Material and Energy Balance Computations

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Lecture –14
Material Balance of Multiple Units (Contd.,)

Hello everyone, welcome back once again in the NPTEL online certification course on Material and Energy Balance Computations. We were in the multiple unit material balance section. And we were discussing a problem on the distillation column.

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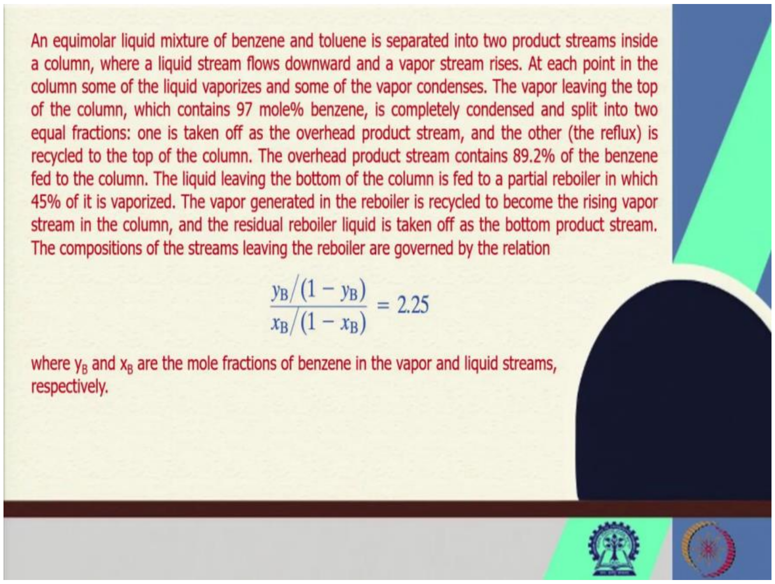

An equimolar liquid mixture of benzene and toluene is separated into two product streams inside a column, where a liquid stream flows downward and a vapor stream rises. At each point in the column some of the liquid vaporizes and some of the vapor condenses. The vapor leaving the top of the column, which contains 97 mole% benzene, is completely condensed and split into two equal fractions: one is taken off as the overhead product stream, and the other (the reflux) is recycled to the top of the column. The overhead product stream contains 89.2% of the benzene fed to the column. The liquid leaving the bottom of the column is fed to a partial reboiler in which 45% of it is vaporized. The vapor generated in the reboiler is recycled to become the rising vapor stream in the column, and the residual reboiler liquid is taken off as the bottom product stream. The compositions of the streams leaving the reboiler are governed by the relation

$$\frac{y_B/(1-y_B)}{x_B/(1-x_B)} = 2.25$$

where y_B and x_B are the mole fractions of benzene in the vapor and liquid streams, respectively.

We have seen this problem statement in the last class. We have understood the principle on which we have to draw the flowchart and level the same. So this distillation column concept we have elaborated in the previous class and based on which we have understood also that what are the things that we have to evaluate. What are the additional quantities that also we have to estimate? So, let us do the flowchart and level it.

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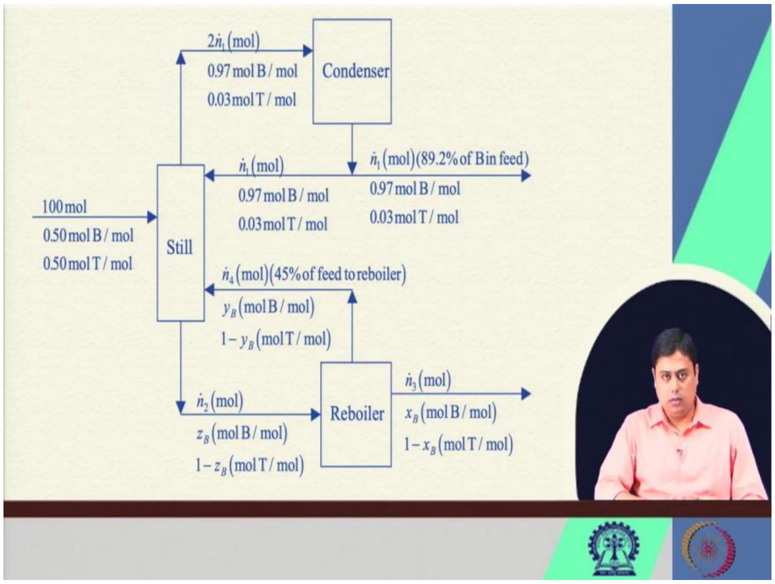

So if you have drawn it by now, then it would look something similar to this one. Now again the material balance computation any problem statement can be solved in an individual manner or based on their individual style. The form that has been shown here is one of that kind which you may find one of the easier way to represent it. So here based on the principle that we discussed that we have a distillation column.

Equimolar flow rate of feed which is again was assumed to be of 100 mole. Equimolar so we have 50 mol % of benzene and rest toluene which is again 50 mol % toluene in the feed stream that is there. It is mentioned again if we refer to the problem statement that the vapour leaving the top the vapour that leaves the top of the column which contains 97 mol % benzene is completely condensed and split into two equal fraction.

So this is the top product from the distillation column which contains 97 mol % benzene and rest toluene is going to a condenser. Condenser job is to liquefy it. So, some part of the liquid stream is taken out. It is also mentioned that it is split into two equal fraction. This information's are quite important. So if it is divided into two equal fractions. So while levelling it if we assume that one fraction is $\dot{n}_1$ mole.

That means the other split is also $\dot{n}_1$ mole which means the feed that is coming into the condenser is $2\dot{n}_1$. Now here the point is that someone can easily assume that here I am writing $\dot{n}_1$ mole. No issues in that case he has to write here $\dot{n}_1/2$ and this is the moles that is being taken out and recycled, accordingly the levelling would be done. To avoid this fractions. It is assumed initially that ok we have $\dot{n}_1$, $\dot{n}_1$ both the splits and the recycle.

So that means the amount that is coming into the condenser is $2\dot{n}_1$. Now remember the condenser is just liquefying the vapour it is condensing the vapour. So the composition would remain identical as that of the feed stream coming into the condenser which was 97 mol % benzene that stream. Now, since it is a mixture of only in benzene and toluene to the rest to automatically be toluene.

Now here, the other thing that is mentioned is that the overhead product stream contains 89.2 % of benzene fed to the column. The amount that has been fed to the column the amount of benzene it is 89.2 % is there in the overhead product stream overhead product steam means? The stream that is collected from the top the others stream is recycled. So here that means we have certain relation. Now, coming to the bottom part of it, the bottom part the stream that comes out again, which is an unknown we levelled it as $\dot{n}_2$ mole.

There we do not also know what is its composition, so that we assume as z_B, which is the amount of mole B stands for the benzene per mole of that streams and so the toluene is automatically $1 - z_B$, the mole fraction. Now, this is going into the reboiler where it is vapourized. The amount of vapourization has also been mentioned in the problem statement.

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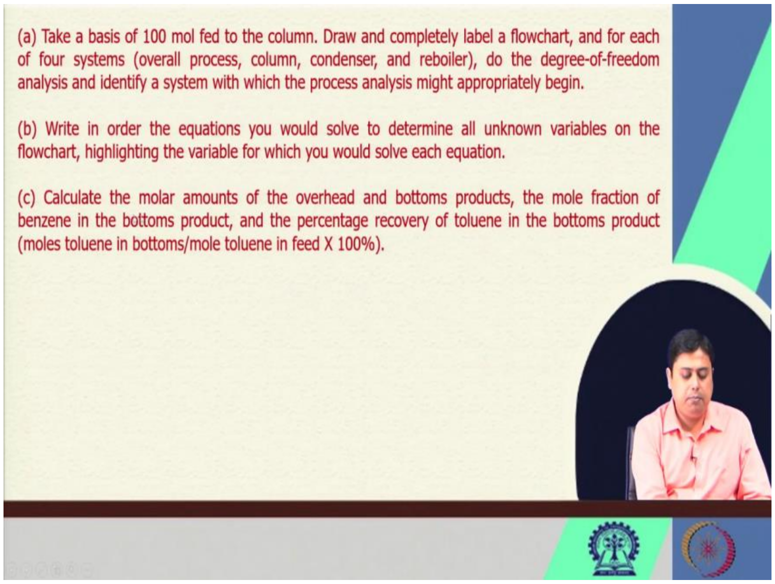

(a) Take a basis of 100 mol fed to the column. Draw and completely label a flowchart, and for each of four systems (overall process, column, condenser, and reboiler), do the degree-of-freedom analysis and identify a system with which the process analysis might appropriately begin.

(b) Write in order the equations you would solve to determine all unknown variables on the flowchart, highlighting the variable for which you would solve each equation.

(c) Calculate the molar amounts of the overhead and bottoms products, the mole fraction of benzene in the bottoms product, and the percentage recovery of toluene in the bottoms product (moles toluene in bottoms/mole toluene in feed X 100%).

The problem statement says that the liquid leaving the bottom of the column is fed to a partial reboiler in which 45 % of it is vaporized. So, which means we have 45 % of feed to the reboiler is being vaporized. Even if we now write an unknown parameter, that means there is a relation between $\dot{n}_4$ and $\dot{n}_2$ which is mentioned. Now the point here again, I told earlier someone can directly translate this information and write this $\dot{n}_4$ in terms of $\dot{n}_2$ which may help while evaluating the degree of freedom.

If somebody does not write that then it should be clearly mentioned or levelled on the flowchart so that we do not forget later while doing the balance or the freedom or degree of freedom analysis. So here, everything are unknown to us that means the molar composition of the recycle feed from the reboiler, the bottom product stream as well as the inlet stream coming into the reboiler. All the things are unknown.

So what should be the strategy to solve this problem? So, that means now we have drawn a flowchart. We have levelled it with the basis of calculation. Now, here the step that we should follow immediately that whether the overall problem can be solved or not? Now the overall system that would encompass all the units and would look like something like this, where we have one inlet stream or input stream and 2 output stream.

On these streams we have to check what are the unknowns? Those are the unknown for the overall process. We have to look into the material balance. How many independent equations we can write for the material balance that would give us the degree of freedom and then we will understand whether the problem is solvable or not.

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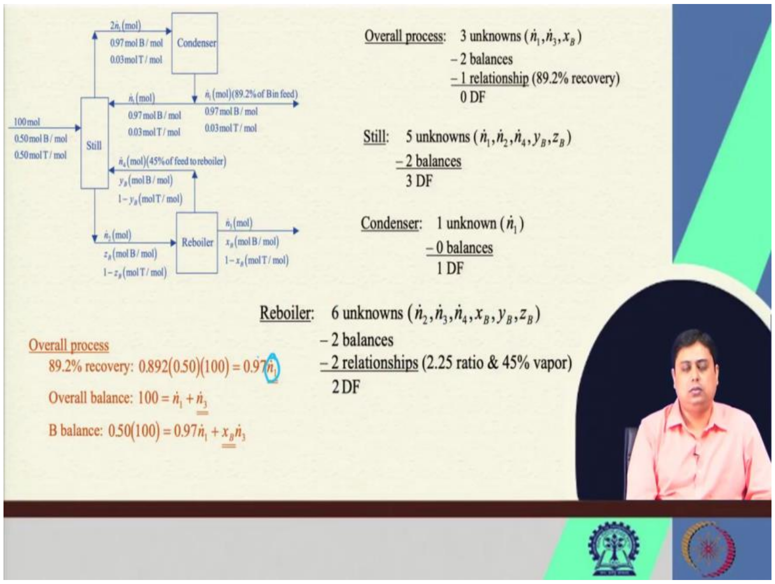

Overall process: 3 unknowns $(\dot{n}_1, \dot{n}_3, x_B)$
$-$ 2 balances
$-$ 1 relationship (89.2% recovery)
0 DF

Still: 5 unknowns $(\dot{n}_1, \dot{n}_2, \dot{n}_4, y_B, z_B)$
$-$ 2 balances
3 DF

Condenser: 1 unknown $(\dot{n}_1)$
$-$ 0 balances
1 DF

Reboiler: 6 unknowns $(\dot{n}_2, \dot{n}_3, \dot{n}_4, x_B, y_B, z_B)$
$-$ 2 balances
$-$ 2 relationships (2.25 ratio & 45% vapor)
2 DF

Overall process
89.2% recovery: $0.892(0.50)(100) = 0.97\dot{n}_1$
Overall balance: $100 = \dot{n}_1 + \underline{\underline{\dot{n}_3}}$
B balance: $0.50(100) = 0.97\dot{n}_1 + \underline{\underline{x_B}}\dot{n}_3$

Now, if we look into the overall process what we see? We see that again if I draw the overall process in closer, which is this. We see that in this stream ṅ1 is unknown, ṅ3 is unknown and x_B is unknown which means we have three unknowns. We have two components here or 2 species, benzene and toluene so we can write at max 2 independent material balance equations which are 2 balances here either two species or one species and one overall mass balance.

And here, one relationship is mentioned which is written here that 89.2 % of benzene is recovered, 89.2 % of the feed that is in the feed is recovered as the overhead product. So one relationship is mentioned where percentage recovery is given that is additional information. That gives us zero degree of freedom. We have to look into the other three systems. One is the distillation column itself, one is the condenser other one is the reboiler that is the first task that is that has been asked in the problem statement.

So now the column in case of column, we have this system boundary. Now on this system boundary, we can see that we have 1, 2 and 3 inlet or Input and 2 output. We have to look into the unknown parameters on those streams. We have to identify those and what have to consider those as unknown. So in that case, what is there for here we have $\dot{n}_1$ in this stream. We have $\dot{n}_4$. We have $\dot{n}_2$ these are unknowns.

So in sequence $\dot{n}_1$, $\dot{n}_2$ and $\dot{n}_4$ the composition of benzene here y_B and z_B these are the unknowns here for the subsystem distillation column. But here we can write only 2 balances because of again we have only two species and no other information is provided here. So which means we have 3 degree of freedom. Then we go in to the condenser. If we now look at the condenser, this is the system boundary around condenser.

We have 1 input 1 output. The only unknown is $\dot{n}_1$. Here it is acting as if a splitter of the flow rate by changing the process condition. So here basically, we cannot write any balance because we have already translated this information that it is being splitted in two equal parts and the total flow rate is written on the flowchart itself already. And also the compositions are identical so we cannot write any balance on the condenser which means we have degree of freedom y.

Now the point you may be thinking that once the overall process we have seen zero, why we are still considering n_1 as unknown. These are unknown. Apparently this is true we should not consider but here I am showing you that without solving or without considering the overall process at first if somebody tries to write the balance equation from say distillation column or say condenser. What are the kinds of situations can be?

So definitely by now we understand the calculation should be started from the overall process so that we can calculate easily n_1, n_3 and x_B and use it further in subsequent states. But as standalone individual components, we are at first analyzing the subsystems. So, then the remaining portion is the reboiler. So here, If I draw the reboiler part. The system is this one. Where everything is unknown that means the input flow rate its composition and output flow rate and its composition all are unknown.

But there we can write two individual material balances because we have 2 species and here two hidden information are there. It is Apparent though that already in the problem statement. It is mentioned that x_B and y_B relation. That is why it is level in such a way x_B is the mole fraction in the liquid part and the reboiler the part that is it is hitting, that means it is being vapourised there the mole fraction is y.

This y and x relation is known to us. So, from this schematic, it is also apparent that in the reboiler the part that is being vapourised; the mole fraction is designated by y_B or y and here the part that liquid part that is taken out from the boiler or since this is a partial reboiler. It is mentioned by x. Now this x and y relation is given, this ratio and it is also mentioned that the amount of vapour being generated with respect to the feed to the reboiler that means 2 relationships are mentioned here which means we have 2 degree of freedom here.

So the logical sequence in order to solve the problem is to start from the overall process. Once we do the overall process we immediately know what is the n_1 in the condenser as well. And then if you look at this reboiler and still we see here, we have three degree of freedom. That means we need another 3 additional information or 3 balances but here we need 2 for reboiler. Now here we see that out of these 6 unknowns we have n_3 which is being calculated in overall process.

We have x_B which we can have after solving the overall process. So once these two are known that means it is becoming 4 unknowns and our degree of freedom can be zero if you solve the sequence the overall process and then the reboiler, once it is done we can calculate the n_2. We can calculate n_4 and y_B which is there in the distillation column. So that means we now know the all unknown variables.

So if we now proceed with this process, by this way we see that the overall process certain percentage of recovery has been mentioned and that involves only one unknown variable. Like the previous discussion of the previous problem, we have mention the input is equal to output here for the percentage recovery information. It is the 89.2 % of benzene is recovered of that is there in the feed. So that means here $0.97 \times \dot{n}_1$ is basically the 89.2 % of this 100×0.5 mole.

So, from here you can understand that we can easily calculate $\dot{n}_1$. And then if we apply overall balance on this overall process that overall mass balance. We have 1 input and 2 outputs. So $\dot{n}_1$ +

$\dot{n}_3$ = 100. We have calculated $\dot{n}_1$, we use it, we get $\dot{n}_3$. So that means $\dot{n}_3$ is now known to us. And if we do any one of the species balance because that would be the only independent equation after overall balance.

So, in that case if you use the benzene balance input is $(100 \times 0.5) = (0.97 \times \dot{n}_1) + (x_B \times \dot{n}_3)$, because this is my overall system. Here $\dot{n}_1$ we have calculated in this step, $\dot{n}_3$ we have calculated here $\dot{n}_1$ and $\dot{n}_3$ both are known so we calculate x_B from this equation which means these 3 unknowns are now known to us. And we should use it as known variable for the subsequent calculation.

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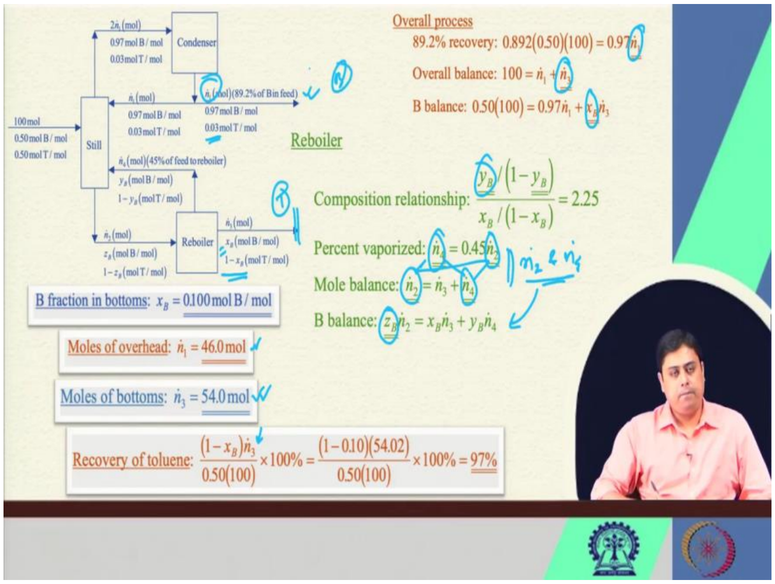

Overall process

89.2% recovery: $0.892(0.50)(100) = 0.97\dot{n}_1$

Overall balance: $100 = \dot{n}_1 + \dot{n}_3$

B balance: $0.50(100) = 0.97\dot{n}_1 + x_B\dot{n}_3$

Reboiler

Composition relationship: $\dfrac{y_B/(1-y_B)}{x_B/(1-x_B)} = 2.25$

Percent vaporized: $\dot{n}_4 = 0.45\dot{n}_2$

Mole balance: $\dot{n}_2 = \dot{n}_3 + \dot{n}_4$

B balance: $z_B\dot{n}_2 = x_B\dot{n}_3 + y_B\dot{n}_4$

B fraction in bottoms: $x_B = 0.100$ mol B / mol

Moles of overhead: $\dot{n}_1 = 46.0$ mol

Moles of bottoms: $\dot{n}_3 = 54.0$ mol

Recovery of toluene: $\dfrac{(1-x_B)\dot{n}_3}{0.50(100)} \times 100\% = \dfrac{(1-0.10)(54.02)}{0.50(100)} \times 100\% = 97\%$

And the subsequent step would be the reboiler one. So these are equations for the overall process we have just discussed and now the sequence we have understood that it should be for reboiler. Now, once we have calculated x_B that is this one for the reboiler the relation y_B and x_B is given, so that means here only one unknown is there in that relation. So y_B can easily be found out from this expression, and then we have percentage vaporization. It is said that the 45 % of the feed to the reboiler is vapourized.

So that means $\dot{n}_4 = 0.45 \times \dot{n}_2$ which is here. We have already calculated here the x_B, and y_B. But here $\dot{n}_4$ and $\dot{n}_2$ both are unknown this one and this one we have not calculated yet. So from overall process we have calculated $\dot{n}_1$, $\dot{n}_3$, x_B and y_B, so, these 4 are now known. So from percentage vapourization, we see that $\dot{n}_4$ and $\dot{n}_2$ are there and also at the same time if we write the mole balance that is in $\dot{n}_2 = \dot{n}_3 + \dot{n}_4$ where $\dot{n}_3$ is known which means we have a simultaneous equation involving $\dot{n}_2$ and $\dot{n}_4$, two equations two unknowns, we can easily solve this set for $\dot{n}_2$ and $\dot{n}_4$.

So that means now $\dot{n}_2$ and $\dot{n}_4$ are known to us. If we now apply any one of the component balance which would be say benzene if you apply it around this reboiler we have $z_B \times \dot{n}_2$ which is the input = output stream which is a $(x_B \times \dot{n}_3) + (y_B \times \dot{n}_3)$. We have calculated $\dot{n}_4$ from the previous step, $\dot{n}_3$ we already calculated in overall system, $\dot{n}_2$ we have calculated here.

So x_B and y_B is also known the only unknown here is z_B, which we can easily calculate. So that means what has happened is that now all the unknowns are known to us $\dot{n}_2$, $\dot{n}_4$, $\dot{n}_1$, $\dot{n}_3$, x_B, y_B, z_B. So which means our solution strategy is fine, we now just do some simple algebra to find out this highlighted variable. In this equation with the known information now, this is the only thing that is coupled here.

And with this known information, we solve this one and everything is known on the flowchart. But the point is what are the additional information that has been asked in the problem statement? So again for that if you have forgotten those go back to the problem statement and see this is the additional information or what has been asked in the problem statement. This is what you had to answer precisely.

That is calculate the molar amount of overhead and bottom products, mole fraction of benzene in the bottom product and percentage recovery of toluene in the bottom product. So, which means the benzene fraction in the bottom product is x_B which you have already calculated you answer that question that part, the moles of overhead product which is the n_1 moles, the moles of bottom product which is the $\dot{n}_3$ mole and the recovery of toluene.

The recovery of toluene means, what is there in the product that we are calculating here, in the bottom product because that is the major percentage of toluene that we have so which is $(1 - x_B) \times \dot{n}_3$ because here you see that its 0.03 % of toluene in the top product. So here the major product that is coming out is Benzene and the bottom product major product is toluene. So the recovery of toluene is $(1 – x_B)$, it is also in fact mentioned in the problem statement for the sake of simplicity that the moles of toluene in bottoms per mole of toluene in feed ×100 %.

So our final answer would be $(1 – x_B)$. The mole fraction × its molar flow rate / the amount that is coming into the system. It is coming to the overall process with respect to the overall process × 100 %, which would be numerically close to 97 %. So, I hope you have understood the sequence of solving multiple unit processes. How we apply degree of freedom analysis, how we judge the order of the equations or the sequence of equations that we have to solve.

We will see it further in the next class, whether you have got the strategy right or not. Until then, Thank you for your attention.