Applied Thermodynamics
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Module - 05
Refrigeration and Air-Conditioning System
Lecture - 37
Vapour Compression Refrigeration System-1

Dear learners, greetings from IIT, Guwahati. We are now in the module 5 of Applied Thermodynamics course and title of this module is Refrigeration and Air Conditioning Systems. So, till this point of time whatever topics we have discussed in this course they were treated as power producing devices.

Now, this is a sector which is refrigeration and air conditioning system where the devices are called as Power Consuming Devices. So, this is again based on the fundamental thermodynamic cycle that is Carnot cycle and when this Carnot cycle is operated in a reverse mode there we can say the heat can be transferred from low temperature region to the high temperature region. If a necessary amount of work is being supplied. So, based on this the Refrigeration and Air Conditioning Systems are evolved.

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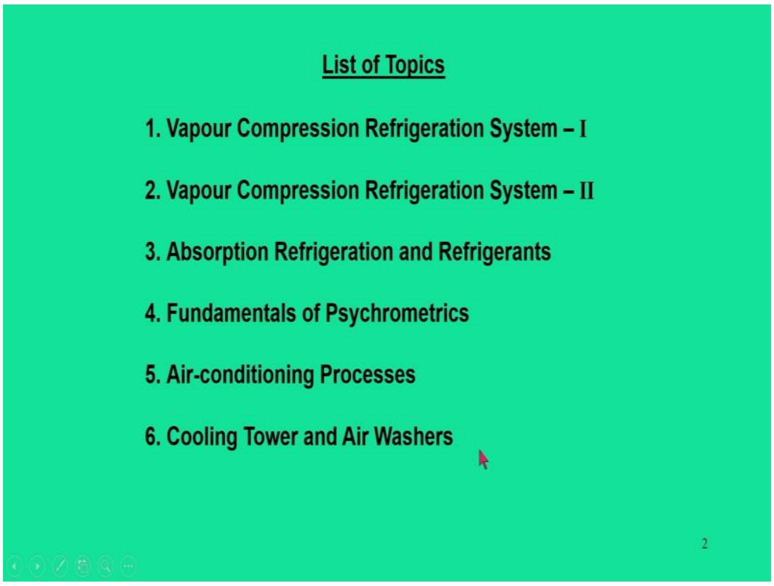

List of Topics

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3. Absorption Refrigeration and Refrigerants
4. Fundamentals of Psychrometrics
5. Air-conditioning Processes
6. Cooling Tower and Air Washers

Now under this particular module we will talk about the following six topics. First two lectures will be devoted mainly on Vapour Compression Refrigerating System. So, this is part I and part II. Then we will move back to the Vapour Absorption Refrigeration and we will give some introduction to the refrigerants.

Then we will move to air conditioning aspects. Now in the air conditioning aspects. The first fundamental things that we are going to study is the principle of Psychrometrics where it deals with the properties of moist air and we would discussed about some fundamental air conditioning processes and finally, in the last lecture we will be mainly focusing on a particular application oriented topic that is cooling towers and air washers.

And with this philosophy we can say how a continuous year wise air conditioning requirements can be achieved through this air washers. So, let us start the first topic or first lecture and that is the vapour compression refrigeration systems.

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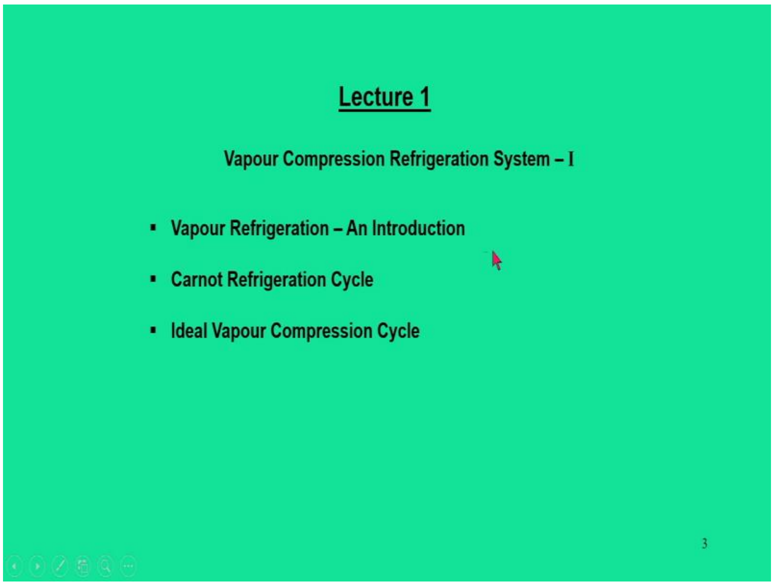

Lecture 1

Vapour Compression Refrigeration System – I

- Vapour Refrigeration – An Introduction
- Carnot Refrigeration Cycle
- Ideal Vapour Compression Cycle

Now, in this Vapour Compression Refrigeration System – I, we will give some brief introductions, then we will talk about how this vapour compression refrigeration was evolved. So, it starts with the Carnot refrigeration cycle with certain limitations and drawbacks in the Carnot cycle, the realistic version of the refrigeration system was evolved and we call this as a vapour compression system. The next we will talk about the Vapour Compression Cycle.

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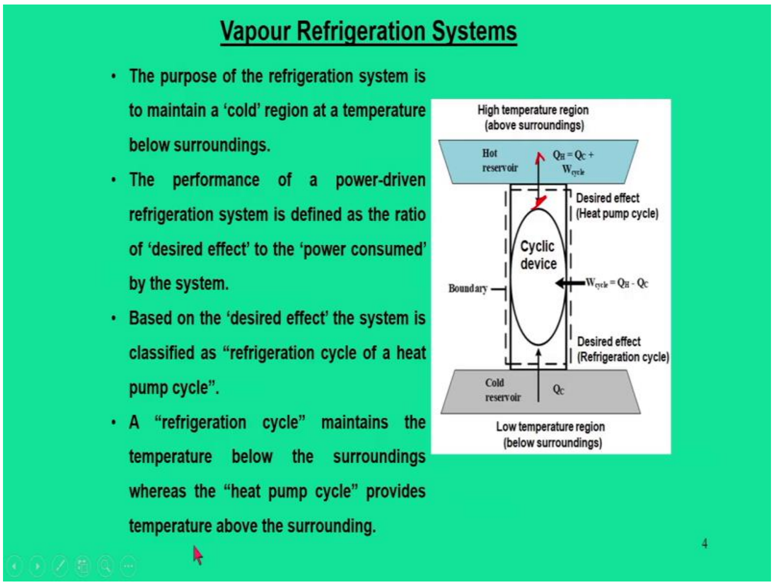

Vapour Refrigeration Systems

- The purpose of the refrigeration system is to maintain a 'cold' region at a temperature below surroundings.
- The performance of a power-driven refrigeration system is defined as the ratio of 'desired effect' to the 'power consumed' by the system.
- Based on the 'desired effect' the system is classified as "refrigeration cycle of a heat pump cycle".
- A "refrigeration cycle" maintains the temperature below the surroundings whereas the "heat pump cycle" provides temperature above the surrounding.

So, let me start the Vapour Refrigeration Systems. So, just to give some introductory remarks, we can say that the purpose of a refrigeration systems is to maintain cold region at a temperature below the surroundings and infact, in our day to day life we all have refrigerators, air conditioning units in our house and these refrigerating systems, they require the electric power as inputs. That is the fundamental source in which is required for them.

And at the cost of that what we are going to get is a desired effect and in our case, this desired effect is the some kind of a coldness or cold region where the bodies has to be maintained. So, the performance of a power driven refrigeration system is defined as the ratio of desired effect to the power consumed by the systems.

So, there are two situations that one can have a refrigeration cycle or a heat pump cycles. So, if you look at this particular figure, here the entire idea and infact, this particular figure is mainly derived from the Carnot cycle which says that we have a cyclic device and in our case its either a refrigerator or a heat pump.

And which consumes work as a input and by consuming this work as input, the cyclic device is able to transfer heat from the cold reservoir and it can the reject this heat to the hot reservoir. So, based on that we say that, from the cold reservoir which is maintained at certain low temperatures it takes Q_C amount of heat and it rejects heat to the hot reservoir at Q_h and based on which we can say the amount of net work which is fed as input and we call as a cyclic work.

Now, here there are two aspects one is this cyclic device can act as a refrigeration cycle or it can as a act as a heat pump cycle and this depends on the what is the desired effect which is required by the user. So, if our desired effect is a hot reservoir that means, if you have a house which requires some kind of heat as a input and you need to supply heat into that house or apartment then that becomes a heat pump cycle because that is our desired effect and based on the work input would be W_{cycle} and this cold reservoir could be ambient conditions.

The other extreme situation could be what we are using in our day to day life that if we have a refrigerator where a space needs to be reserved as a cold compartment, then continuously some amount of heat must be extracted from that compartment and finally, it has to be rejected to the atmosphere.

So, in other side of the story is that your desired effect is the compartment which we need to maintain the low temperatures. So, in that case main requirement is to heat extraction from the compartment. So, if you say that our desired effect is Q_c, then we call this as a refrigeration cycle. So, a refrigeration cycle maintains the temperature below the surroundings whereas, heat pump cycle provides the temperature above the surroundings.

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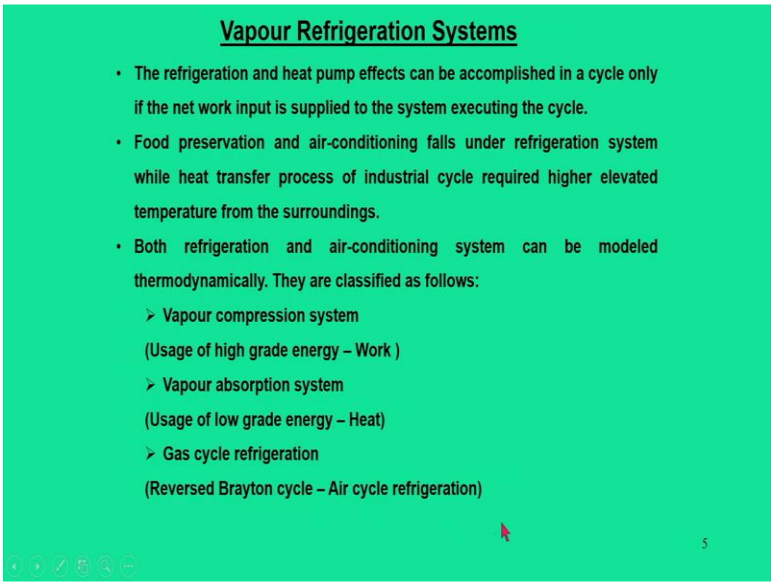

Vapour Refrigeration Systems

- The refrigeration and heat pump effects can be accomplished in a cycle only if the net work input is supplied to the system executing the cycle.
- Food preservation and air-conditioning falls under refrigeration system while heat transfer process of industrial cycle required higher elevated temperature from the surroundings.
- Both refrigeration and air-conditioning system can be modeled thermodynamically. They are classified as follows:
  - ➢ Vapour compression system
    (Usage of high grade energy – Work)
  - ➢ Vapour absorption system
    (Usage of low grade energy – Heat)
  - ➢ Gas cycle refrigeration
    (Reversed Brayton cycle – Air cycle refrigeration)

But both the cycles they require some work input that needs to be supplied for executing the cycle and the common applications in our day to day life is food preservation, air conditioning units, they fall under refrigeration cycle. Heat transfer process in the industrial cycle require higher elevated temperature from the surrounding. So, they require some kind of heat pump cycle.

Both air conditioning and refrigeration systems can be modeled and these modeling can be done by three means. First thing is that the Vapour compression systems. So, in a vapour compression systems, main thermodynamic essential requirement is that in order to get the desired effect or coldness we require the high grade energy as work input. So, in this case it is a electrical work.

So, that is the first essential requirement for a vapour compression systems and of course, since the high grade energy is work. So, efficiency of this system is higher and when you talk about a Vapour absorption systems, there are some situations where we can use the waste heat as one of the requirement of heat source.

So, it uses the major source of energy that comes as a heat source. It could be a solar energy it could be a waste heat or very basic thing is that its a low grade energy resources. But however, there could be some minimal amount of high grade energy in the form of work, but that is not taken into account here because major contribution comes from the lower grade energy.

So, this is another aspect we call this as a vapour absorption refrigeration systems and third category we normally call it as a Gas Cycle Refrigerations and mostly they are used in the aircraft refrigeration systems and infact, this is something similar to a gas turbine cycle which we have covered and this gas turbine cycle is mainly governed through the air standard cycle known as Brayton Cycle.

Now if you use this Brayton cycle in a reverse mode then we call this as a reverse Brayton cycle and simply we call as air cycle refrigeration. This is another fundamental segment which is mostly used in the case of gas turbine engines when the Brayton cycle is operated in a reverse mode.

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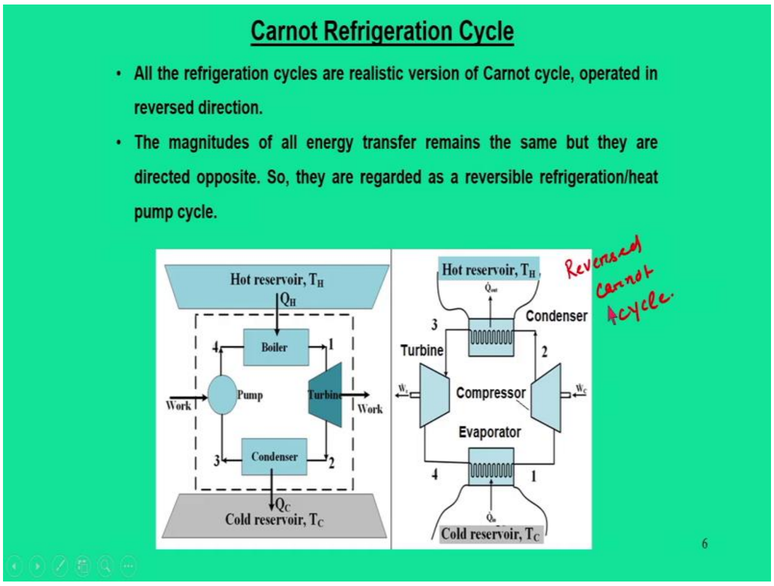

Carnot Refrigeration Cycle

- All the refrigeration cycles are realistic version of Carnot cycle, operated in reversed direction.
- The magnitudes of all energy transfer remains the same but they are directed opposite. So, they are regarded as a reversible refrigeration/heat pump cycle.

Reversed Carnot cycle.

Now, let me start the first basic Thermodynamic aspects that is Carnot refrigeration cycles. We all know from the basic thermodynamics, we have a Carnot cycle and this Cornot cycle is a hypothetical or theoretical cycle which is never achieved in this practice. But however, there are many realistic version of this Carnot cycles.

From this Carnot cycles, other cycles were evolved like steam power plant, the Rankine cycle was evolved in a IC engine. We can evolve Otto Cycle, Diesel Cycle and so many things and in a gas turbine engines Brayton cycle was derived. And similarly here also when you talk about refrigeration cycle, we have to think about a reverse Carnot cycle, then only we can find a realistic version of the refrigeration cycle.

So, first thing is when you look at a Carnot cycle, there are some hypothetical devices what we call as a turbine, boiler, pump, condenser. They are put in a thermal circuit manner and it is a cyclic device and finally, we get a work output from the turbine and in this process this cyclic device takes heat from the hot reservoir and rejects to heat to the cold reservoir. And our main intention is the work output.

Now you think about this particular Carnot cycle in a reverse mode. So, where heat is taken from the cold reservoir and it is rejected to hot reservoir and in this process the work that is getting given as input is mainly given as a work input W_C and it is given through the compressors and here these entire things, we call this as a cyclic device.

And this particular thing we call this as a Reversed Carnot Cycle and many a times you also call this as a Carnot refrigeration cycle instead of using word reverse if you we can also say Carnot refrigeration cycle.

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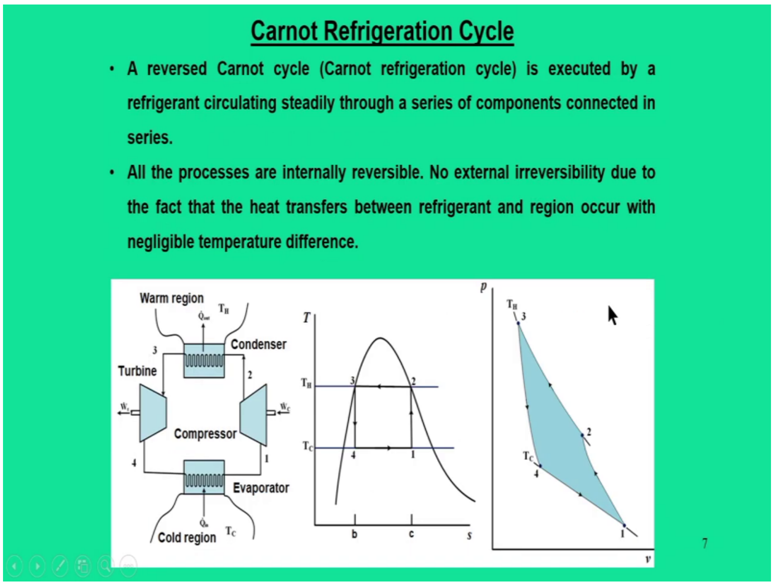

Carnot Refrigeration Cycle

- A reversed Carnot cycle (Carnot refrigeration cycle) is executed by a refrigerant circulating steadily through a series of components connected in series.
- All the processes are internally reversible. No external irreversibility due to the fact that the heat transfers between refrigerant and region occur with negligible temperature difference.

So, in a reverse Carnot cycle or Carnot refrigeration cycle is executed by a refrigerant circulating steadily through series of components connected in series. And here the components are turbine, condenser, compressor and evaporator. All the processes are internally reversible, there is no irreversibility due to the heat transfer between the refrigerant and the region that occur with a negligible temperature difference.

And typical diagram in a TS diagram, the cyclic processes are represented as a rectangle whereas, in the PV diagrams these cyclic processes has two reversible isothermal processes and two reversible adiabatic processes. The process starts from 1 to 2 which is in a compressor.

So, it is a isentropic compression, then 2 to 3 constant temperature heat rejection and 3 to 4 is a turbine process its again isentropic process, 4 to 1 is also a isothermal process in which heat is given as a input from this space to be cooled. And again the cycle starts with 1-2-3-4.

So, the very basic philosophy that there are two temperatures that is warm region temperature which is defined as T_H and cold region temperature T_C. So, these are these two are fixed temperature on which the cycle operates.

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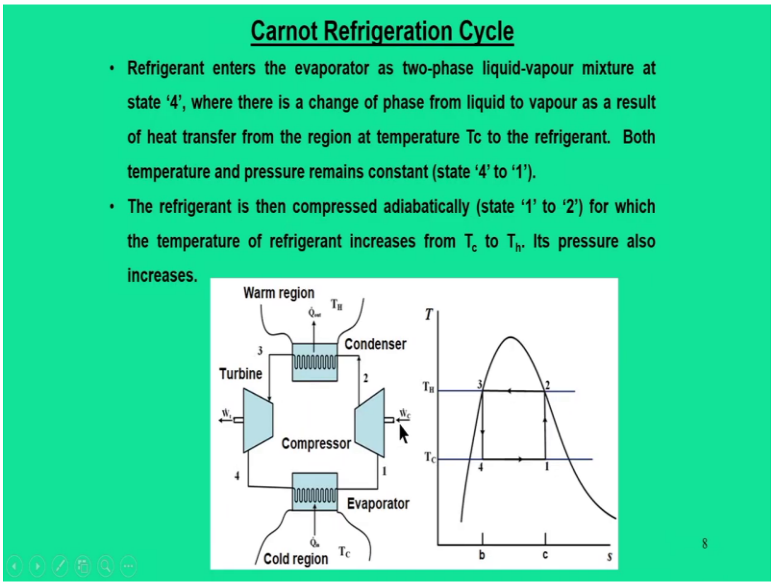

Carnot Refrigeration Cycle

- Refrigerant enters the evaporator as two-phase liquid-vapour mixture at state ‘4’, where there is a change of phase from liquid to vapour as a result of heat transfer from the region at temperature Tc to the refrigerant. Both temperature and pressure remains constant (state ‘4’ to ‘1’).
- The refrigerant is then compressed adiabatically (state ‘1’ to ‘2’) for which the temperature of refrigerant increases from T_c to T_h. Its pressure also increases.

So, here what happens refrigerant enters from a evaporator as a two phase liquid vapour mixture from the state 4 where there is a change in the phase from liquid to vapour as a result of heat transfer from the region at an temperature T_C to the refrigerant. And both temperature and pressure remains constant in the process 4 to 1.

The refrigerant is then compressed adiabatically from 1 to 2 for which the temperature refrigerant increases from T_C to T_H; of course, since the temperature increases, pressure also gets increased.

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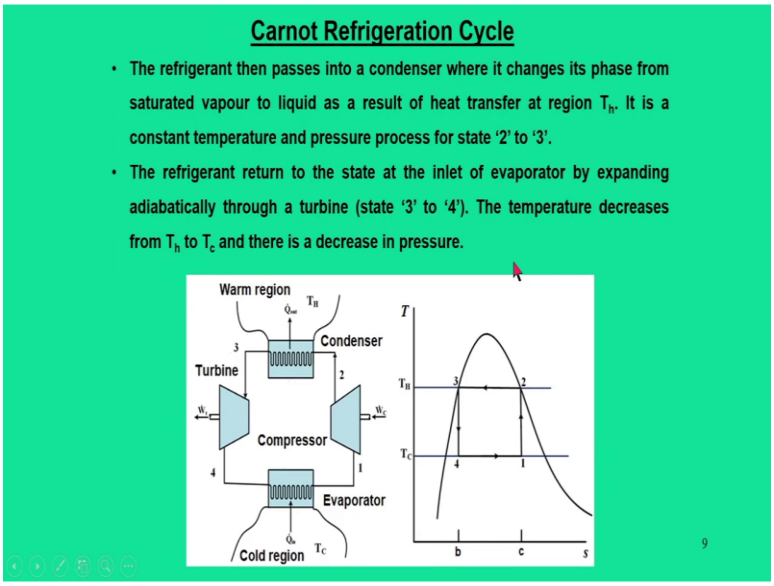

Carnot Refrigeration Cycle

- The refrigerant then passes into a condenser where it changes its phase from saturated vapour to liquid as a result of heat transfer at region T_h. It is a constant temperature and pressure process for state '2' to '3'.
- The refrigerant return to the state at the inlet of evaporator by expanding adiabatically through a turbine (state '3' to '4'). The temperature decreases from T_h to T_c and there is a decrease in pressure.

Then refrigerant passes through a condenser where it changes again its phase from the saturated vapour to the liquid as a result of heat transfer in the region at the region T_H; that means, the constant temperature region heat transfer in the condenser. And this process is denoted as 2-3 and where the temperature as well as pressure remains constant.

Finally, the refrigerant return to the state that is inlet of evaporator by expanding adiabatically through a turbine. So, this process is taken from 3 to 4. So, in this process the temperature finally, drops from T_H to T_C. So, there is decrease in the pressure. So, what we can say is that entire cyclic device operate between two temperature T_H and T_C and it operates in a cyclic manner.

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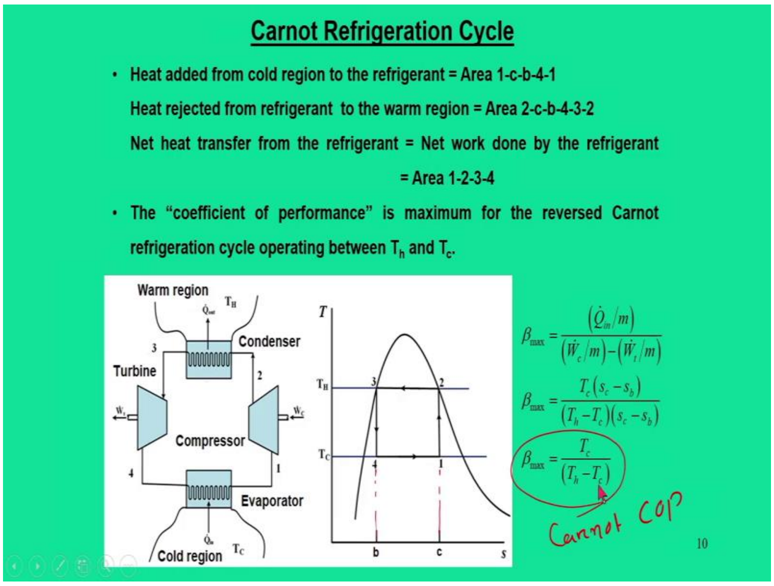

Carnot Refrigeration Cycle

- Heat added from cold region to the refrigerant = Area 1-c-b-4-1

  Heat rejected from refrigerant to the warm region = Area 2-c-b-4-3-2

  Net heat transfer from the refrigerant = Net work done by the refrigerant = Area 1-2-3-4
- The "coefficient of performance" is maximum for the reversed Carnot refrigeration cycle operating between T_h and T_c.

$$\beta_{\max} = \frac{\left(\dot{Q}_{in}/m\right)}{\left(\dot{W}_c/m\right)-\left(\dot{W}_t/m\right)}$$

$$\beta_{\max} = \frac{T_c\left(s_c - s_b\right)}{\left(T_h - T_c\right)\left(s_c - s_b\right)}$$

$$\beta_{\max} = \frac{T_c}{\left(T_h - T_c\right)}$$

Carnot COP

And from this we can do some little bit of mathematical background by looking at the area under this TS diagram for the cycle 1 2 3 4. So, like in a conventional Carnot cycle we call this as efficiency and in this case find the effectiveness of a Carnot refrigeration cycle we call this as a coefficient of performance.

And this coefficient of performance is defined for a reversed Carnot cycle and to get this parameter what we have to look into is that we recall this diagram 1 2 3 4 and we have to see that how much heat gets added from the cold region to the refrigerant which is in this case which is nothing but the refrigerant comes into picture when it is in the evaporator in which heat is taken from the cold regions. So, this process is from 4 to 1.

So, and when you talk about how much heat is added. So, we can say area 1-c-b-4-1 is the area refers to the heat added from the cold regions and heat rejected from the refrigerant to warm region would be the process is 2-3. So, we can say 2-c-b-4-3-2 and from this we can find out the what is the net work done net work done is nothing but area 1-2-3-4.

Then we can calculate the maximum coefficient of performance that is $\beta_{\max} = \frac{\left(\dot{Q}_{in}/m\right)}{\left(\dot{W}_c/m\right)-\left(\dot{W}_t/m\right)}$. So, from this a simple mathematical area we can calculate and finally, we can say we can find a parameter which is $\beta_{\max}$ and we call this as a maximum coefficient of performance and this is nothing but the Carnot COP. And here we will call this as $\beta_{\max} = \frac{T_c}{(T_h - T_c)}$.

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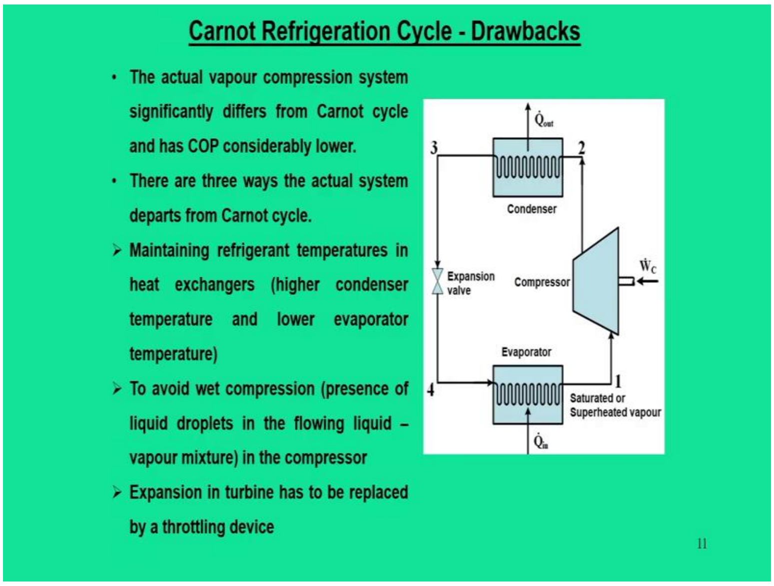

Carnot Refrigeration Cycle - Drawbacks

- The actual vapour compression system significantly differs from Carnot cycle and has COP considerably lower.
- There are three ways the actual system departs from Carnot cycle.
  - ➢ Maintaining refrigerant temperatures in heat exchangers (higher condenser temperature and lower evaporator temperature)
  - ➢ To avoid wet compression (presence of liquid droplets in the flowing liquid – vapour mixture) in the compressor
  - ➢ Expansion in turbine has to be replaced by a throttling device

Now when you deal with Carnot cycle, we also find out that there are many limitations because all realistic cycle which produces power, they cannot work the work on the mode the way the Carnot cycle imposes. Like for example, heat addition or heat rejection by maintaining constant temperature is highly impossible. Although it is the theoretically possible by assuming a very quasi static processes or very slow processes, but that is not possible.

So, for that region in a similar sense we also find difficulties in running Carnot refrigeration cycles and we call this as their drawbacks and because of their restrictions, the actual vapours compression system defers from the Carnot cycle and for which the coefficient of performance is considerably lower.

What are the different drawbacks or important drawbacks? There are basically three drawbacks in which the actual system differs from the Carnot cycle. First is maintaining refrigerant temperature in the heat exchanger or in particular heat exchanger in our term we call this as a condenser or evaporator.

We say the T_H and T_C are the temperature of heat sources that are maintained, but maintaining T_H and T_C it is difficult to extract heat or reject heat, maintaining same temperatures. So, this is one important drawbacks. Second drawbacks that comes in if you look at the compressor. Now available compressors in the market can be used on a gas phase or vapour phase.

Now if you look at our temperature entropy diagram we can see that the compression process is mostly occurring in the wet region where the refrigerant is wet. So, but we require a dry compressions. So, there is a limitations that we have to move from the wet compression to dry compressions. So, thereby the process in which the Carnot cycle says that we have to do it in isentropic compression that is not possible. So, to avoid wet compression in the compressors that is another limitations.

Third limitation is expansion in the turbine. So, ideally our main intention in a refrigeration cycle to maintain the coldness and we do not intend to have a turbine because normally the word turbine is used when it is used as a power producing device, but in our refrigeration cycle that is not the main intention although the turbine power is getting utilized, but that requirement is very low as compared to work input for the system.

So, your main work input that goes into the system is through the compressors. So, ideally putting a very big devices in the name of turbine does not make sense. So, the turbine is replaced with another device and we call this as a expansion valve. So, that is the reason the Carnot cycle departs or defers from a actual vapour compression cycles. So, it refers as a expansion valve.

So, finally, we landed up a by putting these limitations, the components now are called as evaporator in which the heat is extracted from this region to be cooled. Compressor where only dry vapours gets compressed to a high pressure and in the condenser heat is getting rejected its a constant temperature heat rejection.

And finally, while moving from high temperature to low temperature or from high pressure to low pressure, both pressure and temperature can be regulated by a valve or many times you call this is a throttle valve or people call it as a expansion valve or maybe throttle valve is a right word as far as the refrigeration cycle is concerned. And we will we will we say its a expansion valve.

So, in this way the components are now changed and with this change in the component we call this as a vapour compression cycle or refrigeration cycle.

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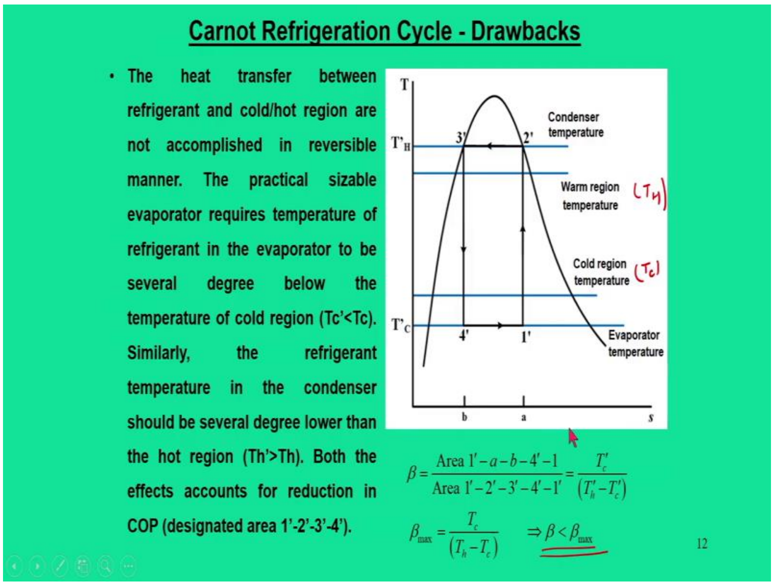

Carnot Refrigeration Cycle - Drawbacks

- The heat transfer between refrigerant and cold/hot region are not accomplished in reversible manner. The practical sizable evaporator requires temperature of refrigerant in the evaporator to be several degree below the temperature of cold region (Tc'<Tc). Similarly, the refrigerant temperature in the condenser should be several degree lower than the hot region (Th'>Th). Both the effects accounts for reduction in COP (designated area 1'-2'-3'-4').

$$\beta = \frac{\text{Area } 1'-a-b-4'-1}{\text{Area } 1'-2'-3'-4'-1'} = \frac{T_c'}{(T_h'-T_c')}$$

$$\beta_{\max} = \frac{T_c}{(T_h-T_c)} \qquad \Rightarrow \underline{\underline{\beta < \beta_{\max}}}$$

So, now let us go deep into the different drawbacks one by one. So, first drawback that Carnot cycle put that if you talk about the warm region temperature which is T_H and cold region temperature which is T_C. But the actual cycle if you talk about evaporator, the evaporator temperature would be much less than this cold region temperatures then only it is able to takeout heat from the cold region.

And similarly, when you take the high temperature side, the condenser has to operate much above. So, that the refrigerant can reject it to the warm region temperature, heat rejection is possible. So, if you look at this particular figure, your actual condenser temperature that is $T`_H$ is higher than the $T_H$ and the evaporator temperature $T`_C$ is lower than the cold region temperatures.

So, these put the restriction and because of this region if you actually calculate the coefficient of performance of a actual vapour compression cycle, it now becomes $\beta = \frac{\text{Area } 1'-a-b-4'-1}{\text{Area } 1'-2'-3'-4'-1'} = \frac{T_c'}{(T_h'-T_c')}$; obviously, $\beta_{\max} = \frac{T_c}{(T_h-T_c)}$. So, by looking at this diagram we can clearly say that actual COP will be always less than the maximum COP of the cycle or Carnot COP.

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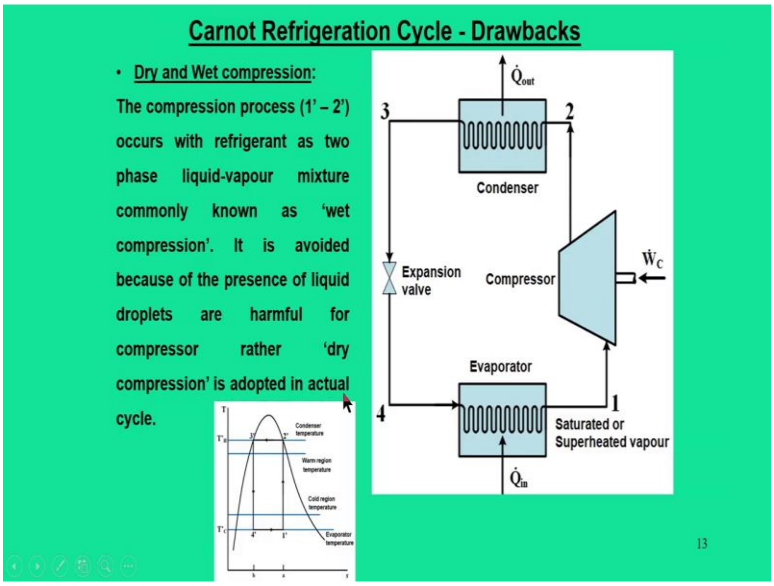

Carnot Refrigeration Cycle - Drawbacks

- **Dry and Wet compression**: The compression process (1' – 2') occurs with refrigerant as two phase liquid-vapour mixture commonly known as 'wet compression'. It is avoided because of the presence of liquid droplets are harmful for compressor rather 'dry compression' is adopted in actual cycle.

And next point that I have also mentioned that dry versus wet compressions. If you look at this particular figure in the compressor what does this happen that the after taking this heat, the refrigerant now enters in a vapour region and at the vapour region at state 1, it enters the compressor.

But if you look at this particular figure, the compression and this particular compression mode 1` is still in the region of wet region and we say that your compression gets terminated at point 2` and that point is only saturated vapour, but this particular process is not allowed because we say that 1` would lie on this saturation vapour curve somewhere at this point.

Then only we have to say that the compressor can operate when the refrigerant is in dry mode. And that particular situation we call this as dry compression. So, here I have made a distinction what is the dry and wet compressions the 1`-2` and of course in a liquid vapour mixture commonly known as wet compression and this particular thing should be avoided because the presence of liquid droplets are harmful for the compressors. So, rather a dry compression is adapted for an actual cycle.

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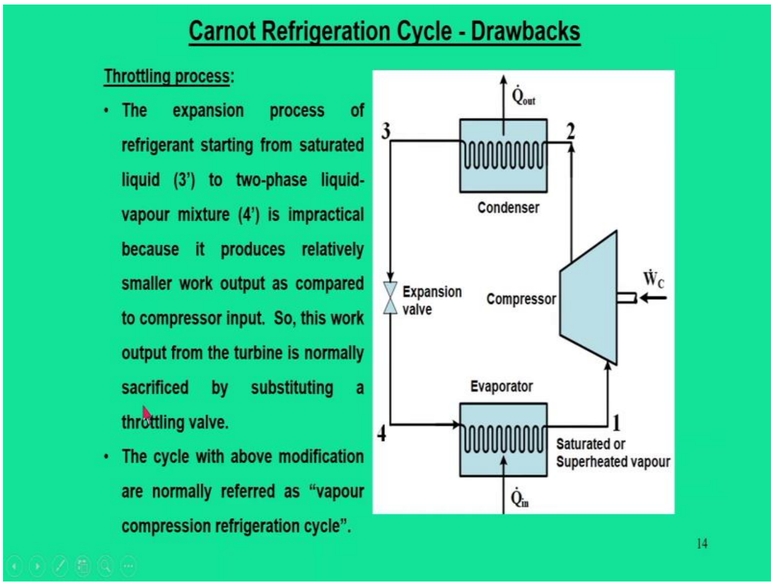

Carnot Refrigeration Cycle - Drawbacks

Throttling process:

- The expansion process of refrigerant starting from saturated liquid (3') to two-phase liquid-vapour mixture (4') is impractical because it produces relatively smaller work output as compared to compressor input. So, this work output from the turbine is normally sacrificed by substituting a throttling valve.
- The cycle with above modification are normally referred as "vapour compression refrigeration cycle".

And third thing is that this Throttling process. So, as I mentioned that there is no requirement of a turbine. So, turbines is replaced with a expansion valve and this particular value we called as a throttle valve and this thermodynamic process for this throttle valve we call this as a throttling process.

So, here the expansion process from refrigerant starting from saturated liquid at 3` to the liquid vapour mixture 4` is impractical because it produces a relative small work output as compared to the compressor input. So, this work output from the turbine is normally sacrificed by replacing it with a throttle valve and so this throttle valve is nothing but your expansion valve and by taking all this modifications, we call this cycle as a vapour compression refrigeration cycle.

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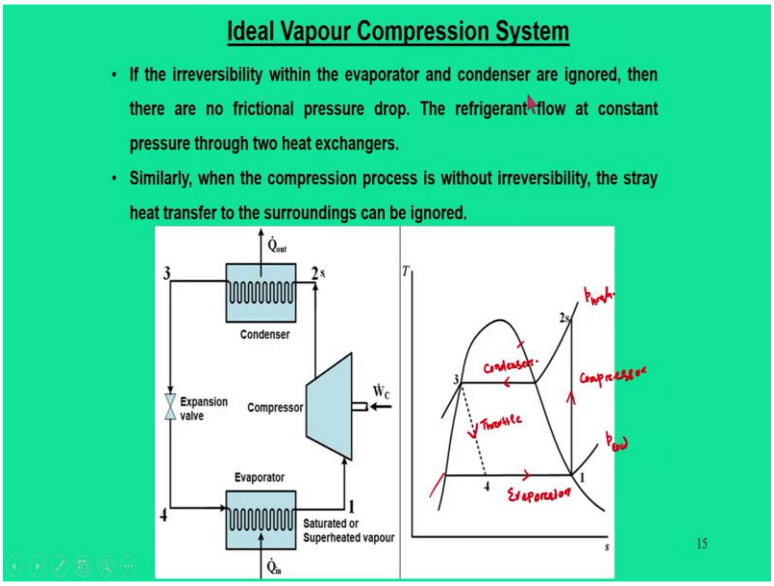

Ideal Vapour Compression System

- If the irreversibility within the evaporator and condenser are ignored, then there are no frictional pressure drop. The refrigerant flow at constant pressure through two heat exchangers.
- Similarly, when the compression process is without irreversibility, the stray heat transfer to the surroundings can be ignored.

Now, we come to know that the Carnot refrigeration cycle is no longer is possible in a realistic way. So, you have to rely on a vapour compression system or cycle and there are two versions here when you talk about vapour compression system, one is ideal version other is actual version.

So, first thing is that we will have to we are replacing those components, let us see that how the diagram looks like in a TS plot. Now, if you look at these components now that is required, our essential requirement that at state 1, the refrigerant should be at least a saturated or super heated vapour and at state 3 that the refrigerant state would be at the saturated liquid state.

And of course, till we have retaining that assumption that compression process is still isentropic. So, if you look at the process, it starts with let us say 4 where the refrigerant takes the heat from the space to be cooled, now after taking the heat, it goes to becomes saturated vapour where it enters into the compressors and after getting compressed in the compressor and this process we call this is a isentropic process and final state becomes 2s.

So, if you look at this TS diagram and these there are two pressure limits that operates, one is low pressure other is high pressure. High pressure is constant that is at condenser. Low pressure is in the evaporator. So, process 4-1 is in the evaporator and process 2s and 3 is in the condenser and on a TS diagrams these are nothing but the constant pressure lines which is represented here.

So, from 4 to 1 the arrow direction shows the which the refrigerant follows in this cyclic process. So, 1-2s is the isentropic compression from 2s to 3 where heat is getting rejected from the refrigerant in the condenser and finally, from 3 to 4 its a throttling process. And here one important things that the line 3-4 is given as a dotted line because the throttling processes is always irreversible whereas, other processes can be considered as a reversible processes except this throttling.

So, evaporator, compressor, condenser then throttle. So, in a TS diagram. Now we are able to show that how the cyclic process should look like in a ideal version of vapour compressions as a system. So, that is the minimum requirement that we must have to run a refrigeration system and we call this as a vapour compression systems or we many times we call as a vapour compression refrigeration cycle.

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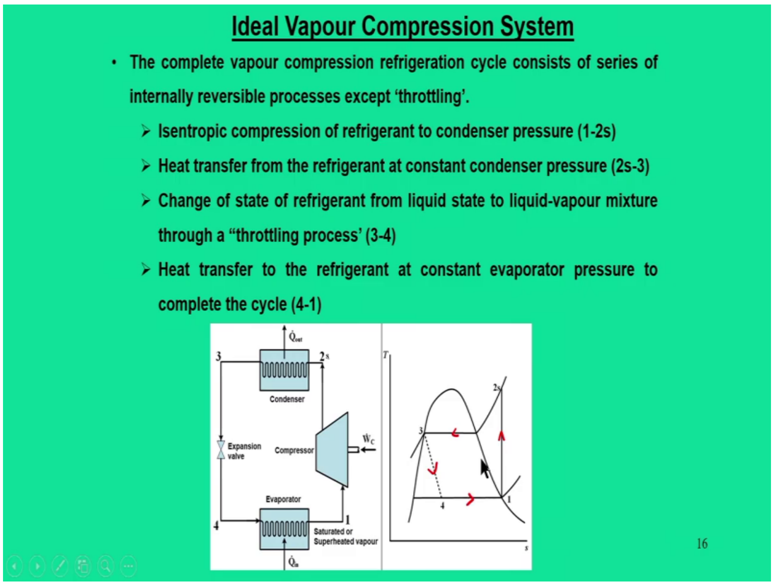

Ideal Vapour Compression System

- The complete vapour compression refrigeration cycle consists of series of internally reversible processes except 'throttling'.
  - Isentropic compression of refrigerant to condenser pressure (1-2s)
  - Heat transfer from the refrigerant at constant condenser pressure (2s-3)
  - Change of state of refrigerant from liquid state to liquid-vapour mixture through a "throttling process' (3-4)
  - Heat transfer to the refrigerant at constant evaporator pressure to complete the cycle (4-1)

So, the complete vapour compression refrigeration cycle now consist of series of internally reversible processes except throttling. One is isentropic compression of refrigerant to the condenser pressure process 1 to 2s. Heat transfer from the refrigerant at condenser pressure that is process 2s to 3, change of state of refrigerant from liquid state to the liquid vapour mixture through a throttling process that is 3 to 4 and finally, heat transfer to the refrigerant at constant evaporator pressure to complete the cycle that is 4-1.

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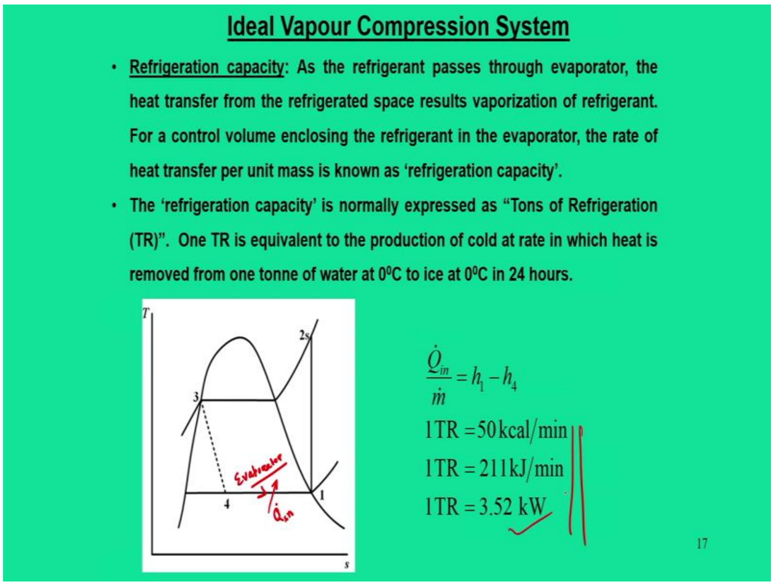

Ideal Vapour Compression System

- **Refrigeration capacity**: As the refrigerant passes through evaporator, the heat transfer from the refrigerated space results vaporization of refrigerant. For a control volume enclosing the refrigerant in the evaporator, the rate of heat transfer per unit mass is known as 'refrigeration capacity'.
- The 'refrigeration capacity' is normally expressed as "Tons of Refrigeration (TR)". One TR is equivalent to the production of cold at rate in which heat is removed from one tonne of water at 0^0C to ice at 0^0C in 24 hours.

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$

$$1\,TR = 50\,kcal/min$$

$$1\,TR = 211\,kJ/min$$

$$1\,TR = 3.52\,kW$$

Now, after having said all these things, now let us find how you need to quantify. So, basically when you talk about refrigeration alone, refrigeration capacity is one of the word that we frequently use, its nothing but how much heat is getting extracted from the cold regions. So, we must quantify from this temperature entropy diagram.

So, if you look at the refrigeration capacity; that means, we are looking at a process 4-1 which occurs in the evaporator. From this if you look at since they are cyclic devices, we can find out the amount of heat comes from the space that is nothing but $\dot{Q}_{in}$ rate of heat transfer and $\dot{m}$ is the unit mass flow of refrigerant, that is nothing but enthalpy difference. We can simply use the steady state energy equation $\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$.

So, this is how we call this as a refrigerating load and, but in a refrigeration term this particular load is called as a refrigeration capacity. So, as the refrigerant passes through the evaporator, the heat transfer from the refrigerated space results vaporization of refrigerant.

Now, considering control volume enclosing the refrigerant in the evaporator, the rate of heat transfer per unit mass is known as refrigeration capacity and in our term, the refrigeration capacity normally referred as tons of refrigeration. In fact, in our commercially when you say that the capacity of AC or refrigerator or something we say 1.5 ton, 2 ton something like that we call this as a tons of refrigeration.

So, what does this mean? One ton ton of refrigerations are simply we call as a 1 TR is equivalent to the production of cold at a rate in which heat is removed from 1 ton of water at 0°C to ice at 0°C in 24 hours. We take 1 ton of water and we want to remove heat from this water to make it ice. So, amount of heat that is required in 24 hours is nothing but 1 TR.

So, simply if you calculate the latent heat of vaporization for ice and putting that value, 1 TR is now equivalent to 3.5 kW or 211 kJ/min or 50 kcal/min.

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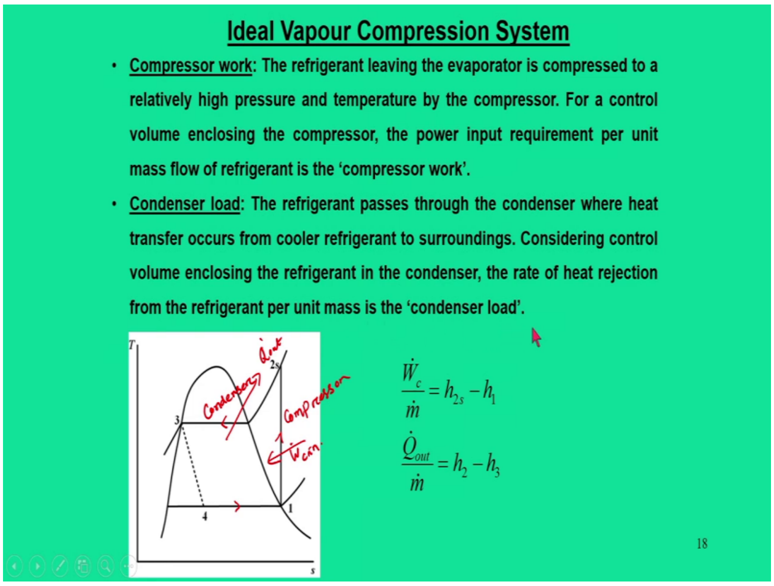

Ideal Vapour Compression System

- **Compressor work**: The refrigerant leaving the evaporator is compressed to a relatively high pressure and temperature by the compressor. For a control volume enclosing the compressor, the power input requirement per unit mass flow of refrigerant is the 'compressor work'.
- **Condenser load**: The refrigerant passes through the condenser where heat transfer occurs from cooler refrigerant to surroundings. Considering control volume enclosing the refrigerant in the condenser, the rate of heat rejection from the refrigerant per unit mass is the 'condenser load'.

$$\frac{\dot{W}_c}{\dot{m}} = h_{2s} - h_1$$

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_2 - h_3$$

Now, moving further we are now going to compressor work and condenser load. This compressor process is 1 to 2s which is isentropic compression and condenser process is 2s to 3. So, it is compressor 1-2s and 2s to 3 it condenser. So, simply steady flow energy equations we can apply. So, compressor work per unit mass $\frac{\dot{W}_c}{\dot{m}} = h_{2s} - h_1$ and condenser load can be calculated as $\frac{\dot{Q}_{out}}{\dot{m}} = h_2 - h_3$.

So, the compressor work is nothing but the refrigerant leaving from the evaporator is compressed to a relatively high pressure and temperature in the compressor. So, for a control volume enclosing the compressor, the power input requirement per unit mass flow of refrigerant is known as the compressor work.

Similarly condenser load; the when the refrigerant passes through a condenser the heat transfer occurs from the cooler refrigerant to the surroundings. So, considering the control volume enclosing the refrigerant in the condenser, the rate of heat rejection from the refrigerant per unit mass is known as the condenser load.

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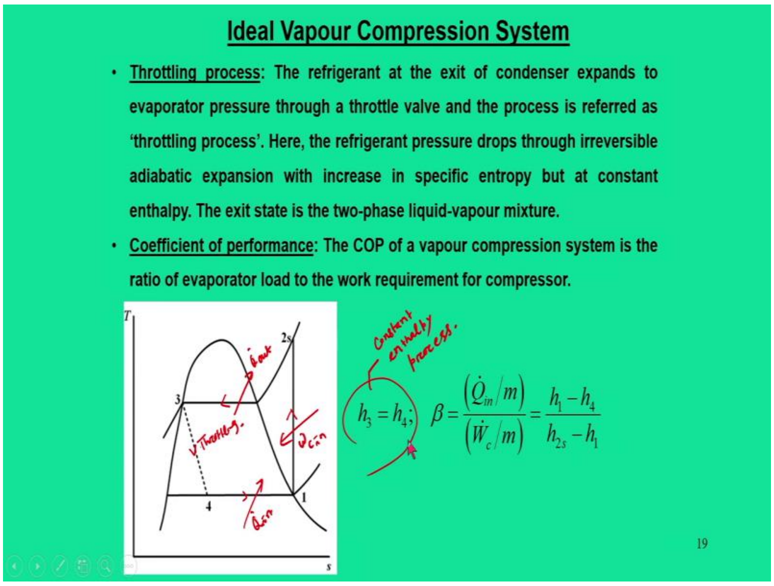

Ideal Vapour Compression System

- **Throttling process**: The refrigerant at the exit of condenser expands to evaporator pressure through a throttle valve and the process is referred as 'throttling process'. Here, the refrigerant pressure drops through irreversible adiabatic expansion with increase in specific entropy but at constant enthalpy. The exit state is the two-phase liquid-vapour mixture.
- **Coefficient of performance**: The COP of a vapour compression system is the ratio of evaporator load to the work requirement for compressor.

Constant enthalpy process.

$$h_3 = h_4; \quad \beta = \frac{\left(\dot{Q}_{in}/m\right)}{\left(\dot{W}_c/m\right)} = \frac{h_1 - h_4}{h_{2s} - h_1}$$

Then next process is Throttling. So, we went 4 to 1, 1 to 2 s, 2s to 3 now this throttling. Throttling process is from 3 to 4. Now here this throttling process is an isoenthalpic process, its a constant enthalpy process. So, in a constant enthalpy process means $h_3 = h_4$.

So, the in a throttling process the refrigerant at the exit of condenser expands to evaporator pressure through a throttle valve and the process is known as a throttling process. Here the refrigerant pressure drops through a irreversible adiabatic expansion with increase in the specific entropy.

That is the region we say its not an isentropic process because if you see there is an increase in the entropy and the exit state is the two phase liquid vapour mixture and we know the evaporator load, from 4 to 1, compressor load 1 to 2s, condenser load 2s to 3. So, we now require what is $\dot{Q}_{in}$ and what is $\dot{Q}_{out}$ and we also know what is $\dot{W}_c$ compressor work which is input.

So, from this we can calculate the coefficient of performance for the cycle which is $\beta = \frac{\left(\dot{Q}_{in}/m\right)}{\left(\dot{W}_c/m\right)} = \frac{h_1 - h_4}{h_{2s} - h_1}$. So, this is how the we define the COP of the refrigerant.

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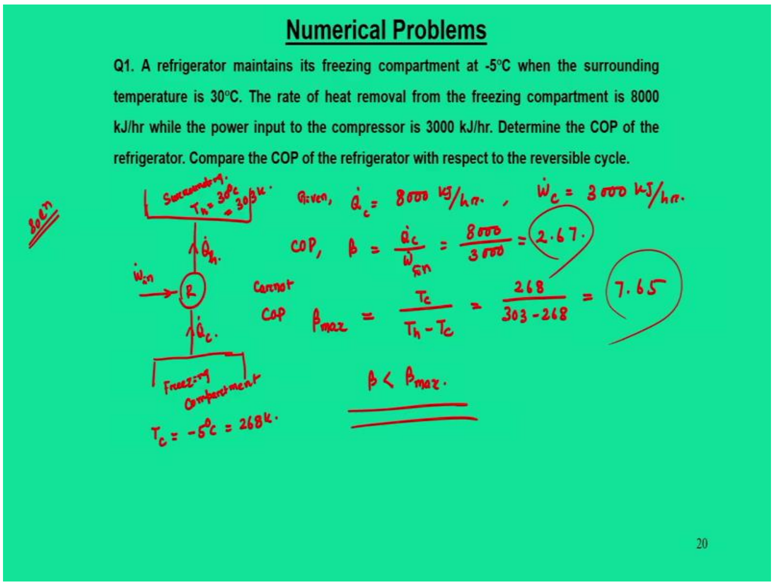

Numerical Problems

Q1. A refrigerator maintains its freezing compartment at -5°C when the surrounding temperature is 30°C. The rate of heat removal from the freezing compartment is 8000 kJ/hr while the power input to the compressor is 3000 kJ/hr. Determine the COP of the refrigerator. Compare the COP of the refrigerator with respect to the reversible cycle.

Given, $\dot{Q}_c = 8000\ kJ/hr.$, $\dot{W}_c = 3000\ kJ/hr.$

COP, $\beta = \frac{\dot{Q}_c}{\dot{W}_{in}} = \frac{8000}{3000} = 2.67.$

Carnot COP $\beta_{max} = \frac{T_c}{T_h - T_c} = \frac{268}{303-268} = 7.65$

$\beta < \beta_{max}.$

So, with this I come to the end of this particular lecture segments and the end we will try to solve some numerical problems which has been covered in this lecture. See the first problem is based on a refrigerator. In fact, this particular module is relatively a easier module as far as the problems are concerned.

So, let us start the first question. A refrigerator maintains a freezing compartment at -5°C when the surrounding temperature is 30°C. The rate of heat removal from the freezing compartment is 8000 kJ/hr. While power input to the compressor is 3000 kJ/hr. We have to determine the COP of the refrigerator.

And here the heat removal as well as power input is given that is one kind of COP that we can get. At the same time, we also know the temperature limits. So, from this we can find the maximum COP or Carnot COP for this cycle and idea is that we have to compare.

So, first thing that to do is that we have to do this thermal circuit. So, freezing compartment is maintained at low temperature that is -5°C = 268K whereas high temperature which is surroundings is maintained as 30°C = 303K. So, we can say Q_c is the heat taken from the freezing compartment, Q_h is the heat that is getting rejected.

$$\dot{Q}_c = 8000\text{kJ/hr},\ \dot{w}_{in} = 3000\text{kJ/hr}\ \Rightarrow \text{COP},\ \beta = \frac{\dot{Q}_c}{\dot{w}_{in}} = 2.67$$

$$\text{Carnot COP},\ \beta_{\max} = \frac{T_c}{T_h - T_c} = \frac{268}{303 - 268} = 7.65$$

Obviously, $\beta < \beta_{\max}$ and we say refrigerator is not performing up to the Carnot cycle limit.

So, we call this as actual refrigerator for which the COP is close to 2.67, but its maximum COP could be as high as 7.65 and one interesting thing COP value could be higher than 1 or less 1, whereas when you talk about efficiency it is always less than 1.

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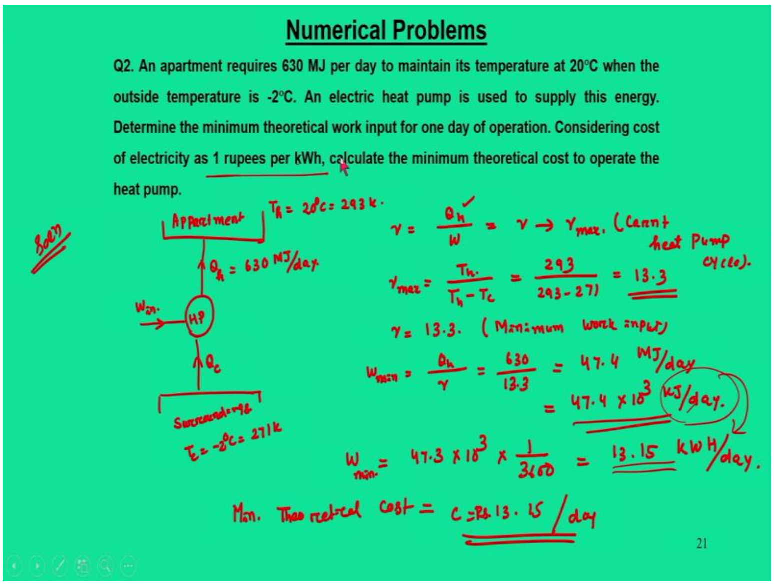

Numerical Problems

Q2. An apartment requires 630 MJ per day to maintain its temperature at 20°C when the outside temperature is -2°C. An electric heat pump is used to supply this energy. Determine the minimum theoretical work input for one day of operation. Considering cost of electricity as 1 rupees per kWh, calculate the minimum theoretical cost to operate the heat pump.

Soln

$T_h = 20°C = 293\,k$

$\gamma = \frac{Q_h}{W} \Rightarrow \gamma \to \gamma_{max}$ (Carnot heat Pump cycle).

$\gamma_{max} = \frac{T_h}{T_h - T_c} = \frac{293}{293 - 271} = 13.3$

$\gamma = 13.3$ (Minimum work input)

$W_{min} = \frac{Q_h}{\gamma} = \frac{630}{13.3} = 47.4$ MJ/day

$= 47.4 \times 10^3$ kJ/day.

$W_{min} = 47.3 \times 10^3 \times \frac{1}{3600} = 13.15$ kWH/day.

Min. Theoretical Cost = C = Rs. 13.15 / day

Now, other problem is based on a heat pump cycle. So, here we have an apartment which requires a 630 MJ per day to maintain its temperature at 20°C when the outside temperature is -2°C. It requires a electric heat pump to supply this energy.

So, you have to calculate a minimum theoretical work input for one day operations and if you take the cost of electricity as 1 rupees per kWh what will be the minimum theoretical cost to operate the heat pump. Now when we say minimum theoretical cost or minimum work input then it must be a Carnot one because the Carnot heat pump or a refrigeration system should require the minimum amount of work.

So, considering that we have to solve this particular problem. Then to solve this problem first thing, we have to draw the cycle. So, we have an apartment which requires heat to be delivered Q_h and this is 630 MJ/day and this to be maintained at 20°C that is 293K.

And this heat needs to be supplied by a heat pump which requires work input and to do that it must take heat from surroundings that is at -2°C that is 271K and in this case it is Q_c and here we have to find this COP. We have to represent this as γ, just to make a notations when I write γ, it refers to COP of a heat pump cycle. And that is nothing but Q_h/w because your desired effect is Q_h and γ goes to γ_{max} and when it is Carnot heat pump cycle.

So,

$$\gamma_{\max} = \frac{T_h}{T_h - T_c} = \frac{293}{293 - 271} = 13.3$$

For minimum work input $\gamma = \gamma_{\max} = 13.3 \Rightarrow w_{\min} = \frac{Q_h}{\gamma} = \frac{630}{13.3} = 47.4\text{MJ/day} = 47400\text{kJ/day}$

Now, for cost of electricity, we can find out $\mathrm{W} = 47400 \times \frac{1}{3600} = 13.15\text{kW/day}$. So, cost of electricity would be 1 rupees per kWh. We are consuming 13.15 kWh. So, minimum theoretical cost would be equal to 13.15 rupees per day. So, this is how we can calculate and you can just multiply with 30, so we can say monthly electricity billing for running this heat pump.

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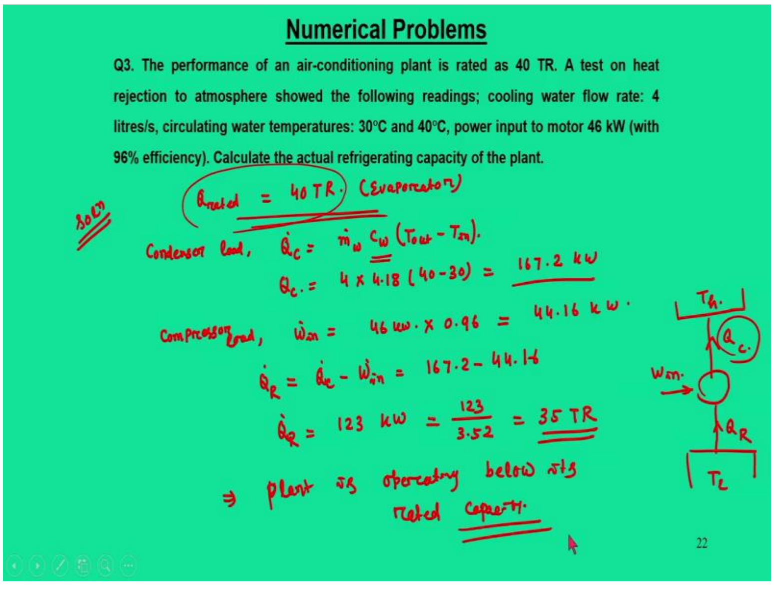

Numerical Problems

Q3. The performance of an air-conditioning plant is rated as 40 TR. A test on heat rejection to atmosphere showed the following readings; cooling water flow rate: 4 litres/s, circulating water temperatures: 30°C and 40°C, power input to motor 46 kW (with 96% efficiency). Calculate the actual refrigerating capacity of the plant.

Soln

$Q_{rated} = 40\text{ TR}$. (Evaporator)

Condenser load, $\dot{Q}_c = \dot{m}_w c_w (T_{out} - T_{in})$.

$Q_c = 4 \times 4.18 (40-30) = 167.2\text{ kW}$

Compressor load, $\dot{W}_{in} = 46\text{ kW} \times 0.96 = 44.16\text{ kW}$.

$\dot{Q}_R = \dot{Q}_c - \dot{W}_{in} = 167.2 - 44.16$

$\dot{Q}_R = 123\text{ kW} = \frac{123}{3.52} = 35\text{ TR}$

$\Rightarrow$ plant is operating below its rated capacity.

Now last problem is in a different context where we have given with a air conditioning plant of rated capacity is 40 tons of refrigerant, but what happens is that a test on heat rejection to the atmosphere showed the following reading.

That means, there is a plant and some test was done based on the calculation how much heat got rejected to the atmosphere and the heat rejection was done by a cooling water which is used in the condenser for which it inlet temperature was 30°C and exit temperature of this cooling water was 40°C; that means, refrigerant rejected heat to the cooling water. And mass of the water flow is 4 liter per second.

Now from this we can calculate the condenser load and also we are given with the power input to the a motor that is 46 kW with 96 percent efficiency; that means, the motor is 96 percent efficient with its rated power 46kW. So, we can know the compressor load or power input load.

So, first thing that we need to calculate what is condenser load. So, we say $\dot{Q}_c = \dot{m}_w C_w (T_{out} - T_{in}) = 4 \times 4.18(40-30) = 167.2\text{kW}$. So, we can say compressor load, $\dot{w}_{in} = 46 \times 0.96 = 44.16\text{kW} \Rightarrow \dot{Q}_R = \dot{Q}_c - \dot{w}_{in} = 167.2 - 44.16 = 123\text{kW}$. Now, if you make it to ton then 123 / 3.52 = 35 ton of refrigeration. So, actual rated load is 40 TR. So, we can say that a plant is operating below its rated capacity. So, its a feasible option.

With this I conclude this talk or class for today. Thank you for your attention.