Basic Thermodynamics

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Lecture - 26

Vapors Power Cycle-III

Last class we discussed about the closed and open cycle gas turbine plant. We will be discussing the ideal thermodynamic cycle known as Brayton cycle, which simulates the processes in an open and closed cycle gas turbine plant.

Let us see what are the closed and open cycle gas turbine plants which were discussed in the last class.

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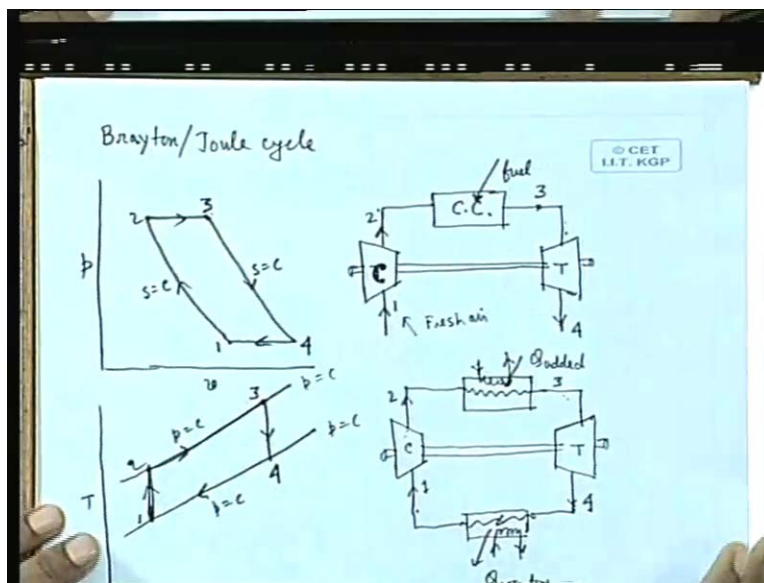
If you remember an open cycle gas turbine plant is like this. This is a <mark>compressor</mark> as you know so which takes air from the atmosphere state 1, then at state 2 it compresses at a higher pressure and temperature then it goes to a combustion chamber.

The compressor which compresses the air to a higher pressure and temperature then the high pressure and temperature air goes to a combustion chamber where fuel is being injected and burned with the air and a temperature is raised to a much higher value the state point3. The fluid or working system remains at the same pressure 2 and 3 at almost the same pressure.

Then it is being expanded in a turbine which gives the work. This turbine and compressor are connected to a same shaft so that the turbine is driven by the compressor. Then it comes out from the turbine at a state 4 which is at a lower pressure but relatively higher temperature compared to 1, the lower temperature compared to 3.

Fresh air is again taken this was the open cycle gas turbine. In a close cycle gas turbine which was the concept like this. The compressor takes air as it is 1 and it delivers the air at a higher pressure and temperature but difference is that instead of a combustion chamber there is an heat exchanger where the heating of this air takes places by an external heat that is Q added by an external heating source If a hot gas is there which is allowed to flow like this which shares or exchanges heat gives it to the air which comes here at 3 and then it is expanded in the turbine as usual to a relatively lower pressure and temperature that is at 4 and these are the turbines and compressors as usual connected by the same shaft.

Then again at 4 what happens, this high temperature air but at the same pressure at 1 is being cooled by an external source that means here $Q_{rejected}$ heat is rejected by an external source that means a coolant is allowed to flow which takes the heat from the air.

Difference is that during the process the fluid changes its composition because here it is air then when it is burned with fuels of this part is the mixture of air and products of combustion but here continuously the fluid is same fluid that is air. It simulates a thermodynamic cycle because the working system remains the same so heat is being added here in this heat exchanger which is the combustion chamber in an open cycle gas turbine that is the heat rejection that is another heat exchanger which is being simulated by the vast atmosphere or surroundings which acts as a heat sink in case of an open cycle gas turbine.

We come to the ideal cycle for this power plant. This cycle is known as Brayton or Joule cycle. Let us draw the cycle diagram in PV and Ts plane. First PV plane let us draw pv plane. This 1- 2

process that is the process of compression is ideally simulated by an isentropic process. S is equal to constant. Then 2 to 3 that is the constant pressure process where heat is added here at constant pressure process so 2 to 3 is a constant pressure process. Then 3 to 4 again an isentropic expansion and this is the direction 4to 1 is again the constant pressure heat rejection in a close cycle gas turbine it resemble. These are the ideal processes. This is a constant pressure process, this is the constant pressure process and this constitutes a thermodynamic cycle in PV plane.

Similar way if we draw this on a TS plane that is the temperature entropy plane this looks like these 1 2 is an isentropic process. This cycle operates on two limiting pressures, this pressures and this pressure because pressure in this half remains constant. If you see the bump 2 to 3 again from 4 to 1 pressure is constant the two pressures.

The compressor compresses from pressure 1 to 2 and the turbine reduces the pressure from 3 to 4 so better to draw before drawing the diagram we should draw the constant pressure lines. These are constant pressure line then it will be easier.

1 and 2 is the isentropic compression process. Then 2 to 3 is the constant pressure heat addition process so this state point3. Then again 3 to 4 which is an isentropic process will be a vertical line in a TS plane so this are the directions and 4 to 1 is again the constant pressure process heat rejection. These are the constant pressure process.

These are the diagrams in PV and TS plane for the thermodynamics cycle is ideal cycle for this power plant or the gas turbine plant, this cycle is known as Brayton or Joule cycle. We will follow in the similar way the work and heat transfers in various processes.

How to find out the work and heat transfer in various processes?

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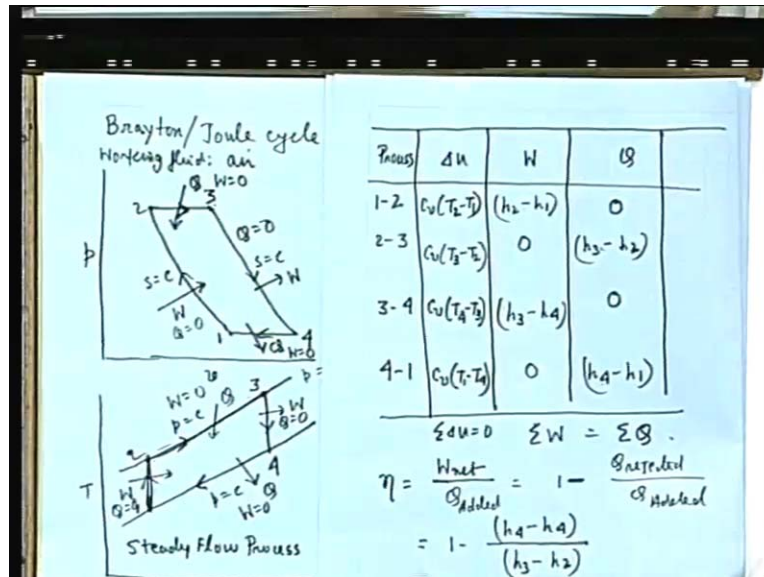
If we draw a table like this, this is the process then this is delta u the way we did for earlier cases this is W and this is Q all right and here one thing we always remember that this is a steady flow process so working fluid is air so here I must write working fluid. Working fluid is air and the process is a steady flow process where I should write here a steady flow process.

This has to be remembered steady flow process so the equation first law dQ is du plus pdv or du plus dw will not be used in that sense because it is a steady flow process open system process. Let us first see process wise 1 to 2 is an isentropic process therefore at the first instant Q will be 0 because there is no heat transfer. What will be the change in internal energy when we consider working fluid as air which is an ideal gas so change in internal energy is simply C_v times the T_2 minus T_1.

What will be the work transfer? There is a steady flow process the process in the compression. The work transfer will be found out by applying the steady flow energy equation. If you consider the process is adiabatic there is no heat transfer because isentropic means reversible adiabatic process. The work is given by the work transfer is given by the change in the enthalpy that means h_2-h_1, this is the work which is being done to the compressor so h_2-h_1. It is always positive h_2 is more than h_1 and I have written taking care that it is done on the compressor so therefore work is done W but Q is 0 here in 1 2 process.

I come to 2 to 3 process what is this process? This is a constant pressure process but in a steady flow system, steady flow system constant pressure process means the steady flow where heat is added and the working fluid is heated or the temperature of the working fluid increases at a constant pressure so there is no work interaction. Therefore in this process 2 to 3 work interaction is 0.

What is the change in the internal energy?

Internal energy change is $C_v(T_3-T_2)$ and we get the Q. What is Q? This is a heat exchange process and the heat transfer is found out. Similarly by considering a steady flow energy equation around this heat exchanger and we get the heat transfer is h3-h2. Which is the heat added to the working system for the process from 2 to 3. Therefore in the process heat is added and work transfer is 0 here.

I come to the process 3 to 4 which is same as that of 1 to 2 where Q is 0 so 3 to 4 Q is 0 isentropic processes. Change in internal energy always since air is an ideal fluid is always C_v as you know T_4 minus T_3 that the change in internal energy of an ideal gas is C_v into change in temperature. Here also the work done by the turbine can be found out by the application of steady flow energy equations as h_3-h_4.

Then comes the last process 4 to 1 which is same as that of 2 to 3 is a constant process heat rejection in the heat exchanger in which case there is no work transfer so therefore work transfer is 0. First I write that then the change in internal energy as usual for the ideal gas T_1-T_4 air is an ideal gas and what is Q? Q is again by this application of the steady flow energy equation.

We can write h_4-h_1which is positive and indicates, this is the scalar value without any sign. That positive sign will indicates the heat which is being coming out from the system. In this case W is coming out so heat is coming out of the system. It is being h_4-h_1 so these are the work and heat interactions.

We can write the similar way the Q is added no work. Here work is coming out no heat transfer. Here the heat transfer heat is coming out but no work transfer W is 0. If you sum up the delta u it will become 0 and if you make the algebraic sum of W and algebraic sum of Q it will be equal

but when you make the algebraic sum of W you have to make one thing sure that $h_2 - h_1$ is negative. That means you will have to make a negative sign and then you will have to add.

Similarly in this case $h_4 - h_1$ with a negative sign then you will have to add so that you can get an algebraic W is equal to algebraic Q this is valid. We come to the definition of thermal efficiency how do you define thermal efficiency?

The net work that means work delivered by the system minus work done on the system the divided by the heat added. From the first law of thermodynamics you know this can be written as $Q_{Rejected}$ minus Q_{Added} because W net is Q_{Added} minus $Q_{Rejected}$. If you write this then we will have to find out what is this $Q_{Rejected}$. $Q_{Rejected}$ is $h_4 - h_1$ is the Q rejected. This is the value of the heat rejection so minus sign is taken care of here 1 minus as the definition of this. This is the scalar value $Q_{Rejected}$ minus Q_{Added}. Q_{Added} is h_3 minus h_2 so this is the expression.

If we want to expand this little more.

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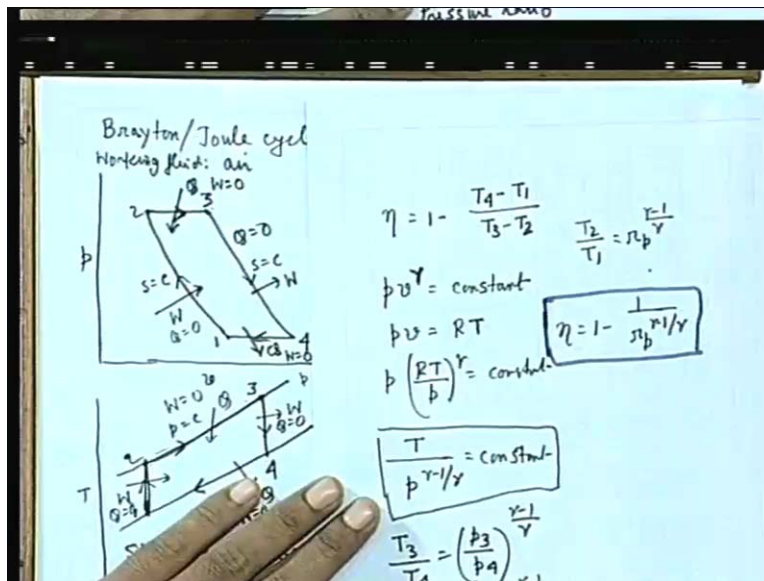
This becomes like this. You can see that h_4. This is again considering an ideal gas we can write $h_4 - h_1$ will be $C_p (T_4 - T_1)$ divided by $Cp(T3 - T_2)$ that means I am replacing the enthalpy changes as the temperature changes because for an ideal gas change in enthalpy C_p times change in temperature.

If C_p is same working fluid is same. It considers an ideal gas where the C_p does not vary with the temperature so we get eta is equal to 1 minus T_4 minus T_1 divided T_3 minus T_2. With little mathematical exercises, we can express this in a different form. If we consider this process 3 4, this is an isentropic process we can develop a relationship between temperature and pressure. I tell you that you will have to remember only for an isentropic process this equation pv to the power of gamma is constant, where gamma is the ratio of specific heat. Other relationships like p and T and v and T in an isentropic process can be developed without remembering it by using the ideal gas equation of state pv is equal to RT.

If you substitute v from this equation of state you get RT by p whole to the power gamma is constant. From where we can tell T divided by p to the power gamma minus 1 by gamma is equal to constant. Therefore this gives the relation for T and p for an isentropic process. If we look on this 3- 4 process then we can write for the process 3- 4 like this. T_3 by T_4 is p_3 by p_4 to the power gamma minus 1 by gamma.

This p_3 by p_4 is defined as pressure ratio r_p to the power gamma minus 1 by gamma, where r_p is known as pressure ratio. Pressure ratio is very important parameter in a Brayton cycle as the volume ratio is for an Otto cycle because Otto cycle works on two limiting volumes. Whereas the Brayton cycle as a gas turbine plant works on two pressure limits, there is one lower pressure and there is an higher pressure that is from compressor inlet up to the turbine inlet the fluid is at some pressure constant pressure this is the higher pressure or the maximum pressure of the cycle and from the turbine outlet to compressor inlet is the lower pressure. Therefore you define that pressure ratio.

In the similar way one can define the T_3 by T_4 is this one can define T_2 by T_1 for this process also T_2 by T_1 considering these isentropic compression process, r_p to the power gamma minus 1 by gamma.

If you replace T_3 in terms of T_4 and T_2 in terms of T_1, we get eta is 1 minus 1 by r_p to the power gamma minus 1 by gamma. This is 1 of the very important relationships or expression for the cycle efficiency of the Brayton cycle or thermal efficiency of the Brayton cycle in terms of the pressure ratio.

It is similar to the expression of eta in terms of the volumetric compression ratio where r_v to the power gamma minus 1 we deduced it in case of Otto cycle now in case of a Brayton cycle this is the expression.

I come to the concept of regeneration. What is that the concept of regeneration?

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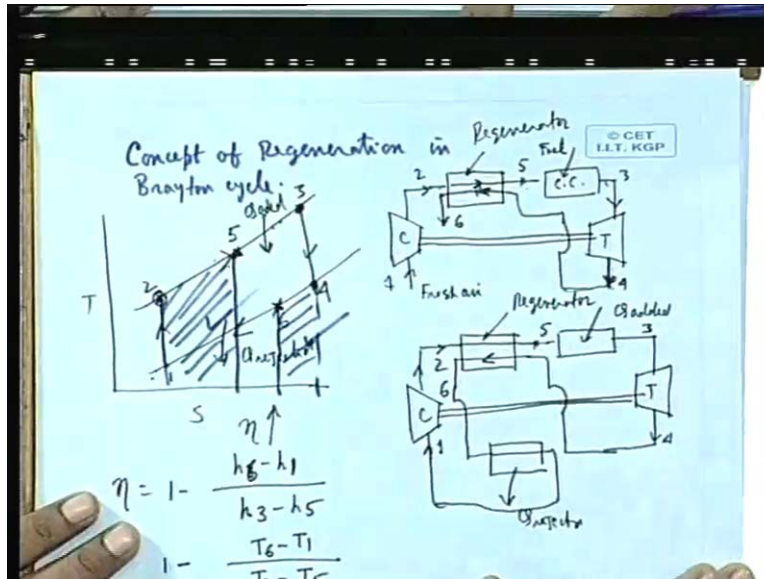
Concept of regeneration in a gas turbine plant, concept of regeneration in Brayton cycle what is that?

If we look to the cycle diagram, we only draw the TS diagram. If we look to the cycle diagram TS diagram. We see the cycle diagram is like this 1, 2, 3, 4 and this is the direction of the process. In this cycle the average temperature of heat addition, if we look from that angle of view is some average between 3 to 2 and the average temperature of heat rejection is some average temperature between4 to 1 that can be found out by dividing the enthalpy differences divided by the entropy change. We can find out the average temperatures.

If we look back to Carnot's theorem, you know that the efficiency of any reversible engine depends upon the average temperature of heat addition and average temperature of heat rejection. Also we know that efficiency of any reversible cycle can be expressed as 1 minus average temperature of heat rejection divided by average temperature of heat addition. Therefore we can

conclude from this, already we have discussed so many times thing earlier that if we increase the average temperature of heat addition the thermal efficiency of a heat engine cycle increases.

Similarly if you decrease the average temperature of heat rejection, the thermal efficiency of a heat engine cycle increases so concept of regeneration does this. If we increase the average temperature of heat addition in this way that this is state of air at the compression inlet before entering into the combustion chamber or the heat exchanger in a closed gas turbine plant.

If it is heated by this hot products which is coming out or the hot fluid which is coming out from the turbine to a temperature of say example, here some state point 5 by which these gas which exchanges heat comes down to it point 6. Then what we do we make an internal use of the heat or the thermal energy of 4 to heat this state 2, the state of fluid 2 to the point 5 we can increase the thermal efficiency.

Let us understand this in this way. Let us consider a open system first so this is the compressor, it takes at 1and delivers it at 2. Before going to the combustion chamber it is being heated internally to the state 5 then it goes to the combustion chamber. Where the fuel is used and this state point is 3. Then it is expanded in the turbine T. So what is done? This 4, this products of combustion and the air that means these the working fluid at 4 degrees at higher temperature this is taken like this to heat it that means this fluid heats the air.

Therefore the temperature is reduced to 6 and then it is being rejected at 6 and again the fresh air is taken. The counterpart diagram for a closed cycle will be like this where this part will remain same that means the air is heated from the state 2, this is the state 1 to this point 5 by the incoming gas or incoming air from the turbine. Here only, it is heated from external heat source. Which raises the temperature to 3 then it goes to the turbine.

They are connected by the same shaft I must show. Then from the turbine this hot gas 4 is going to heat this and then it comes at this 6, where 6 is not rejected. In open cycle rejected and fresh air is taken rather, this is being cooled; here the Q is rejected by the external heat sink. Then this is going to the compressor which means that the external heat is added only in the temperature range 3 to 5 that means to increase the temperature from 5 to 3.

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Similarly heat is being rejected to decrease the temperature from 6 to 1, which makes that the average temperature of heat addition is average between 3 to 5, instead of 3 to 2 earlier because air is already heated to 5 by the use of the internal energy that means there is an internal heat transfer process so there is no external heat source. Therefore the external heat source gives the heat to heat the fluid from 5 to 3 working system from 5 to 3.

The average temperature is between 3 to 5 which is more than the earlier one which was between 3 to 2. Similarly the average temperature of heat rejection is something between 6 to 1 instead of something between 4 to 1 which was the earlier case therefore the average temperature of heat addition is increased average temperature of heat rejection is decreased so there is an increase in the thermal efficiency.

If we write the thermal efficiency expression, obviously the heat rejected, the numerator will be heat rejected that is h_6 minus h_1 divided by h_3 minus h_5 which is equal to 1 minus if you cancels the cp T_6 minus T_1 and T_3 minus T_5. In this case you will see that there will be an increase in efficiency.

This is the concept of regeneration by which we increase the temperature at the outlet of the compressor or the inlet air to some higher temperature by using the thermal energy. I will not tell heat because heat is never content in a fluid the thermal energy or in loosely the heat content in this working fluid coming out from the turbine to heat this so this way the efficiency is increased and this is the concept of regeneration in Brayton cycle. This heat exchanger where air is heated with this fluid at 4 this heat exchanger they are known as regenerator or a regenerator heated. Regenerator they work in the principle of regenerative heat exchange.

One thing before closing this so we can shown it graphically in TS plane that the heat by this system which is denoted by this area must be equal to the heat taken by the fluid at 2 that means from 2 to 5 in the process 2 to 5 so this area must be equal to this domain diagram is not up to the scale so it does not show like that.
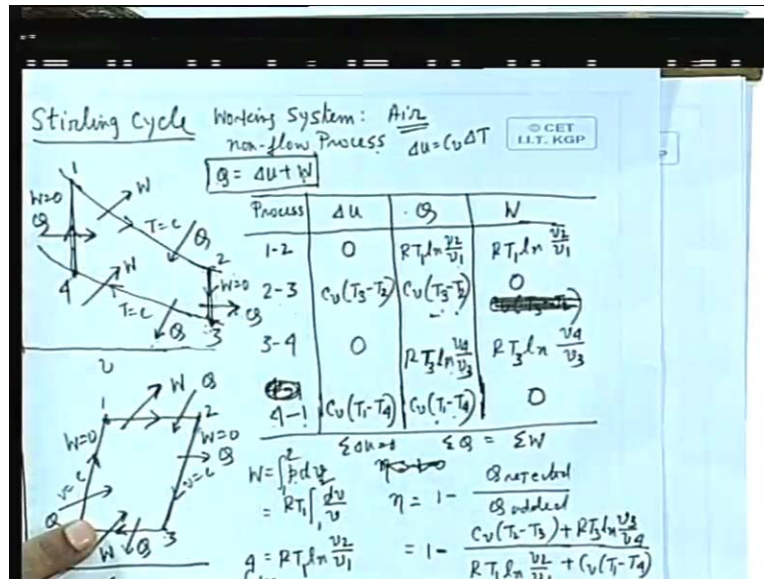
We come to another important part that is the Stirling cycle. What is a Stirling cycle? First of all I tell you this specification Stirling cycle working system is air and the process is non flow process.

What we do? In the similar way we first draw the diagram of the Stirling cycles in PV and TS plane so this is the PV plane. In PV plane this Stirling cycle is like that I just first draw the diagram then I will explain to you. This is the two isothermals and these are the two constant volume varies so these are the isotherms T is equal to constant and obviously these are v constants so vertical length.

Let us start from 1 to 2, 2 to 3, 3 to 4, 4 to 1, so in this direction. A Stirling cycle consists of two isothermal lines and two constant volume lines. This is one isothermal line this goes in this direction from 1 to 2 that means this is an isothermal expansion, this is a constant volume process from 2 to 3 there is a change in the pressure and this is isothermal process constant temperature process. Where there is an increase in pressure and this is again a constant volume process where there is an increase in pressure.

These two process 3, 4, 4, 1the pressure is increase this is an isothermal process. This is a constant volume process. Where process 1, 2 and 2, 3 a volume is increased rather this process

volume is increased and pressure is decreased and this process volume remains constant but pressure is decreased so these four processes constitute the Stirling cycle.

If you draw the same cycle in TS diagram. 1, 2 definitely will be a horizontal line. Now 2, 3 is the constant volume line and the constant volume line gives a curve like this the steep curve which is v is equal to constant and it comes at 3. Where again 3, 4 is a constant temperature of isothermal process and then 4, 1 is the constant volume process v is equal to constant. Therefore the diagram is like that, that means same diagram in the TS plane this is the Stirling cycle.

Now working system and non flow process, non flow process means I can write that Q is equal to delta u plus W which is very important. As you know earlier also use this things and we draw this table as usual that means process then delta u then Q and then W. W Q may be like this earlier I wrote W here and Q does not matter.

We start from process one working system is air so air is an ideal gas and we know delta u for an ideal gas is C_v delta T. When delta T remains constant del u is 0 that means an isothermal process internal energy remains constant for an ideal gas so you have to write this as 0. When del u is 0 so automatically if you put del u 0 here Q becomes equal to W so Q and W will be the same but we will have to find out the expression of anyone of this.

Since it is a non flow process we can find out the expression of W from this equation W is integral pdv per unit mass basis. For an isothermal process, equation of state tells that RTp is RT by v and T is constant so that equation of state is pv RT but for isothermal process I can take T constant so that it becomes dv by v. Process is from 1 to 2 initial 1, final 2 so this becomes is equal to RTln v_2 by v_1 so this is the W.

For 1, 2 processes W is RT ln v_2 by v_1. Since Q is equal to W from first law since delta u is 0 for an isothermal process where temperature remains constant, I can write Q as RTln v_2 by v_1. Now v_2 is more than v_1 from pv diagram therefore this is positive, this is positive. This is positive means what, the heat is being supplied and this is positive means what, work is being delivered. Therefore the work quantity comes out and heat is being supplied because Q is positive. In isothermal expansion work is being done and heat is being supplied.

Then comes to the process 2, 3 and constant v in a close system or non flow process makes W_0 because integral pdv is W so constant volume process means work is 0. When work is 0 immediately from this equation you get Q is equal to delta it is very simple and delta u is as usual for an ideal gas is C_v into change in the temperature T_3 minus T_2 and Q is equal to delta u since W is 0. Q will be also $C_v(T3-T2)$ and from the TS diagram T_3 is less than T_2.

Therefore W is negative this is also negative that means the internal energy is decreased but we bothered more about W and Q so this is negative. Negative W means what work that means here this will be Q, this will not be here so this will be C_v T_3 because delta u is Q minus T_2 so W is 0. Now Q is negative, T_3 is less that T_2 therefore negative Q means what heat is coming out from the system. In this case constant volume the pressure is decreased so heat is coming out from the system.

We go to 3, 4 process again del u is 0 so W gets the same value by integrating this pdv RTln, the final volume is v4 this is v3 then what is Q? Since delta u is 0, Q is W so Q is also RT. Now what is this T I am writing RT but this is 1 2 so this will be RT_1, RT, T1, T2 is same so you write RT1, RT_1. Here I write RT_3 because T_3 and T_4 is constant so RT_3 ln v_4 by v_3 that means I am finding out this W pdv for 3 to 4 process. Again I repeat, we can write it as p is RT by v and T is T_3 and T_4 all same for the entire process I can write either T_3 or T_4 so I write RT_3 that means it is not shown here so W in this case RT_3.

Similar way dv by v and this process is for 3 to 4. So that it gives this expression that means for an isothermal process the work done by a closed system in a non flow process is R into T that the constant temperature in the process into ln final value by initial volume.

Therefore v_4 by v_3, you see v_4 is less than v_3 that means this is negative v_4 is less than v_3 so this is negative so Q is negative, W is negative. W negative means work is being done and Q negative means what? Q is coming out so in this process Q is coming out and work is being given. Now will left with the process 4-1. What is this 4-1 process? 4- 1 process is constant volume process so therefore we can write the work done 0 in a non flow process. 4-1 process the change in internal energy is $C_v(T_1$ minus $T_4)$, since work done is 0 the change in internal energy is Q so Q is $C_v(T_1-T_4)$.

T_1 is higher than T_4 therefore both the quantities are positive. Now Q positive means what? W is 0 first I write Q positive means what? Q is being given. Therefore the process 4-1 receives heat, process 1-2 receives heat while process 2-3 rejects heat, process 3-4 rejects heat that means 3-4 rejects heat.

Process 2-3 rejects heat, process 1-2 heat is given and process 4-1 heat is given and W quantities are 0 for the two constant volume case W quantities are 0, here W work is coming out here work is being given by the arrows also in the cycle diagram we showed you work and heat quantity interactions.

If we have to find out the expression for thermal efficiency for the Stirling cycles we have to follow the same way 1 minus, if you sum up this delta u is equal to 0. If you sum up delta Q is equal to delta W, showing the validation of the first law of thermodynamics. So, 1 minus heat rejected by heat added. That is equal to 1 minus where the heat is rejected, all these quantities are heat transfers but we have to find out in which process 2-3 and 3-4 where they are negative.

2-3 this is negative and 3-4, 2-3 is the heat rejected. We have this is 4-1. So heat is rejected where Q is rejected, this is the constant temperature process so it is heat is rejected here that means 2-3 and 3-4 so 2-3 is $C_v(T_3-T_2)$ it is negative and 3, 4 $RT_3 \ln v_4$ by v_3 it is negative. Now this negative value since here is the negative sign we will have to take in this way only their value C_v T_2 minus T_3 plus RT_3 this is 3, 4 process $\ln v_4$ minus v_3 no it is $\ln v_3$ by v_4.

Why because already negative sign I have taken here so only I want the magnitude of the heat rejection ln it will be v_3 by v_4. Then Q added is which one process 1-2, where Q is positive v_2 by v_1 and therefore I write $RT_1 \ln v_2$ by v_1 and another process where heat is being added is which one 4-1, where this is positive C_v T_1 minus T_4 so plus C_v T_1 minus T_4 so this is the expression of the cycle efficiency for the Stirling cycle or thermal efficiency of this Stirling cycle. But, the major concept of this Stirling cycle lies in the fact that we conceived of heating this part is constant volume part.

Let us see the TS diagram
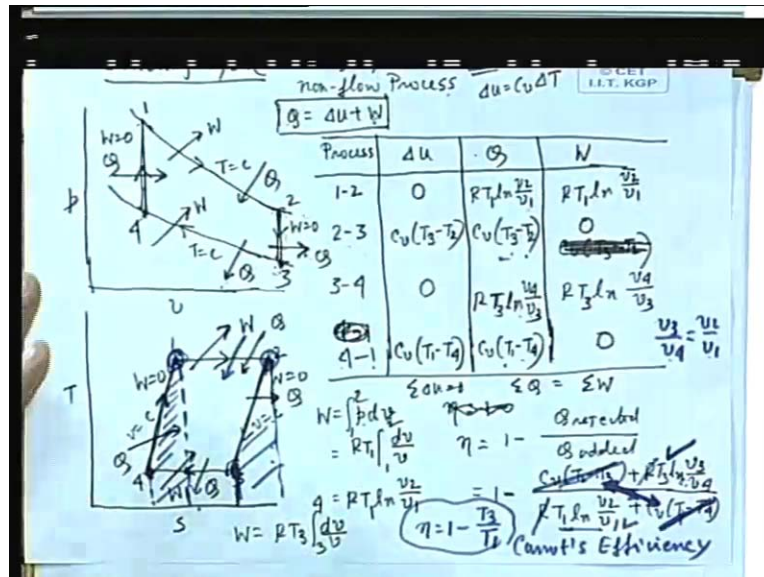
That heating of this working system during this constant volume here heat is added and here heat is rejected so this heat is being utilized to heat this part. That means there is a concept of regeneration, if we think of a regeneration where this area that is the heat which is rejected by the process 2-3 is utilized to heat the working system in the process 4-1 that means if we can make these two areas equal. So, that it utilizing the same heat it is a concept of an ideal regeneration that if we reject the heat from state 2 to 1 by the process and if that heat is taken by the working system during the process 4-1 and reach the same temperature 1 that is that of the 2 that means is inlet temperature and also this while rejecting heat reaches the same temperature that is 3 as that of its inlet at 4 then what happens these two process act in a sense that the heat transfer between the two process are taking place internally that means we are using the energy of the fluid working fluid within the cycle.

Only heat transfer from outside is in this isothermal process 1-2 and the isothermal process 3-4 while heat is added in the isothermal process 1-2 and heat is rejected in the isothermal process 3-4. Therefore it becomes almost Carnot's cycle almost not exactly a Carnot's cycle and we see that in that case we eliminate the heat rejected in the process 1-4 which term we will reject then we will reject this term. That means the process 2 to 3 that means when we get the heat rejection C_v 2 to 3 and 3 to 4 that means this one will neglect because heat is rejected only in the process 3 to 4 that means in isothermal process.

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Similarly in the heat addition process this part we will neglect when you write the efficiency part that means T_1 minus T_4 that means this is the heat rejected at constant temperature this is the heat added at constant temperature because they are internally that means this heat addition takes here to this heat rejection is taken by the fluid to make this addition of heat. Therefore these two things will be cancel so only heat addition is this term which is there at this constant temperature only heat addition is this term which is there at constant temperature.

If we see that since v_1 is v_4 and v_2 is v_3 we can write that v_3 by v_4 equals to v_2 by v_1. Obviously because there the v_2 is v_3 and v_1 is v_4 so therefore v_3 by v_4 is v_2 by v_1 so therefore R and R cancels so eta becomes equal to 1 minus T_3 by T_1, which means that the efficiency equals to the 1 minus the maximum temperature of the cycle divided by the minimum temperature of the cycle this is Carnot's efficiency.

Therefore by a concept of completer regeneration in a Stirling cycle in this way we will give rise to a thermal efficiency equivalent to the Carnot cycle that means this cycle will work as a Carnot cycle provided there is an ideal regeneration. That means we can take the entire heat rejected in this process to heat the working system in this process so that this temperature equals to this temperature after getting the heat its temperature will be equal to the initial temperature of this working system while rejecting heat and these two temperatures are equal so that these two process heat transfer does not come into the calculation of the cycle because only external heat addition at this temperature that is isothermal heat addition and isothermal heat rejection as it happens in Carnot cycle.

We will discuss another cycle known as Ericsson cycle.
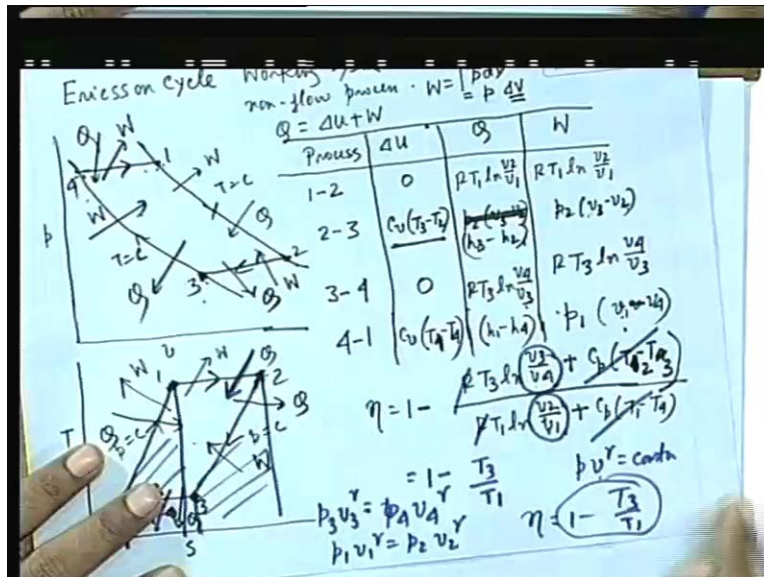
It is similar to Ericsson cycle. It is almost similar to a Stirling cycle, concept is almost same but difference is that their working system is air these are all same and non flow process but the only difference is that the cycle that means the processes in the cycle. In the Ericsson cycle the pv and TS diagram if you draw then you will see that the same isotherms are there but we have constant pressure process in between that means this is the concept that 1, 2 this is the cycle 3, 4 that means this is the Ericsson cycle.

Ericsson cycle comprises two isothermal processes and two constant pressure processes so this is an isothermal expansion. This is a constant pressure process where volume is reduced this is again an isothermal compression process and this is again an isothermal constant pressure process where volume is increased.

Similarly if you draw this thing in TS diagram you will get this 1-2 process and then 2-3 is the constant pressure process is shown in relatively flat curve compare to the constant volume process 2- 3. Then again 1-2, 2-3, 3-4, 4-1 that means 1-2 is isothermal process. 2-3 constant pressure process p is equal to constant 3-4 again is isothermal process. T is equal to constant and 4-1 is again the constant pressure so this comprises the Ericsson cycle, difference is that in Stirling cycle there were two constant volume processes instead of two constant pressure processes in between the two isothermal processes.

Again if we write in the similar way that the first law of thermodynamics Q is del u plus W. Now I go on writing the same way process then delta u, then Q and then W. Now I do like this again the process 1-2 remains the same as usual for process 1-2 deltau 0 isothermal processes as we did earlier. So W is evaluated as pdv and RT_1 T_1 and T_2 are same so this is ln v_2 by v_1 and Q will be RT_2 v_2 by v_1 so v_2 is more than v_1 so both Q and W is positive therefore there is a W coming out and there is a Q going in by the nomenclature so for 1-2 there is a W coming in that work is done and there is a Q going in W coming out and Q going in.

Similarly the 2-3 process but 2-3 process earlier this process was a constant volume process there is a constant pressure process. In constant pressure process first of all there is a change in the temperature between 2 and 3 and therefore we have the internal energy change is $C_v(T_3-T_2)$ because it is an ideal gas change in internal energy is C_v into change in the temperature.

Now Q and W both quantities are there, here at a constant pressure process in a non flow system how do you find out the work? Work is pdv and the constant pressure process p into delta v that means the change in volume therefore it will be p_2 into change in the volume v_3 minus v_2 so this is the W.

Now Q, Q will be found out by either adding these two, same thing will be will result that if we add these two this will be nothing but h_3 minus h_2 and also by applying this concept we know in a non flow process at constant pressure the heat added is equal to the change in enthalpy that means final enthalpy minus initial. If we add this two thing p_2 v_3 minus p_2 v_2 and the p_2 is constant so p_2 is p_3 also the p_3 v_3 minus p_2 v_2 so if you add then it will be h_3 minus h_2. Otherwise we can write simply h_3 minus h_2 because this is a constant pressure process between 2 to 3 so at constant pressure process heat addition is the difference of enthalpy.

Now v_3 minus v_2, v_3 is less than v_2 so this is negative so work is done on this process. In the 2-3 process so this is 1-2, this is 2-3. 1-2 is there so 2-3 the work is p_2 v_3 minus v_2 therefore work is done on this process 2-3.

Then what is Q h_3 minus h_2? h_3 minus h_2 it is nothing but the difference in temperature into C_p specific heat at constant pressure because air is an ideal gas so T_3 is less than T_2 so this is

negative, negative means what? Heat is coming out of this system h3 minus h2 so heat is coming out of the system.

3-4 is again an isothermal process what happens to 3, 4? The same thing delta u is 0 this is RT_3 ln v_4 by v_3 that means this is the work done RT_3 ln v_4 by v_3 and since delta u is 0 Q is W so Q is equal to RT_3 ln v_4 by v_3.

Here v_4 by v_3 so v_4 is less than v_3 therefore this is negative which means v_4 by v_3, v_4 is less than v_3 so this is negative. That means work is being done on the system and v_4 by v_3 negative means heat is being also coming out from the system so in these two processes 2-3 and 3-4 we see work is being done and heat is being coming out.

We see the process 4-1 again is a constant pressure process like 2-3 process. Here the change in internal energy is C_v times the T_1-T_4 as usual. Now the Q is T_1-T_4. Similarly we can write W is the similar way P_4 or P_1 into v_1 minus v_4 and this one will be again h_1 minus h_4 change in the enthalpy. Here if we see the sign we see v_1 is more than v_4 therefore work quantity is positive that means work is coming out. I am showing here it can be shown here also work is coming out and heat quantity h_1 minus h_4 what is h_1? h_1 is higher than h4 therefore heat is being supplied.

You can draw it here 1- 2 work is coming out, heat is going in. 4-1 work is coming out heat is going in. For 1-2 it is there for 2-3 work is going in and heat is being coming out and for 3, 4 work is given in and heat is coming out.

We can find out in the similar way eta as 1 minus heat rejected by heat added. Where are the heat rejections? You see v_2 by v_1 these two processes 1-2 and not the heat rejection is 3-4 and 4-1. So, 3, 4 processes this is RT3 now I write the ln v_3 by v_4 the values not the negative sign v_4 by v_3 already negative sign is taken and 4-1 is h_1 minus h_4 that is Cp T_1 minus T_4 but I write T_4 minus T_1. This is written T_1 minus T_4.

This is the process 4-1 so therefore process 4-1 heat is being supplied not heat is rejected. Heat is rejected in the process 2, 3 so it will be $C_p(T_2$-$T_3)$ that means this one I take T_2 minus T_3 positive value divided by the heat added where the heat is added? heat added we have to find out the processes where heat is being added.

Heat is being added in the process of 1-2, 1-2 is an isothermal process where heat is added RT_1 ln v_2 by v_1 plus when is another process where heat is being added apart from this isothermal process where heat is added in this 4-1 process. Therefore plus what is 4-1 process is h_1 minus h_4

C_p T_1 minus T_4 if you do it carefully it will come.

If we consider a regeneration concept, in the similar way that means heat added in this process of 4, 1 can be made by cooling the working system in the process 2-3 that means if we use the heat rejection in the process 2-3 to heat the working system in the process 4-1 completely so that by taking this heat the working system changes its temperature from 4-1 which is the initial temperature of this fluid rejecting heat and its final temperature equals to this initial temperature.

Which means a complete ideal regeneration, the entire heat transfer for the process 2-3 is use to make the process 4-1 then only addition of heat is that 1-2 process and rejection of heat at 4-3 process that means heat is added and rejected only at the constant maximum temperature and minimum temperatures of the cycle and that make the cycle a Carnot cycle and therefore eta becomes equal to 1 minus in that case this part will be 0 and this part will be 0.

Again you cancel R and we can find out 1 minus T_3 by T_1 but here you have to change this v_3 by v_4 before doing so v_2 by v_1 in terms of the pressure ratio. Otherwise it will be not possible for you to prove so that you have to find out this in terms of the pressure ratio that means you use the pv to the power gamma is constant. So that you can find out the v_3 by v_4 is p_4 by p_3 to the power 1 by gamma then v_2 by v_1 is p_1 by p_2.

p_1 by p_2 is p_4 by p_3 because p_3 v_3 to the power gamma in 3-4 process is p_4 v_4 to the power gamma and again p_1v_1 to the power gamma is p_2v_2 to the power gamma so we can change the ratio v_3 by v_4 is p_4 by p_1 to the power 1 by gamma and v_2 by v_1 is p_1 by p_2 to the power 1 by gamma and p_1 by p_2 is p_4 by p_3. So that we can substitute this and we can see that these terms cancels out so ultimately eta is 1 minus T_3 by T_1.

Therefore, we will see that the concept of Stirling and Ericsson cycle with complete regenerations works as a Carnot cycle. In a Stirling cycle there are two isothermal process and two constant volume process and in an Ericsson cycle there are two isothermal processes and two constant pressure processes. If we can have a completer regeneration that means in a Stirling
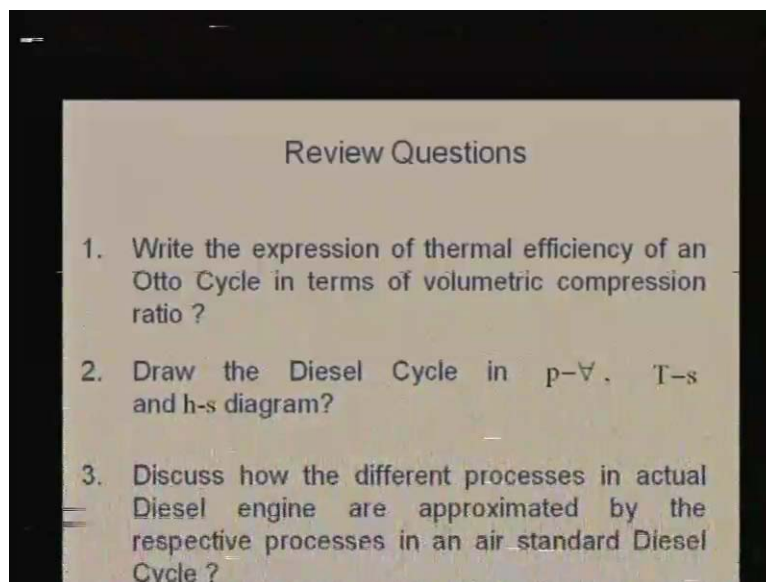
cycle the heat transfer in the two constant volume process are made in such a way the heating process the heat is taken from the cooling process.

Similarly, in case of Ericsson cycle the two constant pressure processes where heat is coming out in one process heat is going in other process and you can make a complete regeneration between this heat transfer then only heat addition and rejection takes place at the constant temperatures isothermal processes it is a maximum temperature of the cycle heat is added and the minimum temperature of the cycle heat is rejected and the efficiency becomes equal to the Carnot cycle.

Therefore, I end the discussions on gas power cycles that is ideal air standard cycles which simulates the gas power plant or which are the theoretical cycles of gas power plant we have discussed Otto cycles, we have discussed Diesel cycles, we have discussed Brayton cycles and finally Stirling and Ericsson cycles. The concept with an ideal regeneration how we can conceive of a process which targets to efficiency it was to that of Carnot's efficiency.

Thank you.

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Review Questions

1. Write the expression of thermal efficiency of an Otto Cycle in terms of volumetric compression ratio ?

2. Draw the Diesel Cycle in $p-\forall$, $T-s$ and h-s diagram?

3. Discuss how the different processes in actual Diesel engine are approximated by the respective processes in an air standard Diesel Cycle ?

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4. How do you define 'cut-off ratio' of a Diesel Cycle ? What practical significance does it have in relation to physical processes in a Diesel engine ?

5. Write the expression of thermal efficiency of a Diesel Cycle in terms of the volumetric compression ratio and cut-off ratio of the cycle ?

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6. Which one of the following statements is true ? Under the same volumetric compression ratio,

$$\eta_{Diesel} > \eta_{Otto}$$
$$\eta_{Diesel} < \eta_{Otto}$$
$$\eta_{Diesel} = \eta_{Otto}$$

7. What is a Brayton Cycle ? Draw the cycle diagram in $p-\forall$, $T-s$ and h-s diagrams ?

(Refer Slide Time: 59:30)

8. How does the thermal efficiency of a Brayton Cycle depend on the pressure ratio of the cycle ?

9. Describe open cycle and closed cycle gas turbine plants. Which one of these two can be described truly by a thermodynamic cycle ?

10. What is meant by regeneration in a gas turbine plant ?

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11. Explain why the thermal efficiency of a gas turbine plant increases due to regeneration ?

12. What are Stirling Cycle and Ericsson Cycle ? Under what circumstances, the thermal efficiencies of these two cycles become identical to that of a Carnot Cycle having the same maximum and minimum temperatures of the two cycles.