Refrigeration and Air-conditioning
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Lecture No. # 15
Vapour Absorption Refrigeration system

Vapour absorption refrigeration systems and I mentioned that the two most commonly used refrigerant absorbent pairs are those based on water-lithium bromide and ammonia water systems. In the present lecture I shall discuss absorption systems based on water and lithium bromide.

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Refrigeration
and
Air Conditioning

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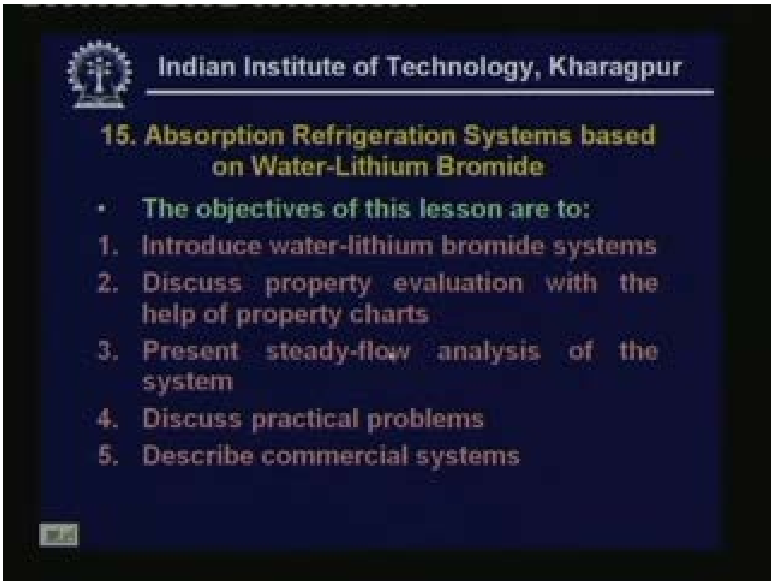

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15. Absorption Refrigeration Systems based on Water-Lithium Bromide

- The objectives of this lesson are to:

1. Introduce water-lithium bromide systems
2. Discuss property evaluation with the help of property charts
3. Present steady-flow analysis of the system
4. Discuss practical problems
5. Describe commercial systems

And the specific objectives of this particular lesson are introduce water-lithium bromide systems, discuss property evaluation with the help of property charts present steady-flow analysis of the system, discuss typical problems associated with the system and finally describe commercial systems and at the end of this lesson.

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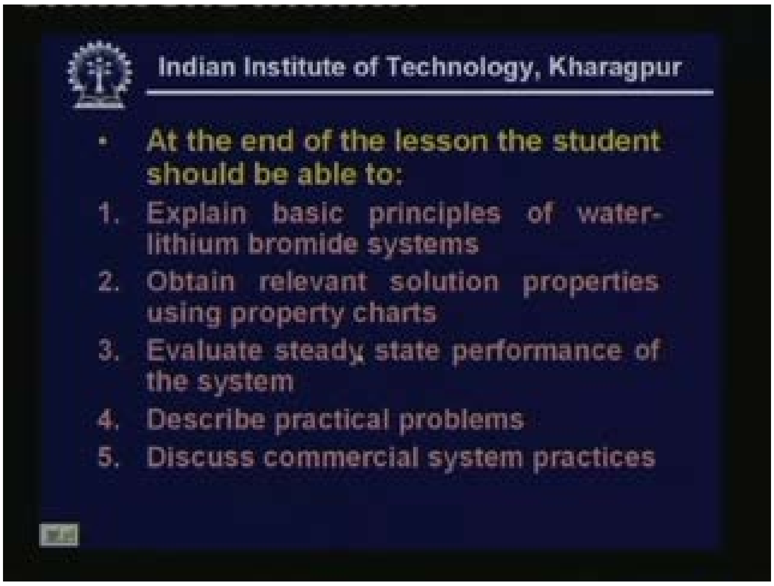

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- At the end of the lesson the student should be able to:

1. Explain basic principles of water-lithium bromide systems
2. Obtain relevant solution properties using property charts
3. Evaluate steady state performance of the system
4. Describe practical problems
5. Discuss commercial system practices

You should be able to explain basic principles of water-lithium bromide systems obtain relevant solution properties using property chart evaluate steady state performance of the system describe practical problems and discuss commercial system practices.

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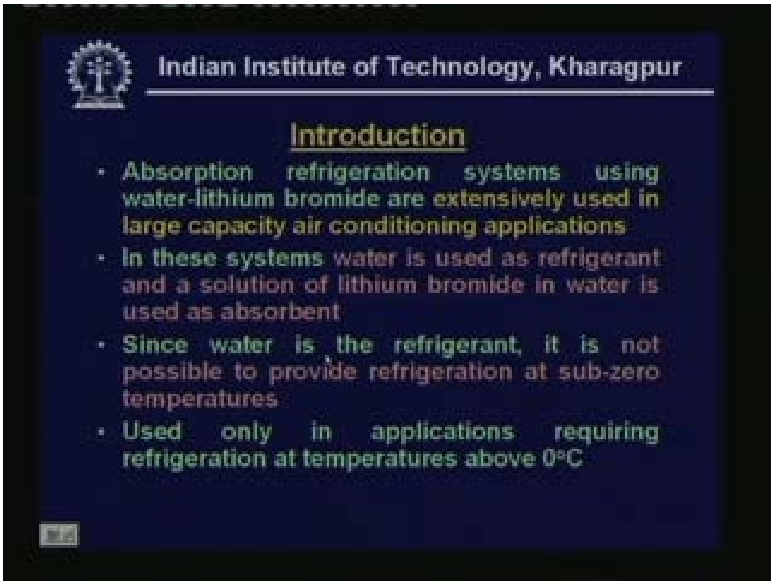

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Introduction

- Absorption refrigeration systems using water-lithium bromide are extensively used in large capacity air conditioning applications
- In these systems water is used as refrigerant and a solution of lithium bromide in water is used as absorbent
- Since water is the refrigerant, it is not possible to provide refrigeration at sub-zero temperatures
- Used only in applications requiring refrigeration at temperatures above 0°C

Let me give a brief introduction absorption refrigeration systems using water-lithium bromide are extensively used in large capacity air conditioning applications. In these systems water is used as refrigerant and a solution of lithium bromide in water is used as absorbent since water is the refrigerant. It is not possible to provide refrigeration at sub-zero temperatures as a result these systems are used in applications where the refrigeration temperature is above zero degree centigrade.

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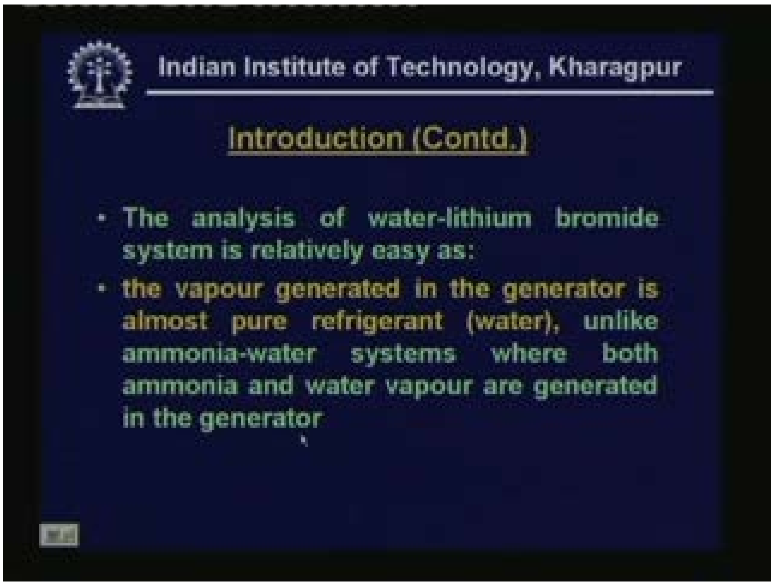

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Introduction (Contd.)

- The analysis of water-lithium bromide system is relatively easy as:
- the vapour generated in the generator is almost pure refrigerant (water), unlike ammonia-water systems where both ammonia and water vapour are generated in the generator

And the analysis of this particular system is relatively simpler compared to the ammonia water systems. Because the vapour is generated in the generator is almost pure refrigerant unlike an ammonia water system where both ammonia and water vapour are generated in the generator. In fact I mentioned in the last class that if the boiling point temperature difference between the refrigerant and absorbent is very high then only pure refrigerant is generated in the generator. This is a case with water -lithium bromide systems whereas in ammonia water system the boiling point temperature difference is not very high. As a result in the generator you find that the vapour consists of a mixture of both refrigerant ammonia and also the absorbent water whereas in lithium bromide systems only pure water is generated as a result you will find that the analysis becomes much simpler. That is the reason why we begin this discussion with water- lithium bromide systems.

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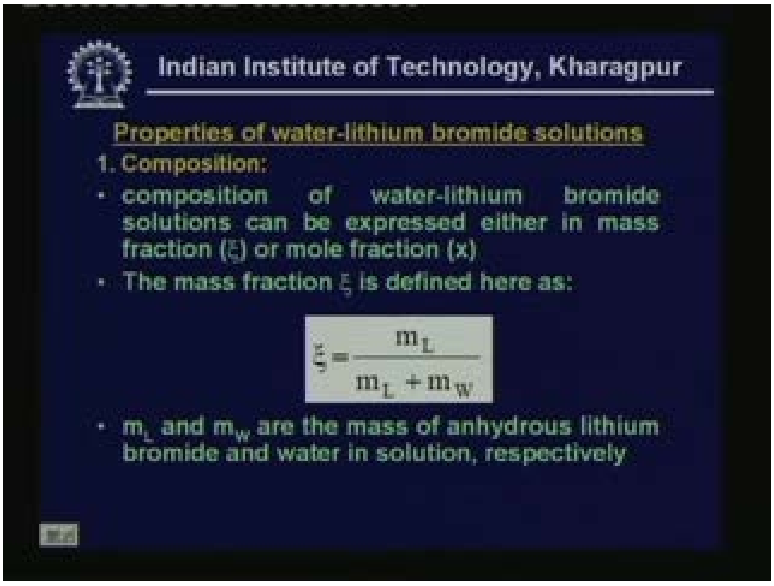

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Properties of water-lithium bromide solutions

1. Composition:

- composition of water-lithium bromide solutions can be expressed either in mass fraction (ξ) or mole fraction (x)
- The mass fraction ξ is defined here as:

$$\xi = \frac{m_L}{m_L + m_W}$$

- m_L and m_W are the mass of anhydrous lithium bromide and water in solution, respectively

First let us look at properties of water lithium bromide solutions the first important property is composition of water- lithium bromide solutions. As I mentioned in the last class can be expressed either in mass fraction zeta or mole fraction x and the mass fraction zeta is defined here as the ratio of mass of anhydrous lithium bromide to the total mass of the solution here mL is the mass of anhydrous lithium bromide.

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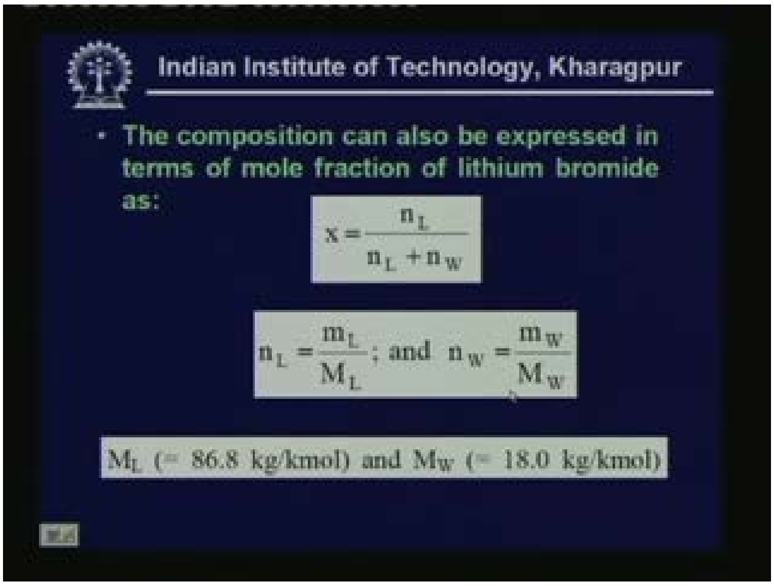

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- The composition can also be expressed in terms of mole fraction of lithium bromide as:

$$x = \frac{n_L}{n_L + n_W}$$

$$n_L = \frac{m_L}{M_L}; \text{ and } n_W = \frac{m_W}{M_W}$$

M_L (= 86.8 kg/kmol) and M_W (= 18.0 kg/kmol)

That means pure lithium bromide and mW is a mass of the water in the solution you can also express composition in terms of mole fraction. And as you as you know the mole fraction is defined as the number of moles of anhydrous lithium bromide to the total number of moles in the solution. And you can easily establish a relationship between the mole fraction masses and molecular weight like this the number of moles of lithium bromide is equal to mass of the lithium bromide divided by the molecular weight of anhydrous lithium bromide. And number of moles of water vapour water is equal to mass of the water divided by the molecular weight of water and for calculation purposes you can take the molecular weight of lithium bromide as eighty-six point eight kilogram per kilo mole and molecular weight of water as eighteen kilogram per kilo mole.

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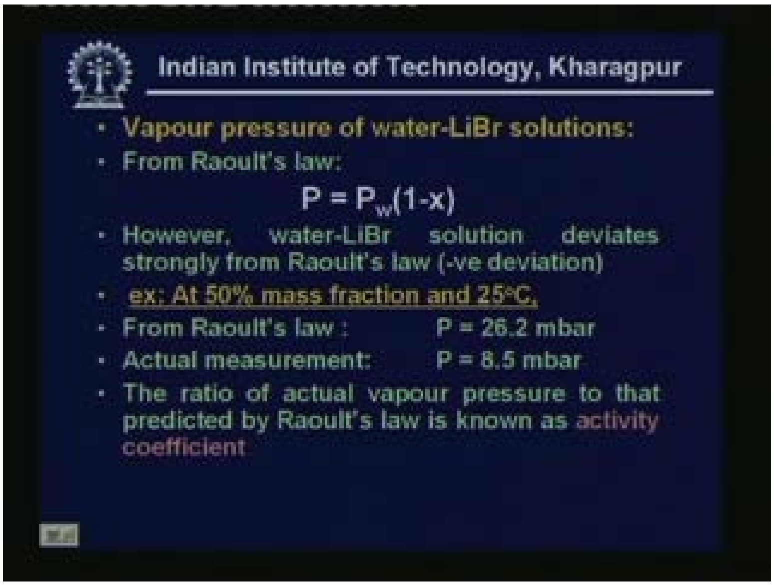

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- **Vapour pressure of water-LiBr solutions:**
- From Raoult's law:

$$P = P_w(1-x)$$

- However, water-LiBr solution deviates strongly from Raoult's law (-ve deviation)
- ex: At 50% mass fraction and 25°C,
- From Raoult's law : P = 26.2 mbar
- Actual measurement: P = 8.5 mbar
- The ratio of actual vapour pressure to that predicted by Raoult's law is known as activity coefficient

Now let us look at vapour pressure of water -lithium bromide solution this is required for your calculation purposes and I have discussed in the last class that one can use Raoult's law for ideal solutions. And from Raoult's law the vapour pressure of lithium bromide water solution is simply equal to Pw into one minus x where Pw is the saturated pressure of water at that particular temperature T and x is the mole fraction of lithium bromide. So one minus x is the mole fraction of water in the solution. So vapour pressure is simply equal to the product of saturated pressure into the mole fraction of water vapour. But we have seen that water -lithium bromide solution deviates strongly from Raoult's law and this deviation is a negative deviation. Let me give a small example at fifty percent mass fraction and twenty-five degree centigrade Raoult's law predicts that, the pressure vapour pressure is equal to twenty-six point two millibar.

But actual measurements of the solution show that the pressure is eight point five millibar. That means actual pressure is much less than the pressure predicted by the Raoult's law. This is because the negative deviation of this solution from ideal solution and the ratio of the actual vapour pressure to that predicted by Raoult’s law is known as activity coefficient. And for this particular mixture you can see that the activity coefficient is much less than one.

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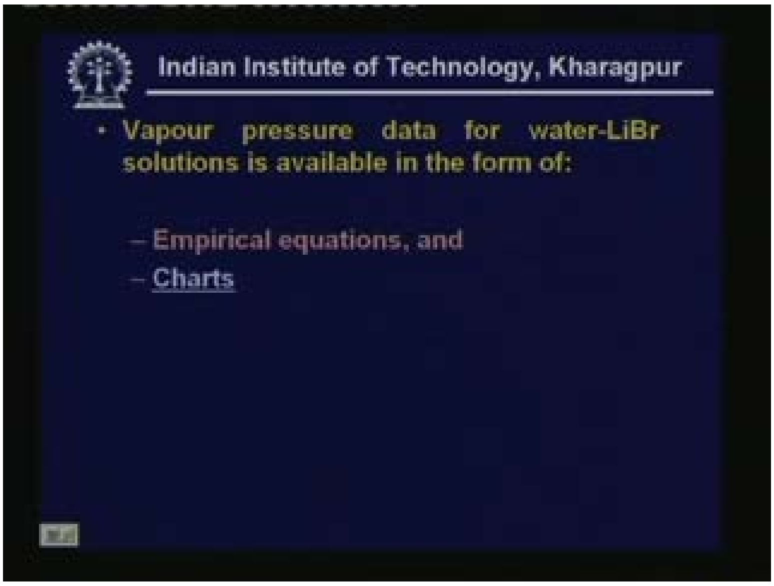

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- Vapour pressure data for water-LiBr solutions is available in the form of:
  - Empirical equations, and
  - Charts

The vapour pressure data for water -lithium bromide solution is available in the form of empirical equations and the it also available in the form of charts let me show a particulars of few charts.

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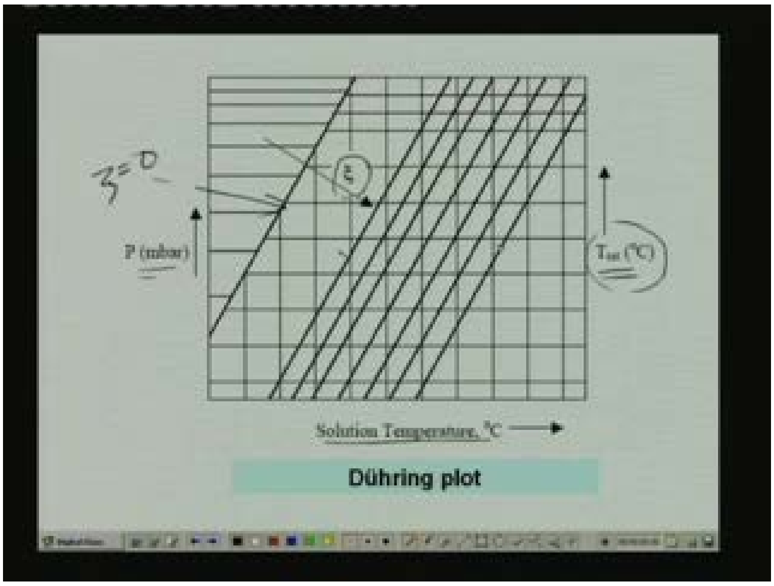

Dühring plot

What I have shown here is known as Duhring’s plot here you have solution temperature on x-axis and the saturated temperature of pure water on one y-axis and you also have on the left hand side of the y-axis the vapour pressure okay. And you can notice here that the x-axis that is the solution temperature is linear. Similarly the saturation temperature is also the scale is linear whereas the vapour pressure scale is non linear you can see that the difference is varying okay.

And you can also see on this the data is available for different constant concentration lines these are the constant concentration lines zeta is the concentration and the concentration increases in this direction and if you are assuming if you are taking this to be pure water then here zeta is zero and zeta increases in this direction. This particular plot is known as Duhring’s plot and this plot can be easily used for obtaining the vapour pressure data you can also use other charts for example I will let me show one more chart.

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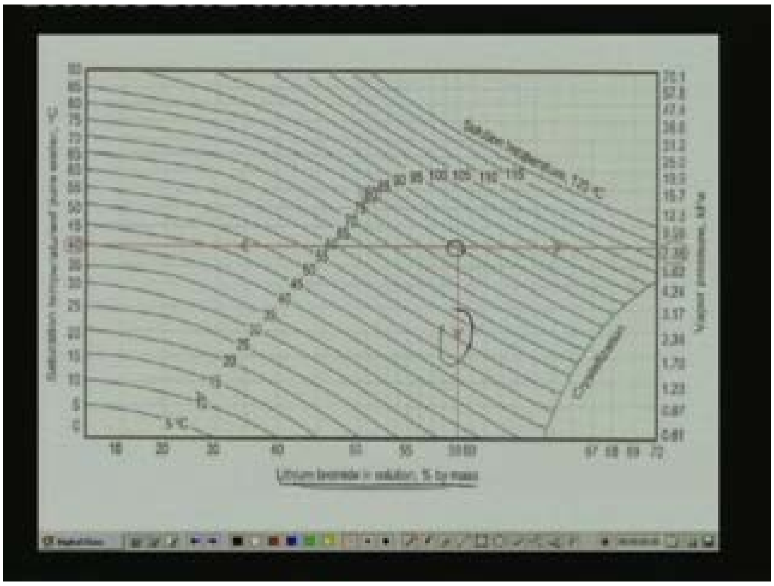

This is another chart where again the same information is available but here on the x-axis you have the concentration of lithium bromide in percentage okay this mass fraction of lithium bromide in percentage and on right hand side of the y-axis you have vapour pressure and on the left hand side of the y-axis you have the saturation temperature of pure water. And here the data is available for different constant solution temperature lines you can see that the five degree ten degree and all that are constants solution temperature lines and also indicated here is how to find out the data.

For example if you have a fifty-nine percent solution you can see that this is the line fifty-nine percent solution line. At fifty-nine percent concentration and eighty degree solution temperature you will find that the vapour pressure is equal to seven point three eight millibar and the corresponding saturation temperature of water is forty degree centigrade okay. Likewise you can find out for at other conditions what is the vapour pressure or at a given vapour pressure and solution temperature what is the lithium bromide percentage etcetera okay, these charts are very useful in actual calculations.

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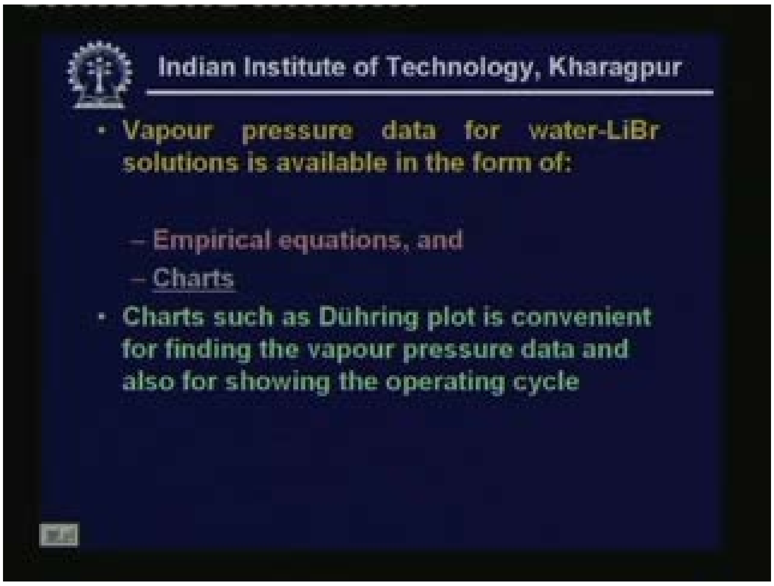

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- Vapour pressure data for water-LiBr solutions is available in the form of:
  - Empirical equations, and
  - Charts
- Charts such as Dühring plot is convenient for finding the vapour pressure data and also for showing the operating cycle

The charts such as Duhring plot is convenient for finding the vapour pressure data and it also convenient for showing the operating cycle normally the operating cycle can be shown on a Duhring plot various component exit and entry points can easily be represented on the Duhring plot.

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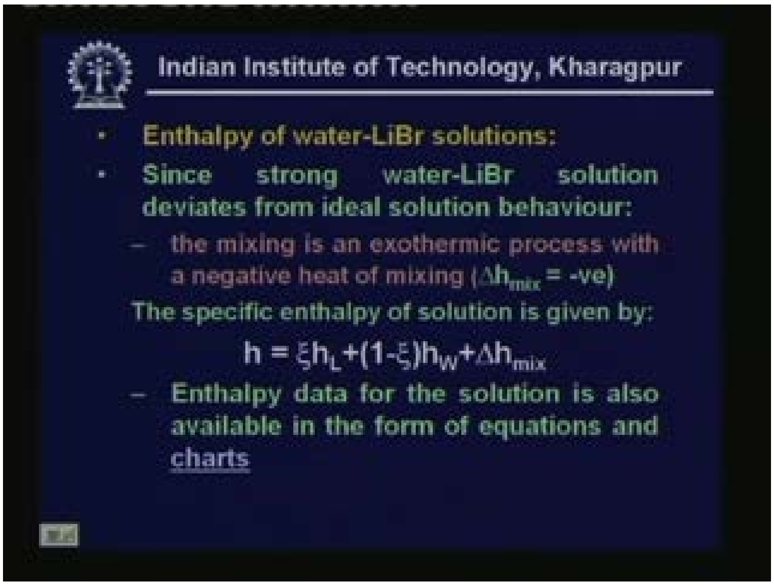

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- Enthalpy of water-LiBr solutions:
- Since strong water-LiBr solution deviates from ideal solution behaviour:
  - the mixing is an exothermic process with a negative heat of mixing (Δh_{mix} = -ve)

The specific enthalpy of solution is given by:

$$h = \xi h_L + (1-\xi) h_W + \Delta h_{mix}$$

- Enthalpy data for the solution is also available in the form of equations and charts

Now let us look at another important property that is the enthalpy of water -lithium bromide solution since strong water- lithium bromide solution deviates. From ideal solution behaviour

You will find that the enthalpy equation is given by the following formulas specific enthalpy h is equal to zeta into hL plus one minus zeta into hW plus delta h mix. Where zeta as you know is the mass fraction of lithium bromide anhydrous lithium bromide and hL is the specific enthalpy of anhydrous lithium bromide at that particular temperature and one minus zeta is the mass fraction of water and hW is the specific enthalpy of water at that particular temperature. And as you know delta h mix is a heat of mixing and in this particular case heat of mixing is negative. Because this particular solution deviates in a negative manner from the ideal solution okay.

That means the mixing process is a exothermic process. So when you mix water with lithium bromide solution heat is generated and enthalpy data just like your vapour pressure data enthalpy, data for solution is also available in the form of empirical equation and charts. Let me show a typical chart here.

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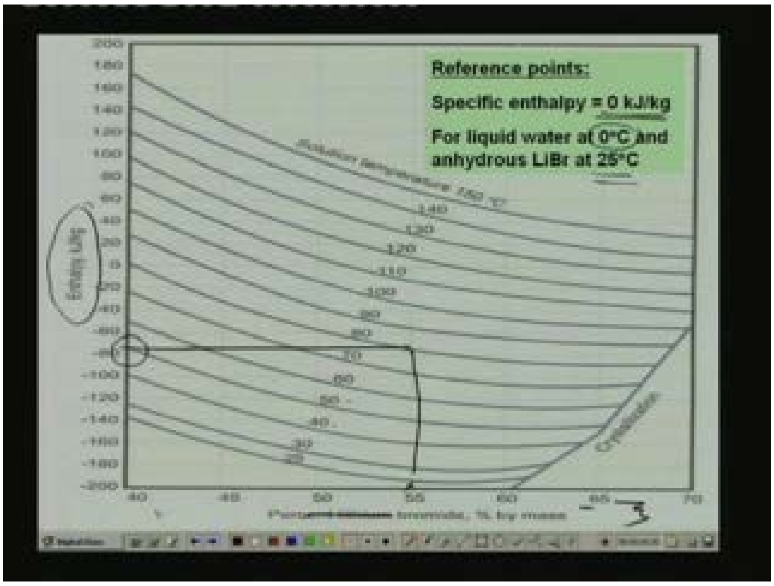

Reference points:

Specific enthalpy = 0 kJ/kg

For liquid water at 0°C and anhydrous LiBr at 25°C

Okay. So water this is a typical enthalpy concentration chart you can again see here that the x-axis is the concentration or zeta in percentage okay, on y-axis you have the enthalpy of the solution and this data is available for different solution temperature you can see that twenty-five thirty forty these are all the constant solution temperature lines. So using these charts again you can find out for example if you know. Let us say fifty-five is the concentration or fifty-five is the mass fraction of lithium bromide and let us say that your temperature is eighty degrees.

Okay. So you have to go like this and you can find out what is the corresponding enthalpy okay. Remember that specific enthalpy and internal energy and entropy do not have absolute values or at least the enthalpy and in a internal energy do not have absolute values. So we have to define some difference points so this particular charts is for the difference points like this the specific enthalpy is taken as zero kilo joule per kilogram. For liquid water at zero degree centigrade and for anhydrous lithium bromide at twenty-five degree centigrade that means taking the specific enthalpy of liquid water as zero kilo joule per kilogram at zero degrees and anhydrous lithium bromide zero kilogram kilo joule per kilogram at twenty-five degree centigrade this particular chart is drawn.

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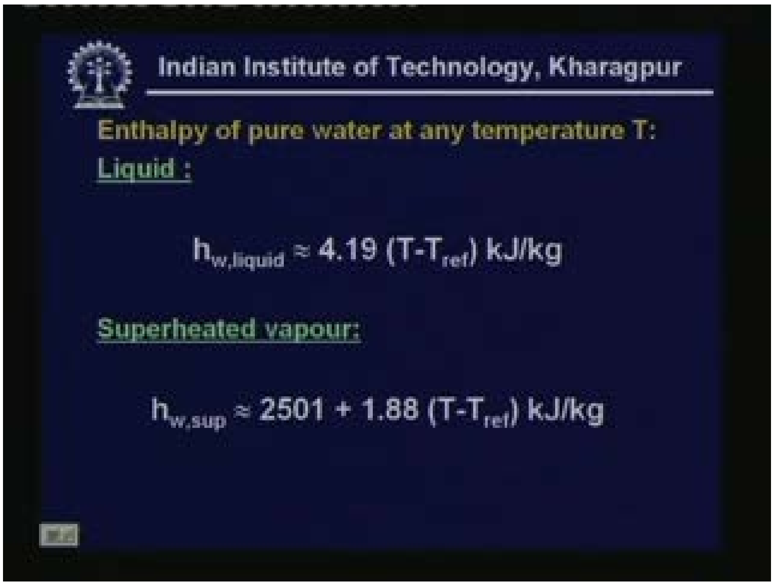

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Enthalpy of pure water at any temperature T:

Liquid :

$$h_{w,liquid} \approx 4.19\ (T-T_{ref})\ kJ/kg$$

Superheated vapour:

$$h_{w,sup} \approx 2501 + 1.88\ (T-T_{ref})\ kJ/kg$$

Now we also need in the calculations enthalpy of pure water both liquid water as well as vapour at any temperature T for liquid water. You can have an approximate equation the liquid water enthalpy is equal to four point one nine into T minus T reference where four point one nine is a specific heat of liquid water approximately approximate value and T is the temperature at which you are finding the enthalpy and T reference is the reference temperature and it happens to be zero degree centigrade here and the units here are kilo joule per kilogram. Because the specific heat is in kilo joule per kilogram. Similarly you can have a an approximate equation which is quite good for practical purposes for superheated vapour for superheated vapour the enthalpy is given as two thousand five hundred one plus one point eight eight into T minus T reference.

Again here T is a temperature at which you are trying to find the specific enthalpy of water vapour and T reference is the reference temperature. This particular equation is valid for water vapour at low pressures. And in fact if you look at this equation you will find that this two thousand five hundred one is nothing but the latent heat of vapourization for water at zero degree centigrade and one point eight eight is an average specific heat for water vapour.

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Crystallization

- Crystallization lines are shown on P-T-ξ and h-T-ξ charts

Now let us look at one typical problem associated with water- lithium bromide systems this is known as crystallization. In fact if you huh if you noticed it on P-Tx and h-Tx charts crystallization lines are shown let me show them again.

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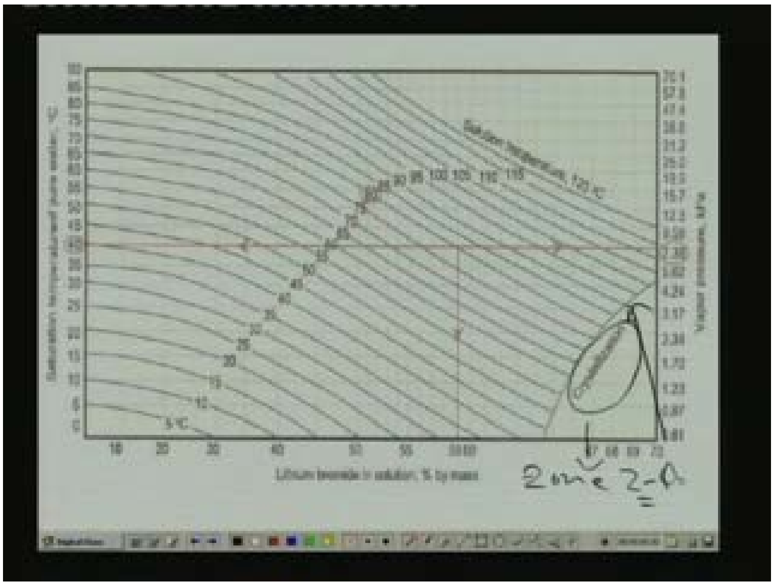

You can see here that this line is a crystallization line and below this the data is not given and simply it is mentioned that it crystallization. Okay, so this is a zone of crystallization okay or crystallization zone what do you mean by crystallization zone crystallization zone is a two phase region okay. When the solution enters into this crystallization zone in order to be at equilibrium some lithium bromide from the solution separates out as solid crystals. That means in the crystallization zone you have a two phase mixture consisting of lithium bromide water solution plus anhydrous lithium bromide in crystal form okay.

So this is the meaning of crystallization zone okay. Crystallization has practical significance in the design of water lithium bromide systems. Because during the operation of the system if the working fluid or the solution enters into crystallization zone as lithium bromide separates into solid crystals. And solid crystals can block the pipes and values etcetera. So they can hamper the performance of the system. So normally all practical water- lithium bromide systems operate away from the crystallization zone. You have to design and you have to maintain a system in such a way that you do not enter into this crystallization zone okay, same thing is shown in h-Tx chart also.

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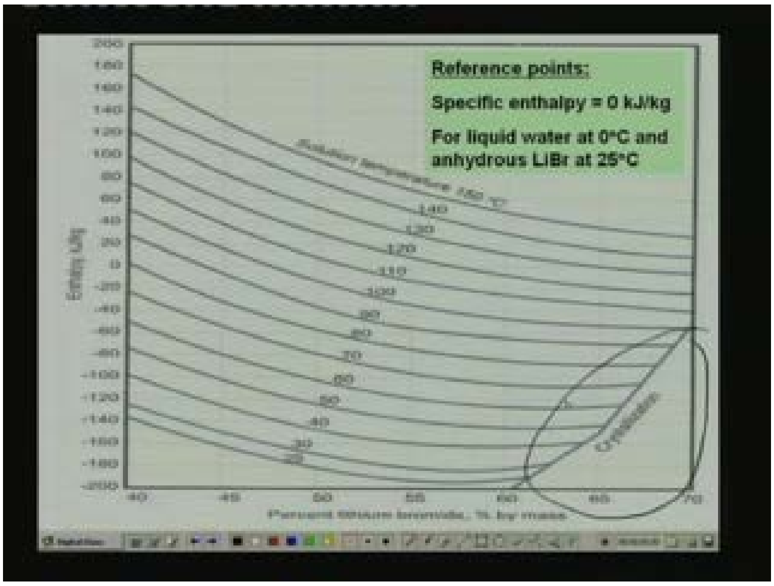

Reference points:

Specific enthalpy = 0 kJ/kg

For liquid water at 0°C and anhydrous LiBr at 25°C

Again in the h-Tx chart this is your crystallization zone and you should operate your system away from the away from this crystallization region okay.

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Crystallization

- Crystallization lines are shown on P-T-ξ and h-T-ξ charts
- The region below the crystallization lines indicates solidification of LiBr salt
- In the crystallization region a two-phase mixture (slush) of water-LiBr solution and crystals of pure LiBr exist in equilibrium
- Systems should be operated away from this region to prevent formation of solid crystals which block the flow

So as I mentioned the region below the crystallization lines indicates solidification of lithium bromide salt. In fact it is called as slushy region. Because in this particular region you have a two phase mixture which is a slush of water- lithium bromide solution and crystals of pure lithium bromide and they exist in equilibrium. And system should be operated away from this region to prevent formation of solid crystals which block the flow.

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Steady-flow analysis

Assumptions:

1. Steady state and steady flow
2. Changes in potential and kinetic energies across each component are negligible
3. No pressure drops due to friction
4. Only pure refrigerant boils in the generator

Now let us look at steady flow analysis of a simple stage vapour absorption refrigeration system based on water- lithium bromide and first. Let me list out the assumptions made the first assumption is usual assumption. It is a steady state and steady flow process then changes in potential and kinetic energies across each component are negligible. And there are no pressure drops due to friction and finally only pure refrigerant boils in the generator.

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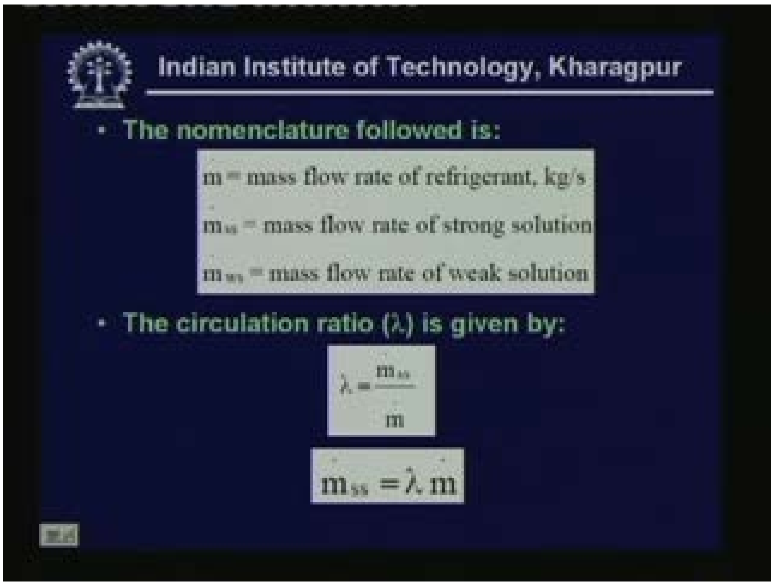

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- The nomenclature followed is:

$\dot{m}$ = mass flow rate of refrigerant, kg/s
$\dot{m}_{ss}$ = mass flow rate of strong solution
$\dot{m}_{ws}$ = mass flow rate of weak solution

- The circulation ratio (λ) is given by:

$$\lambda = \frac{\dot{m}_{ss}}{\dot{m}}$$

$$\dot{m}_{ss} = \lambda \dot{m}$$

And the nomenclature followed here is like this m dot stands for mass flow rate of refrigerant m dot with subscript ss stands for mass flow rate of strong solution strong solution here, means strong in lithium bromide okay. That means it is rich in lithium bromide or in other words the concentration of lithium bromide is higher okay. And m dot ws stands for mass flow of rate of weak solution that means weak in lithium bromide okay. And here we define another parameter call circulation ratio lambda and the circulation ratio is defined as the ratio of mass flow rate of strong solution to the mass flow rate of refrigerant okay, lambda is equal to m dot ss divided by m dot. That means the mass flow rate of strong solution is simply equal to a product of circulation ratio into mass flow rate of refrigerant.

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- The analysis is carried out by applying mass and energy balance across each component of the system

And the analysis is carried out by applying mass and energy balance across each component of the system. So let me first explain the system and let me give me give the equations.

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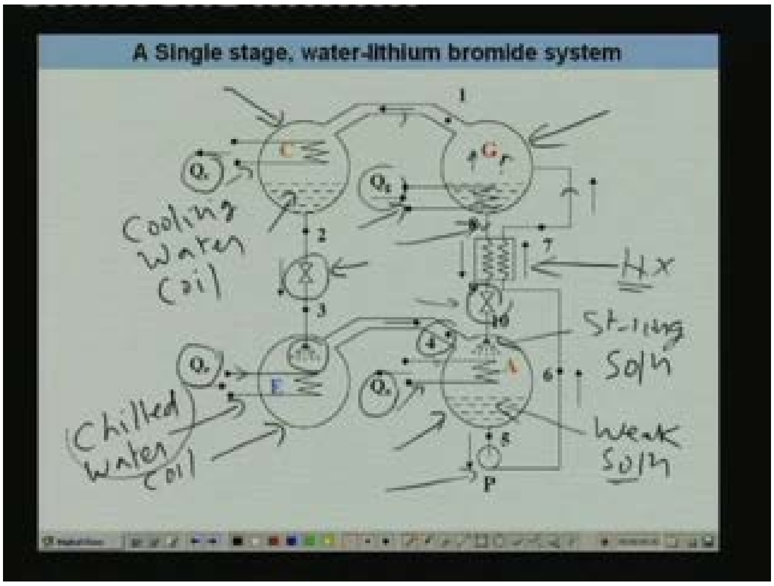

A Single stage, water-lithium bromide system

So as you have in fact you might have noticed that in the last lecture I have explained the basic vapour absorption refrigeration system. So let me once again explain it briefly here you have four basic components this is a absorber A is the absorber E is a evaporator G is a generator and C is a condenser. In addition to that you also have refrigeration expansion valve here and solution expansion value here and a solution heat exchanger which as you know is used for improving the performance. And in addition to this we also use a solution pump here okay. So let us again begin at this point which is which is the exit of the evaporator at the exit of the evaporator as you know you have low pressure low temperature refrigerant vapour.

This low pressure low temperature refrigeration vapour enters into the absorber where it comes in contact with the strong solution okay. Strong solution that is coming from the generator since this strong solution has affinity for the water vapour the water vapour gets absorbed here. Okay. And what forms here is a weak solution or a dilute solution okay. So the is actually the solution is sprayed into this chamber. So that you divide the solution into fine droplets so that they will be good heat and mass transfer okay. And this process as you know is exothermic. So heat is released and this heat is taken out by circulating cooling water through this coil okay and Qa is the heat released during this absorption process okay. So during the due to this absorption what forms is a weak solution this weak solution is at low pressure and it is pumped using this solution pump okay.

So the solution pump increases the pressure of the solution and this high pressure solution now flows through the solution heat exchanger here where it exchanges heat with the hot solution coming from the generator. And it becomes heated up and this hot weak solution enters into the generator in the generator you have to supply heat okay. Heat can be supplied in a wide variety of ways we will see how it can be supplied. But let if at the moment, let us assume that we are somehow supplying the heat required heat Qc okay. So when you are supplying Qc to this weak solution vapour is generated okay. So this vapour flows into the condenser okay so this is the vapour flow to the condenser. In the condenser the vapour comes in contact with the cooling water coils these, the cooling water coil okay. And the vapour condenses.

Since condensation again a exothermic process here heat has to be taken out. So the cooling water takes the heat of condensation out of the system. So what you have here is pure water in liquid form this is still at high pressure. So the pressure has to be reduced. So this water flows through this refrigerant expansion valve where it undergoes pressure drop and this low pressure water is now sprayed into this evaporator okay. Again you can see the, it is sprayed into the evaporator when it is sprayed the liquid droplets flow on to this chill water coil this is a chill water coil. Okay. And as it flows on the chill water coil it evaporates. So as a result of its since evaporation is endothermic the water that is entering into this gets cool. So ultimately what to get out of this is a cooled water okay. That is nothing but your refrigeration effect Qe okay.

And during this process liquid becomes vapour and this vapour goes through the absorber and that, thus the refrigerant cycle is completed. And for the as for the solution is concerned you remember that at the exit of the generator you have strong solution. That means solution that is rich in lithium bromide it is at high pressure and its hot okay. Now it flows through this heat exchanger again where it exchanges heat with the weak solution and its temperature reduces. Since it is still at high pressure it is expanded through this solution expansion device and its pressure drops. And its pressure drops to that of the absorber pressure and so this low pressure which solution is again sprayed into this absorber and the solution cycle is completed and this process goes on. This is a, the simple single stage vapour absorption refrigeration system.

So what we will be doing is, we will be applying steady flow steady state flow analysis to this system to arrive at expressions for COP etcetera, COP mass flow rate et cetera okay. So what we'll do in typically in a steady state steady flow analysis for any refrigeration system is we take control volume across each component. And we apply mass and energy balance for each component like that you have to apply mass and energy balance for all the components. And then you get a set of equations then you have to supply required number of inputs and you get the output when you are getting the properties and all from your inputs okay. So let me explain how this is done and with suitable equations okay. So I will just given an example for example if you are taking.

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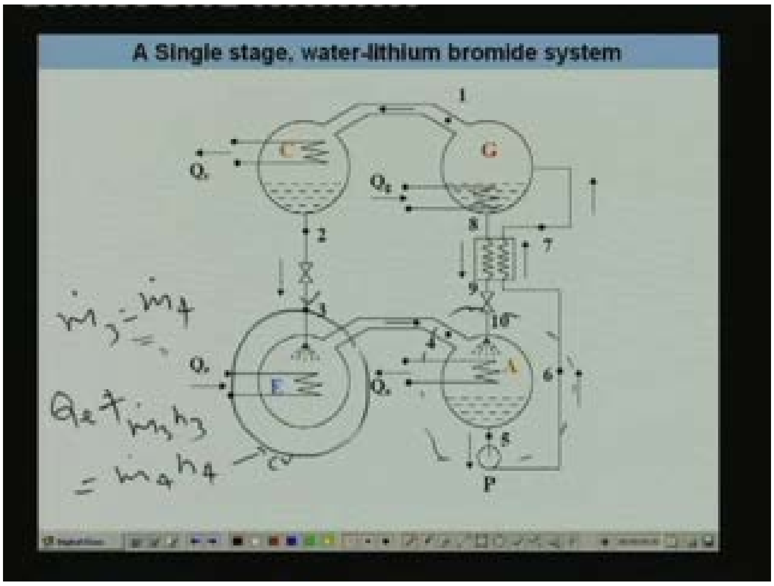

A Single stage, water-lithium bromide system

Let us say the evaporator okay. If you are applying mass balance to the evaporator what is the mass balance to the evaporator remember that here this cooling water chill water. And all do not come into picture okay. Because we are not really considering how we are supplying heat or how we are rejecting heat okay. So for our analysis we are concentrating only on the refrigerant side that means inside the system okay. So if you are applying mass balance for the system you know that is a steady flow. So water mass is entering must go out. That means m dot three should be equal to m dot four this is the mass balance and what is the energy balance.

Since it is steady state what are energy is entering must leave the control volume okay this is our control volume. So for example in this case energy entering is Qe okay, Qe plus m dot in m dot three into h three this should be equal to m dot four into h four okay. So this is the mass balance for evaporator and this is the energy balance for the evaporator similarly you take next you take control volume across the absorber and again you apply mass and energy balance. Similarly you take control volume across each component and apply mass and energy balance. And you arrive at a set of equations okay. Now let me show the equations.

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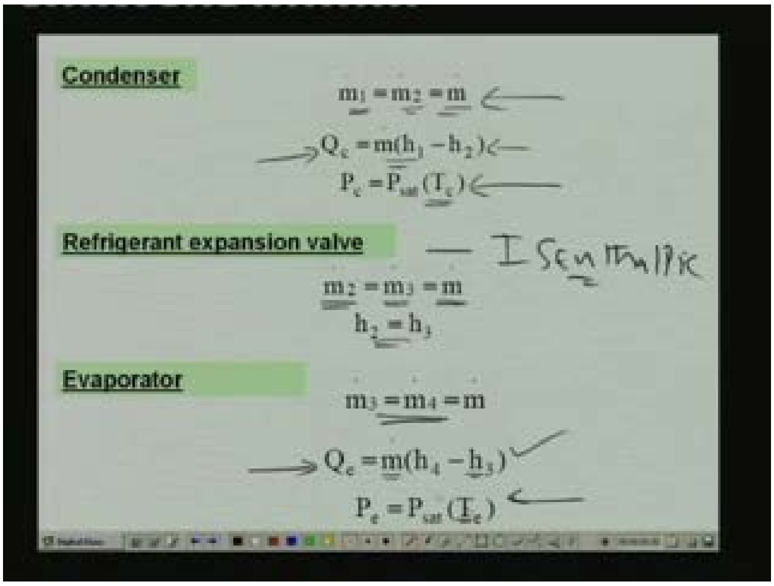

Condenser

$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

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

$$P_c = P_{sat}(T_c)$$

Refrigerant expansion valve — Isenthalpic

$$\dot{m}_2 = \dot{m}_3 = \dot{m}$$

$$h_2 = h_3$$

Evaporator

$$\dot{m}_3 = \dot{m}_4 = \dot{m}$$

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

$$P_e = P_{sat}(T_e)$$

For example for condenser. So let us begin with condenser only refrigerant pure refrigerant vapour enters into the condenser and one is the entry state point at the inlet and two is the state point at the outlet. So m dot one is the mass flow rate into the condenser and m dot two is the mass flow rate out of the condenser okay. So the, they should be equal because it is under steady state. And what is this is nothing but the refrigerant flow rate okay. Because only pure refrigerant is entering into the condenser. So the mass balance is very simple m dot one is equal to m dot two is equal m dot and similarly if you apply the energy balance remember that we are neglecting kinetic and potential energy changes and in condenser there is no work transfer.

So you have only heat transfer and fluid flow okay. So if you are applying that you will find that heat rejecters and the condenser Qc is simply equal to mass flow rate of the refrigerant into the enthalpy difference where h one is the inlet enthalpy and h two is the outlet enthalpy okay. So this is a energy balance for condenser. And what is the condenser pressure? Condenser pressure is nothing but the saturated pressure of pure water at condenser temperature Tc. Tc is the condenser temperature okay. So these are the all that we know need to know about the condenser similarly you apply the mass and energy balance for the expansion valve. This is the mass entering and this is the mass leaving and this is again equal to pure refrigerant flow rate m dot and since expansion process is isenthalpic there is neither heat transfer nor work transfer okay. So the enthalpy remains constant so h two is equal to h three.

Same way if you apply the energy and mass balance for evaporator this is the mass balance pure refrigerant enters and pure refrigerant leaves and this is a refrigeration capacity this is an important parameter. Refrigeration capacity is again given by mass flow rate of refrigerant into enthalpy difference across the evaporator h four is the exit enthalpy h three is the inlet enthalpy okay. Again how do we find the evaporator pressure evaporator pressure is nothing but the saturated pressure of pure water at evaporated temperature Te okay.

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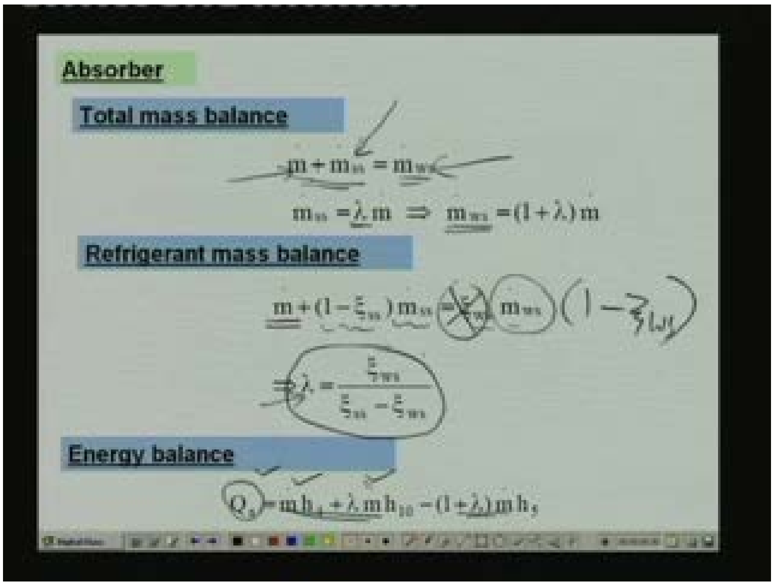

Absorber

Total mass balance

$$m + m_{ss} = m_{ws}$$

$$m_{ss} = \lambda m \Rightarrow m_{ws} = (1+\lambda) m$$

Refrigerant mass balance

$$m + (1-\xi_{ss}) m_{ss} = \cancel{\xi_{ws}}\, m_{ws} (1-\xi_{ws})$$

$$\Rightarrow \lambda = \frac{\xi_{ws}}{\xi_{ss} - \xi_{ws}}$$

Energy balance

$$Q_a = m h_4 + \lambda m h_{10} - (1+\lambda) m h_5$$

Now let us come to the absorber. In absorber we have both refrigerant as well as solution okay. So first, let us apply the total mass balance this is the total mass entering into the absorber this is the total mass leaving the absorber. What is the mass entering into the absorber this is the pure refrigerant mass flow rate and this is a strong solution flow rates from the generator okay. This is what is entering into the absorber. What is leaving the absorber is a weak solution okay. So the total mass flow rate is conserved okay. Now you can from the definition of circulation ratio you can write m dot ss as lambda into m dot where lambda is a circulation ratio.

So if you substitute this here you can easily show that the weak solution flow rate is nothing but one plus lambda into m dot okay. Similarly you can also write an energy mass balance for the refrigerant. So mass balance for the refrigerant means whatever amount of refrigerant is entering into the system must leave the system. So what is the amount of refrigerant entering into the system.

First it is entering in the form of pure vapour that is m dot plus the solution also consists of refrigerant okay. So what is the amount of refrigerant in the solution that is nothing but your solution flow rate into the mass fraction of refrigerant in the solution. That is nothing but one minus zeta ss where zeta ss is a concentration of lithium bromide. So one minus zeta ss is a concentration of water okay. So this is a amount of pure refrigerant entering into the absorber and what is leaving weak solution is leaving the absorber. So what is the refrigerant in the weak solution it is nothing but I am sorry, there is a mistake here this should have been one minus zeta ws into m dot ws okay.

So this is the weak solution refrigerant in the weak solution okay. So from this equation you can easily show that if should combine these two equations you can find an equation for circulation ratio in terms of the concentrations okay. This equation is important because once you know the concentration you can easily find out the circulation ratio circulation ratio is an important parameter. Because it the COP of the system depends upon the circulation ratio okay.

Now let us write the energy balance for the absorber. What is t he energy balance? Whatever energy is entering must leave, what is the energy leaving the absorber energy is leaving the absorber through the cooling water that is equal to Qa is nothing but the absorber load. And m dot h four plus lambda into m dot h ten is the total energy entering into the system through the refrigerant and through the strong solution. So this is the energy entering into the absorber by way of fluid flow okay. And what is leaving the absorber is this by way of heat transfer and this by way of fluid flow okay. So this is the simple expression now we can also write this expression in this form.

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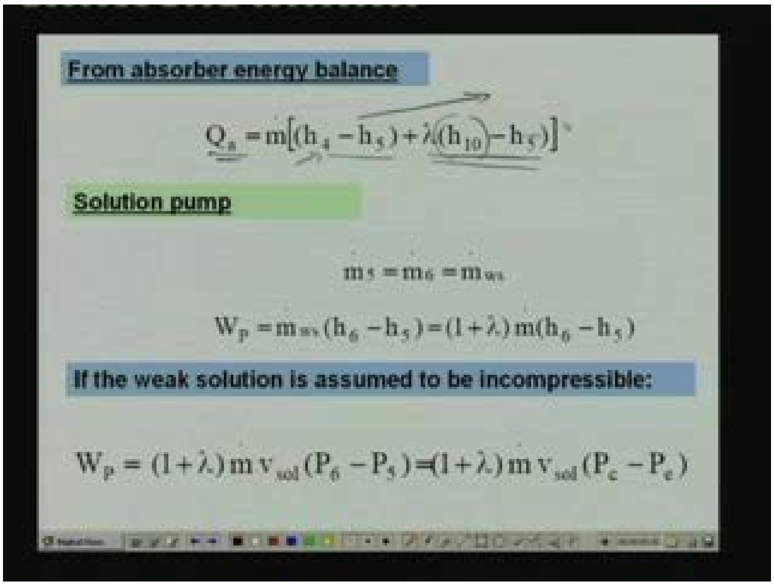

From absorber energy balance

$$Q_a = \dot{m}[(h_4 - h_5) + \lambda(h_{10} - h_5)]$$

Solution pump

$$\dot{m}_5 = \dot{m}_6 = \dot{m}_{ws}$$

$$W_p = \dot{m}_{ws}(h_6 - h_5) = (1+\lambda)\dot{m}(h_6 - h_5)$$

If the weak solution is assumed to be incompressible:

$$W_p = (1+\lambda)\dot{m}\, v_{sol}(P_6 - P_5) = (1+\lambda)\dot{m}\, v_{sol}(P_c - P_e)$$

So the absorber load Qa can also be written as m dot m dot is common h four minus h five plus lambda into h ten minus h five okay. And this term h four minus h five is nothing but the difference in enthalpy as the refrigerant vapour at state four is getting converted into solution at state five okay. So this accounts for the phase change of the refrigerant vapour from vapour to refrigerant from vapour to solution okay. And this accounts for the sensible heat transfer what is this thing. This is nothing but the sensible heat to be transferred as the solution at condition ten is cooled to solution at condition five okay.

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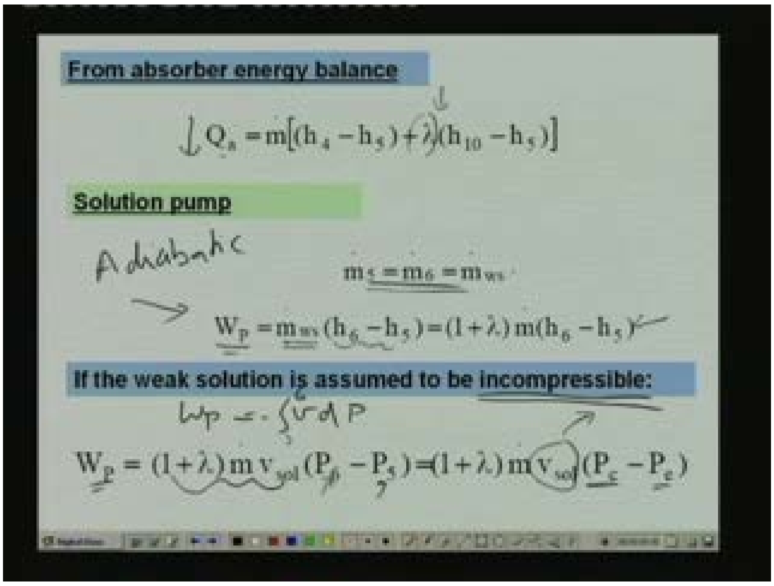

From absorber energy balance

$$Q_a = m[(h_4 - h_5) + \lambda(h_{10} - h_5)]$$

Solution pump

Adiabatic

$$m_5 = m_6 = m_{ws}$$

$$W_P = m_{ws}(h_6 - h_5) = (1+\lambda)\, m (h_6 - h_5)$$

If the weak solution is assumed to be incompressible:

$$W_p = \int_5^6 v\, dP$$

$$W_P = (1+\lambda)\, m\, v_{sol}(P_6 - P_5) = (1+\lambda)\, m\, v_{sol}(P_c - P_e)$$

So you can see that this consists of two terms normally from the performance point of view from the absorber size and all this should be low okay. This should be low one as they, this parameter has got to be low okay. Because other parameters are decided by other performance related issues like your refrigeration capacity and all okay. So you can see that when circulation ratio is low the heat rejected the absorber will be low okay. Now we can also apply mass and energy balance across the solution pump it is very easy only weak solution enters the solution pump and it leaves the solution pump. So m dot five is a weak solution entering into the solution pump and m dot six is the weak solution leave the leaving the solution pump okay.

So this is the mass balance. And what is the energy balance, we assume that this is adiabatic okay. Adiabatic means that is no heat transfer right then there is only work transfer. So work transfer is nothing but if you neglecting kinetic and potential energy changes this is equal to mass flow rate of the solution into enthalpy rise across the pump enthalpy rise across the pump is h six minus h five and m dot ws can be written as one plus lambda into m dot. So this becomes one plus lambda into m dot h six minus h five. Though this equation is a correct equation this not very convenient to use in calculations so we can make one simple assumption that the weak solution is incompressible. Okay.

If you are assuming that it is incompressible. That means its specific volume remains constant then you can get this expression how did you get this expression you can also use expression like this minus vdp okay from state five to six. This we have discussed in the while we have presenting basic thermodynamics. So work input is integral vdp. So if v is constant here so you can write this as this is the mass flow rate into P six minus P five okay. Where P six is a exit pressure P five is a inlet pressure okay. And P six and P five are known to us because P six and P five are nothing but condenser and evaporator pressures okay. And you can take a approximate value for the solution specific volume. Because it does not really very much.

So you can some average value and you can calculate what is the power input to the solution pump the power input to the solution pump in you remember is negligible compared to the heat input to the system okay. That means in COP calculation you can really neglect the solution pump work. But still you have to calculate what is the amount of work of required to the pump. Because when you are designing the system you have select the motor and you have to select a suitable pump and the motor for the pump okay. That means you have to specify what is the required capacity of the motor. So for that purpose you have to know what is the work input to the pump okay.

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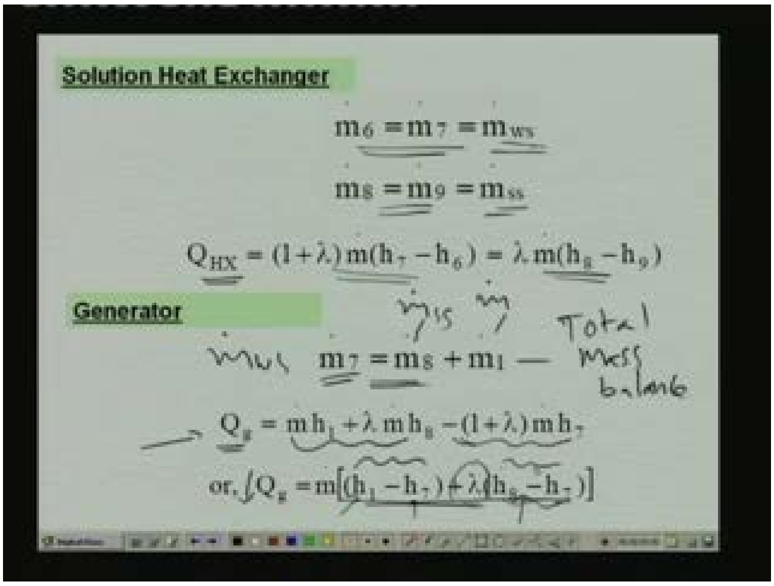

Solution Heat Exchanger

$$\dot m_6 = \dot m_7 = \dot m_{ws}$$

$$\dot m_8 = \dot m_9 = \dot m_{ss}$$

$$Q_{HX} = (1+\lambda)\dot m(h_7 - h_6) = \lambda \dot m(h_8 - h_9)$$

Generator

$\dot m_{ss}$ $\dot m$

$\dot m_{ws}$ $\dot m_7 = \dot m_8 + \dot m_1$ — Total mass balance

$$\longrightarrow Q_g = \dot m h_1 + \lambda \dot m h_8 - (1+\lambda)\dot m h_7$$

$$\text{or, } Q_g = \dot m[(h_1 - h_7) + \lambda(h_8 - h_7)]$$

Now we will continue this and we apply the mass and energy balance to the solution heat exchanger in the solution heat exchanger two streams enter weak solution enters from one side and strong solution enters from the other side both do not get mixed mix. So weak solution flow rate is conserved here and strong solution flow rate is conserved here okay. And the QHX is a heat transferred in the heat exchanger, the, which is nothing but m dot into delta h for the weak solution the, that should be equal to m dot into delta h for the strong solution. This is under the assumption that there are no heat losses are gains in the solution heat exchanger okay.

So this is simple energy balance equation for a heat exchanger. Now we can also write the mass and energy balance for the generator this is the total mass balance okay. This is the total mass balance. So mass entering is nothing but your weak solution mass flow rate m dot seven is a weak solution mass flow rate. And what is leaving is your refrigerant mass flow rate m dot plus strong solution mass flow rate m dot ss okay. Similarly you can write the energy balance equation. This is the energy supplied in the generator and this is the energy leaving the generator. And this is, I am sorry this is energy supplied to the generator this is the energy leaving the generator and this is the energy entering into the generator by way of fluid flow okay.

So this is simple energy balance and there are no work transfers here. So there you do not find any work this can also be written in this form m dot into h one minus h seven plus lambda into h eight minus h seven. That means again it can be written as a sum of two terms h one minus h seven plus h eight minus h seven. What is h one minus h seven h seven minus h seven is nothing but the energy required to generate water vapour from a solution at state seven to superheated vapour at state one okay. So this is the one is required for that purpose and this second term accounts for the sensible heat transfer this is nothing but the energy required to heat the solution from state seven to state eight okay. So one is a some kind of a latent heat term and the other one is a sensible heat term for high COP again Qg should be low.

So you will see that for Qg to be low again the circulation ratio should be small okay. So when you have circulation small circulation ratio you will have small Qg again the difference between h eight and h seven should be small as possible and remember that h eight minus h seven are the enthalpies of strong and weak solutions okay.

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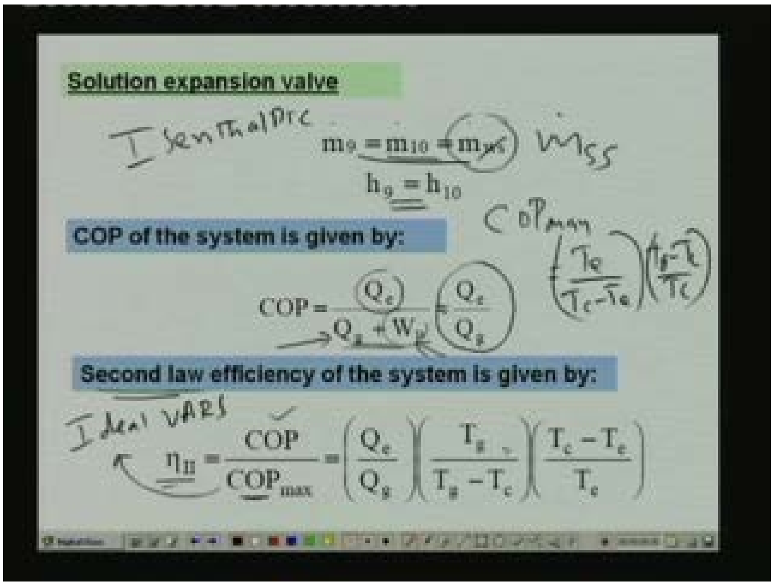

Solution expansion valve

Isenthalpic

$$m_9 = m_{10} = m_{\cancel{ws}} \quad m_{ss}$$

$$h_9 = h_{10}$$

COP of the system is given by:

COP_{max}

$$\left(\frac{T_e}{T_c - T_e}\right)\left(\frac{T_g - T_c}{T_c}\right)$$

$$COP = \frac{Q_e}{Q_g + W_p} \approx \frac{Q_e}{Q_g}$$

Second law efficiency of the system is given by:

Ideal VARS

$$\eta_{II} = \frac{COP}{COP_{max}} = \left(\frac{Q_e}{Q_g}\right)\left(\frac{T_g}{T_g - T_c}\right)\left(\frac{T_c - T_e}{T_e}\right)$$

Now again you can you have finally you have to write the mass and energy balance for the solution expansion valve again mass is entering is leaving and this is nothing but your, I mean there is a mistake this is m dot strong solution okay. And this is a now, we are assuming that this process is isenthalpic process okay. So the enthalpy remains constant there is no work transfer here and kinetic energy changes are negligible. Finally the COP of the system is given by refrigeration capacity divided by the input to the system input is in the form of heat to the generator and the solution pump work as we have seen in the last class this is negligible compared to this.

so this is approximately equal to Qe by Qg. You can also define a what is known as second law efficiency or efficiency as a ratio of the COP of the system divided by the maximum possible COP. If you remember this maximum possible COP is for an ideal vapour absorption refrigeration system and we have we got a derived an expression for this. If you remember that is the expression is nothing but COP maximum is nothing but Te divided by Tc minus Te into Tg minus Tc divided by Tc okay. So this is a expression if you are substituting that expression here you get this expression okay.

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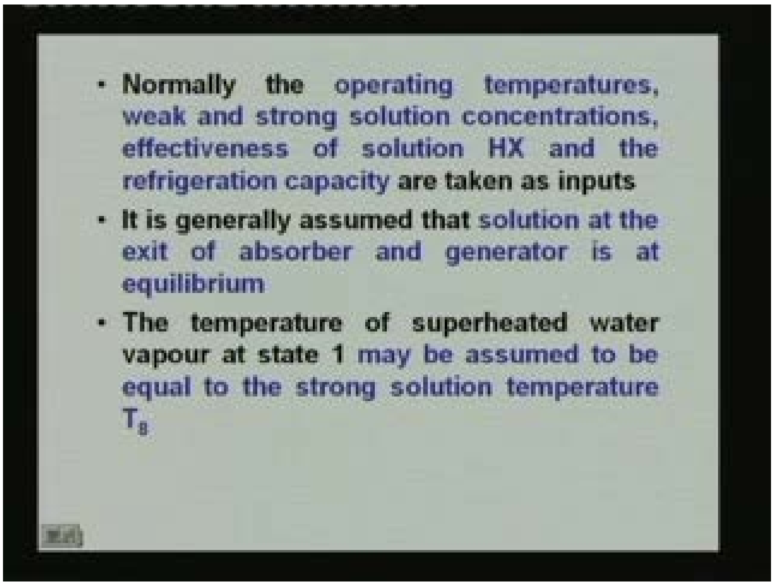

- Normally the operating temperatures, weak and strong solution concentrations, effectiveness of solution HX and the refrigeration capacity are taken as inputs
- It is generally assumed that solution at the exit of absorber and generator is at equilibrium
- The temperature of superheated water vapour at state 1 may be assumed to be equal to the strong solution temperature T_8

Now the normally the operating temperatures weak and strong solution concentrations effectiveness of solution heat exchanger and the refrigeration capacity are taken as inputs. Because to get the performance you have to supply certain inputs and these are the typical inputs to any system design. And from these inputs and the, from the set of equation you have to arrive at the required performance parameters it is generally assumed that the solution at the exit of absorber and generator is at equilibrium okay.

If you want to use the solution property table. That means charts and table there what we have shown P-T concentration and enthalpy temperature concentration charts. Remember that these charts are for equilibrium conditions okay. So in an actual system you may not find equilibrium concentrations or equilibriums situation of equilibrium. But for calculation purposes we have to assume at some points that the solution is at equilibrium okay. So the standard practise is that the solution that is leaving the absorber is assumed to be at equilibrium and similarly the solution that is leaving the generator is assumed to be at equilibrium what is the advantage of as making these kind of assumptions. Once you make these assumptions then you can use the equilibrium P-Tx and h-Tx charts and you can find the required properties like required concentrations temperatures or enthalpies okay. So the, that is why we have to make this type of assumptions remember that the actual situation will be slightly different from this okay.

Now the temperature of superheated water vapour at state one maybe assumed to be equal to the strong solution temperature T eight. Remember that the water vapour that is leaving the generator is at a temperature almost close to the generator temperature okay. And the power to the pressure inside the generate generator it is same as a condenser pressure okay. So the vapour that is leaving the generator is at a pressure equal to the condenser pressure. But at a temperature much higher than the condenser temperature. So obviously it is in a superheated state okay. So typically we assume that the temperatures of vapour that is leaving the generator is equal to the temperature of the strong solution that is leaving the generator okay. So you have to make these kind of simple assumptions so that you can perform the calculation easily okay.

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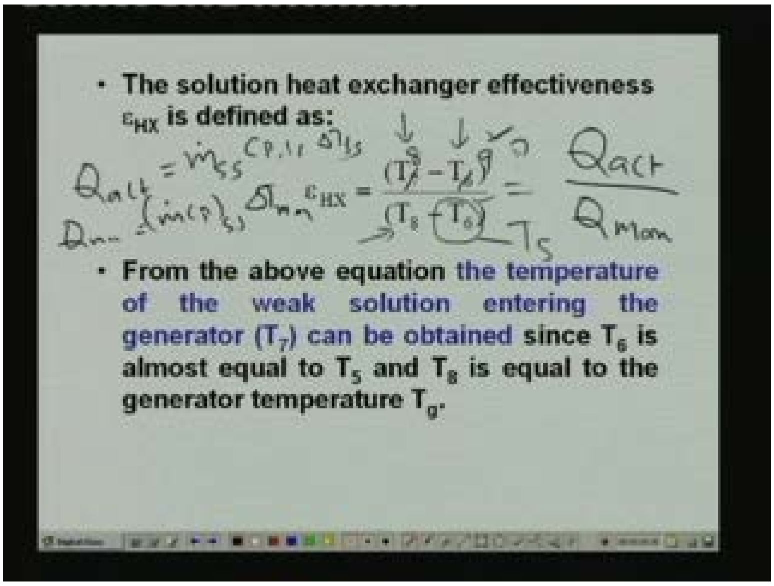

- The solution heat exchanger effectiveness ε_{HX} is defined as:

$$\varepsilon_{HX} = \frac{(T_7 - T_6)}{(T_8 - T_6)} = \frac{Q_{act}}{Q_{max}}$$

$Q_{act} = \dot{m}_{ss} c_{p,ss} \Delta T_{ss}$

$Q_{max} = (\dot{m} c_p)_{ss} \Delta T_{max}$

- From the above equation the temperature of the weak solution entering the generator (T_7) can be obtained since T_6 is almost equal to T_5 and T_8 is equal to the generator temperature T_g.

And we also require solution heat exchanger effectiveness and this is defined as normally heat exchanger effectiveness is defined as. If you remember from our heat transfer discussion on heat transfer this is defined as the actual heat transfer rate to the maximum possible heat transfer rate okay. The actual heat transfer rate can be written as for example Q actual can be written as m dot. For example if you are writing in terms of strong solution m dot ss into cp of strong solution into delta T of strong solution okay. Q maximum is nothing but m dot cp of strong solution into delta T maximum okay.

That is what we have written here delta T maximum is T eight minus T six okay, and T seven minus there is again a small mistake here. So this should have been T eight minus T nine okay. So this is the temperature of the strong solution leaving the entering into the heat exchanger. And this is the temperature of the strong solution leaving the heat exchanger okay. T eight and T nine are inlet and outlet temperatures of strong solution at the heat exchanger okay T eight minus T nine. From the above equation the temperature of the weak solution entering the generator can be obtained since T six is almost equal to T five okay.

So this temperature is almost equal to T five which is nothing but the inlet temperature to the solution pump. That means when you are pumping the liquid using the solution pump its temperature remains almost constant okay. So you can make an assumption that the inlet temperature is same as the outlet temperature okay then you can you know this okay. And T eight is your generator temperature. So from this you can find out what is T nine okay so that is the use of this particular equation. So what I have given here is typical steady state analysis of a single stage vapour absorption refrigeration system. You do not have to remember any of these equations. All that you have to do is draw the system schematic and label them and take component by component and start applying mass and energy balance for each component okay.

And of course you have to make the simplifying assumptions that I have shown earlier. And if you do it in a systematic manner you will have a set of equations and you will find that you have to supply certain inputs to the problem. So that you can get the required performance parameters such as your required mass flow rate of refrigerant. What is the pump solution pump or what is the heat input to the generator. What is the heat rejected at the condenser absorber and all these informations required in the design of the actual system okay.

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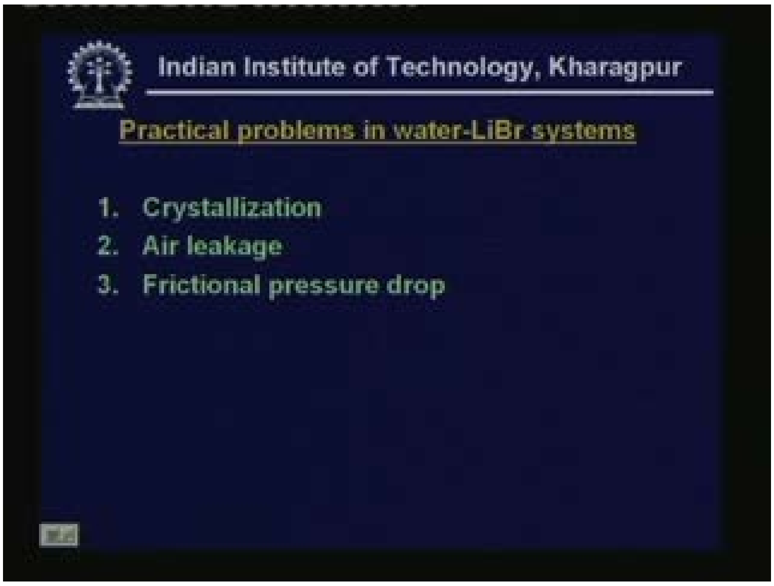

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Practical problems in water-LiBr systems

1. Crystallization
2. Air leakage
3. Frictional pressure drop

Now let us look at some practical problems associated with water- lithium bromide systems the first problem is as I have already discussed is the crystallization second problem is air leakage third problem is frictional pressure drops. Now let us look at one by one.

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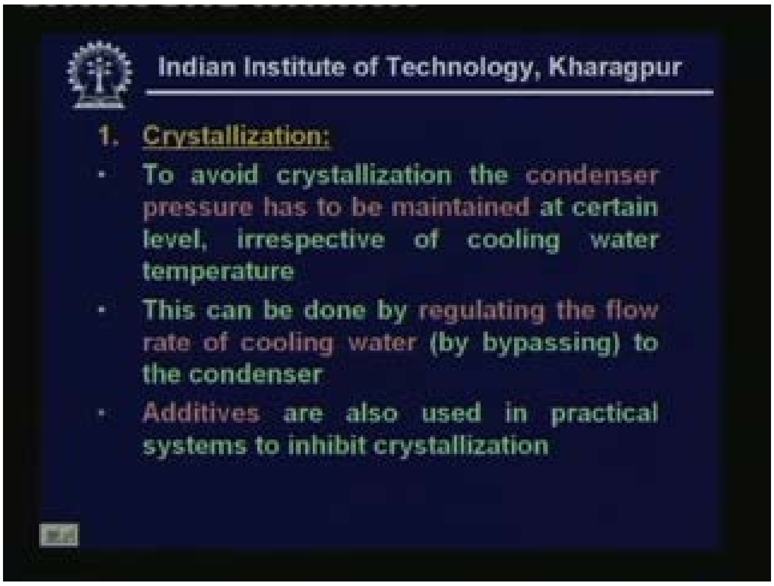

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1. Crystallization:
- To avoid crystallization the condenser pressure has to be maintained at certain level, irrespective of cooling water temperature
- This can be done by regulating the flow rate of cooling water (by bypassing) to the condenser
- Additives are also used in practical systems to inhibit crystallization

Crystallization as you know happens as the solution a strong solution a hot strong solution is cooled okay. So when a hot strong solution is cooled you will find at a particular point if the inlet pressure is not very high. The exit condition or the solution condition may enter into the crystallization region. Once it enters in the crystallization region solid lithium bromide crystals are formed which you want to avoid okay. And where does this crystallization take place in this particular system you will find that crystallization takes place in the system typically at the exit of the solution heat exchanger on the strong solution side. That means the strong solution that is coming from the generator which is rich in lithium bromide. That means its highly concentrated lithium bromide solution and its very hot okay.

So when you are cooling that in the solution heat exchanger there is a possibility that during the cooling process it enters into the crystallization zone and crystals will form and crystals will block the heat exchanger okay. This is got to be avoided at any extent otherwise the system operation will get disturbed okay. The flow gets disturbed flow gets blocked and all that okay. And if you look at your P-Tx and h-Tx charts you will see that at a given solution concentration and temperature crystallization zone can be avoided if the inlet pressure is high. That means when the condenser pressure is high the chances of crystallization are low okay. On the other hand if the condenser pressure is low and if your solution is highly concentrated and hot then the chances of entering into crystallization zone are more okay. So in practical systems what is done is even though your condenser pressure depending upon the cooling availability of cooling water is low you have to maintain the condenser pressure artificially high so that crystallization is avoided.

Okay, that is what is mentioned here to avoid crystallization the condenser pressure has to be maintained at certain level irrespective of cooling water temperatures okay. This can be done by regulating the flow rate of cooling water. That means by bypassing to the condenser additives are also used in practical systems to inhibit crystallization okay. So the two measures used in actual commercial lithium bromide systems are the control of condenser pressure and use of certain additives okay. That means you are introducing a third substance into the system okay, which we are not really considering in the performance analysis okay. Because the small amounts of the third substance is added so that crystallization is inhibited okay.

But the most important measure to control the crystallization is by controlling the condenser pressure sometimes it may, so happen that, for example, in winter you may have cooling water available at very low temperature okay. In fact this is good for the system performance because when you have cooling water at low temperatures condenser pressure will be low once the condenser pressure is low system COP will be high. But you have the practical problem of crystallization. So even though it is desirable from performance point of view you have to artificially maintain the condenser pressure at a higher value okay. So this is done by regulating the flow rate. Because the temperature you have no control over the temperatures. So the flow rate is regulated that means some of the cooling water is bypassed. So as a result the condenser temperature is artificially increased okay. So since the condenser pressure depends upon the condenser temperature condenser pressure also increases okay. Now let us look at the second problem second problem is air leakage.

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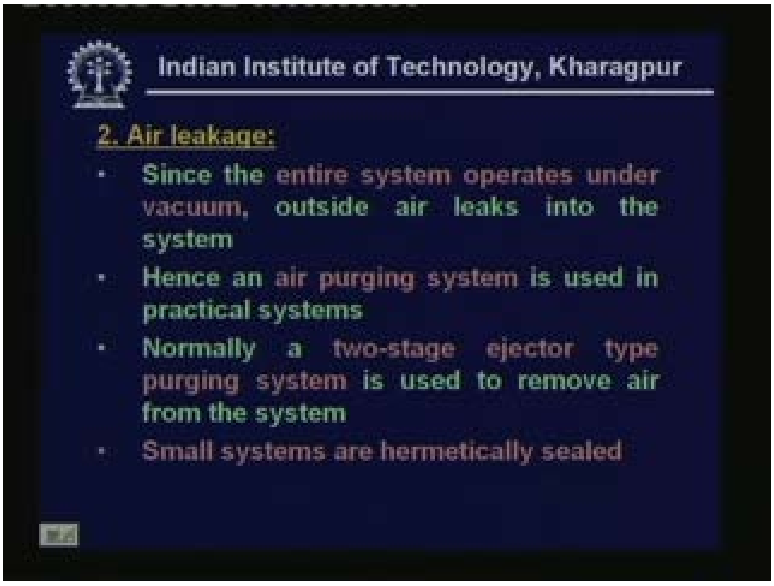

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2. Air leakage:

- Since the entire system operates under vacuum, outside air leaks into the system
- Hence an air purging system is used in practical systems
- Normally a two-stage ejector type purging system is used to remove air from the system
- Small systems are hermetically sealed

If you look at the typical pressure temperature data for water- lithium bromide system you will find that the entire system is operating in vacuum okay. That means, both the evaporator absorber as well as condenser and generator they are operating in high vacuum actually okay. So when you are operating the system in under vacuum there is a possibility of outside air leaking into the system okay. So when outside air leaks into the system since air is a non condensable substance for these operating conditions it will not condense. So it will affect your heat and mass transfer rates within the system okay.

And it will also vary the total pressure of the system as a result you will find that the performance of system gets affected drastically okay. This is not desirable. So you have to make sure that the amount of air inside the system is as small as possible. But in actual systems it may not be really possible to eliminate air completely. That means you will you may have some amount of air but which has got to be minimized. So this is minimized by continuously taking out the air from the system okay. That means you have to have some kind of a vacuum system which takes out the air from the system. As soon as it enters into it okay.

This kind of a system is known as a purging system okay. So as I said since the entire system operates under vacuum outside air leaks into the system. Hence an air purging system is used in practical systems, normally you do not use any mechanical vacuum pumps. But what they use is a two stage ejector type purging system okay. And small systems are hermetically sealed. So the chances of air entering the, into these small systems is virtually nil okay. So the small systems do not have the problem. But whereas the large systems have the problem of air leakage.

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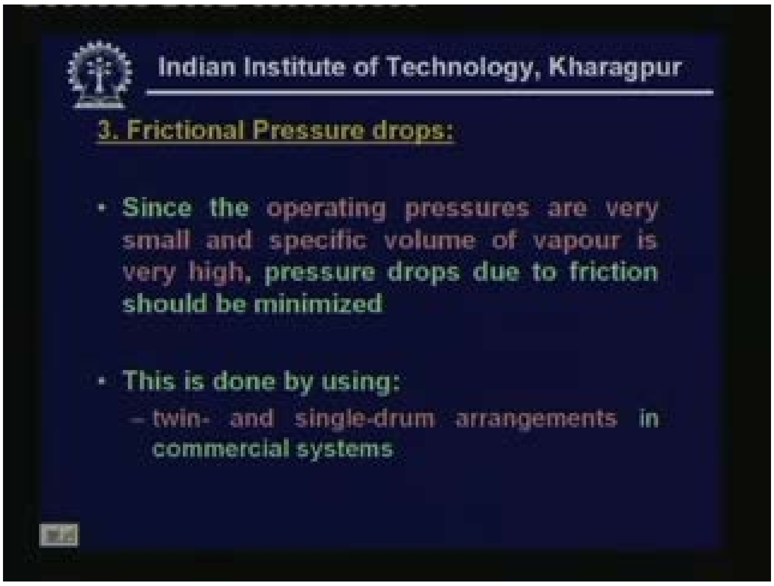

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3. Frictional Pressure drops:

- Since the operating pressures are very small and specific volume of vapour is very high, pressure drops due to friction should be minimized
- This is done by using:
  - twin- and single-drum arrangements in commercial systems

Now let us look at the third system frictional pressure drops since the operating pressures are very small just. Now we have, I have mentioned that the system will be working under vacuum since the pressure is very low the specific volume of vapour will be very high okay. So pressure drops due to friction should be minimized because you have to handle a large amount of in terms of volume a large volumetric flow rate of water vapour okay. So either you have to have a large pipes okay, pipe line have got to be large or which is not really economically good. So what you have to do you have to go for smaller pipes. When you go for smaller pipes since a volumetric flow rate is high the velocity will be high once the velocity is high the friction pressure drops will be high okay. This is a typical problem again in water lithium bromide system.

So most of the times in commercial system what is done is this pipelines are minimized okay. You will see that, I will show you the commercial system schematics the pipelines for water side water vapour side are almost nonexistent okay. That is how you can handle the large volumetric flow rate of water vapour in commercial systems okay. So as I said this is in commercial systems so the pressure drop is minimized by using either a twin-drum arrangement or a single drum arrangement okay. I will discuss this a little later.

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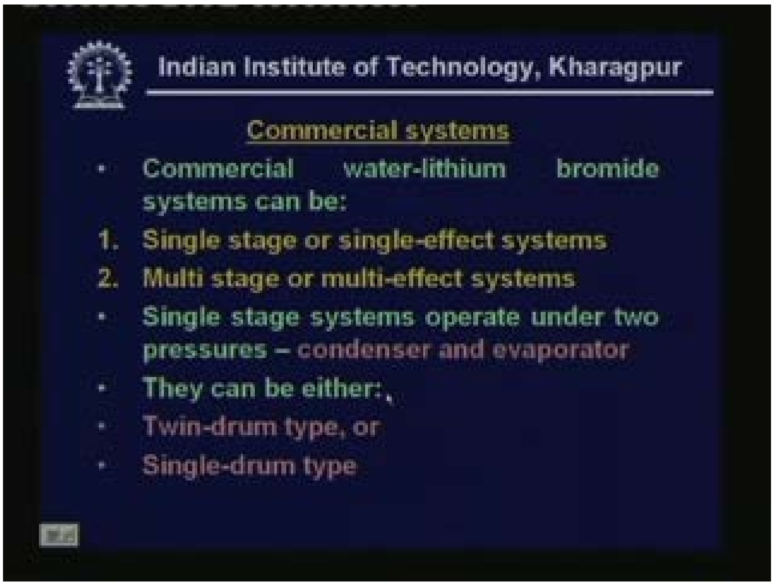

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Commercial systems

- Commercial water-lithium bromide systems can be:

1. Single stage or single-effect systems
2. Multi stage or multi-effect systems

- Single stage systems operate under two pressures – condenser and evaporator
- They can be either:
- Twin-drum type, or
- Single-drum type

Now let us look at commercial systems. Commercial water lithium bromide systems can be a single stage or single-effect systems multistage or multi-effect systems okay. What is a single stage system? In a single stage system there are only two pressures one is a high pressure corresponding to condenser and generator and the other one is a low pressure corresponding to evaporator and absorber. So this is somewhat similar to your single stage vapour compression refrigeration systems where you have one low side pressure and one high side pressure okay. Exactly similar to that in a single stage or single effect vapour absorption refrigeration system you have one low side pressure corresponding to the evaporator and absorber and one high side pressure corresponding to the generator condenser okay. So this is known as single stage or single-effect system. Again the single stage systems can be either twin drum type or single drum type okay. Let me briefly describe twin drum and single drum type.

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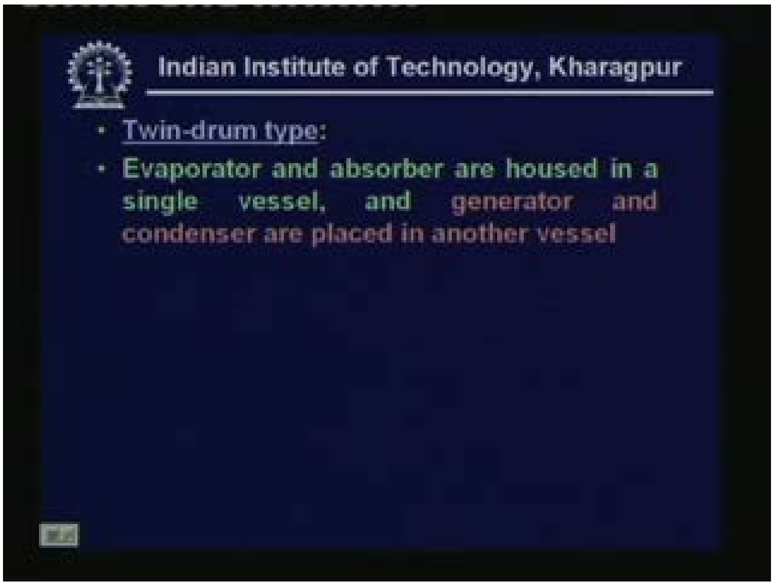

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- Twin-drum type:
- Evaporator and absorber are housed in a single vessel, and generator and condenser are placed in another vessel

Okay, twin drum type system in this system evaporator and absorber are housed in a single vessel and generator and condenser are placed in another vessel okay. So as the name implies this system consisting consist of two drums and one drum or one vessel houses. Both the evaporator and absorber and the other drum houses. Both the generator and the condenser

Okay. This is possible because evaporator and absorber operate at the same pressure almost a same pressure similarly the generator.