Concepts of Thermodynamics
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Lecture – 65
Vapour Compression Refrigeration Cycle

Previously, we have discussed about a Vapour Power Cycle for generating power. Today, we will discuss about a vapour power cycle for refrigeration purposes. So, this is called as Vapour Compression Refrigeration Cycle.

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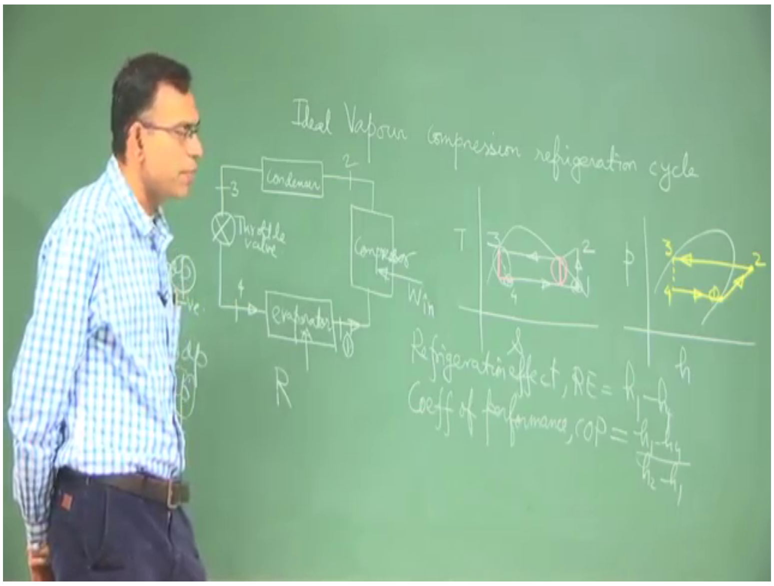

So, in a vapour compression refrigeration cycle, what we are going to study is that how we do get refrigeration? So, in the refrigeration process we see, that heat is continuously extracted from a cool place, that we make a cold place kept always cold. So, how it is possible? It is possible by this set of devices.

So, first we have something called as an evaporator. In the evaporator what is happening by the name it is clear, that the working fluid remember that here the working fluid is not water, but a special type of fluid called as refrigerant and we will try to see that what kind of property that particular fluid should have.

So, in the evaporator, the working fluid it evaporators that is it gets transformed to saturated vapour. That happens at state 1. Then in the evaporator at the exit state of the evaporator, whatever vapour comes out it is compressed in a compressor.

So, if it is a reciprocating compressor it could be of a particular architecture, if it is a rotary compressor it could be of a different architecture, again I am not coming into that engineering aspect I am just we will call this as a compressor without considering what type of compressor it is? Then, after increasing the pressure in the compressor, we pass it to a device which is called as condenser.

So, essentially what we are trying to do is we are trying to reverse the processes that we got that we used in a vapour, in a energy producing cycle. So, this you can understand by the concept of refrigeration or a heat pump, that essentially you are taking heat from a cold place and trying to reject it to a hotter place.

So, you are trying to reverse the processes that would have taken place in a power generating cycle. So, this is a power absorbing cycle. Where the power is absorbed, the power is absorbed in the compressor. Then the fluid passes through the condenser and it gets condensed. After that one could pass it through a expander or a turbine, but here the purpose is not to generate any work. The purpose is to just complete the thermodynamic cycle. So, to expand this a much better opportunity is to use a throttle valve.

So, this cycle with some idealized assumptions forms the ideal vapour compression refrigeration cycle. I will draw this cycle first in a T s diagram. First of all what fluid is circulating here. The refrigerant which is circulating here it is of a particular composition and in the refrigerant world typical refrigerants are given a name starting with R. So, previously we have solved problems with R 12, R 22, R 134 a all these fluids are essentially refrigerants so R for refrigerant.

So, what this refrigerant is doing it is achieving a very special thing. At a very low temperature is gets evaporated, why you want to get habit evaporated at low temperature? Because, it will it is taking how it how it can get evaporated? It is taking heat from a cold space and getting evaporated. So, when it gets heat from a cold space that is getting evaporated. The cold space is still cold, but it is hotter than this, that is how it is transferring heat to the evaporator.

So, if the cold place is at say minus 10 degree centigrade, then this is somewhat less than minus 10 say it is at minus 15 degree centigrade, cold space cannot be at 30 degree, 40 degree centigrade right. So, cold space which is the inner space of the refrigerator or the freezer compartment or different compartments of the refrigerator, that cold space is typically at a cold temperature. So, this temperature would be even colder than that. So, this is sub zero temperature typically.

So, because this is sub zero temperature you must have a fluid, which for it is purpose to be used as a refrigerant should be capable of evaporating or changing phase from liquid to vapour at such a low temperature. Not only that, is latent heat also should be very high at very low temperature. Because, then only a good amount of heat can be drawn by this for getting it converted from it is state 4 to the state 1, which is saturated vapour.

So, we start with state 1 which is saturated vapour, then from 1 to 2 it undergoes let us say if we consider ideal vapour compression refrigeration cycle, it undergoes a reversible adiabatic process. If it undergoes a reversible adiabatic process, it will come like this. Then, heat is rejected and it condenses. Just like we had seen that in a thermal power plant, partial condensation is difficult partial condensation is difficult anywhere. So, instead of condensing it partially we condense it up to full saturated liquid state; state 3 and, then from state 3 to 4 it is expanded in a throttle valve. So, when it is when it is expanded in a throttle valve what happens to the entropy ok?

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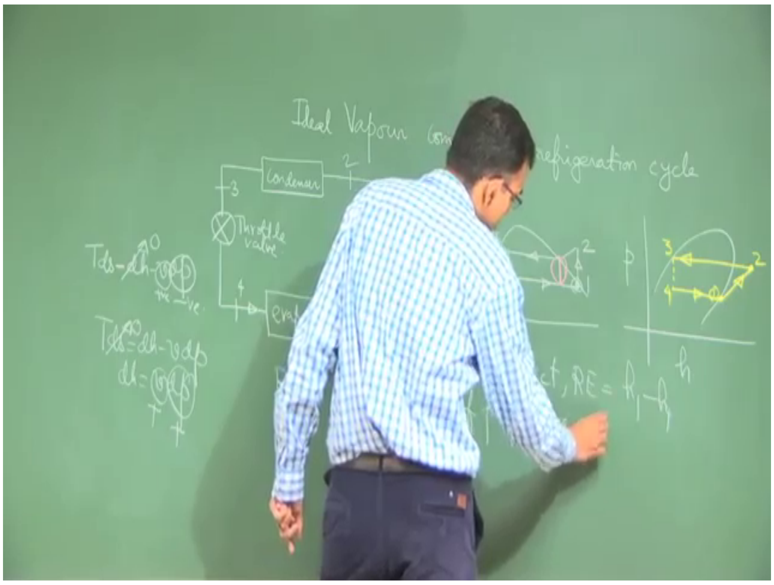

So, to understand that let us use this Tds equal to dh minus vdp. We had earlier proved that under certain practical assumptions the enthalpy before throttling is same as enthalpy after throttling. So, d h is equal to 0 for the throttling process. What is dp? There is expansion of fluid across the throttle valve; that means, dp is negative, v is positive and there is a minus sign; that means, ds is positive; that means, during this process entropy increases and it comes like this back to the evaporator pressure.

One very interesting and important aspect of this diagram is that for all the cycle analysis, we consider the processes to be internally reversible. The cycle may not be totally reversible, but processors are internally reversible. So, that we can draw them by form lines, but this is not internally reversible.

So, we draw it by a dotted line because throttling is such a rapid process that in between 3 to 4 the intermediate states may not attain thermodynamic equilibrium. Therefore, we actually do not know the path by which there has been a change of state from state 3 to state 4. And, hence we have shown it by a dotted line we know only the end states 3 and 4 we do not know what happened for the intermediate states.

Interestingly out of the 4 processes drawn here, you have 3 of the processes or 2 of the processes at constant pressure and one pressure and 1 process at not constant enthalpy, but no net change in enthalpy. So, 2 process out of the 4 processes, 2 processes are constant pressure and one process with no change in enthalpy. Therefore, pressure and enthalpy are some fixed parameter for certain processes in this cycle. To make the plotting of the cycle therefore, more convenient sometimes pressure versus enthalpy diagram is drawn on; p h diagram is drawn.

So, in the p h diagram you have you start with state 1 here, then you go to state 2 which is a reversible adiabatic process. So, how do you know that the state 2 will be like that, again you use Tds equal to dh minus vdp. So, ds is 0 for the process between 1 to 2. So, d h will be equal to vdp, it is a compression process so, dp is positive v is positive; that means, dh is positive. So, during the compression both pressure and enthalpy should increase. So, this is a schematic way of representing that, then it will be a constant pressure heat rejection, then 0 change in enthalpy and then a constant pressure heat addition ok.

Now, again it is very interesting to compare this with a Carnot cycle. So, if had it been a Carnot cycle the difference would have been here and here. So, the throttle valve has to be replaced by a reversible adiabatic expander and the compression process has to be also reversible adiabatic, but to make it a Carnot cycle between 2 constant temperature limits it would be this one and not this one. The penalty that you have to pay is that here you have to compress a 2 phase mixture.

The visco; the compressibility of the liquid and the vapour they are different that makes it very challenging to compress a 2 phase mixture, it consumes a good amount of power not only that if you are using a reciprocating type of compressor, because of the liquid and vapour being differently compressed. And a phenomenon can occur by which the liquid can penetrate into the lubricant gap between the piston and the cylinder and wash away the lubricant; this is known as lubricant washout phenomenon.

So, this is again a not a very desirable phenomenon. So, for from practical considerations having a Carnot cycle all the theoretical is good, but practical it is much better to have a variant of this vapour compression refrigeration cycle. So, in this cycle what is the net effect that you are drawing? The net effect is called as refrigeration effect. This is essentially the change in enthalpy across the evaporator per unit mass flow rate this is the heat that you are extracting from the colds place to the evaporator. And this kind of refrigerant refrigeration effect is used in different languages in industry. For example, sometimes the net effect of refrigeration is expressed in a unit causes called as tons of refrigeration for example, one ton of refrigeration.

So, what it essentially means is that it is equivalent heat extraction that could change 1 ton of water, to 1 ton of ice in 24 hours. Whatever is the rate of heat transfer required to achieve that and that will be in kilowatt unit typically 3.5 kilowatt. So, regarding the definition of this performance parameter 1 is refrigeration effect the other is coefficient of performance.

So, coefficient of performance we have defined earlier what is coefficient of performance, what is the output which is the desired effect? The desired effect is h 1 minus h 4 that is the refrigeration effect. What is the input? Input is the work input for the compressor that is h 2 minus h 1. So, higher the coefficient of performance better the performance of the refrigeration cycle is. So, with this little bit of introduction on vapour compression refrigeration cycle, we will work out a problem and then we will call it a day

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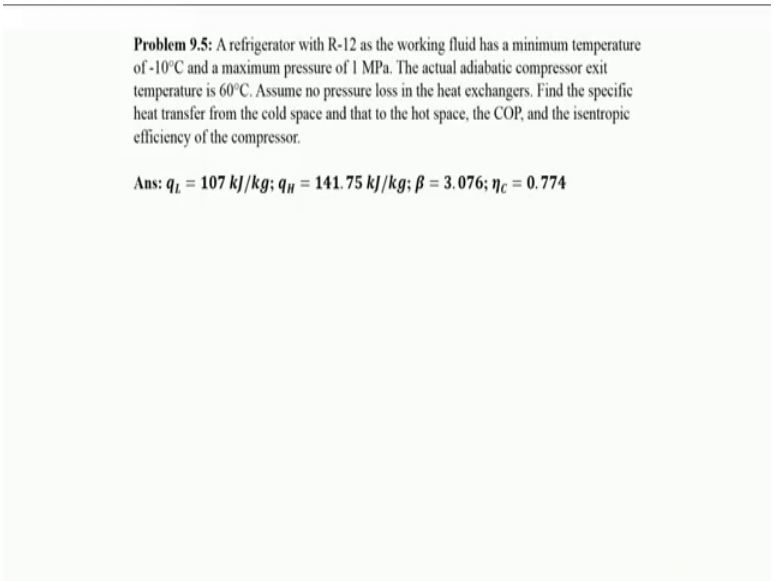

Problem 9.5: A refrigerator with R-12 as the working fluid has a minimum temperature of -10°C and a maximum pressure of 1 MPa. The actual adiabatic compressor exit temperature is 60°C. Assume no pressure loss in the heat exchangers. Find the specific heat transfer from the cold space and that to the hot space, the COP, and the isentropic efficiency of the compressor.

Ans: $q_L = 107\ kJ/kg; q_H = 141.75\ kJ/kg; \beta = 3.076; \eta_C = 0.774$

So, we go to problem number 9.5, which is the last problem of this particular chapter of thermodynamics cycles. A refrigerator with R-12 as the working fluid has a minimum temperature of minus 10 degree centigrade and a maximum pressure of 1 MPa. The actual adiabatic compressor exit temperature is 60 degree centigrade. Assume no pressure loss in the heat exchangers. Find the specific heat transfer from the cold space, and that to the hot space, the cop, and the isentropic efficiency of the compressor.

So, let us go to the board and solve this problem, we have the diagram drawn here, but for this problem we have to modify this diagram. Can you tell where we need to modify? So, look at the problem statement very carefully. It says that the process in the compressor is adiabatic, but not reversible adiabatic, it has a isentropic efficiency. Therefore, the state point 2 is not located on the reversible adiabatic line. So, let us just draw the T s diagram for this we are we will not going to be bothered about the p h diagram and we will create some space here to work out the problem.

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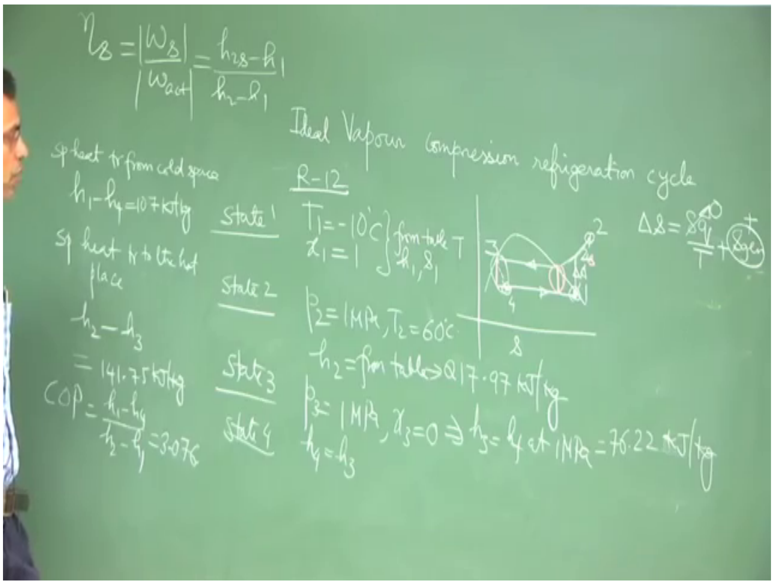

So, here the state 0.2 is not this one this is 2 s. The real state 0.2 will be located on the same constant pressure line, which is the line from 3 to 2 s question is will it be towards the right or towards the left. So, to understand that we will write this expression for change in entropy; the change in entropy is due to heat transfer plus due to irreversibilities entropy generation. Here if you look at the problem statement carefully the actual adiabatic compression; that means, the compressor is adiabatic.

Because, the compressor is adiabatic this is 0 and entropy generation is always positive. Therefore, in an adiabatic situation the entropy will definitely increase. So, the state 0.2 will be somewhere located here, and the actual process 1 to 2 will be like this. This is the only difference between the theoretical discussions that we made and this one.

So, now let us look into the problem definition, a problem statement state 1; state 1 is T 1 is equal to minus 10 degree centigrade first the working fluid is R 12. So, you have to look into the table of R 12, T 1 is minus 10 degree centigrade and x 1 is equal to 1, it is saturated vapour. So, this combination will give you from table what is h 1, s 1 extra. State 2, you have p 2 is equal to 1 MPa and T 2 is 60 degree centigrade.

So, 1 MPa 60 degree centigrade, this will correspond to what, 1 MPa 60 degree centigrade will correspond to h 2 from table. So, if you have h 2, 217.97 kilo Joule per kg then what more is required to work out this problem, you have h 1, h 2 we require state 3 and 4 also because we essentially require the parameters. So, for all cycle problems you will see if it is a steady state steady flow process you will require the enthalpy is essentially for all the state points.

So, h 1 h 2 we have already got. So, now, we will have state 3. State 3 is p 3 is equal to 1 MPa which is same as p 2 and x 3 is equal to 0. So, h 3 is h f at 1 MP and state 4 simply h 4 is equal to h 3. So, we have actually obtained all the state points h 4 I do not have the data h 3 or h 4, yes I have the data for h 3 this is 76.22 kilo Joule per k g ok.

So now, let us see what we need to obtain find the specific heat transfer from the cold space. So, what is that specific heat transfer from the cold space is h 1 minus h 4 right. So, specific heat transfer from the cold space, this is equal to 107 kilo Joule per kg. Specific heat transfer to the hot place, this is h 2 minus h 3. So, this is 141.75 kilo Joule per kg, COP h 1 minus h 4 by h 2 minus h 1 so, this is 3.076.

And isentropic efficiency of the compressor; isentropic efficiency of a turbine what it is the actual work by reversible adiabatic work turbine is a work producing device. So, actual work for a turbine will be less than reversible adiabatic work, for compressor you have to keep in mind is the other way it is a work absorbing device. So, for compressor actual work required to run it will be more than the reversible adiabatic work to run it. So, this will be the W reversible adiabatic by W actual mode of this. So, what is W reversible adiabatic, h 2 s minus 1 and what is W actual that is h 2 minus h 1.

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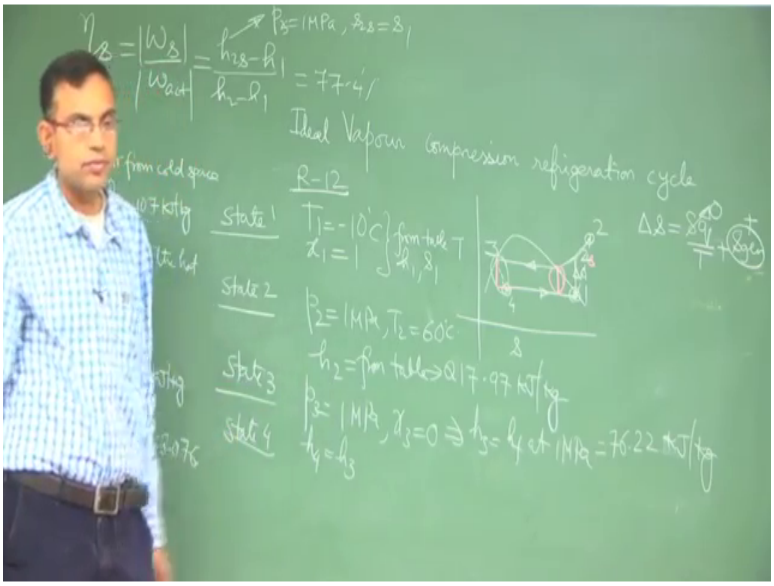

$p_{2s} = 1\,MPa,\ s_{2s} = s_1$

$\eta_s = \frac{|W_s|}{|W_{act}|} = \frac{h_{2s}-h_1}{h_2-h_1} = 77.4\%$

Ideal Vapour compression refrigeration cycle

R-12

from cold space

107 kJ/kg

the hot

kJ/kg

3.076

State 1 $T_1 = -10^\circ C$, $x_1 = 1$ } from table h_1, s_1

State 2 $p_2 = 1\,MPa,\ T_2 = 60^\circ C$

h_2 = from table → 217.97 kJ/kg

State 3 $p_3 = 1\,MPa,\ x_3 = 0 \Rightarrow h_3 = h_f$ at 1 MPa = 76.22 kJ/kg

State 4 $h_4 = h_3$

$\Delta s = \frac{\delta q}{T} + s_{gen}$

How do you know the h 2 s? h 2 s is governed by p 2 is equal to p 2 s is equal to 1 MPa and s 2 s is equal to s 1, this combination from table will give you what is h 2 s. If you substitute these values what you will get is 77.4 percent as the isentropic efficiency.

So, to summarize in today's lecture, we have discussed about the very fundamentals remember that refrigeration is itself a very involved topic. So, we have just given a glimpse to what are the basic premises of refrigeration in terms of thermodynamics cycle, and for that we have touched upon the vapour compression refrigeration cycle, and we have worked out a problem to illustrate how to assess the performance of a vapour compression refrigeration cycle.

Thank you very much.