Material and Energy Balances

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Module No # 01
Lecture No # 05
Material Balance Calculations for Single Units Without Reactions - Part 2

Hello students so in last class we looked at some of the simple processers and solved simple problems for material balances and on operation which are single units without reactions. In today's class also you will continue the same we will look at some other processes and perform more example problems to get ourselves familiarized with the systematic approach of material balances.

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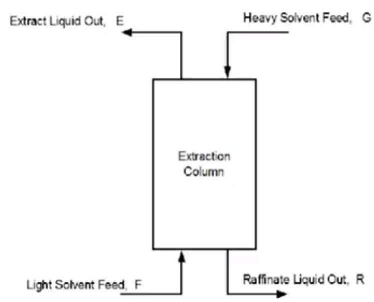
Leaching & Extraction



- Two immiscible solvents with different specific gravities
- At least one component transferred
- Liquid-liquid extraction and Liquid-solid extraction

Leaching and extraction is a very common process which should be seen in the downstream operations of any chemical and biochemical industries. Leaching is a process in which a light solvent feed is fed and another heavy solvent feed is fed. The heavy solvent feed basically contains the component of interest which gets transferred to the light solvent feed and the light solvent feed leaves the system as the extract whereas the heavy solvent feed leaves the system as a raffinate.

So basically there are two immiscible solvent with different specific gravity it is ensured that at least one component of interest is transferred from the heavy solvent feed to light solvent feed.

And this system can either be liquid-liquid extraction or liquid – solid extraction. You need to be familiar with the terminologies which are used here a light solvent feed is the one which has lesser concentration of the component of interest and heavy solvent feed would have the higher concentration of the component of interest.

Extract is the product stream which contains the component of interest and raffinate is the waste stream which leaves the system. The raffinate could be either or be discarded or be recycle.

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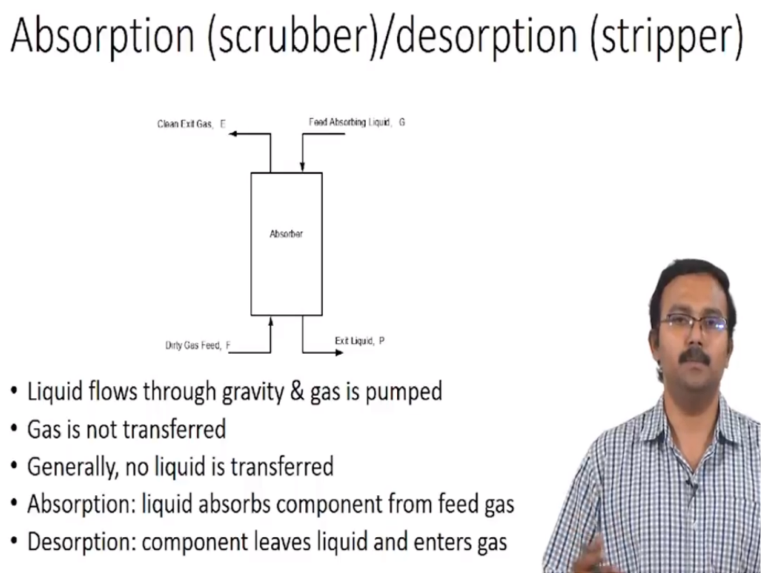

You also have an absorption or desorption system which looks very similar to the extraction process which we looked at. So in this case the difference is there is a liquid and gas instead of two liquids and liquids under solid. You have the liquid which flows from the top to bottom because of gravity and the gas is pumped from the bottom and leaves through the top gas itself is not transferred liquid is not transferred usually however there is one component which is transferred between the liquid and the gas.

In case of absorption the liquid absorbs the components from the feed gas and in these options the components leaves the liquid enters the gas. So these are the two system which are similar and we have been seen in many chemical and biochemical industries.

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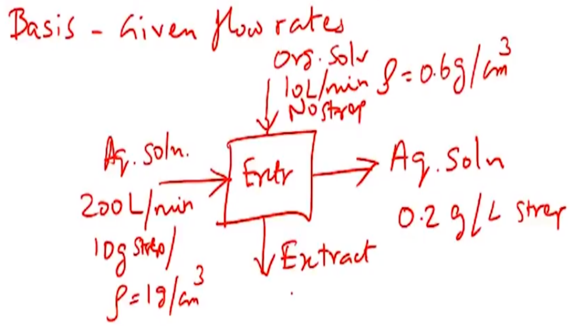
Material Balance – Extraction

- 200 L/min of aqueous solution containing 10 g/L Streptomycin is contacted by 10 L/min of organic solvent. The exit aqueous solution contains 0.2 g/L Streptomycin. Determine the mass fraction of Streptomycin in the exit organic solvent assuming that Streptomycin is the only component that transfers. Assume density of aqueous solution is 1 g/cm^3 and the density of organic solvent is 0.6 g/cm^3.



Let us look at a simple example problem which will help us better understanding the systems and perform material balance calculation for such a system. The problem statement says 200 liters per minute of aqueous solution containing 10 grams per liter of streptomycin is contacted by 10 liters per minute of organic solvent.

The exit aqueous solution contain 0.2 grams per liter streptomycin determine the mass fraction of streptomycin in the exit organic solvent assuming that streptomycin is the only component that transfers that assume density of aqua solution is 1 gram per centimeters cube and the density per organic solvent is 0.6 grams per centimeter cube. Let us try to convert this word problem into a flowchart before we do that we first need to understand the basis for solving this problems.

For this particular problem we have multiple problems which have been given as I have mentioned earlier the way you define a basis is based on what information has been provided to you. Here because multiple flow rates has been given you could either choose all the flow rates as the basis or you can choose the time as the basis and convert these flow rate into volumes and masses respectively.

So for this example I will be using the flow rates which have been given as the basis so we can write the basis as the given flow rates. Now that we have identified as the basis the next step is to convert these word problem into a flow rate so this process is an extraction process which has two inputs and two outputs the first input is an aqueous solution which enters into the system containing the streptomycin and the second input is organic solvent which also enters into the system but foes not contain any streptomycin.

So you also have two exits stream one being the extract which is the organic solvent leaving with the streptomycin and you also have a raffinate which leaves the system as waster product which is basically the aqueous solution containing very low concentration of streptomycin. Now let us label this flowchart with all the information that has been given in the problem.

So this is the extraction process and you have the aqueous solution entering the system at 200 liters per minute and it contains 10 grams of streptomycin per liter and the density has been given as 1 gram per centimeter cube. You also have the organic solvent which is entering the system which is entering as 10 liters per minute containing now streptomycin. So the density of the organic solvent is given as 0.6 grams per centimeter cube.

We have two exit streams one is the aqueous solution which contains 0.2 grams per liter of streptomycin and you have an organic solvent which is extract leaving the system as the product we do not know the concentration of the streptomycin in this particular stream having written all these information let us try and solve these problem.

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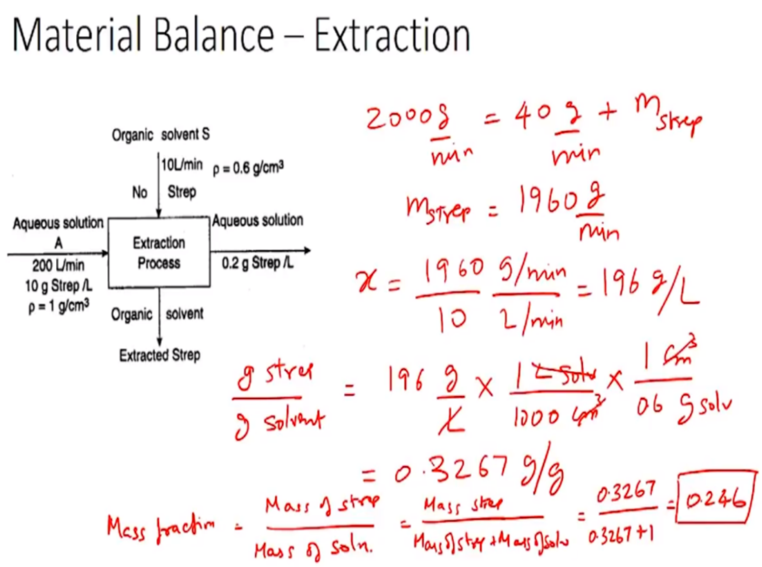

Extraction is the process where two immiscible liquid come in contact with each other these have two different specific gravities which means there is actually no transfer of liquid which is happening only the dissolve components streptomycin which is being transferred from the aqueous solution to the organic solvent. This means the volumetric flow rate of aqueous solution which is entering will be equal to the volumetric flow rate of the aqueous solution leaving.

Similarly the volumetric flow rate of the organic solvent will entering will be the same as the organic flow rate of the extract which is leaving the system. So this means these systems would have a flow rate of 200 liters per minute and this would have the flow rate of 10 liters per minute. As I had mentioned in the earlier classes where we discussed the fundamentals of the material balance it is ideal not to use the volumetric flow rate while we are writing material balance.

So we can convert these into masses using the density has been provided so now that we have the volumetric flow rate for these two streams we can actually convert these volumetric flow rates into masses and if you were to write a total balance equation we would find that the equation is trivial because all the total masses of each of the stream are known. So it does not make sense to write total balances for this system.

Instead we can start with component balances let us try to write a component balance for streptomycin balance input- output + generation – consumption = accumulation. So this being system without any reaction we would not have generation or consumption and considering the system to be at steady state we would also have accumulation to be 0. So we end up with equation which is input = output what are the steps through which streptomycin enters the system?

The streptomycin enters only through the aqua solutions the organic solvent does not contain any streptomycin. So this means the input stream for streptomycin is 200 liters per minute times 10 grams of streptomycin per liter. So the mass flow rate of streptomycin into the system would be 2000 grams per minute. Now we need to calculate the output flow rates for streptomycin we know that the concentration of streptomycin is raffinate solution which is leaving is 0.2 grams per liter.

So in the aqueous solution you have an output of streptomycin as 200 liter per minute times 0.2 grams per liter. So this means in the aqua solutions you have 40 grams of streptomycin leaving the system per minute. Now if you where to continue with the balance equation we would have 2000 grams per streptomycin entering the system = 40 grams per liter of streptomycin leaving through the aqueous solution + the mass of streptomycin leaving through your organic solvent.

So this would be 1960 grams per minute based on the balance equation we have now identified that 1960 grams of streptomycin leaves the system per minute in the form the organic extra. We now need to calculate the concentration of streptomycin in the organic solvent which is the extract. We know the volume the volumetric flow rate is 10 liter per minute for the organic solvent.

Considering that the concentration of X the streptomycin in the organic solvent which is the extract would be 1960 divided by 10 grams per minute divided by liters per minute giving you 196 grams per liter. So this gives you an concentration of streptomycin in the extract the question asked for the mass fraction of streptomycin is the extract. How do we convert this concentration to mass fraction.

For converting concentration to mass fraction we first need to have an understanding of what the mass fraction means what is the definition for mass fraction. Mass fraction is defined as grams of streptomycin per gram of solution so for calculating this we would first required to calculate grams of streptomycin per gram of solvent which is easy to get from your concentration let us first do that.

Grams of streptomycin per gram of solvent would be equal to concentration of streptomycin which is 196 grams per liter which needs to be converted to grams per gram so that means 1 liter of solvent needs to be converted to mass or grams how would you go about doing that? We know the density of solvent so we can convert these liters into grams of solvent so that would be converting liters to centimeter cube we would have 1 liter of solvent divided by 1000 centimeter cube times I centimeter cube by 0.6 grams of solvent.

So now this liters which is here in the concentration and the liter in the conversion factor can get cancelled because both of these represent 1 liter of the solvent the centimeter cube of these two terms can also be cancelled because both of them represent the volume in terms of the centimeter cube of the solvent. However the grams terms cannot be cancelled because this represents the two different grams the first one 196 gram represents 196 grams of streptomycin and the denominator represents 0.6 grams of solvent.

So this is why you would end up with a dimension less number in terms of these particular mass ratio but these would not be unit less. So you end up with the value of 0. So you end up with the value of 0.3267 grams per gram so this is the mass ratio. As I already said mass fraction would be grams of streptomycin per grams of solution not per gram of solvent.

So now we know that there is 0.3267 grams of streptomycin per gram of solvent which means 0.3267 grams of streptomycin is present in 1+ 0.3267 grams of solution basically the calculation goes like this mass fraction is equal to mass of streptomycin divided by mass of solution which is mass of streptomycin divided by mass of streptomycin + mass of solvent. So the ratio is 0.3267 divided by 0.3267 + 1 giving you a final value of 0.246.

So this is the mass fraction of streptomycin in the extract I hope you are able to follow these problem please try this problem by yourself so that you would be able to understand the fundamental which are explained here this would be a simple example problem which uses the concepts of mass fraction and mass ratio and also explains how material balances can be written for this type of a system.

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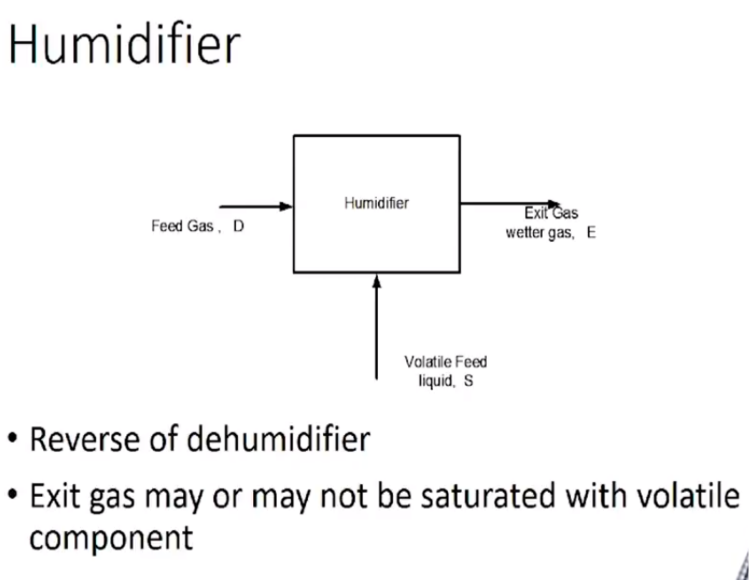

Let us move on to the next type of the process dehumidifier is the common process which is seen in chemical and bio chemical industries here a feed gap which is considered to be a moist gas enters into the dehumidifier and you have exit streams one being the exit gas and other is the density liquid. So the feed stream contains an condensable and non-condensable components.

So condensate which is formed is the liquid which contains only the condensable component and you have a dry exit gas which contains the non-condensable component. So the exit gas does not have to be fully dry it can still contains some of the condensable components along with the non-condensable component. You also have the reverse of the dehumidifier which is called the humidifier the field gas is the dry or gas it enters along with the volatile field liquid and the exit gas ends up being a wetter gas compared to feed gas.

So these two system are very commonly seen in many chemical and bio chemical process we would need humidified or dehumanized as because we would want to maintain the concentration of water vapor present in the air to ensure that process as take place as required. For this reason dehumidifier and humidifiers are used very commonly depending on the environment in which the process are taking place.

In case of humidifier as you might end up with the gas which is either saturated or no saturated in some cases you might want saturated as which is saturated the air which is saturated with the volatile component.

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Material Balance – Humidification

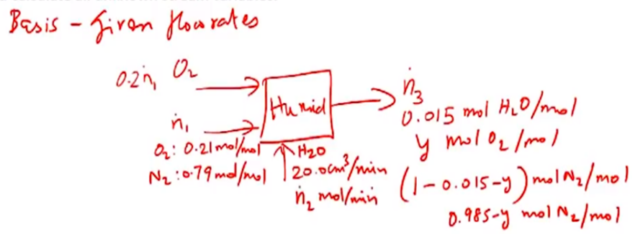
- An experiment on the growth of certain organisms requires an environment of humid air enriched in oxygen. Three input streams are fed into an evaporation chamber to produce an output stream with the desired composition.

  A: Liquid water, fed at a rate of 20.0 cm^3/min

  B: Air (21% O_2, the balance N_2)

  C: Pure oxygen, with a molar flow rate one-fifth of the molar flow rate of stream B

  The output gas is analyzed and is found to contain 1.5 mole % water. Draw and label a flowchart of the process, and calculate all unknown stream variables.



Here is an example fro problem for humidification the experiment on certain growth of certain organisms required and environment of humid air enriched in oxygen. 3 input streams are fed in an evaporation chamber to produce an output stream with the desired composition liquid water which is fed at a rate of 20 centimeter cube per minute the second stream contains air per 21% oxygen and the rest is nitrogen.

And we have the third stream which is pure oxygen with the molar flow rate of one fifth of the molar flow rate of the stream B. The output gas is the analyzed and is found to contain 1.5 mole percent water you are asked to first draw and label the flowchart for the process and calculate all the unknowns stream variable so let us now start with identify the basis for this problem. So the base for this problem would be all the flow rates would be so specifically we have all the flow rate for stream A which is liquid water and it is given as 20 centimeter cube per minute.

So we will assume the basis as given flow rates now let us try and draw a flow chart for the system so this is the humidifier which has three input streams and one output streams. So you have the liquid water entering at 20 centimeter per cube per minute and you have oxygen which is entering into the system as pure oxygen and you have air which is entering the system containing 0.21 moles of oxygen per mole and nitrogen is 0.79 mole per mole.

So we can assume that the molar flow rate for the system is N.1 and it has been given for the flow rate for pure oxygen is one fifth the molar flow rate of stream B which would mean this stream oxygen flow rate of 0.2 N1 you have output stream let us just assume from the flow rate to be N3 naught and this contains 1.3 mole percent of water which is 0.015 moles of water per mole.

So the rest would contain oxygen and nitrogen let us assume that why is the moles fraction of oxygen in the exit stream which would mean you can write the mole fraction of oxygen as Y moles of oxygen per mole and knowing that all the mole fraction add up need to 1 the mole fraction of nitrogen can be written as 1 – 0.015 – Y moles of nitrogen per mole which comes down to 0.985 – Y moles of nitrogen per mole.

So volumetric flow rate which has been given for water should also be converted to molar flow rate. So that we would have all the flow rates in terms of molar flow and we will be able to apply them easily so it is important that we convert the flow rate of water to molar flow rate instead of mass flow so we will call the molar flow rate as water as N2 moles per minute. Now that we have drawn the flow chart let us go about and try to solve this problem.

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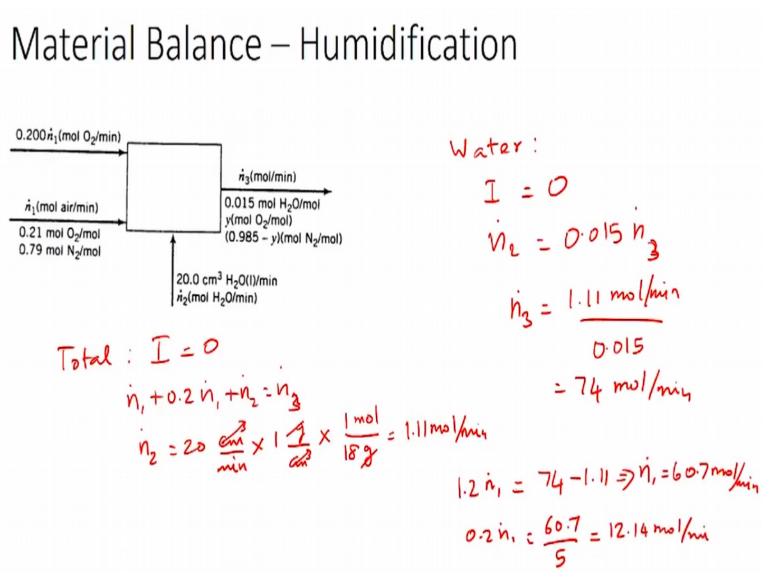

As usual we can write total balances and component balances for any of the system given let us first start with the total. So the total balance for the system would be input = output so the input is you have N1. + 0.2 N1. + N2. = N3. So all these are the molar flow rates which have been given now we can calculate the N2. Because we know the volumetric flow rate of water.

So N2. is calculated as 20 centimeter cube per minute multiplied by density which is 1 gram per centimeter cube which again is converted to number of moles by dividing it with molecular which is 18 gram per mole. So now these centimeter cube gets cancelled grams get cancelled and you end up with 20 / 18 moles per minute which is 1.11 moles per minute. Now that we have in to we can substitute to the first equation we can also write a component balance for water so let us write this water balance.

So the water balance would be again input = output input term for water is only through the liquid water stream we know the concentration of molar flow rate is N2. = 0.015 N3. Now that we have already calculated into N2. We can calculate N3 dot in this equation so N3. = 1.11 moles per minute divided by 0.015 which gives you a value of 74 moles per minute. So the final humid air which is leaving the system is leaving at a molar flow rate of 74 moles per minute.

We still need to calculate the concentration of oxygen and nitrogen in the final stream only when the entire flow chart will be completed what balance can we write to do that. So the total molar flow rate of the product stream as been calculated to be 74 moles per minute indicating that 74 moles per humid air leaves the system per minute.. We still need to calculate the mole flow rate of air and the oxygen which is entering the system.

This we can do by substituting N2 and N3 in the first equation which is total balance equation so substituting them there you would get 1.2N1. = N3. Which is 74 –N2. Which is 1.11 there by you can calculate N1. As 60.7 moles per minute. So the molar flow rate of air which is entering the system is 60.7 moles per minute so the flow rate of pure oxygen which is entering the system which is one fifth of this. So thereby your oxygen flow rate would be 0.2 N1. Which is 60.7 divided by 5 going you have value of 12.14 moles per minute.

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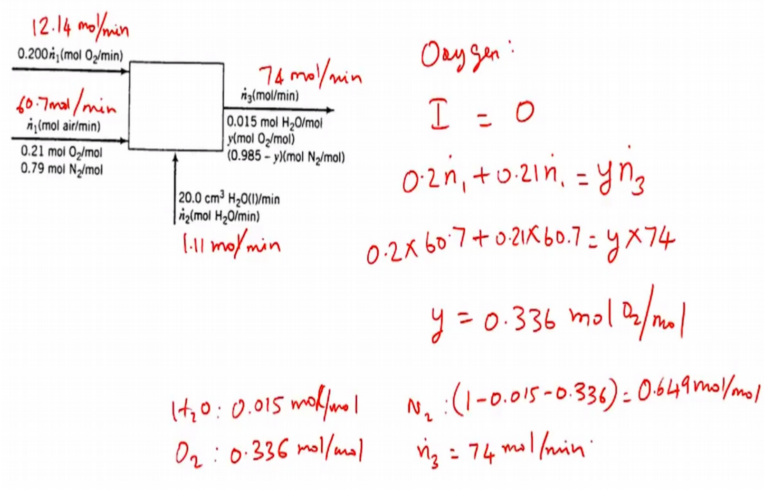
Material Balance – Humidification



So now we have calculated the flow rate of each of the streams so we can fill that information there so in this flow chart we have flow rate of air which is 607 moles per minute. We have the flow rate of water which is calculated as 1.11moles per minute and we have the flow rate of humid air leaving the system as 74 moles per minute and the flow rate of oxygen entering into the system would be 12.14 moles per minute.

Now that we have all the mole of flow rates the only thing which we remains is he concentration of oxygen in the humid air which is leaving the system. To calculate the concentration of nitrogen and hydrogen in this humid air we would have to write another component balance equation we can choose to write oxygen balance for this and that is exactly what we are going to do.

You are writing an oxygen balance you again have input equals output oxygen entering into the system through 2 of the streams 1 being the air stream and the other is your oxygen stream. So you can write this as 0.2N1 dot + 0.21N1 dot and the exit stream would be oxygen leaving through the midair as concentration of oxygen is Y will say it as YN3 dot. We already know the value for N1 dot and N3 dot substituting those values there we can write it as 0.2 times 60.7 + 0.21 times 60.7 = Y times 74.

So solving his equation we can calculate Y as 0.336 moles of oxygen per mole so now with this we have the composition of the exist stream also. The exit stream would not contain 0.015 moles per mole of water it would contain 0.336 moles per mole of oxygen and the rest is nitrogen. So nitrogen would be 1- 0.015 – 0.336 giving you a value of 0.649 moles per mole and the total molar flow rate exit stream is 74 moles per minute.

With this we have solved for all the parameters which are there in this process and we have completed the flow chart hopefully the concepts which is we covered through this examples to this processes have you helped you to understand the process for performing material balance calculation in non-reactive system. There are more examples and more processes which we look at so we will do that in the next class.