

Refrigeration and Air Conditioning
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Lecture No. # 09
Air Cycle Refrigeration Systems

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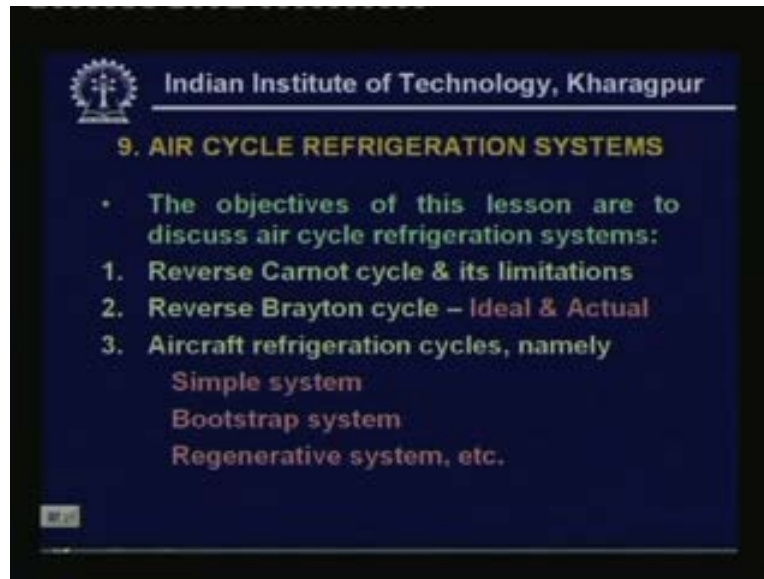


Welcome in this lecture I shall discuss air cycle refrigeration system.

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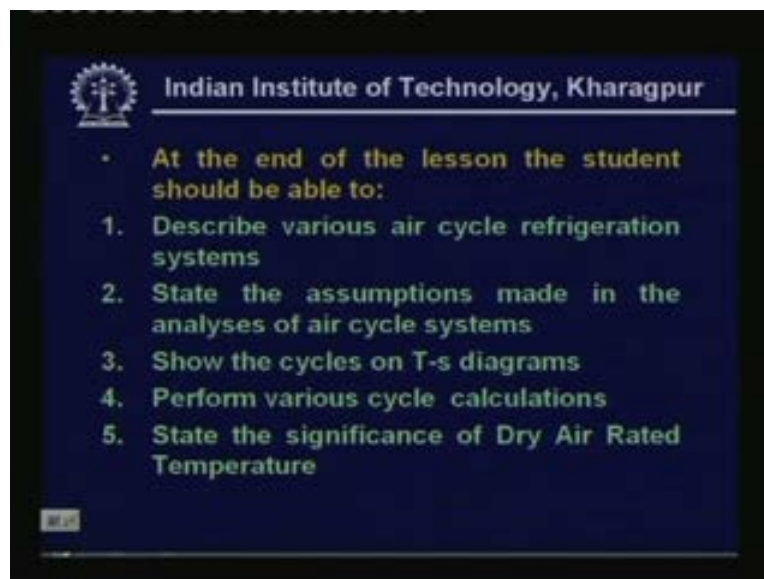


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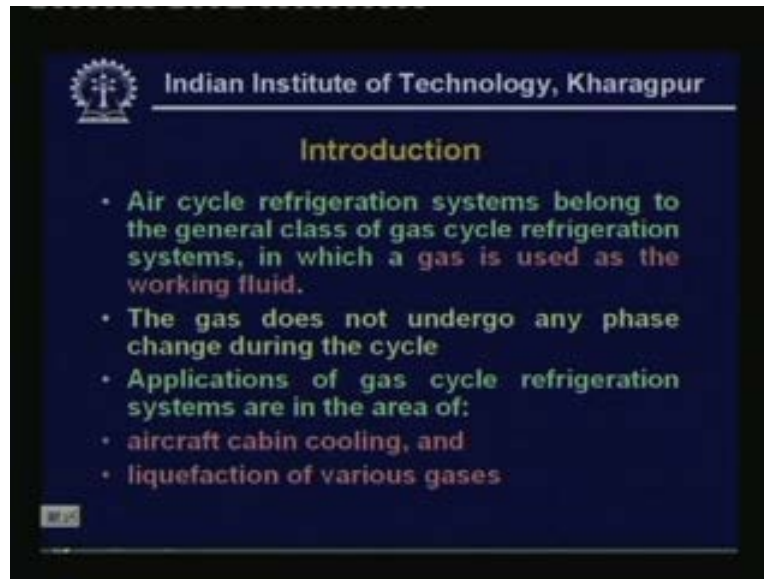
So the specific objectives of this lesson to discuss Reverse Carnot cycle and its limitations, to discuss Reverse Brayton cycle both ideal as well as actual and discuss various Aircraft refrigeration cycles namely Simple system, Bootstrap system, Regenerative system etcetera.

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At the end of this lesson you should be able to describe various air cycle refrigeration systems, state the assumptions made in the analysis of air cycle systems, show the cycles on T s diagrams, perform various cycle calculations and state the significance of dry air rated temperature.

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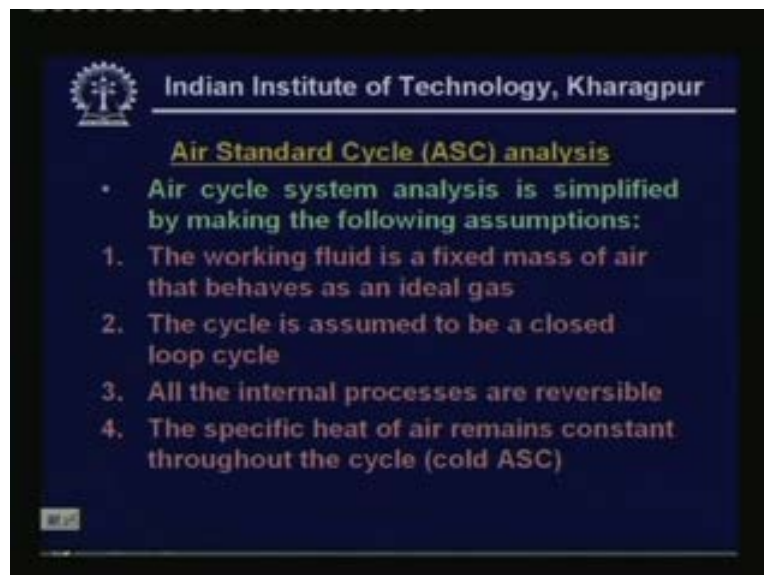
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Introduction

- Air cycle refrigeration systems belong to the general class of gas cycle refrigeration systems, in which a gas is used as the working fluid.
- The gas does not undergo any phase change during the cycle
- Applications of gas cycle refrigeration systems are in the area of:
 - aircraft cabin cooling, and
 - liquefaction of various gases

Let us let me give a brief introduction air cycle refrigeration systems belong to the general class of glass a gas cycle refrigeration systems in which a gas is used as the working fluid. So here the working fluid is the gas and this gas does not undergo any phase change during the cycle. That means basically this cycle is all the processes in this cycle are essentially sensible heat transfer processes. There are no phase change processes and applications of gas cycle refrigeration systems are in the areas of aircraft cabin cooling and liquefaction of various gases. In the particular this particular lecture I will be confining myself to air cycle refrigeration systems. So liquefaction of various gases and all will not be discussed here.

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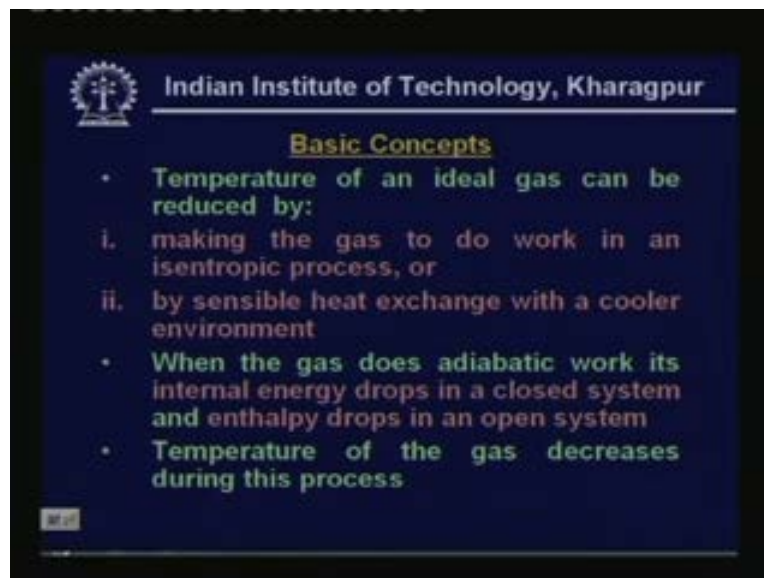
Air Standard Cycle (ASC) analysis

- Air cycle system analysis is simplified by making the following assumptions:
 1. The working fluid is a fixed mass of air that behaves as an ideal gas
 2. The cycle is assumed to be a closed loop cycle
 3. All the internal processes are reversible
 4. The specific heat of air remains constant throughout the cycle (cold ASC)

Before we take up the various cycles I would like to mention here an important type of analysis known as Air Standard Cycle analysis. Air cycle system analysis is simplified by making the following assumptions. The first assumption is that the working fluid is considered to be a fixed mass of air which behaves as an ideal gas. The cycle is assumed to be a closed loop cycle all the internal processes are reversible and the specific heat of air remains constant throughout the cycle. This particular analysis is what is known as cold air standard cycle analysis you might have studied in thermodynamics you might have used this particular analysis for analyzing gas power cycles.

So we will be using the same type of assumptions and same type of analysis for gas cycle refrigeration systems also. This analysis gives reasonably accurate results for almost all situations except for the process of throttling. Because if you remember in the last lecture the throttling cooling during throttling depends mainly on the real gas behavior. So if we are assuming the gas to be ideal then during the throttling there will not be any temperature reduction. So as I said these cold air standard cycle analysis is good for all the processes except the throttling in the cycle. That I am going to discuss in this particular lesson we will not be encountering throttling process so this particular analysis is good for us at this juncture.

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Now let us look at some basic concepts how do we reduce the temperature of an ideal gas we cannot reduce the temperature of an ideal gas by throttling that is what we have seen in the last

class. Then what are the other ways of reducing the temperature you can reduce the temperature by making the gas to do work in an isentropic process or by sensible heat exchange with a cooler environment. So if the, if the gas is doing work in an isentropic processes obviously its enthalpy or internal energy reduces as a result its temperature also reduces. The second way of reducing its temperature is by exchanging heat with a cooler medium. So in the cycles that we are going to discuss in this particular lecture we will be mainly relying on the isentropic process for reducing the temperature.

When the gas does adiabatic work its internal energy drops in a closed system and enthalpy drops in an open system. That means whenever when the process is adiabatic that means there is no heat supply to the system or heat supply from the system and at the same time the system is doing work. Obviously it will be doing work at the cost of its own energy if, if it is in a closed system then it will be an internal energy if it is an open system it will be enthalpy. So it will be doing performing the work at the cost of its internal energy or enthalpy. Since it is delivering a net work output obviously the internal energy or enthalpies have to reduce once these two are reducing. Since we are assuming the working fluid to behave as an ideal gas obviously the temperature has to reduce because internal energy and enthalpy of ideal gases are functions of temperature only.

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- Isentropic process 1-2 in a closed system,

$$W = m(u_1 - u_2) = mc_v(T_1 - T_2)$$
- Isentropic process 1-2 in an open system,

$$W = m(h_1 - h_2) = mc_p(T_1 - T_2)$$
- For isentropic expansion of an ideal gas:

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}}$$
- Where

$$\gamma = \left(\frac{c_p}{c_v} \right)$$

So temperature of the gas decreases during the process. So you can see here for example a closed system undergoing an isentropic process one to two. So the work output is given by $m(u_1 - u_2)$ which can be written as $m c_v (T_1 - T_2)$ where m is the mass of the system undergoing a the isentropic process. u_1 and u_2 are the specific internal energies at the beginning of the process and at the end of the process T_1 and T_2 are the temperatures at the beginning and end of the process and c_v is as you know is a specific heat at constant volume.

So since W is positive u_1 is greater than u_2 so obviously T_1 will be greater than T_2 . So this is the typically equation for an isentropic process affect low system. Of course you can derive this very easily by applying the first law of thermodynamics to a closed system heat transfer rate is zero. So work transfer rate is equal to change in the internal energy if you apply the same first law of thermodynamics to an open system then you get the equation in the form W is $\dot{m}(h_1 - h_2)$ which can be written as $\dot{m} c_p (T_1 - T_2)$ where W is the power output \dot{m} is the mass flow rate of the working fluid h_1 and h_2 are the initial and final enthalpies T_1 and T_2 are the initial and final temperatures c_p is the specific heat at constant pressure.

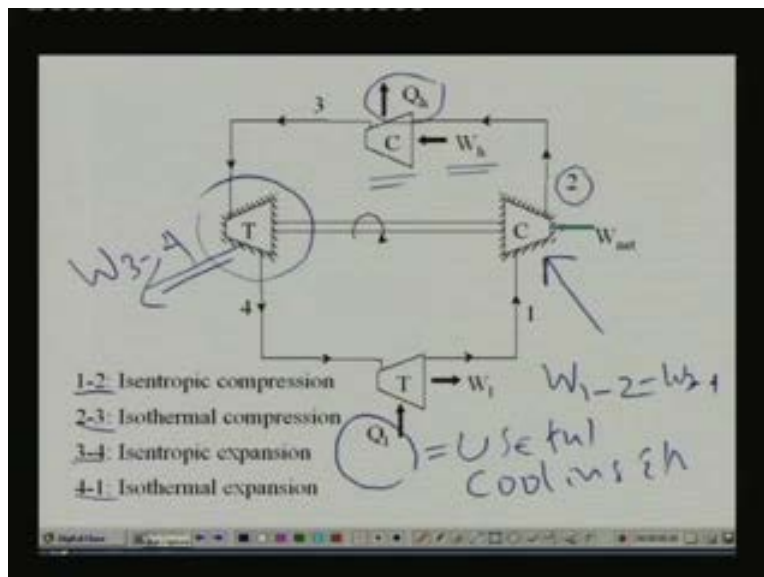
And for both closed as well as open systems you can very easily show that whenever an ideal gas is undergoing isentropic expansion the temperature is related to pressure that is given by this relation shown here T_2 is equal to $T_1 (P_2/P_1)^{(\gamma-1)/\gamma}$ where γ as you know is equal to c_p/c_v for ideal gases. This equation can be very easily derived by applying two equations one is ideal gas equation of state that is $p v$ is equal to $R T$ and second is the process equation for an isentropic process that is $p v^\gamma$ is constant. So if we are using the equation $p v$ is equal to $R T$ and also $p v^\gamma$ is equal to constant then you can get this expression for the temperatures in terms of the pressure ratios.

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Now let us begin our discussion with an ideal cycle called Reverse Carnot cycles for gases this is an ideal cycle for constant temperature heat source and sink. That means whenever we have an external heat source or sink which is at constant temperature then the reverse Carnot cycle is the ideal cycle. So it is a completely reversible cycle so let me describe the cycle now.

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Yeah. So this cycle consists of four processes first process one to two is isentropic compression process two to three is isothermal compression process three to four is isentropic expansion four to one is isothermal expansion. So these can be opt achieved either by using a closed system

concept or in open system concept. For example you can have isentropic compression expansion etcetera using a piston cylinder device, means in which case the system becomes a closed system. Or you can also have an open system where there is steady flow of the working fluid through each component. So what the example I have shown here is for an open system? So typically steady flow energy equations can be applied to each of the components okay. So the first process one to two this is as I said is an isentropic compression this is achieved in a compressor which compresses the working fluid from point one to point two in an isentropic manner.

In fact it is an irreversible I should mention that it should be reversible adiabatic compression process which in turns out to be an isentropic process. So for this process you have to supply some work input okay let that work input be W_{1-2} okay. And there is no heat transfer because this is an adiabatic process okay. So W_{1-2} is the work transfer during this process this is the work input to the compressor. Next what happens is the gas which is now at a high temperature and high pressure undergoes what is known as isothermal compression okay?

You can see that process two to three is an isothermal compression that means its temperature remains constant during the process at that same time its pressure increases okay. This is a compression process. So you have to supply work input to the compressors since its temperature has to remain constant obviously there must be some heat transfer.

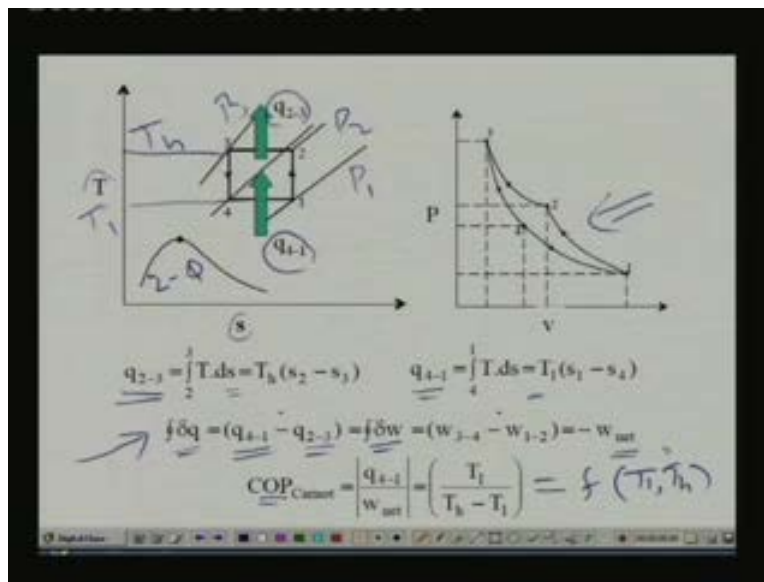
And if you are applying steady flow energy equation you can easily show that the work input should be same as the heat transfer rate so that your temperature remains constant for the ideal gas okay. And process three to four that is taking place in an isentropic turbine so during this process it gives out actually a work output okay. So this is the work output from the turbine and this is as I said is an isentropic process. So during this process its pressure and temperature and enthalpy everything reduces so the enthalpy temperature and pressure at point four will be lower than at point three okay.

And actually what is done here you can see that the turbine and compressor are coupled here. That means the work output of the turbine is applied to the compressor okay. So the network output here will be W_{1-2} minus W_{3-4} okay. The next process is what is known as isothermal expansion process four to one this takes place in an isothermal turbine. Its temperature has to remain constant at the same time it has to extract heat from a low temperature reservoir. That means here it will be rejecting heat to a high temperature heat sink and it will be

extracting heat from a high temperature heat reservoir or heat source okay. Since its temperature has to remain constant. That means obviously this process will take place only when some work is done and this Q_1 will be same as equal to W_1 okay. And this is the useful refrigeration effect useful cooling effect.

So we have four two compressors and two turbines one compressor is an isentropic compressor one compressor is an isothermal compressor one turbine is isentropic or turbine and the other one is isothermal turbine. Let me show this cycle on T S and P V diagrams.

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Okay. So here you can see the T S and P V diagrams here you can see that this is a two phase region okay. Since this is a gas cycle complete cycle will be taking place away from the two phase region so you do not really have any liquid phase okay. And the four processes described earlier process one to two isentropic compression you can see that the x axis is entropy and y axis is temperature. So isentropic compression means it may vertical line from a low pressure P one to an intermediate pressure P two okay. So this is a vertical line and the process two three is isothermal compression okay. So pressure increases again from P two to P three. At the same time temperature remains constant and during this process this much amount of heat is transferred okay. And process three to four is isentropic expansion in the turbine entropy remains constant temperature falls. And process four to one is isothermal expansion so you have to supply heat Q four to one which is the refrigeration effect here.

And the same process is shown here on P V diagram okay. So one to two is an isentropic process two to three is isothermal three to four is again isentropic and four to one is again isothermal process. And by applying our T d s relations and first and second law equations you can show that the heat transferred during the process q two to three is integral T d s from two to three and temperature remains constant. Let this temperature be T h okay. Then q two to three is nothing but integral T d s which is equal to T h into s two minus s three similarly heat transfer during the process four to one is integral T d s from four to one and which is equal to T l s one minus s four where T l is the low temperature.

So basically the Carnot cycle operates between two temperatures one is a low temperature and the other one is high temperature. And this is the heat transfer during the heat rejection process and heat transfer during the heat extraction process. And now if you apply the first law of thermodynamics to the entire cycle, so as you know first law is nothing but cyclic integral of Do q should be equal to cyclic integral of Do w okay so what is the heat different heat transfer rates at heat transfers during the cycle. We have heat transfer taking place only during two processes process two to three and process four to one and q four one is positive. Because you are supplying heat to the cycle and q two to three is negative because heat is being rejected from the cycle.

So we are following the sign convention so cyclic integral of Do q is equal to q four to one minus q two to three. And cyclic integral of Do w is nothing but net work input to the system okay. And then the COP of the system is defined as the cooling effect divided by the net work input. That is q four to one divided by w net okay. So if we are substituting these expressions here you will ultimately find that COP of the Carnot cycle is simply equal to T l divided by T h minus T l that means it is only a function of T l and T h okay. So it is independent of your working fluid and all that this is one very peculiar thing of Carnot cycle. It is only a function of temperatures okay. And you from the expression you can see that COP increases as T l increases and COP also increases as T h reduce. So basically the COP of the Carnot system increases as the temperature different between the high temperature and low temperature reduces okay.

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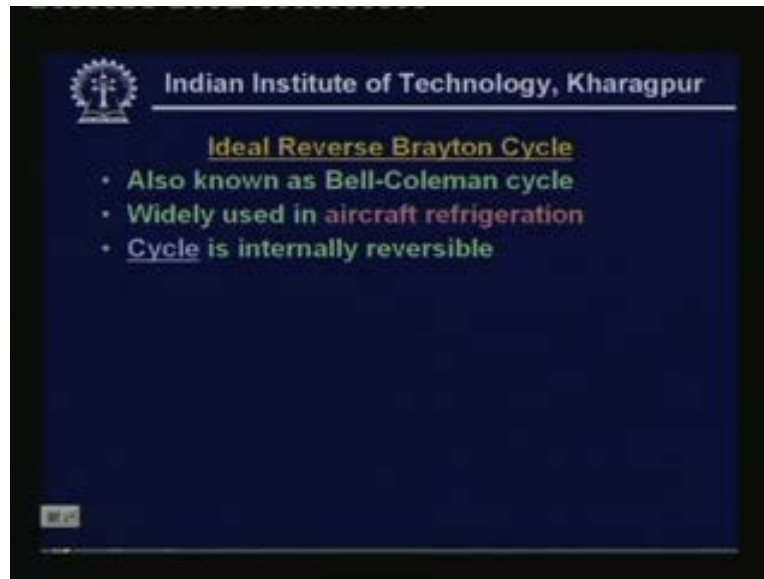


So we have seen that COP is the function of high and low temperatures only. And what are the limitations of as I said this is an ideal cycle so normally Carnot cycle cannot be built in practice but this is used as a reference. So normally we use it as a standard and we compare the actual cycles with the Carnot cycles just to know how good our cycle is compared to the best possible cycle okay. So the best possible or the ideal cycle is most of the cases Carnot cycle okay. But as I said Carnot cycle is not possible in practice especially Carnot gas cycle is not possible in practice because of the limitations. What the limitations are.

The first limitation is that the isothermal compression and expansion are difficult to achieve in practice. So you have seen that process two to three and process four to one are isothermal processes at the same time some work transfer has to take place okay. So this is very difficult to achieve especially when we are dealing with high speed turbines or high speed compressors they will be operating closer to adiabatic conditions than isothermal conditions. So achieving isothermal compression and isothermal expansion is very difficult so normally it is not possible in practice so this is the first limitation.

The second limitation is that Carnot gas cycle offers very small volumetric refrigeration capacity. As a result the amount of air that has to be handle by the system will be very large. So this is another practical limitation. So you really do not find any reverse Carnot cycle working in practice. So now let us look at a cycle which actually found in practice okay, which can be built okay this is high volumetric flow rates.

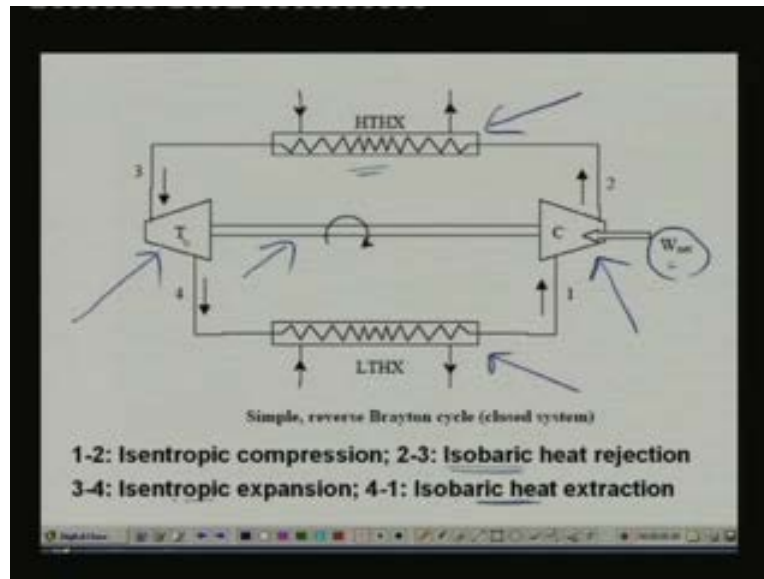
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So such a cycle is known as Reverse Brayton Cycle. Let us first look at ideal reverse Brayton cycle this is actually a modification of Carnot cycle and this is also known as Bell Coleman cycle or sometimes as Joules cycle okay. So Bell Coleman cycle reverse Brayton cycle and Joules cycle means the same thing. And this is widely used in air craft refrigeration and this cycle is internally reversible Carnot cycle is both internally as well as externally reversible. So you call Carnot cycle as a completely reversible cycle. That means the heat transfer rate for example you take a heat transfer process in a Carnot cycle it has to be internally reversible and it has to be externally reversible.

That means heat transfer between the external sources or sink and the working fluid must take place reversibly. That means there should not be any temperature difference between the source or sink and the working fluid okay. Then you call and there is no internal irreversibility also such cycles you call as completely reversible cycle. The Brayton cycle that we are going to discuss now they have to be internally reversible. That means there should not be any internal irreversibility such as friction fluid friction etcetera let me show the cycle now okay.

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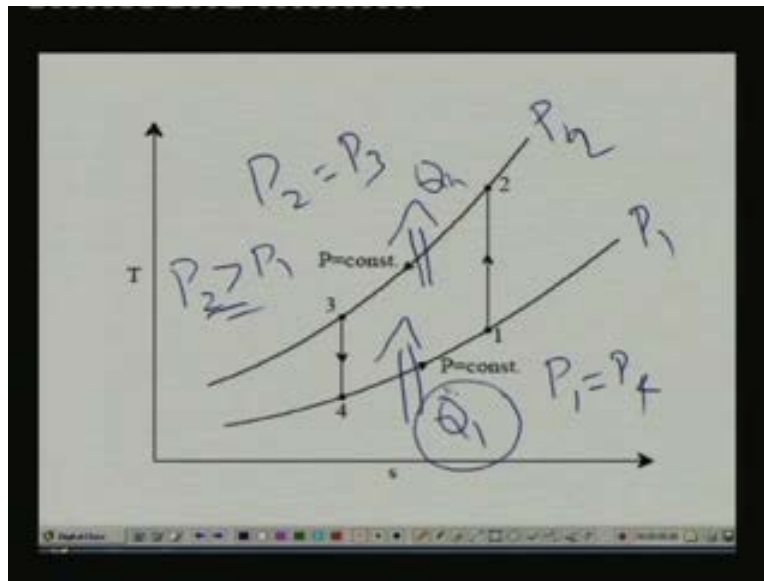
So what I am showing here is a schematic of the cycle. So it consists of four components one is a compressor a high temperature heat exchanger a turbine and a low temperature heat exchanger okay. So if you see if you see the compare this cycle with Carnot cycle you find that there are two changes. The first change is that the isothermal compression here is replaced by a heat exchanger that means isothermal compressor is replaced by a heat exchanger. Similarly the isothermal turbine is replaced by a low temperature heat exchanger okay. So now what are the four processes in this particular cycle the first process one to two is isentropic compression okay. So the air or working fluid gets compressed isentropically in the compressor so its isentropic compression.

And process two to three is isobaric heat rejection. This was isothermal heat rejection in case of Carnot cycle. But in the isothermal process is replaced by isobaric process in Brayton cycle okay. So process two to three is isobaric heat rejection. Then process three to four is isentropic expansion and process four to one is isobaric heat extraction. So the only changes are in the process two to three and four to one process one to two and three to four are same as Carnot cycle okay. So this is the simple reverse Brayton cycle.

Now let me show this cycle on T S diagram before I show this cycle let me once again point it out that here we have clubbed the shaft of the turbine is connected to the shaft of the compressor. That means the work output of the compressor turbine is supplied to the compressor okay. So still the cycle requires some positive network input to the system okay. You can never have the

work output of the turbine greater than the work input required for the compressor because that will violate the second law okay. So there must be always some network input to the system okay. So that network input is the difference between the works of the compressor minus the work of the turbine okay.

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So now the process is shown on T S diagram. As you can easily see that you have two pressures here let us say this is P_h or okay P_2 and this is P_1 and the P is constant so P_2 is equal to P_3 and this is again an isobar so P_1 is equal to P_4 okay. And P_2 is greater than obviously P_1 right so process one to two is an isentropic compression. So it is a vertical line. Process two to three is isobaric heat rejection. That means along the constant pressure line and during this process you can see that the temperature of the air drops from T_2 to T_3 and process three to four is isentropic expansion in the turbine okay. So it is again a vertical line and process four to one is again isobaric heat extraction from the heat source. That means basically you have heat extraction from the low temperature heat source and heat rejection at this point okay. And as you know if we are using it for cooling this is our required cooling output okay.

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$$W_{1-2} = m(h_2 - h_1) = m c_p (T_2 - T_1)$$

$$Q_{2-3} = m(h_2 - h_3) = m c_p (T_2 - T_3)$$

$$W_{3-4} = m(h_3 - h_4) = m c_p (T_3 - T_4)$$

$$Q_{4-1} = m(h_1 - h_4) = m c_p (T_1 - T_4)$$

$$P_1 V_1^\gamma = P_2 V_2^\gamma \quad T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} = T_1 T_p^{\frac{\gamma-1}{\gamma}}$$

Pressure ratio = $\frac{P_2}{P_1} = \frac{T_2}{T_1}$

Now let do we can quickly write the equations for various processes? For example process one to two what we are doing is we are simply applying the steady flow energy equation. We are neglecting changes in kinetic and potential energies okay. So these are the two assumptions. Apart from that we are following the cold air standard cycle analysis okay. That you must keep in mind always for this lecture okay. So for process one to two is isentropic compression. So there is no heat transfer only work transfer takes place. So this is the work input to the compressor. This is simply equal to mass flow rate of the air into h_2 minus h_1 this is enthalpy change during the compression process okay.

So h_2 minus h_1 is written as c_p into T_2 minus T_1 where as c_p is the specific heat T_2 and T_1 are the final and initial temperatures for the compressors okay. And process two to three if you remember is isobaric heat rejection okay. During this process there is no work done. That means there is no work transfer during this process okay. So W_{2-3} is zero because this process was performed in a heat exchanger. So no work was done so when this is zero and when again ΔK and ΔP are negligible if you are applying steady flow energy equation you can easily show that Q_{2-3} is $m \dot{m}$ into h_2 minus h_3 which is equal to $m \dot{m} c_p$ into T_2 minus T_3 . And process three to four is isentropic expansion so Q_{3-4} is zero okay so W_{3-4} is Q_{3-4} $m \dot{m}$ into h_3 minus h_4 which is equal to $m \dot{m} c_p$ into T_3 minus T_4 .

And finally process four to one again work is zero during this process and its isobaric heat rejection. So you can write this as $m \cdot c_p (T_1 - T_4)$ which is equal to $m \cdot c_p (T_1 - T_4)$. Again for the process one to two you can get this equation very easily as I was mentioning in the little while ago you can get this expression how do you get it. We can write $P_1 V_1 = R T_1$ and $P_2 V_2 = R T_2$ and $P_1 V_1^\gamma = P_2 V_2^\gamma$ okay. So if we are using these two equations you can arrive at this expressions okay. So what it shows is the exit temperature of the compressors is equal to the inlet temperature multiplied by the pressure ratio to the power of gamma minus one by gamma where gamma is as you know c_p by c_v okay.

I am writing this as $T_2 = T_1 (r_p)^{\frac{\gamma-1}{\gamma}}$ where r_p is equal to P_2 by P_1 . So this is called as pressure ratio we have only two pressures in this cycle so this is the pressure ratio okay.

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$$\rightarrow T_3 = T_4 \left(\frac{P_3}{P_4} \right)^{\frac{\gamma-1}{\gamma}} = T_4 r_p^{\frac{\gamma-1}{\gamma}}$$

From the above equations;

$$\left(\frac{T_2}{T_1} \right) = \left(\frac{T_3}{T_4} \right)$$

From 1st law of thermodynamics for the cycle

$$\oint \delta q = (q_{4-1} - q_{2-3}) = \oint \delta w = (w_{3-4} - w_{1-2}) = -W_{\text{net}}$$

Similar to the process one to two process three to four process three to four is isentropic expansion. So again you can get this equation for the process three to four where T_3 is equal to T_4 into P_3 by P_4 to the power of gamma minus one by gamma which is again equal to T_4 into pressure ratio to the power of gamma minus one by gamma okay. So from these two relations you can very easily show that T_2 by T_1 is equal to T_3 by T_4 okay. And now we apply the first law of thermodynamics for the entire cycle. So as you know

cyclic integral of δq is equal to cycle integral of δW and heat transfer took place in two processes four to one and two to three and this is positive. Because it is taking heat from the heat source so q_{4-1} is positive it is rejecting heat so q_{2-3} is negative okay.

And there are two work transfer processes process three to four that is an isentropic expansion in the turbine. It is positive because system is doing the work and this is the work input to the compressor it is negative. Because you are supplying the work to the system, okay. And this thing is equal to W_{net} right so finally you find the W_{net} is equal to q_{4-1} minus q_{2-3} .

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Handwritten mathematical derivation of COP for a reverse Brayton cycle:

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \quad \text{COP} = \frac{q_{4-1}}{W_{net}} = \left(\frac{T_1 - T_4}{(T_2 - T_1) - (T_3 - T_4)} \right)$$

Also

$$\text{COP} = \left(\frac{T_1 - T_4}{(T_2 - T_1) - (T_3 - T_4)} \right) = \left(\frac{T_4}{T_3 - T_4} \right)$$

Also

$$\text{COP} = \left(\frac{T_1 - T_4}{(T_1 - T_4)(r_p^{\gamma-1} - 1)} \right) = (r_p^{\gamma-1} - 1)^{-1}$$

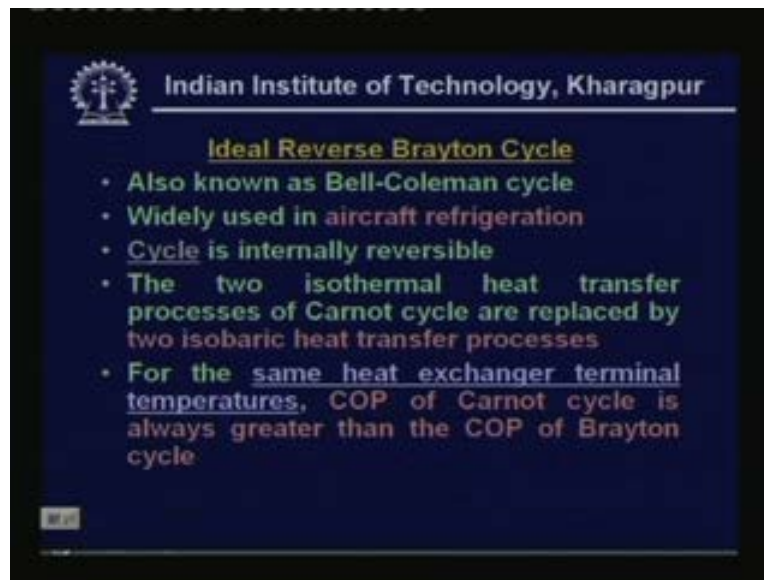
$\therefore \text{COP} = f(r_p)$

So COP again we are defining as q_{4-1} divided by W_{net} so you can very easily show that this is equal to $T_1 - T_4$ divided by $T_2 - T_1 - T_3 - T_4$. And this we can easily show because as I said you can write this expression $T_2/T_1 = T_3/T_4$ so if we are using this expression here you can arrive at this equation okay. And you can also write COP in terms of pressure ratios okay. So again the relation you remember the relation I have shown just now so ultimately you can express COP in terms of pressure ratios and gamma okay.

So finally the COP of the ideal reverse Brayton cycle becomes a function of the pressure ratio and it is very easy to show that COP reduces as pressure ratio increases okay. That means higher the pressure ratio smaller will be the COP okay. So these are the typical equations and it is very

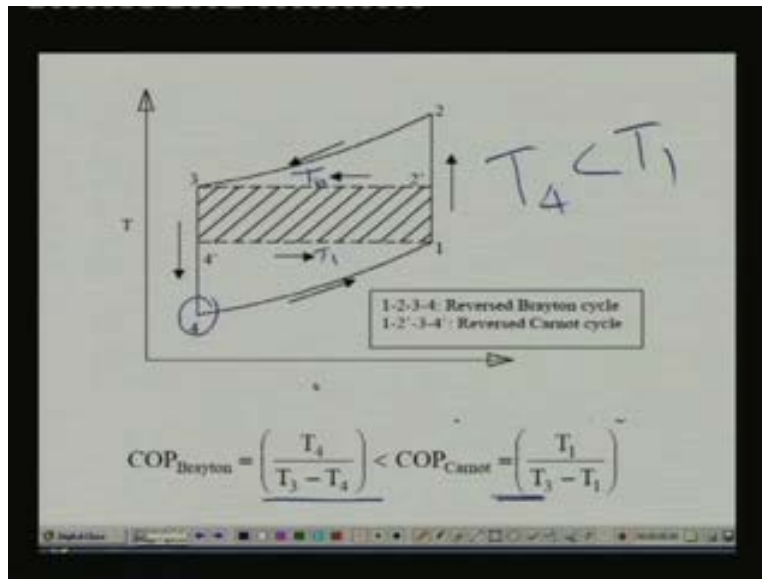
easy to derive these equations on your own. All that you have to do is take each component and apply steady flow energy equation to the component okay. And assume the c_p to be constant neglect kinetic and potential energy changes and apply steady as I said steady flow energy equation to all the components okay.

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Right so we have seen that this is I have already mentioned the two isothermal heat transfer processes are replaced by two isobaric heat transfer processes. And for the same heat exchanger terminal temperatures you can very easily show that the COP of a reverse Carnot cycle is always greater than the COP of Brayton cycle okay. Let me show this. Okay, right I will show this a blank sheet.

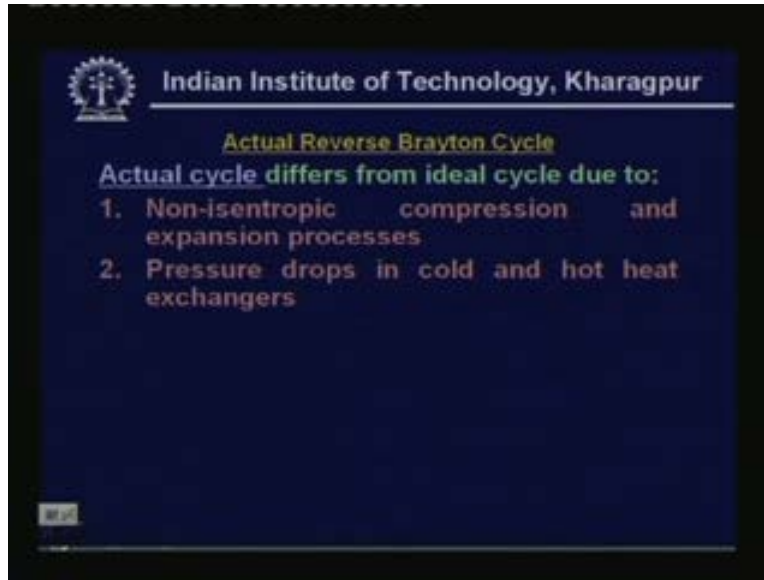
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Okay so what I am showing here is the reverse Brayton cycle one two three four right so you have two isobaric processes here okay. Process two to three and four to one are isobaric processes process one to two and three four are isentropic processes okay. And if I am fixing the terminal temperature of hot and cold heat exchanger that means if I am fixing temperature at point one and temperature at point three then one two dash three four dash will be a Carnot cycle which has the same terminal heat exchanger temperature as that of a reverse Brayton cycle okay right.

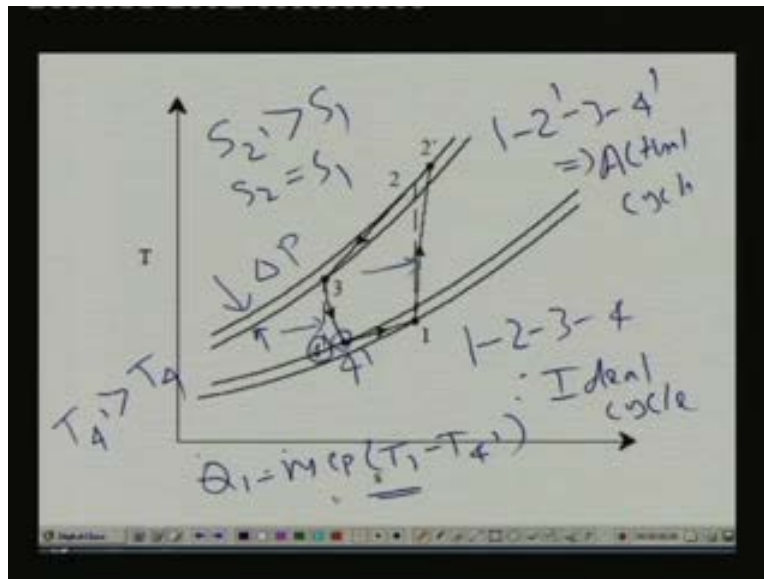
So now for the reverse Brayton cycle just now we have shown that the efficiency is given by T_4 divided by T_3 minus T_4 . That means this temperature divided by this temperature minus this temperature okay. What is the COP of the Carnot cycle COP of the Carnot cycle is obviously depending upon these two temperatures okay. T_h and T_l here T_h and T_l are nothing but T_3 and T_1 so Carnot cycle COP is given by T_1 divided by T_3 minus T_1 okay. So this will always be lower than this why because T_4 is always lower than T_1 okay. T_4 is always less than T_1 as a result COP of the Brayton cycle will always be less than the COP of a reverse Carnot cycle okay.

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Now let us look at actual reverse Brayton cycle whatever we have been discussing so far is an ideal cycle. So the actual cycle differs from ideal cycle due to two reasons the first reason is the non isentropic compression and expansion processes. That means basically the process one to two and three to four could be adiabatic. But there will be definitely irreversible. That means there will be some irreversibility may be due to fluid friction okay. So the process becomes non isentropic this is the first difference between the ideal cycle and the actual cycle. And the second difference is we have neglected all the pressure drops in the cold and hot heat exchanger. Typically when a fluid flows through heat exchanger consisting of long lengths of tubes there will be fluid friction at pressure drops okay. In the ideal cycle we considered that there are no pressure drops so you have only two pressures whereas in an actual cycle there will be pressure drops right. So these are the two reasons why actual cycle differs from an ideal cycle I can show the, this thing on a, so you can see the difference here.

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Here one two three four is the ideal cycle okay. And one two dash three four dash this is point four dash okay. So one two dash three four dash is the actual cycle okay so you can see that.

For example process one to two in the ideal cycle it is an isentropic process okay. In the actual cycle it is non isentropic okay. That means entropy increases during the process because of the irreversibility. That means you will find that entropy at point two S two dashes will be greater than S one where as S two is equal to S one okay so this is one difference.

So what is the consequence of this difference you will find the temperature T two dash will be larger than temperature T two okay. Because the irreversibility you find that the exit temperature is higher compared to the ideal isentropic process okay. And process two to three in actual this thing, this should have been point two should have been here okay. And the heat rejection should have taken place ideally along a constant pressure line but you will find that because of fluid friction there is a pressure drop here okay.

So you find that there is a reduction in pressure during the heat rejection process similarly process three to four three to four entropy remains constant if it is an ideal process. But in actual process again entropy increases. So S four dash will be greater than S three okay. So the process is something like this so as a result you have a cycle one two dash three dash four dash in an actual case what is the consequence of this you can very easily show that the consequence of this is a reduction in the COP okay.

Because COP reduces because of two reasons first reason is that your cooling effect is reduced. Because in an isentropic process, isentropic expansion processes the temperature should have been four. But because of the irreversibility now the temperature is four dashes okay. So T four dash is greater than T four okay and your useful refrigeration effect q_l is $m \cdot c_p$ into T one minus T four dash in case of an actual cycle right. And in case of an ideal cycle this will be T one minus T four since T four is lower than T four dash obviously q_l dash q_l in actual case will be smaller okay.

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Handwritten equations on a whiteboard:

$$W_{net,act} = W_{1-2,act} - W_{3-4,act}$$

$$W_{1-2,act} = \frac{W_{1-2,isen}}{\eta_{c,isen}} \quad \eta_{c,c} < 1$$

$$W_{3-4,act} = \eta_{t,isen} W_{3-4,isen} \quad T_2 > T_2'$$

$$\eta_{c,isen} = \frac{(h_2 - h_1)}{(h_2' - h_1)} = \frac{(T_2 - T_1)}{(T_2' - T_1)} < 1$$

$$\eta_{t,isen} = \frac{(h_3 - h_4)}{(h_3 - h_4')} = \frac{(T_3 - T_4)}{(T_3 - T_4')} < 1$$

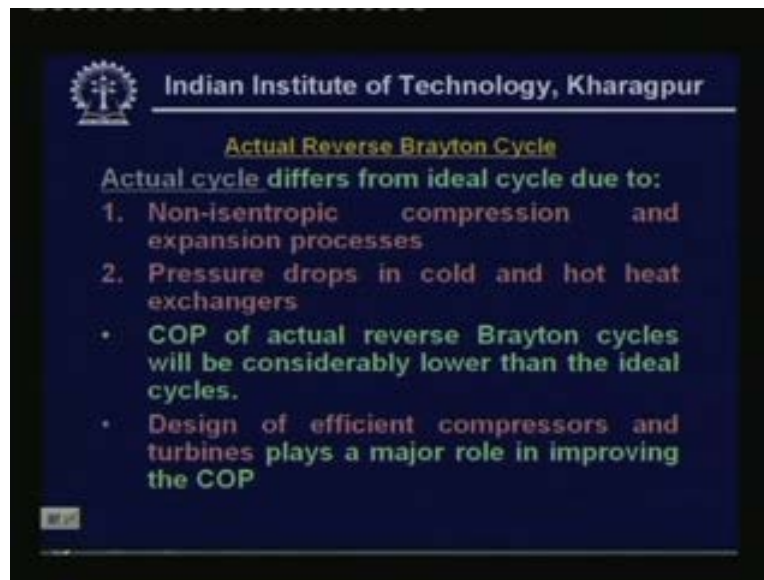
$$W_{net,act} = W_{1-2,act} - W_{3-4,act}$$

And we can also define the actual work of compression and actual work of turbine by defining isentropic efficiencies okay. For example the actual work input to the compressor during the process one to two is defined as an isentropic work divided by the isentropic efficiency okay. So you can see that typically this isentropic efficiency of the compressor will always be less than one. That means $W_{1-2,act}$ will always be greater than $W_{1-2,isen}$ okay. So the required work input increases because of the irreversibility right. And the next process that is isentropic expansion in the turbine the work output of the turbine now gets reduced because of the inefficiency okay. And here again we define an isentropic efficiency for the turbine okay. Again this is lower than one so the work output of the turbine will be lower than the work output of the ideal turbine okay.

So the net result is that W_{net} in an actual case will be much larger than W_{net} of ideal case. Because output is reducing and input is increasing okay. And you can easily write the isentropic efficiency for the compressor in terms of the enthalpies okay. You just look at the earlier diagram. So it is defined as the actual enthalpy change divided by the enthalpy change for an isentropic process. Okay. And this can be written in terms of temperatures because we are assuming the c_p to be constant. So isentropic efficiency of the compressor is written as $T_2 - T_1$ divided by $T_2' - T_1$.

And if you remember T_2 was greater than T_2' okay. So obviously this isentropic efficiency will be, I am sorry, I think it is a, the, it is the other, this thing other way, T_2 is actually lower because T_2' is for the isentropic process okay. So this will be greater than one right and for the turbine. Also you can write the efficiency in terms of the temperatures okay. Again this will be less than one okay. Because as you have seen the actual temperature at the exit of the turbine will be higher than the temperature in an isentropic process okay. So as a result as I said just now the network input increases.

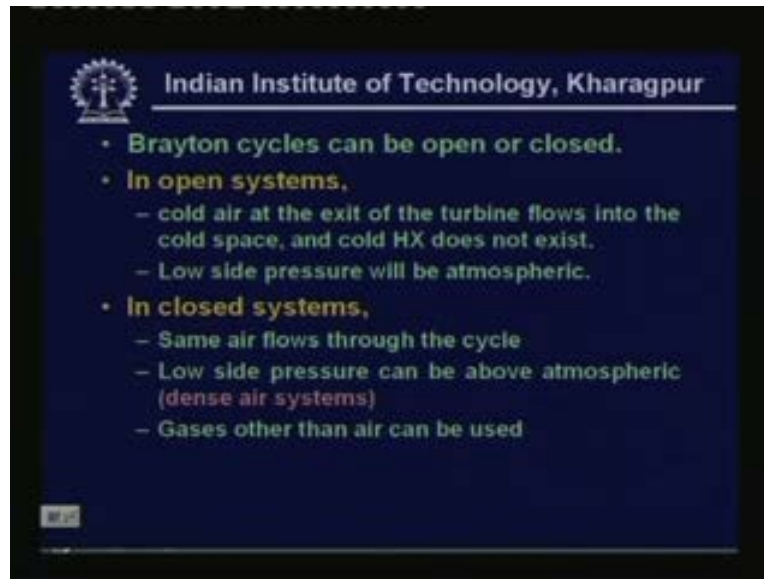
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Right. So we find that COP of actual reverse Brayton cycle will be considerably lower than the ideal cycle because of these two effects reduction in the cooling output and increasing in the network input. In fact the reduction could be quite considerable depending upon the design and one way of improving the system performance is to design efficient compressors and turbines.

Actually this is a very critical issue okay. So if you want to have a good efficiency you must have efficient compressors and turbines.

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Now Brayton cycles can be open or closed okay. So far we have discussed a closed cycle okay. That means the same amount of air is flowing through the cycle repeatedly. But in actual case you can have an open cycle or a closed cycle so let us see what an open cycle is. In open systems a cold air at the exit of the turbine flows into the cold space and cold heat exchanger does not exist. That means what we do in open system is air from the turbine is directly released into a cold space. For example if we are using it for an air craft cooling you directly release the cold air into the cabin of the air craft okay.

So the air gets heated up as it picks the heat from the cabin okay. And then you take the air and send it to the compressor okay. So you really do not have a low temperature heat exchanger okay. So this is an open system right and there is no guarantee that the same air is flowing through the compressor okay. The advantage of this system is obviously its simplicity and since you do not have a cold heat exchanger the total weight of the system will be reduced considerably okay.

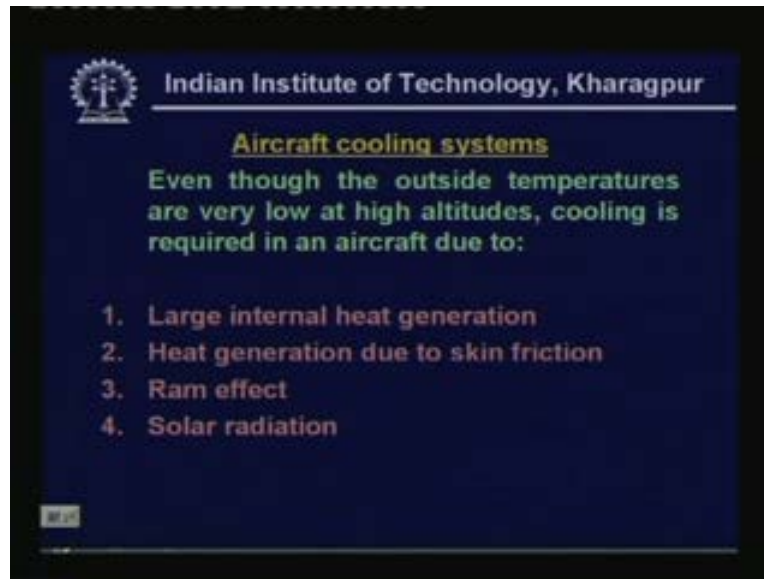
That is the reason why we use this in air craft cooling okay. And second characteristic is typically the low side pressure will be atmospheric. When you are releasing the air into an occupied space typically occupied space pressure should be close to the atmospheric. So the low

side pressure also has to be close to the atmospheric okay. So these are the two characteristics of open systems. As against this open system in a closed system we have two heat exchangers the high temperature heat exchanger and the low temperature heat exchanger and the air in the of the system does not get mixed with the outside air. That means the same air flows through the cycle repeatedly.

And one advantage of this system is that you can have low side pressure higher than the atmospheric okay. Such a cycle is known as dense air system. That means you can operate your low side pressure at pressures much higher than the atmospheric typically three to four bar okay. That means the air will be quite dense okay. So you call this system as dense air cycles. What is the advantage of dense air cycles as you know as you are increasing the pressure the density increases the specific volume reduces and for the same mass flow rate the amount of volume that you have to handle will be reduced considerably okay.

So that means volumetric flow rate of air reduces considerably so this will give you lot of savings in terms of heat exchanger sizes the compressor sizes etcetera. Okay. This is the advantage of dense air cycles okay. So dense air cycles are obviously possible only with closed cycle systems and you can also use gases other than air. For example if you have a close cycle system it is not necessary that you have to use air only okay. You can also use other gases such as helium or any other gas okay. Such systems exist for other applications other than air craft cooling okay. Typically in air craft cooling we use air if normally it will be open okay. Now let us look at air craft cooling systems.

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So why do we need first of all air conditioning or cooling in an air craft. We know that as you go up typically air craft will be flowing very high altitudes it could be as high as let us say ten kilometers or even more. So as you know that as you go up the temperature and pressure both reduce. In fact at an altitude of ten kilometers outside temperature can be as low as minus thirty or minus forty degree centigrade okay, when the outside temperature. So low why do you need a cooling system may be, you may be thinking that you require a heating system because outside temperature is very low.

And the required comfort temperature is about twenty-one degree or so right there is a large temperature difference between the inside and outside okay. So if at all any heat transfer it should take place from the inside to the outside. That means you required a heating system not a cooling system. But you find that in actual practice we need a cooling system not a heating system when the air craft is flying at high altitudes this is because of the following reasons okay. The first reason is that there will be large internal heat generation okay. So typically in an air craft there will be lot of heat generation because of the occupants so normally they are very compacts. Lot of occupants will be there in the population density will be very high in typical air craft and everybody will be releasing heat okay. Due to metabolic rate and also there is large heat generation in a small volume right.

So this will add to the sensible and latent heats of the system okay so as a result temperature and moisture content will increase. Apart from the occupants you can also have, in fact you will also

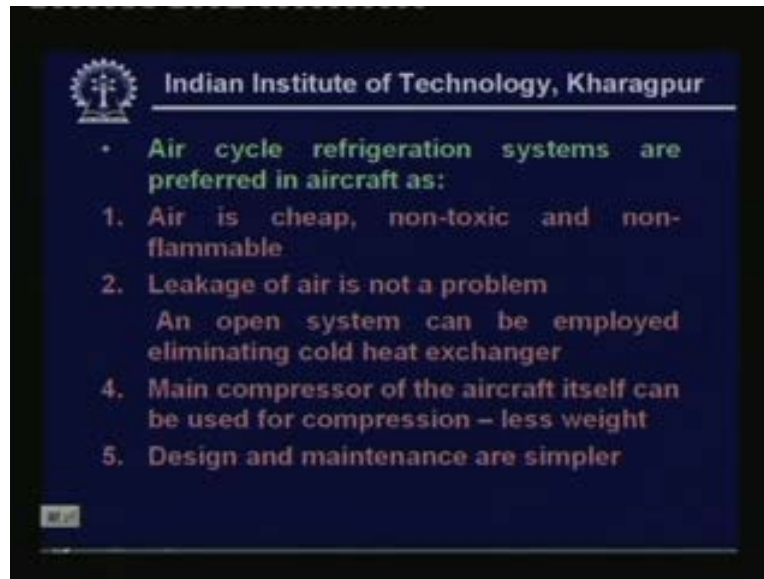
have a large amount of equipment which will be releasing heat okay. Many electronic controls motors etcetera okay. All these equipments will be releasing heat continuously. So you have continuous heat addition to the air inside the cabin because of the people and equipment okay.

So if you do not provide any cooling system because the internal heat generation temperature can shoot up this is not the only reason you also require cooling because there will be heat generation due to skin friction.

Typically aircraft will be at very high speed okay. When it is moving at very high speed in an air there will be large relative velocity okay. So the boundary layers will develop on the surface okay. Since the air has a finite viscosity as you have seen in the earlier classes there will be frictional losses then because of skin friction temperature rises okay. The temperature of the body outside will be higher because of the skin friction. So there will be actually heat transfer from the surface of the body to the interior because of the skin friction okay. So this is the second reason why you need a cooling system. So the third reason is the ram effect so because of the ram effect also the temperature of the air increases okay.

I will explain the ram effect a little while and the fourth effect is solar radiation. For example if the aircraft is flying during the day time then that can be considerable solar radiation and because of solar radiation the temperature can go up. So these are the four reasons why we need a cooling system okay. Typically if the aircraft is flying at low altitudes at low velocities then maybe you can do away with the air conditioning system but if it is flying at high speeds and at high altitudes an air conditioning system is a must.

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Now air cycle refrigeration systems are preferred in aircraft. So why do we use air cycle refrigeration system in aircraft because of the following reasons. The first reason is that obvious reason air is cheap non toxic can non flammable okay. Typically you do not want to use any explosives or flammable gas in an aircraft okay. It has to be absolutely safe so air is the safest refrigerant that you can think off. It is easily available its non toxic and non flammable okay. This is one of the main reasons why we use air in aircraft refrigeration okay. The second reason is leakage of air not a problem. So leakage of air from the system is not a big problem and an open system can be employed eliminating cold heat exchanger.

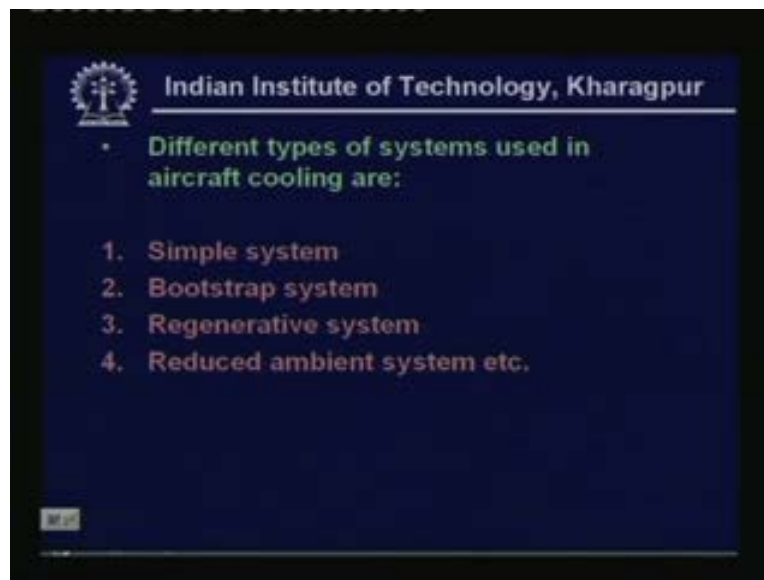
As I was mentioning just now if you are using air you can have an open system. That means you can directly release the air into the system you need not have a cold heat exchanger. What is the advantage of not having a cold heat exchanger? As I have mentioned the system weight will be reduced considerably when you are designing an air conditioning system for aircraft the most important criteria is the weight per kilowatt okay. So the weight is the very important factor and volume is also of course an important factor.

So system that you choose must be lighter okay. So you will see that for aircraft air conditioning the air cycle systems will be lighter okay. One reason is you do not really require a low temperature heat exchanger okay. And the fourth reason is main compressor of the aircraft itself can be used for compression okay. A typical aircraft engine already has a compressor okay. So you also need a compressor for the air conditioning system okay.

So if you are using a air cycle refrigeration for air conditioning you can use the main compressor of the engine itself for compression of the air okay. You do not require separate compressor. So you can see that you do not require a low temperature heat exchanger and you also do not require a separate compressor. So this will lead to significant reduction in the weight okay. So you find that weight per kilowatt of an air cycle system will be much lower than a comparable vapour compression system. For example using a reciprocating compressor in fact the calculation show that the weight will be typically fifty percent that of the comparable vapour compression system okay. So this is these are the reasons why we use air cycle refrigeration systems in aircraft.

Of course the last reason is that these designs of these systems are considerably simpler and the maintenance is also easy okay. So these are the reasons why we prefer air cycle system in aircraft.

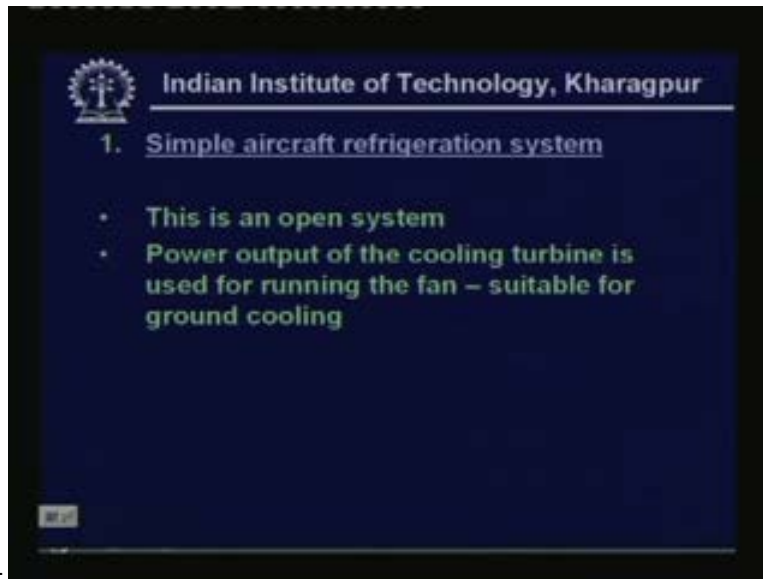
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Now there are different types of systems used in different situations and for different types of aircrafts okay. For example you can have what is known as a simple system you can have a bootstrap system you can have regenerative system. You can also have what is known as reduced temperature system okay. There are other systems also okay. These are the three main systems.

The fourth one as I said is reduced ambient system okay. So each one has its own advantages and disadvantages and applications okay. Let us quickly look at these systems.

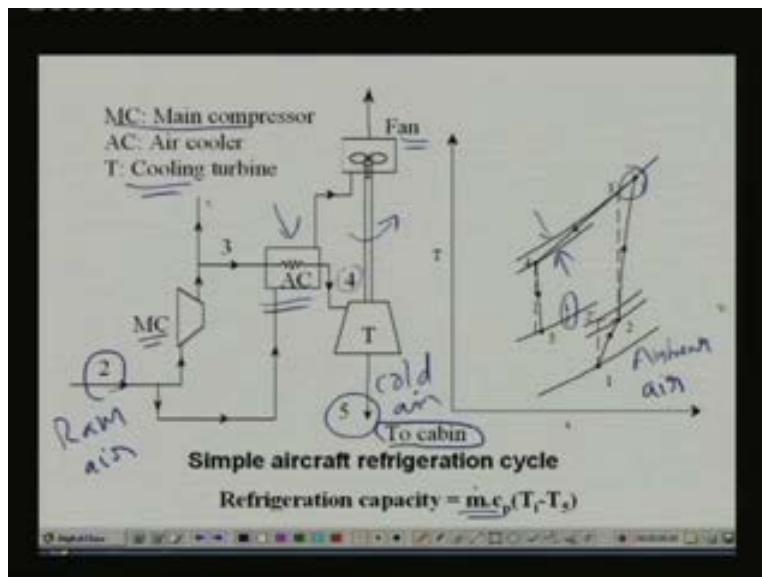
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The first one is what is known as simple aircraft refrigeration system or a simple system. This is an open system the power okay let me first explain the cycle.

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Okay. So let me begin at point two okay. And look at the T S diagram first okay. So this point one is the ambient air okay. So ambient air the pressure and temperature of the ambient air are increased due to ram effect okay, process one to two is what is known as the ram ramming

process okay. During the ram, ramming process its pressure and temperature increases okay. So what we have basically at point two is ram air okay.

So ram air goes to the main compressor okay, M C is the main compressor of your aircraft engine right. So it goes to the main compressor it gets compressed from process two to three okay. So a part of the compressed air goes to your engine and a part of it goes to the air conditioning system okay. So at point three the air that is used for air condition system enters into an air cooler a c so a c is the air cooler and how do we cool this air? Here we again use the ram air for cooling this air. You can see that temperature at point three is much higher than the temperature at point two.

So you can use the ram air for cooling this air okay. So process three four is what occurs in the after cooler the temperature decreases almost isobarically from three to four okay, and ram air is use for cooling this. And at this point at point four it enters into the cooling turbine T okay. And it under goes expansion process four to five and as you know at this pro at this point you have a very cold air okay at point five so cold air at point five is released into the cabin directly okay. So this air goes to the cabin and in the cabin it picks up heat and by the time it comes out of the cabin its condition will be at point I okay. So process five to I is what was happen in the cabin right.

And the power output of the turbine here is not used for running the compressor anything it is used for running a fan okay. So what does this fan do this fan dries the air through the after cooler okay. So that means the power output of the turbine is used for running the fan. And the fan makes sure that sufficient air flows through the air cooler continuously okay. So this is what is known as simple system and here you can see that I have shown the actual cycle. So you have some pressure drops here and non isentropic processes also. So what is the refrigerant capacity of this system? Refrigerant capacity of this system is nothing but $\dot{m} c_p (T_I - T_5)$ where T_I is the cabin temperature okay.

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Ram effect: The pressure and temperature of the outside air increase as it comes in contact with the aircraft due to the conversion of kinetic energy into enthalpy. This is known as ram effect

The temperature rise due to ram effect is given by:

$$\frac{T_2}{T_1} = 1 + \frac{\gamma - 1}{2} M^2$$

a = sonic velocity

$$M = \frac{C}{\sqrt{\gamma R T_1}} = \text{Mach Number}$$

Ram efficiency, η_{Ram} : $\eta_{\text{Ram}} = \frac{(P_2 - P_1)}{(P_2 - P_1)_{\text{isentropic}}}$ *Actual*

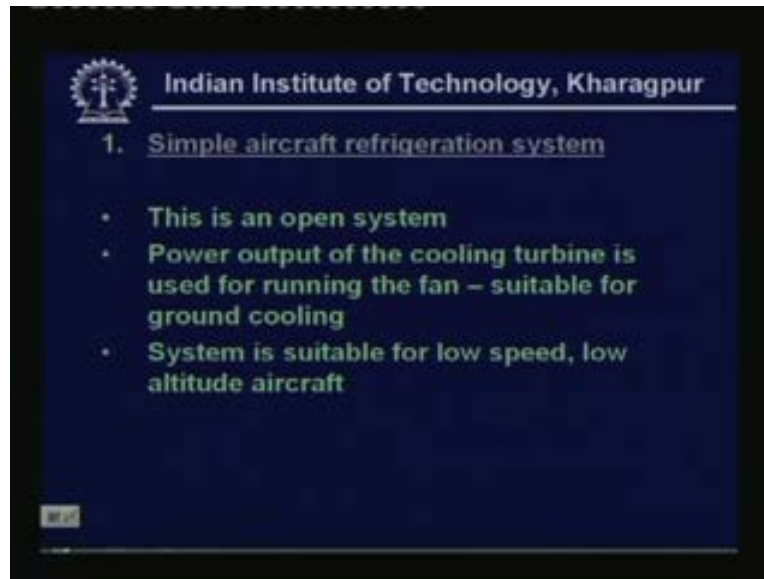
Now let me explain the ram effect. Ram effective is the pressure and the temperature of the outside air increases as it comes in contact with the aircraft due to the conversion of the kinetic energy into enthalpy. See air may be still but the aircraft will be moving at very high speed so there will be a large relative velocity between the air and aircraft okay. So when the air comes in contact with the high relative velocity air comes in contact with the aircraft its kinetic energy will be converted into enthalpy okay. So ultimately you have the enthalpy being converted into temperature and pressure okay. So you have during this process the kinetic energy is converted finally into pressure and temperature okay. So this process is known as ram process or rams effect okay.

And you can very easily shown, show that the temperature rise during ram effect is given by this relation okay. T_2 by T_1 is the temperature at the exit of the ram process T_1 is the temperature of the ambient okay. This is equal to one plus gamma minus one by two into M square okay. Where M is nothing but a Mach number if you remember the Mach number is defined as the ratio of the velocity of the aircraft divided by the sonic velocity. So a is the sonic velocity right and sonic velocity as you know is for an ideal gas is equal to square root of gamma into r into T_1 okay.

And the ram efficiency because the ram process is not strictly isentropic even defined ram efficiency as the actual pressure rise this is actual pressure rise. And the pressure rises if the

process is isentropic okay. So we have the ram temperature rise will be during the ramming and pressure rise during the ram process.

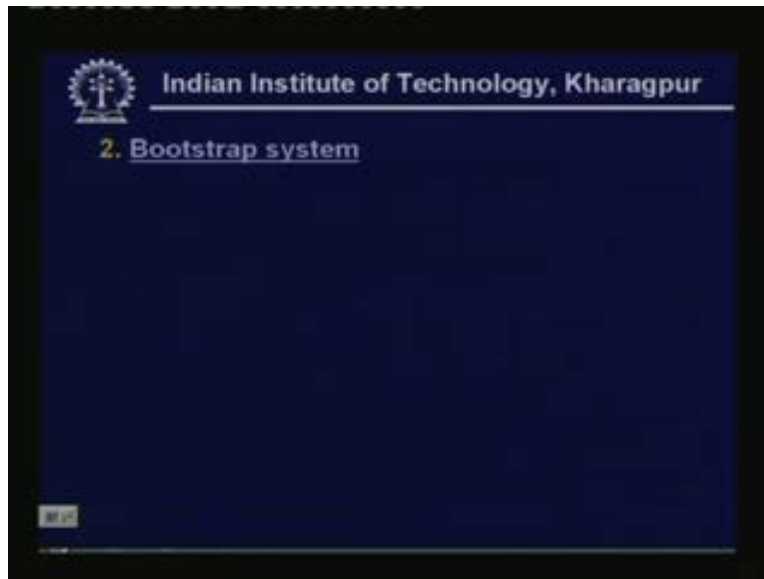
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Okay. So as you can see that the power output of the cooling turbine is used for running the fan and this system is suitable for ground cooling. Why is it suitable for ground cooling? Because on the ground you do not have the ram effect okay. Because the ram effect the always there will be an air flow on the air cooler as long as it is moving.

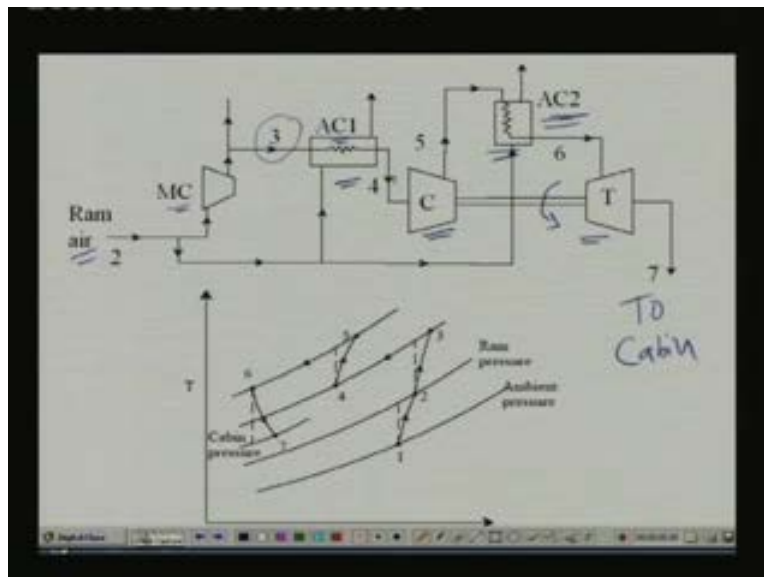
But on the ground aircraft is grounded so the, but still the fan can drive the air okay. So this system is generally suitable for ground cooling. And this system is suitable for low speed low altitude aircraft okay. So simple systems are used for low speed and low altitude aircraft.

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The second system is what you know as a bootstrap system. Let me very quickly explain the bootstrap system.

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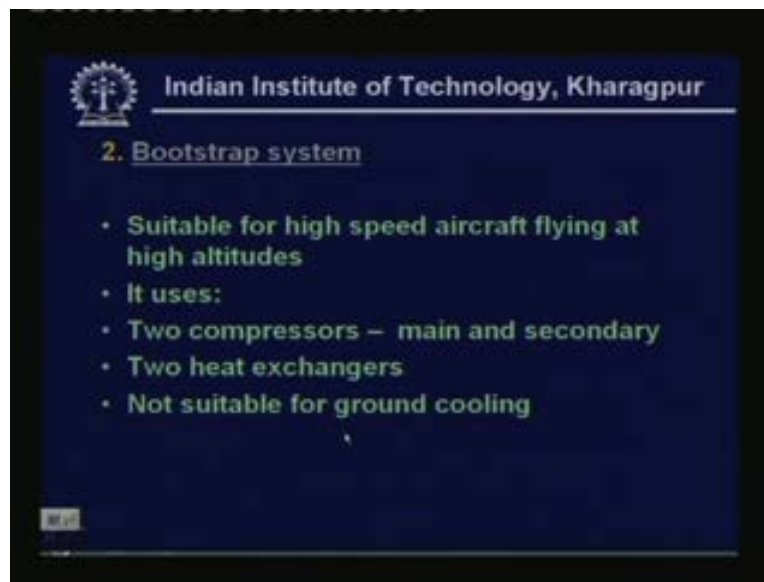


In the bootstrap system we have two heat exchangers and an auxiliary compressor. So the ram air gets compressed in the main compressor M C and at this point it enters into the air cooler. So point three to four temperature reduces and at point four again it is compressed in an auxiliary compressor from point four to five okay. So the of point four to five is what happens in auxiliary

compressor okay. And at point five again it gets cooled as it flows through the air cooler two okay.

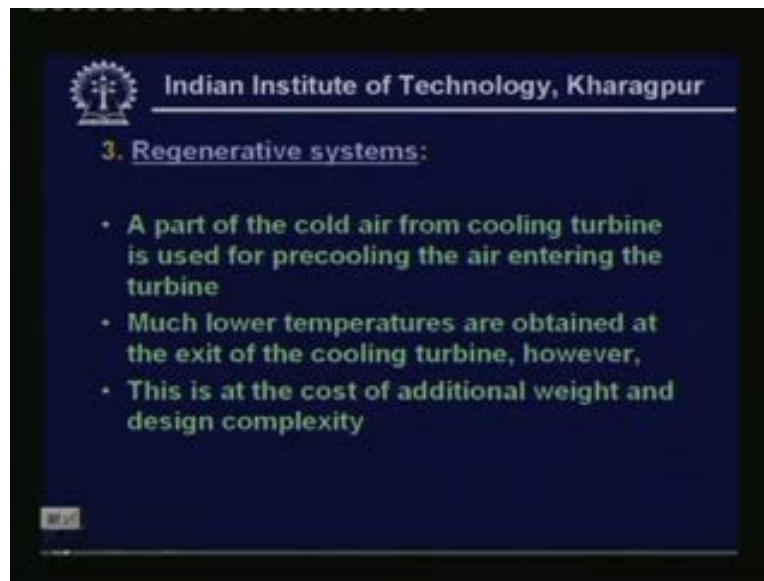
So during this process again the temperature drops from five to six and at this point it enters into the turbine and it undergoes expansion and at this point it goes to the cabin okay. So we can see the difference between the simple system and the bootstrap system okay. And here the power output of the turbine is used for running the compressor right. And the ram air is used for the, for cooling the air cooler one and air cooler two okay, the same ram air is used right. So obviously you can see that this system is not really good for ground cooling. Because when it is on ground you do not have any ram air so the air coolers cannot be cooled. So normally you do not use this system for ground cooling you normally uses it for high speed high altitude flights.

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So as I said suitable for high speed aircraft flying at high altitudes it uses two compressors two heat exchangers and not suitable for ground cooling.

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The other system is what is known as regenerative system I will not explain the system but I will just tell the briefly. In a regenerative system is a part of the cold air from cooling turbine is used for pre cooling the air entering the turbine. That means what is done is you take some cold air from the cooling turbine and use the same cold air for pre cooling the air okay. So that means the air entering into the turbine will be pre cooled okay. So the advantage of this is that exit temperature of the turbine will be very cooled okay. So in a typical regenerative system you can get very cooled air okay. Of course this is at the cost of increased weight and design complexity.

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And one last thing is all the different aircraft cooling systems are compared based on an index called dry air rated temperature or dart DART stands for dry air rated temperature. It is defined as the temperature of air at the exit of the cooling turbine in the absence of any moisture condensation okay. That means when the air is very dry and as it undergoes expansion there should not be any moisture condensation okay. Under such cases what is the temperature at the exit of the turbine that is called as dry air rated temperature okay. And this is the index used for comparing different systems.

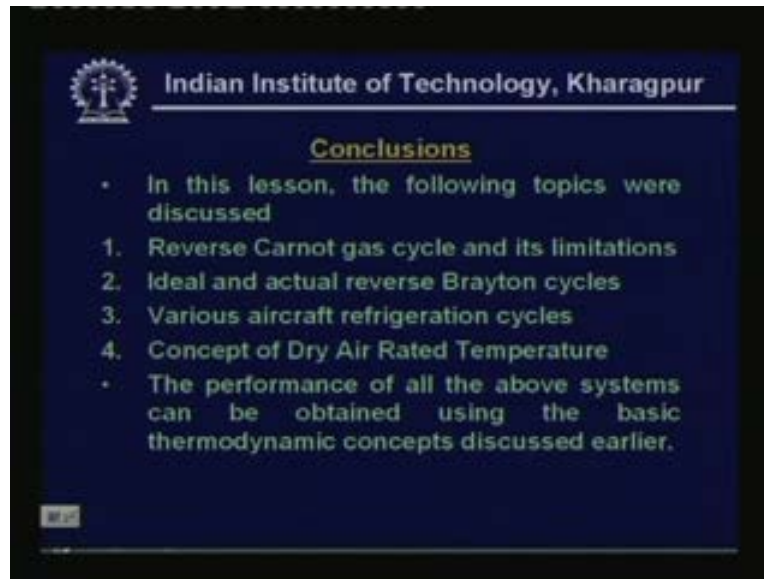
And normally the aircraft systems are rated based on the mass flow rate of air okay. So the rating is done based on the mass rate of air and the refrigeration capacity is obviously given by mass flow rate of air \dot{m} into c_p into T_i minus DART designed DART. That means design dry air rated temperature and T_i is the cabin temperature and \dot{m} is the mass flow rate of the air okay.

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And a comparison of different aircraft refrigeration systems based on DART at different Mach numbers shows that DART increases monotonically for all systems except reduced ambient system. And simple system is good at low Mach numbers and at high Mach numbers we have to use either bootstrap system or regenerative system and the reduced ambient system is generally good for supersonic aircraft okay.

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Let me quickly conclude what we have learned in this particular lecture. We discussed reverse Carnot cycle and its limitations and we have discussed ideal and actual reverse Brayton cycles. And we looked at various aircraft refrigeration cycles and we have also seen the concept of dry air rated temperature. And as I mentioned the performance of all the above systems can be obtained very easily using the basic thermodynamic concepts which we have discussed in the earlier lessons and also in this particular lesson okay.

Right, thank you.