Thermal Engineering Basic and Applied
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Lecture - 60
Vapour Compression Refrigeration Cycle and its Analysis

I welcome you all to the session of Thermal Engineering Basic and Applied. Today, we shall start our discussion on this new topic that is vapour compression refrigeration cycle. So, if we recall our previous classes then we can understand that we have talked about vapour power cycles and we have discussed about those cycles essentially in the context of the development or generation of power.

But today we shall discuss about this particular cycle that is vapour compression refrigeration cycle essentially a vapour power cycle, but the sole purpose is not to produce power, but to produce refrigeration or refrigerating effect.

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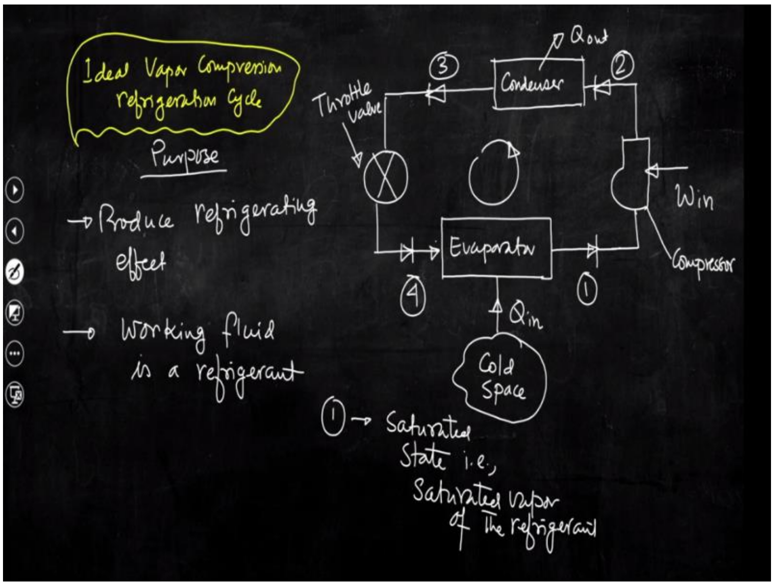

So, as I said the sole purpose is to produce refrigerating effect. Now let us look into this particular cycle and we shall try to analyze the processes those constitute this particular cycle. So, as we can see the sole purpose is to produce refrigerating effect and we had seen from our daily life experience from household refrigerator that a compartment needs to be at a temperature always which is say, for example, at – 10°C or - 5 °C.

So, if we schematically try to draw this particular cycle then essentially this is the space say for example and this space should be always maintained at a temperature which is at a sub zero temperature. So, this is say cold space. So, if you need to maintain the temperature of this particular space at a temperature which is, for example, if it is - 10^oC.

Then certainly you know that to run this we need to have a few mechanical components electrical components. So, as those components will be running, heat will be generated and so we need to have always transfer of heat from this particular space to somewhere so as to the temperature of this particular pace will be maintained at a sub zero temperature. Now this heat will be taken by a device that is called evaporator.

So, this is Q_{in} and if we recall the steam power cycle we had seen that the working fluid that we considered for that particular cycle is steam water mixture or water. Now in this particular cycle as well there is a working fluid, but that working fluid is not water that working fluid is a special type of working fluid and that working fluid is known as refrigerant. So, I am writing the working fluid is a refrigerant.

This is a special type of working fluid we shall be discussing later what kind of property this particular fluid should have and this particular type of, working fluid is given a name start with R and there are different types of refrigerant. We shall be discussing this particular type of fluid later. Now you know that working fluid on receiving heat from this cold space that working fluid will be evaporated.

And that is why this device is known as evaporated. So, this particular working fluid will be having a few distinctive properties and those properties we shall be discussing later in today's class. So, now on receiving heat that working fluid will be converted into vapour and essentially this evaporator is designed in such a way that at the exit of the evaporator will be getting saturated vapour of that working fluid.

So, if we give name So this is 1. So at 1 the refrigerant would be saturated refrigerant and then we need to complete the processes and those processes will eventually form a cycle. So, now that saturated liquid is taken into a compressor. So, this device is basically a compressor. So, this is a device which is work absorbing device.

This is not like a turbine we had seen that turbine is a work producing device, but to run this compressor we need to supply certain energy always in the form of work. So, this is W_{in} so we are supplying work to this compressor. So, essentially we will be getting saturated vapour at the exit of the refrigerator and that is at the inlet of this compressor. Now the sole purpose of providing with this compressor is to develop or build up a pressure and we will be getting, state point 2. So, high pressure refrigerant vapour that would be available at the exit of the compressor. So, essentially compressor is a device which can handle two phase mixture certainly.

But we had seen in a steam power cycle a pump is there to raise the pressure of the working fluid from a condenser pressure to the boiler pressure. So, now that high pressure refrigerant vapour will be now taken into another device that is called condenser and while passing through the condenser it will release heat so Q_{out} because we need to bring back the original state of the refrigerant at the inlet of the evaporator.

So, evaporator on receiving heat from this cold space got evaporated, that refrigerant vapour that is saturated vapour is now taken into this compressor wherein we are supplying energy to run the compressor and the pressure of that refrigerant will increase and that refrigerant which is available at the exit of the compressor is now taken into this condenser and by releasing heat while passing through the condenser the refrigerant will be taken to another device.

So, this is point 3. Now question is in this case we could have installed another one device to produce work and that is what we had seen in a steam power cycle. So, in a steam power cycle we had seen that in turbine basically steam is allowed to expand. So, why steam is expanding it does work on the rotating part of the wheel and we are getting work output.

So, here what is done, instead of a turbine a special type of device that is considered because here the purpose is not to produce work, but to get you know refrigeration or refrigerating effect. So, the special device which is considered here is known as throttle valve. So, this is known as throttle valve and the sole purpose of providing this throttle valve in the circuit is to expand that high pressure refrigerant that comes out from the condenser to the evaporator pressure.

So, this is the total circuit. So, let me tell you once again we are getting high pressure refrigerant at the inlet of the condenser, by releasing certain amount of heat from the condenser that refrigerant which is available at the exit of the condenser is taken into another device that is a special type of device. Perhaps you have studied in thermodynamics that is called throttle valve.

So, while stream is passing through this throttle valve it will expand and this is a very fast process, pressure will decrease and the purpose of providing with this throttle valve in this circuit is to reduce the pressure of the refrigerant from condenser pressure to the evaporator pressure. So, this is the circuit. Now that sole purpose is to get the refrigerating effect.

And we have also discussed many times that whenever we consider any mechanical component or mechanical device and when those components are there in a circuit or in a cycle essentially if you need to measure the performance of the cycle itself we need to map all those processes in several thermodynamic planes. One of the most important thermodynamic planes is the T-s diagram wherein we can represent all these processes.

We have discussed that if we can represent any process in T-s plane and area under the process line in T-s plane will give us at the direct measurement of energy that is either added to the device or energy getting extracted from this device. So, following this discussion which we had earlier and also with this understanding let us now move to draw the T-s diagram corresponding to this cycle rather corresponding to the processes those are there to constitute this cycle.

So, now try to understand this point is 4 and this is this cycle so cyclic process. What we have discussed that when the circuit or cycle is designed certainly evaporator is designed to produce saturated refrigerant vapour. So, now state point 1 is saturated state that is saturated vapour of the refrigerant.

So, that means let us consider point 1 is here. So, this is point 1 then again evaporator pressure is less than the pressure at which condenser is operating. So, we need to raise the pressure of the working fluid from evaporator pressure to the condenser pressure and that is why this compressor is there. So, the compressor will now compress, this saturated vapour from state point 1 to state point 2 following if we assume that it is a reversible adiabatic compression.

So, basically I should say that with this assumption that the process that will occur in this compressor is reversible adiabatic process. So, with this idealized assumption I should say that this is ideal vapour compression refrigeration cycle. So, this is ideal vapour compression refrigeration cycle because in practical case it is very difficult to have a process which should be reversible adiabatic.

But here we are considering this particular assumption and that is why we are writing this is ideal vapour compression refrigeration cycle because this is an idealized assumption not only here we also will consider a few more assumptions to analyze this cycle and that is why I said considering a few idealized assumptions.

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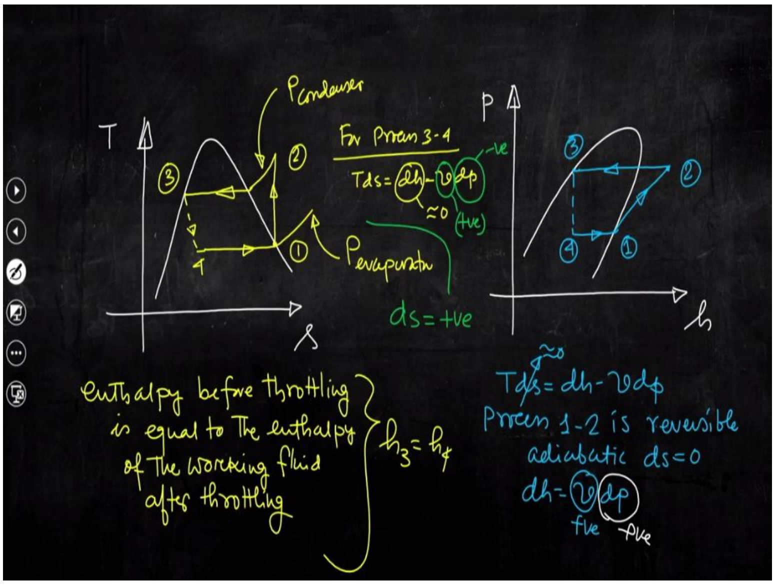

So, this is the evaporator pressure and say this is state point 2 that is the compression process and if we consider this is the Pcondenser and this is Pevaporator. So, what we can understand that now process 1 to 2 is reversible adiabatic process, the compression process. Now state point 2 is the exit state of compressor or inlet of the condenser.

Now there is basically condensation, but we have also discussed that even in the context of steam power cycle that designing a condenser which will allow us to have partial condensation is very difficult. So, here also the condenser is provided with this cycle or circuit to allow not the partial condensation, but to have the condensation up to this saturated liquid.

So, this is state point 3 that is on the saturated liquid line and this is the process. Now consider one important case that what about the process 3 to 4? Process 3 to 4 that we can see from this schematic that is the throttling process. The throttling process is a very fast process so it is basically, kind of the expansion of the refrigerant vapour and the sole purpose is to reduce the pressure of the working fluid from condenser pressure to the evapourator pressure.

Now perhaps you have studied this particular topic in your basic thermodynamics course the throttling is a very fast process, since it is a very fast process so the intermediate states may not attain equilibrium and hence it is very difficult to map this process by a solid line because it is very difficult to get the paths by which the state point 3 will now change to state point 4.

Let me tell you once again throttling is a very fast process and the intermediate states may not attain equilibrium. Hence, if we need to map the process 3 to 4 in the T-s plane here then it is very difficult to get the path by which the state point 3 has now changed to state point 4 and hence this particular process is shown by this dotted line. So, this is basically 1, 2, 3, 4 that is the you know 4 different state points we could map in this T s plane.

Let me tell you one thing because whenever we have discussed any cycle in the context of steam power cycle, also in the context of, gas power cycle we have assumed that all the processes are internally reversible those processes may not be externally reversible, but we could map all those processes assuming that the processes are internally reversible and hence we could use this solid line.

But in this particular case since throttling is a process which is not an internally reversible process as well. So, that is why this process is shown by this dotted line. What we can understand from this T-s plane also from this you know schematic depiction of this ideal vapour compression refrigeration cycle that the process that is there in this evaporator essentially you know conversion of state point 4 into state point 1.

So, that process occurs at a constant pressure. So, we can see from this T-s plane, on the other hand refrigerant vapours changes its state from state 2 to state 3 in this condenser and the process occurs at a constant pressure process. So, this is also a constant pressure process so these two processes are constant pressure processes while the process that is, there in this throttle valve that is not we can say that the enthalpy is remaining constant all throughout the process.

But enthalpy at state point 3 is equal to enthalpy at state point 4. So, enthalpy before throttling is equal to the enthalpy after throttling. So that means $h_3 = h_4$, maybe the enthalpy at intermediate states or enthalpy at many intermediate states may not be equal.

But enthalpy before throttling is equal to enthalpy after throttling. So, what we can, understand out of these 4 processes, 2 processes occur at a constant pressure while another one process that is very important process an interesting process as well which is occurring at constant enthalpy. So, next objective should be to plot all these processes or map all these processes in another plane that is called P-h plane.

So, try to understand for the steam power cycles we had also tried to map all the processes in P-v diagram, but here since 2 processes are at constant pressure and 1 process is at not constant enthalpy, but enthalpy before startling is equal to enthalpy after throttling. So, we can map the processes now all these processes in this P-h plane, pressure enthalpy plane. So, if we now map these processes.

So, again starting point should be 1 because that is the saturated vapour at the exit of the evaporator. So, if we consider this point is 1, certainly pressure would be constant pressure. So, let us assume this is the pressure line. We really do not know where point 4 would be, but we can understand from this T-s plane that you know point 4 is basically, so at the inlet of the evaporator the state point is not the saturated liquid.

So, it is two phase mixture. So, now we have identified state point 1 here, then 1 to 2 that is again reversible adiabatic process. So, question is what would be the enthalpy of state point 2. So, now we also can take point 2 towards right or where point 2 should be there in P-h plane. So if we apply this Tds relation that is $Tds = dh - vdp$. So, process 1 to 2 is reversible adiabatic. So, $ds = 0$ isentropic process. So $dh = vdp$.

Compression process, v is always positive and what about this quantity because dp is also positive for a compression process because the sole purpose of having this process is to raise the pressure in the direction of working fluid flow. So, dp is positive. So, essentially dh is positive that means enthalpy will increase. So, from this discussion now we can map we can identify state point 2 so this is state point 2.

What about process 2 to 3 that is at a constant pressure process, but point 3 as I said you that partial condensation is not possible. So, we can have the process 2 to 3 that is a constant pressure process and this point is 3. Now, 3 to 4 is basically the throttling process. So, we need to map this 3 to 4 process. So, what I said you that enthalpy at state point 3 is equal to enthalpy at state point 4.

So, that means this process should be like this. So, this is point 4. So, this is the P-h representation. So, representation of all these processes in P-h diagram or P-h plane. I forgot to discuss one important point question is comfortably I could locate at point 4 here. Now where is the guarantee that point 4 should not be closer to the saturated liquid line because then if point 4 is closer to the saturated liquid line certainly entropy at state point 4 will be the deciding factor to look at point 4 in this plane.

So, if we can somehow get a clue about the change in entropy of this particular process, from there we can comfortably locate point 4 in this plane. Now let us again do for this particular case. So, again for process 3 to 4. We can write this $Tds = dh - vdp$. Now state point 3 and state point 4 as I said you that if start your process at state point 3 and if you go to state point 4, as I said you that enthalpy at state point 3 is equal to enthalpy of state point 4. So, that is equal to 0, what about other this two, specific volume is always positive what about dp because this throttle valve acting like an expander. So, basically you know pressure drops in the direction of the flow of the refrigerant then dp is negative. So, this is negative.

So, essentially you try to understand this is positive, this is negative, so total is negative which is again multiplied with negative so positive. So, that means from this we get ds equal to positive. So, that means for the process 3 to 4 that is throttling process as you move from state point 3 to state point 4 entropy will increase. Though, I could locate this point 4 comfortably by this, but this is the correct.

So, that means entropy increases as you know the process 3 to 4 takes place in this expander. So, with this understanding now let me discuss one important thing that so even for the, you, know steam power cycle we had tried to compare the performance of Rankine cycle and its modified versions with the Carnot cycle. So, again it would be wise to see if we compare the process or all these processes with the Carnot cycle.

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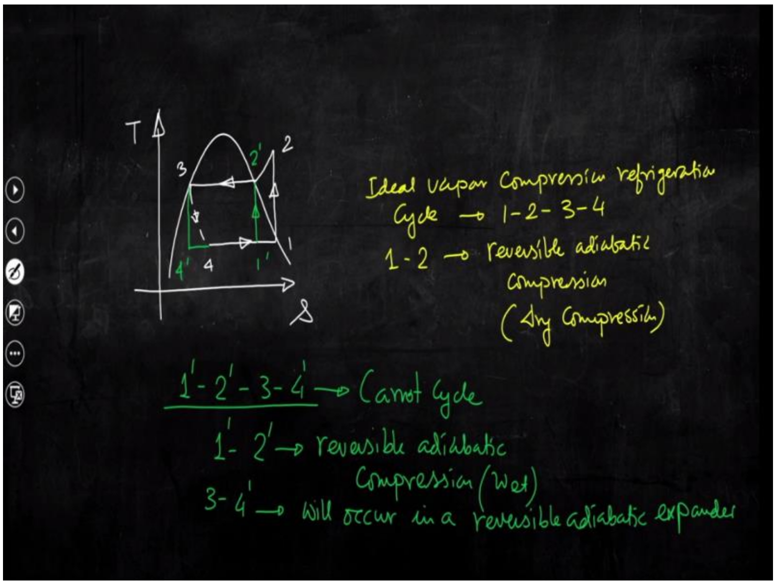

So, we try to draw the T-s diagram here. So, we can see 4-1 constant pressure evaporation, 1 to 2 reversible adiabatic compression, 2 to 3 constant pressure process that is occurring in a condenser and 3 to 4 that is the throttling process. So, this is the throttling process.

Now had it been a Carnot cycle then certainly the processes would have been different and we now discuss had we try to measure the performance using the Carnot cycle what would have been the differences? So, now let us consider this aspect as we had seen the Carnot cycle again this reversible adiabatic process will remain reversible adiabatic, 1 to 2 is basically reversible adiabatic compression.

So, this is dry compression. Why it is dry because try to understand the refrigerant or working fluid available at the inlet of this compressor is saturated, it is not a two phase mixture. So, basically it is called dry compression. Dry compression or dry compressions are preferred to the wet compression because of several advantages that I will be discussing today.

So, basically, as I said we are now trying to compare all these processes with those had we considered this cycle to be a Carnot cycle, then this compression process will be the reversible adiabatic process, but the actual process between these two temperature limits will be like this. So, this is $1'$ say this is $2'$. Similarly, you know, instead of a throttle valve we need to use a reversible adiabatic expander to have this reduction in pressure from condenser pressure to this evaporator pressure.

So, that means this process 3 to 4 will be again this. So, this is $4'$. So, now if I write $1' - 2' - 3 - 4'$ is the Carnot cycle whereas you know ideal vapour compression refrigeration cycle that is 1-2-3-4. So, what are the differences first of all the compression process is now wet compression. So this compression $1' - 2'$ that is again reversible adiabatic compression, but that is wet compression.

Why it is wet? Because you can understand point state of the working fluid corresponding to this point $1'$ is not a saturated vapour. So, this is a 2 phase mixture. So, that time compressor needs to handle this 2 phase mixture. Now handling 2 phase mixture is indeed a challenging task, why it is so I will be discussing soon and 3 to 4 prime now that is the process that will occur in a reversible adiabatic expander.

So, this process is also reversible adiabatic process. So, $3 - 4'$ will occur in a reversible adiabatic expander because the sole purpose is to reduce the pressure. So why Carnot cycle is not preferred? Because the most important part is, you know, this compression process that is wet compression. What will happen because we know compressibility of liquid and vapour is not same.

So, liquid and vapour since the compressibility of these two is different, then liquid and vapour being compressed differently will create an very detrimental phenomenon that is known as lubricant wash out phenomenon. What is this? First of all since now had we considered Carnot cycle, in this case compressor needs to handle 2 phase mixture and liquid and vapour these 2 are having different compressibility.

So now when it would be compressed the liquid refrigerant that would be there in the cylinder head and when the piston is rising and that liquid refrigerant will create or will damage the valves and etc, not only that as I said you that liquid vapour being compressed differently a phenomenon will be there wherein liquid molecule will try to penetrate into the gap between piston and cylinder wall.

So, typically the gap between piston and cylinder wall is filled with a lubricant. Now when that liquid molecule will be there or the where liquid molecule will you know penetrate into this passage that will you know wash away the lubricants and this phenomenon is known as lubricant wash out phenomena. So, considering these two, wet compression is not preferred and rather dry compression that is 1 to 2 is preferred and that is why a variant of the cycle ideal vapour compression refrigeration cycle is preferred over the Carnot cycle.

So, now with this let us try to discuss that essentially what we are looking for by studying this particular cycle? We need to obtain the refrigerating effect or refrigeration effect. What is that? Refrigerating effect or refrigeration effect is essentially if we look at the schematic what would be the extraction of energy from this cold space per unit mass flow rate of the refrigerant so that would be the refrigerating effect.

Typically, that particular effect is represented or expressed in terms of tons of refrigeration. I will be discussing this. So, let me tell you once again we are studying this particular cycle essentially to understand the refrigerating effect, what does it mean? It means the amount of energy that would be extracted from the cold spaces per unit mass flow rate of this working substance that is refrigerant.

Now, if we consider this particular part because finally we need to measure the performance and the sole performance sole purpose of this cycle is to get the refrigerating effect at the cost of some input energy that is the work input or work added to the compressor. So, we are supplying this much amount of energy to run this cycle and at the cost of that input energy we are getting some desired output or desired effect that is the refrigerating effect.

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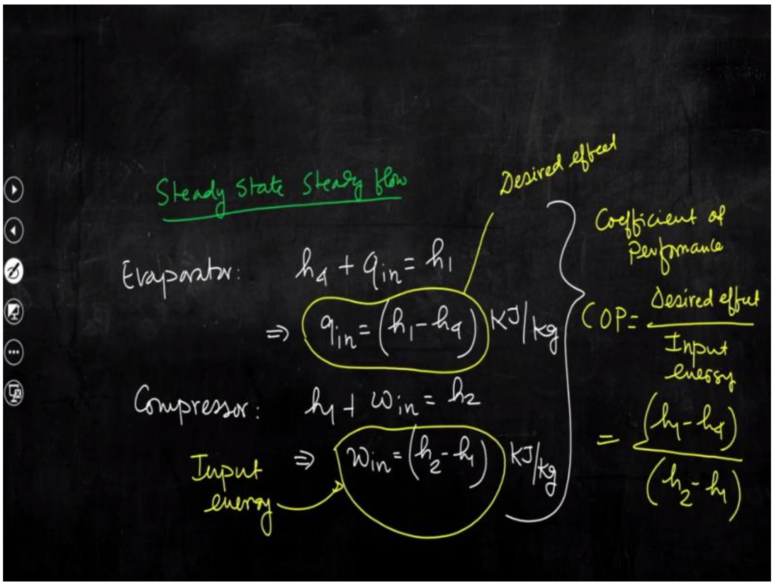

So, now let us consider steady state steady flow equation. If we assume that the steady state has reached and if we consider that 1 kg of the working fluid that is refrigerant. So, then if we just apply the steady state, steady flow equation across all the components, if we assume that all the processes are now at a steady state and then if we consider the working fluid is 1 kg.

So, per kg of working fluid if we apply that steady state steady flow equation across this evaporator what we can write? For evaporator we can write $h_4 + q_{in} = h_1 \rightarrow q_{in} = (h_1 - h_4)\ \frac{kJ}{kg}$. This much amount of heat this evaporator is taking per kg of refrigerant flow at the cost of some input energy and that input energy is the work input or work addition to the compressor. So, if we go back to this schematic depiction then if we apply this steady flow energy equation across this compressor $h_1 + w_{in} = h_2 \rightarrow w_{in} = (h_2 - h_1)\ \frac{kJ}{kg}$.

So, now try to understand so this is basically input energy in the form of work. So, this is input energy and this is the desired effect. So, we can define now coefficient of performance. For any refrigeration cycle we cannot define efficiency that we have discussed. Now we also have studied when you have studied second law of thermodynamics. So, coefficient of performance COP that is desired effect to the input power or input energy. $COP = (h_1 - h_4)/(h_2 - h_1)$

So, try to understand this is the mathematical expression of the coefficient of performance and essentially per unit mass flow rate of working fluid, the change in enthalpy is giving us an estimate about the desired effect and input energy. So, if COP is higher than performance of the refrigeration cycle would be better.

So, higher is the COP better the performance of the refrigeration. So, we have to calculate COP to get an estimate about the performance of the cycle, higher will be the value of COP better the performance of the cycle will be.

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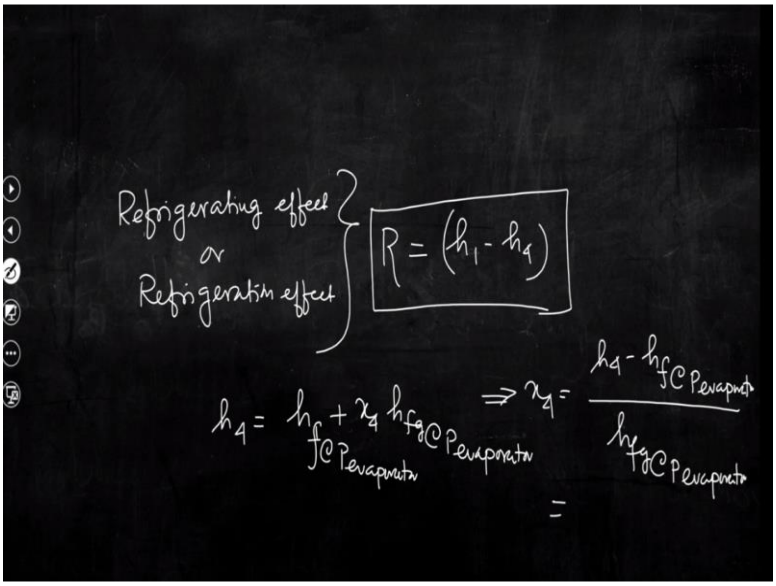

So, now what is refrigerating effect that is also very important. So, though I have already discussed about this particular term refrigerating effect or refrigeration effect. What is this and this is typically denoted by this symbol R. Now what is refrigeration effect? So, this is essentially had we applied steady state steady flow equation across this evaporator so this is $(h_1 - h_4)\ \frac{kJ}{kg}$.

So, as I said few minutes back that the amount of energy that would be extracted by this evaporator for getting the state of the working fluid changed from state point 4 to state point 1 that is the refrigerating effect and that refrigerating effect mathematically is $h_1 - h_4$ so this is the refrigerating effect.

Now let me tell you one thing we shall be solving one numerical problem from this topic as well, but if we try to go back to this T-s diagram we can see that state point 4 that is at the exit of the throttle valve or at the inlet to the evaporator it is the 2 phase mixture. So, we need to know what would be the quality of the you know refrigerant at the inlet of this evaporator.

So, if we look at this T-s plane carefully then we can write

$$h_4 = h_{f\ @\ Pevaporator} + x_4 h_{fg\ @\ Pevaporator} \rightarrow x_4 = \frac{h_4 - h_{f\ @\ Pevaporator}}{h_{fg\ @\ Pevaporator}}$$

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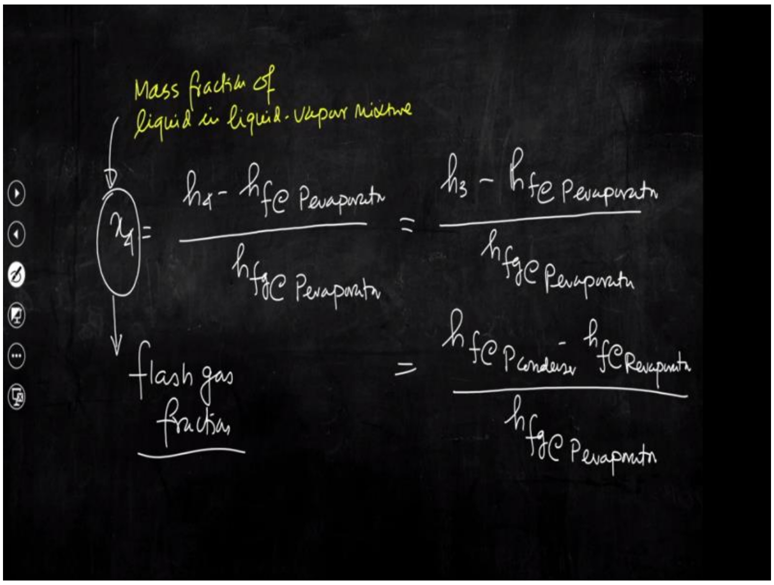

Now, what about h4 because we have discussed that that h4 equal to h3 that is enthalpy of the working fluid after throttling is equal to enthalpy of the working fluid before throttling and what about h3 that is hf at the condenser pressure that we can see from this T s diagram.

$$x_4 = \frac{h_3 - h_{f\ @\ Pevaporator}}{h_{fg\ @\ Pevaporator}} = \frac{h_{f\ @\ Pcondenser} - h_{f\ @\ Pevaporator}}{h_{fg\ @\ Pevaporator}}$$

So, this x4 quantity is very important and it is known as flash gas fraction. What does it mean? So, basically you know so mass fraction of liquid in this liquid vapour mixture.

So, this is important to know to the designer who will be designing this evaporator because you can see that the inlet condition of the working fluid is 2 phase mixture before it enters to this evaporator. So, now the designers should know the quality and that is what we could establish here and that is known as mass fraction of liquid in the liquid vapour mixture.

And known as fly gas fraction. So, to summarize today's discussion we have discussed about the ideal vapour compression refrigeration cycle we have tried to understand all the processes constitute this cycle, we have mapped all those processes in 2 different thermodynamic planes from there we have tried to quantify what is the coefficient of performance and the refrigerating effect.

In this context we have also discussed about several critical issues which are very important to know about this particular cycle. With this I stop here today and we shall continue our discussion in the next class. Thank you.