Applied Thermodynamics for Engineers
Dipankar N. Basu
Department of Mechanical Engineering
Indian Institute of Technology – Guwahati

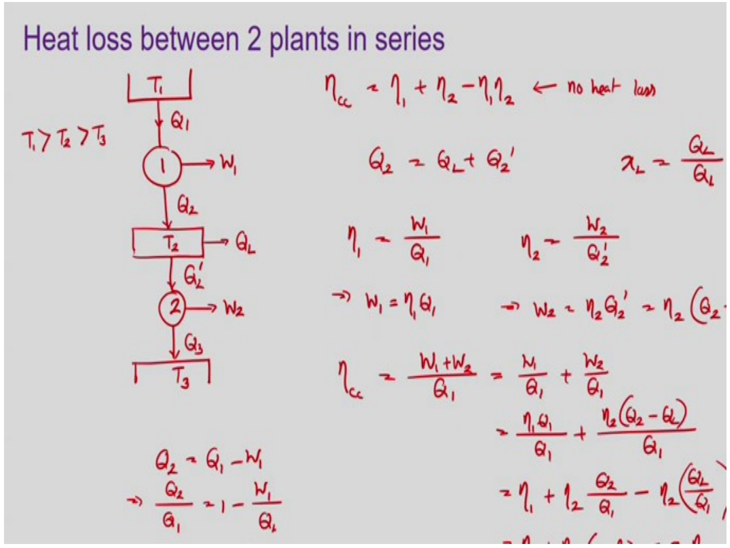
Lecture – 25
Different Arrangements in combined cycles

Hello friends, so welcome back to the second lecture of this module where we are talking about the cogeneration and combined cycles. Over previous few weeks we have talked about different kinds of power producing cycles, gas-based power producing cycles in the form of Otto and Diesel cycles or the Brayton cycle and also the vapor-based power producing cycles in the form of the Rankine cycles. And in the previous lecture you have seen that it is also possible that we can combine these two cycles or this kind of cycles together to have a combined cycle where we can extract higher efficiency compared to any of the individual cycles. The idea in general is always to have a topping cycle and a bottoming cycle such that the energy that the topping cycle is rejecting that is being utilized to or that is being transferred to the bottoming cycle so that the bottoming cycle does not need any separate source of energy and it can produce its own work output.

So, if we see the two cycles in combination it is only the topping cycle which is going to receive energy from the surrounding or from the source. Whereas the bottoming cycle is the one that is going to remove or reject energy to the sink. But in between that is the heat rejection with the topping cycle and heat addition by the bottoming cycle they are clubbed together so that there is no external interference. But we are going to get work out from both of them such that we can get efficiency of this combined cycle higher than the individual efficiency for both of them.

Now the way we have discussed so far at least yesterday that whatever energy the topping cycle is rejecting the entire amount of energy is getting absorbed by the bottoming cycle. But that is hardly the case in practice quite often. There may be a significant portion of energy rejected by the topping cycle gets lost because of the operation malfunctioning or because just of the imperfect insulation used. And therefore, the amount of energy that has been transferred to the bottoming cycle is only a fraction of the amount of energy rejected by the topping cycle.

(Refer Slide Time: 02:32)



And let us try to investigate that case quickly. Here we are talking about two power producing cycles in series with each other but the amount of energy rejected topping cycle entire of that is not able to reach the bottoming cycle. So, we are having T_1 as the highest temperature source from where some Q_1 amount of energy is going to your topping cycle it is producing W_1 amount of work and rejecting the remaining Q_2 amount of heat to an intermediate temperature reservoir which is a temperature T_2, where T_1 is greater than T_2.

And out of this ideally this entire amount of energy *Q2* should go to the bottoming cycle which will convert a part of that as working from the form of *W2* and reject some *Q3* to the lowest temperature sink which is maintained at the temperature *T3,* where *T3* is the lowest temperature. And in this kind of situation we have seen that efficiency for the combined cycle is equal to:

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

where 1 is the topping cycle and 2 is the bottoming cycle.

But the situation that we are going to talk about here, where the topping cycle is rejecting Q_2 but a portion of that say Q_L is getting rejected or getting lost and only Q_2' is the amount of energy that is able to reach the bottoming cycle such that:

$$Q_2 = Q_L + Q_2'$$

and we are also going to define a fraction x_L which is:

$$x_L = \frac{Q_L}{Q_1}$$

where Q_1 is the amount of energy added.

This is the situation when there is no heat loss, but now we have a heat loss which is Q_L. So, let us analyze the situation in here, so efficiency for the topping cycle η_1 is defined as:

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

or

$$W_1 = \eta_1 Q_1$$

Efficiency for the bottoming cycle is defined as η_2 is equal to:

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

where

W_2 is its output and Q_2' is the input now because it is not receiving Q_2 say there is a no reason that we should use Q_2 to define efficiency. And therefore,

$$W_2 = \eta_2 Q_2'$$

that you can write it to be:

$$= \eta_2 \, (Q_2 - Q_L)$$

Now efficiency for this combined cycle now is equal to:

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

where

$W_1 + W_2$ is the total output

Q_1 is the net heat input that you have given

So, if you separate them out, it will be equal to:

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

Put the expressions for W_1 and W_2 which we have just written in the above lines. So, it is:

$$= \frac{\eta_1 Q_1}{Q_1} + \frac{\eta_2 (Q_2 - Q_L)}{Q_1}$$

So, it is:

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

Now how much is your Q_2 in relation with the first cycle? We know that Q_2 is equal to applying first law of thermodynamics on the first cycle on the topping cycle it is equal to:

$$Q_2 = Q_1 - W_1$$

that is dividing this equation by Q_1 on both sides, it is:

$$\frac{Q_2}{Q_1} = 1 - \frac{W_1}{Q_1}$$

is also equal to:

$$= 1 - \eta_1$$

So, putting it back in the expression for this combined cycle efficiency:

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

as we have already defined:

$$x_L = \frac{Q_L}{Q_1}$$

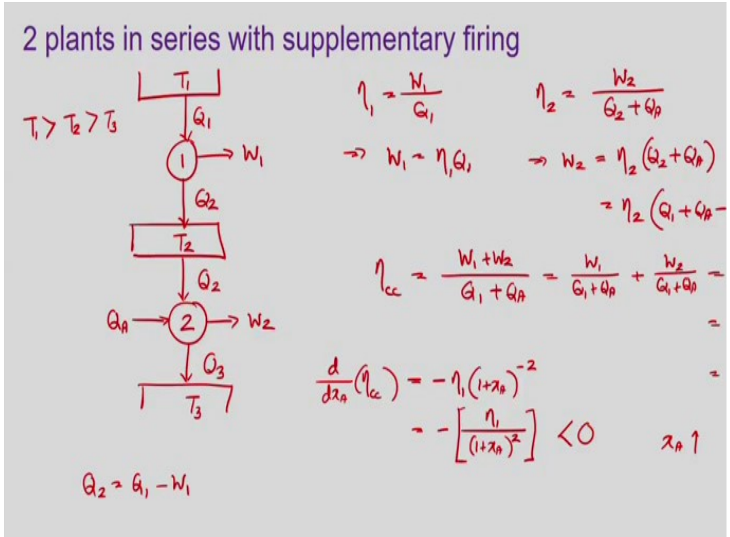
So, we have finally,

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

So, efficiency for the combined cycle where we are losing some amount of heat in the intermediate temperature reservoir can be expressed like this. where of course when x_L is equal to 0 it goes back to the no heat loss situation and that is of course very much logical because in that case it reduces to the ideal scenario.

Now this is one scenario where we are losing some heat. But it is also possible that we are not losing any heat but in the bottoming cycle we are rather adding some additional heat and that thing we call supplementary firing.

(Refer Slide Time: 07:36)



There the bottoming cycle is receiving energy from the topping cycle plus some additional energy. Here we are talking about this particular scenario, so here again the topping cycle which is one is receiving Q_1 amount of heat from this reservoir temperature T_1 and rejecting W_1 amount of heat T_2 is the intermediate temperature reservoir, Q_2 is the amount of heat it is losing to this. Now we are assuming there is no heat loss so this entire Q_2 is going to a bottoming cycle 2 which is producing W_2 amount of heat and rejecting Q_3 to the reservoir temperature T_3, where we have T_1 the highest temperature T_2 intermediate one and T_3 is a lowest temperature. But the bottoming cycle that is cycle number 2 is receiving Q_2 plus some auxiliary amount of energy in the form of Q_A, which we are referring as this supplementary energy of supplementary firing. May be some additional amount of fuel is burned to be added to the energy content of the fluid in cycle number 2 that is what we are having here.

So, if we analyze the situation then, so efficiency for the topping cycle remains the same which is:

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

i.e.,

$$W_1 = \eta_1 Q_1$$

η_2 for the bottoming cycle it is producing W_2 and how much is the net amount of energy is it receiving? It is receiving Q_2 plus this Q_A.

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

So, let us define a fraction x_A as:

$$x_A = \frac{Q_A}{Q_1}$$

So, from there we can write:

$$W_2 = \eta_2(Q_2 + Q_A)$$

Now applying energy balance on the topping cycle, we know that:

$$Q_2 = Q_1 - W_1$$

So, if we write that way, W_2 can also be written as it is as:

$$W_2 = \eta_2(Q_1 + Q_A - W_1)$$

Now efficiency for the combined cycle now can be written as net work output by net heat input. Now how much heat you are giving to this combined cycle? Of course, you are giving Q_1 to the topping cycle plus we are now giving Q_A to the bottoming cycle as additional energy so the efficiency should consider this Q_A as well.

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

So, if we separate them out now,

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

So W_1 if we put the expression for this, the expression will become:

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

and now dividing this expression both numerator and denominator by Q1 we have:

$$= \frac{\eta_1}{1 + x_A} + \eta_2$$

So, this is the efficiency of this combined cycle. If we want, we can simplify this as:

$$= \frac{\eta_1 + \eta_2 + x_A\eta_2}{1 + x_A}$$

this is the efficiency for this combined cycle. So, of course this expression is going to give you the numerical value once you know the value of x the numerical value of the combined cycle efficiency. But still to see the effect of the supplementary firing let us investigate a bit more.

Let us try to see, as the magnitude of x_A increases what is the effect on the efficiency of the combined cycle. And to have that let us try to maximize this combined cycle efficiency in terms of this x_A assuming η_1 and η_2 to be to be constant. So, we are trying to perform differentiation of combined cycle efficiency with respect to x_A and try to see the corresponding expression that is the rate of change of the efficiency of the combined cycle with changing the value of x_A.

So, how much will be this one? η_1 and η_2 are remains constant so once we differentiate this expression with respect to x_A, the expression we can write this is:

$$\frac{d}{dx_A}(\eta_{CC}) = -\eta_1(1 + x_A)^{-2}$$

that is,

$$= -\frac{\eta_1}{(1 + x_A)^2}$$

Now what should be the symbol of this quantity? η_1 is the efficiency for the topping cycle so that is always positive. And x_A is a positive quantity and we do not need to consider that because the numerator is a square quantity so that is also a positive.

So, that means this entire term you have in the square bracket is a positive one and now we are having a minus sign outside. So, this quantity is a negative one, what does that mean? That means as x_A increases, the efficiency for the combined cycle that actually decreases. So, as we are having the supplementary firing, we are basically losing the advantage of a combined cycle and we are having a reduction in the overall efficiency for this, which is not at all desirable.

And that is why the supplementary firing are generally not used. In earlier times, supplementary firing was a quite common option in combined cycle. But nowadays we can find only two limited cases of supplementary firing. One is combined cycle plant with limited supplementary firing where only a small fraction of this x_A is used just to put some additional work output to get some additional work output from the bottoming cycle, particularly when required. Means your cycle has the option of supplementary firing but not necessarily you are going to use it always, only when you need an increase in the value of this W_2 we are adding this supplementary firing. That is what we refer as the limited supplementary firing or control supplementary firing.

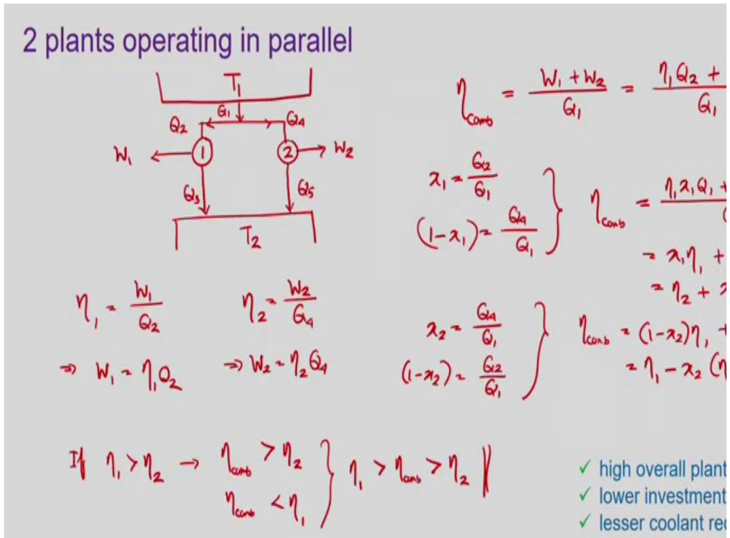
There is another thing combined cycle plant with maximum supplementary firing. It refers that the exhaust gas that is coming out of the topping cycle may be a topping gas turbine plant, that quite often has some amount of unburned fuel left in it. Then we shall be supplying only that quantity of additional oxygen, so that, that onward portion of the fuel gets completely exhausted. Or the other way: it is often possible that the fuel is completely burned but the gas exhaust gas coming out of the gas turbine has some quantity of fresh oxygen still left in it. Then we shall be supplying some additional quantity of fuel such that that fill will be completely combusted or completely burned using whatever amount of oxygen left in it. And at the end of the process there will be no unburned fuel there will be no unused oxygen as well. That is what we refer as a maximum supplementary firing where we are making maximum use of the unburned fuel or un-burnt oxygen that is left there.

So, these are the two options of supplementary firing that are quite commonly done in industries but still as the improvement in material is on, we are able to produce newer materials, newer pipe materials which are able to sustain high temperatures for much longer period, accordingly the temperature level prevailing in the gas turbine combustor or in the turbine itself that keeps on going upwards. And we are now approaching a maximum temperature of about 2,000 ^{0}C in a gas turbine which is an extremely high temperature that we are talking about. And subsequently that gas that comes out of that gas turbine plant that is also at a very high temperature. And that is quite easily capable of increasing the temperature of the steam in the bottoming Rankine cycle to something in the range of 500 to 550 to 600 ^{0}C.

And therefore, we may not at all be having any need of any supplementary firing in the days to come. In fact, I should say with new modern combined plants that are getting developed, there we hardly need to go for any kind of supplementary firing. Simply because the gas turbine is operating at a much higher temperature level and energy left in the exhaust gas or is temperature level is significantly higher so that there is no need of any supplementary firing.

Now we are so far talking about the combined cycle plant all are in series mode, that is, the amount of energy rejected by the topping plant is being absorbed by the bottoming plant. But cannot we operate the cycles in parallel mode? That is two cycles operating in parallel that is they are operating between the same temperature reservoirs. Of course, that is still possible let us try to see a situation like this.

(Refer Slide Time: 16:55)



We have a temperature reservoir operating at temperature T_1, another operating at temperature T_2 and we have two plants: this is 1 and this is 2. They are operating in parallel that means both are receiving energy from the same reservoir T_1. Let us say Q_1 is the total amount of energy being extracted from this out of that Q_2 is going to the first one which is rejecting Q_3 to this T_2 reservoir and producing W_1 amount of work.

And amount Q_4 is going to the second one which is producing W_2 and again rejecting say some Q_5 amount of heat to that same reservoir. So, both the cycles are operating between the same 2 reservoirs temperature T_1 and T_2 and they are giving work output. So, if we analyze this one, then for cycle number one we can define its efficiency as:

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

$$W_1 = \eta_1 Q_1$$

For the second cycle,

$$\eta_2 = \frac{W_2}{Q_4}$$

$$W_2 = \eta_2 Q_4$$

So, the efficiency of this combination I am not going to say it is a combined cycle I will say it is more like a combination, and that will be equal to:

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

So, if we separate them out let us express W_1 and W_2 in terms of its efficiencies, so it becomes:

$$= \frac{\eta_1 Q_1 + \eta_2 Q_4}{Q_1}$$

Now, if we define a fraction x_1 as the amount of energy received by plant number 1, that is:

$$x_1 = \frac{Q_2}{Q_1}$$

then,

$$(1 - x_1) = \frac{Q_4}{Q_1}$$

which is the to the fraction of energy received by the second plant that is, Q_4/Q_1. If we combine this, efficiency for this combination will be what? It can be represented as:

$$\eta_{Comb} = \frac{\eta_1 x_1 Q_1 + \eta_2 (1 - x_1) Q_1}{Q_1}$$

so it is,

$$= x_1 \eta_1 + (1 - x_1)\eta_2$$

or if we write in a separate way it becomes:

$$= \eta_2 + x_1(\eta_1 - \eta_2)$$

Similarly, if we express this x_2 as the amount of energy received by the second plant that is,

$$x_2 = \frac{Q_4}{Q_1}$$

then,

$$(1 - x_2) = \frac{Q_2}{Q_1}$$

So, combining this we can write the efficiency for this combination is equal to, just directly I can write it by putting the expression for x_2 and $(1 - x_1)$. So, it becomes:

$$\eta_{Comb} = (1 - x_2)\eta_1 + x_2 \eta_2$$

which is now:

$$= \eta_1 + x_2(\eta_1 - \eta_2)$$

Now if we assume a scenario where $\eta_1 > \eta_2$ then for x_1 and x_2 both are positive quantities because they are heat energy fractions or fractions of heat supplied.

So, when $\eta_1 > \eta_2$, then, if we look at the first expression,

$$\eta_{Comb} > \eta_2$$

But now look at the second expression, this combined cycle expression will be less than η_1,

$$\eta_{Comb} < \eta_1$$

when $\eta_1 > \eta_2$, $\eta_1 - \eta_2$ is a positive quantity. So, from the first expression when we are seeing that the $\eta_{Comb} > \eta_2$, $\eta_{Comb} < \eta_1$, that is for this particular scenario, η_{Comb} though it is greater than the second one efficiency for the second one is less than efficiency for the first one.

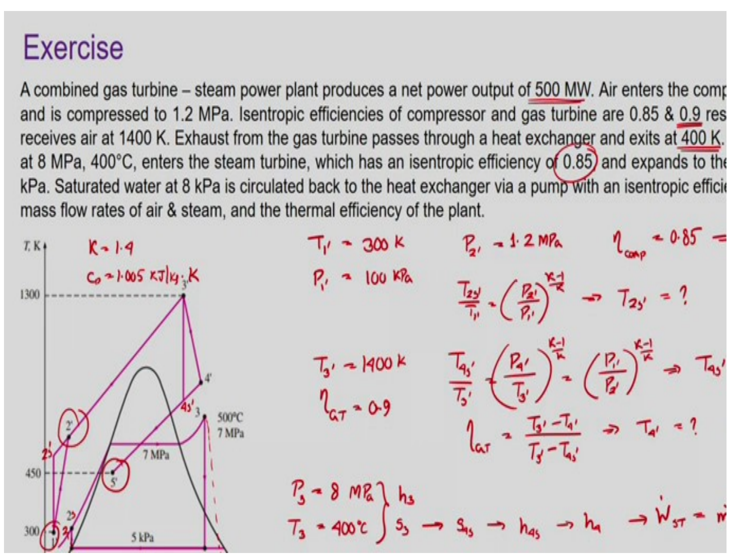
If we see other way around, if we have $\eta_1 < \eta_2$, then η for this combination we shall be seeing again. Let us see from the second expression now. Now $\eta_1$is smaller, so as η_1 is smaller, $\eta_1 - \eta_2$ is a negative quantity. So, in this case η_{Comb} is greater than η_1. But now look at this expression η_2 is a positive quantity and $\eta_1 - \eta_2$ is a negative quantity. So, what about η_{Comb}? So η_{Comb} becomes less than η_2 that is, for this case η_1 is smaller, η_{Comb} is in between and η_2 is the highest. So, for both this case, in this case we can see that efficiency for this combination is just in between the efficiency of either of them. So, we are truly not gaining anything, both the plants are operating on their own and therefore there is no advantage of having a parallel configuration like this. Rather we can easily connect them in series to get much better performance.

Of course, if each of their temperature levels are compatible in each other. Therefore, we always go for this parallel combination in combined cycle where the outlet or the exhaust of the exhaust heat from the topping cycle is directly being added to the bottoming cycle, and thereby having a suitable utilization of energy and also again in the overall efficiency. So, just to summarize the advantages of the combined cycle as I have mentioned earlier also but still a repeat of that we are going to have much higher overall plant efficiency which will be higher than both individual efficiencies.

And that is the reason we want to go for parallel series operation and not parallel operation because we want to have the combined efficiency to be higher than the individual efficiencies. Secondly, a lower investment just to have the same net work output definitely we have to give lesser amount of heat input. So, we are investing less, less current requirement, like if we are having only the topping cycle then the total amount of energy that has been exhausted or leaving the topping cycle, the much lesser amount of energy will be leaving the bottoming cycle. So, we need much lesser amount of cooling requirement or coolant requirement. Greater operating flexibility as I mentioned it is always possible under in case some special condition or emergency situation, we can easily just switch off one plant and run the other on its own. So, both the plants are actually fully self-sustaining plants and they are generally modern combined cycle plants that have the option of running each of them individually without depending on the other also just to tackle certain emergencies.

Also we can easily go for phased installation, like it is very much possible that we initially set up the gas turbine plant and allow it to run as a standalone unit for certain period of time, a few months maybe one year or more and then once the second unit the bottoming one is ready then we start operation as a combined cycle unit. Simplified operation because of this combination of the two cycles lower environmental impact that is a very big point to be considered as we are investing less amount of fuel. We are adding energy only to the topping cycle and also referral heat rejection from the bottoming cycle is much lesser compared to the topping cycle. So, we are reducing environmental impact from both point of view. And finally, it is possible to a cogeneration of both heat and electricity and though we are not at all talking about cogeneration or generation of heat. But it is always possible at the bottoming cycle if its temperature level is too low to run any turbine we can just use a bottoming cycle to produce hot water or steam, that is always a possibility. So, cogeneration is very much in the heart of the things for combined cycles. Quite often we may have the plant where we use the bottoming cycle for production of both electricity and thermal energy, therefore going for direct cogeneration.

(Refer Slide Time: 26:11)



So, before I close on the gas turbine steam turbine combined cycle discussion, I have one final numerical problem for you to talk about, this a big statement just read it carefully. And this is a corresponding cycle diagram. Here we have a gas turbine - steam turbine combination and a net power output of 500 MW. So, air enters the compressor at 100 kP and 300 K. So, air enters the compressor means we are talking about this particular point.

So, we have I am not going to solve this problem by showing all the steps rather I am just going to show you the procedure, I am leaving the calculation to you. So,

$T_1' = 300$ K

$P_1' = 100$ kPa

and is compressed to 1.2 mega Pascal and there is isentropic efficiency as well. So, it is given that it is compressed to this pressure of P2'which is:

$P_2' = 1.2$ MPa

$\eta_{comp} = 0.85$

So, how can we calculate the temperature at the point 2'?

We can easily use the value for this, let us identify this point as *2s,* so we know that:

$$\frac{T_{2s}}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

and those information's are not given let us consider,

$k = 1.4$

$C_{p\ for\ air} = 1.005$ kJ/kgK

So, as we know P_2', P_1', T_1' and T_{2s}'. So, from there we shall be able to identify T_{2s}'.

And now the isentropic efficiency for this compression process defined as actual energy input divided by ideal possible energy input which is possible only in case of isentropic compression, i.e.,

$$\eta_{Comb} = \frac{T_2 - T_1}{T_{2s'} - T_1}$$

from there we are going to get T_2 or I should say $T_{2'}$.

So, we have point 2', now the isentropic efficiency of the gas turbine is also given as 0.9, the gas turbine receives air at 1400 K. So, T_3' is 1400 K and pressure levels we already know because P_3' will be as same as P_2' *and* P_4' will be same as P_1' and also the isentropic efficiency for the gas turbine is given as 0.9. So, we can easily calculate the efficiency of 4s, let us say this point is 4s', so we can write:

$$\frac{T_{4s'}}{T_{3'}} = \left(\frac{P_{4'}}{P_{3'}}\right)^{\frac{k-1}{k}} = \left(\frac{P_{1'}}{P_{2'}}\right)^{\frac{k-1}{k}}$$

which will be allowing us to calculate T_{4s}' and the isentropic efficiency for the gas turbine is given as actual work output by ideal possible or maximum possible work output, i.e.,

$$\eta_{GT} = \frac{T_{3'} - T_{4'}}{T_{s'} - T_{4s'}}$$

from here we shall be able to calculate T_4'.

So, the total work input requirement for the gas turbine or the compressor how much will be that? So

$$W_{comp} = C_p(T_{2'} - T_1)$$

Similarly, the work output that we are going to get from the gas turbine plant will be equal to:

$$W_{GT} = C_p(T_{3'} - T_{4'})$$

So, the calculation for the gas turbine part is more or less done, the exhaust from the gas turbine passes through a heat exchanger and exits at 400 K. So, this point temperature is 400 K we already know T_4' so you know how much amount of energy it is rejecting in the heat exchanger and the same amount of energy is being received by the steam turbine part. Now the steam at 8 MPa and 400 ^{0}C enters the steam turbine which has an isentropic efficiency of 0.85.

Now in this diagram the point that is shown that is actually 4s but and truly the expansion is something like this it is going up to a point 4 somewhere here. So, for the steam turbine part we know that,

P_3 = 8 MPa

T_3 = 400 ^{0}C

combining these you can get h_3 and s_3. Using s_3 we can identify s_{4s} and then using the isentropic efficiency for the steam turbine which is 0.85 you can also locate the point number 4. So, using s_{4s} we can get h_{4s} and then using the isentropic efficiency we can get h_4. Accordingly, we get the total work output from the steam turbine is equal to, if we talk about the net work output. So,

$$\dot{W}_{ST} = \dot{m}_{ST}(h_3 - h_4)$$

Similarly, if we convert all the work expressions for the gas turbine to the total expression, then the net work input requirement for the compressor will be equal to:

$$\dot{W}_{comp} = \dot{m}_g C_p(T_{2'} - T_1)$$

Similarly, the total work or total power produced by the gas turbine will be equal to:

$$\dot{W}_{GT} = \dot{m}_g C_p (T_{3'} - T_{4'})$$

So, we know how much work is being rejected by the steam turbine or rather how much work is produced by the steam turbine. Now we know the condenser pressure is given as 8 kPa of course we are using that to get point 4. Saturated water at 8 kPa is circulated back to the heat exchanger by a pump with an isentropic efficiency of 0.8. So, the pump has an isentropic efficiency of 0.8, so this process may be ending up at point somewhere here as 2'.

And finally, if we talk about the heat exchanger, so total amount of energy gained by the steam in the heat exchanger is equal to:

$$= \dot{m}_g (h_3 - h_2)$$

if we say this point is point is 2 and this point is 2s these are total amount of energy gained by the steam. And total amount of energy lost by the gas will be equal to:

$$= \dot{m}_g (T_{4'} - T_{5'})$$

and T_5' is 400 K. So, from there you will be getting the ratio of the mass flow rate of steam and mass flow rate of gas.

$$\frac{\dot{m}_{st}}{\dot{m}_g} = ?$$

And finally, the net output from the plant is 500 MW, so that 500 MW is equal to the net output that is the net output from the gas turbine side and net output from the steam turbine side. Now from the steam turbine inside how much is the output we are getting? We are getting:

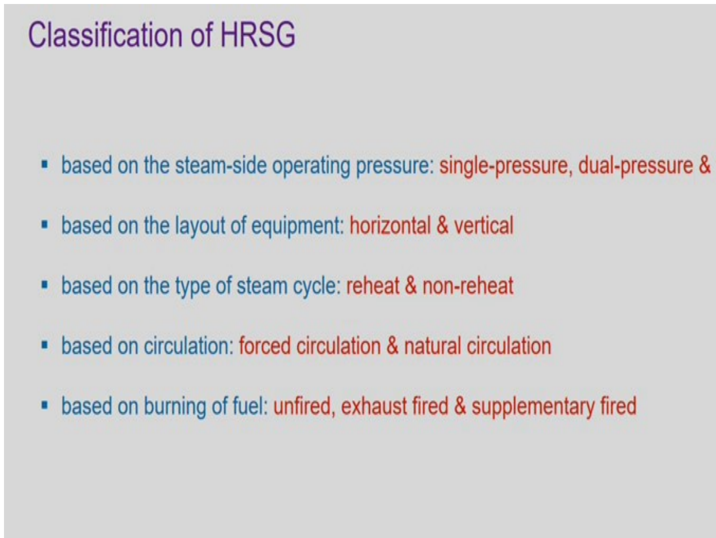
$$500\, MW = [\dot{m}_{st}(h_3 - h_4) - \dot{m}_{st}(h_2 - h_1)] + [\dot{m}_g C_p (T_{3'} - T_{4'}) - \dot{m}_g C_p (T_{2'} - T_1)]$$

The terms in first square bracket is the net output from the steam turbine side. Similarly, net output from the gas turbine side is in the second square bracket, from where we shall be able to get the value of $\dot{m}_g$ and subsequently the mass flow rate of steam. So, we can easily calculate both the mass flow rate and finally the thermal efficiency for this plant.

So, you please calculate the number, if thermal efficiency the final calculation in this case is going to be 53.1% approximately. So try to see whether you are getting this result or not. So, up to this we have talked about only one kind of combined cycle which is the combination of Brayton cycle and Rankine cycle or practically the combination of a gas turbine plant as a topping unit and the steam turbine plant as a bottoming unit.

But there are a few other kinds of combined cycle plants which are also possible some of them are still conceptual design, but they have huge potential for real life practical application particularly for large scale power generation.

(Refer Slide Time: 35:26)

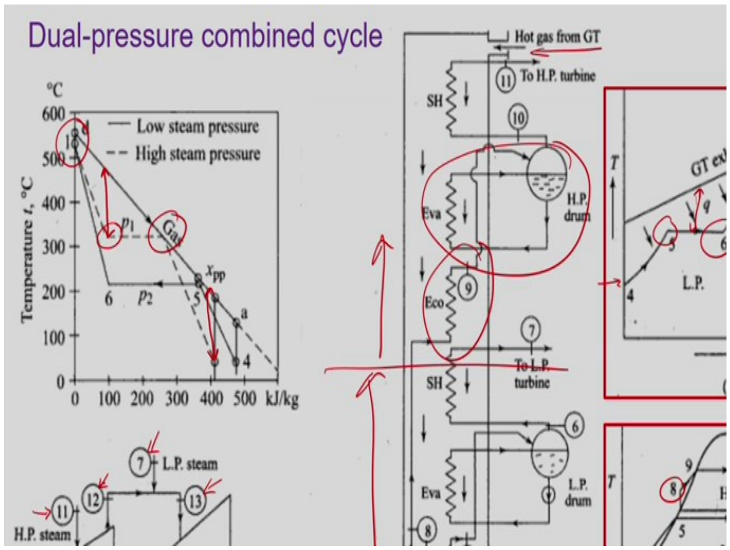


And one such parent plant is the MHDS plant. But before going there, let us quickly talk about another important component of the steam turbine base cycle. Or actually in any kind of cycle that I am going to talk about in always you will find or invariably the lowest or the bottom most cycle is a steam-based Rankine cycle. And the heat exchanger where we produce the steam using the energy loss by the topping cycle is called HRSG or Heat Recovery Steam Generator, which is probably the most important component of a steam turbine gas turbine combination or rather in any combined cycle with Rankine cycle as the bottoming unit. So without going into the technical details we should just like to see what are the different kinds of HRSG we can have? There are several types of classifications one is based upon the steam side operating pressure, we can have a single pressure just the ones that we have discussed so far, they are all single pressure.

But you can also have dual pressure or triple pressure cycles. I shall be discussing about a dual pressure option in the next slide. Then we can have based upon the layout of the equipment: horizontal or vertical, based on the type of steam cycle: reheat or non-reheat, whether it is: forced circulation or natural circulation and also based upon the burning of fuel: unfired exhaust fired or supplementary fired.

Unfired refers where we are not adding any additional energy from external sources for the bottoming one. Exhaust fired means where some additional fuel is added in the gas that is coming out of the topping cycle and thereby producing some additional amount of energy where supplementary fired as I have talked about where we are trying to utilize the unburned oxygen or unused oxygen of the exhaust gas that we can refer to as a supplementary fired.

(Refer Slide Time: 37:21)



Now the dual pressure combined cycle is something that requires a very brief mention. Just look at this diagram where we are having temperature on the vertical axis and amount of heat transfer in the horizontal axis. This continuous line represents the gas. As it is passing through HRSG it is continuously losing the temperature where it is supplying energy to the steam. Now there are two stream lines shown one at low pressure and other at high pressure.

Let us first talk about the low pressure which is given by this continuous line. It starts from this point for from point 4 to 5 this is single phase liquid heating, that is the above that is the economizer. Then 5 to 6, it is the evaporation where the phase change goes on and then 6 to this final point where we have the super heater part. Everything is happening at constant pressure but still three separate situations 4 to 5 is a single phase heating 5 to 6 is phase change and 6 to 1 is single-phase vapour heating.

Now just observe the difference in the temperature between the two streams in each of the regions. In the economizer part the temperature difference is quite small, the largest temperature difference can be only something like this. But in the two-phase part at any point the temperature difference is very significant. Like at this point you look at this how much is the temperature difference say huge temperature difference that we are talking on between the two streams of the order of something like 250 to 300 ^{0}C.

And you know that larger the temperature difference associated with heat transfer larger will be the entropy generation. So, significant amount of entropy generation will be there and therefore it is a highly irreversible heat transfer process which finally leads to the loss of work potential and hence loss of energy and loss of efficiency from this. Now instead of operating at such low pressures, if we operate the steam at much higher pressure then we have this dotted line.

So, starting from this point up to this point we are having single-phase heating in the economizer, single-phase liquidity. Then from this point to the next point we have the two-phase operation, phase change and then up to point number 1 we are super heating that is heating of single-phase vapour. Now what is happening here? The temperature difference during the phase change operation is definitely much smaller, it is almost half compared to the previous case.

But what is happening in the single-phase operation? Here in the economizer we have much larger temperature difference. So, here there will be significant amount of entropy generation in the single-phase part and in the two-phase part the temperature difference is small but still not that small as well. That is why quite often we go for two different pressure levels to have these operations done. One pressure level which operates close to the lower sides of the or low temperature side of the exhaust gas. Other pressure which operates close to the high temperature side of the exhaust gas.

In a configuration something like this, where the hot exhaust goes from the gas turbine is entering from here and it is directly going down to the HRSG and finally leaving through this exhaust gas. This is the corresponding steam turbine organization. The steam which is coming here from point number 4 that is being separated or split into two streams here. In one stream, look at this in this particular zone the temperature of the exhaust gas is much lower whereas on this side the temperature is much higher.

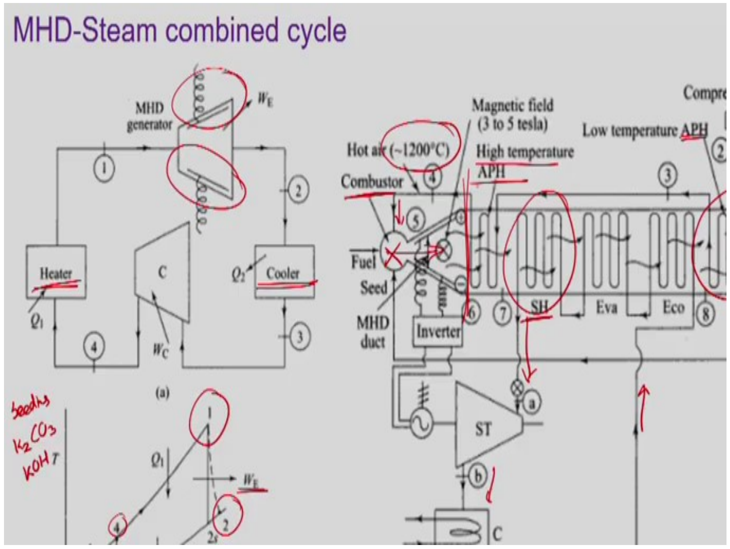
So, in this side the point number 5 where we are talking about a single-phase heating, here actually we are talking about a low-pressure operation. Here the pressure is low, corresponding saturation temperature of the steam also will be low. So we have single-phase heating up to point number 5, then we have the phase change and done in this phase and then we have the super heating done from point 6 to point 7. In a configuration like this, it is entering at point 4 then single phase heating up to point number 5, then constant temperature phase-change up to 6 and then super heating done up to point number 7. This is the low-pressure steam.

And the other stream that we are separating here that is going by this route at point number 8 where we have the pressurized it to much higher-pressure level at this particular point. Here the pressure is higher so saturation temperature is also higher, so it is heated up to point number 9, this is the corresponding economizer. Then we have the evaporator part where you are having the phase-change going up to point number 10 much higher-pressure level. Look at the temperature difference, here the temperature difference between the steam and the corresponding gas is quite smaller.

The temperature difference between low-pressure steam and the gas was also not that significant, not that high as we should have had in a single pressure situation. And then finally we have the super heating from 10 to 11. This superheated vapour at point number 11 is going to the high-pressure turbine from there once it is coming back with point number 12 it is mixed with point 7 and the superheated steam coming from the coming the low-pressure, the exit pressure of the high-pressure turbine and the low-pressure steam they are having the same pressure levels actually. So, this mixture with state point 13 is going to be supplied to the low-pressure turbine. This is the corresponding diagram. On the low-pressure side we are starting with point 4 and ending up with point 7 as a superheated vapour. And at the high-pressure side we are starting with point, 8 ending with point 11 as a superheated vapour which is expanded to point 12 in the high-pressure turbine. Then we are mixing the exhaust of the high-pressure turbine with the steam coming from the low-pressure turbine to reach this final point 13 here, which is getting expanded to the low-pressure turbine till state point 14.

So, this is a dual pressure combination, similarly we can also have a triple pressure combination where we shall be using an intermediate pressure level as well. More the number of pressure levels, less is the irreversibility and if the number of such pressure levels approaches infinity, we are actually of trying to approach an isothermal heat transfer. But practically more than three stages are never used. In fact more than two stages are also quite rare in practice.

(Refer Slide Time: 43:48)



Now we would like to talk about a few other kinds of combined-cycles. As I have just mentioned and I shall be talking about three innovative approaches very quickly. And the first one of them is MHD. MHD refers to magneto hydrodynamic generator: M for magneto, H for hydro and D for dynamic generator. Here the idea is very interesting you know that from Avogadro's principle that whenever a conductor moves in a magnetic field, we have electricity generation.

So, what we do? We create a field with permanent magnet. Here we have a magnetic field and as a conductor we are using a high-temperature gas. You probably know that as we keep on increasing the temperature of a gas beyond a certain threshold temperature it starts to ionize. Ionize means, as the temperature increases the electrons from there atom starts to move towards a higher orbit or higher energy orbits and beyond the threshold temperature the electrons completely come out of that, thereby becoming free electron.

And consequently, the atom from where it has come out that becomes a charged one. So, if we are able to go to very high temperatures well above the threshold temperature then your originally non-conducting gas becomes a combination of, or it will contain several free electrons and also equal number of positively charged atoms, along with of course the neutral body of the main molecule. And now if we allow this gas to flow through this magnetic field, then that is going to act as a conductor and accordingly it is going to give electricity.

So, that is the idea of this MHD or magneto hydro dynamic. One issue is that in order to have sufficient level of conductivity we need to increase the temperature to the level of 2500 or maybe in the level of 3000 K. So, it is extremely high temperature that we are talking about. And even at such high temperature levels we may not be having sufficient conductivity. Because to have a suitable MHD operation, we are generally looking for a conductivity level of approximately 10 mho/m, per unit length of your MHD duct. So even at such temperature levels around 2500 K if we are not able to reach such high temperature levels then we need we go for something known as seeding. What is seeding? Seeding means, in the gas we add a very small percentage maybe just 0.5 or 1% of my mass some small quantity of some alkaline matter, which is highly conducting. Something like say potassium carbonate or potassium hydroxide, very popular seed materials at this potassium carbonate or potassium hydroxide or sodium-based materials. These materials once we add to this even at low temperature levels of 22 to 2300 K the gas may be able to achieve this level of conductivity and thereby it is capable of producing very high temperatures.

Generally, we operate this MHD ducts to temperatures will beyond 2500 K with 0.5 to 1% of alkaline material seeding and accordingly the power that gets generated per unit length of the duct that can be represented something like:

$$P/length = \frac{\sigma U B^2}{\rho}$$

where

ρ is the density of the gas

σ is its electrical conductivity

U is the velocity

B is the strength of the magnetic field

So, the power generated per unit length of the duct because proportional to this particular quantity approximately equal to.

Here the magnetic field requirement is also quite strong in the level of 4 to 5 Tesla which is a huge magnetic field that you are talking about. So MHD is a very complicated system to handle in practice, we require huge magnetic field, we require extremely high temperature and also decent level of electrical conductivity by virtue of this seeding. But the potential is enormous because this is a direct energy conversion mechanism, we don't need any intermediate mechanism, intermediate material or intermediate system.

We do not need any turbines or any rotational machinery, we can directly convert the kinetic energy of the gas which is flowing through the duct to DC electricity or direct current. Generally, we need an alternator to convert this direct current to AC. If we compare this to a gas turbine plant it may look quite similar to a gas turbine plant. This is the point 3 from where we are starting, 3 to 4 is the compression stage where you are raising its pressure and also temperature and also we are doing the seeding.

Then we have this heater portion we are adding heat, so that the temperature at this point number 1 is well beyond 2500 K. Then it passes to the magnetic duct, MHD in duct which is quite similar to a turbine expansion during which it loses this energy to come down to point number 2 and we are getting this energy. But remember here this work output that we are getting that is not a shaft work rather it is direct electricity.

And now whatever energy that is still left in this that is still significant. Because once the temperature drops below 2000 K it hardly has any usable electrical conductivity. All the electrons again recombine with the free atoms so that we again are back to a neutral body of gas. And therefore, we may have to think about some other option of utilizing the energy. Remember a conventional steam turbine plant the highest temperature that we have for the exhaust gas in a gas turbine plant maybe only of the order of 800 ^{0}C, which is still sufficient to heat the steam in a Rankine cycle.

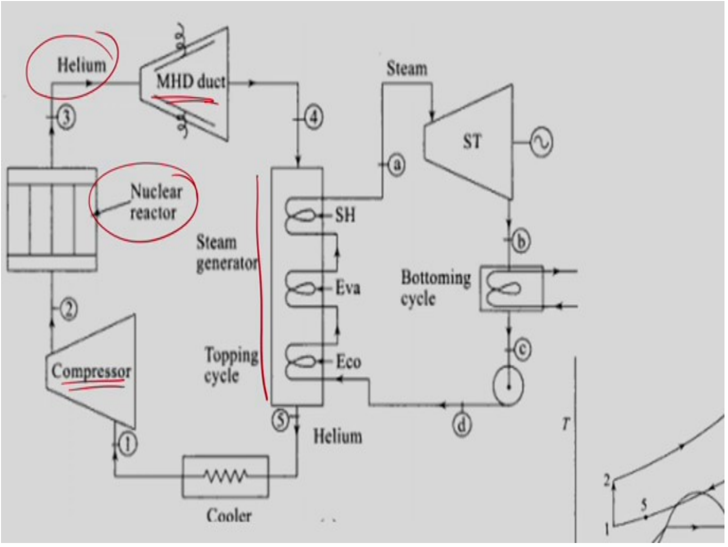
And here we are talking about temperatures in the level of 1600 to 1700 ^{0}C, which is huge. So, we can allow the gas to pass through a heat exchanger where we shall be raising the steam to be utilized in a steam turbine plant, a configuration something like this. So, here is we have a combustor, this is the combustor that we are talking about where we are supplying the fuel and we are producing very high temperature gas which is passing to the magnetic duct or MHD duct. After it comes out of the MHD duct may be somewhere here then it has still very high temperature, so this it is allowed to pass through a long duct. And in this duct, we continuously keep on extracting its energy. What are the ways you are extracting its energy? This is the flow of liquid water that is coming to this. First, we have the economizer here, where the liquid water is heated to the saturation temperature. Then, we have the evaporator where it is converted to a two-phase mixture. We may have our steam drum somewhere here where we separate the liquid and vapour phases and then we have the super heater in this portion.

So, this is your super heater and from that super heater it is going to a steam turbine and then we have the conventional Rankine cycle. Then we have the condenser, we have the boiler heat pump, we may have feed water heaters and then going back to the duct. We may have a reheater as well. Once it comes out of this high-pressure steam turbine it may be taken back to the duct to heat it back to the initial temperature. And what about air? The air which is taken from the atmosphere is initially passed through a compressor. Then we have a low temperature air pre-heater. APH refers to air pre-heater, where we heat the air to high temperature level, then it is taken to the highest temperature zone of the exhaust coming from the MHD duct which we call the high temperature air pre-heater. And the air that is coming out of the high-temperature air pre-heater is already at a very high temperature in the order of 200 ^{0}C. Subsequently it goes to the combustor and because of the combustion reaction, its temperature reaches to that 2500 K range and we can use it in the MHD duct.

Finally, after all these levels of heat rejection it may be having a temperature of something only around 150 to 180 ^{0}C and so we can easily allow you to go to the surroundings. We cannot reduce the temperature lower than this because generally the fuel that we use that may have such certain sulphur content and during combustion that sulphur gets converted to sulphur dioxide and sulphur trioxide. Now if the temperature becomes lower than this level of 150 ^{0}C, then this sulphur dioxide or sulphur trioxide can get combined with the water vapour to produce sulphurous and sulphuric acid.

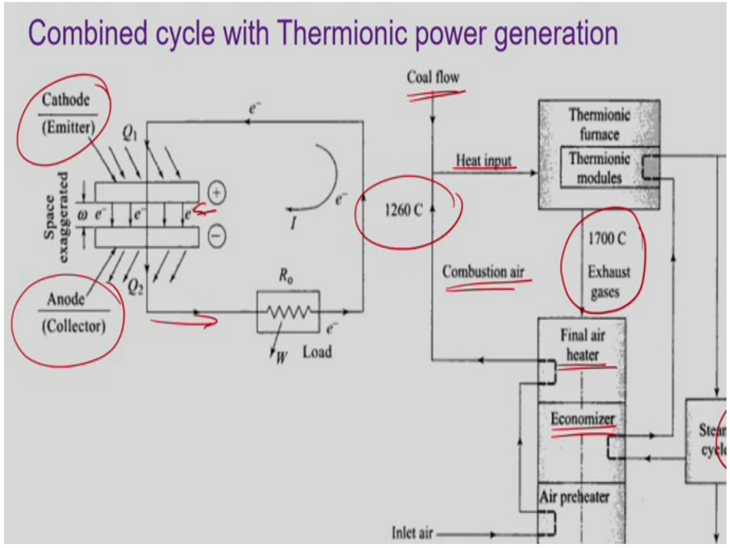
And below 150 ^{0}C that acids may become liquid, that liquefies and thereby it can lead to significant amount of corrosion. So, we have to be careful about the lowest temperature that we can reach depending upon the fuel content. Now, the cycle that I am showing here that is an open cycle because the exhaust is finally allowed to go through a stack, go out to the surrounding.

(Refer Slide Time: 53:50)



We can also run in a closed cycle mode where we are not using any fuel rather using a we are using helium kind of some neutral gas. So, it passes to the compressor, then a high temperature source, something like a nuclear reactor where it picks up the heat, then it has the MHD duct and here we have the heat recovery steam generator. In fact, the energy with which it comes out of the MHD duct that is so high that quite often we may also use three different cycles: where your MHD is the topping cycle, then we may have a gas turbine as an intermediate cycle and the exhaust of the gas turbine can still be used to run a steam turbine in the inner bottoming Rankine cycle. So, though MHD based power generation has not been commercialized yet there are certain instances of MHD and nuclear power submarines etc. But for large scale power generation this is a technology that is yet to be commissioned or yet to be implemented in practice but something with a huge potential.

(Refer Slide Time: 54:07)

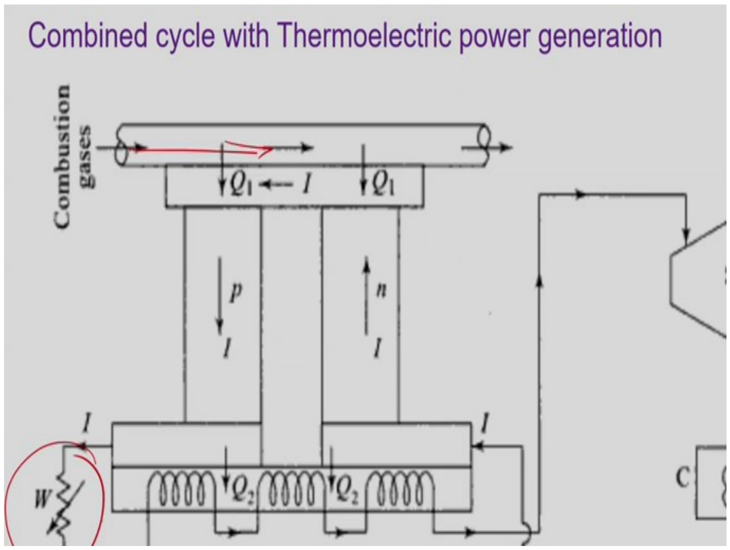


Another quite potent option is thermionic power generation. When we heat certain material beyond certain temperature that can emit electron. That is something we will refer as thermionic power generation. Generally, metals when they are heated to a temperature beyond the threshold, free electron starts coming out of this. So, this material is called cathode and also emitter which rejects these electrons and then we have an anode or collector where these electrons are collected.

And now, if we have an external circuitry then these electrons flows through this and we allow it to flow through a resistor, then that produces electrical electricity or electrical current. So, the heat that is being supplied to the cathode and removed from the anode, that is getting directly converted to electricity, that means it is again an option for direct electricity production. Now we can go for a combined cycle using this in the anode. The amount of energy that is being raised, that is being rejected in the anode that is generally at quite high temperature and that energy can be utilized to raise steam in a heat recovery steam generator, just like the scheme shown here. We are supplying fuel that is being combined with air at very high temperature combustion air. So this heat input in the form of very high temperature combustion gas goes to your thermionic furnace where we have the thermionic modules: the cathode and both the anodes from where we are getting the electrical output. And from the anode, the exhaust gas that comes out that is still at very high temperature in the level of 70 to 100 ^{0}C quite similar to the MHD duct. So, that is used for an air pre-heater, then you have the economizer and we may have evaporators and steam separators also. From here we are getting the power generation in the form of mechanical rotation of the turbine connected to the alternator which is giving us the electrical output.

So, finally you are having exhaust gas leaving maybe only at 150 ^{0}C. The direction of this arrow is not correct it should have been this way. So, this is the thermionic power generation.

(Refer Slide Time: 56:20)



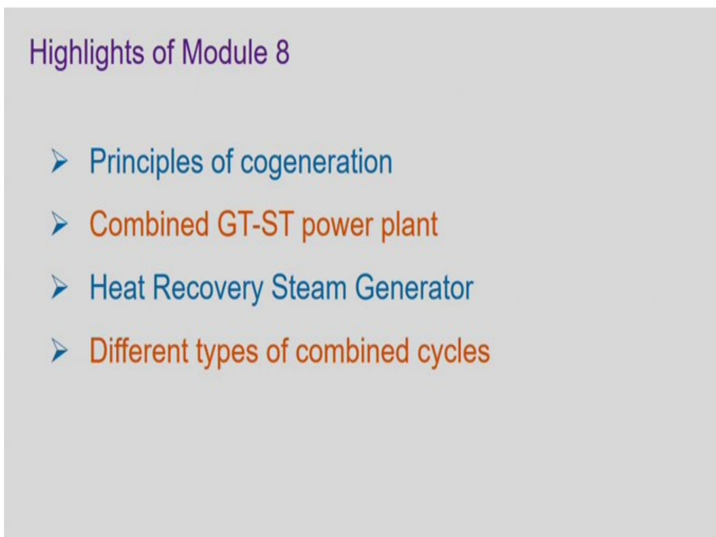
Another quite similar option is the thermoelectric power generation, where the idea is based upon the Seebeck effect. Have you heard about Seebeck effect? If not please refer to the books or maybe the internet to learn about Seebeck effect. Seebeck effect says that when we connect two dissimilar metals and prepare two joints, that means you take two wires of two dissimilar metals and connect them at two ends. Now if these two junctions or ends maintained at separate temperatures, then an electrical current start flowing from through from one conductor to the other, or there is a potential difference that gets created between these two junctions. Of course, any combination of metals will not do there are certain combinations like copper and constantan, constantan is an alloy, that is a very popular combination to get something like this.

So, instead of maintaining at separate temperatures we actually heat one of the junctions and remove that heat from the other junction thereby raising the temperature of one junction and reducing the temperature of the other junction. Hot combustion gas is allowed to flow through one junction accordingly we have direct electrical current production which is passing through this resistor and the heat that is being removed from the other side that is used to run a heat recovery steam generator and subsequently steam cycle.

So, thermoelectric power generation quite similar to MHD and thermionic power generation again allows you to have direct electricity production and then combining that with a steam power plant we can also have a combined cycle running. So, these three are all conceptual designs, none of them are having any practically commissioned unit for large-scale power production.

But we may see such kind of combined cycle in practice in next 15 to 20 years and they have the potential of offering huge efficiency well in the range of 50 to 60% whereas present coal based power stations can have efficiency will only in the high 20s or very low 30's and the same about nuclear plants as well.

(Refer Slide Time: 58:30)



So, combined-cycle is a very potent technology already used particularly, the gas turbine steam turbine combination is already in use in several phases in several countries. And we are looking for even further improvements and modifications.

So, to summarize the discussion of this week we started with the principle of cogeneration and combined cycle, then we discussed in detail about the gas turbine steam turbine combination. We talked today about the heat recovery steam generator the dual pressure cycle and then different types of combined cycles, where we have the option of direct electricity and power production, that also we have discussed. So, that takes us to the end of module number 8. I hope you have enjoyed this series of lectures particularly these two lectures where we are talking about every modern and innovative technology.

Now up to this week we have talked about only about power generation, starting from this week number 4 to this week number 8 we have talked only about power production option. From the next week onwards, we are going to the other spectrum where we shall be talking about the power absorbing cycle that is the refrigeration cycle and subsequently going to the air conditioning cycles.

Till then you revise this lecture try to solve the assignment problems and in case of any query please write back to me. Thank you.