Steam Power Engineering

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Lecture - 14
Binary/Multi-fluid Cycles

Welcome to the class. Till time what we had seen is if we have to generate electricity, then we can opt for Rankine cycle where we have seen that there are four major processes which will comprise the cycle. Then in that case we had seen that okay steam is the working medium. So it is also called as steam power cycle. Steam was also thought to be useful in case of the processes which were having the requirement of a constant temperature source.

So those were the cases where we were seeing that it is the industrial heating processes. So in such cases we had seen steam is a working medium for Rankine cycle. But now we are going to assess whether steam is really a working, good working medium or what are the characteristics of an ideal or good working medium for steam power plant.

Also we had seen that we were supposed to work for electricity generation or maybe coal generation, where one Rankine cycle was our thought. But if we can use one Rankine cycle or multiple Rankine cycle or how to combine Rankine cycle with other cycle? This is the topic of discussion for this class.

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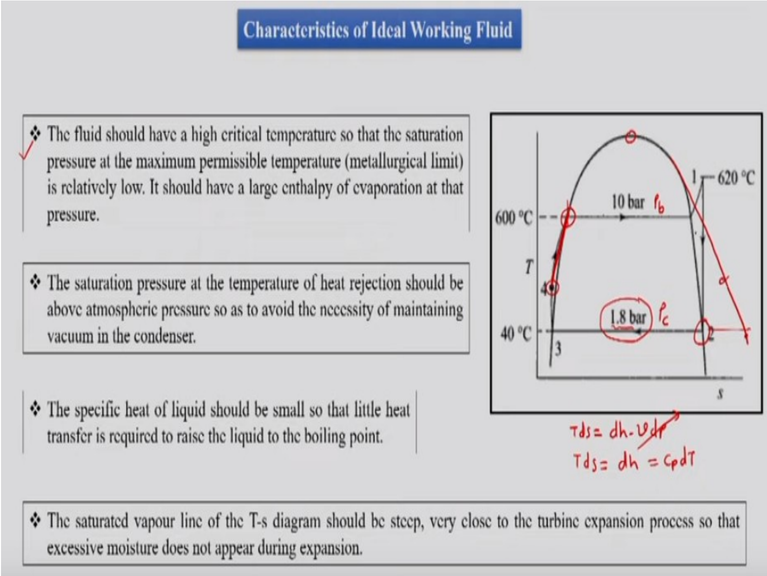

In this case, first thing what we are going to discuss is characteristic of ideal working fluid. So this is a diagram, T-s diagram, for the ideal working fluid which we will be discussing or which we will be making use of. So the working medium which is supposed to be the medium, which is going to get heat in the steam generator or boiler which is going to regenerate the heat into the condenser and which is going to expand into the turbine, which is getting compressed into the pump.

That working medium were coming out of the domain where we are not now feeling that it is just a steam. Practically although name suggest where we are adding heat as the steam generator, but we practically do not mean that steam is the only working medium for this lecture. Then, the fluid which is going to go through the circuit should have critical temperature high such that the saturation pressure at the maximum temperature is relatively low.

So what would happen is we want critical temperature. We know the definition of critical temperature as per the basic thermodynamics is a point on the dome at which we have zero latent heat. So that critical temperature should be very high such that the working pressure of ours should have temperature which is in the range of metallurgical limit.

We have said that metallurgical limit is a limit at which we have the practical working impossible for the materials of our choice. So we have large enthalpy of vaporization at that pressure. We know that as we want we go towards the higher point or toward the critical point we have lower and lower latent heat. So if this critical point is high, then our working pressure, we will have sufficiently large latent heat and since we have sufficiently large latent heat, we will add more heat at constant temperature.

So we will add less heat in the economizer means or main temperature or heat addition would remain high. So our basic requirement here is we should have high critical temperature and that high critical temperature would serve two points, where we will have basically higher saturation temperature corresponding to our working pressure and also it would give us larger latent heat of vaporization.

Then saturation pressure at the temperature of heat rejection should be above atmospheric. So the pressure, this is the boiler pressure and this is condenser pressure. Here we mean that condenser pressure should be above atmosphere. Practically we had seen till time the condenser pressures where conventional power plant work would have a constraint since we know that the working medium in the condenser which absorb the heat from the steam is a natural resource which is like a water.

So in that case cooling water will be used to take the heat. So cooling water will have room temperature or atmospheric temperature in the range of $30°C$. So since we are using water as the working medium, so 30°C, saturation temperature means low pressure and it corresponds to of the order 10^{-2}¿. So it is a very low pressure.

Now we want that at room temperature if we want to work it should have very high pressure. For the saturation corresponding to room temperature, the saturation pressure should be more than atmosphere and this would help us about the maintenance since we are not going to maintain vacuum. Then, specific heat of liquid should be small so that little heat transfer is required to raise the liquid to the boiling point.

We know that slope of T-s diagram, we can find out $TdS=dh-VdP$. We know that the process of heat addition is constant pressure. So we have this term VdP to be the zero. So we have $TdS=dh=c_p dT$. So basically we have $\frac{dT}{dS} \vee ¿_{P=const}=\frac{T}{c_p}¿$. This is for the amount of heat addition what we are going to do for the constant pressure process.

So we practically mean over here that the heat addition process will have a slope dependent on specific heat. So if it has lower specific heat, then the slope will be high. That means it will be a steep line. So economizer will be a steep line. So what would happen is for less amount of heat addition we will have large amount of temperature rise.

So we will basically need lesser amount of heat addition to rise the temperature from the pump outlet temperature to the temperature corresponding to boiler saturation pressure. So this would reduce the problem of irreversibility due to economizer. And hence it will increase the mean temperature of heat addition. Saturated vapor line of T-s diagram should be steep, very close to the turbine expansion process such that so that excessive moisture does not appear during expansion.

Here we mean that the saturation line which is this it should be steep like this. So if it is not steep and if we feel that this line is not a steep line and like this line of slow slope, then what would happen is that we will have very large wet steam at the exit of the turbine. So we would have problem in the maintenance of the turbine. So our expectation is this vapor line should not be like this and it should be a very steep line.

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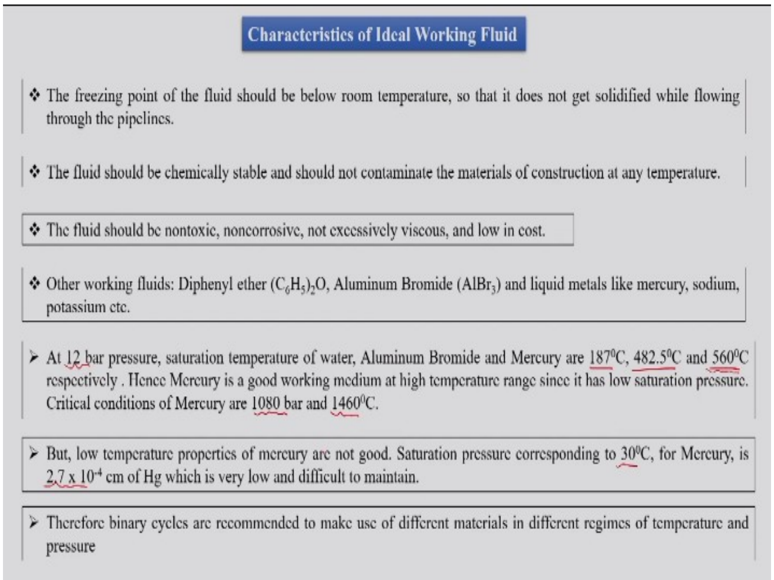

So freezing point of the fluid should be below room temperature so that it does not get solidified while flowing through the pipeline. This will help us in actually selecting a working medium which is capable to get handled for the given working temperature. The fluid should be chemically stable and it should not react with the materials. This is what our one more expectation.

It should also be nontoxic noncorrosive, and it should be having a comparatively low viscosity and it should be of low cost. This would help us in maintenance and it would also help us in having lower cost of working. So these are the basic requirements or these are the ideal, characteristics of a ideal working medium for Rankine cycle. Then what are the other options for us?

If not steam what are the other options for us as the working medium So we have options like dimethyl ether, aluminum bromide. We have liquid metals like mercury, sodium, potassium. So these can be alternative options to the steam. We use steam since it is abundantly available. That is the only reason, otherwise these mediums which are other than steam have equal or maybe better properties than the steam.

We can assess them. So at 12 bar, saturation temperature of water, aluminum bromide, and mercury are, at 12 bar saturated temperature of water is only 187 °C, aluminum bromide it is 482°C, but for mercury it is 560°C. Such a low pressure of 12 bar, but such a high saturation temperature for mercury. Hence, mercury happens to be a good working medium.

Since at low saturation temperature it has very high, at very low saturation pressure it has very high saturation temperature. Further critical conditions of mercury are 180 bar and 1460°C. So these are good points about mercury. But bad point about mercury is at 30°C saturation pressure is very low and it is 2.7×10^{-4}cm of Hg.

So it is a very low saturation pressure corresponding to room temperature and hence we will have problem in the condenser. Hence, it looks to us that water is comparatively good than mercury at low temperature, but mercury happens to be good at higher temperature. Similar will be the condition for some other working material.

Suppose take the condition like refrigerants then they will be good at low temperature, water will be comparatively good at intermediate temperature. Mediums like mercury will be good at high temperatures. So we have choice of working medium at different temperatures. But we were seeing that there is a Rankine cycle working with only one working medium.

Properties of ideal working fluid suggest us that we need not have only one working medium or rather we need not have only one working fluid for the Rankine cycle, we can have multiple fluids and multiple Rankine cycle operating between different temperature limits. And then this is what the initial point of having binary cycle. So what does it mean by binary cycle?

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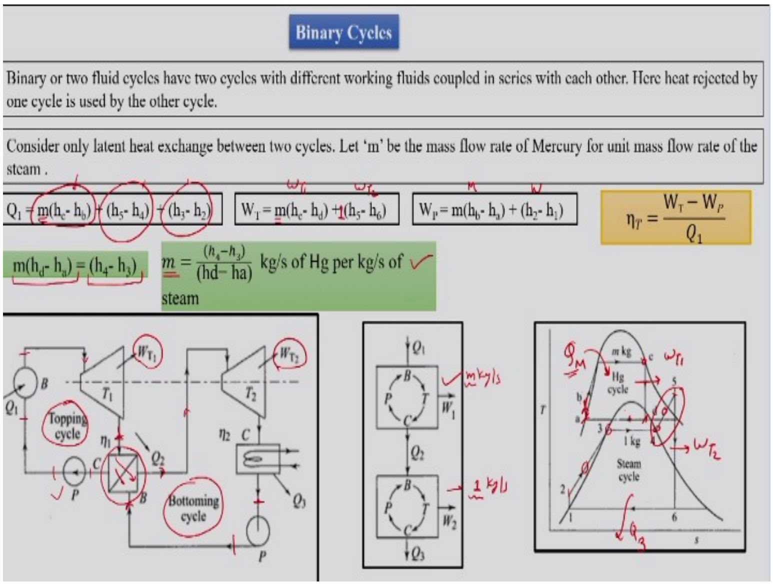

So binary or two fluid cycles, where we are having two different working fluids and then they are flowing through different two different cycles and those cycles are basically interacting with each other. That is what we are calling it as binary cycle. Binary cycle uses two working fluids flowing through two different cycles. But those two cycles will have heat exchange that means heat rejected by one cycle will be gained by the other cycle.

So if m is the mass flow of mercury for unit mass flow rate of water then we will have two cycles. Let us say that this cycle is for mercury where m kg/s flow rate is for mercury and this cycle is for water or steam where we have 1 kg/s. So for 1 kg of water, let us say that m kg of steam is flowing into this cycle. And how does this cycle operate?

This combined cycle is operating like this where we have the cycle of mercury as the top cycle or high temperature cycle and we are calling it as topping cycle. Water is flowing from the low temperature part. So it is called as bottoming cycle. So how would it happen? For mercury itself, we will have a pump which will pump the mercury from low pressure to high pressure.

We will have boiler for mercury where we will have heat addition for mercury. Then mercury will expand in the turbine. Then we will have mercury in the condenser. So let us say that we have got mercury entered into the condenser. But by that time we will have water pumped from low pressure to high pressure in the pump and water will also enter into the condenser of mercury But it is practically boiler or the water.

And then this water will flow into this boiler where it will take heat from the mercury and then it will go for the turbine, it will do the work which is W_{T2}. Mercury would have done W_{T_1}work. Then water will come to the condenser where coolant will come in and go and then it will take heat from the water and water will get condensed and enter into the pump.

This is the gross combination of two working mediums, rather two Rankine cycles. Then the T-s diagram is as usual, where we have one a to b as pump for mercury then we have this b to c as heat addition which is for mercury that is Q_1 for us. Then we have c to d as turbine W_{T_1}work by mercury, d to a is heat rejection. Now for this particular case, we are just considering only heat rejection by mercury equal to heat addition by water.

But there can be multiple sense this statement can be considered. We might have as per our design, complete heat rejection by mercury equal to complete heat addition into the water. But this looks that temperature having different. But in this case so we have only latent heat exchange. Mercury will release the heat and only latent heat will be taken by the water.

So here heat exchange is only latent heat and water will take these two sensible heats from the outside like what mercury has already taken. So water will expand into the turbine and give W_{T_2} amount of work and then it will reject heat into the condenser as what it is Q_3. Having done this, we know that Q_1 is the amount of heat, total heat taken by this combined cycle. So this heat is only taken by the mercury.

So we have totally taken Q_1 by the cycle. So it is the heat which is $h_c - h_b$ by mercury we have $h_5 - h_4$. So this heat is super heat of water and this heat is economizer c 2 of water cycle. So some heat is from the topping cycle and some heat is for the bottoming cycle. So total amount of heat taken from the external sources is Q_1. Then we have W_T.

There are two turbines, one turbine is W_{T_1} and other turbine is W_{T_2}. So we know that m is the amount of mass flow rate of mercury for unit amount of the steam. So we have unit here. So we have m here; $h_c - h_d$ is the turbine work by mercury and $h_5 - h_6$ is the amount of turbine work for the water. But we have two pumps. So one pump is for mercury. So we have $h_b - h_a$ mercury work and this is for water.

So this is work input. So we have cycle efficiency. Thermal cycle efficiency is $\eta = \frac{W_T - W_P}{Q_1}$. And now what we have said that you have only heat exchanger at the latent heat since. So we have heat rejected by the mercury is equal to heat gain by the water from the latent heat since. So we have $h_m(h_d - h_a)$ is the heat rejected by the mercury and $h_4 - h_3$ is the heat gain by the steam.

So we can find out here that we have $m = \frac{h_4 - h_3}{h_d - h_a}$. So this is what we can use this formula to find out how much kg per second of steam, how much kg per second of mercury is required for 1 kg per second of steam.

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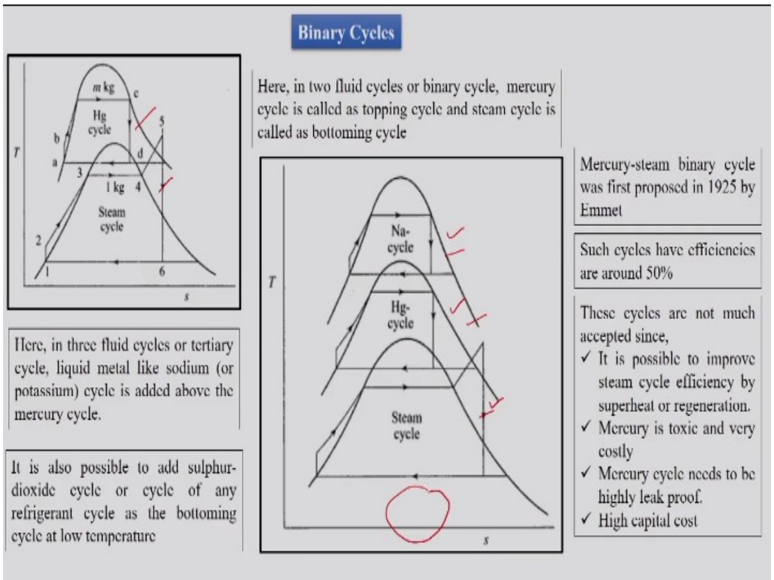

Now we know that this is our cycle for mercury and water. So here we are having two fluid cycles. So it is a binary cycle. So mercury cycle since it is a high temperature cycle, it will be called as topping cycle and then we have water as our low temperature cycle. So it will be called as bottoming cycle. So we can have multiple temperature cycle.

So we have topping cycle one intermediate cycle and the bottoming cycle. So we can have different combinations of working mediums accordingly chosen. So if we have three working mediums, so we will call it as a tertiary cycle as what we were calling it as binary cycle since there were two working mediums. So there are three working mediums, so it will be tertiary cycle.

It is possible to add sulfur dioxide or cycle of any refrigerant as a bottoming cycle. So we can have mercury and steam as topping and bottoming cycle but further we can add a low temperature cycle here where refrigerants can be our choice. So different working mediums, which are potential or good at different temperature limits will be accordingly used and those cycles will be coupled to form multi-fluid cycles.

So we will have mercury steam as binary cycle. Basically we have such an invention first in 1925. Such cycles when we are using combined tertiary binary cycles, they enhance the efficiency. We are going to see it in next slides, how their efficiency is higher. But we can cross 50% efficiency if we combine different working mediums.

The cycles which are binary cycles of or working mediums of different Rankine cycles are not that much acceptable or not that much famous since there are multiple problems. One such problem is it is possible to improve the efficiency of steam alone. Why we were not considering steam at a particular temperature limit? Since steam efficiency is fixed for a given temperature range as what we can think but we can try to improve the efficiency of the steam cycle itself.

That is what it had happened from 1925 we had regeneration, superheating and we had an optimum case of reheating. So these three things can increase the efficiency of Rankine cycle where steam is working medium. So we do not have to couple it with other cycles. Beyond that mercury is a toxic medium. Mercury also needs very leak proof piping, since we have seen that it is having very bad condition of pressure corresponding 30°C.

So if you have to use mercury at lower temperature corresponding to its per pressure then what will happen is we have to take it as a leak proof piping. Further it increases the cost of the cycle. So due to these considerations, binary cycles where we have two Rankine or multiple Rankine cycle coupled this concept did not become commercially viable. So but still we will see Rankine - Rankine cycle coupling.

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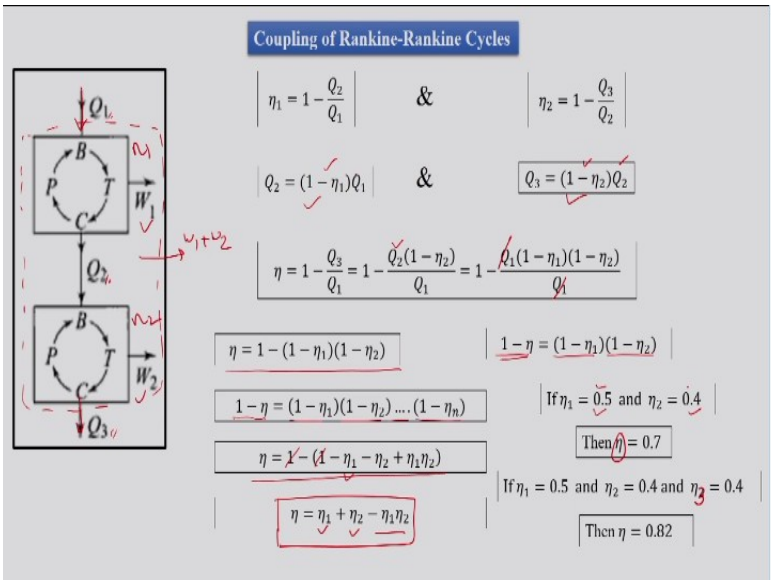

This is topping and bottoming Rankine cycles where Q_1 is the amount of it taken by topping cycle. Q_2 is a heat rejection by topping cycle which will be taken by bottoming cycle and bottoming cycle will reject Q_3 amount of heat where topping cycle will W_1 amount of work, bottoming cycle will do W_2 amount of work as per this figure. So let us say that η_1 is efficiency of topping cycle.

Practically speaking we are not talking that which is a topping cycle which is a bottoming cycle. We are not focusing upon whether Rankine cycle exists in the topping or bottoming, but in general this derivation is valid for the cases where we have two Rankine cycles coupled also. So this cycle has efficiency η_1. This cycle has efficiency η_2.

So we know it $\eta_1 = 1 - \frac{Q_2}{Q_1}$ and $\eta_2 = 1 - \frac{Q_3}{Q_2}$. So we can know $Q_2 = (1-\eta_1)Q_1$. Similarly, we are $Q_3 = (1-\eta_2)Q_2$. So eta is a combined cycle efficiency. So combined cycle is getting, combined cycle means, like this and this combined cycle is doing $W_1 + W_2$ amount of work. It is taking Q_1 amount of heat and it is rejecting Q_3 amount of it.

So efficiency is $\eta_2=1-\frac{Q_3}{Q_1}, Q_3=(1-\eta_2)Q_2$. But $Q_2=(1-\eta_1)Q_1$. So this is the formula. So we have $\eta=(1-\eta_1)(1-\eta_2) since\, Q_1, Q_1$ get cancelled. So we have 1 – η_1 is equal to 1 minus sorry $(1-\eta)=(1-\eta_1)(1-\eta_2)$. However, if we would have multiple cycles more than two, then this formula would be written as $(1-\eta)=(1-\eta_1)(1-\eta_2)(1-\eta_3)$.

Like that 1 – η eta or η_n. Then we have practically this formula can be expanded and written like this where we have $\eta=1-(1-\eta_1-\eta_2+\eta_1\eta_2)$. So we have 1, 1 getting canceled. We have $\eta=\eta_1+\eta_2-\eta_1\eta_2$. So this is a formula in case of binary cycles where two cycles are clubbed with each other. So now take that η_1 is efficiency 50%, η_2 is 40% efficient cycle.

Now if we combine these cycles, then what we will have is $\eta=70\%$. So this eta is improved. If you club two cycles then clubbed cycle will have higher efficiency than individual cycles. Similarly, now take a case that we have three cycles clubbed together, where $\eta_1=$¿50%, $\eta_2=$¿40% and $\eta_3=40\%$.

And if we club 3 cycles, then combined efficiency is 82%. It is a huge efficiency. So combined efficiency is always greater than the individual efficiency and this is what the advantage of having binary or multiple cycle is.

Now we have seen that, till time we have seen that we are going to combine Rankine cycle with Rankine cycle. But Rankine - Rankine cycle combining is seen to have a problem due to multiple facts like mercury's problem at low pressure. Like mercury's problem of toxicity or like mercury’s problem of the higher cost. Like that there will be some problems if we try to combine two Rankine cycles.

Instead of having combining two Rankine cycles this processes says that we can combine Rankine cycle with gas turbine cycle also. So lt us see that. For that gas turbine cycle is what call it as Brayton cycle.

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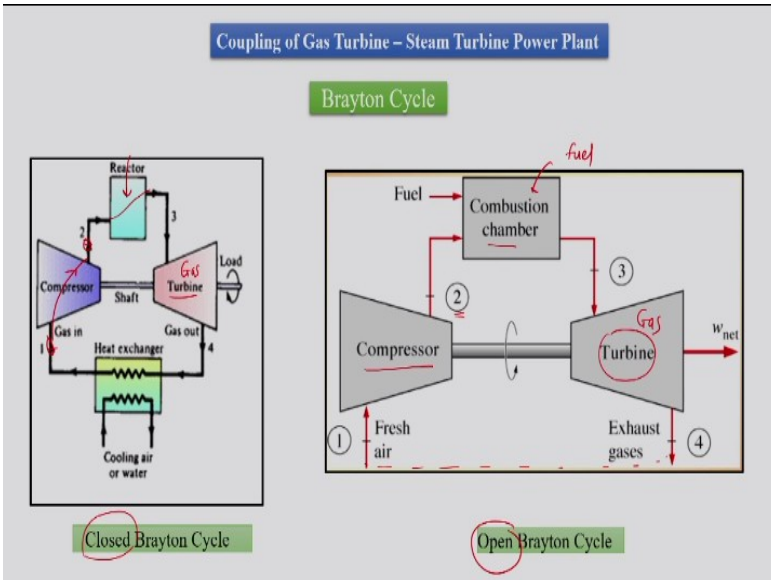

So let us first understand this cycle can be thought for a binary cycle where we should know what do we mean by a Brayton cycle. So this is the figure which says that how is the Brayton cycle going to work, what is the Brighton cycle. So here this figure says that there would be one compressor which will compress the gas first into it from low pressure to high pressure state 1 to state 2.

Then we will have a reactor or we will have combustion chamber where we are going to add heat into the Brayton cycle. So basically we are saying that there is a heat exchanger or reactor which will add heat into the gas which was compressed in the compressor. Then we will have expansion of the gas in the turbine. Since this is a gas it is called as a gas turbine and this gas will be then exchanging heat to the ambience in the heat exchanger.

So this is closed cycle gas turbine power plant or Brayton cycle. Similarly, we can have open cycle gas turbine power plant or Brayton cycle and this is called as aircraft engine cycle. Here we know that we will have compressor taking the air. It will be compressing it to state 2. At state 2 to 3 we will have combustion chamber where we will inject the fuel and fuel will be getting compressed since we have air as the working medium or oxidizer.

Then this high temperature high pressure air will expand into the turbine which is again a gas turbine and then we have exhaust into the atmosphere. We assume that same amount of mass flow rate of fresh air is going to enter into the compressor. This is how the cycle for open Brayton cycle will be there.

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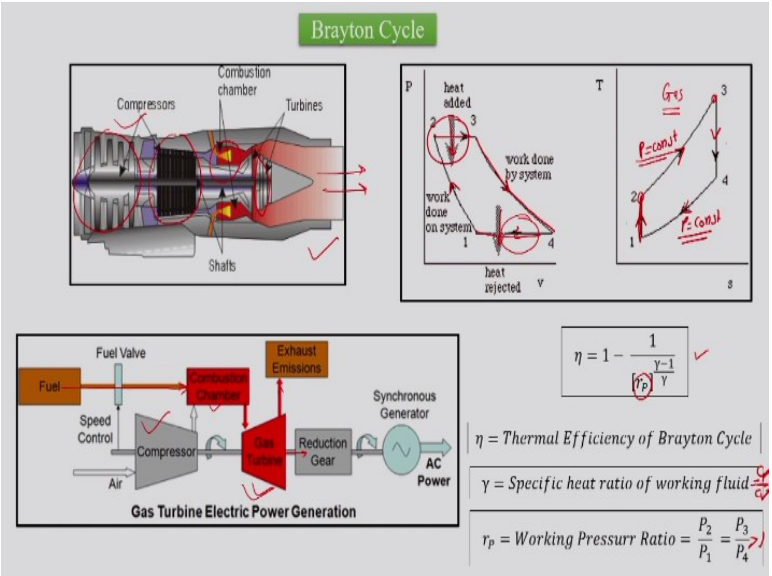

Having said this, this is the physical power plant, which is a gas turbine power plant for open cycle and this is also open cycle. This is for gas turbine power plant for aircraft engine and this is for the generator which is the electricity generation. We can see we have compressor which will compress air here. Then we have high pressure compressor which will further compress the air to high pressures.

Then we have combustion chamber and then we have turbine. This is for aircraft we needed thrust. So this is expanded into the nozzle. But when we are going to work for electricity generation then we have compressor which is compressing the air, maybe multiple compressors compressing the air. Then we have combustion chamber which is going to produce heat due to chemical reactions for which we have supply of fuel.

Then high pressure high temperature air will be expanded into the turbine. Then we have exhaust but this turbine is connected to the generator which will generate a electricity. Practically the T-s diagram or P-v diagram for Brayton cycle is like this where we have compression which is isentropic compression 1 to 2. We again have constant pressure heat addition into the combustion chamber or heat exchanger, maybe cycle is closed or open.

So this is still a constant pressure process of heat interaction. We have isentropic heat rejection. So we have isentropic expansion in the turbine and then we have constant pressure heat rejection into the Brayton cycle. So this Brayton cycle has four processes which are practically same as what the four processes of the Rankine cycle except for the point that we are having gas as the working medium.

And in case of Rankine cycle we have the two phase matter in the working medium as pump we have the liquid is the working medium, for turbine we might have two phase or we have only vapor as working medium. This is a P-v diagram. We have compression process in the compressor. Then we have constant pressure heat addition. We have expansion in the turbine as isentropic.

We have heat rejection as constant pressure. For this course, insist we will have eta directly we will take as efficiency of the Rankine cycle sorry, Brayton cycle as

$\eta = 1 - \frac{1}{(r_P)^{\frac{\gamma-1}{\gamma}}}$ where η is thermal efficiency, where γ is the specific heat ratio, which is

$\gamma = \frac{C_p}{C_v}$ for the gas, specific heat at constant pressure divided by specific heat at constant volume.

Then r_P, the turnover here is the working pressure ratio, which is a quantity which is more than 1 and then this is basically the pressure at which we are adding the heat divided by the pressure at which we are rejecting the heat. So it is $P_2/P_1 \vee P_3/P_4$.

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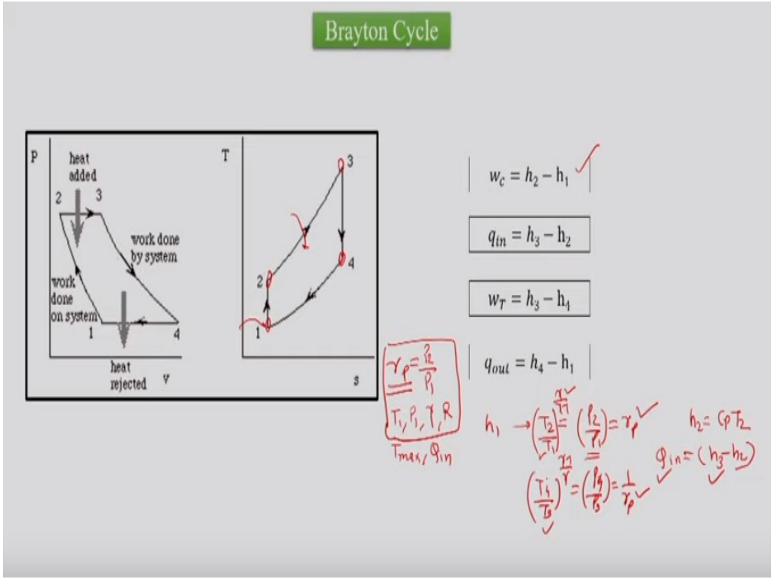

So this is the Brayton cycle. Now we can use these Brayton cycle for further calculations which we would be needing for combining the two cycles. First, what is the compressor work? Compressor work in the Brayton cycle is simple as what we do it for the pump, which is $h_2 - h_1$ but for pump we consider the medium to be ice. So we consider the medium to be incompressible. So we take it as v into delta P.

But here we can consider as a compressible medium as it is a compressor and then we can take it as $h_2 - h_1$. Then we have heat addition, it is $h_3 - h_2$ as the heat addition. Then we have turbine work which is $h_3 - h_4$ and then we have $q_{out} = h_4 - h_1$. So by these here as well we will know everything at state 1. We will be also knowing what is r_P what is the pressure ratio of the cycle.

So practically we know what is P_2/P_1. So these quantities will be known and we know every quantity at the compressor inlet. So we will be knowing T_1, P_1 at the compressor inlet. We know also the working medium for Brayton cycle. So we know gamma. We know R for the gas. So all these quantities will be known to us for the Brayton cycle. So knowing this we practically know h_1 or the Brayton cycle.

Then we know P_2/P_1. So we can calculate basically $h_2; h_2$ can be calculated from the fact that we should know T_2. So T_2 can be calculated from the formula $\left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}=\frac{P_2}{P_1}$.

But $\frac{P_2}{P_1}=r_P$; r_P is known, T_1 is known, gamma is known. So we can find out T_2. So we can find out $h_2=C_P T_2$. So we know h_2.

So then we known h_2. Then we would be also knowing what is the $T_1$for a cycle in most general case. Or we will be knowing q in. So knowing this $q_{¿}=h_3-h_2$ we can calculate h_3; q in is known and h_2 is also known. Then we can know 3 point below P_3 earlier and now we know T_3 also. Parallelly we can know everything at 4 by using same formula, $\left(\frac{T_4}{T_3}\right)^{\frac{\gamma}{\gamma-1}}=\frac{P_4}{P_3}$

But $\frac{P_4}{P_3}=\frac{1}{r_P}$. So r_P is known, T_3 is known. We can find out T_4. So that is how we will calculate each and every quantity. Since it is simple over here we can use isentropic relations of gases and we also can find out and enthalpy by using formula $h=C_P t$. So practically knowing these all points, we can calculate work and heat interactions as what we have said in this formulas.

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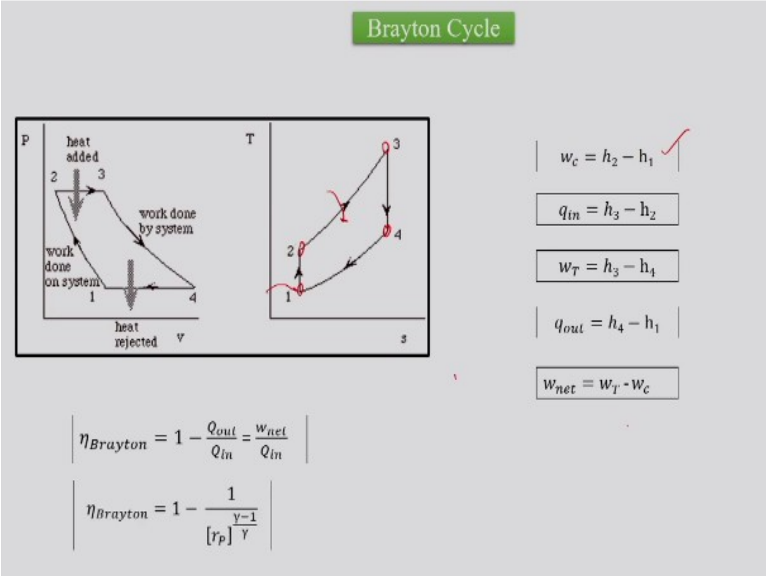

So knowing these work and heat interactions, we can find out what is the net work for the gas turbine power plant and that is $W_{net}=W_T-W_c$. So knowing the net work, we can find out Brayton cycle efficiency, which is $\eta=1-\frac{q_{out}}{q_{¿}}$. However, we can also use the formula $1-\frac{1}{(r_P)^{\frac{\gamma-1}{\gamma}}}$ as what we have seen in previous case. This formula can as well be used or we can use the formula in this case as $\frac{W_{net}}{Q_{¿}}$.

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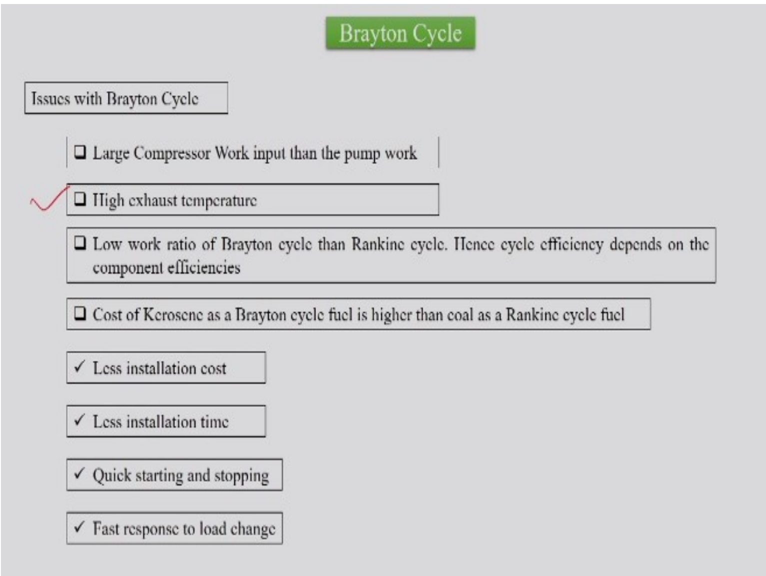

Then there are certain issues with Brayton cycle. It has basically a compressor which is a replacement for pump and compressor work is large in comparison with the pump work. We have very high exhaust temperature for the Brayton cycle. We have very low work ratio of the Brayton cycle and hence the efficiency depends upon the component efficiencies.

We have seen what do we mean by work ratio. It is net work upon turbine work and that was very high for Rankine cycle and since it was very high, the Rankine cycle was less sensitive to the component efficiencies, but Brayton cycle is more sensitive to the component efficiencies. Since it is more sensitive to component efficiencies, it needs basically more maintenance of the components.

Then, the working medium or fuel, but we are using is kerosene as an example and it is having higher cost than what we are trying to use as any medium like any fuel like coal will be used in the Rankine cycle. But there are certain advantage of Brayton cycle. It needs less installation cost. We can quickly install. Its installation time is less and then it is having quick starting and stopping.

So basically it has good fast response to the load. So these are some good points of Brayton cycle and there are some disadvantages of Brayton cycle. So one point which we have said over here, it has very high exhaust temperature. Considering this point, we can think of it to be coupling with the Rankine cycle of ours where we have water as the working medium. So we will see in the next class where how we can think of coupling Brayton cycle with the Rankine cycle or Rankine cycle with the Brayton cycle in binary cycle. Thank you.