IC Engines and Gas Turbines
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Lecture – 34
Brayton Cycle- Introduction and General Relationships

Welcome, to the class. Today, we will start acting upon the Brayton cycle. In last class, we were seeing about the basics of thermodynamics and we are now trying to link it with the Brayton cycle. In last class what we had seen was about first law of thermodynamics, its application to closed system means how to write the expression for first law for closed system, then we saw how to write the expression for first law for open system.

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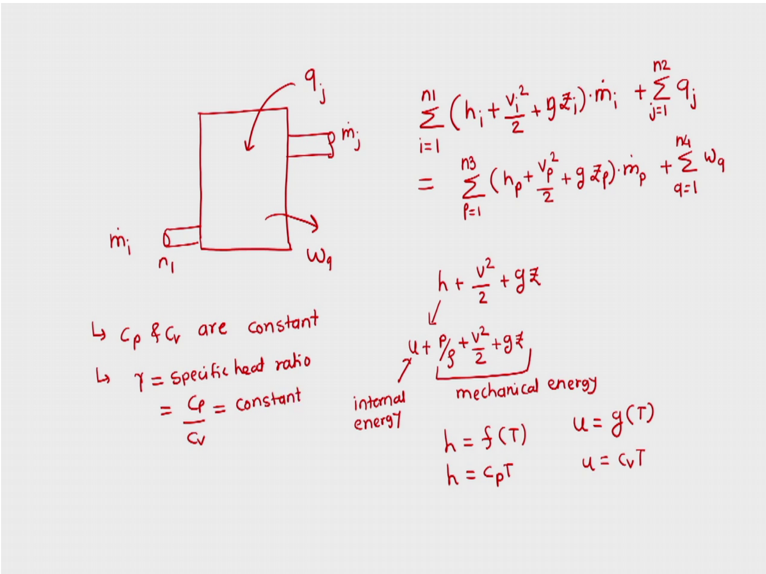

Some points which should be explained here for the first law of thermodynamics when it is concerned with the open system was that in last class we had seen that there is an open system; here we actually mean that we are dealing with a thermodynamic system. So, this is an inlet, this is an outlet and then there is some Q and then there is some w. Then, we wrote an expression saying that let there be many inlets and let there be many outlets.

Then, what did we write that sigma i is equal to 1 to n 1 let there be those number of inlets. So, expression is h i plus v i square by 2 plus g z i into m i dot m i dot is the mass flow rate through corresponding inlet then there will be some heat sources which are associated with the open system. So, let there be j.

So, j is equal to 1 to n 2 and then this is equal to then there will be energy which is going out of the system for that we said that there will be n 3 outlets and then we have h P plus v P square by 2 plus g z P into m i m dot P then plus there will be q as an index for work interactions and then that is equal to n 4 w q this is the expression for first law of thermodynamics applied to open system.

Here in last class it was yet to be explained that what are these terms this is h is enthalpy, v square by 2 is kinetic energy and gz is potential energy, m dot is mass flow rate through corresponding inlet or maybe m dot P is outlet. So, this h plus v square by 2 plus g z this energy is total energy which is coming from the inlet and which is going out from the inlet. So, this is balance between energy coming from the inlet, energy going from the outlet and then there are further work and heat interaction h is basically enthalpy and enthalpy internal energy plus P by rho.

So, we have h plus P by rho plus v square by 2 plus gz. So, this is mechanical energy, this is mechanical energy and then this is internal energy. So, what we are getting in the control volume is internal energy plus mechanical energy summation which is entering into the control volume now which is also living from the control world. However, further h is represented as function of temperature like u which is internal energy is also a function of temperature where we know from basics of thermodynamics h is C P into T and u is equal to C V into T.

Here C P is specific heat at constant pressure and C V is specific heat at constant volume. So, what we are having is C P and C V to be constant for our course and here only we define something like the gas to be calorically perfect. Suppose, I am working with a gas which is said to be calorically perfect then what would happen? Basically gas is a perfect gas when it is actually following the equation of state, but then we are further adding one more concept to it as I mean saying a gas to be calorically perfect.

So, for calorically perfect we are actually having C P and C V are constant are constant C P and C V are constants in a calorically perfect gas. So, gamma which is specific heat ratio and that is C P upon C V and this is also constant when we are saying that some gas is calorically perfect we need this concept to be explained or to be used rather when we are going to deal with Brayton cycle calculations.

So, now we will start with Brayton cycle which is a thermodynamic cycle.

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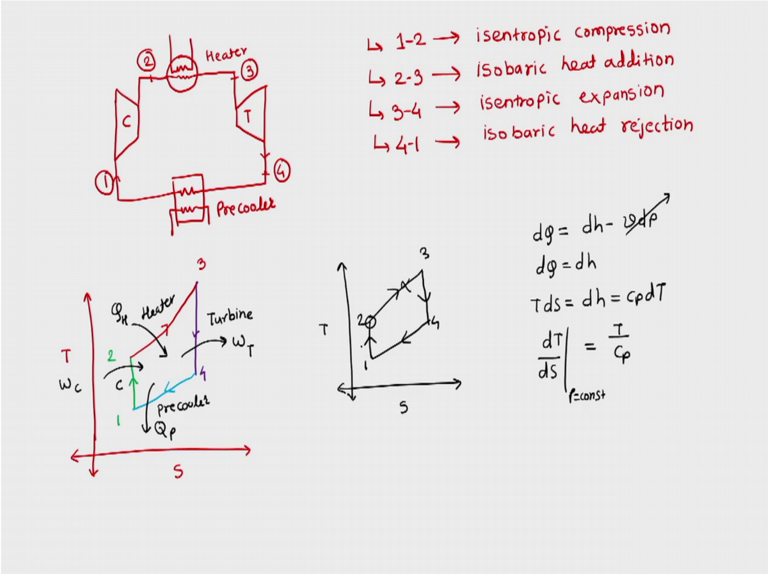

Suppose, we have now something as our closed cycle power plant. So, we know that in the closed cycle power plant there is first one compressor. So, C is compressor and then from that we will get some aspirate inside the compressor. Then we will have some heat exchanger and that is giving heat to our working medium and then we have turbine.

So, this is turbine, this is heater and we then have a pre-cooler as what we had seen in previous class; so this is a pre-cooler. Now, we have to draw thermodynamic cycle for this complete mechanical circuit we will say that 1 is the state thermodynamic state at the entry to the compressor, 2 is the thermodynamic state at the outlet to the compressor and inlet to the hitter, 3 is the thermodynamic state for the entry to the turbine and 4 is the thermodynamic state for the exit of the turbine.

So, first is the process which is 1 to 2. Process 1 to 2 is isentropic compression isentropic compression here we practically mean that the compression process is adiabatic and reversible. So, the process 1 to 2 is isentropic compression. Since it is adiabatic there is no expectation that there is heat addition or heat transfer and then further we are doing process of compression in a smooth compressor where there is no friction loss. So, process is isentropic and this is reversible and adiabatic.

Then, we have process 2 to 3. Process 2 to 3 is isobaric heat addition heat addition. So, this process as name suggests isobaric means constant pressure heat addition process. Then, we have processed 3 to 4 reaches isentropic expansion isentropic expansion process 3 to 4. Again, it is similar to compression that we have isentropic means we are adiabatic and reversible we expect there is no heat transfer, turbine blades are smooth there is no loss due to friction and then there is an expansion process in the turbine.

Then, we have process 4 to 1 which is isobaric heat rejection. The process of isobaric heat rejection; it is same as process 2 to 3 where we have constant pressure. So, process 4 to 1 also has constant pressure, but it is the process only for heat rejection. So, these four processes these four other thermodynamic processes constitute a cycle which is theBrayton cycle as the title of this today's presentation.

So, now we have to draw the thermodynamic cycle for this the thermodynamic cycle on the PVTS diagram for this Brayton cycle. So, let us first draw a thermodynamic cycle on T – S diagram. Let this be the T axis and this be the S axis. We know that T is temperature and S is entropy. These terms are known to us from the basics of thermodynamics. Now, we are supposed to draw the process. So, here let us draw the process 1 to 2 and then the process 1 to 2 is heat addition is isentropic compression.

So, here is the process 1 to 2. We have to keep in mind that line since it is an isentropic compression. So, what is happening isentropic means entropy should remain constant. So, this is a vertical line on T – S diagram and then we have next process which is isobaric process which is isobaric heat addition. Since it is an heat addition process we will indicate it as isobaric process then this is 2 to 3 is I say isobaric heat addition and then we have process which is isentropic expansion. So, this 3 to 4 is isentropic expansion.

Now, we have process which is 4 to 1 and then that 4 to 1 process is isobaric heat rejection. So, this process is remaining is 4 to 1. So, we have basically we have in this T – S diagram we have here as compressor as what we indicated here and then we have here heater, here we have turbine and here we have pre-cooler. So, heater will give you heat, this is Q heater and then pre-cooler will reject the heat this is Q pre-cooler here compressor will give W compressor in and turbine will give W turbine out. So, this is work and heat interaction in the Brayton cycle.

There is one problem while drawing the T – S diagram which we generally commit. While drawing the T – S diagram generally what we try to draw is like this we draw it as T axis, S axis and then we draw it this way 1, 2, 3 and 4. If we draw it like that where we are drawing it as a parallelogram then there are two problems. One is we are drawing this line 2 to 3 as a straight line and it is not true. Line 2 to 3 is a curved line as you can see you are here and why it is a curved line, we can know from first law of thermodynamics that is dQ is equal to dh minus vdp.

What is line 2 to 3? Line 2 to 3 is isobaric heat addition. So, isobaric means this is 0. So, we have dQ is equal to dh, but if you combine first and second law then we can say Tds is equal to dh, but as what we have seen just in previous slide the dh, h is equal to C p into T. So, dh is equal to CpdT. So, dT by dS at pressure constant we get it as T upon C p. So, T upon C P is slope of isobaric line on T-S diagram. Now, by addition of heat temperature is increasing so, slope should also increase. So, line should be the red line what we have drawn on one side and it is not this kind of this is wrong.

So, further these two lines 2 3 and 1 4 should not be other process 2 3 and process 4 1 should not be parallel to each other since temperature at 2 is higher. So, it should have higher slope to start with or it has rather different temperature than 4 that is why their slope should be different to start with further from 2 temperature is increasing. So, slope should increase from 4 temperature is decreasing; so slope should decrease. So, if we draw a parallelogram like this, then we are committing mistake for drawing the T-S diagram.

So, having said this now we know how to draw the T-S diagram for the Brayton cycle having said this we can now draw T-S diagram. Once T-S diagram is drawn we can now draw h-s diagram for theBrayton cycle.

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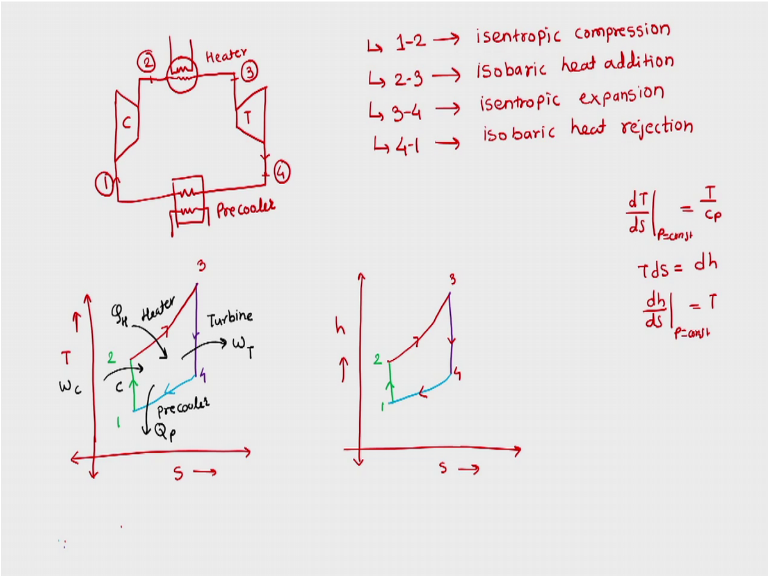

Now, in case of h-s diagram we have again we will first draw the axis which is h-axis and s-axis. We have h which is enthalpy on y-axis and we have s which is entropy on x-axis h-s diagram also gives us a representation which T-S diagram would also give, but at the start it is necessary to draw the diagram in all sense.

So, we have first process 1 to 2, process 1 to 2 which is isentropic compression then we have process 2 to 3 which is in red colour. So, that is process of isobaric heat addition. Then we have process of isentropic expansion in the turbine. We have isentropic expansion in the turbine and then we have then we have pre-cooler which is heat rejection process. So, we have 1 to 2; so, then we have 2 to 3, and we have 3 to 4. So, this is what our h-s diagram. Representation of h-s diagram and representation of T-S diagram will not be different they would look similar curves.

But, only difference would be the slopes and what is that difference as we have seen dT by dS at constant pressure for T-S diagram is equal to T upon C p if we go back we got this expression from TdS is equal to d h here we can know now that d h by dS at constant pressure is equal to T. So, slope of constant pressure line on h-s diagram is equal to local temperature. So, local slope is dependent on local temperature. So, C P is always greater than 1. So, what would happen T upon C p is the number which will be lower than T. So, slope will be higher on h-s diagram in comparison with T-S diagram.

So, having said this now we will draw the next curve which is P-v diagram for theBrayton cycle.

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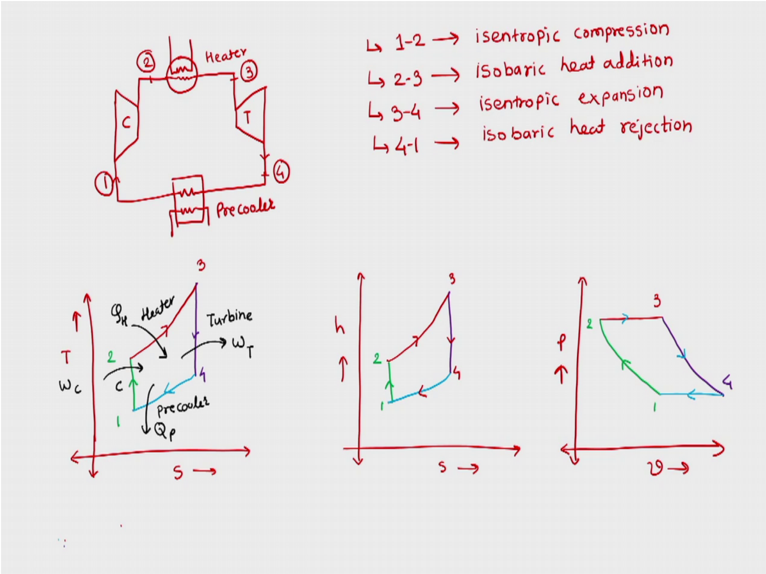

So, in case of P-v diagram we have again axis which is P and v; v is volume specific volume P is pressure and now we are supposed to draw the P-v diagram, but first process is compression process. So, in the compression process we have increase in pressure. So, we have to keep it in mind. So, process 1 to 2 is increasing pressure. So, process 1 to 2; process 1 to 2 which is isentropic compression. Then we have process 2 to 3 which is again process of heat addition. So, we have process, but that is isobaric process. So, as name suggests it is an isobaric process. So, pressure should remain constant y-axis is pressure; so it has to be a horizontal line.

And, then we have isentropic expansion. So, the process is isentropic expansion isentropic expansion 3 to 4 and now, we have last process which is heat rejection and then we have 4 to one as heat rejection. So, this is P-v diagram for earth in case ofBrayton cycle. So, now we have drawn T-S diagram, h-s diagram and P-v diagram for Brayton cycle.

Now, we will try to do the basic calculations for Brayton cycle. Here one more thing we should remember that if instead of having the open cycle gas turbine power, closed cycle gas turbine power plant we can have open cycle based gas turbine power plant also. So, if there is an open cycle gas turbine power plant then process 4 to 1 practically is not existing, but instead of that we pretend that there is a heat rejection to the atmosphere. And, from atmosphere we are taking same here of same mass flow rate, but at the temperature which was at the inlet of the compressor.

So, there is no practically 4 to 1 process in open cycle gas turbine power plant, but it also runs on Brayton cycle as we can see for the closed cycle gas turbine power plant. Now, having said this we will start with the calculations for the Brayton cycle. Now, I will redraw for all set T-S diagram for Brayton cycle.

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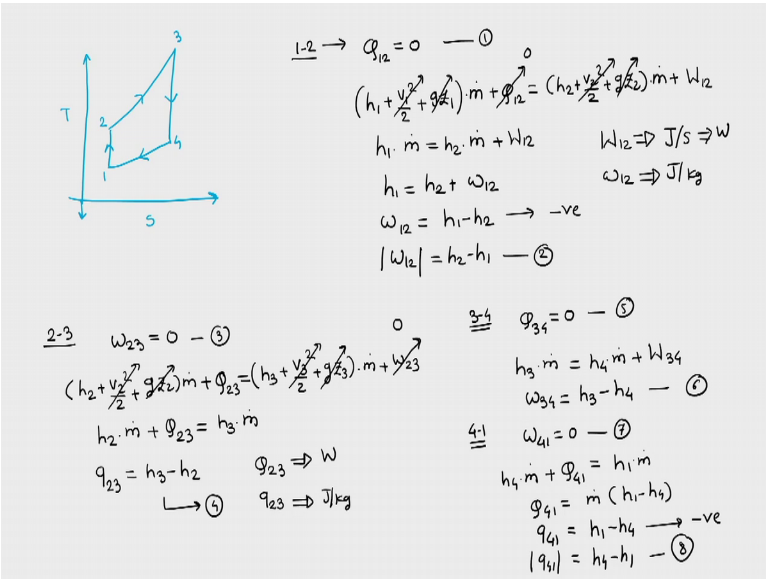

Now, this is T axis, this is S axis and we drew like this we have 1, 2, 3, 4. These are the four processes. Now, let us try to find out what is first the heat and work interaction in each process. So, let us see for process 1 to 2; for process 1 to 2 we have isentropic compression. So, process 1 to 2; since we are saying that process 1 to 2 is isentropic compression then we have Q which is heat interaction in 1 2 to 0 since we say that process is isentropic. So, process is reversible and adiabatic. So, W Q 12 is 0. Now, only what we have to do in process 1 to 2 is find out work interaction. So, how to find out work interaction?

So, now we can apply the steady state energy equation for or steady flow energy equation what we had derived for the compressor. As per the steady flow energy equation and with the fact that compressor has only one inlet and only one outlet we have h 1 plus v 1 square by 2 plus g z 1 into m dot plus q plus Q 12 is equal to h 2 plus v 2 square by 2 plus g z 2 into m dot plus W 12, but here Q 12 is 0.

Further we will neglect for the sake of simplicity the change in potential energy between inlet and outlet of the compressor. Further we will also neglect change in kinetic energy between inlet and outlet of the compressor. Basically this neglection has a reason that the term h is much greater than the kinetic energy and potential energy terms. So, this h is sufficient for us to give the work or work input that is why we have h 1 into m dot is equal to h 2 into m dot plus W 12

Now, we will write it as h 1 is equal to h 2 is equal to w 1. Now, this w 12 is a specific work output means w 1 here w 12 has units of joule, but here w 12 has unit of joule per kg per second, ok; this per unit mass flow rate. So, this is what specific work output. So, we were interested in finding out w 12 and we got it as h 1 minus h 2, but h 1 is lower than magnitude of h 2. So, this term is negative and we should have expected it, since w 12 in case of compressor is the work absorbed by the system. So, work up by the convention work absorbed by the system is negative. So, we will take for the sake the modulus of w 12 and it is h 2 minus h 1. So, this is the calculation equation 1 and equation 2; equation 1 gives that heat interaction for the compressor and equation 2 gives us work interaction for the compressor.

Now, we have process 2 to 3; process 2 to 3 is the process of constant pressure heat addition. So, as the process indicates it is a heat addition process, but it is a non work interaction process. So, w 23 is equal to 0. Again, we have to find out Q 23. So, to find out Q 23 we will again take help of steady state steady flow energy equation. So, we will say that h 2 plus v 2 square by 2 plus gz 2 is equal to sorry into m dot plus Q Q 23 is equal to h 3 plus v 3 square by 2 plus gz 3 into m dot plus w 23, but we know w 23 is 0.

So, what we have is this expression, but again we will neglect the change in potential energy at the inlet at the and at the outlet or between inlet and outlet of the combustion chamber or the heater we will neglect the change in kinetic energy between the inlet and outlet of the combustion chamber then we get h 2 into m dot plus Q 23 is equal to h 3 into m dot. So, we will specify heat it as q 23 which is heat added per unit mass flow rate and then that is equal to or per unit mass, ok. There is slight correction here as we know that unit of W is joule, but here we have m dot which is kg per second and then this h is in joule per kg. So, unit of W 12 a joule per second and then that is watt. So, unit of w 12 will become only joule per kg, ok. So, here unit of w 12 is joule per kg and unit of capital W 12 is watt.

So, similarly now we will come back here for the process 23 where we say that now q 23 is equal to h 3 minus h 2. Same way here also we have Q 23 capital and that has unit of W which is watt which is joule per second and unit of small q 23 is joule per kg. So, we say that q 23 small is a joule per kg heat added into the system. So, there are some more things for the rest of the processes.

Similarly, for process 3 to 4. For process 3 to 4 we have isentropic expansion. So, in case of isentropic expansion everything will go same as process 1 to 2 here also we have Q 34 as 0 and we here will have h 3 into m dot is equal to h 4 into m dot plus W 34 this will be the work interaction. So, we will say that w 34 which is small w which is joule per kg it is equal to small h 3 minus small h 4, ok. So, here we get equation if we remember then equation 3 here for work interaction in 2 3; equation 4 here for heat interaction in 2 3; then equation 5 here for heat interaction in 3 4 and equation 6 here for work interaction in 3 4.

Now, we have process 4 to 1. So, in the process 4 to 1 it will be again similar to process 2 to 3, it is a isobaric heat rejection. Since it is a heat rejection process and non work interaction process w 41 is equal to 0, this is equation number 7 and now we will have h 4 into m dot plus Q 41 is equal to h 1 into m dot. So, we will have Q 41 is equal to m dot into h 1 minus h 4 or Q 41 is equal to h 1 minus h 4. One more thing to remember or here that Q 41 is a negative quantity since it is a heat rejected from the system, since h 1 is lower than h 4. So, practically if I want to find out q 4 1 I will say that I will take modulus and say that it is h 4 minus h 1.

Now, we got such seven and eight expressions where we can know the work and heat interaction for the Brayton cycle. Now, we will use those expressions for further calculation. So, what was our first expression?

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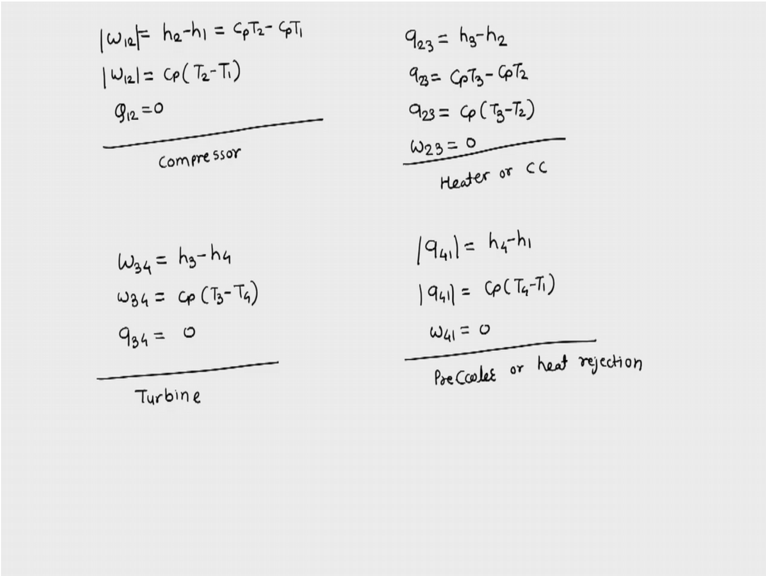

We have w 12 is equal to modulus w 12 is equal to h 2 minus h 1, but we know h is equal to C p into T and we know that we are using calorically perfect gas C P into T 2 minus C p into T 1. So, modulus w 12 becomes C P into T 2 minus T 1. So, knowing the temperatures at the inlet and at the outlet of the compressor we can find out work interaction.

Then, we have Q 12, 0; this is for compressor. Now, we here, this whole thing is for compressor. Now, for turbine or for heater or combustion chamber we had seen that q 23 is equal to h 3 minus h 4 sorry it is h 3 minus h 2. So, again q 23 is equal to C p into T 3 minus C p into T 2. So, q 23 is equal to C p into T 3 minus T 2. So, knowing the temperatures at the inlet and at the outlet of the heater or combustion chamber we can find out heat interaction in the combustion chamber since we only have it interaction and work interaction is 0. So, this is for heated heater or combustion chamber.

Now, we have turbine. So, for turbine we have w 34 and then that is equal to h 3 minus h 4. So, w 34 is equal to C p into T 3 minus T 4 as what we got it for compressor. Similarly, q 34 is equal to 0 and this whole thing is for turbine.

Now, we have the similar expression for pre cooler or heat rejection process. So, heat rejection process we have q modulus q 41 is equal to h 4 minus h 1 and so, modulus of q 41 is equal to C P into T 4 minus T 1. Then, we have w 41 is equal to 0 whole this thing is for T pre-cooler or heat rejection process. So, now, we have derived the basic requirements for the gas turbine power cycle. This we can use for further calculations of gas turbine power plant.

Now, what we can need to find out is what are the basic governing parameters for the gas turbine power plant and if we know their values of the governing parameters we should able to find out the rest of the quantities of the gas turbine power plant. We practically mean that suppose we know few things of the gas turbine partner and now using those things I should calculate what are the values of pressure, temperature and other quantities at all corners of the this cycle.

So, what are those governing parameters for the Brayton cycle?

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$$r_p = \frac{P_2}{P_1}, \gamma, T_1, T_3$$

So, those governing parameters for the Brayton cycle are pressure ratio and that pressure ratio is P 2 by P 1 which is P 2 is the pressure at the outlet of the compressor, P 1 is the pressure at the inlet of the compressor. So, that pressure ratio is a governing parameter. Apart from that we have governing parameter is gamma which is specific iteration. We further have governing of the gas turbine power cycle dependence on inlet temperature and maximum temperature what cycle can sustain.

So, if we know these conditions, then we can find out the properties or the pressure and temperature at all corners of the cycle. So, we can do this exercise here onwards knowing these values of the governing parameters we can find out the properties required at all corners of the cycle. So, we will do this calculation and we will also do the calculation or derivation for the performance parameters like efficiency, network output for theBrayton cycle in the next class.

Thank you.