Applied Thermodynamics for Engineers

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Lecture – 28
Vapour Absorption Refrigeration Cycle

Hello friends, so this is the last lecture on the series of lectures on refrigeration cycles in our module number 9. In the previous two lectures we have been introduced to the compression refrigeration system. Particularly we have discussed about the vapour compression refrigeration cycle where we have evaporator where the refrigerant picks up the energy from the space which we want to be refrigerated and it gets converted to vapour, generally saturated vapour or in certain occasions can be superheated vapour.

And subsequently compress the air in the compressor so that its pressure and subsequently the temperature level rises, so that its temperature becomes higher than the surrounding temperature and accordingly we can reject the heat to the surrounding the condenser. We have discussed about the different variations of the vapour compression cycle in the previous lecture like the use of multi-staging, multiple compressors, the application where we are looking for extremely low temperature refrigeration and also, we have discussed about the gas refrigeration cycles. So there is no phase-change where it is just a reverse Brayton cycle, where the working medium remains as gas throughout and therefore instead of having any evaporator and condenser, we basically have two heat exchangers. One where the working fluid, the gas, picks the heat from the refrigerator and other space and other where it rejects the heat from the surroundings. Just the way we analyse the Brayton cycle, quite similarly we can analyse that gas refrigeration cycle as well. And I have told and mention the name of the Stirling future cycle, which is the reverse Starling cycle, if you are interested you can search in the books for the same as well.

Now today I shall be talking about another kind of refrigeration system, which is again vapour-based, but not a vapour compression one because there is no compressor at all. The biggest issue in vapour compression refrigeration system is, though I have to mention that is the most popular one, about 85-90% of the application of refrigeration of cooling that you can find that generally belongs to this reverse compression category, or in certain conditions like the aircraft applications etc. the gas compression-based refrigeration systems. However, the new that I am going to talk about where there is no compressor, but it is still vapour-based that is I should not say that the new technology, because the technology is also quite old but because of certain shortcomings of this it has not been achieved that much level of commercialization, but over last few years, particularly with the focus of global warming and other environmental effect caused by synthetic refrigerants etc, this one which is actually a green technology. This is coming up in which time particularly for large-scale applications. When we are looking for very large-scale refrigeration like a centralized air conditioning for a shopping mall or centralized air conditioning for big theatre, there this kind of system is quite profitable.

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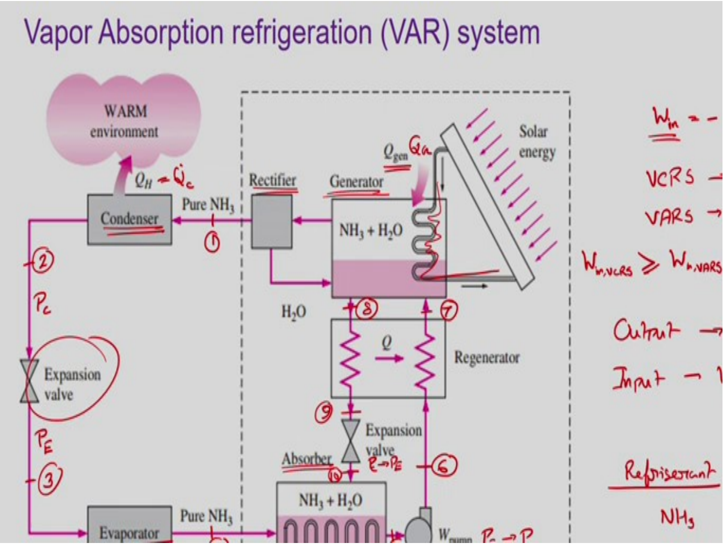

Vapor Absorption refrigeration (VAR) system

So that particular system is known as vapour absorption refrigeration system for VAR system. Like the vapour compression refrigeration VCR this is VAR, vapour absorption refrigeration system. And as the name suggest here is your compressing the vapour, we are actually going to absorb the vapour. Here the compressor parts like in classical vapour compression refrigeration system you have four components. We have one evaporator where we have to pick up the energy of the refrigerant space. We have a condenser where the vapour is going to reject the heat to the surrounding. We have an expansion valve where the pressure of the vapour is going to drop from the condenser pressure level back to the evaporated pressure level and subsequently facilitate the change in temperature or lowering of temperature. But there is a fourth components to the compressor which is the work consuming component. In vapour absorption system also the other three components, that is evaporative condenser and expansion valve remains as it is.

However, the condenser is replaced by a combination of several other components. The arrangement is such that we use a second material the refrigerant of course will be there plus we are going to introduce and absorbent or an absorber and the refrigerant is going to get absorbed in the observer and subsequently the operation whatever we get from the compressor, that we are going to achieve by some other means.

Just think what is the function of having a compressor? The function of having a compressor used to compress the vapour of course, but why you want to compress a vapour? Because we want to raise the pressure of the vapour from the evaporator pressure level to the condenser pressure level, such that the saturation temperature at condenser pressure level is higher than the surrounding temperature. So, the ultimate aim of having the compressor is to gain this rise in pressure or to change the pressure from evaporator level to the condenser level.

And any option of achieving that is welcome and particularly if we can device something where the work input requirement for the compressor can be substantially reduce that is definitely very much desirable, and that is why we have this. Ammonia and water written here is only to focus that much on this but, on this combination because I want to talk more on this. But here just think there is a big rectangle covered by the dotted line. What components we have outside the rectangle? We have the condenser; we have the expansion valve and we have the evaporator. In the evaporator your refrigerant is picking of the heat that is Q_L or as per our terminology $Q_{dot\ E}$ from the cold refrigerated space. In the condenser it is rejecting $Q_{dot\ C}$ as per our terminology to the surrounding. In the expansion valve pressure is dropping from the condenser pressure level to the evaporator pressure level on this side. On the up side of the expansion valve, pressure is the condenser pressure level and on the downstream it is the evaporator pressure level.

So, these three components are doing their normal operation only. But the compressor which should had on the exit of the evaporator and entry of the condenser that is replaced by this big rectangle. Now what we have in the rectangle? Just look at it component wise starting from the evaporator exit. Here the refrigerant that we are using is ammonia, one of the natural refrigerants. One big advantage of vapour absorption system is that we can easily user natural refrigerants like ammonia or water vapour.

Now this ammonia vapour which is coming out of the evaporator normally saturated vapour or maybe slightly superheated vapour. Now that we are taking two big chambers known as the absorber. And in this chamber, we have water or maybe a low concentration of solution of ammonia, aqueous solution of ammonia, that is ammonia water mixture. Once ammonia comes in contact this mixture, it also gets absorbed in this and during this process usually have heat rejected to the surroundings. Therefore, we need to have some kind of cooling jacket so that we can maintain a low temperature in this and also, we can continuously remove the heat that is generated that is gaseous ammonia get absorbed in this mixture.

So, this component is called absorber because the ammonia is absorbed in water or maybe in an aqueous solution of ammonia to produce another solution with higher concentration. So, initial solution that we had that is low in ammonia concentration and after this ammonia coming from the evaporator that gets absorbed, we get another solution with which is having higher concentration. Let us give some name to the states, let us say this is a state number 1, 2 at the exit of condenser, 3 entering the evaporator, then 4 coming out of the evaporator. So, we are calling this status 5 where we are having an aqueous solution is quite high concentration in ammonia.

Now we are having the pump, and in this pump, we are causing the change from this evaporator pressure level to the condenser pressure level, just what we did in the compressor. Now in the compressor what is our working medium? Our working medium is a vapour. So, we know that this being a steady flow kind of device or an open system, the work input requirement W_{in} is generally represented as:

$$W_{in} = -\int_{P_E}^{P_C} v dP$$

where

P_E is the evaporator pressure level

P_C is the condenser pressure level

In this, two pressures are same, that is, P_E and P_C remains same. Then the magnitude of this input work requirement definitely depends upon the specific volume of the working medium. Now in vapour compression system, what is your working medium? You are working with vapour, saturated vapour or superheated vapour. So, its specific volume maybe v_g for notation, if it is a saturated vapour. When you are talking about the vapour absorption refrigeration system what you are working with? We are working with an aqueous solution of ammonia, in this particular case. So, we are working with some liquid. And if we term this as liquid, is an aqueous solution of ammonia in this case. Now out of these two specific volumes, which one is lower? Definitely the v_{liquid} is much lower than v_g, it can always be negligible compared to this. Then which one will require less input? So, definitely the work input requirement for the VCRS is significantly greater compared to the work input requirement for the VARS. Or you can see the other way working input requirement for the VARS where we actually found for the solution pump that is significantly lower.

So, the mechanical input requirement to the cycle is much lower. Then what else is happening? The solution which has been pumped to a higher pressure to the condenser pressure now goes through another component which is known as a generator, another compartment which is generator. In between we may have regenerator where we are using some solar heat to rise the temperature of this, so the status 6 coming out of the pump and then after the regeneration we have a state 7, for the moment you can ignore the regenerator.

So, it is entering the generator, in the generator we are adding heat where the heat can be coming from waste energy source maybe solar energy or whatever the source of energy, but something which is capable of rising the temperature of the solution to something around 100 120 or 140 ^{0}C not more than 180 ^{0}C. So, we do not need to go to very high temperature, we need some source of energy which is able to rise the temperature of this aqueous solution of ammonia to that level.

And generally, any waste energy sources or maybe solar energy or sometimes geothermal energy, just may be the exhaust gas coming out of some automobile vehicles that have sufficient amount of energy to raise to this temperature. Like in this diagram is shown in the form of a solar flat plate where solar energy is collected. Where the water is absorbing the solar energy and that is circulating through the tubes that are shown here. It is passing through these tubes and as this heating jacket is passing through the solution it is adding heat to this. So this Q_{gen} or let us write as Q_G, this amount of heat is being added to the generator.

And as heat is being added, then ammonia will get separated from this, will get liberated from the mixture and the gaseous ammonia will come back and that is going to go back to the condenser for this. Generally, ammonia and water vapour both are quite evaporative in nature. And therefore, we need this rectifier so that we can separate water vapour and send the water vapour back to the generator and only pure ammonia is allowed to go the condenser.

So, ammonia as got separated and then what we have left in the generator? On this line state number 8 what we have left? Ideally it should be only water vapour truly speaking it is not water vapour, because it is a low concentration aqueous solution of ammonia, that is generated much higher temperatures. So, we have a regenerator it gets cooled to get converted to state 9 and while it is getting cooled, it adds energy to the other stream that was coming, the stream is higher concentration. Then you have higher expansion valve where the pressure again falls from this condenser pressure level back to the evaporator pressure level.

And finally, back to your observer, which state number 10 where this low concentration solution is coming and getting mixed with pure ammonia coming from the evaporator, again to form that high concentration solution. So, what are the inputs that you are giving? Your output remains the same. Your output in this case is this Q_E or $Q_{dot\ E}$? What is your input to the system? Definitely your input is the pump work that you are giving or the power that you supplied to the solution pump plus there is another input.

We are also giving this $Q_{dot\ G}$, the thermal energy that you are adding to the generator. So it is more like a thermally driven system instead of having mechanical energy, we are definitely giving mechanical energy as the input in the form pump work but that is an extremely small compared to the work required for the compressor. And that is why it is more thermally driven system or we call it a thermal compression that is happening to the working medium.

So, ammonia water mixture is a very common kind of working fluid combination that we use here. We are using two fluids; one is the refrigerant which is ammonia and other is the absorber or absorbent which is water vapour in this case. There can several such combinations, like you can also very popular combination of water is used as refrigerant and we use Lithium Bromide as the as absorbent, that is also quite common or popular solution. And similarly you can have a few other mixtures as well.

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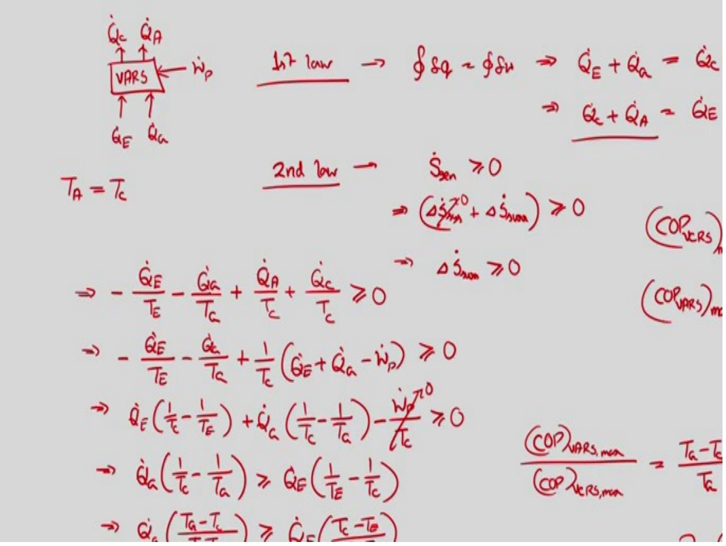

1st law → $\oint \delta q = \oint \delta w \Rightarrow \dot{Q}_E + \dot{Q}_G = \dot{Q}_C$

$\Rightarrow \dot{Q}_C + \dot{Q}_A = \dot{Q}_E$

$T_A = T_C$

2nd law → $\dot{S}_{gen} \geq 0$

$\Rightarrow \left(\cancel{\Delta \dot{S}_{sys}}^{0} + \Delta \dot{S}_{surr}\right) \geq 0$

$\Rightarrow \Delta \dot{S}_{surr} \geq 0$

(COP_{VCRS})

$(COP_{VARS})_{m}$

$$\Rightarrow -\frac{\dot{Q}_E}{T_E} - \frac{\dot{Q}_G}{T_G} + \frac{\dot{Q}_A}{T_C} + \frac{\dot{Q}_C}{T_C} \geq 0$$

$$\Rightarrow -\frac{\dot{Q}_E}{T_E} - \frac{\dot{Q}_G}{T_G} + \frac{1}{T_C}\left(\dot{Q}_E + \dot{Q}_G - \dot{W}_P\right) \geq 0$$

$$\Rightarrow \dot{Q}_E\left(\frac{1}{T_C} - \frac{1}{T_E}\right) + \dot{Q}_G\left(\frac{1}{T_C} - \frac{1}{T_G}\right) - \cancel{\frac{\dot{W}_P}{T_C}}^{0} \geq 0$$

$$\Rightarrow \dot{Q}_G\left(\frac{1}{T_C} - \frac{1}{T_G}\right) \geq \dot{Q}_E\left(\frac{1}{T_E} - \frac{1}{T_C}\right)$$

$$\frac{(COP)_{VARS,max}}{(COP)_{VCRS,max}} = \frac{T_G - T_C}{T_G}$$

So, if you quickly want to perform mathematical analysis or thermodynamic analysis of the system, if you take this is your vapour absorption refrigeration system, then what are the amount of energy that you are giving input to this? Of course, Q_E or Q *dot E* is input to this and also Q *dot G* is the thermal energy that is given as input to the generator. From here heat is being rejected in the condenser and also heat is being rejected in the absorber plus we are having the pump work as the input.

So, if you apply first law of thermodynamics on this, then as this device is working over a cycle. So, you know that:

$$\oint \delta q = \oint \delta W$$

correspondingly in written in red form. We can write the total amount of energy given as input that is:

$$\dot{Q}_E + \dot{Q}_G = \dot{Q}_C + \dot{Q}_A + \dot{W}_P$$

the total amount of energy that is giving as a input or we can write this as:

$$\dot{Q}_C + \dot{Q}_A == \dot{Q}_E + \dot{Q}_G - \dot{W}_P$$

So, this is the first law form.

Now let us look at second form from second law perspective. From second law point of view we know that, total entropy generation over the cycle has to be greater than equal to zero. In the ideal case of reversible process, it is equal to zero otherwise entropy is always getting generated.

$$S_{gen} \geq 0$$

That is the sum of the total change in entropy for the system and change in entropy for the surrounding this combination has to be greater than or equal to zero.

$$\Delta S_{sys} + \Delta S_{surr} \geq 0$$

Now here the system is working over cycle and we know that for any cyclic process the change in entropy is equal to zero.

Because the system is always keeps on coming back to the same so,

$$\Delta S_{sys} = 0$$

So for this process to be realistic the total change in entropy for the surrounding has to be greater equal to zero, i.e.,

$$\Delta S_{surr} \geq 0$$

If it is a reversible process the surrounding will be restored and so the change in entropy for the surrounding also will be equal to zero, but for reversible process entropy of the surrounding will be increasing.

So now let us look at the heat transfer that is happening. From the surrounding point of view what is the amount of energy the surrounding is losing? Before going to that, let us give some names to this. Let us say the evaporator is working at a temperature level of T_E, condenser at temperature T_C, generator is working temperature of T_G and the absorption is working and temperature of T_A. So, how much energy the surrounding is losing? $Q_{dot\ E}$ and $Q_{dot\ G}$ are getting added to the system that is coming out of the surrounding.

So, it is losing entropy in that form and we are talking about the rate at quantities. So we can write this is as:

$$-\frac{\dot{Q}_E}{T_E} - \frac{\dot{Q}_G}{T_G} + \frac{\dot{Q}_A}{T_A} + \frac{\dot{Q}_A}{T_A} \geq 0$$

this combination has to be greater equal to zero because both $Q_{dot\ A}$ and $Q_{dot\ C}$ are going to the surroundings. Now for most of the practical situations we generally have T_A and T_C to be equal to each other. In all practical systems there we have the same situations.

So, we replace this T_A with T_C. Now we combine the first law with this:

$$-\frac{\dot{Q}_E}{T_E}-\frac{\dot{Q}_G}{T_G}+\frac{1}{T_C}(\dot{Q}_E+\dot{Q}_G-\dot{W}_P)\geq 0$$

or combining *Q* *dot E* together:

$$\dot{Q}_E\left(\frac{1}{T_C}-\frac{1}{T_E}\right)+\dot{Q}_G\left(\frac{1}{T_C}-\frac{1}{T_G}\right)-\frac{\dot{W}_P}{T_C})\geq 0$$

Now the pump work or the magnitude of this is very small compared to all the heat interaction, the *Q* *dot E* and *Q* *dot G* particularly, so let us remove this work term from this.

So, if you now reorient the terms, we can write that:

$$\dot{Q}_G\left(\frac{1}{T_C}-\frac{1}{T_G}\right)\geq\dot{Q}_E\left(\frac{1}{T_E}-\frac{1}{T_C}\right)$$

or

$$\dot{Q}_G\left(\frac{T_G-T_C}{T_C T_G}\right)\geq\dot{Q}_E\left(\frac{T_C-T_E}{T_E T_C}\right)$$

and finally removing T_C from here if we write that if you reorient the terms once more then we can write that this:

$$\left(\frac{T_G-T_C}{T_G}\right)\left(\frac{T_E}{T_C-T_E}\right)\geq\frac{\dot{Q}_E}{\dot{Q}_G}$$

But why are we doing all this derivation? Because if you think about a compression-based cycle vapour compression cycle working between the same temperature limits of T_E and T_C, then what would be its *COP*? *COP* of equivalent vapour compression cycle, the maximum value should be equal to the corresponding Carnot cycle *COP*, which is nothing but,

$$(COP_{VCRS})_{max}=\frac{T_E}{T_C-T_E}$$

so, this the maximum *COP* of an equivalent VCRS system can have and the VARS that you are talking about. This cycle is completely reversible then it is going to have the maximum *COP*.

And if the cycle is completely reversible then the rate of entropy generation also will be equal to 0. In that case what will be the *COP*? So, *COP* for this VARS_{max} will be the normal definition of COP for this case is the refrigeration effect divided by total energy input that you are giving which is:

$$(COP_{VARS})_{max}=\frac{\dot{Q}_E}{\dot{Q}_G+\dot{W}_P}$$

Again, the work component is very small let us remove that one so it is:

$$= \frac{\dot{Q}_E}{\dot{Q}_G}$$

that is the *COP* always and when we are talking the maximum *COP*, then delta surrounding will be equal to 0. And then picking up from there we can say that this will be equal to:

$$= \left(\frac{T_G - T_C}{T_G}\right)\left(\frac{T_E}{T_C - T_E}\right)$$

So,

$$\frac{(COP_{VARS})_{max}}{(COP_{VCRS})_{max}} = \left(\frac{T_G - T_C}{T_G}\right) < 1$$

and therefore, *COP* for the *VARS* is always less than 1 because T_G always operating temperature much higher than the condenser evaporator temperature and therefore COP for the absorption system always will be much lower compared to the equivalent compression system.

And that is a primary reason of the absorption system despite being the very classical design is not the most popular one. It is not the most popular one simply because of its low *COP*. If we take a quick example, let us take a situation where your T_G = 100 ^{0}C which is something like which is quite practical value and this is 373 K. Let us say T_C is atmospheric temperature, which is 27 ^{0}C so, 300 K and take we take a T_E of let us take 0 ^{0}C so which is just 27 K. So, what will be the *COP* for corresponding VCRS the maximum *COP*, so,

$$(COP_{VCRS})_{max} = \frac{T_E}{T_C - T_E}$$

so,

$$(COP_{VCRS})_{max} = \frac{273}{27} \approx 10$$

Similarly,

$$(COP_{VARS})_{max} \approx 2$$

it is only one fifth and practical the COP of VARS system is the maximum one, is always of the order of 1 or maybe one less than 1. So the absorption system despite being very less work input requirement is not something that is going to be very high *COP*. Only if you have no source available of very large quantity of thermal energy, then only the absorption system becomes very productive because then we can use the waste energy and run the system almost without any mechanical energy input.

In that case only there was a system is economic and that is why we generally use absorption system for large-scale application with some source of low-cost, large quantity of wastage. Something or maybe just renewable energy sources like solar energy.

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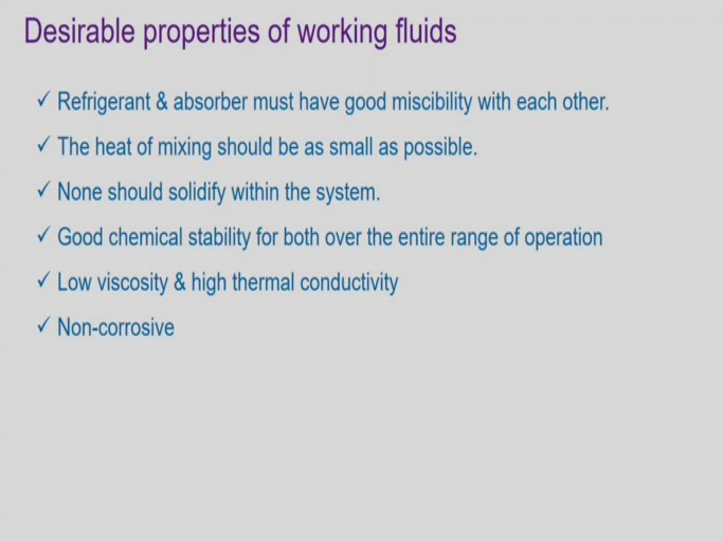

Desirable properties of working fluids

- ✓ Refrigerant & absorber must have good miscibility with each other.
- ✓ The heat of mixing should be as small as possible.
- ✓ None should solidify within the system.
- ✓ Good chemical stability for both over the entire range of operation
- ✓ Low viscosity & high thermal conductivity
- ✓ Non-corrosive

Some of the desirable properties that we need to for the work input that we use, the refrigerant or the absorber combination must have good miscibility with each other over the range of working conditions, nowhere it should get separated from each other. The heat of mixing should be as smallest possible so that the Q_A remains small then they should not solidify the system. That is one problem with water-based systems because the temperature falls below 0 ^{0}C then water becomes solid and that is why water-based systems like the water Lithium Bromide system is not used below 0 ^{0}C. That is why its application is restricted only above 0 ^{0}C, that is primary to air conditioning application. Whereas ammonia can we go to – 15 to– 20 ^{0}C, so ammonia-based system is more commonly used for large scale refrigeration. They should have good chemical stability of the entire range of operation, viscosity should be low so that there is a very small frictional losses pump work input must be less and also the thermal conductivity should be high to have a good heat transfer characteristic. And they should also be non corrosive to the metals that are being used.

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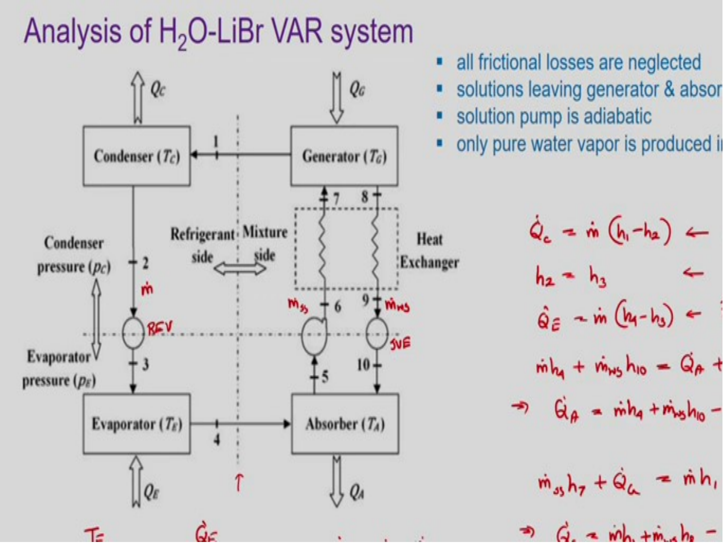

Analysis of H_2O-LiBr VAR system

- all frictional losses are neglected
- solutions leaving generator & absor
- solution pump is adiabatic
- only pure water vapor is produced i

$\dot{Q}_c = \dot{m}(h_1 - h_2) \leftarrow$

$h_2 = h_3 \leftarrow$

$\dot{Q}_E = \dot{m}(h_4 - h_3) \leftarrow$

$\dot{m}h_4 + \dot{m}_{ws}h_{10} = \dot{Q}_A +$

$\Rightarrow \dot{Q}_A = \dot{m}h_4 + \dot{m}_{ws}h_{10} -$

$\dot{m}_{ss}h_7 + \dot{Q}_G = \dot{m}h_1$

$\Rightarrow \dot{Q}_G = \dot{m}h_1 + \dot{m}_{ws}h_8 -$

If let us quickly analyse one water Lithium Bromide absorption system. The cycle is shown here; here you have the condenser, generator, evaporator and absorber. The temperature and corresponding heat interactions are given. Look at this dotted line, above this you have the condenser pressure below this you have the evaporator pressure. The solution pump is the one that is rising the pressure whereas we have two expansion valves one corresponding to the refrigerant other corresponding to the mixture where we are using the expansion valves to lower the pressure.

And also, this line separates the refrigerant and the mixtures. Let us assume that the refrigerant flow rate to be equal to ṁ. Now there are two mixtures so we commonly call one mixture to be strong solution, the one having larger fraction of refrigerant, other we call a weak solution. So, here out of the two lines which one is going to be having a higher concentration of the refrigerant, remember the refrigerant is water in this case.

The one going from absorber to generator is more water content. So, this one we are calling ṁ strong solution ($\dot{m}_{ss}$) for this on your calling ṁ weak solution ($\dot{m}_{ws}$). So, let us analyse it quickly, for that we are assuming all the frictional losses to be negligible. Solutions leaving generator and absorber are in equilibrium. That is an important assumption because that allows us to calculate the absorber and generator, the mixture qualities that are leaving the absorber and generator.

Solution pump is assumed to be the adiabatic and only pure water vapor is producing at the generator. With these assumptions, if we are quickly do the analysis starting from the condenser. So, we can write,

$$\dot{Q}_C = \dot{m}(h_1 - h_2)$$

and the whatever mass is entering in that is leaving and for the expansion valve. Let us call this one to be refrigerant side expansion valve and this one we are calling the solution side expansion valve, as there are two expansion valves.

So, this is for the condenser and for the refrigerant expansion valve we can easily write,

$$h_2 = h_3$$

This is for the refrigerant expansion valve then for the evaporator. We can write

$$\dot{Q}_E = \dot{m}(h_4 - h_3)$$

this is for the evaporator. Commonly we are aware about the temperature levels because T_E is something that is determined by our target application. T_C depends on the surrounding condition and T_C and T_E generally equal to each other.

And generator temperature that generally requires some optimisation but still it depends more on the temperature of the source that you are using. And $Q_{dot\ E}$ also has to be known because that is the refrigerant load that you are talking about. So, using this we can easily calculate the mass flow rate for the refrigerant that is flowing through this. Now coming to the absorber, in the absorber there are three lines.

So, total amount of energy that is entering and leaving this is:

$$\dot{m}h_4 + \dot{m}_{ws}h_{10} = \dot{Q}_A + \dot{m}_{ss}h_5$$

This is for the absorber. So, by rearranging the term we can write,

$$\dot{Q}_A = \dot{m}h_4 + \dot{m}_{ws}h_{10} - \dot{m}_{ss}h_5$$

Now if you perform a mass balance across the absorber then what we can write?

$$\dot{m}_{ws} + \dot{m} = \dot{m}_{ss}$$

And now what is the mass flow rate of weak solution? $\dot{m}_{ws}$ is actually that actually depends upon the concentration of the Lithium Bromide that you are using. The amount of Lithium Bromide that remains same. Is not it? The amount of Lithium Bromide that was there in the weak solution is the same Lithium Bromide remains strong solution as well. Lithium Bromide remains actually is a solid that just get dissolved in the water.

So, if x is the mass fraction of lithium Bromide that is there mass of lithium bromide in the weak solution can be written as:

$$x_{ws}\dot{m}_{ws}$$

and the mass of lithium bromide that is present in a strong solution will be:

$$x_{ss}\dot{m}_{ss}$$

where x again replaces the mass fraction and they are equated.

$$x_{ws}\dot{m}_{ws} = x_{ss}\dot{m}_{ss}$$

So, from there, we can easily calculate the mass of each of the solutions. And, how to calculate the x? The x depends upon the absorber temperature.

As we have assumed the solutions leaving the heat exchanger is to be in equilibrium. So, your x for the strong solution actually will be a function of the absorber temperature and x for the weak solution will be a function of the compartment that is leaving is a generator temperature. So, from where we can easily calculate the mass fractions or the mass fractions for the water and lithium bromide in the lines and accordingly, we can get the value of the energy content.

Similarly, if we perform the energy balance of the generator, then total energy that is coming in is:

$$\dot{m}_{ss}h_7 + \dot{Q}_G = \dot{m}h_1 + \dot{m}_{ws}h_8$$

On rearranging we can write,

$$\dot{Q}_G = \dot{m}h_1 + \dot{m}_{ws}h_8 - \dot{m}_{ss}h_7$$

this is for the generator.

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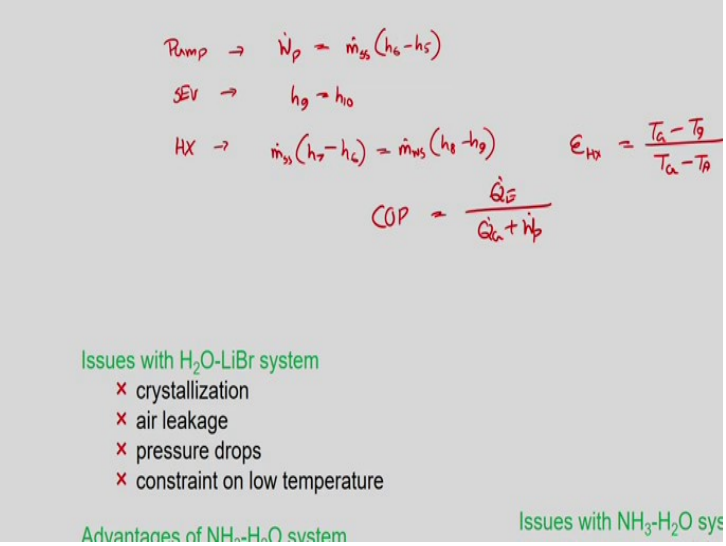

Pump → $\dot{W}_p = \dot{m}_{ss}(h_6 - h_5)$

SEV → $h_9 = h_{10}$

HX → $\dot{m}_{ss}(h_7 - h_6) = \dot{m}_{ws}(h_8 - h_9)$ $\epsilon_{HX} = \frac{T_G - T_9}{T_G - T_A}$

$COP = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_p}$

Issues with H_2O-LiBr system

- × crystallization
- × air leakage
- × pressure drops
- × constraint on low temperature

Advantages of NH_3-H_2O system

Issues with NH_3-H_2O sys

Also, we have the pump, so across the pump we can write the solution pump, the total pump work that you are giving as input is equal to:

$$\dot{W}_P = \dot{m}_{ss}(h_6 - h_5)$$

The solution side expansion valve it is again an isenthalpic valve because we are assuming it to adiabatic. It is,

$$h_9 = h_{10}$$

And finally, we have the heat exchanger. So, the amount of energy exchange across the heat exchanger that has to be equal, if it is an ideal heat exchanger.

So, across the heat exchanger, is the amount of energy gained by the strong solution is equal to the amount of energy lost by the solution, we can write it as:

$$HX \rightarrow \dot{m}_{ss}(h_7 - h_6) = \dot{m}_{ws}(h_8 - h_9)$$

Quite often we need to have one parameter which characterize the performance of the heat exchanger, which is given as the effectiveness for this heat exchanger. And its effectiveness is defined as the actual temperature change a weak solution attains is the maximum possible temperature change.

Now actual temperature change is happening from point 8 to point 9 that is, from generator temperature to point 9. So, the change is:

$$T_G - T_9$$

and what is the maximum possible change in temperature that is that can happen? That is,

$$T_G - T_A$$

Effectiveness of the heat exchanger is:

$$\varepsilon_{HX} = \frac{T_G - T_9}{T_G - T_A}$$

Quite often the effectiveness is provided by the manufacturer and as T_G and T_A are known to calculate T_9 from this and accordingly can perform the energy balance across the heat exchanger. And finally, we get the *COP* for this cycle as:

$$COP = \frac{\dot{Q}_E}{\dot{Q}_G + \dot{W}_P}$$

quite often the pump work can also be neglected from this. So, this is the way we can analyse an absorption refrigeration cycle. Now though we have talked about water Lithium Bromide (H_2O-LiBr) based system but that has certain issues to be talked about, like that can be crystallization problem. If the temperature particularly in the evaporator draws below certain limit as if pressure drop, then Lithium Bromide which actually a solid can get separated from the mixture and can be deposited in the form of crystals which can lead to severe blockage issues.

So, there are certain limits below which we cannot lower the temperature. Then, there can be air leakage problem the H_2O-LiBr system always works under atmospheric condition at both condenser and absorber and also in the evaporator. Therefore, it is possible that air can leak into the system and we have to be very careful to protect from this air leakage. To protect the system from the leakage though it cannot be avoided completely only by frequent maintenance maybe we can get rid of this eliminating effect.

There can pressure drop, as the solid solution of lithium bromide is flowing to this mixer side lines, there can be significant amount of pressure drop. So, additional work on the solution pump and also considering the low temperature as we are using water as a refrigerant so we cannot go very close to 0 ^{0}C and therefore its application is restricted only to air conditioning purpose.

And that point ammonia water mixture is very much advantages, because it can at be very low temperatures can easily go to −15 to - 20 ^{0}C, so very suitable for large scale definition. There is no air leakage because the pressure always remains above atmospheric. There is no crystallization problem because ammonia is a vapour only. But ammonia has his own issues like ammonia is toxic, that is one big problem and that is something that has restricted is use.

Particularly in big applications like cold storage etc. But again, I should mention that ammonia has the advantage that it is cheaper compared to that water Lithium Bromide solution. So, if you are looking for a very big application cold storage problem you can go for ammonia vapour despite having its own problems like: there is temperature in the condenser, like when ammonia vaporises in the generator and tries to go to the condenser there it will always be mixed with some water vapour.

So we need some rectifiers, some columns etc to remove the water from their mixture and allow only water only pure ammonia to go into the condenser. But still that process is never 100% fool proof. And that is why some water vapour is always likely to enter the condenser thereby severely affecting the performance. The temperature glide refers to that we may not be able to maintain that isothermal condition. There will be some temperature change during the condensation process and because of that heat transfer also will be interior.

Incomplete evaporation as I have just mentioned, some liquid may enter along with the water vapour when it passes through the expansion valve. It gets condensed to form some liquid water and evaporation process, while ammonia evaporates that water vapour may remain in the liquid form affecting evaporation process and again the heat transfer characteristics. And in order to remove all these things the system becomes much bulkier and costlier compared to H_2O-LiBr systems.

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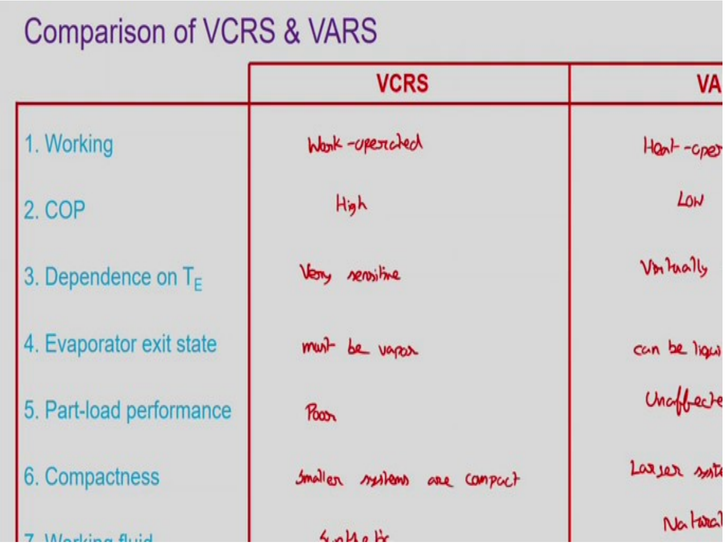

Comparison of VCRS & VARS

	VCRS	VA
1. Working	Work -operated	Heat -oper
2. COP	High	Low
3. Dependence on T_E	Very sensitive	Virtually
4. Evaporator exit state	must be vapor	can be liqu
5. Part-load performance	Poor	Unaffecte
6. Compactness	Smaller systems are compact	Larger syst
7. Working fluid	Synthetic	Natural

So, finally I would like to quickly compare the absorption and the compression-based systems. The first criterion is based on working. So, the compression-based systems are work operated because we are giving mechanical energy as the input, whereas this is heat operated. Though mechanical energy is required in the pump but primary input is in the form of heat in the generator. Then *COP* is definitely much higher *COP* you get compared to the absorption system.

Then dependence on T_E the performance is very sensitive. Any changes in the evaporation temperature the *COP* and other performance of compression refrigeration system gets affected very strongly. Whereas it is virtually independent of the evaporation temperature.

Then the evaporator exit state, the evaporator exit state as evaporator is going to pass through a compressor so must be vapour. We have to ensure that in the evaporator we have at least saturated vapour or preferably superheated vapour leaving and going to the compressor. But in the absorption system it is it is finally going to the absorber, so it can be liquid also. We always want this to be vapour but even if some liquid enters the absorber also, there is no issue. So, it is much safer from that point of view.

Part Load performance: part load performance refers to whenever we design a system design for the maximum load or full load. But quite often we have to run the system at part load condition. Like suppose, your domestic refrigerator has been designed so that it can simultaneously 50 kg of vegetables, but a particular instant of time just 1 kg and that is a case of running under part load condition. So, part load performance for VCRS is poor but this is a more or less unaffected over a wide range of load situation it performance is the same. And that is why it is very much preferred for large-scale application.

Like in shopping mall you may have designed air conditioning system assuming that there will be 500 persons inside simultaneously, but even if there are 50 persons, its performance may not be affected whereas for compression refrigeration system, the performance will be very much inferior.

Compactness; now for small capacity system, smaller systems are more compact. Whereas here the larger systems are more compact. Because here we have two additional compartments in the form of absorber and generator so we are talking about a smaller system quite bulky compare two equivalent in VCRS.

Working fluids, primarily we are using synthetic fluid here. Synthetic refrigerants, where is here we are using natural refrigerant in the form of ammonia, or water vapour.

And finally, in the economical point of view. this is generally economics and also available over large range of sizes but it is economic only when some wastage is available. If some sort of wastage is not available need is not economic at all. And that is why VARS is more preferred for large-scale application because of this.

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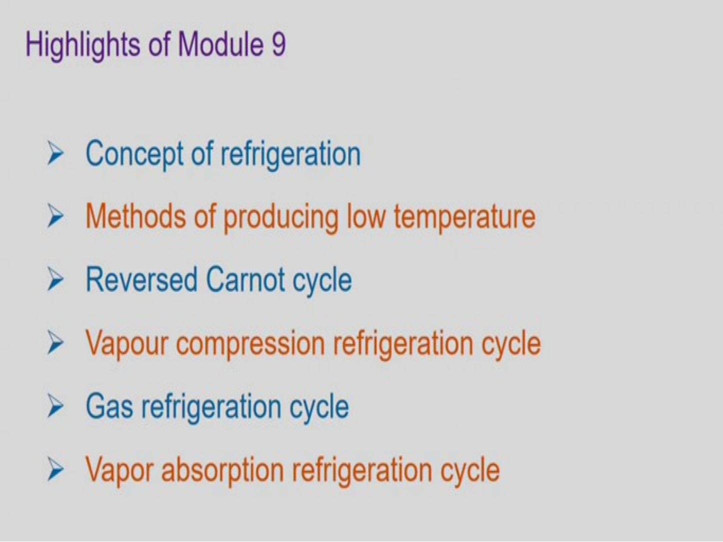

Highlights of Module 9

- Concept of refrigeration
- Methods of producing low temperature
- Reversed Carnot cycle
- Vapour compression refrigeration cycle
- Gas refrigeration cycle
- Vapor absorption refrigeration cycle

So, takes us to the end of this particular module where we have have talked about the concept of refrigeration, discussed about refrigerant applications, different methods of producing low temperature. Then we talked in detail about the compression resistance, starting with the reverse Carnot cycle and then the vapour compression refrigeration cycle, different variations of that, then we talked about the gas refrigeration cycle. And today I have talked about the absorption refrigeration cycle, its primary characteristics and also compared with the compression cycle.

So, we know that why do we prefer the compression based cycles for small scale applications or small to large scale application and absorption system more preferred for large-scale applications. So, that takes us to the end of lecture number 9, the assignments will be available soon. So, you please call the assignments and if you have any query, please write back to me. Refrigeration is a huge subject often taught as separate subjects and the final year subject, as a final year elective at master degree level and a very very interesting and practical subject as well.

So, if any of you have further interest, please refer to text books, there are several very good textbooks available on refrigeration. Thank you.