Applied Thermodynamics
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Module - 05
Lecture - 39
Absorption Refrigeration and Refrigerants

Dear learners, I welcome to this course Applied Thermodynamics, Refrigeration Air Conditioning, Module 5.

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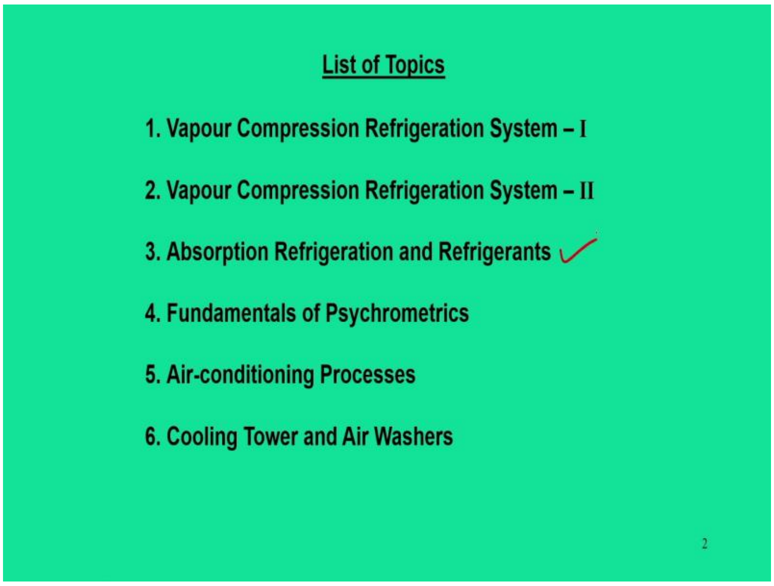

List of Topics

1. Vapour Compression Refrigeration System – I
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3. Absorption Refrigeration and Refrigerants ✓
4. Fundamentals of Psychrometrics
5. Air-conditioning Processes
6. Cooling Tower and Air Washers

Overall there are six lectures for this module, in the first two lectures we have discussed about vapour compression refrigeration systems part 1 and part 2 and in this lectures we mainly focused on refrigeration cycle as well as heat pump cycles. Today we will start the lecture number 3 it is a new topic Absorption Refrigeration and Refrigerants.

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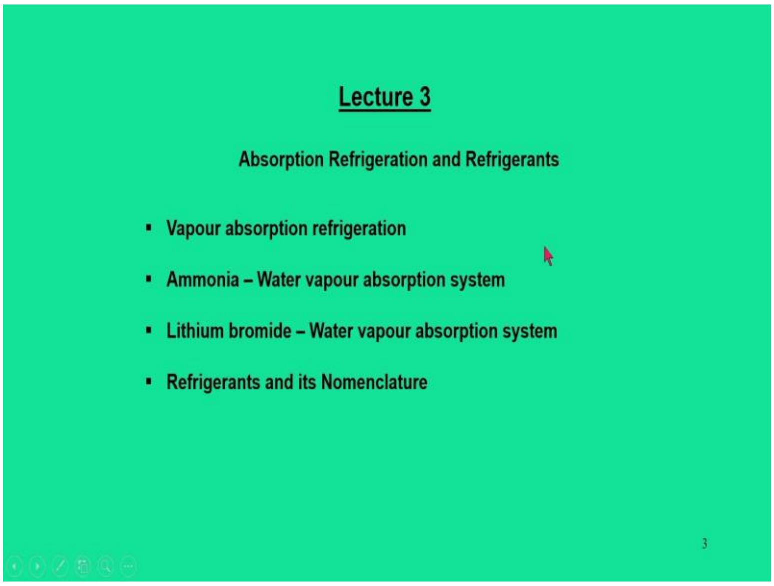

Lecture 3

Absorption Refrigeration and Refrigerants

- Vapour absorption refrigeration
- Ammonia – Water vapour absorption system
- Lithium bromide – Water vapour absorption system
- Refrigerants and its Nomenclature

So, under this lecture we will discuss upon some important aspects of vapour absorption refrigerations, how it is different from vapour compression systems and also of course, this vapour absorption refrigeration is not widely used, but it has its own importance. And in particular there are two types of vapour absorption refrigeration system that commonly used in practice one is ammonia water systems, other is the lithium bromide water system and towards the end of this lecture we will discussed about refrigerants and its nomenclature.

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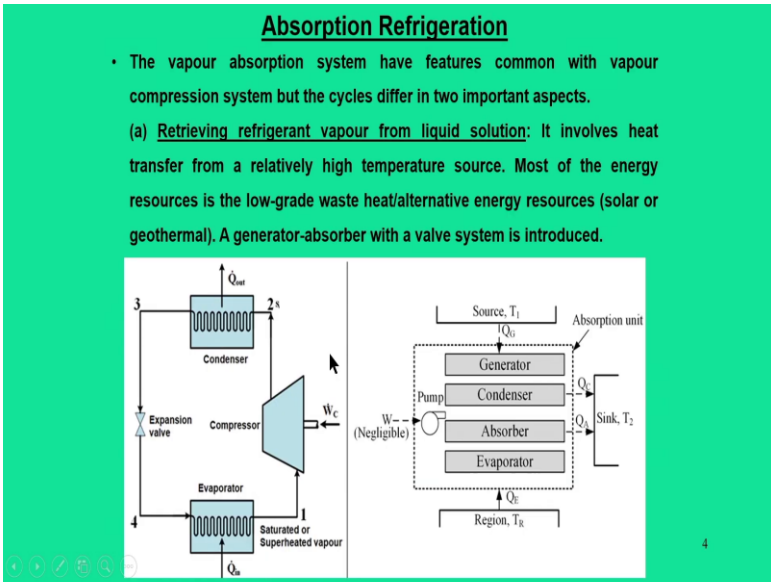

Absorption Refrigeration

- The vapour absorption system have features common with vapour compression system but the cycles differ in two important aspects.

  (a) Retrieving refrigerant vapour from liquid solution: It involves heat transfer from a relatively high temperature source. Most of the energy resources is the low-grade waste heat/alternative energy resources (solar or geothermal). A generator-absorber with a valve system is introduced.

So, first of all let me start the vapour absorption systems let us see that how this vapour absorption systems is different from a vapour compression systems. So, if you recall our analysis that a vapour compression systems consists of evaporator, compressor, condenser and expansion valve. And one more important aspects here is that we have a compressor and this compressor takes majority of heat input and in fact, most of this power that comes from the electrical power which we call as work input.

But many a times what happens there are some instances that if at all instead of work as input if you can think of some kind of heat as a source to run this system then we can think of this vapour absorption refrigeration. So, here the entire compressor unit of a vapour compression system is replaced with a pump. And this pumps takes minimal power and at the same time two additional components gets connected here, one is generator, other is absorber and other components like condenser and evaporator remains as it is.

And the circuit combination goes like this that if you look thermodynamically we have some source which is at maintained at T_1 and the generator takes Q_G amount of heat and we have also the space which needs to be cooled that is heat get extracted and goes to the evaporator.

And this condenser and absorber operates at some intermediate temperature T_2 in which heat is rejected. So, basically from two sources heat is getting added into the system and in one sources heat is getting rejected out of the systems. So, in a sense that there is no electrical work in the form high grade energy rather we are entirely using this heat sources as the source of input to drive the systems. This is one of the important aspects of a vapour absorption system.

Other important aspect of this is that when you look at this refrigerant in a vapour compression system, the refrigerant continuously circulates within this vapour compression circuit and in evaporator it takes the heat from the source and it becomes vapour and in the condenser it releases heat to the surroundings and it again becomes liquid.

So, through this process the refrigerant does its phase change during this process, but here it also does the phase change, but at the same time it is continuously absorbed by another component and we call this as a absorbent. So, it is continuously absorbed and continuously also dissolved means, when it is absorbed the solution become strong and when it is dissolved solution becomes weak.

So, in the sense that; that means, in a absorber unit there is a absorbent which absorbs this liquid and it forms a strong solution which is fed to generator and side by side when it comes out from the generator, only gas goes to the generator and week solution comes out of the generator. So, this is how it operates broadly in this thermal circuit.

So, the first way that a vapour absorption system differs is the retrieving refrigerant vapour from a liquid solutions. So, it involves heat transfer from a relatively high temperature source. Most of the energy sources is the low grade heat energy or alternative source of energy such as solar geothermal and to use this energy we are using a combination what we call as a generator absorber with a valve system.

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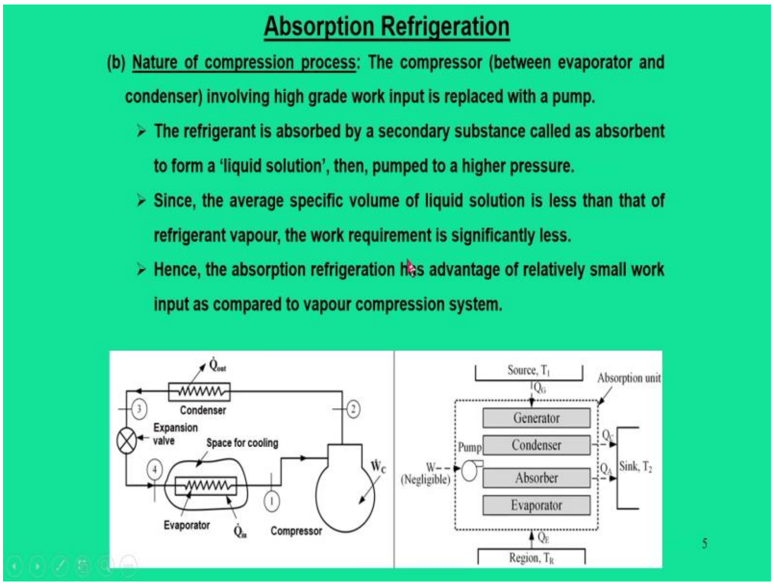

Absorption Refrigeration

(b) Nature of compression process: The compressor (between evaporator and condenser) involving high grade work input is replaced with a pump.

- The refrigerant is absorbed by a secondary substance called as absorbent to form a 'liquid solution', then, pumped to a higher pressure.
- Since, the average specific volume of liquid solution is less than that of refrigerant vapour, the work requirement is significantly less.
- Hence, the absorption refrigeration has advantage of relatively small work input as compared to vapour compression system.

And also I have also mentioned that nature of the compression systems. So, here there is no compressor it is replaced with a very small pump which takes minimal amount of high grade energy and in addition to that the refrigerant gets absorbed by a secondary substance which we call as a absorbent to form a 'liquid solutions' and which is pumped to high pressure.

The average specific volume of the liquid solution is less that of refrigerant vapours. So, the work requirement is significantly less. So, absorption refrigeration has a advantage of relatively small work input as compared to vapour compression system.

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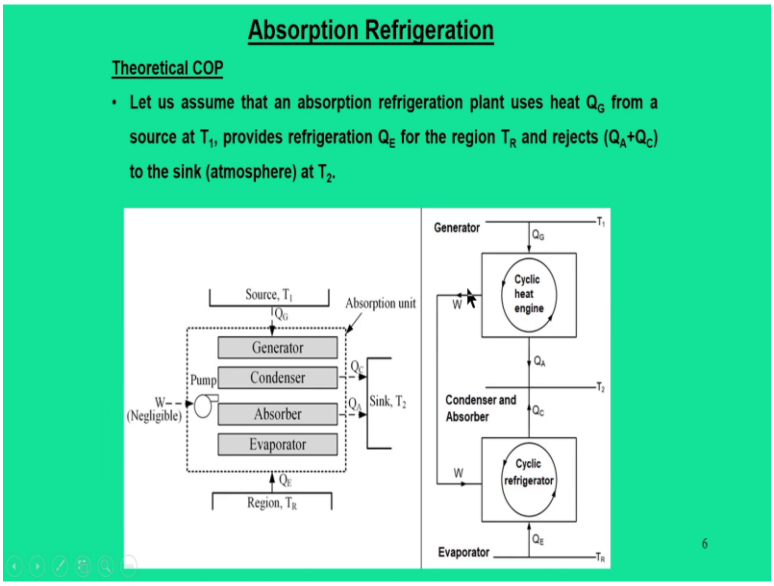

Absorption Refrigeration

Theoretical COP

- Let us assume that an absorption refrigeration plant uses heat Q_G from a source at T_1, provides refrigeration Q_E for the region T_R and rejects (Q_A+Q_C) to the sink (atmosphere) at T_2.

Now let us talk about some theoretical aspects. So, this particular things can be integrated in a manner that we will be able to find the thermodynamic estimates of COP for this kind of vapour absorption systems.

So, the system is modeled in a way that this plant uses Q_G amount of heat from the source T_1 that goes to the generator and it provides a refrigeration load Q_E; that means, the space that is going to be cooled, the amount heat that is taken from the space is Q_E and finally, heat rejection takes place to the sink which is atmosphere that comes from the condenser and absorber. So, that is Q_C and Q_A and they are maintained at temperature T_2.

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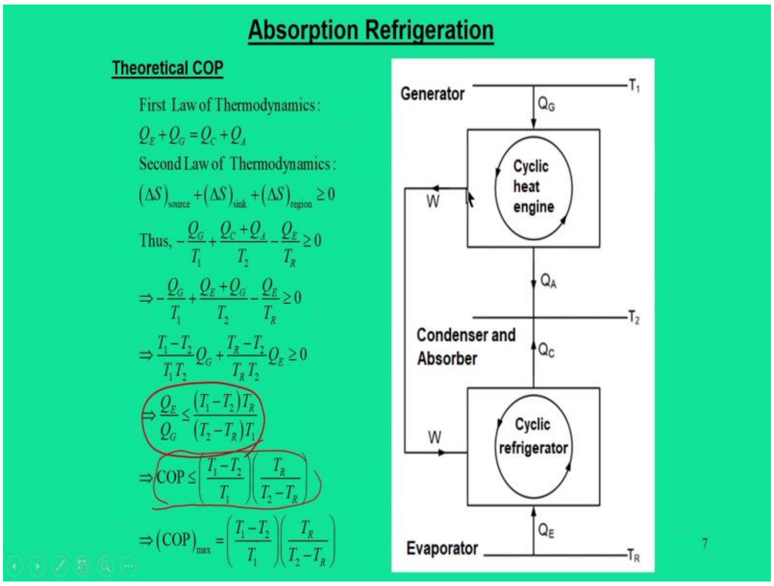

Absorption Refrigeration

Theoretical COP

First Law of Thermodynamics:

$$Q_E + Q_G = Q_C + Q_A$$

Second Law of Thermodynamics:

$$(\Delta S)_{\text{source}} + (\Delta S)_{\text{sink}} + (\Delta S)_{\text{region}} \geq 0$$

$$\text{Thus, } -\frac{Q_G}{T_1} + \frac{Q_C + Q_A}{T_2} - \frac{Q_E}{T_R} \geq 0$$

$$\Rightarrow -\frac{Q_G}{T_1} + \frac{Q_E + Q_G}{T_2} - \frac{Q_E}{T_R} \geq 0$$

$$\Rightarrow \frac{T_1 - T_2}{T_1 T_2} Q_G + \frac{T_R - T_2}{T_R T_2} Q_E \geq 0$$

$$\Rightarrow \frac{Q_E}{Q_G} \leq \frac{(T_1 - T_2) T_R}{(T_2 - T_R) T_1}$$

$$\Rightarrow \text{COP} \leq \left(\frac{T_1 - T_2}{T_1}\right)\left(\frac{T_R}{T_2 - T_R}\right)$$

$$\Rightarrow (\text{COP})_{\max} = \left(\frac{T_1 - T_2}{T_1}\right)\left(\frac{T_R}{T_2 - T_R}\right)$$

Now, one can write the first law equations. So, heat balance equation $Q_E + Q_G = Q_C + Q_A$. Second equation also tells that we can recall the entropy principle or law of entropy where total entropy change of the system is always greater than or equal to 0. $(\Delta S)_{\text{source}} + (\Delta S)_{\text{sink}} + (\Delta S)_{\text{region}} \geq 0$

So, here the systems involved is the source, sink as well as the region which is getting cooled and all this happens at constant temperatures. So, from this we can write down the basic equations of entropy in the form of $-\frac{Q_G}{T_1} + \frac{Q_C + Q_A}{T_2} - \frac{Q_E}{T_R} \geq 0$.

So, here the heat that comes out becomes negative, heat that goes out is positive. So, in a sense that if you frame this equations and ultimately if you use this first law equations in the entropy equations and finally, we come up a relations which is function of three temperatures T_1 that is source temperature, T_2 which is sink temperature and T_R is the evaporator temperatures. $\frac{Q_E}{Q_G} \leq \frac{(T_1 - T_2) T_R}{(T_2 - T_R) T_1}$

This is nothing but your COP. So, $\text{COP} \leq \left(\frac{T_1 - T_2}{T_1}\right)\left(\frac{T_R}{T_2 - T_R}\right)$, one interesting thing you can see that COP we have represented as a function of two parameters one is $\frac{T_1 - T_2}{T_1}$ that is nothing but a efficiency of a Carnot cycle or heat engine, other term $\frac{T_R}{T_2 - T_R}$ is nothing but the COP of a refrigerator. So that means, we can model this particular things that when you calculate COP of a vapour absorption systems, it can be modeled as a heat engine part and as a refrigerator part.

So, if you look at this particular figure the system can operate in a manner that whatever work that comes from the engine we can get it utilized in the cyclic refrigerator and through this we can maintain a condenser and absorber at certain temperature T_2 and the heat balance Q_A and Q_C; that means, heat rejected from the heat engine and heat rejected from the refrigerator that goes to a common unit what we call as a condenser and absorber unit. So, by virtue of this we can maintain a temperature T_2.

So, this work input from the cycle in heat engine that is nothing but your pump work that goes into the system and at the end of the day what we get out of it is that we get a cooling load in the evaporator that is Q_E; that means, it takes the heat from this space which is going to be cooled. So, for which the evaporator temperature is maintained as T_R.

And when you remove this inequality sign we can obtain maximum COP of a vapour absorption systems which is nothing but efficiency of a system which operates in a Carnot cycle or Carnot efficiency multiplied by Carnot COP of that cyclic refrigerator .

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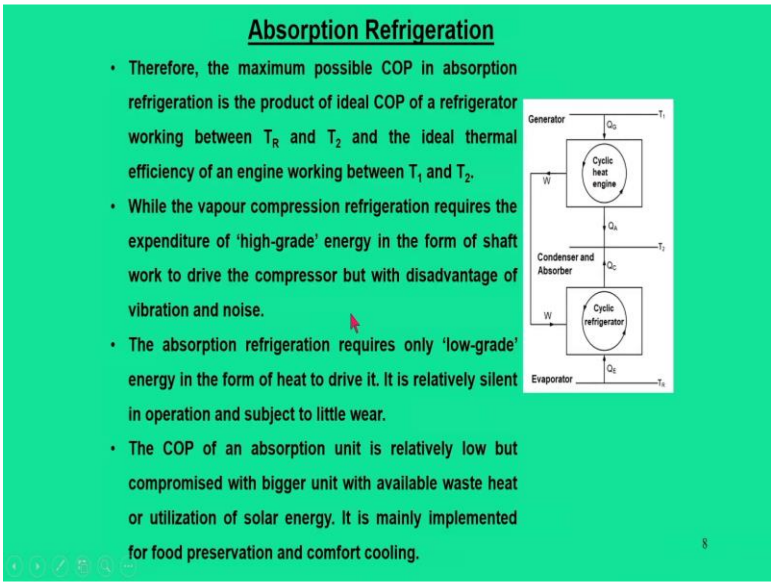

Absorption Refrigeration

- Therefore, the maximum possible COP in absorption refrigeration is the product of ideal COP of a refrigerator working between T_R and T_2 and the ideal thermal efficiency of an engine working between T_1 and T_2.
- While the vapour compression refrigeration requires the expenditure of 'high-grade' energy in the form of shaft work to drive the compressor but with disadvantage of vibration and noise.
- The absorption refrigeration requires only 'low-grade' energy in the form of heat to drive it. It is relatively silent in operation and subject to little wear.
- The COP of an absorption unit is relatively low but compromised with bigger unit with available waste heat or utilization of solar energy. It is mainly implemented for food preservation and comfort cooling.

So, the summary that we can get out of this analysis is that maximum possible COP in a vapour absorption unit is nothing but the product of ideal COP of a refrigerator working between T_R and T_2 and ideal thermal efficiency of the engine working between T_1 and T_2. Now, while vapour compression refrigeration requires expenditure of ‘high - grade’ energy in the form of shaft work to drive the compressor. But it has a disadvantage of vibration and noise.

And in that sense, the absorption refrigeration requires ‘low - grade’ energy in the form of heat to drive it. So, it is relatively silent in operations and it is subjected to very little wear. Of course, since we are not using the high grade energy, the absorption unit has always relatively low COP, but this particular concept or thought is being compromised by incorporating larger or big unit whenever there is a waste heat available for utilization such as solar energy.

And so, it is mainly implemented for food preservation and comfort cooling where we have main thrust is utilization of waste heat or renewable energies.

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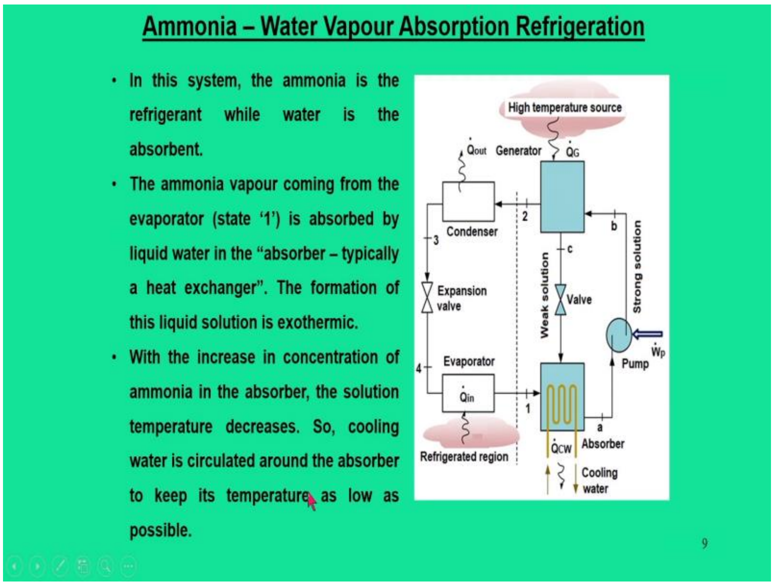

Ammonia – Water Vapour Absorption Refrigeration

- In this system, the ammonia is the refrigerant while water is the absorbent.
- The ammonia vapour coming from the evaporator (state ‘1’) is absorbed by liquid water in the “absorber – typically a heat exchanger”. The formation of this liquid solution is exothermic.
- With the increase in concentration of ammonia in the absorber, the solution temperature decreases. So, cooling water is circulated around the absorber to keep its temperature as low as possible.

The practical utility of vapour absorption systems is the ammonia water vapour absorption systems. So, here the ammonia is used as a refrigerant. And water is the absorbent because there is a combination of ammonium water is that ammonia gets absorbed in water very quickly.

So, we have to take the advantage of this so that it can be used as a vapour absorption unit and of course, ammonia is also a good refrigerant. So, vapour absorption systems normally use ammonia as one of the refrigerant and of course, ammonia can be available in large quantity, because when you think about vapour absorption unit you think about a big units in terms of large installations.

So, in a sense that you have to require large quantity of refrigerant which is in this case is your ammonia. So, if you look at this particular figure there are four input and units condenser, generator, absorber and evaporator.

So, the ammonia vapour which comes out from the evaporator which is at state 1 is absorbed by the liquid water in absorber and this absorber is nothing but a heat exchanger. And because of this we will get a liquid solution and here this thermodynamic process is exothermic; that means, lot of heat is released. So, we require a cooling water to take the out the heat.

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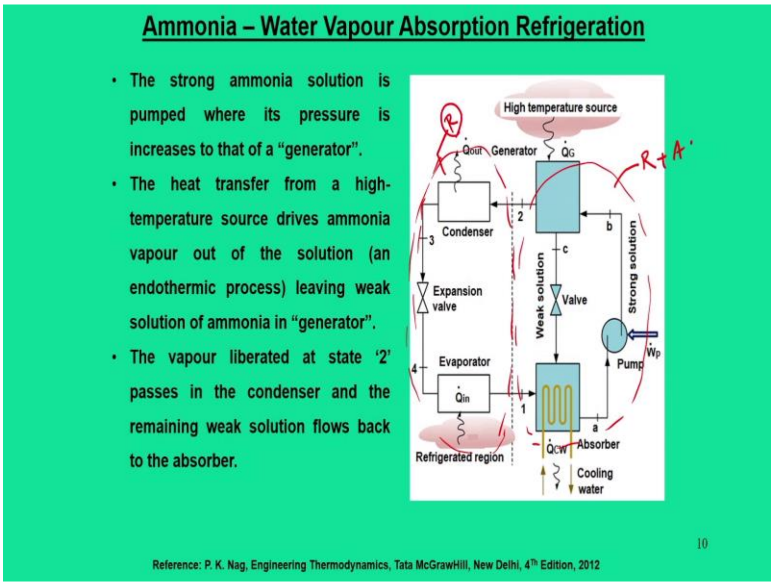

Ammonia – Water Vapour Absorption Refrigeration

- The strong ammonia solution is pumped where its pressure is increases to that of a "generator".
- The heat transfer from a high-temperature source drives ammonia vapour out of the solution (an endothermic process) leaving weak solution of ammonia in "generator".
- The vapour liberated at state '2' passes in the condenser and the remaining weak solution flows back to the absorber.

Reference: P. K. Nag, Engineering Thermodynamics, Tata McGrawHill, New Delhi, 4Th Edition, 2012

And when you take out this heat and you maintain that absorber temperature constant and the strong solution is now pumped to "generator". So, there is a pump and pump work is getting added here and it is a minimal work and when it gets added this strong solution is spread to the generator.

So, the vapour liberated from the state 2 passes in the condenser. Now what happens in the generator? It interacts with the high temperature source, heat is getting added, only vapour comes out from the generator and it goes to condenser where heat is released. And finally, the refrigerant vapour that comes out goes into the expansion valve and in the expansion valve once pressure drops, it goes to the evaporator and it takes the heat from the space which is going to be cooled.

So, if you look in a broad sense, there are two circuits one is this particular circuit which call this as a refrigerant circuit where the flow of refrigerant is allowed. Here we have refrigerant as well as absorbent circuits and in this circuit only refrigerant flows.

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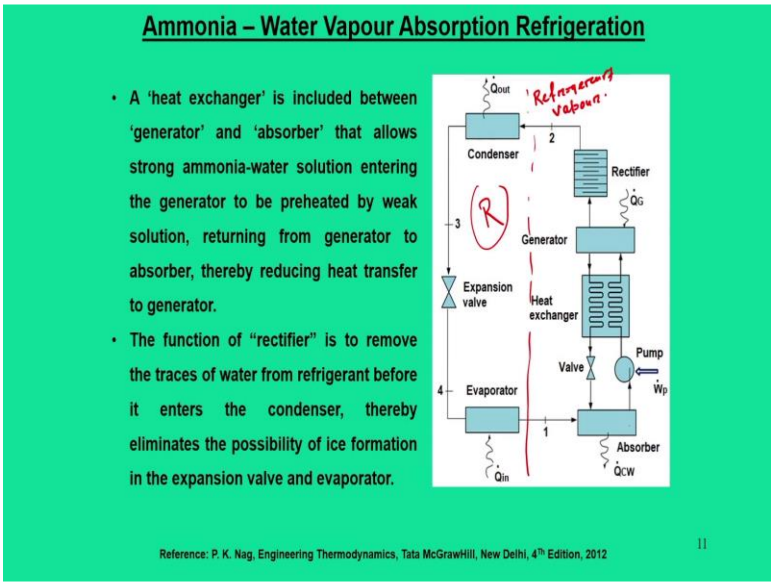

Ammonia – Water Vapour Absorption Refrigeration

- A 'heat exchanger' is included between 'generator' and 'absorber' that allows strong ammonia-water solution entering the generator to be preheated by weak solution, returning from generator to absorber, thereby reducing heat transfer to generator.
- The function of "rectifier" is to remove the traces of water from refrigerant before it enters the condenser, thereby eliminates the possibility of ice formation in the expansion valve and evaporator.

Reference: P. K. Nag, Engineering Thermodynamics, Tata McGrawHill, New Delhi, 4th Edition, 2012

And in a more concise manner, a ammonia water systems uses other components like rectifier and also we have a 'heat exchanger' which is placed between the 'generator' and 'absorber' unit and this is used to modify the systems and we say it is a modified vapour absorption systems.

And the entire idea is that when heat is released in the absorber; so, continuously how you are going to utilize this heat. So, one sense that the weak solution that comes from the generator to the absorber, it has lot of heat. So, this heat is getting utilized to cool this pumped liquid strong solutions.

So, that is a heat exchanger. So, from the absorber we have a strong solution that goes out this strong solution gets preheated by taking the heat from this weak solution which is release from the generator at high temperatures. So, that where the heat is getting utilized and the system performance gets improved, otherwise when you think about the refrigerant that goes to the condenser we ensure that it is only refrigerant vapour.

So, since it is a solution; so, we should not allow the water components or moistures to get into the condenser and in this particular circuit, only we have refrigerant that circulates between the condenser and evaporator, but through this process, generator and absorber unit make the refrigerant strong solutions or weak solution by continuous absorption or desorption.

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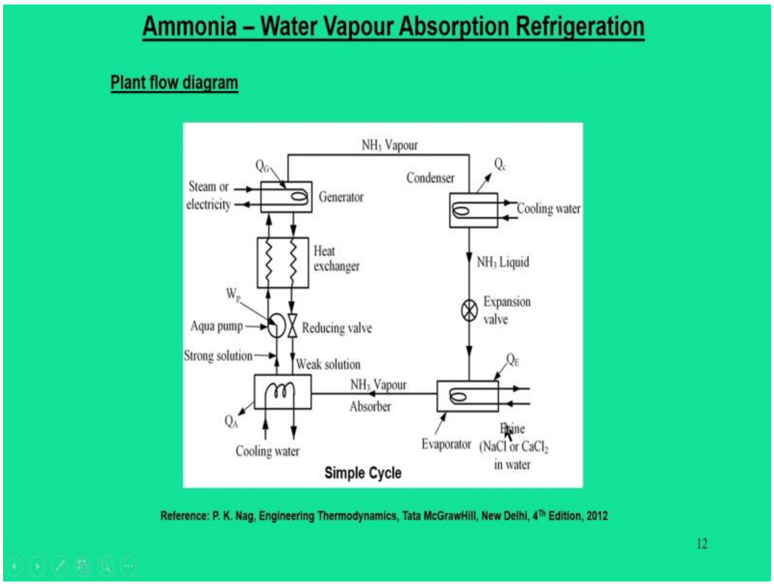

Ammonia – Water Vapour Absorption Refrigeration

Plant flow diagram

Simple Cycle

Reference: P. K. Nag, Engineering Thermodynamics, Tata McGrawHill, New Delhi, 4th Edition, 2012

This is the another versions of a plant flow diagram which is I have taken it from this book P K Nag Engineering Thermodynamics. So, here they also talk about so many things like we have a expansion valve, reducing valves just to regulate the pressures and we have strong solutions and we have weak solution that comes from the generator and many a times we also use brine in water to improve the system performance.

So, very basic bottom line is only NH_3 vapour goes into this refrigerant circuit; to improve the system efficiency, we have other devices like expansion valve and reducing valve.

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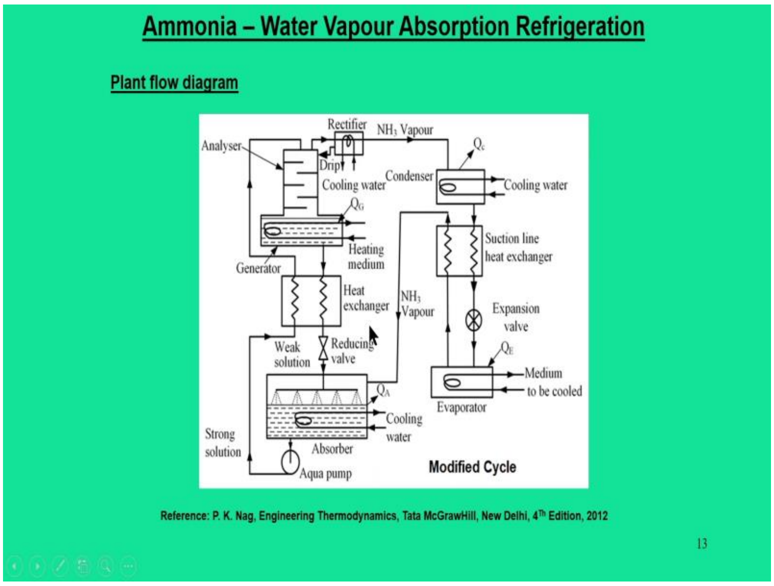

Ammonia – Water Vapour Absorption Refrigeration

Plant flow diagram

Modified Cycle

Reference: P. K. Nag, Engineering Thermodynamics, Tata McGrawHill, New Delhi, 4Th Edition, 2012

This is another modified diagram of this.

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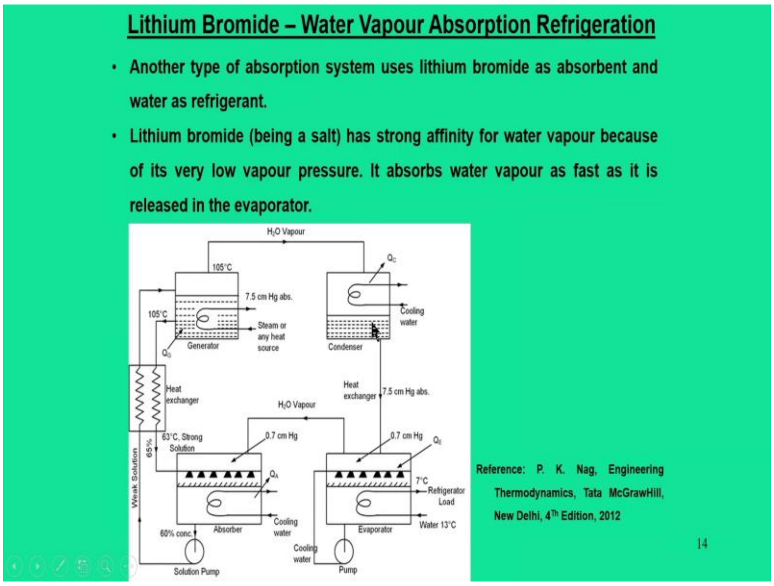

Lithium Bromide – Water Vapour Absorption Refrigeration

- Another type of absorption system uses lithium bromide as absorbent and water as refrigerant.
- Lithium bromide (being a salt) has strong affinity for water vapour because of its very low vapour pressure. It absorbs water vapour as fast as it is released in the evaporator.

Reference: P. K. Nag, Engineering Thermodynamics, Tata McGrawHill, New Delhi, 4Th Edition, 2012

The other version of vapour absorption unit is a lithium bromide water systems. So, here important aspect is that water is used as a refrigerant. So, that is the important factor and of course, lithium bromide is nothing but a salt; it is a solid form, but when it mixes with water we can prepare a solutions.

And lithium bromide being a salt has a strong affinity to water and because they operate at very low vapour pressure. So, it absorbs water vapour very fast and it is released in the evaporator, rest of the philosophy remains same as that of a ammonia water vapour absorption systems.

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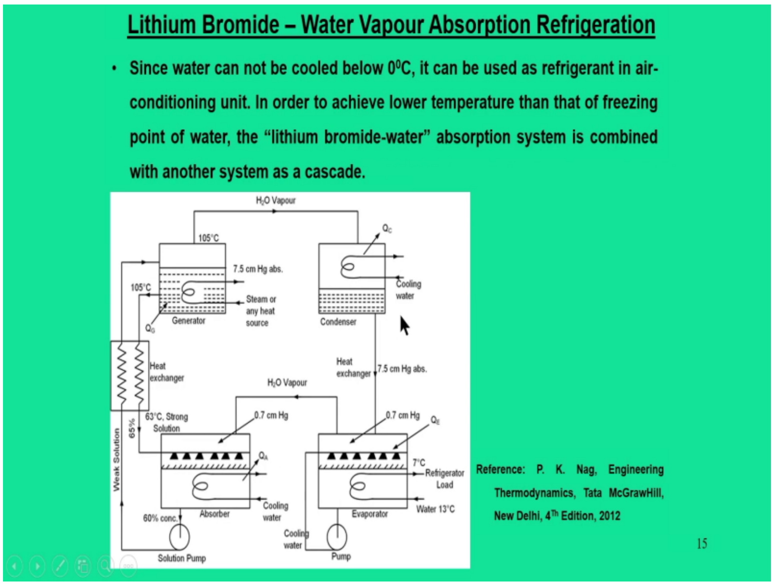

Lithium Bromide – Water Vapour Absorption Refrigeration

- Since water can not be cooled below 0^0C, it can be used as refrigerant in air-conditioning unit. In order to achieve lower temperature than that of freezing point of water, the “lithium bromide-water” absorption system is combined with another system as a cascade.

Reference: P. K. Nag, Engineering Thermodynamics, Tata McGrawHill, New Delhi, 4Th Edition, 2012

Only difference is that water is used as a refrigerant, other important aspect is that water has a limitations that we cannot cool it below 0°C. So, when a “lithium bromide - water” vapour absorption system is only used for comfort cooling where you are cooling requirement is maybe higher than 5 to 8 °C. So, it is a comfort cooling systems and it can be used in combination as a cascade system with any other unit.

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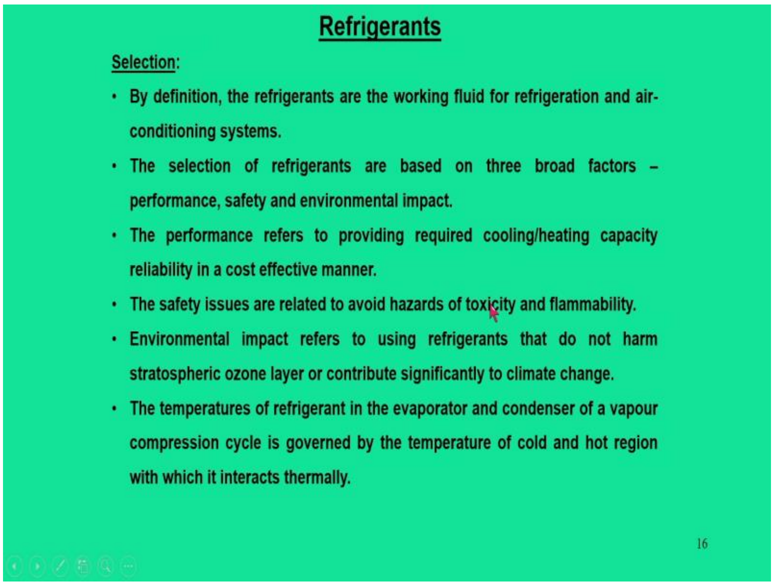

Refrigerants

Selection:

- By definition, the refrigerants are the working fluid for refrigeration and air-conditioning systems.
- The selection of refrigerants are based on three broad factors – performance, safety and environmental impact.
- The performance refers to providing required cooling/heating capacity reliability in a cost effective manner.
- The safety issues are related to avoid hazards of toxicity and flammability.
- Environmental impact refers to using refrigerants that do not harm stratospheric ozone layer or contribute significantly to climate change.
- The temperatures of refrigerant in the evaporator and condenser of a vapour compression cycle is governed by the temperature of cold and hot region with which it interacts thermally.

Now next topic that I am going to discuss is about refrigerants. So, till this point of time we have talked about vapour compression systems and vapour absorption systems and in a vapour compression systems, we have a refrigeration systems and heat pump systems and we all say that every system require a refrigerant.

So, refrigerant when you are using there are two categories of refrigerant that are fixed here that when you say it is a vapour absorption systems, I already mentioned ammonia and water these are the two refrigerants which are commonly used in the vapour absorption systems. And in fact, these are inorganic compounds, but we will talk about vapour compression systems; the refrigerants of this nature may not seems to be a good alternative because these units or vapour compression units or heat pump cycle they use some kind of specific requirement for which low temperature is desired.

So, in a sense that sometimes your temperature may be below 0°C. So, for such applications we use specific refrigerant and those refrigerants are organic in nature. And of course, when you talk about those refrigerants they have very specific properties and those properties are required for the choice of a particular applications.

So, the selection of refrigerant is very vital, because it is a working fluid for refrigeration and air conditioning applications and it is based on basically three factors one is performance; that means, we should get the desired effect and it should have a a minimal environmental impact. And the performance I refer to cooling and heating capacity and the safety issues are mainly due to the hazards of toxicity, flammability.

Environmental factor mainly refers to that they do not harm the ozone layers in the atmosphere and these environmental effect has a another link to the climate change. And when you choose a refrigerant, the temperature of the refrigerant in the evaporator and the condenser for a vapour cycle is mainly governed by the temperature of cold region and hot region and with which the system interacts thermally.

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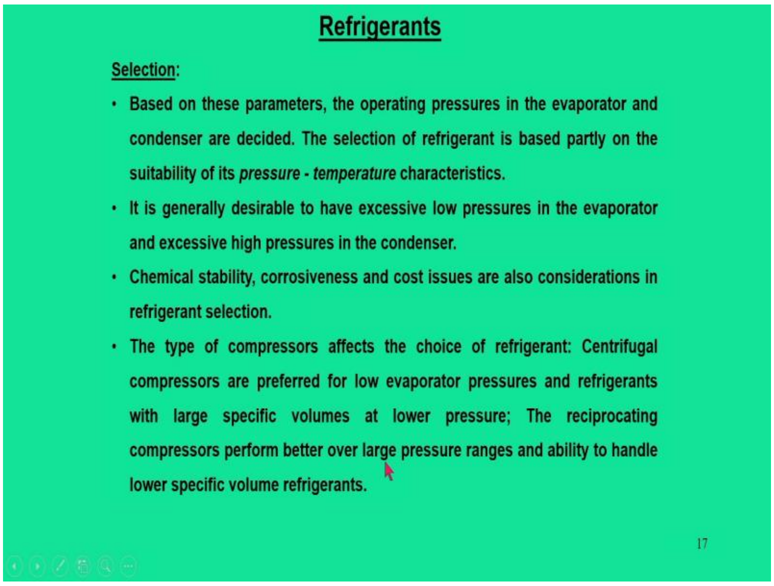

Refrigerants

Selection:

- Based on these parameters, the operating pressures in the evaporator and condenser are decided. The selection of refrigerant is based partly on the suitability of its *pressure - temperature* characteristics.
- It is generally desirable to have excessive low pressures in the evaporator and excessive high pressures in the condenser.
- Chemical stability, corrosiveness and cost issues are also considerations in refrigerant selection.
- The type of compressors affects the choice of refrigerant: Centrifugal compressors are preferred for low evaporator pressures and refrigerants with large specific volumes at lower pressure; The reciprocating compressors perform better over large pressure ranges and ability to handle lower specific volume refrigerants.

And of course, their suitability is based on the pressure temperature characteristics. So, it is always desirable to have a excess low pressure in the evaporator and excessively high pressure in the condenser, so that we can get a desired cooling effect without any hamper.

Other aspects are chemical stability, corrosiveness and cost issues are also consideration for this refrigerant selection and many a times what happens the compressor unit. So, the compressor is available for a particular refrigerant; that means, if at all you want to use this particular refrigerant, there is a specific compressor design.

So, the type of compressor also affects the choice of the refrigerant: for example, centrifugal compressor are preferred for low evaporator pressure and refrigerants with large specific volume at low pressure whereas, reciprocating compressor perform better over large pressure range, but they have ability to handle only low specific volume refrigerants. So, this is another important aspect for the choice of the refrigerant.

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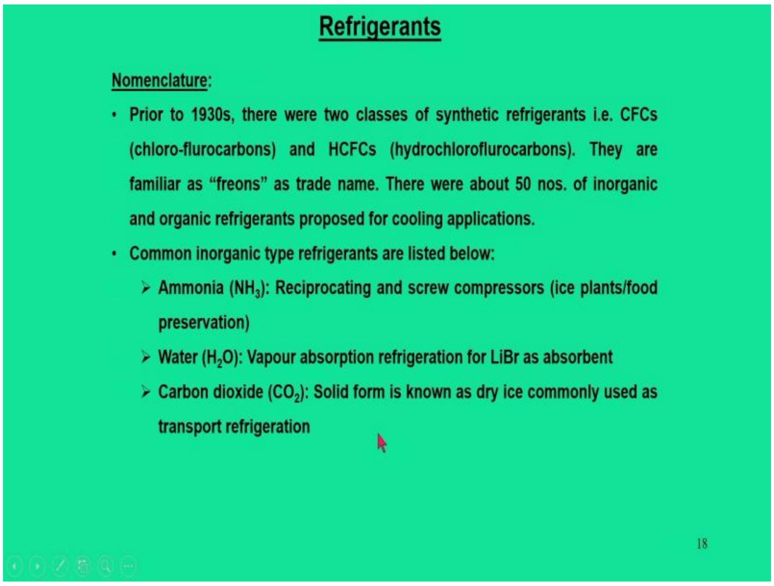

Refrigerants

Nomenclature:

- Prior to 1930s, there were two classes of synthetic refrigerants i.e. CFCs (chloro-flurocarbons) and HCFCs (hydrochloroflurocarbons). They are familiar as “freons” as trade name. There were about 50 nos. of inorganic and organic refrigerants proposed for cooling applications.
- Common inorganic type refrigerants are listed below:
  - Ammonia (NH_3): Reciprocating and screw compressors (ice plants/food preservation)
  - Water (H_2O): Vapour absorption refrigeration for LiBr as absorbent
  - Carbon dioxide (CO_2): Solid form is known as dry ice commonly used as transport refrigeration

Now, moving to the type of refrigerant that are used for refrigeration systems, prior to 1930, there were only two classes of refrigerant we called as a synthetic refrigerants and they come under chloro-fluro carbons or hydro chloro fluro carbons. So, these are the categories and they are known as “freons” during that time and about 50 number of inorganic and refrigerants were proposed for their applications.

And inorganic type we have ammonia which is mainly used for reciprocating and screw compressors. Water is used in the vapour absorption refrigeration for lithium with lithium bromide as a absorbent and also we have a another inorganic refrigerant which is carbon dioxide and you also commonly known as a dry ice and mostly used in the transport refrigeration.

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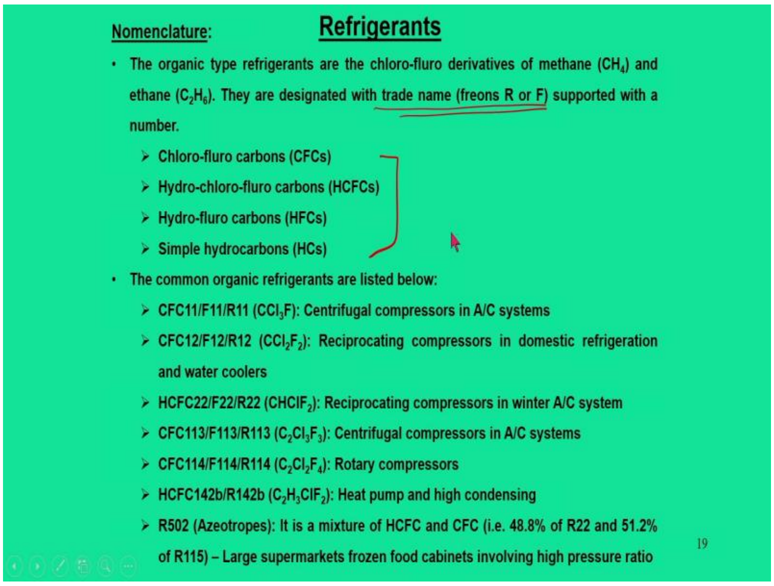

Nomenclature:

Refrigerants

- The organic type refrigerants are the chloro-fluro derivatives of methane (CH_4) and ethane (C_2H_6). They are designated with trade name (freons R or F) supported with a number.
  - Chloro-fluro carbons (CFCs)
  - Hydro-chloro-fluro carbons (HCFCs)
  - Hydro-fluro carbons (HFCs)
  - Simple hydrocarbons (HCs)
- The common organic refrigerants are listed below:
  - CFC11/F11/R11 (CCl_3F): Centrifugal compressors in A/C systems
  - CFC12/F12/R12 (CCl_2F_2): Reciprocating compressors in domestic refrigeration and water coolers
  - HCFC22/F22/R22 ($CHClF_2$): Reciprocating compressors in winter A/C system
  - CFC113/F113/R113 ($C_2Cl_3F_3$): Centrifugal compressors in A/C systems
  - CFC114/F114/R114 ($C_2Cl_2F_4$): Rotary compressors
  - HCFC142b/R142b ($C_2H_3ClF_2$): Heat pump and high condensing
  - R502 (Azeotropes): It is a mixture of HCFC and CFC (i.e. 48.8% of R22 and 51.2% of R115) – Large supermarkets frozen food cabinets involving high pressure ratio

So, when you deal with the nomenclature we are going to classify in basically four broad categories first thing either they come under chloro-fluro carbons CFC, they come under hydro - chloro - fluro carbons HCFCs. Then hydro-fluro carbon HFCs and simple hydrocarbon HCs and for all these case although they are very difficult to remember. So, they are given a trade names either we call this as a refrigerant R or freons and they are supported with a number and we will we will talk about those numbers later.

So, let us say CFC11 or F11, R11. So, F or R stands for trade name and 11 stands the number which is design. So, in CFC, HCFC, when you use those refrigerant then what it says is that it is represented by its chemical compound or it can be represented by its trade name.

And with respect to trade name they are most commonly known because with respect to their trade name, the compressor units gets specified. For example, if you say you want to centrifugal compressor in AC systems R11 or F11 is a common choice. Although, another number could be R 113 can be common choice for centrifugal compressor when you move to the reciprocating compressors then R11 may not be a good choice rather R12 may be another choice.

And for rotary compressors, we can have R114 and for heat pump systems one particular refrigerant could be R142b and there are other class of refrigerants we call as a azeotropes R 502 and those azeotropes are kind of new refrigerants which takes the mixture of hydro chloro-fluro carbons and chloro-fluro carbons for example, azeotropes are 502 is a mixture of 48.8 percent of R22 and 51.2 percent of R115 and they are mostly used in the large super markets. These are the common names.

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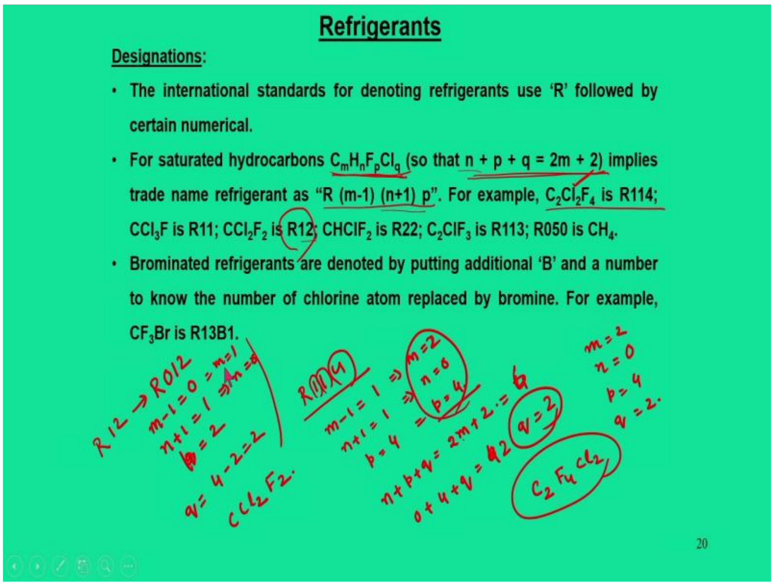

Refrigerants

Designations:

- The international standards for denoting refrigerants use 'R' followed by certain numerical.
- For saturated hydrocarbons $C_mH_nF_pCl_q$ (so that n + p + q = 2m + 2) implies trade name refrigerant as "R (m-1) (n+1) p". For example, $C_2Cl_2F_4$ is R114; CCl_3F is R11; CCl_2F_2 is R12; $CHClF_2$ is R22; C_2ClF_3 is R113; R050 is CH_4.
- Brominated refrigerants are denoted by putting additional 'B' and a number to know the number of chlorine atom replaced by bromine. For example, CF_3Br is R13B1.

R12 → R012
$m-1=0 \Rightarrow m=1$
$n+1=1 \Rightarrow n=0$
$p=2$
$q=4-2=2$
CCl_2F_2.

R114
$m-1=1 \Rightarrow m=2$
$n+1=1 \Rightarrow n=0$
$p=4 \Rightarrow p=4$
$n+p+q=2m+2 = 6$
$0+4+q=6$
$q=2$
$C_2F_4Cl_2$

$m=2$
$n=0$
$p=4$
$q=2$.

20

Now I am going to talk about what is this R and how the refrigerants are designated. So, there are two categories, one is first category is the saturated type hydrocarbon. And when you say saturated hydrocarbons it consists of hydrogen, carbon in addition to that we have fluorine as well as chlorine.

And the combination of those things is CmHnFpClq and for this n + p + q = 2m + 2 seems to be valid because by virtue of their characteristics or bond or affinity. When they are satisfied then only we can say it is a saturated hydrocarbon. So, if this is your refrigerant and I want to assign it as a trade names, either I can use R or F.

So, it is mainly mentioned here as R (m-1) (n+1) p. So, for this particular refrigerant chemical name the trade name becomes "R (m-1) (n+1) p". So, by these things we can say $C_2Cl_2F_4$ is R114. So, basically when you say R114 which means m-1=1, n+1=1, p=4. So, this will take you m=2, n=0, p=4 and from n + p + q = 2m + 2, we can get q=2.

So, from this m=2 means carbon 2, n = 0 means there is no hydrogen, F =4, p is equal to 4 means and Cl chlorine is 2. This is how it is written here.

So, accordingly for all other cases you can write this. So, another important point is when you talk about R12, but here there are three numbers here. So, in that case when you talk R12 we have to rewrite is at R012 and when you say R012 then we have to work like this m-1=0, n+1=1, p=2.

So; that means, m=1, n=0, p=2. So, q can be find out as q is equal to 2. So, from this we can find out this refrigerant would be CCl_2F_2. So, likewise all other refrigerant we can note it this way.

And there are other category of refrigerant which are brominated refrigerants they are denoted by putting an additional ‘B’ and to know that the chlorine atom is replaced with a bromine atom. So, basically CF_3Br means one chlorine atom is replaced with a bromine atom. So, they are brominated refrigerant.

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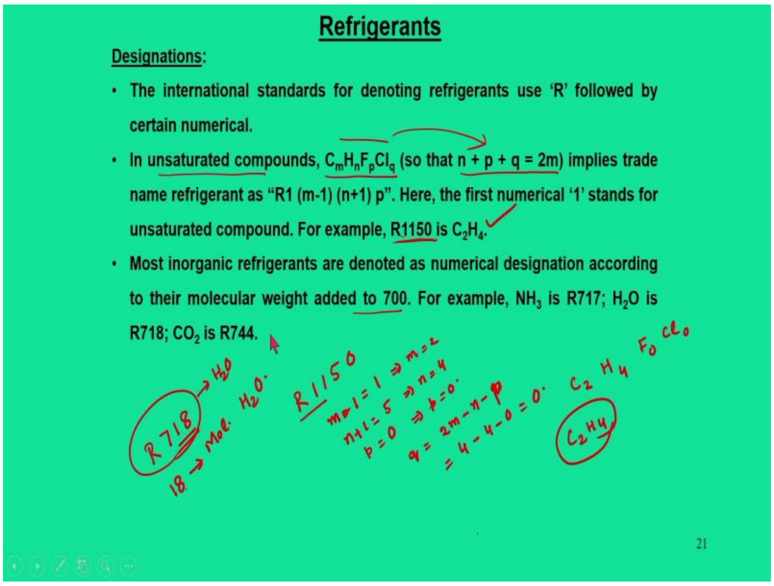

Refrigerants

Designations:

- The international standards for denoting refrigerants use ‘R’ followed by certain numerical.
- In unsaturated compounds, $C_mH_nF_pCl_q$ (so that n + p + q = 2m) implies trade name refrigerant as “R1 (m-1) (n+1) p”. Here, the first numerical ‘1’ stands for unsaturated compound. For example, R1150 is C_2H_4.
- Most inorganic refrigerants are denoted as numerical designation according to their molecular weight added to 700. For example, NH_3 is R717; H_2O is R718; CO_2 is R744.

This is the next category of refrigerant is unsaturated compounds, for unsaturated compounds their chemical formulas are $C_mH_nF_pCl_q$ and where n + p + q = 2m. So, this things must be satisfied for the compound to be unsaturated one and here important thing is that denotion is four numbers.

So, R has no meaning. So, for example, if I say R1150 so, first R1 remains as it is. So, 150 means your m-1=1,n+1=5,p=0. So, this means m=2,n=4,p=0. So, q can be find out 2m-n-p=0.

So, from this we can now say that it is C_2H_4. So, we have got saturated and unsaturated compounds and they are organic compounds. The other inorganic refrigerants we have choices ammonia, water and carbon dioxides, there are three choices of refrigerant.

So, for that, the standard designation will be 700 added to its molecular weight. For example, if I say R718. So, 18 is molecular weight of water, so 700 added to it. So, R718 is for water. So, similarly for CO_2 it is R744. So, this is how the refrigerants are designated.

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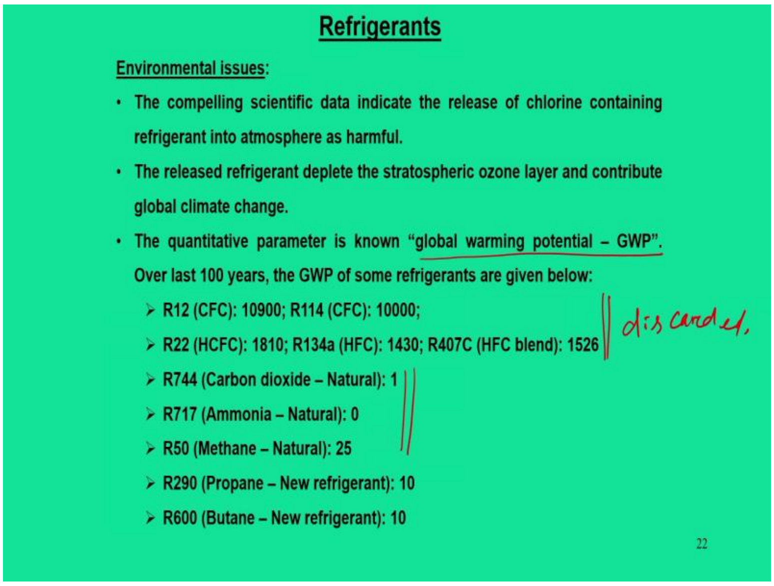

Refrigerants

Environmental issues:

- The compelling scientific data indicate the release of chlorine containing refrigerant into atmosphere as harmful.
- The released refrigerant deplete the stratospheric ozone layer and contribute global climate change.
- The quantitative parameter is known "global warming potential – GWP". Over last 100 years, the GWP of some refrigerants are given below:
  - R12 (CFC): 10900; R114 (CFC): 10000;
  - R22 (HCFC): 1810; R134a (HFC): 1430; R407C (HFC blend): 1526 || discarded,
  - R744 (Carbon dioxide – Natural): 1
  - R717 (Ammonia – Natural): 0
  - R50 (Methane – Natural): 25
  - R290 (Propane – New refrigerant): 10
  - R600 (Butane – New refrigerant): 10

And the last part of this refrigerant is the environmental issues. So, till this point of time there are compelling scientific data that indicates that release of chlorine containing refrigerant into atmosphere is harmful and because this released refrigerant deplete the stratosphere ozone layer and they contribute global climate change. For this a quantitative parameter is formed what we call as a "GWP- global warming potential".

And over last 100 years this particular GWP was estimated for different refrigerants and it is found that when you use CFC category refrigerant like R12 or R114. their GWP is about higher than 10000. But when you use a HCFC a type of refrigerant or HFC type of refrigerant, their GWP is about more than 1000. So, this refrigerant is to be discarded.

The common choice is that we have to design our new refrigerants. So, the new refrigerant they are come under propane, methane, butane which are much better than this CFC type refrigerant. Other choice is that we have to use the gases like carbon dioxide, ammonia, methane, these are very less threat for the global warning. So, these are mostly used refrigerants in practice.

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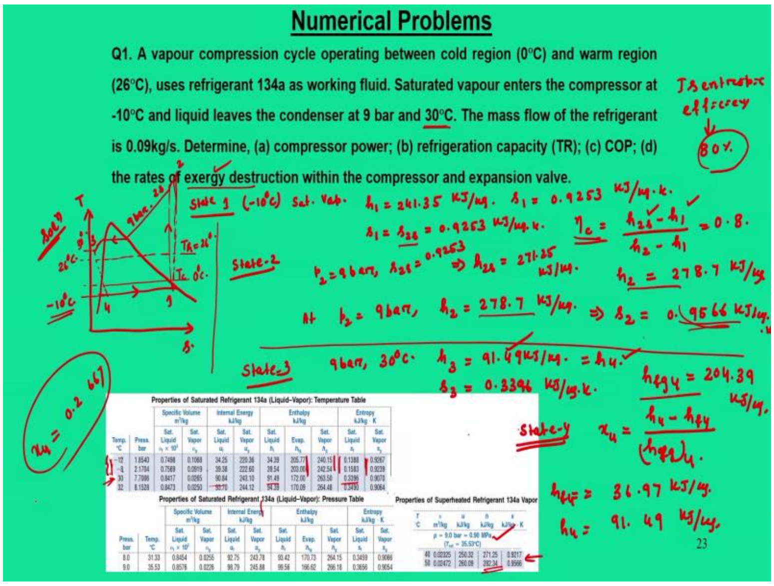

Numerical Problems

Q1. A vapour compression cycle operating between cold region (0°C) and warm region (26°C), uses refrigerant 134a as working fluid. Saturated vapour enters the compressor at -10°C and liquid leaves the condenser at 9 bar and 30°C. The mass flow of the refrigerant is 0.09kg/s. Determine, (a) compressor power; (b) refrigeration capacity (TR); (c) COP; (d) the rates of exergy destruction within the compressor and expansion valve.

Isentropic efficiency → 80%

Sol^n

State 1 (-10°c) Sat. Vap. $h_1 = 241.35$ KJ/kg. $s_1 = 0.9253$ KJ/kg.k.

$s_1 = s_{2s} = 0.9253$ KJ/kg.k. $\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1} = 0.8.$

State-2 $p_2 = 9$ bar, $s_{2s} = 0.9253 \Rightarrow h_{2s} = 271.25$ KJ/kg. $h_2 = 278.7$ KJ/kg

At $p_2 = 9$ bar, $h_2 = 278.7$ KJ/kg. $\Rightarrow s_2 = 0.9566$ KJ/kg.k

State-3 9 bar, 30°C. $h_3 = 91.49$ KJ/kg. $= h_4$. $s_3 = 0.3396$ KJ/kg.k.

State-4 $x_4 = \frac{h_4 - h_{f4}}{(h_{fg})_4}.$ $h_{fg4} = 204.39$ KJ/kg. $h_{f4} = 36.97$ KJ/kg. $h_4 = 91.49$ KJ/kg.

$x_4 = 0.2667$

Properties of Saturated Refrigerant 134a (Liquid–Vapor): Temperature Table

Temp. °C	Press. bar	Specific Volume m³/kg Sat. Liquid $v_f \times 10^3$	Specific Volume m³/kg Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Internal Energy kJ/kg Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Enthalpy kJ/kg Evap. h_{fg}	Enthalpy kJ/kg Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Entropy kJ/kg · K Sat. Vapor s_g
-12	1.8540	0.7498	0.1068	34.25	220.36	34.39	205.77	240.15	0.1388	0.9267
-8	2.1704	0.7569	0.0919	39.38	222.60	39.54	203.00	242.54	0.1583	0.9239
30	7.7006	0.8417	0.0265	90.84	243.10	91.49	172.00	263.50	0.3396	0.9070
32	8.1528	0.8473	0.0250	93.70	244.12	94.39	170.09	264.48	0.3490	0.9064

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Press. bar	Temp. °C	Specific Volume m³/kg Sat. Liquid $v_f \times 10^3$	Specific Volume m³/kg Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Internal Energy kJ/kg Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Enthalpy kJ/kg Evap. h_{fg}	Enthalpy kJ/kg Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Entropy kJ/kg · K Sat. Vapor s_g
8.0	31.33	0.8454	0.0255	92.75	243.78	93.42	170.73	264.15	0.3459	0.9066
9.0	35.53	0.8576	0.0226	98.79	245.88	99.56	166.62	266.18	0.3656	0.9054

Properties of Superheated Refrigerant 134a Vapor

p = 9.0 bar = 0.90 MPa (T_{sat} = 35.53°C)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
40	0.02325	250.32	271.25	0.9217
50	0.02472	260.09	282.34	0.9566

With this I come to the end of this segment of this lecture. So, we will try to solve some problems. So, till this point of time there is no major requirement of problems as far as the vapour absorption is concerned, but I will try to sum it up some of the vapour compression systems which you have already discussed in the last class and some important point that I need to emphasize how to include exergy in the vapour refrigeration systems.

So, to have some kind of application that how you calculate exergy in a vapour compression systems, I have included this particular problem. So, let me start this problem which involves the calculation of exergy lost due to irreversibility. Now in a vapour compression system the irreversibility mainly comes from two thing, one is in the expansion valve other is in the compression. In addition to that your evaporator and condenser temperatures, they are operated at different temperatures than that of the warm region or this space to be cooled.

So, let me start the first problem. So, the vapour compression cycle operates between the cold region that is 0°C and warm region 26°C uses the refrigerant R134a as a working fluid. Remember this is the same problem which was discussed in the last lecture, but here the emphasis was given something different is that here we want to introduce irreversibility into the system. The saturated vapour enters the compressor at -10°C and remember your cold region was 0°C, liquid leaves the condenser at 9 bar and 30°C.

So, normally liquid leaves the condenser at saturated liquid, but we have specified it is at 9 bar and 30°C. So, here another irreversibility comes in to picture that this particular state could be a sub cooled region and we have to calculate the mass flow rate of the refrigerant. So, another point is that when saturated vapour enters the compressor at -10°C, but we do not know where it leaves.

So, it leaves probably at 9 bar, but what enthalpy or entropy we do not know. Of course, we have to introduce isentropic efficiency of the compressor. So, let me put the isentropic efficiency of the compressor as 80 percent. So, the solution can be stated like this.

So, first we have to draw this temperature entropy diagram. So, you have to create a dome. So, we have to draw the cycle, we have sub cold region here. So, first thing we have to denote the states, entry to the compressor and if the process is isentropic it would have gone this. So, it would reach 2s and this constant pressure is at 9 bar.

But the exit of the condenser is at 30°C, but your warm region is 26°C. So, point 3 would be located here and 4 would be here and you do not know the location of 4 and we also know that there is a isentropic efficiency of the compressor is 80 percent. So, 2 will be here.

Now to solve the problems you have to go state by state. So, let us see state 1. So, this evaporator temperature is -10°C, but your warm region is above it that is 0°C. So, T_h hot region, T_c cold region. So, this is the very basic T s diagram that we can draw.

So, state 1 is -10 degree and it is saturated vapour. So, when it is saturated vapour, we can refer this particular table we have data at -8 and -12°C. So, all these datas needs interpolations enthalpy, entropy. So, by interpolating h_1 as 241.35 kJ/kg and s_1 is 0.9253 kJ/kg-K and $s_1=s_2$.

State - 2: $@p_2 = 9\text{bar}, s_{2s} = 0.9253\text{kJ/kg-K} \Rightarrow h_{2s} = 271.25\text{kJ/kg}$

$$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1} \Rightarrow h_2 = 278.7\text{kJ/kg}$$

$@p_2 = 9\text{bar}, h_2 = 278.7\text{kJ/kg} \Rightarrow s_2 = 0.9566\text{kJ/kg-K}$

State - 3: $@p = 9\text{bar},\ T\ =\ 30°C \Rightarrow h_3 = 91.49\text{kJ/kg} = h_4; s_3 = 0.3396\text{kJ/kg-K}$

State - 4: $h_{f4}\big|_{-10°C} = 36.97\text{kJ/kg}, h_4 = 91.49\text{kJ/kg}, h_{fg4} = 204.39\text{kJ/kg} \Rightarrow x_4 = \dfrac{h_4 - h_{f4}}{h_{fg4}} = 0.2667$

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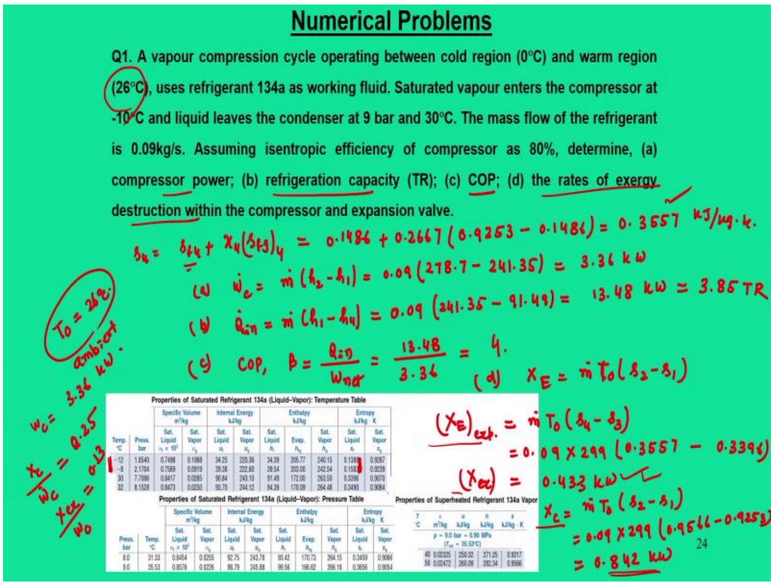

Numerical Problems

Q1. A vapour compression cycle operating between cold region (0°C) and warm region (26°C), uses refrigerant 134a as working fluid. Saturated vapour enters the compressor at -10°C and liquid leaves the condenser at 9 bar and 30°C. The mass flow of the refrigerant is 0.09kg/s. Assuming isentropic efficiency of compressor as 80%, determine, (a) compressor power; (b) refrigeration capacity (TR); (c) COP; (d) the rates of exergy destruction within the compressor and expansion valve.

$s_4 = s_{f4} + x_4 (s_{fg})_4 = 0.1486 + 0.2667 (0.9253 - 0.1486) = 0.3557$ kJ/kg·K.

(a) $\dot{w}_c = \dot{m}(h_2 - h_1) = 0.09(278.7 - 241.35) = 3.36$ kW

(b) $\dot{Q}_{in} = \dot{m}(h_1 - h_4) = 0.09 (241.35 - 91.49) = 13.48$ kW ≈ 3.85 TR

(c) COP, $\beta = \dfrac{Q_{in}}{W_{net}} = \dfrac{13.48}{3.36} = 4.$

(d) $X_E = \dot{m} T_0 (s_2 - s_1)$

$(X_E)_{exp.} = \dot{m} T_0 (s_4 - s_3)$

$= 0.09 \times 299 (0.3557 - 0.3396)$

$(X_{ex}) = 0.433$ kW

$X_c = \dot{m} T_0 (s_2 - s_1)$

$= 0.09 \times 299 (0.9566 - 0.9253)$

$= 0.842$ kW

$T_0 = 26°C$ ambient

3.36 kW.

$w_c = 0.25$

$x_E / w_c = 0.13$

x_{ex} / w_0

Properties of Saturated Refrigerant 134a (Liquid–Vapor): Temperature Table

Temp. °C	Press. bar	Specific Volume m³/kg Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Sat. Vapor s_g
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Press. bar	Temp. °C	Specific Volume m³/kg Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Sat. Vapor s_g
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9.0	35.53	0.8576	0.0226	98.79	245.88	99.56	166.62	266.18	0.3656	0.9054

Properties of Superheated Refrigerant 134a Vapor

p = 9.0 bar = 0.90 MPa (T_{sat} = 35.53°C)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
40	0.02325	250.32	271.25	0.9217
50	0.02472	260.09	282.34	0.9566

$$s_4 = s_{f4}\big|_{-10°C} + x_4 s_{fg4} = 0.1486 + 0.2667(0.9253 - 0.1486) = 0.3557\text{kJ/kgK}$$

$$\dot{w}_c = \dot{m}(h_2 - h_1) = 0.09(278.7 - 241.35) = 3.36\text{kW}$$

$$\dot{Q}_{in} = \dot{m}(h_1 - h_4) = 0.09(241.35 - 91.49) = 13.48\text{kW} = 3.85\text{TR}$$

$$\text{COP}, \beta = \frac{\dot{Q}_{in}}{w_{net}} = \frac{13.48}{3.36} = 4$$

Last one is rate of exergy destruction, the rate of exergy destruction has two parts one is in expansion and other is in compressor.

$$(X_E)_{\exp} = \dot{m}T_0(s_4 - s_3) = 0.09 \times 299(0.3557 - 0.3396) = 0.433\text{kW}$$

$$(X_E)_{comp} = \dot{m}T_0(s_2 - s_1) = 0.09 \times 299(0.9566 - 0.9253) = 0.842\text{kW}$$

So, exergy destruction in the expansion valve is 0.433 kilowatt, exergy destruction in the compressor is 0.842 kilowatt. Now if you actually quantify wc is already calculated 3.36

kilowatt and $\frac{X_C}{\dot{w}_C}$ it is roughly about 0.25 and $\frac{X_E}{\dot{w}_C}$ is roughly about 0.13. So, 13%of exergy is lost in the expansion valve and 25% of exergy is lost in the compressors.

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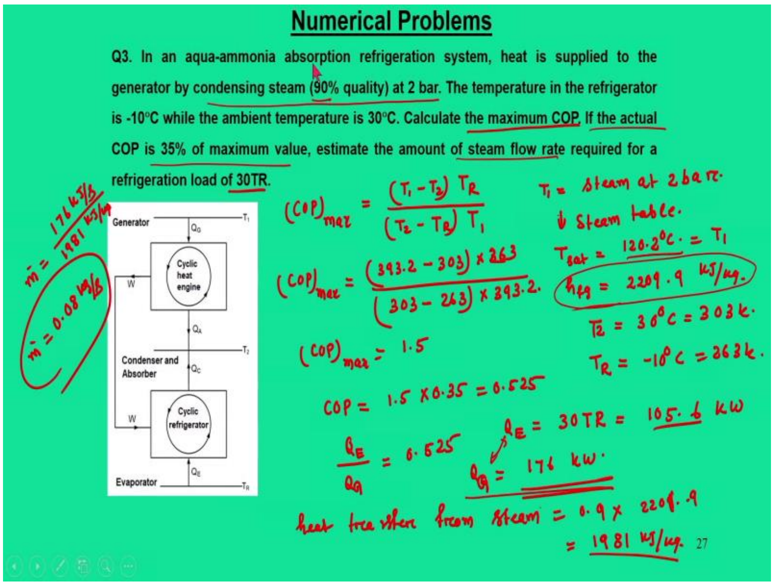

Numerical Problems

Q3. In an aqua-ammonia absorption refrigeration system, heat is supplied to the generator by condensing steam (90% quality) at 2 bar. The temperature in the refrigerator is -10°C while the ambient temperature is 30°C. Calculate the maximum COP. If the actual COP is 35% of maximum value, estimate the amount of steam flow rate required for a refrigeration load of 30TR.

$$(COP)_{max} = \frac{(T_1 - T_2)\,T_R}{(T_2 - T_R)\,T_1}$$

T_1 = steam at 2 bar.

↓ Steam table.

$T_{sat} = 120.2°C = T_1$

$h_{fg} = 2209.9$ kJ/kg.

$$(COP)_{max} = \frac{(393.2 - 303) \times 263}{(303 - 263) \times 393.2}$$

$T_2 = 30°C = 303$ k.

$T_R = -10°C = 263$ k.

$(COP)_{max} = 1.5$

$COP = 1.5 \times 0.35 = 0.525$

$\frac{Q_E}{Q_G} = 0.525$

$Q_E = 30\,TR = 105.6$ kW

$Q_G = 176$ kW.

heat transfer from steam $= 0.9 \times 2209.9$

$= 1981$ kJ/kg.

$\dot{m} = \frac{176 \text{ kJ/s}}{1981 \text{ kJ/kg}}$

$\dot{m} = 0.08$ kg/s

Now I will switch over to another problem which we discussed in this particular class it is a aqua ammonia vapour absorption refrigeration systems, in which heat is supplied to the generator by a condensing stream with 90 percent quality at 2 bar. So, the temperature in the refrigerator is -10°C while ambient temperature is 30°C. We have to calculate maximum COP and if the actual COP is 35 percent of the maximum value, we have to estimate the amount of steam flow rate required for refrigeration load of 30 TR.

So, for example, you have to recall this particular diagram in which COP of the system can be model as a cyclic heat engine and cyclic refrigerator and for which we have already derived COP max.

$$(\mathrm{COP})_{\max}=\left(\frac{T_1-T_2}{T_1}\right)\left(\frac{T_R}{T_2-T_R}\right)$$

T_1= steam at 2 bar; From steam table: $T_{sat}=120.2°C=T_1$

$h_{fg}=2209.9\mathrm{kJ/kg};\ \mathrm{T}_2=30°C=303K;\mathrm{T}_R=-10°C=263K$

$$\Rightarrow(\mathrm{COP})_{\max}=1.5$$

$$\mathrm{COP}=1.5\times0.35=0.525$$

$$\Rightarrow\frac{Q_E}{Q_G}=0.525;Q_E=30\mathrm{TR}{=}105.6\mathrm{kW}\Rightarrow Q_G=176\mathrm{kW}$$

$$\text{Heat transfer from steam}=0.9h_{fg}=0.9\times2201.9=1981\mathrm{kJ/kg}$$

$$\dot{m}=\frac{176\mathrm{kJ/s}}{1981\mathrm{kJ/kg}}=0.089\mathrm{kg/s}$$

This is the amount of steam that is required to for refrigeration load of 30 TR.

So, this is how you are going to solve these problems on vapour absorption systems, for this particular course only this kind of problems are normally referred, we are not going very deep into.

And here one more thing is that when you think about aqua ammonia absorption systems of course, we have to recall this steam table. So, steam table data is very vital to get temperatures in particular for the generator and that is what it is used here to calculate the saturated temperature for water which is at 2 bar.

Thank you for your attention.