Thermal Engineering Basic and Applied

Prof: Pranab K Mondal
Department of Mechanical Engineering
Indian Institute of Technology – Guwahati

Lecture - 61
Problems on Vapour Compression Refrigeration Cycle

Very good afternoon I welcome you all to the session of Thermal engineering Basic and Applied and today we shall solve two numerical problems from vapour compression refrigeration cycle. If we recall our discussion that we had in the last class, then we can understand the operational aspects of a vapour compression refrigeration unit. So, in the last class mainly we have discussed about the processes those constitute together to form the vapour compression refrigeration cycle.

Then we have also identified the role of several components, I should say mechanical components pertinent to the vapour compression refrigeration cycle and identifying all those components we had mapped several processes occurring in different components both in T-s and P-h diagram. So, in the last class just we have mentioned about the refrigerating effect or refrigeration effect.

And typically that refrigerating effect is represent represented by the Tonnes of refrigeration. So, what is the physical significance of this particular unit? Let us discuss here today.

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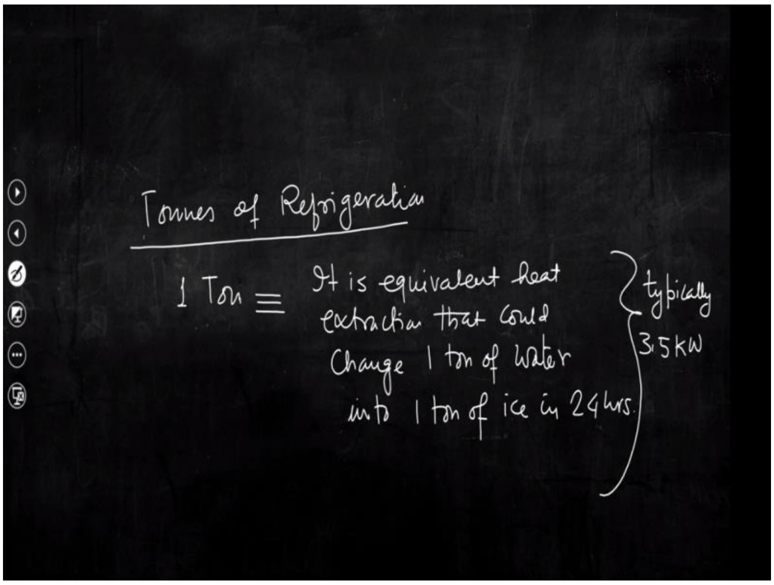

So, if we try to recall Tonnes of refrigeration. So, this is basically the unit of refrigeration effect or refrigerating effect and whenever a designer designs, refrigerating or refrigeration unit system typically the most important, term that is taken into account is the tones of refrigeration. So, this is basically the capacity of that particular unit, capacity of having refrigerating effect.

So, what is the physical meaning of this? This is basically, equivalent heat extraction that could change 1 ton of water into 1 ton of ice in 24 hours. Typically, 1 ton of refrigeration is 3.5 kilowatt in SI unit or 211 kilo joule per minute.

So, you also can define it as this is equivalent heat transfer from the surroundings that is to melt or convert 1 ton of ice into water in 24 hours. So, this is basically 1 ton of refrigeration. Why it is important because in most of the refrigeration units this unit is typically used to denote the capacity of that particular unit.

Now if we recall in the last class we have also discussed about the working fluid and if we try to recall the working fluid typically used in the refrigeration cycle is basically a refrigerant. So, what kind of property this particular working fluid should have is very important to know. So, today let us discuss a bit more about this particular aspect that is the properties of the refrigerant.

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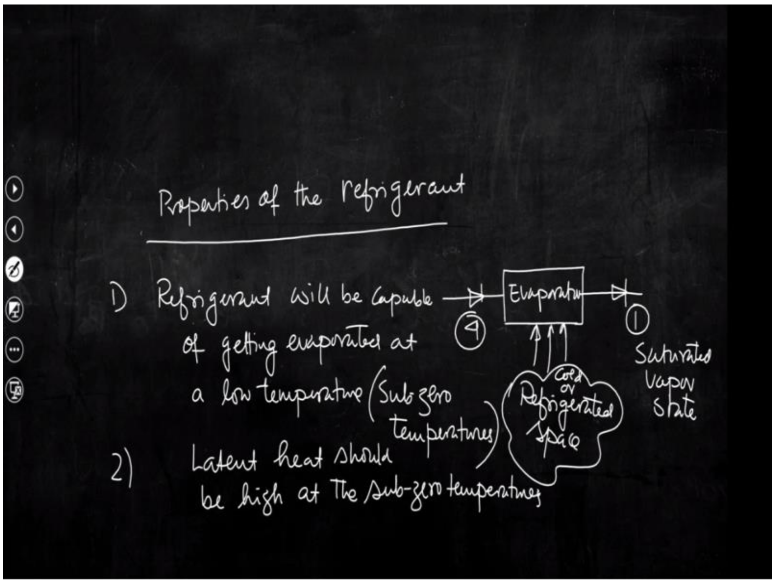

So, I am writing properties of the refrigerant, you know, if we recall the schematic depiction. So, this is basically evaporator and this is basically refrigerated space and temperature of that particular space is always maintained at a very low limit that is up to the designer. If you need to maintain temperature of this particular space should be at -10 degree Celsius; so, this is basically cold space temperature will remain always - 10 degree Celsius. So, there must be a continuous heat extraction from the space by the working fluid and that process occurs here in evaporator. So, basically the quality of the refrigerant at the exit of the evaporator is saturated vapour. If we try to recall that point 1 that is located on the saturated vapour line.

Now we have also discussed that the quality in the point 4 is inside the dome. So, basically this quality of the refrigerant at the inlet of the evaporator that is mass fraction of vapour in a liquid vapour mixture is also known as flash gas fraction. So, this is neither purely liquid nor purely vapour so it is 2 phase mixture. Now question is upon receiving heat from this refrigerated space that that refrigerant will be evaporated.

And essentially we will be getting saturated vapour at state 1. So, the question is temperature you need to maintain always at a sub zero level at this space. So, the refrigerant that should be, circulated through this evaporator will be able to evaporate or should get evaporated at a sub zero temperature. So, that is the most important property that is number 1 the refrigerant will be capable of getting evaporated at a low temperature.

And then this low temperature is again subjective, what is the temperature. So, basically sub zero temperatures. The amount of heat that should be extracted from the refrigerated space that will depend on the mass flow rate of the refrigerant and also the latent heat.

So, we really cannot increase mass flow rate of the refrigerant for a smaller unit otherwise the system will be bulky and also the power input or energy input to run the compressor will be more because the specific value will be more. So, another important quality of the refrigerant is that this particular working fluid should have high latent heat at the sub-zero temperature.

So, more amount of heat can be extracted from this refrigerated space. So, this is another quantity that is latent heat should be high at the sub zero temperature. So, these two are basically the properties of a refrigerant should have. So, we have understood the physical significance of tonnes of refrigeration, that means the amount of heat should be extracted by the refrigerant from this refrigerated space or cold space.

So, this is also cold space and then we have also discussed about the properties that a particular refrigerant should have. So, with this we shall discuss little bit more about this particular type of working fluid. So, basically you know this refrigerants are halogenated hydrocarbons and marketed under different proprietary names like Freon, Genitron, Ecotone etc and the refrigerants are typically either methane based or ethane based.

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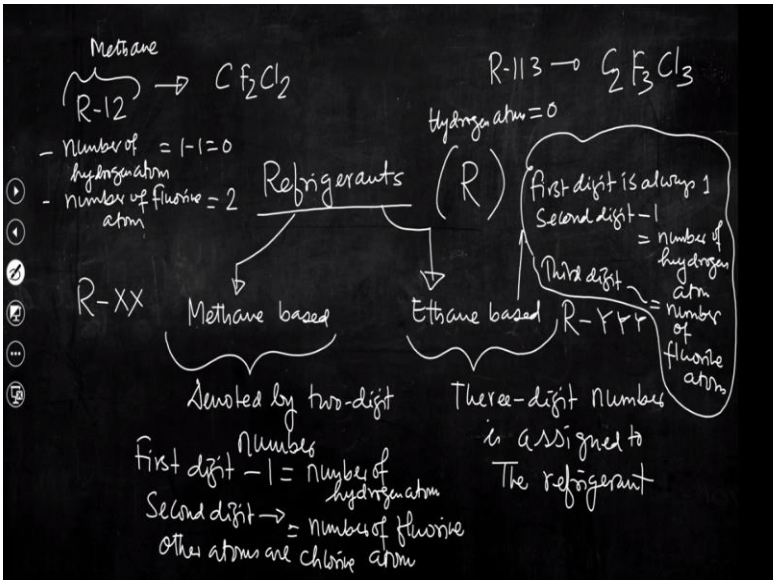

So, refrigerants are either methane based or ethane based. As I said you the refrigerants are halogenated hydrocarbons. So, try to understand and marketed under different proprietary names. So, basically though it is methane based or ethane based, you know, hydrogen atoms should be replaced by several fluorine and chlorine atoms, halogens. Now this methane based refrigerants are basically denoted by two digit number while the ethane based are a 3 digit number. So, now as I said you that refrigerants name starts with R. So, if it is methane based it is denoted by 2 digit number. If it is ethane based it is denoted by 3 digit number. So, now for the methane based let us briefly discuss here.

The hydrogen atoms should be replaced by halogens that is fluorine and chlorine atom. So, for the methane based first digit - 1 is the number of hydrogen atom. Second digit indicates number of fluorine atom, other atoms are basically chlorine. So, for example, R 12, so this is methane based we can see because it has 2 digits and then basically first digit - 1 that is number of hydrogen atom.

So, number of hydrogen atom is 1 - 1 that equal to 0, number of fluorine atom is the second digit that is 2. So, basically, hydrogen atom is 0, fluorine atom is 2. So, carbon has 4 valence.

So, basically this methane based refrigerant is C, hydrogen 0, F 2, so basically there will be another 2 atoms needed to make carbon saturated.

$$R - 12 \rightarrow CF_2Cl_2$$

So, this is Cl 2. So, this is basically R 12. So, this is how name of the refrigerant is given. So, this is basically dichloro, difluoromethane. Similarly, you also can find out what would be the chemical structure and chemical formula for another methane based refrigerant. Similarly, for the ethane based 3 digit number is assigned to the refrigerant.

So, first digit is always 1. Second digit – 1 equal to number of hydrogen atom. Third digit equal to number of fluorine atom and remaining atoms are chlorine. So, for example if we take one common example that is R 113 or R 134. First digit is always 1 then this is C, because ethane based so this is C2.

Second is - 1 is number of hydrogen atom. What is second digit 1 so 1 - 1 that is 0 hydrogen atom is 0. So, basically hydrogen atom equal to 0 then third digit is number of fluorine atom. So, number of fluorine atom that is 3. Then basically there are total 6 valance as ethane based. So, the other or remaining atoms are chlorine atom. So, basically 3 are fluorine atom and remaining 3 are chlorine atom. So, basically this is the chemical formula of this particular refrigerant which is ethane based.

$$R - 113 \rightarrow C_2F_3Cl_3$$

So, I have discussed this aspect because that may help you to understand how the refrigerants are given chemical name and they are chemical structures as well. So, with this let us now solve one problem.

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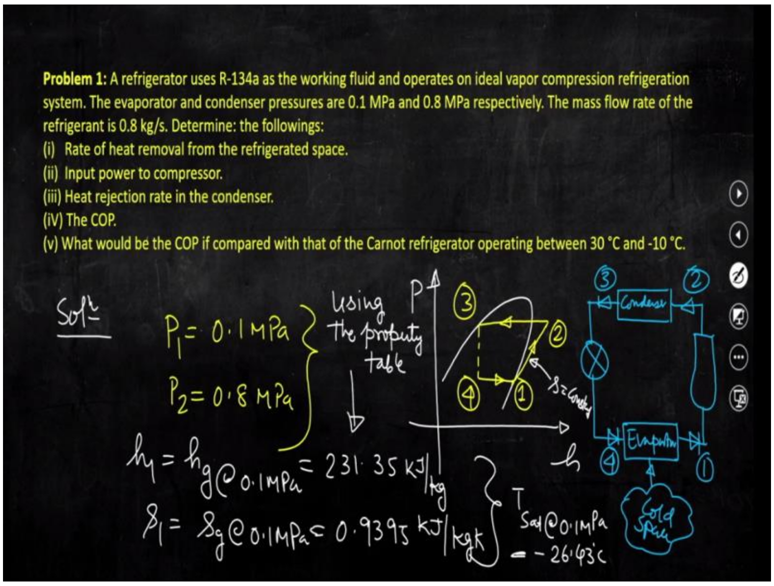

So, the first problem is our refrigerator uses R 134 as the working fluid and operates on ideal vapour compression refrigeration system. So, basically you know working fluid is R134a. So, you can understand this is 3 digit number. So, certainly the refrigerant is ethane based. So, it operates on ideal vapour compression refrigeration cycle, the evaporator and condenser pressures are 0.1 MPa and 0.8 MPa respectively.

The mass flow rate of the refrigerant is 0.8 kg per second, determine the followings. Rate of heat removal from the refrigerated space, input power to the compressor. Heat rejection rate in the condenser the COP, what would be the COP if compared with that of the Carnot refrigerator operating between the temperature limits that is $30°C$ and $-10°C$ you can understand that is the temperature of the evaporator.

And $30°C$ that is at the condenser temperature. So basically do we need to draw the, you know, P-h diagram. As I said you that if you recall in an ideal vapour compression refrigeration cycle out of the 4 different processes 2 processes occur at constant pressure, one process is basically not isenthalpic process, but that is the process for which enthalpy before throttling is equal to enthalpy after throttling.

So, out of these 4 processes we have seen in one process enthalpy before throttling is equal to enthalpy after throttling and for another two processes pressure constant. So, try to draw the P-h diagram. So, now as I mentioned that point 1. So, basically if we try to draw the schematic of this particular cycle so this is condenser.

This is evaporator extracting heat from this cold space and that is throttle valve. So, point 1, point 2, point 3, point 4. So, this is the schematic description of this cycle. So, this is point 1 that is on the saturated vapour line because we have discussed today again that quality of the refrigerant at the exit of the evaporator is saturated. Now process 1 to 2 for which entropy is constant assuming that compression process is an reversible adiabatic process.

So, this is the point 2, certainly you know pressure increases from 1 to 2 because that is why compressor is needed and now 2 to 3 that is again constant pressure condensation. Now question is it is a difficult to design a condenser which will ensure us to have partial condensation. So, in a condenser refrigerant vapour will be condensed after the saturated liquid so this is point 3.

And then from 3 to 4 this process is highly irreversible even internally. So, this process is represented by this dotted line because the process is very fast and I have discussed very difficult to identify the intermediate states and hence it is very difficult to know the path by which the process will occur and state 3 will be changed to state 4. So, this is the P-h diagram.

Now from the given data it is given that the evaporator pressure is 0.1 MPa. So, $p_1 = 0.1 MPa, P_2 = 0.8\ MPa.$ So, this is what we can write from the problem statement. Now question is if we try to recall in the last class we also have discussed whether we would like to calculate the power needed to be supplied to the compressor to drive it or the amount of heat that will be extracted by the evaporator from this cold space essentially per unit mass flow rate of represent is enthalpy change across those devices.

So, across those devices or components change in enthalpy is a measure of the heat or work interaction. So, now question is what would be h_1? So, we try to understand h_1 is basically h_g at 0.1 MPa because this is on the saturated vapour line. So, using the property table for the refrigerant R134a $h_1 = h_g @0.1\ Mpa = 231.35\ kJ/kg$; $s_1 = s_g @0.1\ Mpa = 0.9395 \frac{kJ}{kg-K}, T_{sat} = -26.43°C.$

Now h_1 is needed to calculate the amount of fluid should be extracted provided you know h_4. Why these two are important because you know entropy is also important to calculate because for this process entropy equal to constant.

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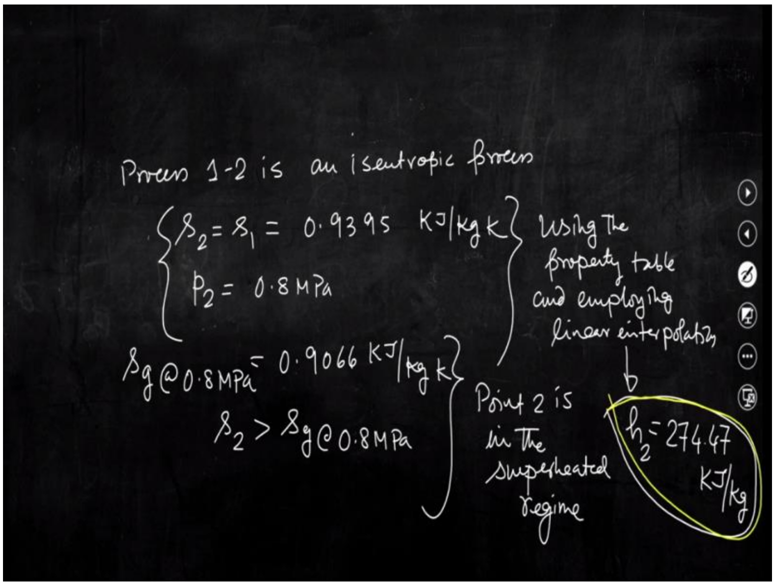

Process 1-2 (Isentropic)

$$s_2 = s_1 = 0.9395 \frac{kJ}{kg - K} > s_g @0.8\ Mpa \ \rightarrow \ \text{point 2 is superheated}$$

Now question is as we also need to calculate what would be the enthalpy. So, even if you recall the problem that we have solved for the steam power plants, essentially you had to calculate enthalpy at each and every state point. Similarly, for this cycle also we need to calculate enthalpy at each and every state point. Note that enthalpy at state point 1 already you have calculated. We are trying to calculate enthalpy at state point 2 by knowing the other two properties and if we can calculate enthalpy at state point 3 that would be equal to the enthalpy of state point 4 because the process that you know occurs in this device that is throttle valve.

So, this is throttle valve and this is compressor. So, basically, we need to calculate enthalpy at state point 2. So, knowing the entropy and pressure we also can calculate enthalpy from the property table. Now question is you we will certainly use the property table, but at least we should know where this point should be.

Though, we can really understand from this P-h diagram that point 2 is outside this dome. So, that is in the superheated regime, but let us verify it what we can do, you know, we can calculate sg corresponding to this pressure 0.8 MPa and that is equal to, you know, $0.9066 \frac{kJ}{kg-K}$. Now the enthalpy of the refrigerant at the exit of the compressor for this particular problem statement is $0.9395\,\frac{kJ}{kg-K}$.

So, which is that means s_2 is greater than s_g at that pressure that is the 0.8 Mpa. So, this indicates point 2 is in the super heated regime. Now using the property table as I said you that you can use the property table for R 134a and you can calculate just by linear interpolation. So, using property table and employing linear interpolation we can have $h_2 = 274.47\ kJ/kg$.

I would like to tell you one important point. See certainly we can get it from the property table there is no doubt about it even we can get the value from the property table, but here the pressure that is given 0.8 MPa it may so happen that we may require to calculate enthalpy at point 2 corresponding to pressure that may not be 0.8 MPa that may be 0.815, 0.8075 like this.

For that you may not get data tabulated in the table for that particular pressure. In such a case we need to go for interpolation twice because in that case neither entropy nor pressure for which we are interested in calculating this enthalpy will not be readily available because for 0.8 MPa it is readily available, but it may not be available may say for example 0.8135.

For that it is little tricky that we have to go for linear interpolation twice because for that we need to take at least 3 different data points for which the linear variation assumptions we can consider and we can calculate by using linear interpolation theory. Now have to calculate enthalpy at state point 3. If we can calculate enthalpy at state point 3 then we have no need to calculate enthalpy at state point 4 because this is the process for which enthalpy before throttling is equal to enthalpy after throttling. So, $h_4 = h_3$.

Now we have to calculate enthalpy then what is the clue? Clue is, you know, the process 2 to 3 that is the condensation process for which heat should be rejected. Now the process terminates at a saturated liquid line that means this is not a partial condensation. So, superheated refrigerant vapour should be now converted into saturated liquid.

And hence we can calculate enthalpy at state point 3 that is the enthalpy of saturated refrigerant corresponding to the pressure that is 0.8 MPa.

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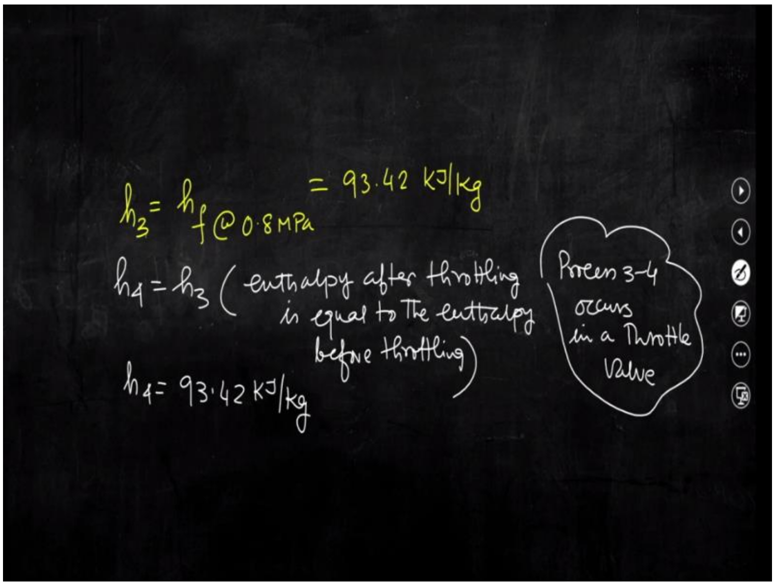

So, basically $h_3 = h_f@0.8\ Mpa = 93.42\ kJ/kg$ and $h_4 = h_3$.

So, we have now calculated enthalpy at all state points. Next let us look into the problem statement once more. We have to calculate rate of heat removal from the refrigerated space. So, what would be the rate of heat removal from the refrigerated space? Here mass flow rate of the refrigerant is given multiplied with the change in enthalpy.

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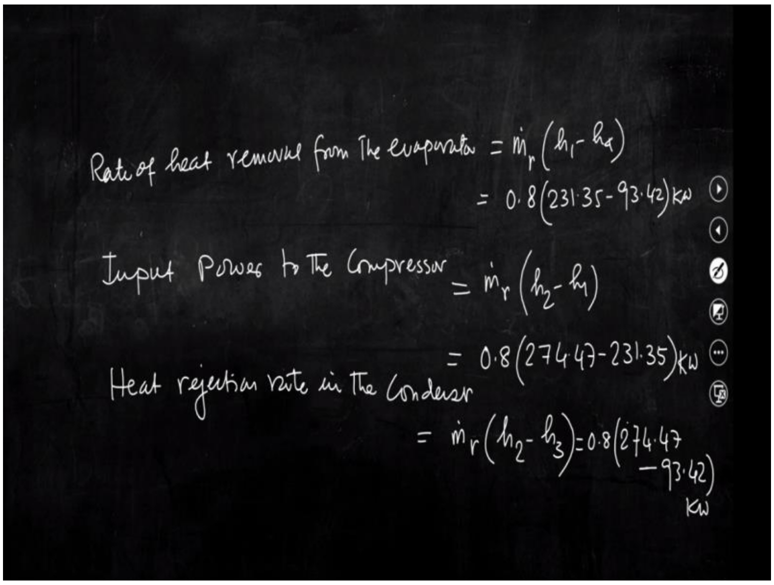

So, rate of heat removal from the evaporator = $\dot{m}_r(h_1 - h_4) = 0.8(231.35 - 93.42)\ kW$.

Input power to the compressor = $\dot{m}_r(h_2 - h_1) = 0.8(274.47 - 231.35)\ kW$.

Heat rejection rate in the condenser = $\dot{m}_r(h_2 - h_1) = 0.8(274.47 - 93.42)\ kW$

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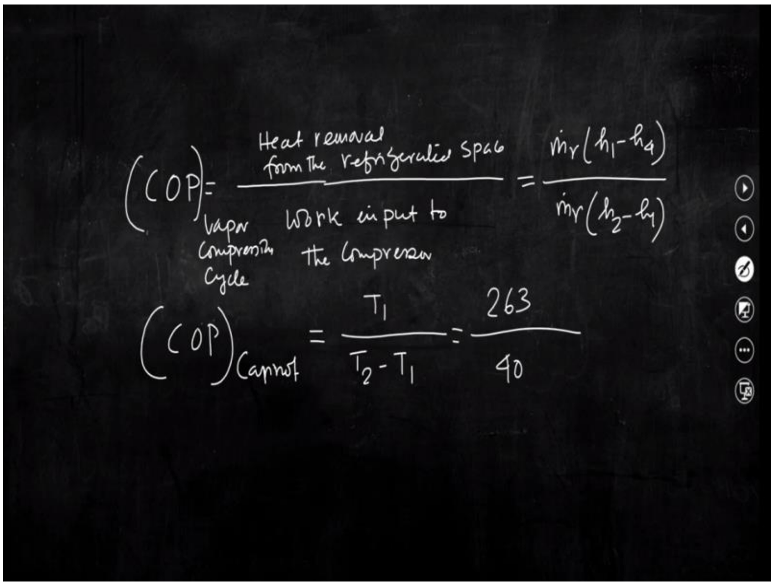

Next, is we have to calculate what is COP? So, that is coefficient of performance for this particular case it is not heat engine. So, this is basically refrigerator. So, for this coefficient of performance is heat removal from the refrigerated space divided by work input to the compressor. In fact this heat removal from the refrigerated space is also known as refrigerating effect.

$$COP = \frac{\dot{m}_r(h_1 - h_4)}{\dot{m}_r(h_2 - h_1)}$$

Now last part of the question is very important that what would be the COP if compared with that of the Carnot refrigerator operating between $30°C$ and $-10°C$.

So, try to understand in the last class also we had tried to discuss that what would be the differences had it been a Carnot cycle. So, instead of a variant of the vapour compression refrigeration cycle had it been a Carnot cycle what would have been the differences.

$$COP_{carnot} = \frac{T_1}{T_2 - T_1} = 263/40$$

So, summarize today's discussion we have discussed about the unit of refrigerating effect then we have discussed about the important properties of a refrigerant should have then we have also talked about the nomenclature of the refrigerant and finally we have solved one example illustrating the concept that we have discussed in the previous class. So, with this I stop here today and we shall continue our discussion in the next class. Thank you.