Applied Thermodynamics for Engineers
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Lecture – 26
Vapor compression refrigeration cycle

Good morning everyone. So, today we are going to start our discussion on refrigeration cycles. In the previous three weeks we have talked about the power producing cycles, the power producing cycles using gas as working medium, using some compressible vapour as the working medium. Accordingly, we have discussed about several kinds of ideal cycles such as Otto and Diesel cycle, Brayton cycle and Rankine cycle. And also have discussed in detail about the ways of analysing those cycles and also the possible ways of improving their performance.

Now we are going to the other spectrum from where we shall we talking about particularly this week we are going to talk about the work absorbing cycle that is in the form of refrigeration. And to start the discussion, the first thing of course, comes is the second law of thermodynamics.

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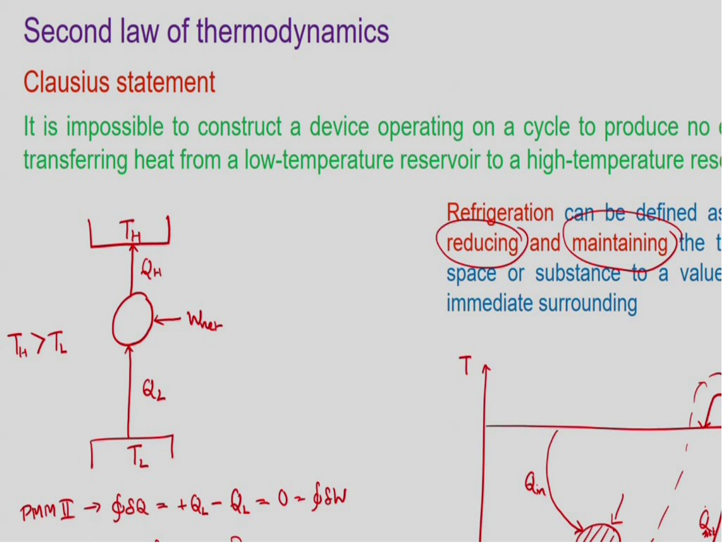

Second law of thermodynamics

Clausius statement

It is impossible to construct a device operating on a cycle to produce no
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Refrigeration can be defined as
reducing and maintaining the t
space or substance to a value
immediate surrounding

PMM II → $\oint \delta Q = +Q_L - Q_L = 0 = \oint \delta W$

In the very first module of this particular course, we have briefly reviewed the laws of thermodynamics where the second law was also there. And you definitely know that there are several statements of second law of thermodynamics, but two of them are very popular: the

Kelvin planck statement and the Clausius statement. And the second one that is a Clausius statement is the one that is related to the refrigeration cycle.

So, I have repeated that one here which says that: It is impossible to construct a device operating on a cycle to produce no effect other than transferring heat from low temperature reservoir to a high temperature reservoir. Means, here we are talking about a cyclic device, let us say this is a cyclic device and we have two temperature reservoirs: one at temperature T_H, other at temperature T_L. Where this T_H is higher temperature this is it is greater than T_L.

Now if you are trying to postulate a device which is going to take say, take some Q_L amount heat it is going to extract Q_L amount of heat from low temperature reservoir deliver exactly the same amount of heat to the high temperature reservoir without any other kind of energy insertion. Then, though this is not violating the first law of thermodynamics because as per the first law, the cyclic integral of δQ in this case is equal to the amount of energy added to the system is Q_L minus, again it is receiving Q_L amount of heat which is equal to zero which is equal to cyclic integral of δW.

$$\oint \delta Q = +Q_L - Q_L = 0 = \oint \delta W$$

But any effort to produce such device result in failure and that is why we call them the perpetual of the motion of the second kind (PMM-II) because this is theoretical impossible or sorry at least possible for the first law of thermodynamics but it is violating the second law of thermodynamics.

Then, what can be the option of realising such device? To make it in practice we have to produce or we have to give some work input to this let us say W_{net} is the amount of work input that has been given to this. So, it is now having both heat and work interaction then if we apply for thermodynamics on this:

$$\oint \delta Q = \oint \delta W$$

Cyclic integral of δQ in this case is again amount of heat received by this is Q_L and as per conventional energy added to the system is positive and energy rejected by the system is negative. In this case as the amount of heat received by the high temperature reservoir is not be Q_L let us that is going to be Q_H, i.e.,

$$+Q_L - Q_H$$

So, this is a heat interaction and the work interaction, the magnitude of work interaction is W_{net}. It will be positive or negative? We know that work done by the system is positive and work done on the system is negative. Here work has been given to the system that is working is done on the system. So, it is negative.

$$+Q_L - Q_H = -W_{net}$$

Accordingly, we get the magnitude of W_{net} to be equal to:

$$W_{net} = Q_H - Q_L$$

So, this is definitely satisfying the first law of thermodynamics and also it is satisfying the second law of thermodynamics. Because here we are not transfer energy from low temperature reservoir to high temperature reservoir without any other effort. Therefore, we are having this much of effort which is W_{net} that is being imposed on this system and accordingly what we get this particular system is called a reverse heat engine. Because if you look carefully, if you just alter the direction of the three arrows, the direction corresponding to the three heat and work interactions that we have shown on this particular schematic. If you just reverse direction of all three of them when you are going to get heat engine.

Then you are talking about the system receiving Q_H amount of heat from the high temperature reservoir converting W_{net} for as a work output and rejecting Q_L to the low temperature reservoir which is exactly what we have a heat engine. And here the directions have reversed and that is why we call it reverse heat engine.

And Clausius statement of the second law of thermodynamics is the working statement for this particular scenario. But now what is the relevance to this reverse heating to refrigeration: Because reverse heat engine is primary can be of two types: one is a refrigerator and other is the heat pump. Their working principle is exactly the same both from theoretical and practical point of view.

However, their objectives are different and that is why we use two different names. And accordingly, the refrigeration can be defined something like this. It can be defined as a process of reducing and maintaining the temperature of a space or substance to value lower than the immediate surrounding. Here it is very important to consider there are two constraints: one is reducing and other is maintaining. That is your refrigeration system not only has to reduce the temperature of space rather it has to maintain that low temperature as well.

Like for example, you take an ice cube and put it on a table with surrounding temperature 30 ^{0}C. As the ice cube under normal atmospheric pressure is 0 ^{0}C then the immediate vicinity of that is on the portion of the table top where you kept the ice that will try approach 0 ^{0}C. So there is a cooling effect. The temperature of that particular portion will reduce to that temperature of the ice cube.

But will that be maintained? That cannot be maintained because the ice will be receiving or ice cube you will be receiving heat from the surrounding which is at a much higher temperature and quickly that ice will melt. And if you allow you to stay there then the corresponding water which has resulted because of the melting of ice that will soon at attain or will soon approach the atmospheric temperature.

Accordingly, the surface temperature of the table also will go back to its initial temperature. So, though we are able to reduce the temperature of the surface we are not able to maintain this. So, that is not refrigeration. That is only temporary cooling situation that you are getting. But refrigeration talks about a permanent or long-term cooling option, so that we can reduce the temperature of a space or substance to value lower than the surrounding and also you are able to maintain that over a desirable period of time.

Then how can we do this? Let us say this is scale for temperature we are taking and this is the surrounding temperature. And let us say this is some desirable temperature levels which we want to maintain in a space. This is T, let us say target, which is lower than the surrounding temperature and this is your space where you want to maintain this T_{target}. But, because heat always flows from high temperature to low temperature. So, this particular space or substance will keep on receiving say Q_{in} amount of heat from the surrounding and its temperature is always trying to increase unless we devise some option of leaving this Q_{in} amount of heat from this. So, the objective of refrigeration is to find another space which is having a temperature even lower than this T_{target}. Let us say this particular space at a temperature of some T_{sink}, which is lower than this T_{target}.

Now, if somehow, we can create a zone temperature is lower than this T_{target} and then bring this particular zone in contact with the target substance. Then again, heat will be going to this let us say Q_{out} is amount of heat been lost by the substance. Then as heat is being flowing from the target to the sink. So, the by proper combination of this Q_{in} and Q_{out} we can maintain a constant temperature in the substance.

But for that we have to maintain the T_{sink} and how to maintain the T_{sink}? To maintain the T_{sink} on the temperature of this rectangle to the T_{sink} we somehow have to remove this heat and put it back to the surrounding, put it at the environment. Now, this is as per the Clausius statement. This is not possible on its own, for that we have to give some work input. Which is W_{net} that you are talking about which is work of course is a high-grade energy that compared to heat.

Work is a much higher-grade energy compared to heat. And therefore, it is by providing this work input we shall be able to transfer heat from the sink to the surrounding which is kept a much higher temperature. And accordingly, we shall be able to maintain the temperature of this particular space to the target temperature by suitable controlling this Q_{out} and also whatever that which heat is being a flowing. To the let us Q_{sink} to whatever it is flowing to the surrounding. By proper combination this Q_{out} and Q_{sink} we shall be able to maintain the T_{sink} and accordingly shall be able to maintain the T_{target}.

Then what is your refrigeration system? Your Refrigeration system is this one, which is taking W_{net} input and it is able to maintain this T_{sink} in this particular position. So, our objective in nutshell or objective of our refrigeration system is not only to reduce the temperature but also to maintain that low temperature of a space or a substance to a level much lower than is immediate surrounding. And for that we need some kind of work input because heat always flows from high temperature to lower temperature. So, to facilitate this low temperature to high temperature heat transfer we have to provide some hybrid energy at the input, just which is work.

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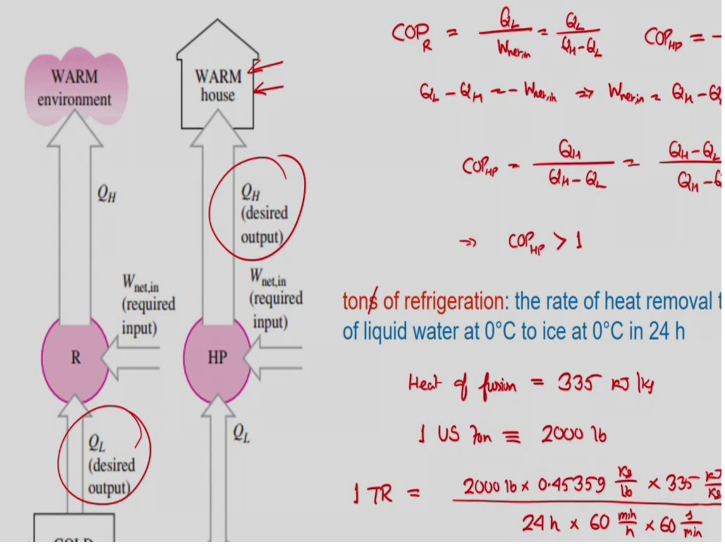

$$COP_R = \frac{Q_L}{W_{net,in}} = \frac{Q_L}{Q_H - Q_L} \qquad COP_{HP} = -$$

$$Q_L - Q_H = -W_{net,in} \Rightarrow W_{net,in} = Q_H - Q$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{Q_H - Q_L}{Q_H -}$$

$$\Rightarrow COP_{HP} > 1$$

ton~~s~~ of refrigeration: the rate of heat removal t
of liquid water at 0°C to ice at 0°C in 24 h

Heat of fusion = 335 kJ/kg

1 US ton ≡ 2000 lb

$$1\ TR = \frac{2000\ lb \times 0.45359\ \frac{kg}{lb} \times 335\ \frac{kJ}{kg}}{24\ h \times 60\ \frac{min}{h} \times 60\ \frac{s}{min}}$$

Now, as I have mention that there are two kinds of reverse heat engine possible one is refrigerator other is heat pump, so that they differ only in terms of objectives. Like for a refrigerator, the objective is to extract Q_L from cold refrigerated phase by our target is this and then dispose this heat to the surroundings. Whereas in case of our heat pump, our target is to keep the temperature of some interior warmer than the surrounding. For that purpose, heat will be removed from the cold environment and this is a desirable one desirable quantity which is supplied to the house to keep it warmer.

So, to characterize the performance of refrigerator and heat pump we have to use alternate definitions. And for any reverse heat engine, you know that we use the terms *COP*, coefficient performance to define it actual characteristic or actual performance. And *COP* is defined as the desirable output to the input that is given to get that output done. So, for the refrigerator and *COP* for the heat pump for both the cases the input that we are giving that is your $W_{net\ in}$. So, in the denominator effort that we are putting in is $W_{net\ in}$ which is the same.

However, what will be coming in the numerator? For Refrigeration system, our objective is the Q_L, so it will be Q_L. For heat pump system, objective is Q_H, so it will be Q_H in case of heat pump system. Now, if we apply first law of thermodynamics on any one of them then we can easily write that:

$$Q_L - Q_H \text{ is} = -W_{net\ in}$$

that is

$$W_{net\ in} = Q_H - Q_L$$

So, from there *COP* for refrigerator is written as:

$$COP_R = \frac{Q_L}{Q_H - Q_L}$$

and *COP* for the heat from pump can be written as:

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L}$$

Remember, their operating principles are same, there thermodynamic principle is also same. Only difference is in the objective. In case of refrigerator our objective is to remove heat from the cold refrigerator space which is the temperature lower than the surroundings. Whereas in case of heat pump the objective is to add energy to this interior, which is the temperature higher than the surroundings But, in both cases,, we are taking energy from low temperature zone and supplying to the high temperature zone with the help of work input.

Now, before we move on to see different applications of thermodynamics or I should say different applications of refrigeration, I have to define this called tons of refrigeration. But before that quickly if you try to see the relation between the *COP* for heat pump and refrigerator, if we write this as:

$$COP_{HP} = \frac{Q_H - Q_L + Q_L}{Q_H - Q_L} = 1 + \frac{Q_L}{Q_H - Q_L} = 1 + COP_R$$

Therefore, *COP* is a positive quantity, *COP* for heat pump is always greater than 1. However, for the refrigeration system theoretically it can be less than 1. But practically it can generally be well above the value of 1. Now whenever you purchase some refrigerator or may be an air conditioner which is nothing but refrigeration unit only, we always use this term tons of refrigeration. You must have heard that we purchased A/C of 1 ton, 1.25 ton or 1.5 ton. What is the tons of refrigeration? That is nothing but the refrigeration capacity and refrigeration capacity is defined in terms of the rate of heat removal. That is a rate at which we are able to remove heat from the space maintained at the low temperature. I repeat refrigeration capacity of cooling capacity is defined as the rate at which we are able to remove heat from the space maintained at low temperature. And tons of refrigeration is just one measure of the cooling capacity. It is defined as the rate at which we can convert 1 ton of liquid water at 0 ^{0}C to ice at 0 ^{0}C over a period of 24 hours. That is, you are given 1 ton of liquid water maintained at 0 ^{0}C and you have to convert that to 1 ton of ice at 0 ^{0}C over a period of 24 hours, then the rate of heat removal that you need to proceed with that is known as the 1 ton or that is called 1 ton of refrigeration. I should not have used this ‘s’ here is a ton of refrigeration. Then how can we calculate? So, the heat of fusion or you can say the latent heat corresponding to the solidification of liquid water is approximately 335 kJ/kg, i.e., to convert 1 kg of liquid water at 0 ^{0}C to 1 kg of ice at 0 ^{0}C you have to remove 335 kJ of energy.

And what do you mean by 1 ton? 1 ton, it is important that here we are talking about 1 US ton. So, 1 US ton is corresponding to 2000 pound. Then 1 ton of refrigeration, often referred to as capital *TR* to denote ton of refrigeration. How much energy that we have to extract? That is the mass which is 2000 lb into 0.45359 kg/lb, here we are converting this mass to kg multiplied by 335 kJ/kg. So, this is the total amount of energy that you have to extract. That is in the numerator of the expression for 1 TR provided below. How much is the time period? Your time period is 24 hours multiplied by 60 minute per hour multiplied by 60 second per minute. The expression for 1 TR is as follows:

$$1\,TR = \frac{2000\,lb\ \times 0.45359 kg/lb \times 335\ kJ/kg}{24\,h \times 60\ min/h \times 60 s/min}$$

So, if you calculate this number will be roughly 3.52 or 3.5167 kW. Here very important to know that we are talking about 1 US ton, like 1 metric ton is equal to 1000 kg, but 1 US ton is equal to as I have written 2000 pound which will be approximately 907.2 kg.

If you use 1000 kg here in case of 1 ton, then you will be getting this number to something around 3.8. But practically it is not true because we talk about when 1 US ton which is just around 907.2 kgs. Using that value and using suitable conversion you are getting 1 ton of refrigeration to be equivalent to heat removal rate of about 3.5167 kW. But practically what we do is we always take 1 ton of refrigeration to be equal to 3.5 kW which is the 3.5 multiplied by 60, that is 210 kJ/min.

So, this is practical value that generally take while doing any kind of refrigeration calculation that is 1 ton of refrigeration is equal to 3.5 kW. But you looking for very precise calculation, then you have to go by this particular number. So, whenever you are purchasing 2 ton AC basically looking for cooling capacity of 2 × 3.5 which is approximately 7 kW. So, I hope it is clear. From now onwards these tons of refrigeration will you repeatedly be used for solving numerical problems.

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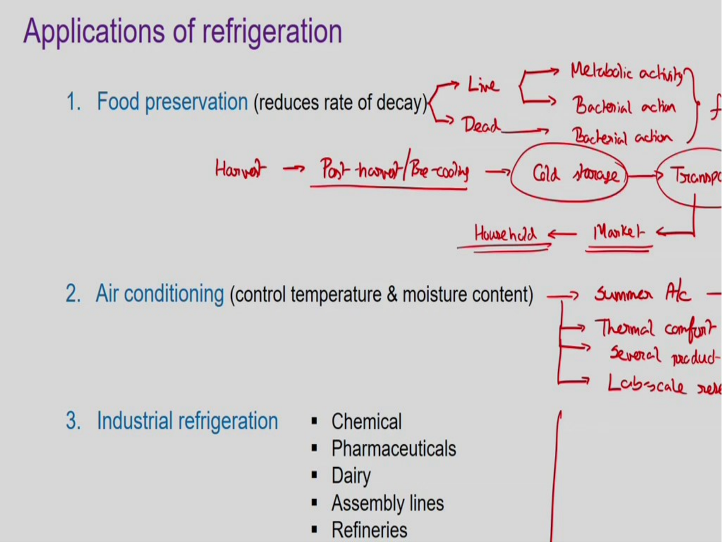

Applications of refrigeration

1. Food preservation (reduces rate of decay)

2. Air conditioning (control temperature & moisture content)

3. Industrial refrigeration
   - Chemical
   - Pharmaceuticals
   - Dairy
   - Assembly lines
   - Refineries

But what are the application areas of refrigeration? There are infinite number of applications. Just to report some of the most common ones. You definitely know the domestic refrigerators is used for food preservation because it reduces the rate of decay. When you are talking about the food preservation then generally we talk about two different kinds of food: one is live foods like fruits and vegetables other is dead foods like when you purchase some fish or meat kind of substances that is dead food.

Now in case of live food, there are two factors to be considered one is the metabolic activity as it is live metabolic activity goes on. Other is the bacterial action which is always present or bacterial activity for dead food however, we have only the bacterial activity or bacterial action to be taken into account. And generally, both and all these factors are function of the temperature. As the temperature goes on the metabolic activity or rate of metabolic activity decreases similarly the bacterial activity also decrease to a substantial level.

So, in food preservation purposes refrigeration or the role of refrigeration is to reduce the temperature so that the rate of a metabolic activity and bacterial activity reduces so the rate of decay of both live and dead food products also decreases. And therefore, we are able to maintain the food in usable condition for much longer period. And food preservation we are not at all restricting ourselves only to domestic refrigerators rather think about in much larger scale something like cold storage that is nothing but a big refrigerator or a huge refrigerator.

But why you need to go for food preservation? Because there are several reasons. There can be seasonal imbalance, certain vegetables are available only in certain seasons and not during rest of the year. The locational dependencies also there, certain fruits available in colder areas, whereas certain fruits can be cultivated only in the warmer areas. So, we need to refrigerate them for the transport purpose from one area to another area, the lack of proper storage also be another reason.

So, in food industry or agriculture industry at every step actually we need refrigeration. Because if you think about something so called the food chain then we start with the harvest. After the harvest, we go for something called the post-harvest or precooling some kind of initial preparation that always is required before storing in the cold storage. Then we go for the cold storage, where it is stored over a long period of time may be a few weeks maybe several months. From the cold storage it goes to the market via air-conditioned transport. So, we have transports through which it is going to the market and from the market it comes to the household. Now in which steps, there are six steps that I have written, six steps of this food chain in which places you need refrigeration?

Definitely refrigeration pre-cooling, enormously in the cold storage, quite often we need air-conditioned transport to transport highly perishable goods. In the market we may have to go for refrigeration also particularly talking about some fruits or the fish and meat kind of highly perishable substances and in the household also we shall be using refrigerator to store the same items. Therefore, at every step of this food chain we need the refrigeration.

Next is the air conditioning, air conditioning as mentioned is again great application of refrigeration. Here our objective is to control the temperature and the moisture content. There are several steps of air conditioning like, in warmer countries like India we generally talk about the summer air conditioning where our objective is to reduce the temperature and also want to reduce the relative humidity, a process is known as cooling and dehumidification.

A little bit more about this air conditioning and corresponding processes, we shall be talking about in week number 11, when we talking about psychometry. But in summer air conditioning we need to control or reduce both temperature and relative humidity. Whereas is in colder countries our objective may be different, we want to increase the temperature and we may have to increase the relative humidity as well.

So, to increase the temperature to this we do not need a refrigerator basically the heater. So, in warmer countries, that is why you need to give the summer air conditioning, we have a direct application of refrigeration. Also, we need the thermal comfort. Thermal comfort refers to the temperature zone at which all persons are comfortable. Generally it has been found that any human being is comfortable with the temperature range of 24 to 26 ^{0}C is may vary by one or two degrees, depending on the individual, but generally everyone is comfortable using this particular zone.

And therefore looking for large scale application like a centralised air conditioner in a large office or in a big market, shopping complex where we need big air condition unit ,there we have to ensure the thermal comfort as well by maintaining proper temperature levels there, which is not too cold not to hot but comfortable for everyone and they are generally they go for this comfortable level of temperatures.

Air conditioning is also required in several product development. And also, maybe the large-scale research in different research lab we often have to maintain constant temperature as well. So, these are the purposes of air conditioning. Next application, industrial refrigeration and there are again enormous list that I can put in. Just mention few if you can talk about the chemical industries, pharmaceuticals, dairy is a very big application, assembly line, refineries again, medical is a huge role of air conditioners and refrigeration systems and computer centres also generally use to maintain constant temperature, printing, textiles. Photography etc. And this is an endless list, this list can go on and on.

And there are miscellaneous applications also just think about some amusement park where you have an ice drink or some low temperature activities which can come on these miscellaneous things. So, refrigeration similar to the power cycles, refrigeration cycles are also used important because they have so many kind of applications and so many varieties applications to talk about.

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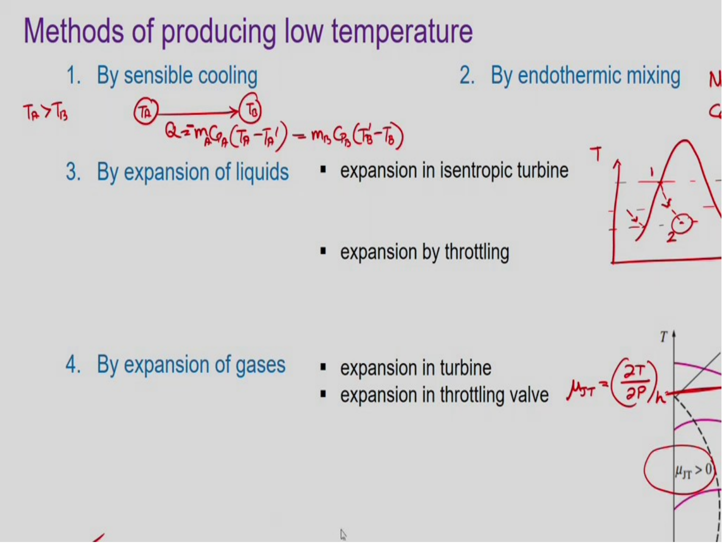

Methods of producing low temperature

1. By sensible cooling
2. By endothermic mixing
3. By expansion of liquids
   - expansion in isentropic turbine
   - expansion by throttling
4. By expansion of gases
   - expansion in turbine
   - expansion in throttling valve

$T_A > T_B$

$Q = m_A C_{p_A}(T_A - T_A') = m_B C_{p_B}(T_B' - T_B)$

$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_h$

Then what is the mode at which we can produce the low temperature or we can have the refrigeration affect? There are quite a few different kinds of applications, like a historically there refrigeration effect was I should say historically even in the prehistoric ages also people used to find some ways of getting the cooling effect like just by putting the example that I gave putting ice on top of a table.

It has been, there are stories that is the during the Roman Emperor they used to bring ice from the poles from the north poles to maintain low temperature. And you must have seen the earthen pot where we keep water. All the water is allowed to come or leak to the pores and evaporates the surrounding thereby reducing some cooling effect. So, this are very natural kind of ways of producing low temperature, which people are using for hundreds and thousands of years.

Even the use of ice for cooling was used in not so old days also. Like early 20 century 1930 to 1940 is very common to bring ice from the poles for using in for not only producing cooling effect body when for using the food industries as well. Use of the nocturnal effect to produce ice, that is in night time in the temperature reduces if we can produce a proper arrangement, it is possible that by using the radiative heat loss from liquid surface to the open surrounding we can convert liquid water to ice, that is something as a nocturnal cooling effect. Those natural kinds of effects are always there.

The first reported attempt to artificially produce the cooling effect was reported probably in 1755 by Dr William Cleveland who used ether for producing the cooling effect. Subsequently has been found that it is not the most healthy or healthiest option of producing low temperature and because of sort health hazards and also its pressure etc. or not comfortable, it is also flammable. But that was the first attempt of producing in industrial cooling which later led to several other kinds of options.

The first option is why sensible cooling that is very logical. Suppose, we have a body at temperature T_A and another body at temperature T_B where this T_A is higher than T_B. If they are brought in contact with each other then, this T_A will be losing heat to T_B thereby some cooling effect produced in the body. And how much change in her how much cooling effect you can produce here? We can very easily calculate this sensible heat transfer only. So, the amount of heat transfer associated here can easily be written, the rate of heat transfer can easily be written as:

$$Q = m_A C_{PA}(T_A - T_A')$$

where

m_A is the mass of body A

C_{PA} is the specific heat for the body A

T_A is the initial temperature

T_A' is the final temperature

This is the amount of heat that has been lost by this particular body A and the same will be the gain for the body B. So, heat gained by body B is:

$$= m_B C_{PB}(T_B' - T_B)$$

where

m_B is the mass of body B

C_{PB} is the specific heat for the body B

T_B is the initial temperature

T_B' is the final temperature

This should be equal to each other, i.e.,

$$Q = m_A C_{PA}(T_A - T_A') = m_B C_{PB}(T_B' - T_B)$$

So, this way we can produce the cooling effect the rate of cooling easily be calculated by differentiating this with respect to time.

And other option is by endothermic mixing. Now what do you mean by endothermic mixing? You know, that is when certain substances are mixed with water, they produce some cooling effect. Something like sodium chloride, calcium chloride etc, they mixing with water gives you a cooling effect. Like sodium chloride solution can go up to − 21 ^{0}C and calcium chloride can go up to − 61 ^{0}C. So, at least for smaller duration we can definitely produce cooling effect using them.

And third more industrial that is by expansion of liquid. And there are two options expansion in an isentropic turbine, you know that when if it gets expanded in a turbine its temperature generally reduces. So that can be one option, second option is expansion by throttling. Like if you draw a *Ts* diagram this is for water and initially suppose it is at a saturated liquid condition at this particular temperature level. Then if we allow it to throttle through some valve or capillary tube, then at the end of the process we shall be getting this particular instant. this are starting state, this is process to two. Then the temperature is reduced because of the throttling and so by this throttling effect we can definitely produce a cooling effect. If it is desirable to have the end state as saturated liquid, then we have to start from some point here and get the throttling done so that you reach finally the saturated liquid condition.

Similar effect can also be obtained for gases. By expanding gases in the turbine, we can have the cooling effect and also by throttling. Now for the throttling of gases we have already discussed about this particular thing in a week number 2, where you were introduced to the concept of the Joule-Thomson coefficient. You know that this dotted curve which is known as the inversion curve operating on the left-hand side of the curve that is one is the Joule-Thomson coefficient is positive then the throttling effect during is a pressure reduces the temperature also reduces. Because this Joule-Thomson coefficient μ_{JT} is defined as:

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_h$$

for an isentropic process in which throttling is an example of an isentropic process.

So, when the Joule-Thomson coefficient is greater than 0 and also if your operating temperature level is lower than this maximum inversion temperature then through throttling, we can produce cooling effect as well. However, if you are operating on the right-hand side of this curve, when Joule-Thomson coefficient is negative then throttling will lead to an increase in the temperature level. So, by suitably positioning on either side of the curve we can get both heating and cooling effect by expansion of gases through a throttling valve.

Then by phase-change process which is the one we are most interested about, but there can be some other modern options also, innovative options like the use of thermoelectric method and also by adiabatic magnetization. So, we shall be talking little bit more about this option number 5 which is by the phase-change process.

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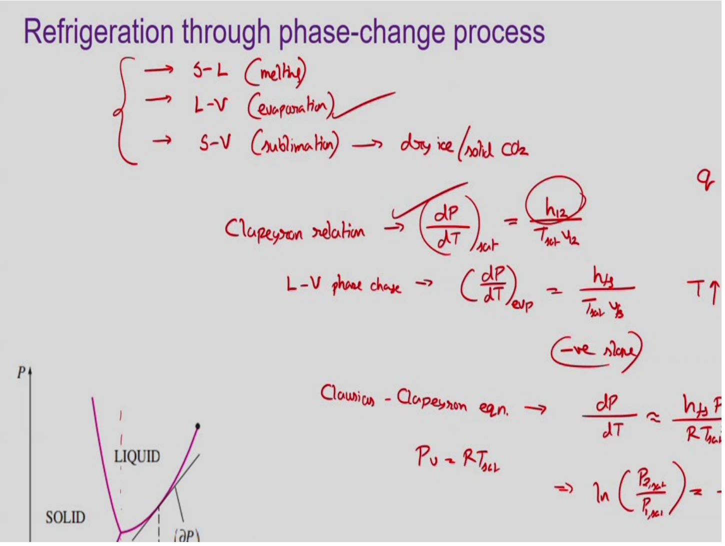

Refrigeration through phase-change process

→ S-L (melting)
→ L-V (evaporation)
→ S-V (sublimation) → dry ice / solid CO_2

q

Clapeyron relation → $\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{12}}{T_{sat} v_{12}}$

L-V phase change → $\left(\frac{dP}{dT}\right)_{evp} = \frac{h_{fg}}{T_{sat} v_{fg}}$ T↑

(-ve slope)

Clausius - Clapeyron eqn. → $\frac{dP}{dT} \approx \frac{h_{fg} P}{R T_{sat}}$

$Pv = RT_{sat}$

$\Rightarrow \ln\left(\frac{P_{2,sat}}{P_{1,sat}}\right) = -$

Now, phase-change always is associated with the conversion of one phase to another. And if you want to have cooling effect to phase-change then your phase-change in material must absorb energy, and as it absorbs energy then its phases always go from one to the more dynamic one. That is, we can have phase conversion like solid to liquid, which is nothing but melting. So, this is possible to have during which the solid will absorb energy from whatever location where you want the cooling effect and itself will get converted to liquid.

We can also have the conversion of liquid to vapour which is evaporation or vaporisation and we can also have solid directly been converted to vapour which is called the sublimation. We can have some sublimation solid can get converted to both liquid and vapour directly. But when we shall have melting and when we can have sublimation? Sublimation happen only when you are operating the temperature lower than the triple point temperature. You can revise our earlier lectures that is, when substance is at a temperature lower than triple point as it is not possible to have liquid which is below the triple point temperature, then solid-phase has to get converted directly to vapour.

So, all this three can lead to a cooling effect, however this one is the most popular one. But solid to vapour, sublimation most common example, is that of dry ice which nothing but solid carbon dioxide So dry ice is used which can take a to quite low temperature as well. Solid to liquid melting have seen? These ice boxes have you seen to store some perishable items? That is nothing but a solid to liquid melting. We pack ice in a box and within that bulk of ice we store the item that you want to maintain, then we also provide sufficient amount of insulation surrounding that box. Then the ice will be able to maintain the temperature over a significant period of time, even if some quantity of ice melt because of heat leakage from the surrounding, but it will able to maintain the 0 ^{0}C temperature inside thereby reducing the rate of decay of the corresponding perishable substance.

But the major application is the liquid to vapour evaporation. And for liquid to vapour evaporation, this is something that we have to be bothered about. Actually, not only liquid to vapour evaporation, for any kind of phase-change process we can use the Clapeyron relation. Again, this is just a recap of some discussion that we had in week number 2. In Clapeyron relation we have defined their which shows that the saturation curve on a PT plane, the slope of the saturation curve can be written as:

$$Clapeyron\ relation \rightarrow \left(\frac{\partial P}{\partial T}\right)_{sat} = \frac{h_{12}}{T_{sat}\,v_{12}}$$

where 1 is initial phase, 2 is the final phase and this is the corresponding curve for any general substance.

So, this is a triple point, we have solid on one side liquid and vapour on other side. And this curve is shown here for water, however for other substances because for water, even below the triple point temperature, we can have liquid state but for other substances of this line only something like this so that we cannot have liquid state below triple point temperature. Now this is the Clapeyron relation which we have seen earlier also.

If we are talking about the liquid to vapour phase-change, then we are talking about:

$$L - V\ phase\ change \rightarrow \left(\frac{\partial P}{\partial T}\right)_{evp} = \frac{h_{fg}}{T_{sat}\, v_{fg}}$$

Now, as the temperature increases h_{fg} also increases no by a great amount. but it increases definitely and v_{fg} that decreases. So, what about the slope of this curve? h_{fg} increases T increases, but there also increases, accordingly we get a negative slope for this particular curve, for liquid vapour phase-change process.

Another way of identifying the pressure corresponding to this is the Clausius Clapeyron equation. Do you remember what is the Clausius-Clapeyron equation?

$$Clapeyron\ relation \rightarrow \frac{\partial P}{\partial T} = \frac{h_{fg}}{T_{sat}\, v_{fg}}$$

From Clausius-Clapeyron equation we approximate the vapour state to be an ideal gas and accordingly represented as v. By using this relation:

$$Pv = RT_{sat}$$

we replace this v as with RT_{sat}/P, so that we get:

$$Clapeyron\ relation \rightarrow \frac{\partial P}{\partial T} = \frac{h_{fg}\, P}{R{T_{sat}}^2}$$

from where we can write:

$$ln\left(\frac{P_{2,sat}}{P_{1,sat}}\right) = \frac{h_{fg}}{R}\left[\frac{1}{T_{1,sat}} - \frac{1}{T_{2,sat}}\right]$$

So, assuming the vapour state to be an ideal gas we can relate the saturation pressure and temperature from this. But our more interest is in this, the Clapeyron relation which gives us a relation between the enthalpy of vaporization and the saturation temperature in terms of the slope of this corresponding curve. Using this line, we can easily identify the magnitude of the enthalpy of operation just from this *PT* diagram.

And whenever we are talking about phase-change process this is very very important. Because the amount of energy absorbed during phase-change will always be the mass of the corresponding substance multiplied by h_{fg}. So higher the value of h_{fg}, higher the rate of heat removal and hence we always want the substance or rather the phase-change process to be associated with the high value of enthalpy of vaporization.

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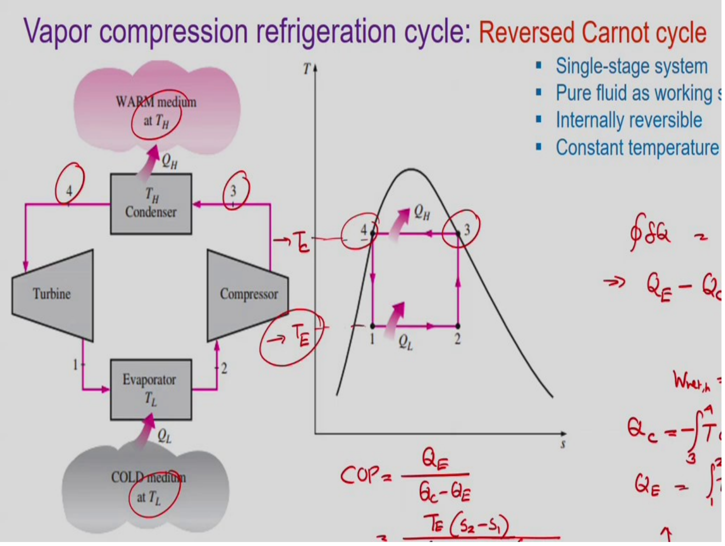

Vapor compression refrigeration cycle: Reversed Carnot cycle

- Single-stage system
- Pure fluid as working
- Internally reversible
- Constant temperature

$\oint \delta Q =$

$\Rightarrow Q_E - Q_c$

$W_{net,in} =$

$Q_c = -\int_3^4 T$

$Q_E = \int_1^2$

$COP = \frac{Q_E}{Q_c - Q_E}$

$= \frac{T_E(s_2 - s_1)}{}$

Accordingly, we reach to our first cycle for analysing first refrigeration cycle, which is the reverse Carnot cycle. We also called this as vapour compression refrigeration cycle because here we are using a compressor to compress of a vapour stage. The Carnot cycle diagram that we have seen earlier it is just the reverse of that. Here we have an evaporator where the working substance absorbs Q_L amount of heat from the low temperature medium.

Then by absorbing this let us add the *Ts* diagram to this. At state number 1 from there we have this heat addition starts because of that heat addition there is a phase-change from a very low-quality mixture to high quality mixture to point 2. Then here the high-quality mixture which is compressed in the compressor to this point 3 which is generally saturated vapour. Then we have the condenser where the temperature of this T_H is higher than the temperature of the surrounding. So, it rejects Q_H amount of heat to the surrounding and accordingly the working medium gets converted to saturated liquid at 4. Finally, we have at 4, a turbine where it is expanded to its initial point 1. Here the role of the compressor is very important.

Before saying that, just compare this one with the Rankine cycle that we had or maybe just Carnot cycle diagram, what components we had? We had an evaporator or boiler, we have condenser here, then we have a pump and we have a turbine here. Then we have a condenser and instead of compressor we have the turbine here. Or you can say the directions to reverse a bit, because the compressor is the one that is taking mixture as the inlet and producing saturated vapour at the outlet. Now, what is the role of the compressor here? The role of the compressor here is to call this change in temperature.

This is the low temperature level and this is the high temperature level. Often, we refer this one as the evaporator temperature because evaporation temperature and this is one is referred as the condenser temperature. Now, the objective of the compressor is to change the pressure of the working medium such that its saturation temperature changes from the T_E level to the T_C level.

I repeat, the work or function of this compressor is to increase the pressure such that the saturation temperature of the working substance changes from T_E to T_C. And accordingly, the working medium rather will be able to reject heat to the surroundings. T_C is generally higher than the surrounding temperature whereas T_E is lower than the temperature of that refrigerated space. So, this T_E is the sink temperature that we mentioned earlier. In one of the earlier slides, the sink temperature that I mentioned that is this T_E, it is lower than the space from where I want to remove it. So, heat will be removed from this. And T_C is surrounding temperature, so the working substance will be rejecting heat into the surrounding and the compressor is doing this change in pressure from 2 to 3, such that the saturation temperature changes from T_E to T_C. As we are compressing a vapour here, that is why often this kind of cycles of this group of cycles are called the vapour compression refrigeration cycles. Now a few conditions, here talking about a single state system only. That is a compression is only of single stage, there is no multistage compression.

We are using a pure fuel as the working substance no mixture then we are assuming all these four processes to be internal reversible but externally irreversible. For Carnot cycle we are actually considering this to be a perfectly irreversible one, but the next cycle that I am going to talk about there I shall be considering only the internal irreversible cycle.

And also, we are assuming the temperature of the source and sink to be constant that this cold medium we have constant temperature T_L, this one medium to the constant temperature of T_H. Then if you want to calculate the net heat introduction for this particular cycle, then how can you do this? Here the amount of heat rejection is Q_L, conventionally write Q_L as Q_E the evaporator heat and Q_H is the amount of heat rejected to the high temperature reservoir, from the condenser we generally call it Q_C. So also using the same terminologies, similarly instead of T_H I shall using the term T_C and instead of T_L I shall be using the term T_E is condenser and evaporator temperature.

Now in this case how can we apply the first law of thermodynamics? We know that:

$$\oint \delta Q = \oint \delta W$$

So total amount of heat added to the system is QE and rejecting QC amount of heat and net work transfer work output for getting from the turbine and work input you are getting from the compressor, i.e.,

$$Q_E - Q_C = W_T - W_C$$

The turbine work generally is much smaller so I can write this one as $W_{net\ in}$ where this is equal to:

$$W_{net\ in} = (W_C - W_T)$$

Now, this being a Carnot cycle or reverse Carnot cycle all the processes are perfect reversible. So, we can write Q_C to be how much? For perfectly reversible cycle, we know that it is equal to:

$$Q_C = \int_3^4 Tds$$

Now this Q_C process is working state point 3 and 4. So it is between 3 to 4 and the temperature remains constant, the condenser temperature so it is:

$$= T_C(s_4 - s_3)$$

Similarly,

$$Q_E = \int_1^2 Tds = T_E(s_2 - s_1)$$

where Q_E is the evaporator heat transfer

Now the *COP* will be equal to:

$$COP = \frac{Q_E}{Q_C - Q_E}$$

So just putting expression this:

$$= \frac{T_E(s_2 - s_1)}{T_C(s_4 - s_3) - T_E(s_2 - s_1)}$$

Now, just look at the diagram process 2 to 3 and 4 to1 being isentropic.

So, we have

$$s_2 = s_3$$

and

$$s_4 = s_1$$

so, if you replace s_4 with s_1 and s_3 with s_2, then what we can write? We can write this to be:

$$= \frac{T_E}{T_C - T_E}$$

here one change we have to do is here the QC is the amount of heat rejected so there will be minus sign coming in, so here the minus sign coming in here which we have to incorporate into this also so that it gets converted to:

$$= \frac{T_E}{T_C - T_E}$$

or we can often write this as:

$$= \frac{T_E}{\Delta T}$$

where

ΔT the temperature change that takes place over the cycle.

If you want to see the effect of this you can easily put some numbers on to this, the *COP* corresponding to the evaporator temperature. As the evaporator temperature increases the numerator increases and the denominator decreases for a given to *TC*. So, the effect will be an increase in the *COP* for this. Whereas if *TC* increases for a given *TE* then what will happen? Then the numerator of *COP* expression remains the same but the denominator increases so efficiency reduces, so this is direction for *TC*. So with increase in *TE*, *COP* increases but with increase in *TC, COP* decreases for this reverse Carnot cycle.

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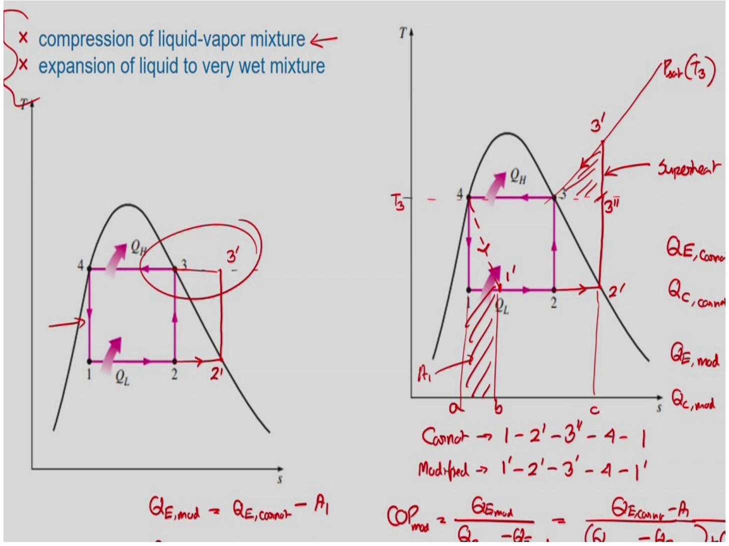

× compression of liquid-vapor mixture

× expansion of liquid to very wet mixture

$Q_{E,mod} = Q_{E,carnot} - A_1$

Carnot → 1 − 2' − 3'' − 4 − 1

Modified → 1' − 2' − 3' − 4 − 1'

Now, for the reverse Carnot cycle it looks perfectly alright because we are getting extremely high efficiency, it is the theoretical maximum that we can have this, being a perfectly reversible cycle that is logical also, but there a couple of problems. One problem is the compression of liquid in our mixture. In the compressor as your moving from state 2 to 3 we are starting with liquid-vapor mixture and then we are moving to saturated vapour and that is very very difficult in practice.

And the second posing problem is the expansion of a liquid to very weight mixture. As a turbine proceeds you starting with liquid and dealing with very wet mixture which has lots of liquid content, so there will be lots of erosion in the turbines and that is also very inefficient process. The work output that you are going to get from this turbine is practically is very very low. The condensation evaporation process does not have any issue because here we are having heat transfer, constant temperature heat transfer with phase-change which is definitely achievable in practice. So, in order to reduce the effect of this particular thing one possibility is that we continue with this condensation process to the saturated vapour line to reach this point 2'. Then if we want to complete the cycle then your compression process will start from 2' and will move to this 3' and from there it will continue in this way.

Now expanding the condensation upto 2' is fine, compressing the saturated vapour to a superheated vapour from 2 point to 2' is also not an issue. But the biggest problem is in this zone, the condensation part particularly the portion 3' to 3. Here it is a constant temperature, but what is happening in the pressure? As we are moving from 3' to 3, we are moving to higher pressure zone continuously. So, we have to maintain constant temperature, at the same time we have to compress the gas also, because we are going to a higher pressure which is practically impossible to have. We are trying to devise a compressor which will allow isothermal heat transfer while compressing the superheated vapour from point 3' to the pressure at point number 3, that is very difficult to have. And also, the work output that we can get from start one that I have mentioned that is practically very very small. So, to eradicate this we can go for a few options.

One option is expanding the condensation process up to this point, up to this 2', then condense this in the compressor, but not up to this temperature level, this highest temperature let us say T_3. We are not stopping the compression at this point 3, rather we are following the constant pressure line. This is the saturation pressure corresponding to this T_3 here we allowing the gas to be vapour to be compressed up to this particular point so that we have 3' here. And then the heat rejection process is being done at constant pressure, heat rejection at constant pressure, not at constant temperature anymore.

So that is one big change that we can do. Now here what is the additional thing that we have to do? The compression work will remain same upto this particular point. But for this particular zone some additional amount of compression work that you have to provide and this particular zone is known as superheat horn, it is the additional amount of work input that we have to provide. The superheat horn let us say we call the corresponding area to be A_2.

Another change that we practically do, as the work output, we are getting from the turbine is practically difficult to have and also not a very much significance, we replace that turbine with just a throttling valve. Remember to get the cooling effect we can use or we can use the liquid expansion in two ways, one is turbine, isentropic turbine like done here or maybe in a valve.

And we go for the second option so that, we go for isenthalpic throttling process, so that the point 1 shifted some as 1' for this. So accordingly, this is the amount of heat rejection there is a change in the heat rejection part let us call this area as A_1. Now if we want to calculate for this second cycle the condensation heat and evaporation heat.

So, QE for this modified cycle, let us say first we write for the Carnot cycle. For the Carnot cycle, we are trying to compare this modified cycle with the Carnot cycle where we are having the condensation of up to point 2'. So, the Carnot cycle here is 1- 2' - 3''- 4 - 1 and the modified cycle starts from 1' - 2 '- 3' - 4 - 1'.

So, if you compare the areas, then there are these two zones of heat transfer, one is superheated horn denoted by A_2 were additional heat input has to be given, additional amount of heat rejection is involved and whereas in is this area A_1 where the addition where we are losing some amount of evaporator heat transfer. Now for Carnot cycle this Q_E is the area. What is the area corresponding to Q_E in case of Carnot cycle? For the Carnot cycle your area will be 2'-1 area under the curve. Ok let us give some names let us call this point is A this point as B and we call this point as C. So

$$Q_{E,\ \text{Carnot cycle}} = \text{area } 2' - 1 - a - c - 2'$$

and

$$Q_{C,\ \mathit{Carnot\ cycle}} = \text{area } 3''\text{- } 4 \text{ - } a \text{ - } c \text{ - } 3''$$

Now

$$Q_{E,\ \mathit{modified\ cycle}} = \text{area } 2' \text{ - } 1' \text{ - } b \text{ - } c \text{ - } 2'$$

and

$$Q_{C,\ \mathit{modified\ cycle}} = \text{area } 3'\text{- } 4 \text{ - } a \text{ - } c \text{ - } 3'$$

So, if you compare these two now,

$$Q_{E,\ \mathit{modified\ cycle}} = Q_{E,\ \mathit{Carnot\ cycle}} - A_1$$

$$Q_{C,\ \mathit{modified\ cycle}} = Q_{E,\ \mathit{Carnot\ cycle}} + A_2$$

A_2 is additional amount of heat that you have to supply. So, if we write the *COP* for this modified cycle then it will be equal to:

$$COP_{modified} = \frac{Q_{E,modified}}{Q_{C,modified} - Q_{E,modified}} = \frac{Q_{E,modified} - A_1}{\left(Q_{C,Carnot} - Q_{E,Carnot}\right) + (A_1 + A_2)}$$

Quite often we define an efficiency for this modified cycle, which is defined as the *COP* for this modified cycle divided by *COP* for the Carnot cycle.

$$\eta_{modified} = \frac{COP_{modified}}{COP_{Carnot}}$$

For the Carnot cycle, efficiency already know which will be:

$$\eta_{Carnot} = \frac{Q_{E,Carnot}}{Q_{C,Carnot} - Q_{A,Carnot}}$$

So, if we divide this entire thing, then what we are going to get? We are going to have:

$$\eta_{modified} = \frac{COP_{modified}}{COP_{Carnot}} = \frac{1 - {}^{A_1}\!/_{Q_{E,Carnot}}}{1 + \frac{A_1 + A_2}{(W_{net\ in})_{Carnot}}}$$

So, the efficiency of the cycle will definitely be less than the Carnot cycle, but the magnitude depends upon the individual values of this A_1 and A_2. Though practically it is since quite difficult to have the practically it is very excellent to have this reverse Carnot cycle for producing refrigeration effect, but there are this problems that has marked out. And that is why we go for these 2 modifications that is, one we have this condenser working not at isothermal way, but is isobaric way that is isobaric heat rejection in the condenser. And also, the turbine is replaced by a pump.

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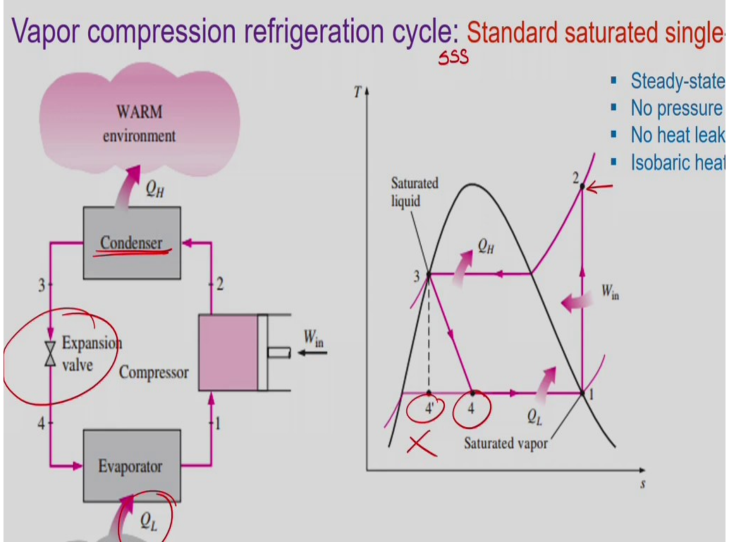

Vapor compression refrigeration cycle: Standard saturated single

SSS

- Steady-state
- No pressure
- No heat leak
- Isobaric heat

According is the cycle that we get that is called the standard saturated single stage cycle. Also, sometimes called triple S cycle: standard saturated single stage cycle, but the use of the cycle is so so common that it is the one that is also known as the vapour compression refrigeration cycle. Though it is just one kind of vapour compression refrigeration cycle as we have already seen the example of two. But still if someone mentions about a vapour compression refrigeration cycle that will always be referring to this SSS cycle or standard saturated single stage of refrigerated cycle. Its use is extremely common almost more than 90% applications of refrigeration you will find this particular one only. This is a very well-developed device. It is available in a wide variety of ranges, ranging from just a few watts to several megawatt ranges.

And also, as we need to provide mechanical input to this, we can run it and several possible ways. So, this is your practical cycle will look like. Here you have the evaporator which has not been touched upon, the evaporator region is as it is and it will receive Q_L amount of heat. Then the compressor is there also. Then the condenser, here is the change that the condenser is not working in isothermal way rather than condition is working in isobaric way and the big change to have an expansion valve here.

Accordingly, our *Ts* diagram look like this. Here the compression is done up to this particular point. So that we can have isobaric heat rejection in the condenser and then we have this isenthalpic expansion in the expansion valve. So that the end state is not 4' anymore that is, it is 4. So, generally we consider this device to be a steady state steady flow device for all analysis. No pressure drop in the pipeline, neglect any kind of heat leakage as well and isobaric heat addition and heat rejection. The heat rejection there is no issue because that is an instant process which is both isothermal and isobaric simultaneously.

We shall be analysing the cycle in the next class. Again, we shall be starting with this particular cycle and continuing with analysis by each of the four processes involved while considering the assumptions. Quite often the cycle is also represented on *Th* plane because there are two constant pressure process and one constant enthalpy process. This is a unique diagram, which is used only in refrigeration industries.

Here again 4 to 1 is a condensation process, where this Q_L is nothing but our Q_C, Q_H is equal to Q_E. This evaporation is also constant pressure process, 3 to 4 is the isenthalpic expansion in the valve, often it is represented by dotted line also because this an irreversible process and 1 to 2 is the compression process.

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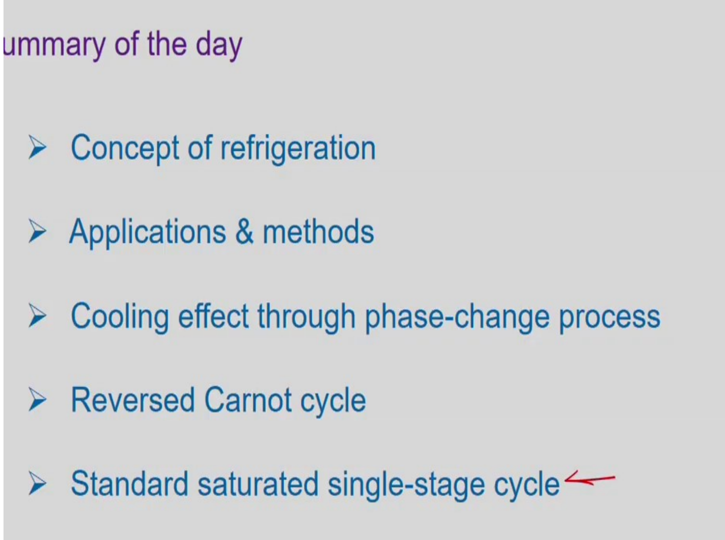

ummary of the day

- Concept of refrigeration
- Applications & methods
- Cooling effect through phase-change process
- Reversed Carnot cycle
- Standard saturated single-stage cycle

So today if you want to summarise, we have discussed about the initial concept of refrigeration. And also define refrigeration is a process of removing energy or producing zone with low temperature then surrounding and also maintaining that low temperature there. We have discussed about different applications of refrigeration and also several methods of producing the low temperature with particular emphasis on producing the cooling effect to the phase-change process.

Then we have discussed about two kinds of vapour compression refrigeration system, one is the reverse Carnot cycle we have also discussed about its practical problems and then we move down to the triple SSS cycle: the standard saturated single stage cycle, which is also the most common type of vapour compression refrigeration cycle. So, in the next class I shall be starting with the analysis of this one.

I shall be discussing several aspects of this one as well. Something like the effect of T_C and T_A also other parameters on its performance. Then we shall be relaxing a few of the assumptions like negligible pressure drop etc. and then I shall also be talking about the common refrigerants that we are using in vapour compression refrigerator. So, this lecture will be continued with to the next one till then you please rehearse this one and if you have any query, please write back to me. Thank you.