Engineering Thermodynamics

Dr. Jayant Kumar Singh
Department of Chemical Engineering
Indian Institute of Technology Kanpur

Week-10
Lecture-46
Refrigeration Cycle

Welcome to our channel. We are going to start a new topic, Refrigeration Cycle. In this topic, we will talk about Ideal Vapor Compression Refrigeration Cycle. Then we will talk about the actual Vapor Compression Refrigeration Cycle. In general, we will discuss the refrigerant to be used, and what are the factors that are there in it. and some operations of refrigeration and heat pump and innovative compressor, vapor compression, refrigeration system So, in this lecture we will cover this refrigeration cycle because this is something that we have studied in the previous video how to use the saturation system or the saturation dome Vapor or liquid compression which runs in back and forth cycle we have understood that So on the basis of that, your Vapor Compression Refrigeration Cycle we will make it on the basis of this So we will not spend much time on this but we will do some examples with which you will understand what is a refrigeration cycle So, as we talked about heat engine, when heat is given, then to convert heat to work, you need a special device which is called heat engine. Similarly, you know that heat flows from high temperature to low temperature. If you want to reverse, in which you have to plot heat from low temperature and you have to do some extra work in the refrigerator and we call these special devices refrigerator so in the refrigerator you have to do some additional work you need a work net to extract the heat from the refrigerator so that you can maintain the cold refrigerator space and then you can reject it here because it is a warm environment. So, this special device is called a refrigerator. There are 4 processes involved in this as well. Which you can see here. Similarly, you have this heat pump. The same thing is there in the heat pump that your outside environment will be cold. Like it is in winters, and you have to maintain your house at a warm temperature. So naturally you have to work separately to extract heat from outside and then we will transfer heat flow through heat pump so that the temperature of the house can be warm.

The purpose of this experiment is different, but you can see that both of them have similar flow of work and process. But the purpose of this experiment is different. In each case, maintain low temperature and in each case maintain high temperature. For this type of device, we consider efficiency as a coefficient of performance. And for this, we are calling desired output by required input as COPR. Which in this case, when it is refrigerant, the desired output will be the cooling effect. The cooling effect is the amount of heat that we are getting from our cold refrigerant space divided by how much we had to work. W-19. Desired output is the heating effect. In this case, we have Qh because we have to transfer this amount of heat to the region where you have to maintain the temperature. So, this is the amount divided by the amount of work that has to be done. So, you can see that the desired output has changed. The required output is working but the desired output has changed because the purpose is different. If we fix QL and QH, then the COPHP is COPR.

As I said, the objective of the refrigerator is to remove QL from the cold space. And the objective of the heat pump is to supply QH to the warm space. So, the cooling capacity of the refrigeration system, how do we call it? Like, if we want to buy a ton of refrigerant for free, we go to the market, it's a different 10-H. So, the rate of heat in the refrigeration system depends on that, and it always depends on the tons of refrigeration. We call it that term. We use the terms in the language of the air. What does it mean? It means that one ton of air conditioning is used. Air condition is different because we use air. But in refrigeration, we use liquid water. We use refrigeration to freeze something. If we look at the freezer, the space is sometimes below zero. So, the capacity of the refrigerator is related to the water. If the capacity of the refrigerator is 1 ton, and if the water is converted to ice at 0 degree Celsius in 24 hours, then the capacity of the refrigerator is 1 ton. This is the capacity of the system to convert 1000 kg of water into ice in 0 degrees in 24 hours. This means that 1 ton of refrigeration system capacity is there. We will call it 1 ton refrigerator. Now the question arises that how do we model this system? If you remember, we did Carnot cycle. Carnot cycle is a totally reversible cycle in which two are reversible isotherms and two are isentropic processes. Its maximum thermal efficiency is at a given temperature limit, TH and TL. So, this is a standard for our actual power cycle. That's why it becomes a limit. If it is reversible, we can consider it, we can reverse the process of the is, we can reverse it in the opposite direction. So, if we reverse the cycle, then we call it reverse Carnot cycle. So, when everything happens clockwise in the TS diagram, then it becomes a reversed Carnot cycle. Normally, the Carnot cycle is clockwise, and the reverse Carnot cycle is counterclockwise. If we count the clockwise in the TS diagram, then we will get the reverse cornered cycle and the cornered cycle will be only clockwise the diagram. So, this is important that you have come to this point. Now the question is, can we use this to represent the refrigeration cycle? So here if we try to execute the reverse Carnot cycle in the saturation dome, then how will it come out? So, as we said that this is R, you are working in the compressor. After working, the gas phase is released from the evaporator. So, from here, you compress and condense it. Then you expand it with turbine. Then you evaporate it with low pressure and bring it to the gas phase. So, in a way should be close to glass phase by evaporating If we talk about saturation dome 1 is here which is here before evaporating When we apply heat to it will naturally go into vapor phase After that if we compress it will compress and come into saturated vapor and then when you lose the heat, it gets completely condensed so if you assume that 4 is your saturated liquid then these turbines expand and come into the two phase system so this is 1, so this is the saturated vapor ok So this is a concept that we are trying to come up with in which the reverse Carnot cycle that we have executed we said that this is a saturation dome of the refrigerant system so here this working fluid is the refrigerant remember this so in such cases we know that this is working in TH and this will work in TL so naturally COPR we have already said that we can write the ratio of QH by QL in Carnot. We can always write QH by QL in Carnot. Tl by TL. So, if we apply this, then this comes out as COP of Carnot and this comes out as heat pump. In both cases, if you reduce TL or increase TH, then your coefficient performance will increase. But there is a difficulty in applying reverse Carnot cycle for refrigeration cycle. The reason for this difficulty is that if you have a system like this, then 2 and 3 are two-phase systems. So, you will have to handle the compressor in a two-phase system. The compressor will work well in the gas phase, but the two-phase system will be difficult. Then you see 4-1. 4-1 is again high moisture content, this is also difficult for turbines. If the method is to take it up, then take it up more. Take it up at least one more time, as we said earlier. What is the problem in that, that the high isothermal condition of boiler will be difficult to maintain. And the evaporator, if we take it up from the saturation system, take it separately. That's why the reverse Carnot cycle is not an approximate model for our refrigerant cycle.

So, we have to find a realistic model for this because reverse Carnot cycle is not a realistic model. It is not a practical model. So, we will find something else which we will call as ideal vapor compression refrigerant cycle. Now I would like to say one more thing that even if it is not practical, But it can still work as a standard which we can always check that if we had done it with reverse Carnot cycle then what would be the efficiency whether we are equal to it or not because if we see it, it is totally reversible So if we see this, this reverse Carnot cycle is totally reversible So in this case, we can give a limit and we can use it So the impracticality that we saw in this How to remove the reverse Carnot cycle? First, the refrigerant that we are vaporizing, before compressing, the 2, if we do the complete vaporization, before compressing, half the work, half the issue will be reduced. That your compressor is not working in the two-phase system. So, for the two-phase system, if it works in the gas phase, then it is good. So that's why you do the complete vaporization. one is in the saturated vapor second the compressor will be completely out of the gas phase, and this will be the compressor and this 2 to 3 which is 3 this was also a problem we saw 2 to 3 so 3 to 4 if it condenses completely than half the problem will be reduced So our condensers should definitely be saturated liquid. So, this is important, that it is a saturated liquid. And it is important that it is saturated vapor. So, this is important. This will solve half of our problems. The second problem is that it is a turbine. If the turbine is expanding, if it is working on two-phase, if it is having to do it, then it is getting a problem. So, to avoid that, we can put a throttling wall. Or we can put capillary tube. There is a capillary tube between the refrigerators for this purpose. So, if we apply this, the turbine issue will be reduced. And after this, what will come out will come out in saturated mixture. We will call this the ideal vapor compression refraction cycle. The throttling valve in this process will have some irreversibility associated with it.

Let's try to understand this in the form of a diagram. This is your ideal vapor compression refraction cycle. The inlet is saturated vapor. From here, you are going to 2, which is compressed. This is called isentropic compression, because we consider it ideal. After that, 2 to 3 is constant pressure heat rejection in a condenser. Condensers have constant pressure. Note what we did, we also super-heated 2. We changed the saturated whipper to this one. Then we changed it to this one. Then we decided to change it to this one. So, we did exactly the same. Point 2, the point that is coming out of the compressor, is superheated. After that, if you have throttling of 3 to 4, then it is turbine. Because in this process, entropy is not constant, but enthalpy is constant, so throttling is a 3 to 4 throttling process. So, you can see a curve like this. And after that, 4 to 1 is constant pressure, heat addition. This is especially used in refrigerators, AC and heat pumps. COP can be increased by 2-4%. If you increase the TL and reduce the TH. You can increase COP by this. You can see that with the expression Carnot.

Stedy state flow energy balance,

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

$$COP_R = \frac{q_L}{W_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$COP_{HP} = \frac{q_H}{W_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

If you balance the ideal Vapor Compression, then it will be considered as a steady flow. The corresponding steady flow in the energy balance is what we have done earlier. Condenser and evaporator do not work in this. We can consider the compressor as adiabatic. So, these are your kind of steady flow devices. In this case, your COPI is equal to QL divided by Wnet. QL is here. If we talk about pH, it will look like this in pH. In T-S, as we said, it will look like this in T-H. But what is QL? QL is equal to H1 minus H4. So, this is your QL. And what is Wnet in? Wnet is here. expansion valve, this throttling valve, it is not working, it is only working in this, so this will be H2 minus H1, so this is your networking. Similarly, you can also remove COP HP, and H1 will be your gas phase vapor at P1, and H3 will be HF at PV3, so H1 is this and H3 is this, these two things are important, Another important thing is that if we talk about the normal household refrigerant system, then this is the compressor, this is the condenser, after the compressor, it goes to the condenser, then the expansion valve, which is working like a capillary tube, then comes the evaporator, so this is the process, you can see the whole process from this way. This is your evaporator which is extracting the condenser coil. Note how normal works and how it is represented.

Let's take an example of an ideal vapor compression refrigeration cycle. It works between 0.14 and 0.8 Mass flow rate is 0.8, so 0.14 and 0.8 MPa is the limit. One is the evaporator limit, and the other is the condenser limit. Now we have to remove the rate of heat removal from the refrigeration space, which is QL. Power input to the compressor, Win. Rate of heat rejection to the environment, which is QH. And COP of the hour. to figure it out. Let's start with the test. First, we have already been given the T-S diagram. We will consider this as an isentropic compressor. The condenser that is coming out of the refrigerant is coming out like a saturated liquid. We will consider this as well. We will also consider this as an evaporator compressing and making a saturated vapor. So, this is our assumption. and this is the diagram given on the basis of this. So now the question arises that you have to find the state properties. So, let's start with state 1. So state 1 is your 0.14 M. and in this case you have to use the data from the table on the refrigerator table I already write the data, you can see it from the table there is no such issue in general I am simplifying it by giving you the data so that you can understand how it is so if you check from the table, it is 0.14 MPa which is a saturated system from here you have to extract h1 which is H vapor which is vapor or gas or vapor so you can write vapor or Hg but it is 8.14 Mpa and your S1 is also S vapor at 0.1 and assume G, it is Sg at 0.1 Mpa Now let's talk about state 2 Here you know that P2 is 0.8 Mpc And you also know that S2 is S1 Which we know from this table From here you will get information about the temperature at which it comes out and its enthalpy. Enthalpy is 275.40 kJ per kg. This is the same process as we did before. There are no changes. You just have to understand what the ideal vapor compression refrigeration cycle is and how to draw its TS diagram. And what are its basic assumptions. Once you understand that, then the rest are table extractions. We have to write the property; we have to put in enthalpy and other data. After that, Let's talk about P3. P3 is 0.8 MPa but since it is a saturated liquid, we know that h3 is hF at 0.8 MPa. This is important to know. h4 is in straight form. h4 is up to h3. It is the same because it is in Enthalpy constant. It is in Throttling valve, and it is in Enthalpy constant. And that's why the value of h4 will be the same. Now this is important because you will get the value directly. If you wanted to know the composition of this, what is its quality, then it would be different. Then you use this and use 0.14 MPa and then extract the quality from there. Because you can write h4. Edge. F plus hx hfg So this data can be written at 0.14 MPa in this way you get the quality Now you know h4 Now the question arises that we have to get the rate of heat We have to get QL What will be QL? QL will be h1 minus h4 Qh will be 2-3 We will multiply m. So you will get this value which is 7.19 kW Similarly, we will get Win which will be h2 minus h1 M. And Qh will be m dot h2 minus h3 We can also use QH as QL plus Win We can also use this balance Once you get QL and Win, then QH can be obtained Now let's talk about the coefficient of performance So coefficient of performance is known For this refrigerant, QL divided by W in So this will be obtained So this is how you have accessed this simple But generally, this ideal will not be there. There is some irreversibility in it. Wherever it is, if there is friction, it will drop the pressure. It can also be due to heat transfer. So, because of this, the normal diagram you get is slightly complicated. In this, like 1, here 7 to 8 reaches, then you come to 1. and one is your compressor, one to two, two to three your pressure can drop in between three to four, four to five, six, seven so you get a diagram like this.

let's simplify this a little so in this question we will do some other simplification in this case it is shown to be very complicated In this case, we have shown that the pressure drop is also happening. The isentropic process is also changing. So, we will assume that the pressure drop in this example is zero. Only the compressor has irreversibility, and the isentropic process will not happen. In this case, we will try to solve this example. so in this case you have rest of the data is given evaporator is working at 0.15 Mpa condenser value is given at 0.8 Mpa this is at minus 10 degree refrigerator is entering on superheated vapor which is here and it is 0.10-10 degree Celsius so it is not entering on the saturator it is entering on the superheater notice it and it is coming out at 0.8 MPa at 50 degree Celsius the refrigerant is cooled in the condenser to 26 degree Celsius 0.72 so it is cooled to 26 degree celsius and it came here 0.72 MPa came here and after that it got throttled and came to this point so this means that here 0.8 is here and later we went here So, how will we solve this question? So, the process is the same, you have to extract information from every state, property data, which you will extract from the table. So, let's start from state 1. In state 1, P1 is 0.14 MPa T1 is given as minus 10 degrees Celsius From here, you will see table of refrigerant 134A From here, you will get h1 This is h1 table In this case, you will see superheated table And from here, you will get H1 This is also given to you, P2 is 0.8 MPa and T2 is 50 degrees Celsius from here also in superheated condition it will be obtained State 3 is your compressed liquid it has 0.72 MPa and T3 is 26 degrees Celsius so in this we will approximate hF at 26 degrees Celsius Check the temperature and use hF Now state 4 In state 4, h4 is h3 This is throttling so we will do it directly So you have all kinds of data enthalpy All kinds of state enthalpy Now the question is what is QL? QL will be the same which we discussed earlier, h1-h3 and if you say h then that will be your total h2-h3 and if you say Win then that is your m dot h2 minus h1 the question that I asked was, how much heat is QL removing and how much power input is there? So basically, we are talking about this and this, which we need. We can take out the data because we have already given this data.

Now the question arises that, in other questions, we have taken out the rate of this and power input. Now we have to take out the isentropic efficiency and coefficient performance. So to take out the isentropic efficiency, you have to see this. Isentropic means that you have to compare it with an ideal. So, in this case, the approximate is this, that H2S, because it will work more in actual, so this is done in ideal case, in isentropic case, divided by the actual, 2-H1. Now to get H2S, because h1 is fixed, what we have to do to get H2S is, that H2S means this state. In this case, entropy of 1 will be equal to entropy of 2. So P2 is 0.8Mpa and S2 is S1 So we already know this data. So, using both of them, we will see where this data fits in this table. And from there we will take out enthalpy. After that we will identify the data in which condition like in this case, at what temperature and then according to that, in that condition, your enthalpy will be taken out which will be 2S and this will be your value whatever value comes out here, so it is important that you get this data at what temperature and at this temperature, your S2S will be taken out So this thing has to be used from the table. And here you will get your eta. When you get this, we know this, we know this, we know this, so you will also get eta. Which is 93.8% in this case. Now you have the last question, which is COPR. COPR is your QL dot divided by W dot. So, the whole refrigeration is 3.93. You will get similar questions. You can analyze systematically. You can also do the second law of analysis on everything. Which we will not discuss in this lecture. But you can see the textbook of this book. There are many examples of the second law of analysis. Which you can do in the refrigeration cycle.

Now let's talk about how to choose the right refrigerant. Let's talk about how to select Bright Refrigerant Because in refrigeration system, whatever refrigerant you use, it has a chloro fluoro based compound. And it has become very important to reduce it nowadays, so that it does not affect the ozone layer. So, normally, they used to use chlorofluorocarbons. It is still being used to a large extent, but there is some banning. The second option is ammonia hydrocarbon. Propane is quite popular in hydrocarbon. The content of hydrocarbon is less, and it is a little bit more friendly than ozone. The rest of the carbon dioxide, air, even water can be used as refrigerant. Especially this compound is 90% available in the market. In the industry and heavy commercial sectors, ammonia is mostly available. It is toxic in a way. We do not prefer it much. But in the future, as ammonia will be used in many other places, we have given control over it. because people are not paying attention to it in general it is not environmentally friendly but still it is used the water chiller R11 is used in it R134 has been replaced R12 has been replaced which used to damage this is being used now but there are other variants of R22 and then blend is also there. So, what is happening on the common topic is that we are mixing it with the most effective one which is ozone friendly. And maximum attention has been paid to this. First, environmentally the refrigerant should be friendly on ozone level. So, on this, in fact, now the government also wants you to find alternative refrigerant which is ozone friendly and still you can work on the purpose of the It is a huge prospect of increasing refrigerant because AC is very limited in our country. As industrialization and uplifting of the country increases, AC and other things will also increase. So, there are many requirements, so it is very difficult to work on it. India and other countries.

Now let's talk about the innovative Vapor Compression Refrigeration Cycle. It is important to note that the ordinary refrigeration system is trying to modify it. The ordinary refrigeration compression refrigeration cycle, which we call Vapor Compression Refrigeration System, is normally ordinary, simple and inexpensive, but it is not efficient. So, we want an efficient system, we will have to innovate. So simple vapor compression is sufficient for our major work. But it is not sufficient industrially because it requires efficiency and there is a lot of temperature variation. In such a case, you will have to modify this simple vapor compression refraction cycle. There are many possibilities. Like Cascade Refrigeration System, Multi-stage Compression Refrigeration System, Multi-purpose Refrigeration System, single compressor, liquefaction of gases. There are many options. We can discuss a lot on this. But if you are interested in understanding this, then you can read the book which is our textbook and then study it more. You can read literature about it.

For example, if we talk about cascades, then cascades are useful when your temperature is very high. So, if the temperature is very high than low temperature, then the range becomes very high. In such a case, one vapor compression cycle does not work. That is why we put two. For example, this is an example to show how two compression cycles are attached. like cascading effect and in this case you can see in your TS diagram that this is one and this is another and because of this if you do one then it would be like this ok so it would be this big so we have done the same thing in two so because of this some of our cooling capacity increased and some work we have reduced efficient 2 cascade system will be more valuable for us.

$$\dot{m}_a(h_5 - h_8) = \dot{m}_b(h_2 - h_3)$$

$$\frac{\dot{m}_a}{\dot{m}_b} = \frac{(h_2 - h_3)}{(h_5 - h_8)}$$

$$COP_{R,cascade} = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{\dot{m}_b(h_1 - h_4)}{\dot{m}_a(h_6 - h_5) + \dot{m}_b(h_2 - h_1)}$$

So, these solutions are used a lot. As I said, we will not discuss much on this because it can take a lot of time. But if you are interested, you can read it. You can read it in an advanced textbook. You can read it deeply and pay attention to the examples. You can also do good examples in your textbook. So, in summary, we tried to understand the refrigeration cycle with reverse Carnot cycle. Refrigeration and heat pump are used to transfer heat from low to high temperature. And for that, you need a special device which we call refrigerators and heat pumps. We said that reverse Carnot cycle is not sufficient, so we used ideal vapor compression refrigeration cycle. Then we discussed the actual vapor compression cycle and some questions. Then we discussed how to select refrigerant. This is an area where a lot of research can be done for refrigerant selection and new refrigerant designs. Finally, we said that the vapor compression refrigerant system can innovate it. Because the industry needs and demands are not possible with one Vapor Compression Refreshing System. We have to do cascading and many other things. So, in this way, many creative Vapor Compression Refreshing Systems have been created. We will stop the power and gas power cycles and the coefficient cycles here. In the next lecture, we will discuss the power and gas power cycles and the coefficient cycles. We will start the second topic which will be on thermodynamic properties. See you in the next lecture with a new topic. Till then bye.