**Material and Energy Balances**
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**Module No # 02**
**Lecture No # 06**
**Material Balance Calculations for Single Units Without Reactions - Part 3**

Hello everybody today we are continuing with forming material balance calculation for single unit processes without reactions. We have already looked at many processes you will continue looking at some of the most common processes in chemical and biochemical industries and try to perform material balance calculations on these processes.

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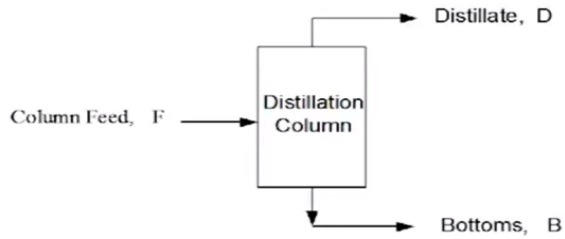
Distillation




- Distillate – more volatile components
- Bottoms – less volatile components
- Separation by boiling
- Perfect separation not possible

The next process we are going to look at distillation, a distillation is a process which tries to separate two liquids based on their difference in boiling point. The distillate which comes out contains the more volatile components and you have the bottom which contains the volatile components. The separation is done by boiling the difference in the boiling point of these material which is entering is used as the way to separate these two.

We need to understand that perfect separation is not possible in distillation you end up getting a mixture in both the distillate and the bottoms the accomplishment which you will get a look for is to get a purer form in your distillate.

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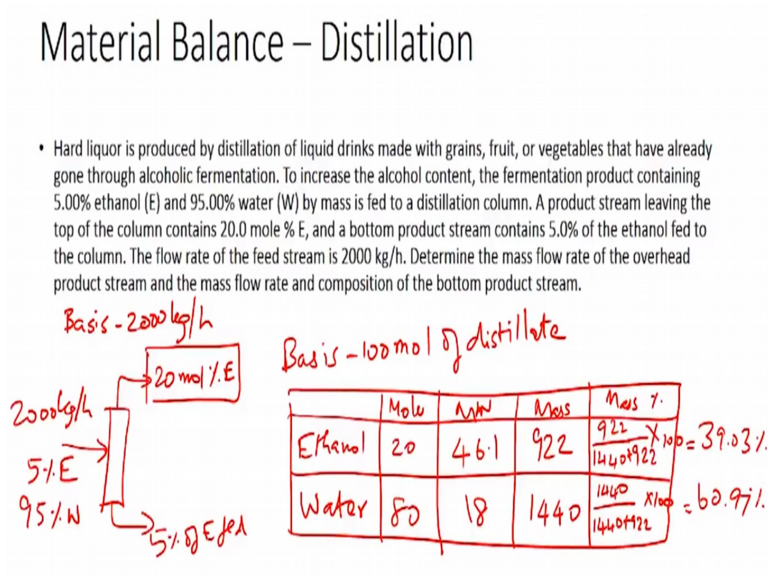


Here is an example problem which we shall try to solve today hard liqueur is produced by distillation of liquid drinks made with grains fruits or vegetables that have already gone through alcoholic fermentation. To increase the alcohol content the fermentation product containing 5% ethanol and 95% water by mass is fed to a distillation column a products stream leaving the top of the column contains 20 mole % ethanol and the product stream contains 5% of the ethanol fed to the column the flow of the feed stream is 2000 kilograms per hour.

Determine the mass flow of the overhead product stream and the mass flow rate and the composition of the bottoms of the product. So now we have been given a lot of information we need to find the basis and draw the flow chart to describe the process. So here I want you to look at the problem statement carefully so there is one flow rate which has been given which we can use as the basis.

So the flow rate of feed entering into the distillation column is given as 2000 kilograms per hour so that would be the basis for our calculation based on the flow rates given in the problem we can identify that the basis for the problem would be 2000 kilograms per hour. So that is the flow rate of the feed stream entering into the system. So we will say that basis is 2000 kilograms per hour and now let us try and draw the flow chart to describe the process.

We have a distillation column which has one feed and two output stream so the feed stream as been told that flow rate is 2000 kilograms per hour and contains 5% ethanol and 95% water so it is has been clearly stated that these percentages represent the mass percentages conventionally liquid and solid streams would be expressed in terms of mass fraction and mass percentages whereas gases are usually represented in terms of mole fraction that is why you would see that the distillate stream which would contain the volatile has been given has 20 mole percentage ethanol.

So this conventional is followed because measuring the volume of gases is a lot simpler and measuring the masses of solid and liquids is easier so when you measure volume for a gas it can be easily converted to mole percentages under ideal gas condition so using mole percentages and volume percentages are more common for gases.

So here it has been told that the distillate stream contains 20 mole % ethanol and the bottom stream contains 5% of ethanol fed so you need to be careful you need to understand that the problem statement clearly says 5% of the ethanol which is leaving the system leaves through the bottom.

This 5% does not represent the mass percentage or mass fraction of the stream so this has nothing to do with the composition of your bottom stream it only says that 5% of ethanol which is entering into the distillation column leaves through the bottom which would mean the rest will be leaving through your distillation. So now if you look at the problem we have one issue when we discuss the fundamentals of solving material balance problems one thing which is told was to convert all the values given either masses or to moles.

Here your feed stream is given in terms of mass fractions and your distillate stream given in terms of mole fraction so to avoid confusion we need to convert one of these to the other so that calculation becomes easier in this case I have chosen to convert the mole percent of distillate into mass percentage how to we go about doing this we already seen an example problem why do not you pass this video and try to continue with that calculation so that you can get the actual mass percentage of the distillation.

Now that you would have been completed it please have a look at how I get it and confirm if you answers are correct to convert the 20 mole % at ethanol into mass percentage we first need to assume a basis of 100 moles of distillate stream which is leaving the system. So we will start with a basis for this conversion alone as 100 moles of distillate as we did in the example problem I the earlier table we will build a table which will help us to convert these mole percentages to mass percentages.

So the table would contain ethanol and you would have so the table would contain the component which are ethanol and water you would have to write down the number of moles each the molecular weight of these streams and the mass of these components and finally you will be able to calculate the mass percentage.

So the moles have been given as 20 mole % and 80 mole % for ethanol and water assuming the basis of 100 moles of distillate we know that 20 moles of ethanol and 80 moles of water would be present in this 100 mole distillate  the molecular weight for ethanol is 46.1 grams per mole and the molecular weight of water is 18 grams per mole so using the molecular weight we can convert the moles to masses by multiplying moles times molecular weight this gives us the mass of 922 grams of ethanol and 1440 grams of water.

So this can be added to find the total and dividing the mass of ethanol divided by the total of these two masses would be 922 divided by 1440 + 922 this times 100 will give you the mass percentage of ethanol and similar 1440 divided by 1440 + 922 times 100 will give you the mass percentage of water so this is calculated to be 39.03% and 60.97% now that we have converted the system these values to mass percentages.

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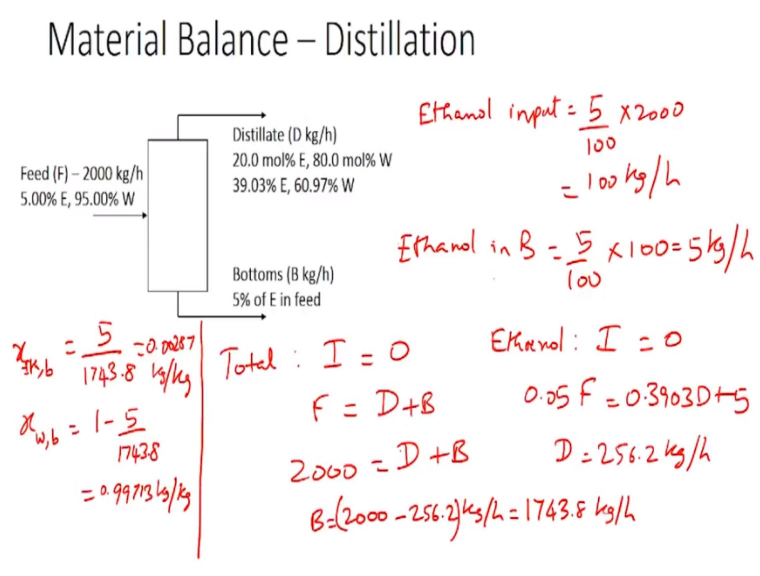


So let us move on to the solving the material balances problem so this flow chart gives you all the information that has been obtain from the problem and all the information that we have these calculated now so he problem statement clearly states that 5% of ethanol entering the system is actually leaving through the bottoms. So we also know that 5% is the mass fraction for ethanol in the feed stream.

So we can calculate the amount of ethanol entering into the system as ethanol input = 5% of 2000 kilogram which is 100 kilograms per hour out of this 5% leaves through the bottom. So ethanol in bottom so ethanol in bottoms would be equal to 5% of this 100 kilograms in entering which is basically 5kilograms per hour leaving through the bottom stream now that we have calculated all the information from the problem let us perform the total and component balances for this system.

What would be the total balance for the system the total balance is given as input = output so input here is F of the feed which is equal to the sum of the distillate and the bottom giving you 2000 kilograms = D kilograms per hour + B kilograms per hour. We can also write a component balance for ethanol and that would look like this again input = output and input for ethanol is 0.05 times F = 0.3903 times D + 5.

So from here we can calculate D as 256.2 kilogram per hour so the distillate which is leaving the system = 256.2 kilograms per hour substituting this back into the total balance equation we can calculate the bottom stream to be B = 2000 – 256.2 kilograms per hour which is 1743.8 kilograms per hour so now we have the information about the mass flow rate of the bottom stream and the mass flow rate of distillate we need to calculator of the bottom stream so that all the information which is required from the problem is complete.

To calculate the mass fraction of the bottom stream we have the information about the mass of ethanol leaving the system through the bottoms and the total mass of the bottom stream. So the mass fraction of the ethanol in the bottom stream would be let us call it as X ethanol in bottom as 5 divided by 1743.8 and the rest would be the concentration of water which would be 1- 5 divided by 1743.8.

So these values are 0.002 87 kilograms per kilogram and 0.99713 kilogram per kilogram which these we have calculated all the parameters that need to be measured for defining these process.

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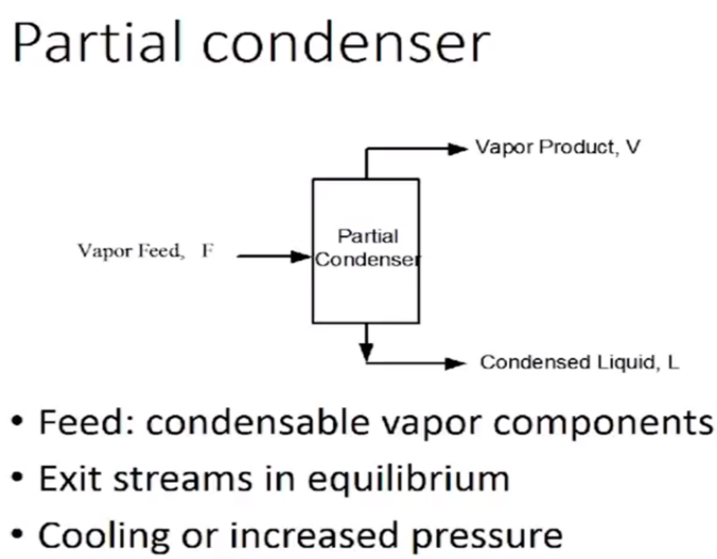


Let us move on to the next process which is a partial condenser for a partial condenser you have a vapor feed which is fed to the condenser some of the vapor feed is condensed to form the condense liquid and leaves through the bottom of the column and the rest leaves as the vapor products so the feed actually would contain the condensable vapor component and non-condensable components of also the exit stream is always in equilibrium.

So that is why you have a vapor product and condense liquid leaving from the system so these process is usually done through cooling or increasing the pressure.

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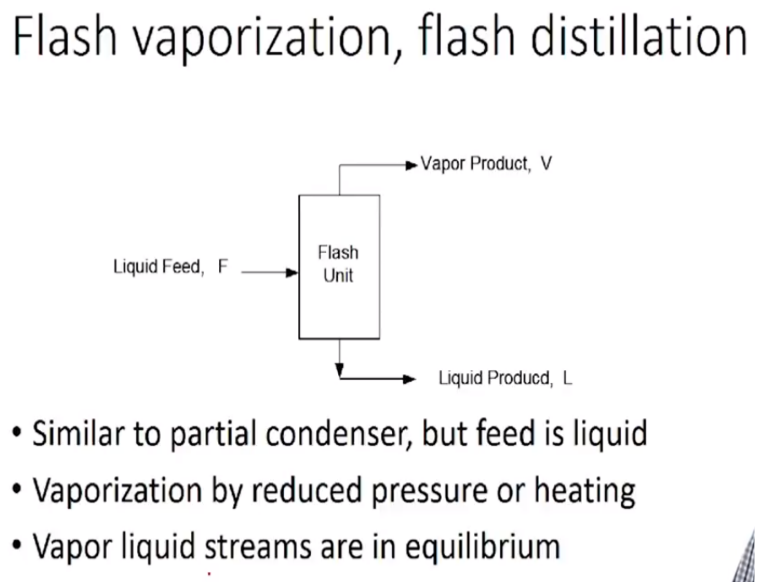


You also have a process called flash vaporization or flash distillation so here what happens is a liquid feed which is fed to the flash unit and you have a vapor product or liquid product leaving the system this is similar to the partial condenser except that feed here is the liquid instead of the vapor which should be the vapor which could be the case in partial condenser.

Vaporization here is done by reducing the pressure or by heating the vapor liquid streams are in equilibrium and they exit the system in equilibrium conditions.

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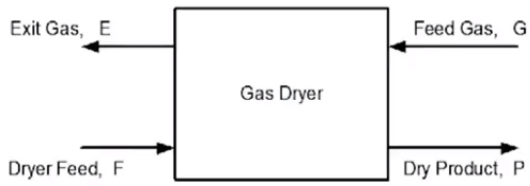
## Gas dryer




- Solvent is transfer from dryer feed to feed gas
- Can be split in to 2 units for analysis
  - Direct dryer
  - Mixer of feed gas and solvent

You also have a gas dryer so the earlier dryer which we looked at the direct dryer where the heat was directly supplied to the system instead you have a gas dryer you have a feed gas which enters into the system and you also have a dryer feed which need to be dried entering into the system. So the volatile components in the dryer feed are evaporated and entered into the feed gas and leave as exit gas and you get the dried product through the other side.

So the solvent is transferred from the dryer feed to the feed gas this process can actually been split into two units the first unit would be the right dryer and the next would be the mixer for the feed gas and the solvent in case of the direct solvent what you would have done is you would have dryer feed and the dryer product and heat being supplied where the solvent exit the stream in the vapor phase.

So the next step could be the vapor phase solvent getting mixed with the feed gas and leaving as the exit so that is why this single process can actually be divided into two processes into analysis.
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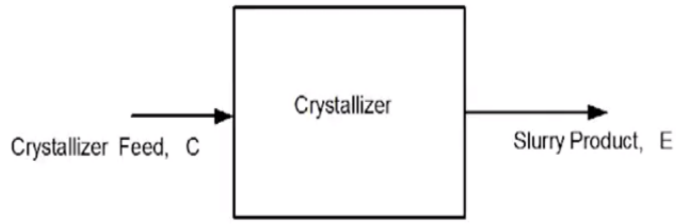
# Crystallizer




- Solid crystals by change in temperature
- Flow sheet may also include a filter

Here is the another common system which is used in many chemical and biochemical industry it is called a crystallizer. A crystallizer feed enters into the crystallizer and you end up with the getting a slurry product which leaves the system so what happens here is solid crystals are produced from the crystallizer feed from change in temperature so this flow sheet many a times would include a filter also because the crystals which are produced need to be separated from the liquid which is accompanying in the slurry.

So for this reason you would have a filter attach to this remove the solids from the slurry and the liquids can be sent out as the filter.

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# Material Balance – Crystallization

- A tank holds 10000 kg of a saturated solution of $Na_2CO_3$ at 30°C. You want to crystallize from this solution 3000 kg of $Na_2CO_3.10H_2O$ without any accompanying water. To what temperature must the solution be cooled?

| T (°C) | Solubility (g $Na_2CO_3$/100 g $H_2O$) |
|---|---|
| 0 | 7 |
| 10 | 12.5 |
| 20 | 21.5 |
| 30 | 38.8 |

Here is an example problem for a crystallization for process a tank holds the 10000 kilograms of the saturated solution of NA2CO3 at 30 degree Celsius you want to crystallize from this solution 3000 kilograms of NA2CO3 10H2Owithout any accompanying water to what temperature must the system be cooled. Now until this point every material balance problem that we have performed that we have always asked us to calculate mass flow rate or mass action or mole flow rate or mole fractions.

Here the problems statement ask us to calculate temperature so that is the reason we are giving with addition data which is the solvability of NA2CO3 in water if you look at this data it shows the dependent of the solvability of NA2CO3 with respect to temperature you have been given solvability in the terms of grams of NA2CO3 per 100 grams of water you need to carefully understand that these units are grams of solute per 100 grams of water when you are using these values you should appropriately use the correct there by eliminating any error okay.

Now let us move on to see how we go about solving these problem and how do we arrive at the temperature finally.

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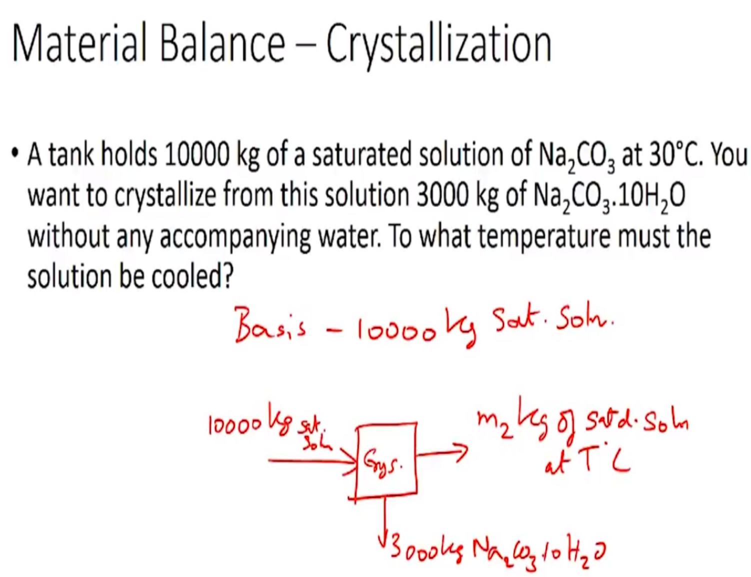


As with every other material balance problem kilograms of saturated solution so we will go with 10000 kilograms as the basis. So we write down the basis as 10000 kilograms of saturated solution now we need to identify the flow chart which describe this process so we have a crystallizer and we have 1 feed which is the saturated solution entering as 10000 kilograms of saturated solution and we have two different stream which will come out.

So the problem says that we will have 3000 kilograms of NA2CO3 10H2O leaving the system and the rest will be leaving in the form of the solutions. So these would be a saturated solution which we do not know the mass so we call it M2 kilograms of saturated solution at T degree Celsius as we do not know the temperature we need to finally calculate what these T is.

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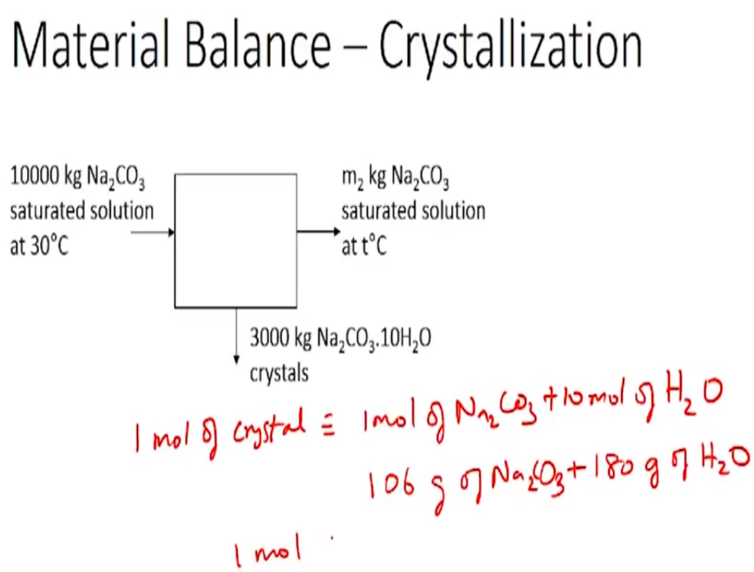


So now we have the flow let us see if we can solve this problem so the solid crystal which are leaving the crystallizer are actually not just NA2CO3 they contain the water of hydration which is the 10H2O molecule which are attached with every molecule of NA2CO3. So now we need to calculate the mass fraction of NA2CO3 in the 3000 kilogram which is leaving in the form of crystals.

So for that we need to understand the molecular wright of NA2CO3 and the molecular weight of 10H2O and use that for calculating the mass fraction so one mole of the crystal contains 1 mole of NA2CO3 and 10 moles of water. So the mass fraction can be calculated using the molecular weight so 1 mole of NA2CO3 technically contains 106 grams of NA2CO3 and 180 grams of water.

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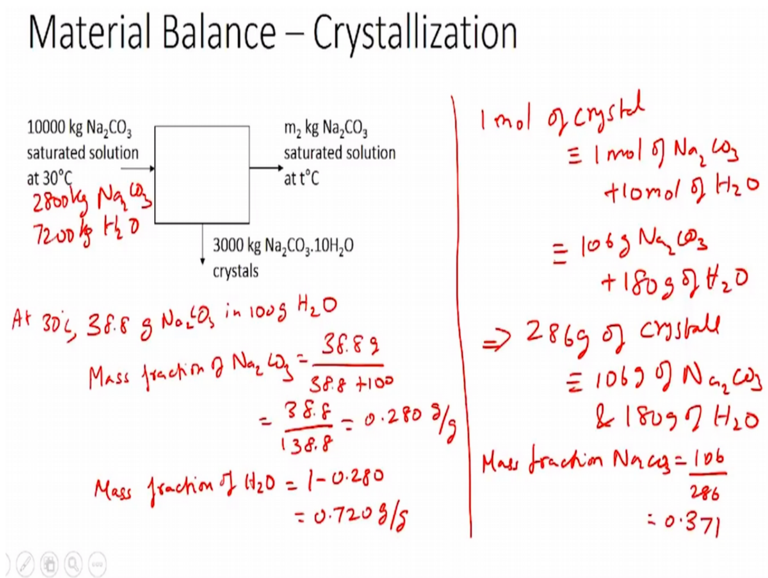


So the 1 mole of the crystal so now that we have calculated now that we have drawn the flow chart and identified the basis let us look at solving this problem. So there are few things which we need to understand clearly so we have been told that 10000 kilogram of saturated solution of NA2CO3 is entering the crystallizer first we need to know what is the mass fraction for NA2CO3 in the saturation solution.

For this we can use the solvability data so the solvability data tells us that 38.8 grams of NA2CO3 can be dissolved per hundred grams of water. So at 30% Celsius the saturation data is 38.8 grams of NA2CO3 in 100 grams of water will give you a saturated solution this is at 30 degree Celsius. This means the mass fraction of NA2CO3 can be given as 38.8 grams divided by total mass of solution which is 38.8 + 100 giving you 38.8 divided by 138.8 which is 0.280 grams per gram.

So mass fraction of water into the solution entering would be 1 – 0.280 giving you 0.720 grams per gram. So this means we have 2800 kilograms NA2CO3 and 7200 of water entering the system so the next step is to identify the mass fraction of NA2CO3 in your exit streams. The first exit stream is the crystal although this is only the solids this also contains water which is the water of hydration you can see that every mole of NA2Co3 is accompanied by 10 moles of water to form the crystals.

So 1 mole of crystal basically contains 1 mole of NA2CO3 and 10 moles of water so we can calculate the mass fraction of NA2CO3 using this system 1 mole of crystal contains one mole of NA2CO3 + 10 moles of water which is 106 grams of NA2CO3 and 180 grams of water so this implies 286 grams of crystals will contain 106 grams of NA2CO3 and 180 grams of water so mass fraction of NA2CO3 in the crystals would be equal to 106 divided by 286 which is 0.371.

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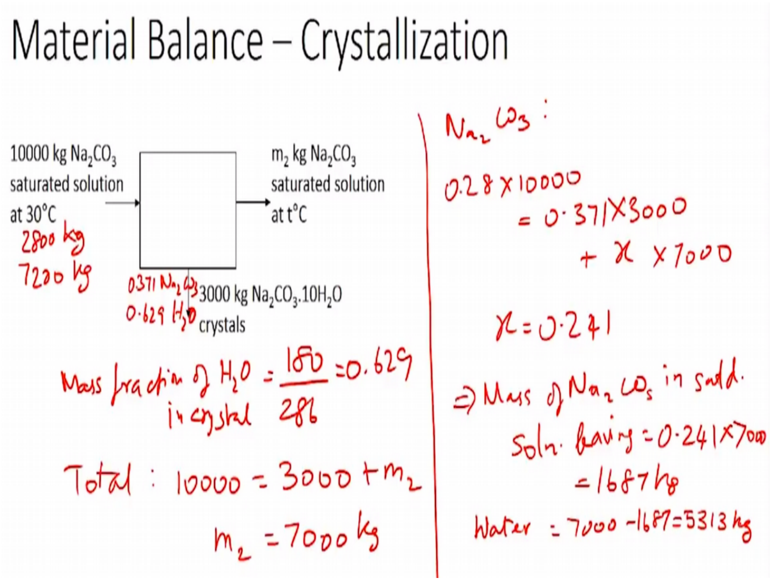


Similarly mas fraction of water in the crystals would be 180 / 286 or 1-0.371 giving you a value of 0.629. So now that we have all the information about the mass fraction let us go ahead and perform the balance equations. So let me just fill this table so that we have all the information that we calculate. So we had calculated that the mass of NA2CO3 entering in through the solution is 2800 kilograms and water is 7200 kilograms and we have calculated the mass fractions for these NA2CO3 and water here as 0.371 NA2CO3 and 0.6329 water.

So if you were to write the balance equation we can start with the total balance which would be 10000 kilograms feed entering would be equal to 3000 kilograms crystals + M2. So M2 will be equal to 7000 kilograms so the next step is to perform the component balance. NA2CO3 balance can be written as follows.

So you have 0.28 times 10000 which is entering which is 2800 and you have 0.371 times 3000 as the mass of NA2CO3 leaving the crystal + an unknown concentration of NA2CO3 in the saturated solution leaving which will be called as X times 7000 which is the mass of the saturation solution. Now using this equation we can calculate the mass fraction of NA2CO3 which is leaving along with the saturated solution.

So this value can be calculated as X = 0.241 so based on this mass of NA2CO3 in the saturated solution leaving = 0.241 times 7000 which gives you a value of 1687 kilograms. So water in the same stream would be equal to 7000 – 1687 which is 5313 kilograms. So now that we have these values we can calculate what would be the solubility here.

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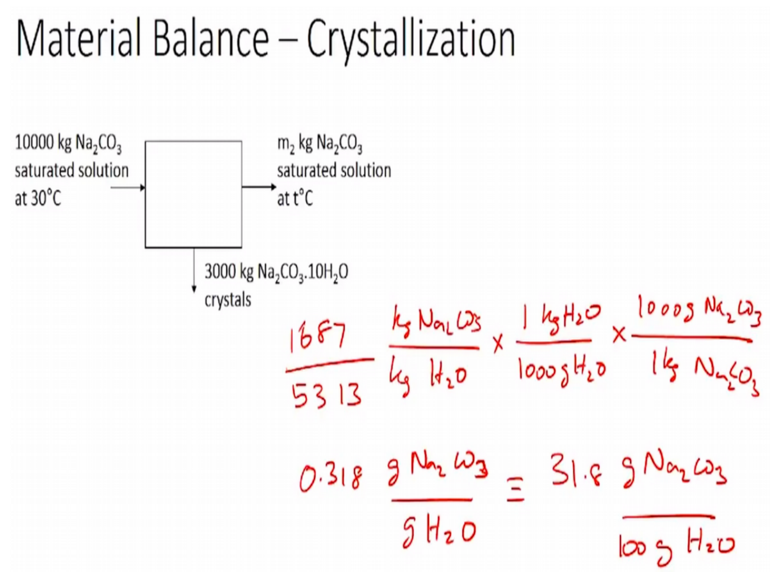


Now that we have calculate the mass of NA2CO3 and the mass of H2O leaving through the saturation solution we can calculate the solubility data for this particular stream when we look at the solubility table which was given we knew that the units which we used was grams of NA2CO3 per 100 grams of water. So we need to calculate the same units for this particular streams also.

For this what we will do is we know that the mass of water which is leaving 5313 and the mass of NA2CO3 which is leaving is 1687. So these are given as kilograms of NA2CO3 per kilogram of water now first thing we need to do is convert these kilograms to grams so that we can do by 1 kilogram of water divided 1000 grams of water times 1000 grams of NA2CO3 divided 1 kilogram of NA2CO3 by doing this you would get the values of solubility in terms of grams of NA2CO3 per gram of water.

So that value would be 0.318 grams of NA2CO3 per gram of water as we needed to calculate the amount of NA2CO3 dissolved in 100 grams of water multiplying this with 100 would give you 31.8 grams of NA2CO3 dissolved in hundred grams of water so this would be the solvability data which you will use to fit in the curve we can generate through the data provided.

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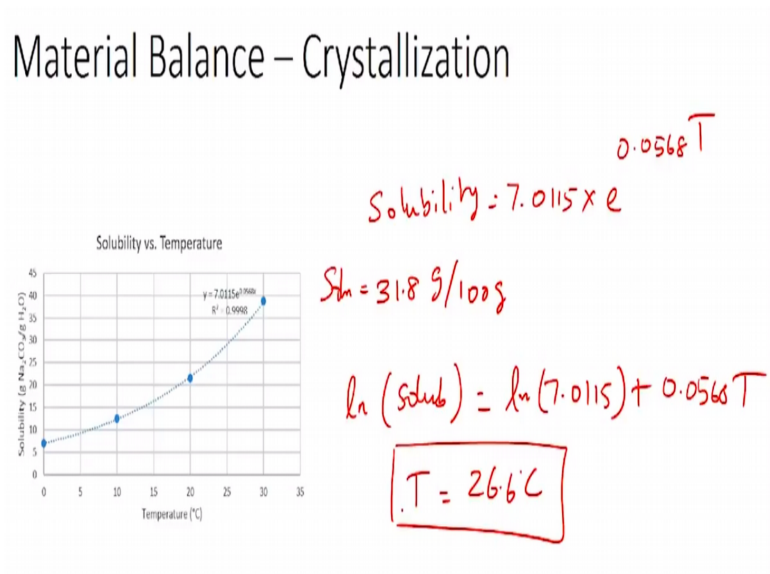


So if you look at the curve this is the solvability data plotted against temperature so we had the values for temperature and we plotted it using excel and the curve which we obtained was fitted for an exponential curve so the equation which fits this curve a very nice R-squared value also the equation is Y = 7.0115 e-power 0.068X where Y is the solvability and X is the temperature.

So now we can actually plug in the value for solvability that we calculated which was 31.8 and we can try to calculate the temperature from the equation so what do for that is the equation is written down as solubility = 7.0115 times E-power 0.00568T where T is the temperature. So we calculate the solubility for the exit stream as 31.8 grams of NA2CO3 per 100 grams of water. So that needs to be used.

So taking the logarithm on both sides we can actually get lon of solubility equals lon of 7.0115 + 0.01568 T. Substituting the value of solubility here we can calculate the temperature to be 26.6 degree Celsius by cooling the temperature by cooling the temperature of the stream entering at

30 degree Celsius to 26.6 degree Celsius we can actually crystalize 3000 kilograms of NA2CO3 10 is to O crystals.

So with that we conclude the lectures for today I hope you have understood the principles of distillation and crystallizer so in tomorrow lecture we will talk about filtration which is an important process in any downstream operation and we will discuss the fundamental associated with that and how to perform material balance for a filtration process thank you.