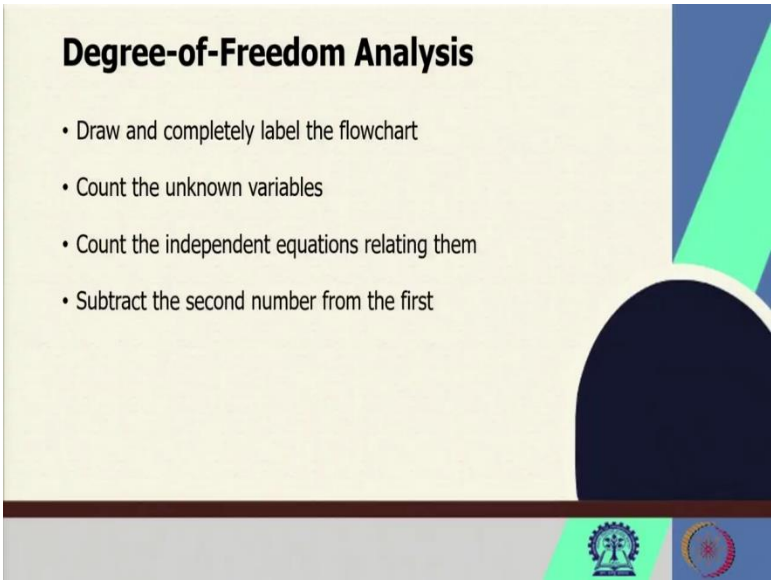
Material and Energy Balance Computations
Prof. ARNAB ATTA
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Lecture –10
Material Balance of Single-Unit

Hello everyone, welcome back once again in the NPTEL online certification course on Material and Energy Balance Computations. We are in the final lecture of module 2 that is on material balance calculation, the fundamentals and its application in a single unit. So we were discussing the material balance for a single unit processes.

(Refer Slide Time: 00:40)

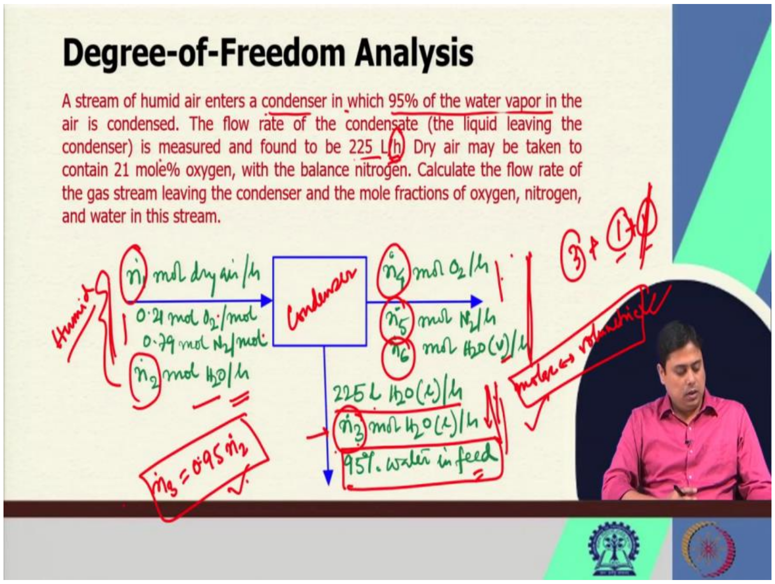


Now while doing so; we realised that we have to understand whether the problem statement that is given whether we have sufficient information go ahead and solve the problem or not. Because once you start solving it and then after spending some time we realise that this information is not given or that information is needed. Then this is the wastage of both time and effort. So, the degree of freedom analysis comes in handy in such case that we have to analyse at first whether the problem that is given has sufficient information to solve the problem or not.

To do so what we have to do is to draw and completely level the flowchart. We have to count the number of unknown variables. We have to count the number of independent equations that we can write relating those unknown variables, and then we have to check the difference between these two. If there is no difference, that means the degree of freedom is zero where the degree of freedom is defined as I said, it is say $n_{unknown}$ and this is if I say $n_{independent}$ then basically $n_{unknown} - n_{independent}$ is the degree of freedom.

In order to solve a problem, the degree of freedom has to be zero. If it is greater than one, which means we have more number of unknown variables than the number of independent equations that we can write relating those variables then the problem is under specified. Not sufficient information has been provided. If the difference is greater than zero that means excessive information has been given, and those may be redundant, or there may be some issue or some error with the reporting of the values. So again, do not solve that problem check the consistency.

(Refer Slide Time: 03:23)



So say we have a problem statement like this that a stream of humid air enters a condenser in which we have 95% water vapour in the air that is condensed. The flow rate of the condensate that means the liquid leaving the condenser is measured and is found to be 225 l/h. The dry air that may be assumed that it contains 21 mol % oxygen with the balance nitrogen. Now I mentioned earlier as well that such kind of statement when it is not mentioned that what is the composition of dry air, we still typically considered that it is of 21 mol % Oxygen and rest Nitrogen, but since this is the beginning of these material balance calculations, it is being specified again and again.

So, we have to calculate the total flow rate of the gas stream leaving the condenser and the mole fractions of oxygen, nitrogen and air in this stream. So now we understand the utility of drawing a flowchart because we have to simplify these wordings and present it in a schematic.

So what we do is we draw the schematic at first and we level it in detail. So there is no flow rate of the input stream is mentioned. We have the scenario that we have a condenser where we have humid air comes in humid air means the combination of dry + some moisture. Both the combination is not known so to simplify the scenario we assume that we have $\dot{n}_1$ mole of dry air per hour that is coming into the condenser and at the same time we have $\dot{n}_2$ moles of water in that air.

And if you combine this dry air + moisture it becomes humid air. So, humid air has this combination. The dry air part and the moisture part so in the condenser what happens the water condenses and it flows and is collected as liquid and the rest evaporate or the rest goes out from the system as vapour. So now the point is that here one thing is mentioned if we read the problem statement couple of times that the flow rate of the condensate is measured and is found to be 225 l/h.

That is this stream where we have the water that is being condensed this is the flow rate, the volumetric flow rate of water. Now, when we write these unknown variables on the flowchart that means this $\dot{n}_1$ and $\dot{n}_2$ the unit should be consistent that is per hour, the molar flow rate per hour. This is the thing we have to remember the unit has to be consistent while writing or levelling the flowchart for the sake of simplicity in subsequent calculations.

Now the dry air here contains 21-mol % oxygen which means 0.21 mol of oxygen per mol of this dry air, and the rest, which is 0.79 mol of nitrogen per mol of this dry air. This is the amount of water per hour or the moisture content. In the output stream, we have 2 output streams one is the condensate that is going out from the condenser as water. The other one will contain definitely then the other species and some of the water vapour because not all water is being condensed here.

So those are labelled as $\dot{n}_4$, $\dot{n}_5$ and $\dot{n}_6$ for oxygen, nitrogen and water vapour respectively. Again the unit is per unit time, which is here per hour, since this information is given per hour in order to be consistent, we have written everything every flow rate in per hour and we have now labelled the flowchart. Now say we have to solve this problem. We have to calculate the flow rate of the gas stream leaving the condenser.

This complete stream is living the water for the condenser and mole fractions of oxygen, nitrogen and water in that stream. So, if you start immediately solving the problem, the first step should be to calculate the degree of freedom. You have to analyse its degree of freedom. Now, in this case, how many unknowns we have if we try to label it. So, already 2 we have in circle that is $\dot{n}_1$ and $\dot{n}_2$. We have here $\dot{n}_3$ which is relating this volumetric flow rate of water to the molar flow rate of water although this can easily be calculated but say apparently this is unknown and this composition.

So, apparently, we have 6 unknown variables here. Now the point comes how many independent equations we can write. Now for that we understand that for non-reactive species, non-reactive system the species that are involved in the input and output give me those numbers. So, now here what we see that 1 unknown can easily be calculated depending on the volumetric flow rate and the molecular weight.

This is one of apparently hidden information, and now if we see the number of species here what we see that because for each and every species, we can write one independent equation. So, now here we have other information that is mentioned a stream of humid air enters a condenser in which 95% of water vapour in the air is condensed, which we have not mentioned on the flow stream. That is why we have to write this on this connecting which stream it is being mentioned.

So here it is mentioned 95% of water in the feed is being condensed. So whatever the feed rate we had here, there is a connection between this n_3 and we have what here n_2 that means n_3 or $\dot{n}_3$ is basically 0.95 of $\dot{n}_2$. So we have another equation that is known, or we can write that equation apart from the number of species that we have. The number of species what we have here is oxygen, nitrogen and water.

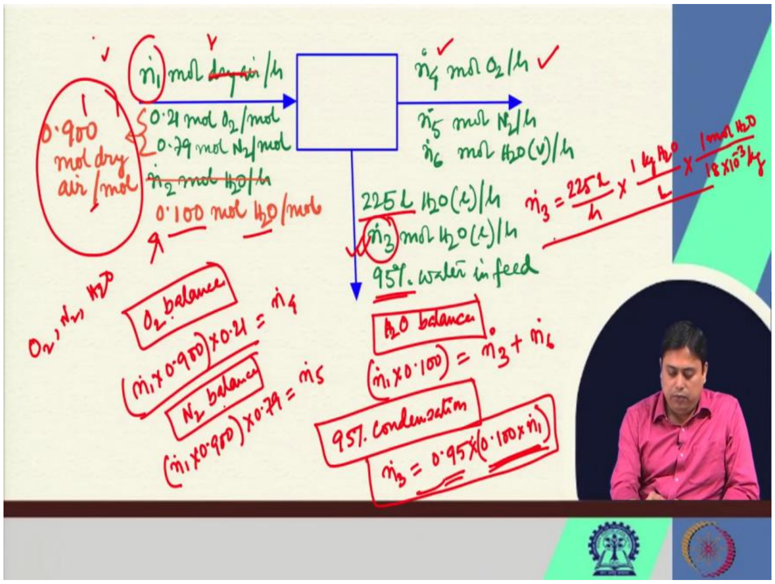
So we have three species here. We have further 2 equations that we can write from the problem statement based on the link that is provided or the information that has been provided. So that means how many equations that we can form here or the independent equations that we can write. So, here we can write 5 equations, 3 for the species one based on this volumetric flow rate and molar flow rate and the other one relating the percentage of water vapour being condensed.

How many unknowns we have? We have 6. So which means the problem is underspecified. The degree of freedom is 1 in this case, that means this problem cannot be solved if we do not provide any other information. This is the utility of analysing the degree of freedom at the first place. Once again, let me summarize the scenario here. We had a problem. We had 2 apparently hidden information. 1 is the percentage of water being condensed that is in the feed that link is there.

And we had written here forcibly that although we knew that the amount of water being condensed and the molar flow rate, we consider this as unknown. Someone can consider this as known but then this equation or see this molar flow rate and the volumetric flow rate this relation has been exploited already. So we further do not have the additional equation that we had there. In that case, although one variable will be lesser at the same time, there will be 4 independent equations that you can write, and you will have 5 unknowns there.

Eventually, the degree of freedom would be 1 and the type of details or the details manner that you would write that can be the individual-centric way. One of the way is that what I have shown here that one can write clearly 6 unknown variables in which you can write or you should write the relation between the molar flow rate and the volumetric flow rate of the known species. This is another additional equation, and we have here 3 species for which we can write 3 individual and independent equations. But still, we feel one equation short in order to solve the problem that is the degree of freedom is 1.

(Refer Slide Time: 18:50)



Now the same problem, so this problem now say it is given that we have 10 mol % of water in the inlet stream or the input stream. This composition is now mentioned which means now it is not the simple dry air it is the complete humid air in which we have 10 mol % of water that means the rest is dry air which means 0.100 mol of water per mol of this humid air we can write and the rest that is 0.900 mol of dry air per mol of this humid air.

Again in which in this dry air we have this composition which is 0.21 mol of oxygen per mol of this dry air and the rest that is 79 mol % nitrogen is there in this dry air other information remain identical that means this is now provided. So, one additional, information is now given that means our degree of freedom becomes zero. Because now if you see we can assume that this $\dot{n}_2$ is now known there is no other additional unknown variable there in the input stream except for the total molar flow rate of air.

So now, this problem is solvable because now it is having a degree of freedom as zero and we should proceed with the solution. So, how do we do this? So first of all, we consider $\dot{n}_3$ here as unknown. So that means this mole of water and this volumetric flow of water. This can easily be related and that how do we calculate that? It is nothing but say $\dot{n}_3$ is basically 225 litre of water. So 225 l/h multiplied by we have 1 kg of water per litre of water.

This is the density relation multiplied we have basically 18×10^{-3} kg of water in one mole of water. So here we see only one unknown which is $\dot{n}_3$ and it can be easily calculated the value of $\dot{n}_3$. So that means $\dot{n}_3$ is now known to us. In fact, it was known in the last schematic as well. Now the second step we have to check that which species balance involves a lesser number or the fewer number of unknown variables.

That we can look at it for say oxygen, nitrogen or even for the water balance. If we look at the oxygen balance the species that we have, as I mentioned we have now 3 species oxygen, nitrogen and water. So, either if you look at oxygen or nitrogen, it is involved in only two streams in one place and in the outlet and in the inlet both the streams. And what we have; So in this case what we have say if we now write the O_2 balance or look at the O_2 balance what we have is that the fraction of oxygen that is this much we have as the dry air out of which we have the oxygen content that is 0.21 mole per mole of this amount of dry air.

That is equal to our $\dot{n}_4$ in this case. Again if we write nitrogen balance we see is equals to $\dot{n}_5$. We further write water balance. What we see is that $\dot{n}_1 \times 0.2100$ this is the amount of water that we have in the input or the inlet, this is equal to $\dot{n}_3 + \dot{n}_6$. We have finally the total balance. If you say the total now, once we have written O_2 balance N_2 balance and H_2O balance.

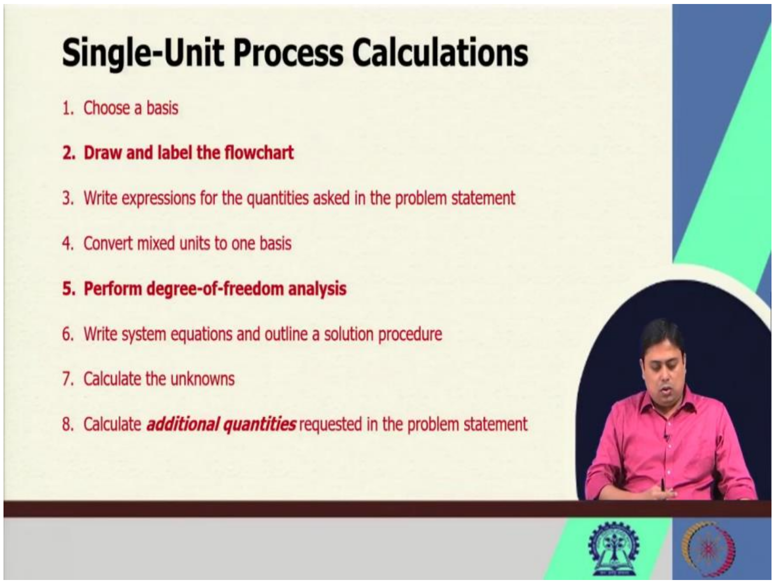
If we again write total balance here that would be a redundant thing. Because the total balance involved these 3 species itself so it would not be further another independent equation. So we have now got one equation and for the 3 species balance 3 questions and then we must not forget this 95% water in the feed has now condensed. So what we have the relation for 95% condensation is that $\dot{n}_3$ is basically 0.95 of $0.100 \times \dot{n}_1$.

This is the amount of water that is there in the feed; of that water 95% has been condensed. Now we see the sequence of solving the problem. If you had written all these equations and like I have done it here, you see that in all the cases we had 2 unknowns n_1 n_4, n_1 n_5 here n_1 n_3 n_6. But the only thing that is known till now is $\dot{n}_3$. Now if you write the 95% condensation balance at the second stage, then you could have easily calculated the value of $\dot{n}_1$ with the help of the value that is $\dot{n}_3$.

Once $\dot{n}_1$ is known, if you had written O_2 balance or nitrogen balance that could have been solved for the values of $\dot{n}_4$ and $\dot{n}_5$ respectively, and so the n_6 after knowing the value of $\dot{n}_1$ and $\dot{n}_3$. So, that means the sequence of solving this calculation is important in order to reduce the time that you spend in the calculation stages. So which means now everything we can solve.

We can calculate the solution you can do it on your own. Once it is known we know now everything that is $\dot{n}_4$, $\dot{n}_5$ and $\dot{n}_6$. We add those 3 to know the total outlet gas flow rate. So, say when we do this the summation of all these three would give me the $\dot{n}_{total}$ mole of output stream. What is my composition? The respective composition would be $\dot{n}_4/n_t$ or $\dot{n}_t$ because this is a flow rate. For nitrogen, we have $\dot{n}_4/\dot{n}_t$ and H_2O we have $\dot{n}_6/\dot{n}_t$. Those would be the mole fractions in those cases.

(Refer Slide Time: 31:42)



So, in summary, when we apply this knowledge that we have learnt the last couple of classes that while doing it for a single unit process calculation, we must choose the appropriate basis of calculation which is consistent with the problem statement. We have to draw and level the flowchart. This levelling also involves consistency in the unit. The basis of calculation involves consistency with the unit as well as with the desired variable that we are trying to calculate.

Then we write the expressions for the quantities that have been asked in the problem statement. We must not lose focus of the final goal. We must not leave it in the intermediate stages. We have to convert units to one consistent basis. We need to perform the degree of freedom analysis within write the system equations and realise what should be the solution procedure. Because once we write the system equations, we can understand that how many variables are involved in those equations, and then we calculate the unknown.

And the final stage, which is connected with this step 3 you calculate the additional quantities that has been asked in the problem statement. Like the example, we had it earlier that in one of the problem. It was asked that how much volume of water you need to dilute the aqua solution of sodium hydroxide 1 kg per kg. This was the questions that per kg of the aqueous solution of sodium hydroxide, what is the volume of water that you need to dilute the solution.

In that problem, we calculated initially based 100 kg basis of calculation the amount of water. But this additional quantity means that we have to convert it per kg of the feed stream. Such steps are often forgotten those must not be. So we calculate the additional quantity based on now the levelled and all the balanced flowchart. Because once we calculate all the variables if we write that on the flowchart, it becomes a balanced flowchart.

So, I hope this fundamental of the material balance and its application to the single unit process will be helpful to you for our future classes that will be dealt on the multiple units. We will solve couple of problems in the multiple units, and then all the things should be much more clearer because eventually in the multiple units, we have to balance the single units as feed. So see you in the next week with the multiple unit balances till then, thank you for your attention.