or steam. Instead of using this for heating and cooling applications if we use this for power production, we call that a combined cycle because you are getting electricity from two sources. But if you stay in this particular form where we are not getting electricity from the steam side, rather getting only hot water or steam, then we call it a cogeneration plant. There are several advantages that we have to consider for this.

The biggest advantages an increase is in the overall plant efficiency which we shall be seeing that one. Of course, as the plant efficiency increases then if your objective is to get a particular amount of power output, then we need less amount of fuel. Efficient resource utilisation, the hot exhaust gases are being used as a resource so we are able to manage resources properly. Lower production cost, as a fuel cost is reducing correspondingly electricity production cost also will go down. Lesser impact on the environment, as I have talked about the thermal pollution that may appear because of this hot exhaust gases being used to the surrounding that also can be avoided for this. And finally, lesser susceptibility to the local interactions when we have a combined plan, a combine cycle kind of option where we can produce electricity from both gas turbine mode and steam turbine mode. Then because of some problem, if suppose gas turbine fuel is not available and you may not be able to run the gas turbine. You can still run the steam turbine by auxiliary heating by supplying energy from some additional source and still your plant will be giving some reduced quantity of power, it will just not get stopped completely.

You can generally, combine cycle plants for the option of running any one of the individual as well just to tackle such kind of special situations. Couple of factors that have to be careful of, generally for every steam turbine you need more than one number of gas turbines, at least two, because the flow rates etc. for gas turbine and steam turbine needs to be compatible. Otherwise just one gas turbine you used may not have sufficient amount of energy available in exhaust gas to raise significant amount of steam to be used in steam turbine. So, we often need at least double number of gas turbine plants.

And also, if you are looking for some kind of superheating and reheating particularly in case of the steam turbine, we may have to use some additional heating option, because the energy again available in the exhaust gases of may not be sufficient to be used in a reheater as well.

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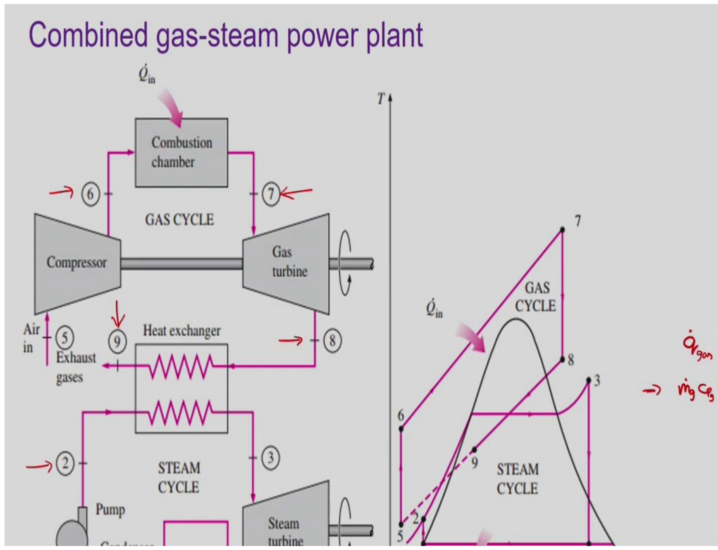

So, this is what we are talking about. There are several kinds of combined cycle plant, the common choices for the topping cycle and bottoming cycle or I should say the combination of topping cycle in bottoming cycle can give you different conceptual design of combined cycles. But the most common combination is the one that you are talking about is a gas turbine as the topping cycle and steam turbine as the bottoming cycle.

We can have a few others also like MHD - Magneto Hydro Dynamic generator as a topping cycle and steam turbine as the bottoming cycle that can be an option. MHD is still a very very potential technology for renewable power generation, but it has its own shortcoming and it is yet to be commercialized fully. We can also have even innovative options like MHD as the topping cycle and thermoelectric as the bottoming cycle, MHD as the topping cycle and thermo-ionic as the bottoming cycle.

So, all these are different kinds of combined cycles. But the principal is the same, the amount of heat rejected by the topping cycle is being absorbed by the bottoming cycle, and therefore we need to have external energy input only to the topping cycle not at the bottoming cycle at all. Look at the cycle time showing here. Then here above this we have the Brayton cycle, the conventional Brayton cycle where air from the atmosphere is supplied at state 5, then it gets raised to higher pressure in the compressor to 6. Then we have the combustion chamber where heat is being supplied. In practical case you are adding fuel there and have the combustion to get large amount of energy released. And at this high temperature combustion gas which is state number 7 is passing gas turbine plant to give you energy.

And now this exhaust coming out of the gas turbine that is at state 8, we are not using it for regeneration purpose there. We made definitely use a regenerator as well, but at least in this cycle we are not using any regeneration. We are also not allowing it to exit directly, rather we are supplying through a heat exchanger where it is releasing some energy and leaving finally at the state number 9. Now below this straight line we have the Rankine cycle, where the liquid water coming from the pump is passing through the same heat exchanger so that at the exit of this it gets converted to conventionally superheated vapour or maybe saturated vapour, which is passing through steam turbine. Then we have the condenser as it is and the pump completes Rankine cycle. Look at this is Rankine cycle does not need any external for input because it is getting the power of heat required in the boiler from the topping cycle only.

This is the corresponding diagram on the *Ts* plane that we can see. The states 5, 6, 7, 8 and 9 corresponds to the gas turbine and 1, 2, 3 and 4 corresponds to the steam turbine or the Rankine cycle. Where this 9 to 5 is the incomplete part of the topping cycle because here heat is being supplied at state 5 and it is finally leaving the gas turbine plant with state 9. So, it is not a complete cycle. However, if the temperatures of the gases are significant or a suitable then we can raise the steam to superheated level. See here, the temperature of the gas at state number 8, that is at the exit of the turbine is this, and the maximum temperature that you are reaching in the steam turbine front is this. So still we have a significant amount of temperature difference which we have to maintain in order to have a reasonable degree of heat transfer in general rate of heat transfer. If we quickly see these plants, just look at the heat exchanger.

In the heat exchanger, amount of heat rejected by the gas turbine plant or I should say amount of heat rejected by the gas has to be equal to the amount of heat absorbed by the steam, i.e.,

$$\dot{q}_{gas} = \dot{q}_{steam}$$

What is the amount of heat rejected by the gas? It is:

$$\dot{m}_g c_{pg} (T_8 - T_9)$$

where

$\dot{m}_g$ refers to the corresponding gas flow rate

And of course, we are assuming the gas here similar to the air standard assumption, we are assuming it to be an ideal gas with constant specific heat. So, this will be amount of heat rejected by the gas.

And how much is amount of energy received by the steam? It will be:

$$\dot{m}_s(h_3 - h_2)$$

where

$\dot{m}_s$ refers to the mass flow rate of the steam

$h_3 - h_2$ refers to the changes in enthalpy.

So, if there are no losses in heat exchanger, no amount of heat is leaving the surrounding then this is the one, that is going to be the amount of heat rejected by the gas turbine plant and heat received by the steam turbine plant, i.e.,

$$\dot{m}_g c_{pg}(T_8 - T_9) = \dot{m}_s(h_3 - h_2)$$

Rest of the calculation procedure remains very much the same, just individual to the gas turbine and steam turbine.

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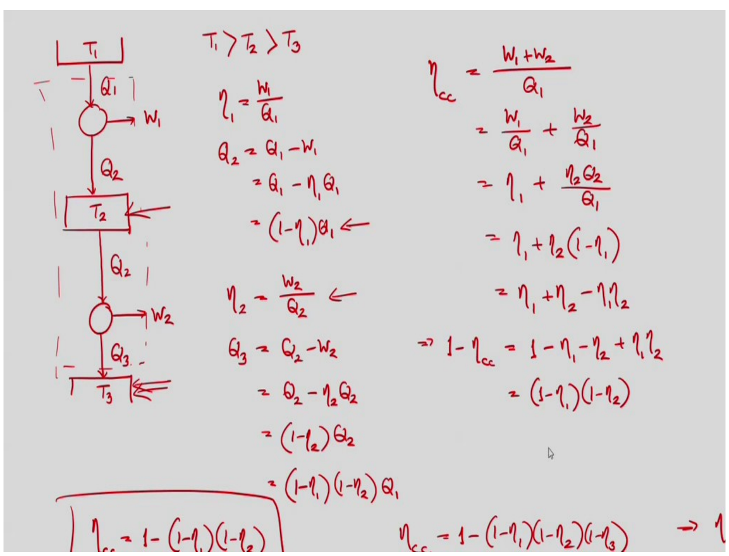

Let us quickly try to get an idea about the efficiency of such a combination. Let us consider our topping cycle is working between the temperature range of T_1 and T_2, this is the topping cycle which is receiving Q_1 amount of heat it from the reservoir at temperature T_1, producing W_1 an amount of work and rejecting Q_2 amount of heat, here:

$$T_1 > T_2$$

So for this topping cycle, efficiency can be written as:

$$\eta_1 = \frac{W_1}{Q_1}$$

$$Q_2 = Q_1 - W_1$$

$$= Q_1 - \eta_1 Q_1$$

$$= (1 - \eta_1)Q_1$$

that is the amount of heat being rejected by the topping cycle. Now what about the bottoming cycle? The bottoming cycle will be taking the same amount of heat Q_2 from this reservoir T_2, will be producing W_2 amount of work. And you will be rejecting heat to another reservoir kept at temperature T_3 is rejecting Q_3 amount of heat where T_3 is even lower.

Just compare this gas turbine steam turbine combination. Here T_1 can be around 1400 ^{0}C that is the temperature of the combustion gases at the exit of the combustion chamber T_2 can be around 500 or 600 ^{0}C which is the temperature of the exhaust gas which is leaving that a gas turbine and T_3 can be the atmospheric temperature. So, we are able to cover the entire temperature in starting for the maximum possible temperature of the gas turbine plant and atmospheric temperature.

Now, look at the second cycle. For the second cycle efficiency can be given as:

$$\eta_2 = \frac{W_2}{Q_2}$$

$$Q_3 = Q_2 - W_2$$

$$= Q_2 - \eta_2 Q_2$$

$$= (1 - \eta_2)Q_2$$

$$= (1 - \eta_1)(1 - \eta_2)Q_1$$

What about this combined cycle? The combined cycle is operating between this temperature range of T_1 to T_3. It is taking Q_1 amount of heat from the reservoir temperature T_1 and rejecting Q_3 amount of heat and temperature T_3, reservoir temperature T_3, giving W_1 and W_2 as the combined output. Then efficiency of the combined cycle will be:

$$\eta_{CC} = \frac{W_1 + W_2}{Q_1}$$

$$= \frac{W_1}{Q_1} + \frac{W_2}{Q_1}$$

$$= \eta_1 + \frac{W_2}{Q_1}$$

and how we can represent the second term in the above equation? Just look at the expression that we have got earlier and we can write efficiency of the combined cycle as:

$$= \eta_1 + \frac{\eta_2 Q_2}{Q_1}$$

using this particular expression, we can write:

$$= \eta_1 + \eta_2(1 - \eta_1)$$

$$= \eta_1 + \eta_2 - \eta_1\eta_2$$

or if you write:

$$1 - \eta_{CC} = 1 - \eta_1 - \eta_2 + \eta_1\eta_2$$

$$= (1 - \eta_1)(1 - \eta_2)$$

So, we are getting the efficiency for the combined cycle which will be equal to:

$$\eta_{CC} = 1 - (1 - \eta_1)(1 - \eta_2)$$

which is a very important equation to develop, where we have represented the efficiency of the combined cycle in terms of the individual efficiencies for both cycles. You can assume any value for η_1 and η_2 and you can do the calculation. Just proceeding in the same way, if you are trying to deal with three cycles in combination that is where the bottoming cycle shown here is acting like an intermediate cycle and then that Q_3 amount of heat rejected by this one is being observed by third cycle which is giving W_3 amount of work. Then for that kind of cycle you will find that you η_{CC} will be coming as:

$$\eta_{CC} = 1 - (1 - \eta_1)(1 - \eta_2)(1 - \eta_3)$$

and in general, we can always write:

$$\eta_{CC} = 1 - \prod_{j=1}^{N}(1 - \eta_j)$$

N is the total number of cycles that you are combining here. If you take an example suppose, we are talking about a case where there are three cycles in combination where

$\eta_1 = 0.55$

$\eta_2 = 0.55$

$\eta_3 = 0.45$

If you combine this and put the numbers, you can easily calculate this is becoming something around 0.89. So, the combined cycle is going to give you an efficiency of 89%. What is the reason, why the efficiency is increasing by some drastic amount? Though the individual cycles are having maximum size of 55% but the combination is giving an efficiency of 89%. The reason lies in the effective utilisation of the rejected heat. Here the lower the temperature of effective heat rejection, higher is the efficiency and the same is happening. Like the diagram shown here for the topping cycle the temperature of heat rejection is T_2 and the bottoming cycle it is T_3 and when you are combining them, then the temperature of heat rejection remains this T_3 only.

And as this temperature T_3 is lower than T_2, so definitely efficiency of this common circle will be higher than the efficiency of the topping cycle. So, what about the bottoming cycle? For the bottoming cycle, the temperature of heat addition is T_2 whereas the same for the topping cycle is T_1. T_1 means much higher so we can expect the effective temperature of the topping cycle to be much higher and as a combined cycle is using this T_1 as the temperature of heat addition, so its efficiency is increasing from that count as well. So, the combination of these two cycles is allowing us to get the heat addition done at the maximum possible temperature and heat rejection done at the minimum possible temperature. And that is why we are getting this high level of efficiency. I would like to solve one numerical problem here, just to show you the way of tackling this combined cycle.

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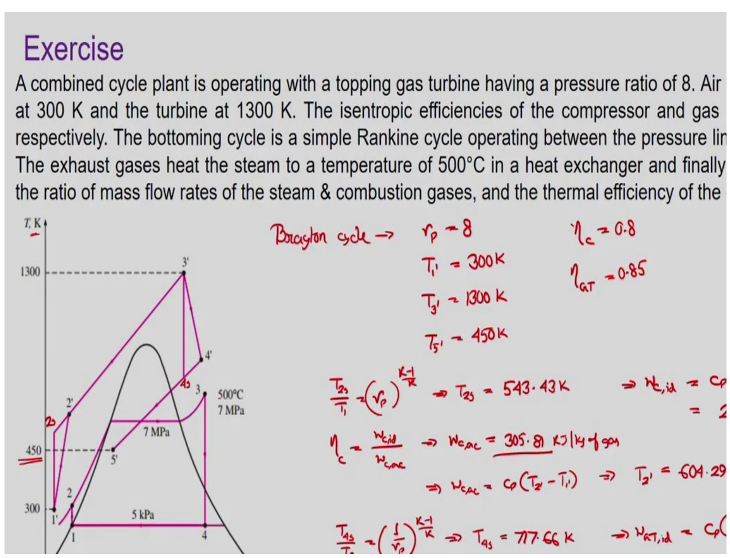

A combined cycle plant is operating with the topping gas turbine having a pressure ratio of 8. Air enters the compressor at 300 K and turbine at 1300 K. Isentropic efficiencies for the compressor is 80% and gas turbine is 85%. Bottoming cycle is a simple Rankine cycle operating between the pressure limits of 7 MPa and 5 kPa.

The exhaust gases heat the steam to temperature of 500 ^{0}C in heat exchanger and finally leave at 450 K. We have to find the ratio of mass flow rates and the thermal efficiency of the combined cycle. This is the corresponding cycle diagram. Here 1, let us mark this as 2s, 2', 3 and let us mark it as 4s, 5' corresponding to the Brayton cycle. Where is 1-2-3-4 corresponds to the Rankine cycle.

So, at point 4' it is the turbine exit point, the temperature of the gas is very high and that heat is being utilised to raise the temperature of the steam to a level of 500 ^{0}C where the gas is finally leaving at 450 K. This is given in kelvin. So, let us first talk about the Brayton cycle part. For the Brayton cycle part, we know that it is given:

$r_p = 8$

$T_1' = 300$ K

$T_3' = 1300$ K

$T_5' = 450$ K

$\eta_C = 0.8$

$\eta_{GT} = 0.85$

Look at this, for the steam turbine part, isentropic efficiency is not given. So, you can assume the expansion in steam turbine to be isentropic in nature, that is ideal expansion. But for the gas turbine cycle isentropic efficiency is given for both the compression and expansion sides.

So now, we analyse it. Look at the compression process first. So had there been an isentropic expansion then we know that:

$$\frac{T_{2s}}{T_1} = (r_p)^{\frac{k-1}{k}}$$

These values are not given so we are taking the general values

$k = 1.4$ and

$c_p = 1.005$ kJ/kgK

which are the standard values for air. So T_{2s} this, putting the values T_{2s} will be:

$$T_{2s} = 543.43\ K$$

Now, correspondingly the work input requirement for the compressor, ideal one will be assuming it to be an ideal gas with constant specific heat, it is:

$$W_{C,ideal} = c_p(T_{2s} - T_1)$$

$$= 244.16 \frac{kJ}{kg} of\ gas$$

that is important because here we have two media with different flow rates. So, this ideal compressor work is in unit's kJ/kg of gas.

What about the actual temperature? We know that the compression efficiency can be defined as:

$$\eta_C = \frac{W_{C,ideal}}{W_{C,actual}}$$

From there we get the actual compression work of requirement:

$$W_{C,actual} = 305.81 \frac{kJ}{kg} of\ gas$$

and from there we can calculate as the temperature of T_2', because it is nothing but:

$$W_{C,actual} = c_p(T_{2'} - T_1)$$

giving us,

$$T_{2'} = 604.29\ K$$

We could have got T_2' directly using expression for η_C also, but I wanted to have this numbers. So, I have calculated separately. Now come to the expansion side, following the same way:

$$\frac{T_{4s}}{T_3} = \left(\frac{1}{r_p}\right)^{\frac{k-1}{k}}$$

giving us, T_{4s} that is the temperature of the gas, had the expansion been isentropic,

$$T_{4s} = 717.66\ K$$

from there the ideal work output that you would have got from turbine comes to be:

$$W_{GT,ideal} = c_p(T_{3'} - T_{4s})$$

this is the ideal work output that you have got from the turbine, it is

=585.25 kJ/kg of gas

Let here a small change here is your writing this way between this is the work output from the gas turbine because there are two gas turbines to talk about. Now efficiency for the gas turbine is defined as the actual work output that we are getting from the gas turbine by the ideal work output that we are getting from the gas turbine.

$$\eta_{GT} = \frac{W_{GT,actual}}{W_{GT,ideal}}$$

You are getting from the gas turbine from there we get the actual work output from the gas turbine will be only 85% of this ideal one predicted which will be coming as 497.46 kJ/kg. So this is the work that you are getting from the gas turbine in practice, per kg of gas of course. And using this in terms of temperature, this one can be written as:

$$W_{GT,actual} = c_p(T_{3'} - T_{4'})$$

which gives us,

$$T_{4'} = 805.01\ K$$

So, we have got the temperature of the five points on the five points of the gas turbine cycle and also the amount of energy absorbed or amount of work produced by the gas turbine in practice and also the amount of work consumed by the compressor in practice. So, if you want numbers, we can calculate now. If you want to calculate I will do in the next slide.

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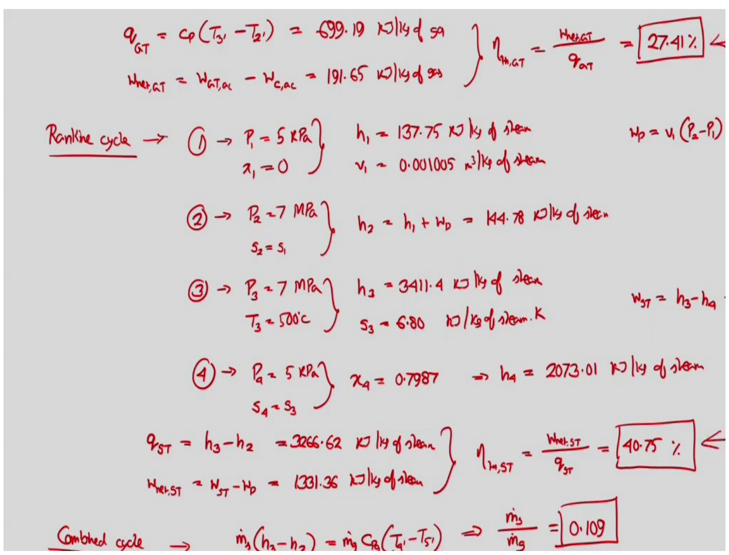

Here to have some more space, so the amount of heat input or amount of energy absorbed by the gas turbine, then how much will that be? The heat has been done from point 3' to 2'. So that will be equal to:

$$q_{GT} = c_p(T_{3'} - T_{2'})$$

it is the amount of heat absorbed by the gas turbine and that will be coming as:

$$= 699.19 \text{ kJ/kg of gas}$$

and

$$W_{net,GT} = W_{GT,actual} - W_{C,actual}$$

= 191.65 kJ/kg of gas

It is a small number because if you look at the calculation, 497.46 kJ/kg of gas is being produced by the gas turbine but 305.81 kJ/kg has been absorbed by the compressor giving us acquired small amount of net power output.

And combining the individual thermal efficiency for the gas turbine plant will be equal to:

$$\eta_{th,GT} = \frac{W_{net,GT}}{q_{GT}}$$

And the efficiency will be coming in the range of 27.41%. This is the individual efficiency for the gas turbine. Now we come to the Rankine cycle part, the Brayton cycle part is done. We come to the Rankine cycle; I am not put the cycle diagram here which I should have done but repeatedly have to go back to the previous slide now, just to get the idea of the points. So, in the Rankine cycle, we have to get point 1, 2, 3 and 4, all the sufficient number of information are given. Point 1 corresponds to 5 kPa and saturated vapour. So, point number 1 corresponds to a pressure of 5 kPa and saturated liquid not vapour. So putting this we have from the table, we have:

$$h_1 = 137.75 \text{ kJ/kg}$$

and

$$v_1 = 0.001005 \text{ m}^3\text{/kg}$$

Here, per kg of steam that you are talking about. Because you are the working medium is same now, which is in the Rankine cycle. Now the pump work will be equal to:

$$W_P = v_1(P_2 - P_1)$$

where

P_2 is the boiler pressure which is 7 MPa

P_1 is a condenser pressure which is 5 kPa

be careful about the units one is in MPa other is in kPa. So, if you put the numbers your pump work is coming as well as very small number 7.03 kJ/kg of steam.

Just compare this work input that you to provide to the Rankine cycle is 7.03 kJ/kg. Whereas that in the gas turbine cycle is 305, just no compression between them at all. And that is because you must be knowing by now is because of the difference in the specific volume of the liquid present the gaseous phase. So, now point number 1, using this pump work now you can go to point number 2.

For point number 2, we know that the pressure is of the boiler pressure that is 7 MPa. And

$$s_2 = s_1$$

but we generally don't use this, we just directly calculate:

$$h_2 = h_1 + W_P = 144.78\ kJ/kg$$

Point number 3, that is superheated vapour 500 ^{0}C at 7 MPa. So,

$$P_3 = 7\ MPa$$

$$T_3 = 500℃$$

So, combining this we can directly get the numbers from the superheated table, 3411.4 kJ/kg of steam, this is for per kg of steam and entropy this corresponding expansion is isentropic. So, we need the value of entropy also is equal to:

$$s_3 = 6.80 \text{ kJ/kg of steam. K}$$

Now, point number 4, is the condenser pressure which is 5 kPa and this expansion being isentropic. So,

$$s_4 = s_3$$

so, combining this, you know the procedure. From there we are getting you quality x4 is becoming corresponding to the 5 kPa you can see that is s_4 is lower than is s_g is greater than s_f in a mixture side correspondingly, we can get

$$x_4 = 0.7987$$

putting this will get the values of:

$$h_4 = 2073.01 \text{ kJ/kg of steam}$$

So, let us perform the individualistic analysis for the steam turbine first, then total amount of heat that you need on the steam turbine cycle or Rankine cycle will be equal:

$$q_{ST} = h_3 - h_2$$

$$= 1338.39 \text{ kJ/kg of steam}$$

and

W_{net} from the steam turbine is equal to work produced by the turbine, that I have not written separately. Okay W_{ST} I should have written earlier. W from the steam turbine should be equal to:

$$W_{net,\ ST} = h_3 - h_4$$

because turbine expansion corresponds to this particular process 3 to 4, which is:

$$h_3 - h_4 = 1338.39\ kJ/kg\ of\ steam$$

If we compare this number it was produced by the gas turbine, we can see in the gas turbine cycle, total work produced was also much lesser 497. 46. Here we are getting much higher amount of work output from the steam turbine and much lesser amount of consumption. And accordingly, the network output from the steam turbine:

$$W_{net,\ ST} = W_{ST} - W_P = 1331.36\ kJ/kg\ of\ steam$$

So, the work output that you are getting from this actually I have written the value for q_{ST}, you must have noticed this, because h_3 is 3411 and h_2 is a very small number of 144. This number is 3266.62. So, I am rewriting the expression for q_{ST} below:

$$q_{ST} = h_3 - h_2 = 3266.62\, kJ/kg\ of\ steam$$

In my notes I have just randomly written these numbers and sometimes having trouble to pick up the correct one. So, the thermal efficiency for the steam turbine plant alone will be the network output that you are getting from the steam turbine and the amount of energy that has been absorbed by the steam thermal in the form of heat which is:

$$\eta_{th,ST} = \frac{W_{net,ST}}{q_{ST}} = \frac{1331.36}{3266.62} = 40.75\%$$

So, we know the individual performance of the gas turbine plant and the steam turbine plant. Then what about the combined cycle then? For the combined cycle part, you first need to know the individual mass flow rate. How can you calculate that? To calculate that you need to go to the location where they are coupled and the coupling is taking place in the heat exchanger where the gas is changing the state from 4' to 5' and steam is changing state from 2 to 3. We have to perform an energy balance across this heat exchanger.

If we perform the energy balance then for the steam side we shall be having:

$$\dot{m}_s(h_3 - h_2)$$

that is the total amount of energy gained by the steam plant, i.e., from point 2 to point 3 is moving and during this movement, gas temperature is dropping from 4' to 5'. So, it will be:

$$\dot{m}_s(h_3 - h_2) = \dot{m}_g c_{pg}(T_{4'} - T_{5'})$$

We know all these temperatures by now and from there you can easily calculate:

$$\frac{\dot{m}_s}{\dot{m}_g} = 0.109$$

So, you can see that the flow rate for steam industry in the Rankine cycle path is only about 1 % of the flow rate of the gas in the gas turbine path. And any higher flow rate is not possible for the gas turbine to raise the temperature. So, this is one result and we have to get the efficiency as well. So, what is the net output from the combined cycle?

From the combined cycle, if I write in capital sense, $W_{dot\ net}$ that will be equal to, actually we do not know their individual flow rates. Let us write in this way, we only know the ratio.

$$\dot{W}_{net,\ CC} = \dot{m}_g W_{net,GT} + \dot{m}_s W_{net,ST}$$

given in both sides by the mass flow rate of the gas stream.

$$\frac{\dot{W}_{net,\ CC}}{\dot{m}_g} = W_{net,\ CC} = W_{net,\ GT} + \frac{\dot{m}_s}{\dot{m}_g} W_{net,\ ST} = 336.77\ kg\ of\ gas$$

So, this is the net work output that you are getting from the combined cycle per unit flow rate of gas. Accordingly, the thermal efficiency for the combined cycle will be equal to the net output that we getting from the combined cycle per unit flow rate of the gas to the net input that you are getting per unit flow rate of the gas, which is nothing but q_{GT}. An the mathematical expression is as follows:

$$\eta_{th,CC} = \frac{W_{net,CC}}{q_{GT}} = 48.17\%$$

and the efficiency becoming as 48.17% which is significantly higher than the efficiency for both the gas turbine part as well as the steam turbine part and that is very important. Because the individual plants, if you are operating the gas turbine alone, not only we are producing efficiency of 27% but also look at this, had there been not the heat exchanger then the gas would have gone out the atmosphere at this point 4 prime and your T_4' was 800 K. So is there no combination of the cycles then we are getting only 27% efficiency and allowing a gas stream of 800 K temperature to go to surrounding. Similarly, if you are looking only for the steam turbine then the entire amount of heat that the steam turbine received from the gas turbine plant that has to be supplied externally and still you are getting efficiency of about 40 % only. This combination is allowing us to get higher power output and enhancing the efficiency to 48.17%.

And also, what is the lowest temperature? Now the gas is going out at 450 K instead of 800 K, 450 K is significantly lower and also the lowest temperature of the plant is the saturation temperature corresponding into 5 kPa. So, the lowest temperature of this combined cycle is the saturation temperature corresponding to 5 kPa which will be only around 33 ^{0}C.

So, we are able to run this combined cycle between the temperature range of 1300 K and 306 K. That is a very large temperature is to be considered giving us such high level of efficiency. And we could also have calculated the efficiency following the method that we have developed two slides back that is this particular one I am talking about. But one problem is that in this cycle the gas turbine, the compressor and turbine have isentropic efficiency is non-unity isentropic efficiency. So you are not getting exactly the same value if we had calculated the efficiency that way if the isentropic efficiencies are not there, rather I should say the isentropic efficiency is one, then this particular valuable much higher and also calculate the same values thereby combining these individual efficiencies.

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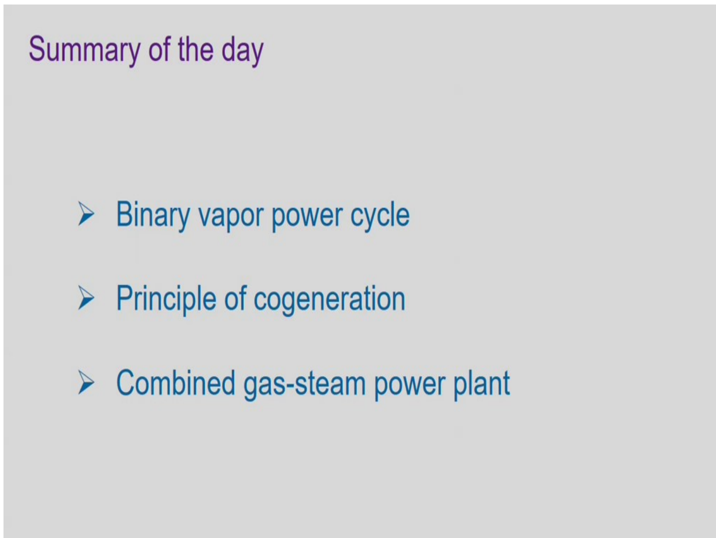

That is the discussion about the cogeneration that you wanted to have for today's lecture. So today I started with the binary vapour power cycle and in conjunction with that explained the importance of the combined cycle and the principle of cogeneration. And then I have talked about the combined gas steam power plant wherewe are using Brayton cycle as the topping cycle and Rankine cycle as the bottoming cycle.

There are several industries or I should say several commercial plants, which are operating on this particular combination in different parts of the world and operating very successfully since late 1980's. So, it a very potent option of commercial power generation and is only expected to grow more in future. We shall be talking about a bit more about the combined cycle in the next lecture where we would like to talk about a few other kinds of combined cycles. Till then you just revise the lecture and try to solve a few relevant problems. Thank you.