Applied Thermodynamics for Marine Systems
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Lecture - 18
Refrigeration Vapour Compression Cycle

Good afternoon. We have started discussing, regarding refrigeration and we will continue with that. We are familiar with the Carnot cycle. Carnot cycle is basically a heat engine cycle. The Carnot cycle is made up of all reversible processes. If the processes are reversedd, if all the processes of a Carnot cycle are reversedd, then we get a reversedd Carnot cycle. The reversedd Carnot cycle can be utilised for production of low temperature or for the production of cooling effect or for the production of refrigerating effect and that cycle can be called also as a refrigeration cycle. The cycle can also be called as a heat pump cycle because the same arrangement can be utilised for making one heat pump.

Basically, the design or the configuration of heat pump cycle and refrigeration cycle is the same. Only thing is that the purposes of these two cycles are different. As the purposes are different the expression of COP of these two cycles are different. That is what I have discussed in the last class. I have also discussed or I have shown that reversed Carnot cycle, though it is a reversible cycle, an ideal cycle and it is supposed to give a higher COP or the maximum COP for a given temperature limit for two given temperature source and sinks, but there are practical limitations. There are practical limitations in realising Carnot cycle if we use a gas as the working fluid or refrigerant. There will be practical limitations if we use a vapour as the refrigerant. That is why we will not have reversed Carnot cycle as the preferred cycle for the refrigeration.

Now, let us see how we can modify the reversed Carnot cycle so that we can get a workable cycle for refrigeration systems. Let us start with vapour as the refrigerant. There will be a suitable fluid which will be selected and we will use that particular fluid in the two phase conditions. That means, in part of the cycle it will be as vapour and in part it will represent as liquid and then, we will have the cycle. This type of working substance is called a vapour.

Taking the vapour as the working fluid we will try to constitute a cycle. In doing so, we will see how we can modify so that the limitations or the drawbacks of Carnot cycle can be eliminated.

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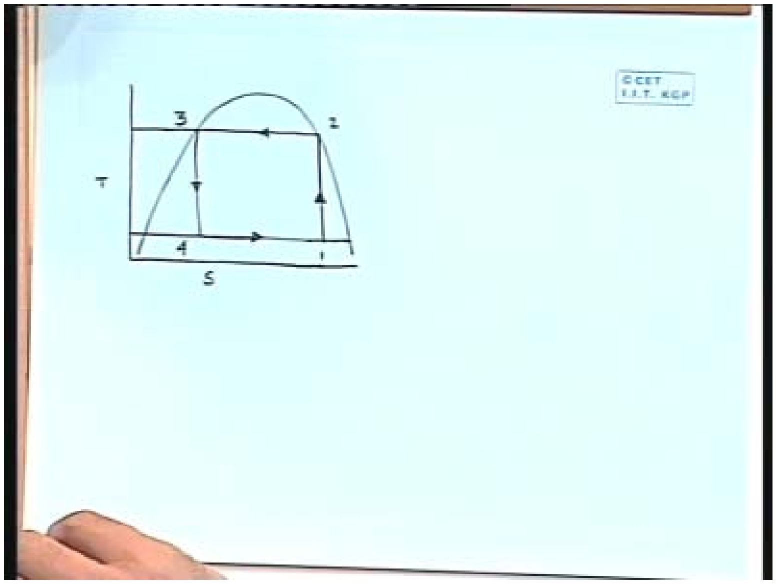

Let us start with our TS diagram. This is one temperature limit and another temperature limit. This is the two phase dome. Our traditional Carnot cycle is like this. 1 to 2 is the isentropic compression, 2 to 3 is the isothermal heat rejection, 3 to 4 is the isentropic expansion and 4 to 1 is the isothermal heat absorption or heat addition.

Let us start from the first process, that is, 1 to 2 isentropic compressions. If we do this isentropic compression and if we start from the wet state of the fluid that means here it is partially liquid and partially vapour, if we start from this state, then we have to handle a mixture of liquid and gas. I have told you a number of times that this is difficult. Another thing is, we know that not only the design of the equipment is difficult when liquid refrigerant is present, but it will damage the compressor. If we have any compressor and even if a smaller quantity of liquid refrigerant is present then it will damage the compressor. Particularly, the liquid refrigerant becomes a droplet of liquid refrigerant and it moves with a high velocity. So, it damages the valves and piston head etc. Particularly towards the …. centre, there should not be any liquid refrigerant present in the compressor. We have to ensure that; then we have to start with at least dry saturated vapour if not super heated vapour.

The first modification which we like to have is dry saturated vapour. We are going for the modified configuration of the cycle.

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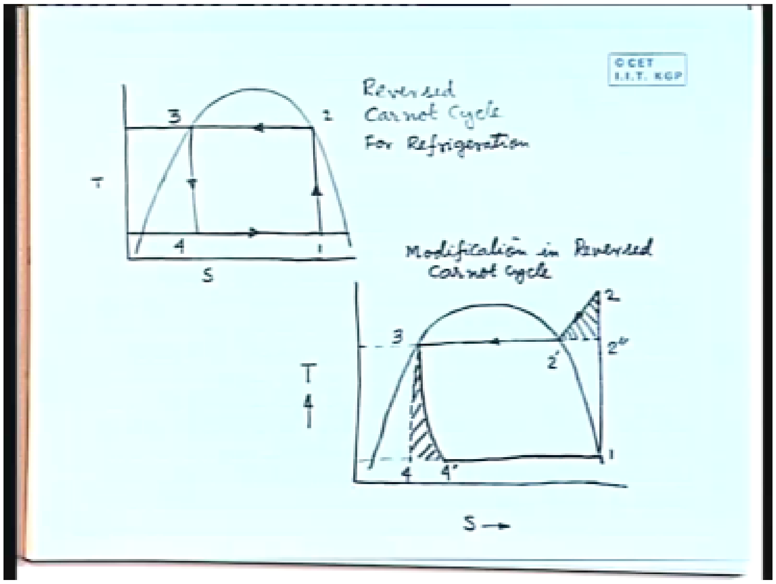

We will have S here, entropy, temperature here and this is our two phase dome. We will start with dry saturated vapour. This is point 1 and this is the end of compression, point 2. We have started with two temperatures like this. Probably one can argue that I will stop my compression process over here and then I will come back like this. That means after that my heat rejection will start from here. But then, this process becomes a constant temperature heat rejection process for a superheated vapour; that means, for a single phase fluid it becomes a constant temperature heat transfer process which is not possible. We cannot have constant temperature heat transfer process for a single phase fluid. Only for a two phase fluid or only for a fluid when there is phase transfer we can have constant temperature heat rejection or heat addition. That is why this is not possible. What is possible is we can do like this. This process actually is a constant pressure process.

I call this as 2, this as 2 dash and this as 2 double dash or 2, 2 prime, 2 double prime. So, 2 to 2 prime is a constant pressure process and from 2 prime to 3, again that is a constant pressure process but as it is within the two phase dome, it is also a constant temperature process. If I call it 3, 2 dash to 3 will have a constant pressure heat rejection as well as that will also be a constant temperature heat rejection. This particular area given by this triangular shape 2, 2 prime, 2 double prime is known as superheat horn. This area is known as super heat horn. You see the green dotted line that I have drawn; one can define a Carnot cycle with this green dotted line. We are getting something extra above this Carnot cycle and this extra area is in the superheated region and it is known as the superheat horn. Then, physically what is happening? 2 to 3 is the condensation process and inside a condenser, the pressure drop is small; we assume it to be negligible, so we have a constant pressure heat rejection process here. Then, 3 to 4 in the Carnot cycle... (12:50). Let me write it down. This is your reversed Carnot cycle for refrigeration. Here, if I want to give some sort of a heading we like to give this is modification in reversed Carnot cycle.

After condensation, at point 3 we have a saturated liquid. Now in the reversed Carnot cycle we had isentropic expansion. How can you have isentropic expansion? Probably you can think of some sort of an expander or if it is a flow system, a turbine kind of a thing. The thing is that for a refrigeration system, this isentropic expander or if we have some sort of an expander which will allow the gas to expand and at the same time it will extract some amount of work from the expanding gas, we will find that the design is complex because it has to handle both liquid and gas; that is one thing. The work which we will extract will be very small and the cost of the expander, whatever we may design, will be prohibitively high.

These are the problems we will have. The first thing is that the design is not very simple because we have to have some good design which can extract work out of this. for liquid flowing through... (15:36), Basically, it will start from saturated liquid and here it will come out as a mixture of liquid and vapour; the design is not simple. We will see there are so much of losses, we will not be able to extract enough amount of work. On the other hand, the device will become complex and you will have cost implications. The idea of having one isentropic expansion process is not a very buyable one; we do not want to have any expander or any sort of active device there. But, we can see that there should be some sort of a temperature drop and not only that, these two are at two different pressures; there should be some sort of a pressure drop. We should have a device which will allow this.

We simply select some sort of expansion device. There could be different expansion devices. This expansion we want to have by throttling process. Throttling process means Joule Thomson expansion process. So we want to have throttling process. If we have a throttling process then we know that enthalpy before throttling is equal to enthalpy after throttling. That is one thing we know and another thing we know is that throttling process is an irreversible process. If it is an irreversible process then what will happen? We will have an increase in entropy.

If it is an isentropic expansion process then we could have the entropy of point 3 and point 4, which are identical that is what I have drawn earlier. But, if it is a throttling process then the entropy of 3 and entropy after the throttling process will be different. The entropy after the throttling process will be more than the entropy of the fluid at point 3. What I mean to say is like this. This is our point 4 and we will have point 4 dashed. Let us draw it with …. line. So, point 4 dash is the point after throttling. We can see that 4 dashed is at a higher entropy compared to 4. Here, you can see that this dashed area shows the difference between the reversed Carnot cycle and the modified cycle.

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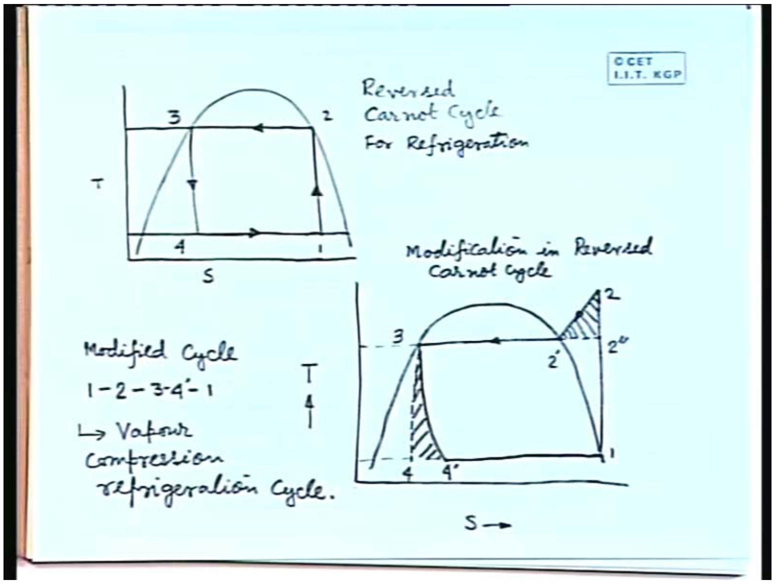

Basically, now we will have our modified cycle. 1-2-3-4 dashed and 1; this is known as vapour compression refrigeration cycle. I have shown the vapour compression refrigeration cycle like this. Actually, you can see that there is a loss in refrigeration effect due to this area 3, 4, 4 dashed and there is some gain in refrigeration effect due to this area 2 prime, 2 double prime and 2. What are the processes there? A vapour compression refrigeration cycle generally starts from saturated vapour condition; then we have got isentropic compression, then we have got constant pressure heat rejection till we have got saturated liquid that is actually taking place inside a compressor. Then, we have an expansion process and this is expansion by throttling, so that enthalpy before expansion and after expansion remains constant; that is process 3, 4 dashed and 4 dashed to 1 is heat absorption and that is isothermal. This takes place in evaporator.

As I have told, in part of the cycle the fluid is in liquid condition and in part of the cycle it is in vapour state. We will have two pressures, basically. One is a condenser pressure which is high pressure and another is the evaporator pressure which is at lower value or low pressure.

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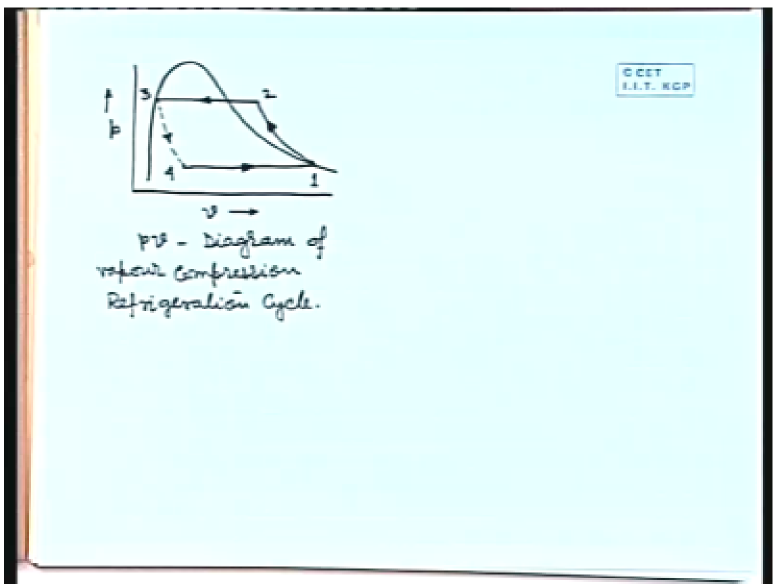

If we want to see this diagram in pv plane, this is a constant pressure process. One should start from here. Basically it is like this. 1, we are starting from saturated vapour condition; then it is an isentropic expansion process; then, this is constant pressure heat rejection process. Then, we have got this which is not a constant enthalpy process and it is an irreversible process, so, we do not know the exact path; that is why we are showing it like this. But, enthalpy here and here are same. So 1, 2, 3 and this is 4 and we will have the end of the cycle by a constant temperature heat absorption process. This is your pv diagram of vapour compression refrigeration cycle.

We have seen the TS representation of the vapour compression refrigeration cycle and we have seen the pv representation of the vapour compression refrigeration cycle. But, the thing is that conventionally, this cycle is expressed in ph plane- pressure enthalpy plane, which has a few advantages. Instead of representing it in TS plane or pv plane it is advantageous to represent the cycle on a ph plane. Conventionally, vapour compression refrigeration cycle is represented on a ph plane. So we will try to do that.

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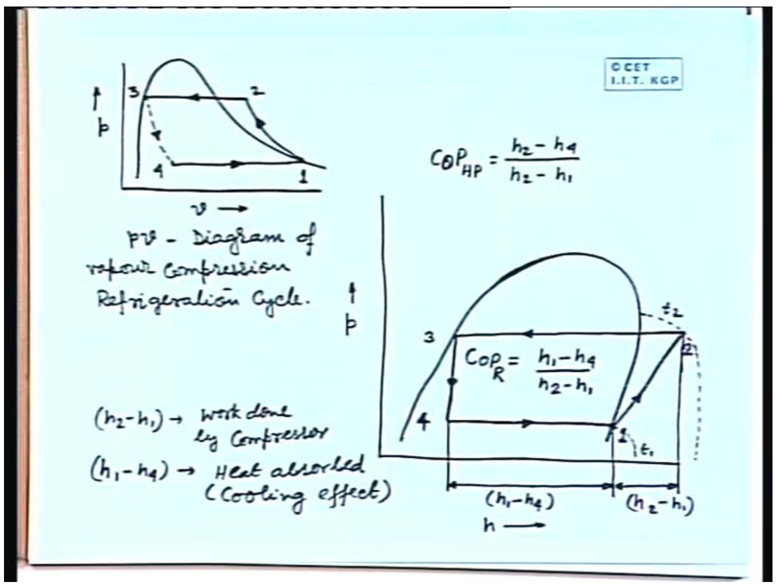

This is our ph plane. In the ph plane this is your pressure, this is your h and the vapour dome is something like this. Let us start from here. This is your 1, that is, the initiation of compression. We start the compression from saturated vapour condition. We will have compression from 1 to 2; this is your compression. Then, the heat rejection process; the heat rejection process will be from 2 to 3 and that is a constant pressure process at least for the ideal cycle. So, 2 to 3 is a constant pressure process. Then 3 to 4 is a constant enthalpy process. In between the process, we do not know the enthalpy but we think that during the entire process enthalpy remains constant. If we do that then we will get 3 to 4 like this; this is a constant enthalpy process. Then 4 to 1 is the constant temperature or isothermal heat absorption process. Two temperatures are very important. That is this temperature; actually constant temperature lines are like this and this is the temperature t_2 at which the vapour comes out of the compressor and enters the condenser and this is the temperature at which dry saturated vapour comes out of the evaporator and enters the compressor. We can put different values; this is t_2 and here, if you like you can put this value as t_1. You see from the curve we can get some more information. So this is giving some sort of enthalpy difference from the graph itself. This enthalpy difference is given by h_1 minus h_4. This is the enthalpy difference. This one is again another enthalpy difference, so this one is h_2, this is h_2, minus h_1. So, h_2 minus h_1 is the enthalpy difference and what does it mean? It is the work done by the compressor. So let me write. h_2 minus h_1 is the work done by the compressor. Actually from first law, we will get this. If we have negligible change in kinetic energy and potential energy, we will get, h_2 minus h_1 is the work done by the compressor for unit mass flow rate. Similarly, h_1 minus h_4 is the heat absorbed by the evaporator. That much amount of heat we are taking from the low temperature body or the sink and we call this as refrigeration effect or cooling effect. So, this is the amount of heat absorbed. We can also call it a cooling effect.

We can have efficiency COP is equal to h_1 minus h_4 divided by h_2 minus h_1. Let me write it as COP_R - coefficient of performance for the refrigerating cycle. Some may write it as COP_C, COP cooling. If it is used for cooling purpose then $COP_{cooling}$ is equal to h_1 minus h_4 divided by h_2 minus h_1. If we do it for heat pump, then $COP_{heat\ pump}$ is equal to, then what is the heating effect? h_2 minus h_3; that is nothing but h_4; h_3 and h_4 are the same, so h_4. We can write this is nothing but h_2 minus h_4 and energy supplied has remained the same, so that will be h_2 minus h_1. Whatever may be the diagram you can find that h_2 minus h_4 that is always greater than h_2 minus h_1. The COP of heat pump will be always more than 1. But COP of refrigeration cycle that may be more than 1 or that may be less than 1 depending on the diagram or depending on the different properties taken. But COP of the heat pump will be more than 1.

I think it will not be out of context if I mention at this point. That is why, nowadays, we are having a lot of interest on the development of COP. It can be utilised keeping in mind that we are able to use some amount of extra energy. The amount of energy for which I am paying is h_2 minus h_1. This is the energy which is being supplied to the compressor. But as a return, we are able to utilise energy which is equal to h_2 minus h_4 which is more than the energy being supplied. We have got some advantage in heat pump and that is why in number of applications we will find that heat pumps are being used. Now, it may sound little bit anomalous because from our childhood or in every sphere we have seen that, generally we cannot get more than what we pay for. There should be somewhere some sort of thing which we are missing when we are telling that we are getting more than what we are paying in a heat pump and it is actually shown.

What is happening is, in case of heat pump, the energy which we are supplying to the compressor is a high grade energy or high quality energy. What energy are we supplying? We are supplying either mechanical energy or electrical energy. So, some amount of work we are supplying that is a high grade or high quality energy. It comes from second law that this is high quality energy. Supplying some less amount of high quality energy we are getting a large quantity of low grade energy or low quality energy. We are getting more quantity of energy but what we are losing? We are losing the quality of the energy; we are getting thermal energy that too at a moderately low temperature; not very low temperature but moderately low temperature or medium level temperature; we are loosing the quality of energy.

Even then, in some application use of heat pump is advisable. Let us say we have an application where we have to do heating. That heating you may prefer to do by electrical energy; electrical heating can be done or you may prefer to do it with the help of a heat pump, where electrical energy will be used only to run the heat pump but the heat rejected by the heat pump will be utilised for heating. If we do that and generally if we do it for a large system then we will see that we are gainers. That is why when room heating is needed for a large system, let us say, space heating, not room heating; space heating is needed for a large system then we will see that heat pump is beneficial. Let us say, for a large desalination plant, when your heating is needed probably, we can do it in a better way with the help of your heat pump.

That is one important issue nowadays because, day-by-day energy is becoming costlier and one needs to save energy. To save energy means whatever resources are there we have to use it judicially. Simultaneous heating and cooling is also possible. If there are certain applications where both heating and cooling is needed, heating is needed somewhere and cooling is needed somewhere, we can do it by having some sort of a heat pump. The only problem is temperature matching, which means we need heating at a certain temperature; we need cooling at another temperature, which is also fixed. We have to select some sort of a cycle and some sort of a fluid that matches these two. It is not a very easy task but to some extent it is possible and we should look into that possibility where we can use it.

Basically, you see that instead of pv or TS representation, ph representation or representation of the vapour compression cycle in ph plane is more advantageous. It is easy to draw and from the diagram itself you can get a lot of information. Particularly, the useful quantities like the power required for heating, the power required for cooling and how much power is required for running the compressor and efficiency? Everything can be directly obtained from the diagram. That is why we like to represent the vapour compression refrigeration cycle on a ph plane.

Now I will draw a block diagram of the refrigeration cycle.

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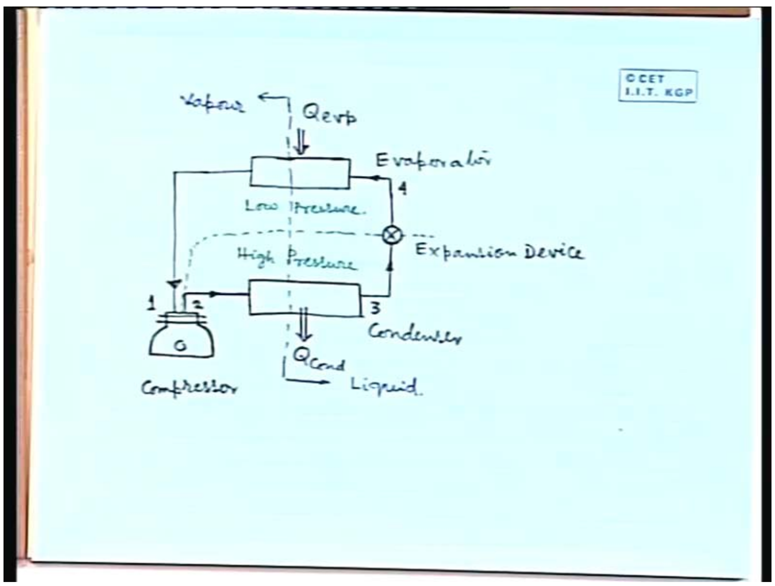

In the refrigeration cycle we will have a compressor. What I have drawn schematically is a reciprocating compressor. It need not be a reciprocating compressor. Nowadays there are centrifugal systems, where we can use a rotary compressor. Actually, a reciprocating compressor is a positive displacement compressor. There are other types of positive displacement compressor nowadays. Earlier also it was there, but nowadays, it is used for energy saving because in other compressors energy dissipation due to some friction etc., are less like screw compressor that is more compact. Depending on the design you can have a longer life in case of other type of compressor. But still in smaller establishments, reciprocating compressor is very widely used.

Maintenance is easier in case of a reciprocating compressor. Maintenance is one thing and cost is another thing. The technology of reciprocating compressor has developed over the years; many manufacturers are there and old establishments are there. Some time will take when more of reciprocating compressor will be replaced by other compressors; so it will take some time. After the compressor, we will have the condenser. In the condenser, heat will be rejected. This is heat rejection, we can show it like this; Q condenser and then after this we will have an expansion device. This is our expansion device. Let me write compressor, then condenser, then expansion device, and then we will have the evaporator. In the evaporator, you will have absorption of heat. We can do it like this, Q evaporator, so we can write evaporator. After the evaporator it is coming back to the compressor again; it is in the vapour state and it is coming back to the compressor again.

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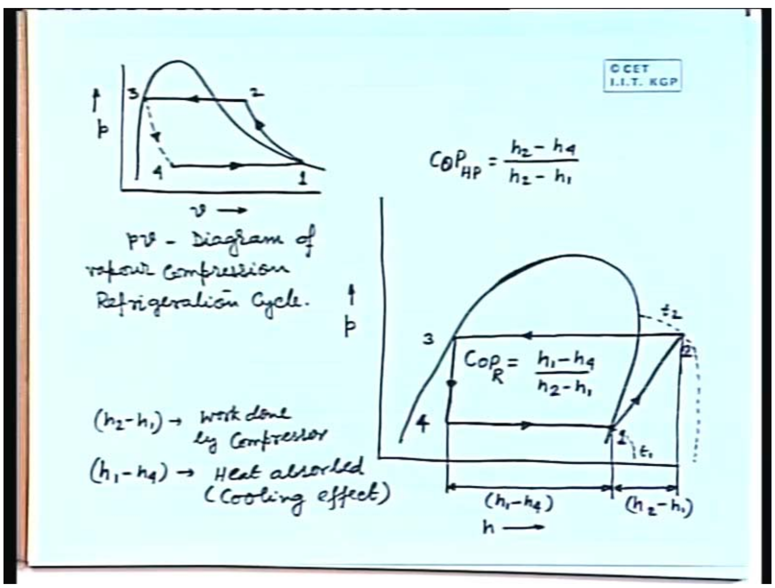

Let me show you this diagram. 1 to 2 is the compression process, 2 to 3 is the condensation process, 3 to 4 is the expansion process and 4 to 1 is the evaporation process. Let me put the numbers here. 1 to 2 is the compression process, so we can write this is 1, this is 2. Then 2 to 3 is the condensation process; 3 to 4 is the expansion process or throttling process, so I have written 3 to 4; then 4 to 1 is the evaporation. Actually, 1 is here to here and we do not consider any change of property, so 4 to 1 is the evaporation process. We can show a part of the compressor like this. This is high pressure and this is the low pressure zone. We can write this is high pressure and this is low pressure. The gas is entering the condenser and after that some sort of phase change is taking place. So, at point 3 this is liquid. Actually, it is not instantaneous. So, what we can show is that on this side we have got gas or vapour. Let us say this is vapour and on this side we can say that this is liquid. In the cycle, we will have different states, different pressure and temperature condition, and different states of the fluid also. Basically, these are the demarcation lines across which we will have these changes.

If we see the physical construction of the cycle then we will have the compressor. The compressor could be positive displacement type of compressor or it could be a rotary compressor or we should say roto-dynamic compressor, centrifugal compressor. Then, we will have two heat exchangers- different types of heat exchangers could be there. Big condensers are generally shell and tube condensers but there could be other type of condensers also. There are small condensers; starting from your domestic refrigerator very small condensers or compressor-? and you can see very large condensers or compressor-? in a large machine. Then, the expansion device; the expansion device could be of different types. Basically, it is a throttling device so it is a narrow aperture device and this narrow aperture you can obtain through different means. It could be a valve and it is called expansion valve, or it could be a capillary tube or a number of capillarity tubes, where it is a very small diameter but long tube placed here for the pressure drop; if we want to achieve the pressure drop then we can put a capillary tube. Both have their limitations and merits. In small establishments we have capillary tube but in case of large establishment we have expansion valves. Sometimes it is controlled also so we have got thermostatic expansion valve.

Then, we have got an evaporator. Basically, this is a heat exchanger. Depending on what we are trying to achieve from the refrigeration cycle we can have different type of heat exchanger. If it is a chiller, then we can have a shell and tube type of heat exchanger. If we are using the refrigeration for an air conditioning purpose so then we can have pin tube type of heat exchanger as our refrigerator. Now, in practical situations design of these components, size of these components will vary. But in general, we will have these four basic components: compressor, condenser, expansion device and evaporator. Now we can see that there are certain variations in the actual cycle compared to the ideal cycle, which I have drawn just now.

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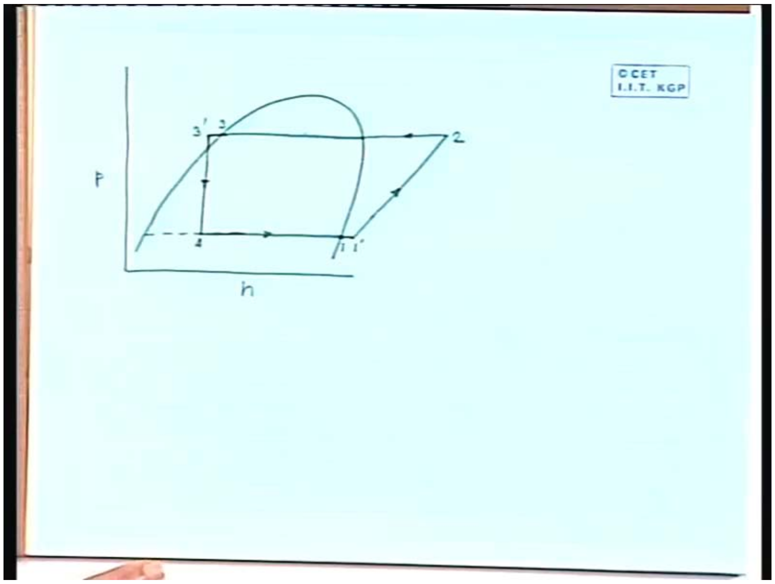

I like to highlight some of the important variations. This is the ph diagram of your refrigeration cycle. The compression process will be initiated from dry saturated condition. But in number of designs we will find that there is a superheating at this end; so, superheating at constant pressure itself and then the compression will start. Similarly at this end, the throttling process or expansion process will start from the saturated liquid state, but in number of systems we will see that there will be a slight sub cooling of the liquid and then, the throttling process will start. This is a very common feature of any refrigeration cycle. We have got superheating in the suction. This is called the suction and here, before throttling, we have got subcooled liquid. Now, our cycle diagram becomes - this is 1, this is 1 dashed; this is 2, this is 3, 3 dashed and 4, Here the liquid is being sub cooled. Sometimes, it is called undercooling also. You cannot control the process in such a manner so that just at the saturated state your vapour will come out of the evaporator and will go to the compressor. Then, there are two possibilities. It can either go in slightly wet condition or it can go in slightly superheated condition. We will not allow wet condition, so it is better to allow it in superheated condition.

We will discuss the implication of this undercooling and superheating afterwards in our next class.