Principles and Practices of Process Equipment and Plant Design

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Module - 02
Lecture - 11
Fractionation (Contd.)

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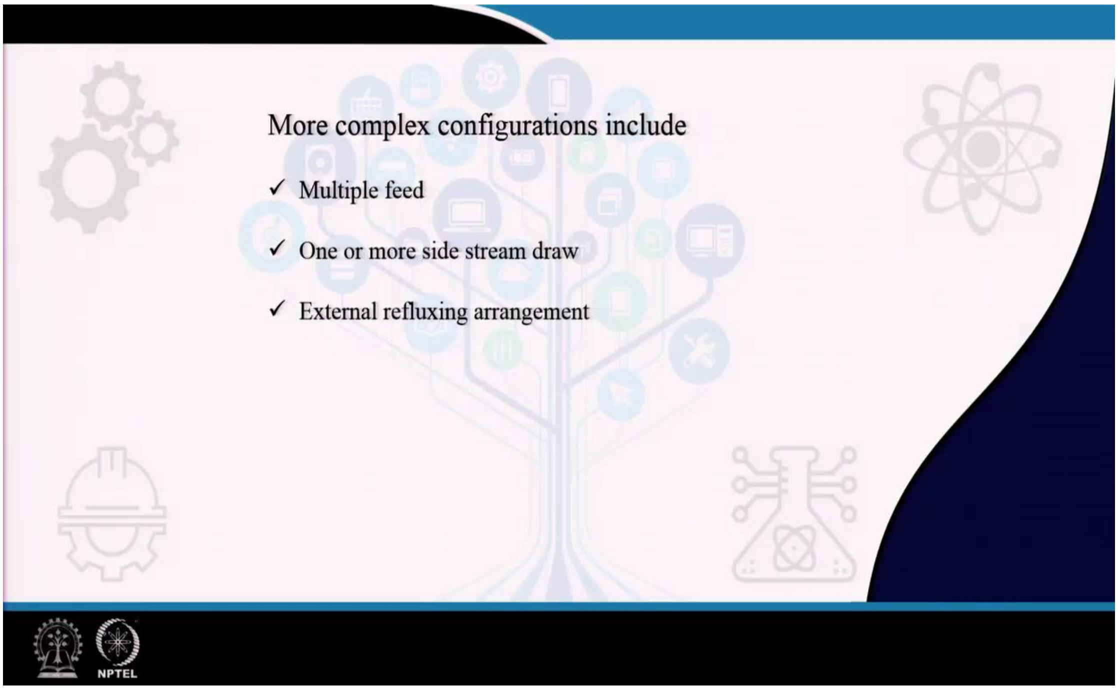

More complex configurations include

- ✓ Multiple feed
- ✓ One or more side stream draw
- ✓ External refluxing arrangement

Well, hello everybody. So, in this particular class, I would just touch upon certain things that I could not complete in the last class, particularly in the more complex form. The configurations should be including the multiple feeds, side stream draw, external refluxing arrangement.

So, particularly we will be discussing the arrangement for side stream draw, and what is this external refluxing arrangement, why do you need it. But before that there were certain things about the feed which I would like to mention, and I will touch upon those things, and then I will proceed, and after that definitely, we go for the design of the distillation column.

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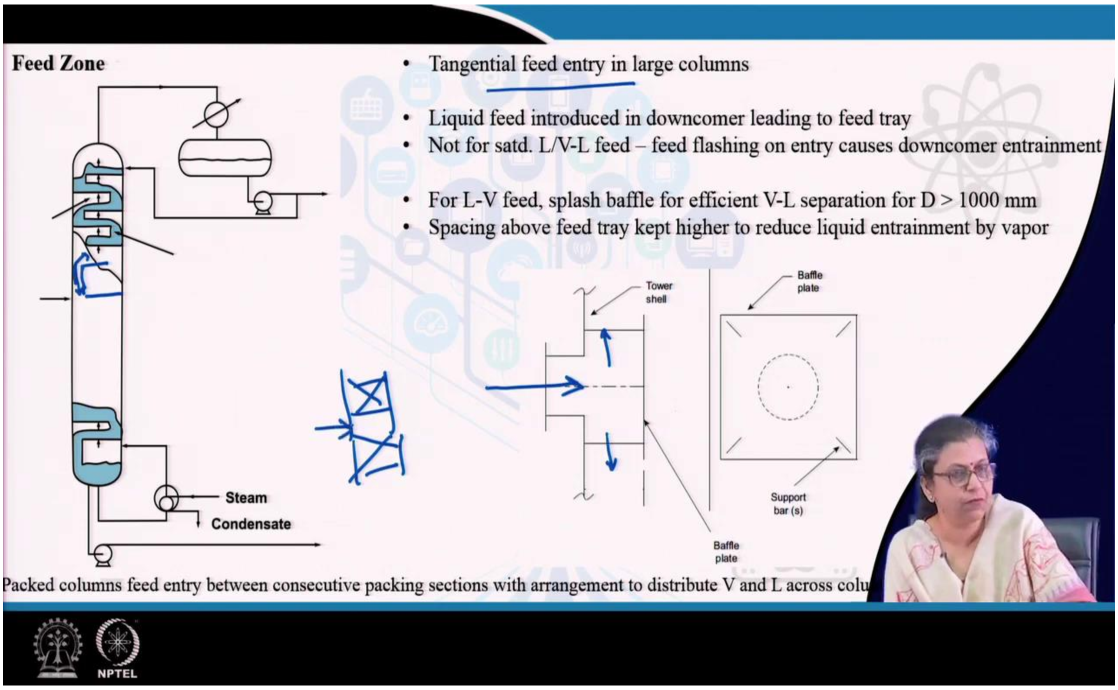

Feed Zone

- Tangential feed entry in large columns
- Liquid feed introduced in downcomer leading to feed tray
- Not for satd. L/V-L feed – feed flashing on entry causes downcomer entrainment
- For L-V feed, splash baffle for efficient V-L separation for D > 1000 mm
- Spacing above feed tray kept higher to reduce liquid entrainment by vapor

Packed columns feed entry between consecutive packing sections with arrangement to distribute V and L across colu

I had to mention during the reflux entry into the column that you just cannot pour the reflux into the column through the nozzle. The same thing for the feed zone. Normally, we have a tangential feed entry in the large columns. Now, when you have just a liquid feed, it can be introduced in the downcomer which leads to the feed tray. So, therefore, there is a downcomer from the top tray on the feed tray. So, in the downcomer, you can introduce it.

Now, tell me if you have a liquid-vapour feed or you have a liquid feed at its saturation point under that condition if I introduce it at the downcomer, what do you expect is going to happen? The liquid feed is going to flash. If it is a vapour-liquid feed, the vapour is already available in this particular case.

So, what this vapour would try to do? It will try to rise through the liquid here. While it tries to rise, it will try to take some amount of liquid with it. This is going to lead to the entrainment of the liquid from here. This leads to something which is known as downcomer entrainment and a downcomer flooding which we will be discussing in more detail when we go for the design part.

So, naturally for the liquid-vapour feed what do we have is for efficient removal of the liquid and the vapour such that the liquid can flow down, and the vapour can flow up. So, the liquid-vapour feed when it is introduced through the nozzle, it strikes on a baffle plate. This is known as a splash baffle. It strikes on a splash baffle, and then the vapour goes up, and the liquid comes down in this particular case.

Although we are not discussing packed columns, here I would like to mention that. The packed columns have two packing sections. So, between these two packing sections, usually, the feed is introduced. Then, there are of course arrangements for distributing the vapour and liquid across the column section. We will be discussing it later.

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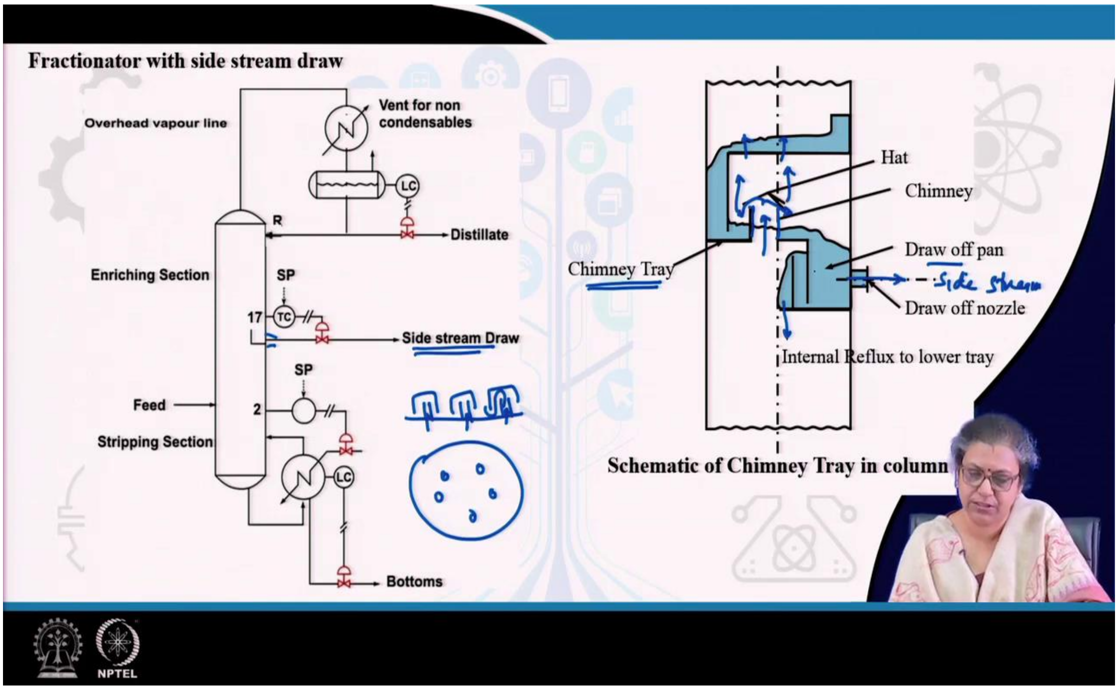

Fractionator with side stream draw

Schematic of Chimney Tray in column

Very frequently, we not only need the distillate or the bottoms, but we also need a side stream draw. The side-stream draw is drawn from any plate. It has a composition between the distillate and the bottom. Depending upon the plate composition, it is drawn from any particular plate.

Now, tell me one thing, how do you draw it out? Is it that you just have a nozzle here you open the nozzle and simply draw out the side stream? You cannot do it. The liquid-vapour mixture will be coming out and the equilibrium inside the column is going to be disturbed. So, the tray, from which the side stream is drawn, has got a slightly different arrangement from the other fractionating trays.

In the fractionating trays, we will be going into the details. What do we have, we can either have some riser sort of things through which the liquid can rise and then over the riser we can have such bubble caps through which the vapour can bubble through. Or, normally what do we have, we have several perforations through these perforations the vapour can rise, and the liquid flows across this column and the tray.

Well, for drawing out the side-stream, we have a special arrangement. This tray is known as a chimney tray. In the chimney tray, what happens, we have very long risers such that the riser ends above the liquid column in the tray. The vapour, which is rising through this tray, does not come into contact with the liquid here. The vapour rises and goes out through the between the hat and the chimney, and then it rises up, and then it bubbles through the liquid on the upper tray. In the upper tray, the enrichment goes on as usual.

In this tray, what happens, the liquid from the upper part of the column enters, flows through the tray, it collects in a draw off the pan. In the draw off pan, we have got a draw off nozzle from where the side stream is withdrawn from here. The remaining amount of the liquid overflows over a weir, and it comes down into the tray below. It provides internal reflux to the lower tray. It occurs above the chimney tray, at the chimney tray. Definitely, this is not a fractionating tray. There is no fractionation occurring here. We just draw the side-stream from this particular tray. So, therefore, this is ineffective as a fractionating tray.

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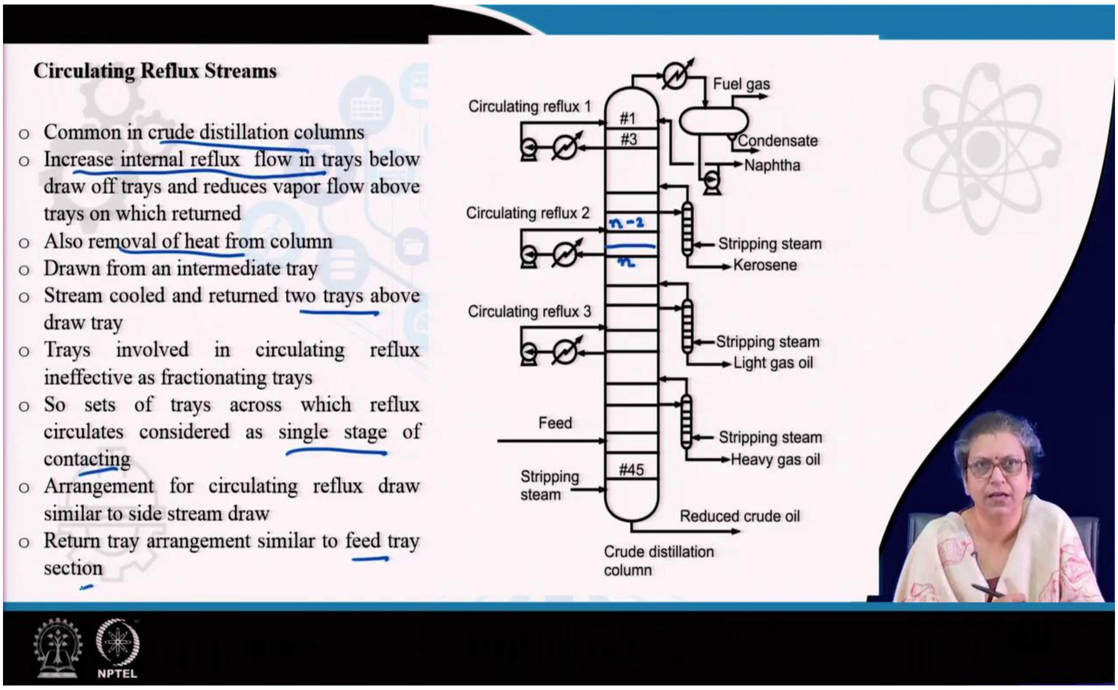

Circulating Reflux Streams

- Common in crude distillation columns
- Increase internal reflux flow in trays below draw off trays and reduces vapor flow above trays on which returned
- Also removal of heat from column
- Drawn from an intermediate tray
- Stream cooled and returned two trays above draw tray
- Trays involved in circulating reflux ineffective as fractionating trays
- So sets of trays across which reflux circulates considered as single stage of contacting
- Arrangement for circulating reflux draw similar to side stream draw
- Return tray arrangement similar to feed tray section

Now, it is quite natural. So, therefore, the internal reflux goes to the tray from the chimney tray. It is less as compared to the liquid which flows from tray to tray.

So, quite frequently, we find that if you have to increase the internal reflux flow from the trays or rather from the draw off trays to the trays below and to reduce the vapour flow above the tray on which it is returned. We use something known as the circulating reflux streams. It also removes heat from the column. This is very common in crude distillation columns.

Now, in this case, what do we do? Just below two side stream draws or maybe below the overhead product draw and the side stream draw, we have an arrangement which is known as circulating reflux. It means from some particular tray we draw out the liquid. We cool it, and we introduce it usually two trays above the tray. That means, if this is nth tray then this is going to be the (n-2)th tray.

So, therefore, it is usually drawn from here, and the stream is cooled. It is returned two trays above the draw off tray. If we draw the circulating reflux from the third tray, we introduce it in the first tray. This is the way. So, quite naturally in this particular way what happens, we can increase the internal reflux, and therefore, we can maintain the enrichment which we want in the trays below the draw off trays, and we can also reduce vapour flow above the trays.

But it is quite evident that definitely this set of three trays, these trays they are ineffective as fractionating trays. Definitely fractionation does not occur to the same extent. So, therefore, what we do is by convention, the set of these three trays are taken as a single stage of contacting. Accordingly, we compute the number of trays here. So, therefore, n, (n-1), (n-2), these three trays are taken as one tray. Accordingly, the total number of trays are arranged here.

It is needless to say that the arrangement for drawing out this circulating reflux, is the same as the side stream draw. In the same way, we draw it from a chimney tray. The arrangement for introducing the reflux is the same as a feed tray arrangement. So, therefore, this was the basic description of a conventional, the simplest distillation column.

I discussed certain additional features which are there particularly because you need side stream draws which is very common. After this, we will be discussing the design aspects, how to start a design, what are the inputs, the deliverables etcetera. Then we will be proceeding into the details of the design.

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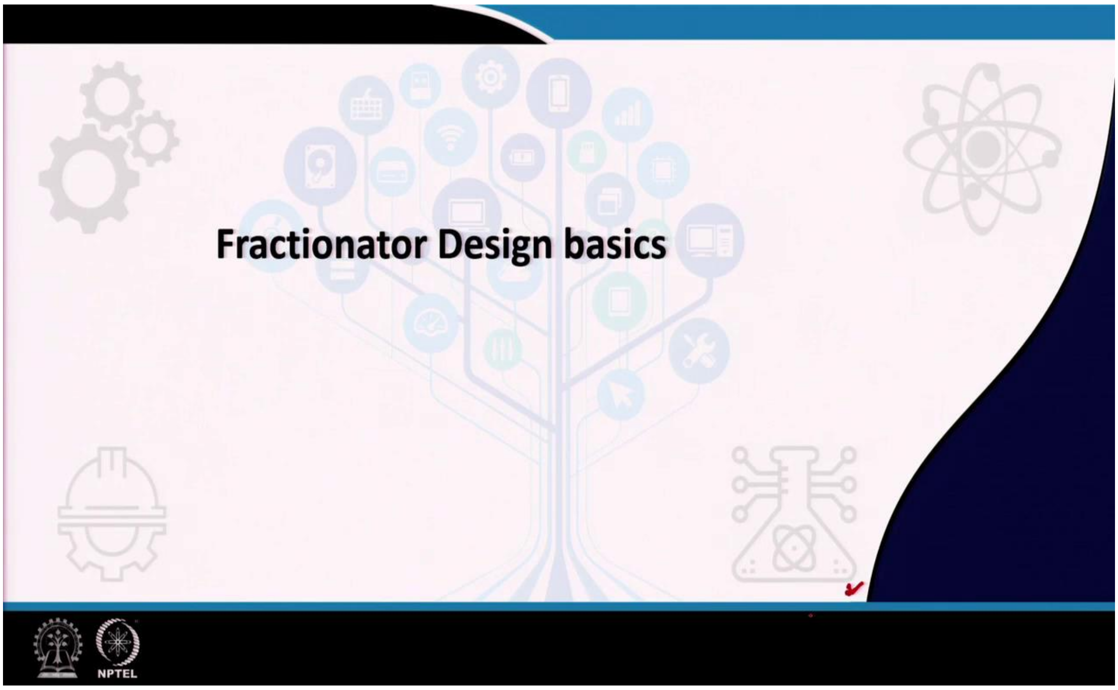

Fractionator Design basics

Well, this is a continuation of what has been taught to you by Prof. Das. It is basically about the fractionation and the fractionated parameters. The basics are already over. You are aware of the equilibrium, and you are aware of the fractionated stages.

In this particular session what I am going to deal with is the basics of fractionator design. The detailed things you would follow immediately after this. If you are talking about the design of a fractionator, the first thing that you need to know is about its configuration which means, what exactly is a fractionated consisting of.

The next thing that is expected to be covered is if you are going to design such a thing what exactly will be the relationship between the different process parameters of the fractionator, and how they are related to the functional output of the fractionator, that means, enrichment from a feed composition to the product composition. The product could be the top product or the bottom product.

Beyond this, we need to have a list of outputs for the design process. Quite naturally, we would like to fractionator is a steady state process, that means, we have to keep all the process parameters steady at their fixed values i.e. their desired values. We must have some sort of handle with us so that we can manipulate some of these parameters or rather adjust some of these parameters, so that we achieve the functional objective. It may be a range of x_b, a range of x_d, or something similar.

So, we need to know about the control of the process also. That means, we will have to look at the parameters which are to be varied by the design group followed by keeping provision for the operating group to change those using controllers, and also providing certain parameters which are important otherwise also, but need not have direct control, but should be monitored that also should have the monitoring facility.

Beyond this, we have to find out a set of a process procedures for finding out the number of stages and the related operating conditions which will be taken up after this.

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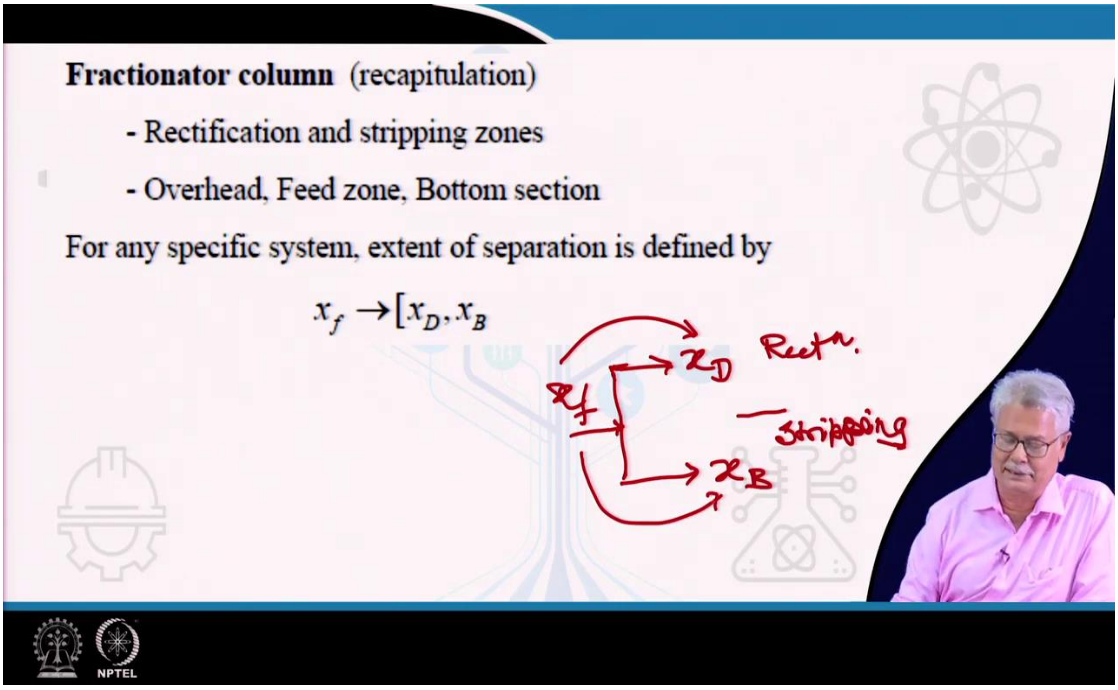

Fractionator column (recapitulation)

- Rectification and stripping zones
- Overhead, Feed zone, Bottom section

For any specific system, extent of separation is defined by

$$x_f \to [x_D, x_B$$

To start with we go for we look at the fractionating column. We go for a little bit of recapitulation. We know here that naturally if my feed is x_f composition. It will be split into a distillate with having a composition of x_D and a bottom of composition x_B mole fractions. We are going to use the same mole fraction as has been introduced to us.

We also know the upper section is going to be the rectification section, the bottom section is going to be your stripping section. For any specific system, the extent of separation is going from x_f to x_D if my top product or the distillate is my desired product, or going to an x_f to x_B if my bottom product is the desired product here.

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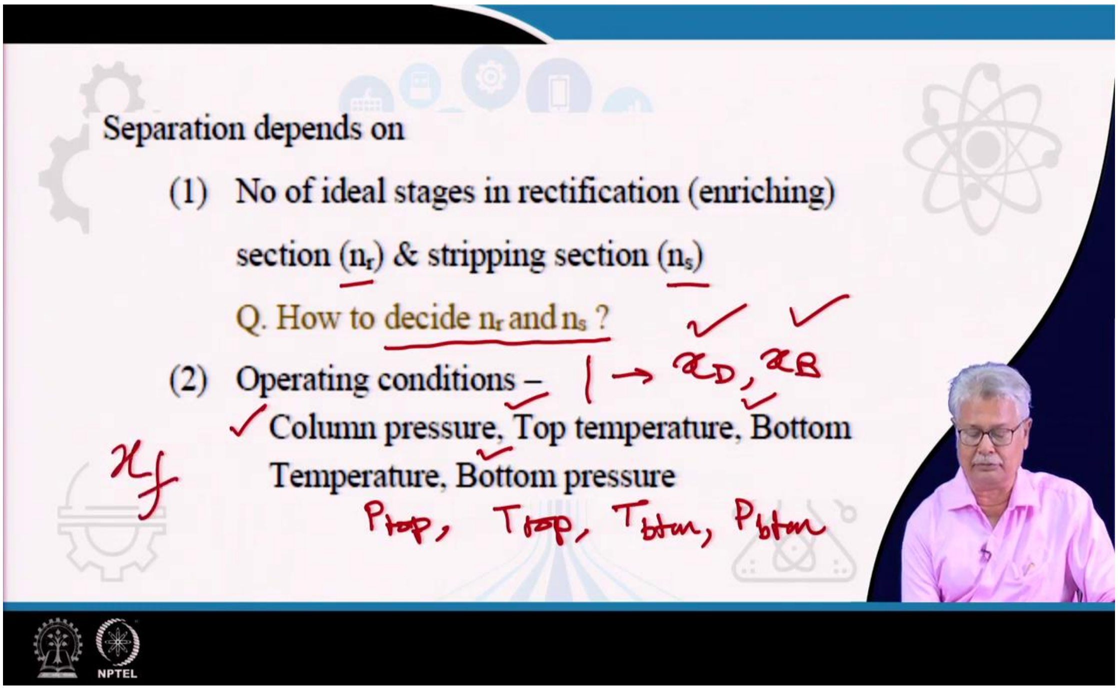

Separation depends on

(1) No of ideal stages in rectification (enriching) section (n_r) & stripping section (n_s)

Q. How to decide n_r and n_s ? ✓ ✓

(2) Operating conditions – | → x_D, x_B

✓ Column pressure, Top temperature, Bottom Temperature, Bottom pressure

x_f

P_{top}, T_{top}, T_{btm}, P_{btm}

Now, we know about the functional requirements. We need to know the number of stages in rectification which is the enriching section and the number of ideal stages in the stripping section. So, these are two parameters n_r and n_s which definitely have to be provided by the column itself. So, a major step is to find out n_r and n_s which is the number of ideal stages above the feed and below the feed which will be dealt with by the next detailing later on.

Now, if you look at a distillation column, there are a few operating conditions that decide this x_D and x_B. Basically, these are the operating conditions which are expected to decide the x_D and the x_B. The first thing is the column pressure; the second thing is top temperature. You already know that whenever we say column pressure loosely we really mean the column top pressure that is the convention. Similarly, the bottom temperature and the bottom pressure are also two very important parameters.

So, if I write here symbolically, I will write here these as P_{top}, T_{top}, T_{bottom}, and perhaps P_{bottom}. So, these are the four extremely important parameters that are to be held and manipulated and kept constant to achieve x_D and x_B starting from a feed composition of x_f.

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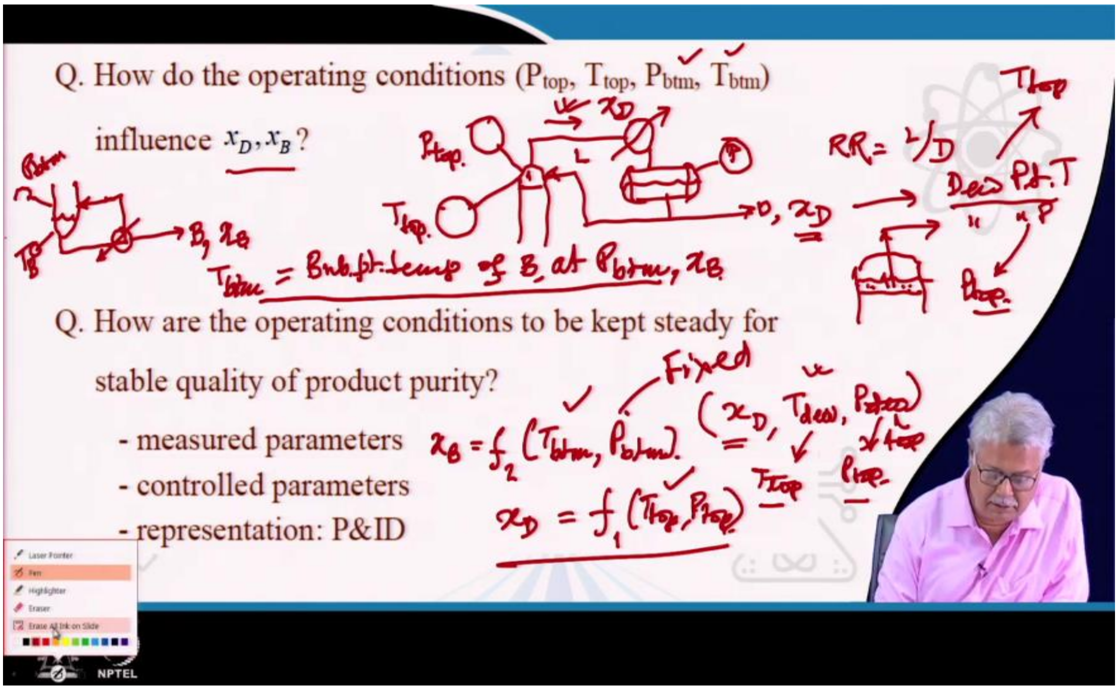

Q. How do the operating conditions (P_{top}, T_{top}, P_{btm}, T_{btm}) influence x_D, x_B?

Q. How are the operating conditions to be kept steady for stable quality of product purity?

- measured parameters
- controlled parameters
- representation: P&ID

So, the next question comes up, how do these four operating conditions influence x_D and x_B for a given x_f? Now, let us look at the distillation column itself. We look at the top portion. We have here a condenser. From below that, we have the accumulator. In our accumulator, we have vapour and liquid. We have reflux which goes back to the column, and here we have the distillate with a composition x_D. The reflux flow is L. The reflux ratio is L/D. This is above tray number 1.

You definitely will be having here a pressure P_{top} rather you have a pressure indicated here. The P_{top} is this particular point. You have the T top at this particular point also. If I look at the top tray (number 1), the vapour leaves from here as overhead vapour goes here and gets condensed that means on the liquid, from the liquid top, what leaves and whatever liquid you have here they are in equilibrium.

So, it is obvious that the top vapour which leaves and gets finally condensed. I am right now showing here a configuration that has got a total condenser with a composition of x_D, the same composition x_D remains here (at the inlet to condenser). So, x_D is also the vapour composition. Now, this x_D is what? This x_D has been just generated from the top tray liquid.

So, if we reduce its temperature by a small amount, the heavier components in larger proportion would start condensing, which means, the vapour would start condensing and composition would shift from x_D.

So, quite naturally, this vapour is at its, dew point. Now, whenever we say the dew point temperature, there is a corresponding dew point pressure. The dew point temperature here is what, the temperature of the top which is T_{top}. The dew point pressure here is what? It is a P_{top}.

So, this x_D is a composition. Its dew point is T_{dew}. Its dew pressure is P_{dew}. What we know here is that this T_{dew} is what, it is T_{top} and this is P_{top}. I am intentionally repeating this so that, this becomes amply clear that my main by if I can alter these two conditions my x_D would change.

So, if I change my column top temperature, my dew point would change for the corresponding pressure, and my composition x D would change. So, this establishes that x_D is a function of T_{top} as well as P_{top}. I believe this is amply clear to you.

$$x_D = f_1(T_{top}, P_{top})$$

Now, I would like to add something more about the bottom section. If you look at the bottom section, which has got a liquid, part of the liquid is vaporized and put back. This happens in a reboiler. This is my column bottom material. With a composition what? The composition is x_B. What is here I have? I have T_B or my T_{btom}. At what pressure? At a pressure of P_{btom}.

Here if I see this is again a saturated liquid, it is giving of vapour. So, what happens here? So, this is at a condition of its bubble point. So, naturally, your T_{btom} is equal to the bubble point temperature of B at P_{btom} pressure. What its composition is x_B. Therefore, I can also write again the way I had written in this particular case, my x_B will be some function, I am going to call this f_2 of T_{btom} and P_{btom}.

$$x_B = 2(T_{btom}, P_{btom})$$

So, I believe you have right now an idea that if you would like to change the top composition x_D and the bottom composition x_B, one of the ways is to change T_{btom} and

T_{top}. Now, there is something in addition to this. We normally would like to keep the column top pressure constant. If you calculate, it is something very interesting.

Suppose we are talking about a 1.5m diameter column, and a column pressure fluctuates by an amount of approximately 0.1 kg/cm^2. You will evaluate the pressure differential that it generates across the top tray. It will be in 100 of kilograms force which means, usually such pressure surges at sufficient to dislodge trays.

So, one thing is true normally you would not like the column pressure to vary, and so naturally, you would like this to be kept fixed by using some sort of controller. So, you usually keep this fixed.

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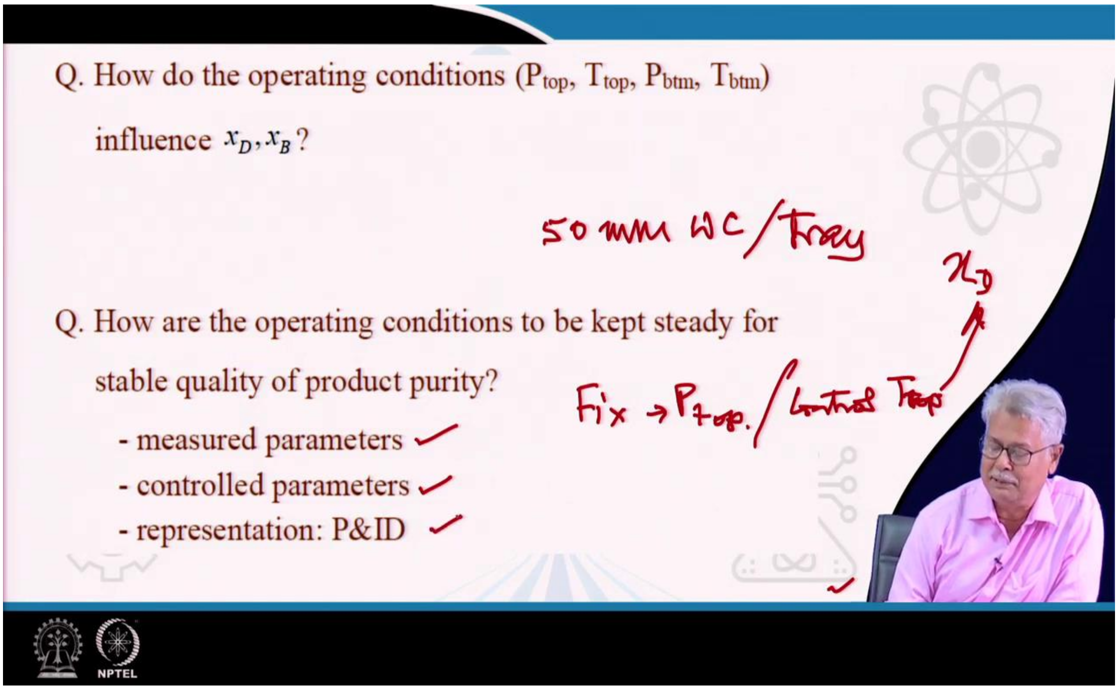

Q. How do the operating conditions (P_{top}, T_{top}, P_{btm}, T_{btm}) influence x_D, x_B?

50 mm WC / Tray

Q. How are the operating conditions to be kept steady for stable quality of product purity?

- measured parameters ✓
- controlled parameters ✓
- representation: P&ID ✓

Fix → P_{top}. / Control T_{top} → x_D

We fix P_{top}; we control T_{top}. The result is a fixed x_D to the desired value. Now, once you fix P_{top}, you will find your column bottom pressure will also get fixed. The reason is simple. The column top pressure has to be lower than the column bottom pressure because the vapour generated by the reboiler ultimately has to pass through the trays.

Across each tray, there will be a pressure drop. These trays typically will have roughly around 50 mm of liquid on them. Including other additional pressure drops, the pressure drop per tray normally amounts to roughly 50 mm water column per tray.

While we are designing if you have an estimate of the total number of trays involved in my column, I can estimate the column bottom by adding the total pressure drop in each. Now, to do this, it has to be a steady operation. We must have some parameters which are controlled. We need to have certain parameters which are measured also. We have to represent the control scheme using a P & ID.

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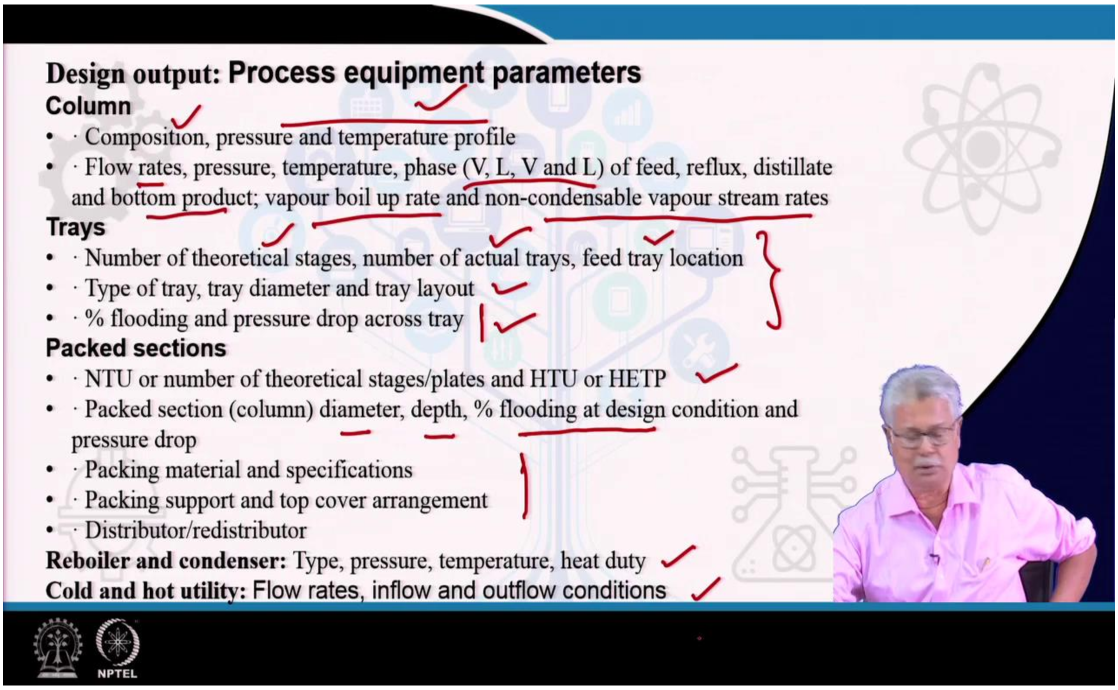

Design output: Process equipment parameters

Column

- · Composition, pressure and temperature profile
- · Flow rates, pressure, temperature, phase (V, L, V and L) of feed, reflux, distillate and bottom product; vapour boil up rate and non-condensable vapour stream rates

Trays

- · Number of theoretical stages, number of actual trays, feed tray location
- · Type of tray, tray diameter and tray layout
- · % flooding and pressure drop across tray

Packed sections

- · NTU or number of theoretical stages/plates and HTU or HETP
- · Packed section (column) diameter, depth, % flooding at design condition and pressure drop
- · Packing material and specifications
- · Packing support and top cover arrangement
- · Distributor/redistributor

Reboiler and condenser: Type, pressure, temperature, heat duty

Cold and hot utility: Flow rates, inflow and outflow conditions

Before going into the control scheme, we talk about the design output list. Naturally, regarding the column, we have a lot of process parameters. These are composition, temperature and pressure profiles in the column that we already have decided on. The flow rates across each tray and their phases of feed, the reflux, distillate and bottom product; The vapour boil up rate, and the non-condensable vapour stream rates.

Similarly, we have not detailed how to find these out, but whenever we are talking about the process output for the trays, we need to know the number of theoretical stages, the number of actual trays or stages or tower plates or whatever you may call, the feed tray location, the type of tray diameter and layout. Naturally the operating percentage flooding and the pressure drop in each tray.

If it is a packed section, there will be equivalent items. So, it will be the number of transfer units or the number of theoretical stages or per plate, and naturally the HTU or HETP which are already defined in your mass transfer course. In the case of a packed column, the diameter has to be known naturally that is the tower diameter. The depth gives us how many stages of equivalent contact we are providing and the percentage flooding at the design conditions and the pressure drop. We definitely have to detail the packing material as well.

Regarding the reboiler and the condenser, we have to give the details. We definitely have to provide the pressure the temperature and heat duty, so that these can be designed by the appropriate group. In your reboiler and condenser, we are going to use hot and cold utilities. Their requirement is also definitely a process parameter that has to come out from your exercise.

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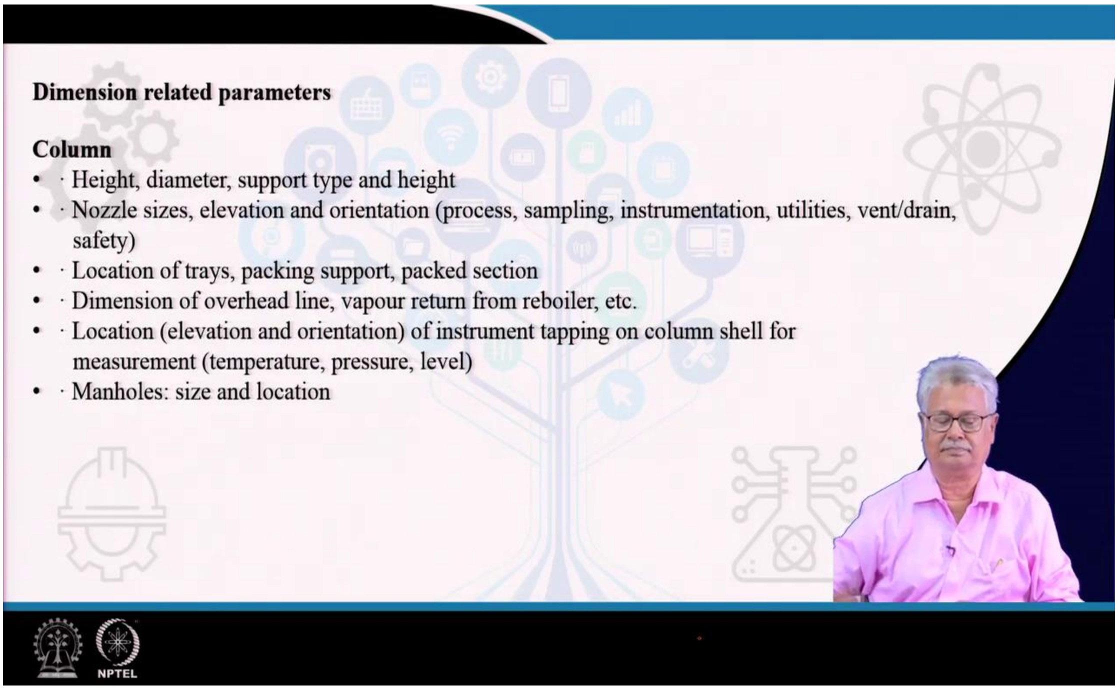

Dimension related parameters

Column

- Height, diameter, support type and height
- Nozzle sizes, elevation and orientation (process, sampling, instrumentation, utilities, vent/drain, safety)
- Location of trays, packing support, packed section
- Dimension of overhead line, vapour return from reboiler, etc.
- Location (elevation and orientation) of instrument tapping on column shell for measurement (temperature, pressure, level)
- Manholes: size and location

When you are finally making a summary of the design, before that you have to give and generate all dimensional parameters which are listed here. This set of output is going to be the design basis or rather the basis of drawing for making a fabrication drawing which will be given to the fabricator for fabrication, and ultimately this will become your column itself.

So, quite naturally these are all dimensional parameters which are listed here, which are height, diameter, location of trays, location of instrument, nozzles and all. Definitely you have to have some idea about the safety aspects also so which will be detailed slightly after this, immediately after in fact.

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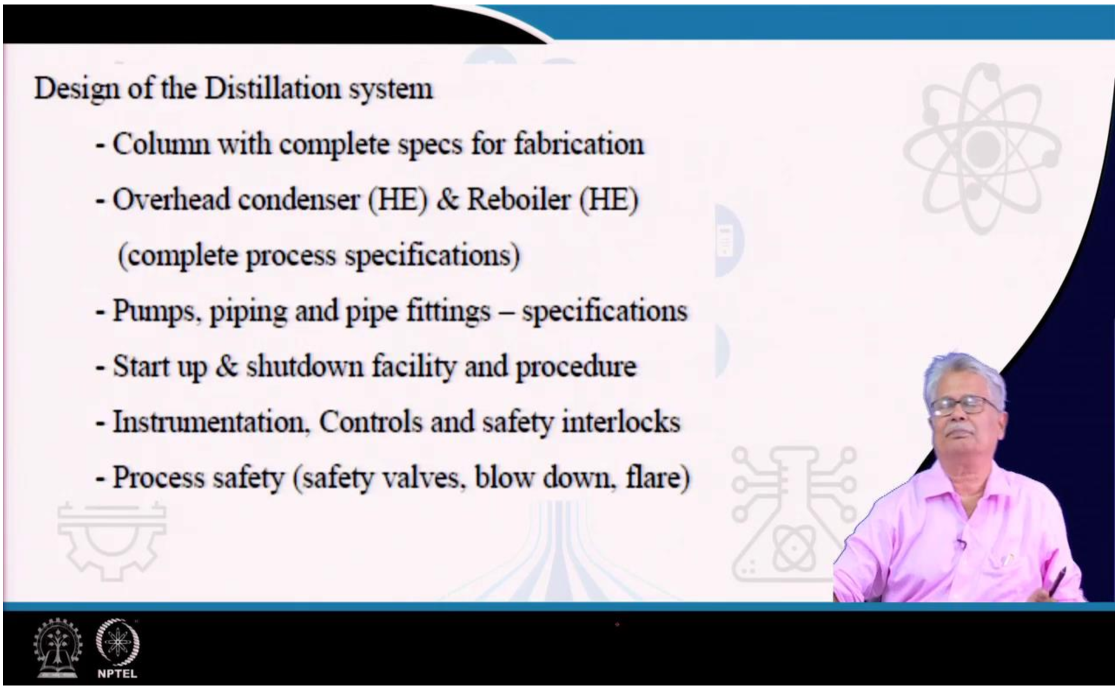

Design of the Distillation system

- Column with complete specs for fabrication
- Overhead condenser (HE) & Reboiler (HE) (complete process specifications)
- Pumps, piping and pipe fittings – specifications
- Start up & shutdown facility and procedure
- Instrumentation, Controls and safety interlocks
- Process safety (safety valves, blow down, flare)

That means as a part of the design of the distillation system, we are going to provide a column with a complete specification for fabrication, that is the drawing. The details of the heat exchanger which is which are the condenser and the reboiler; pumps, piping and pipe fittings – their specifications and sizing; startup and shutdown facility and procedure – definitely this has also to be defined.

You have to talk about and provide in the form of a P and ID – the instrumentation control and the safety interlocks which are implemented through instrumentation. The safety valves, or blow-down arrangement and the flare for process safety whatever is required for your plant the distillation system has to be provided.

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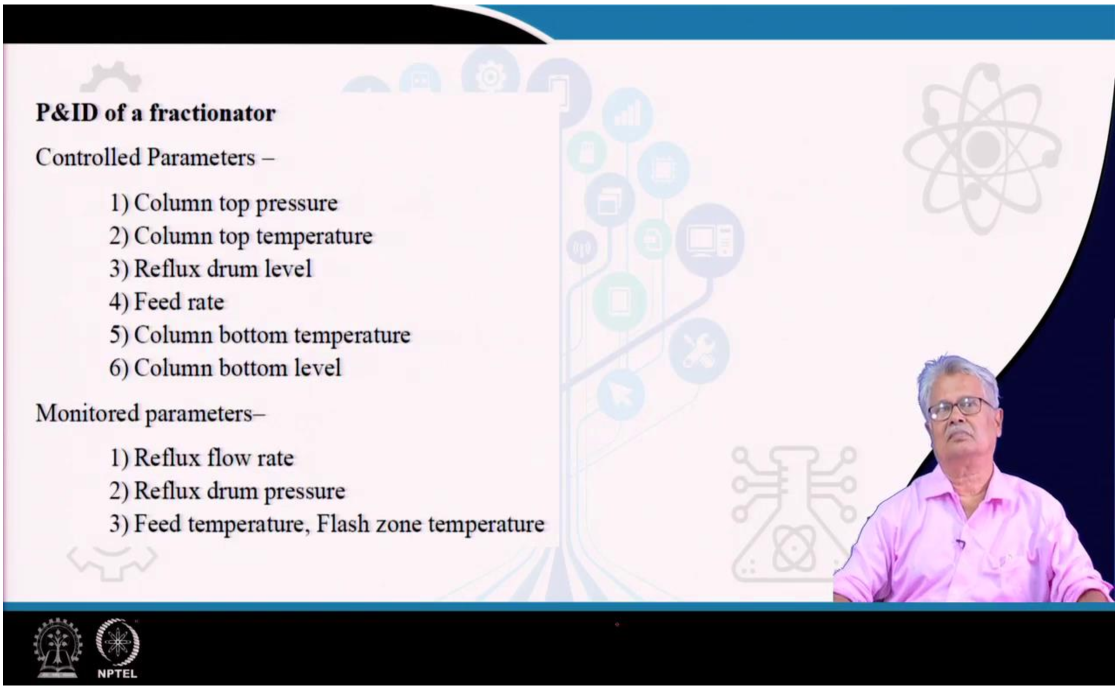

P&ID of a fractionator

Controlled Parameters –

1) Column top pressure
2) Column top temperature
3) Reflux drum level
4) Feed rate
5) Column bottom temperature
6) Column bottom level

Monitored parameters–

1) Reflux flow rate
2) Reflux drum pressure
3) Feed temperature, Flash zone temperature

So, these are nothing but the P and ID details of a fractionator which I provide in the next slide.

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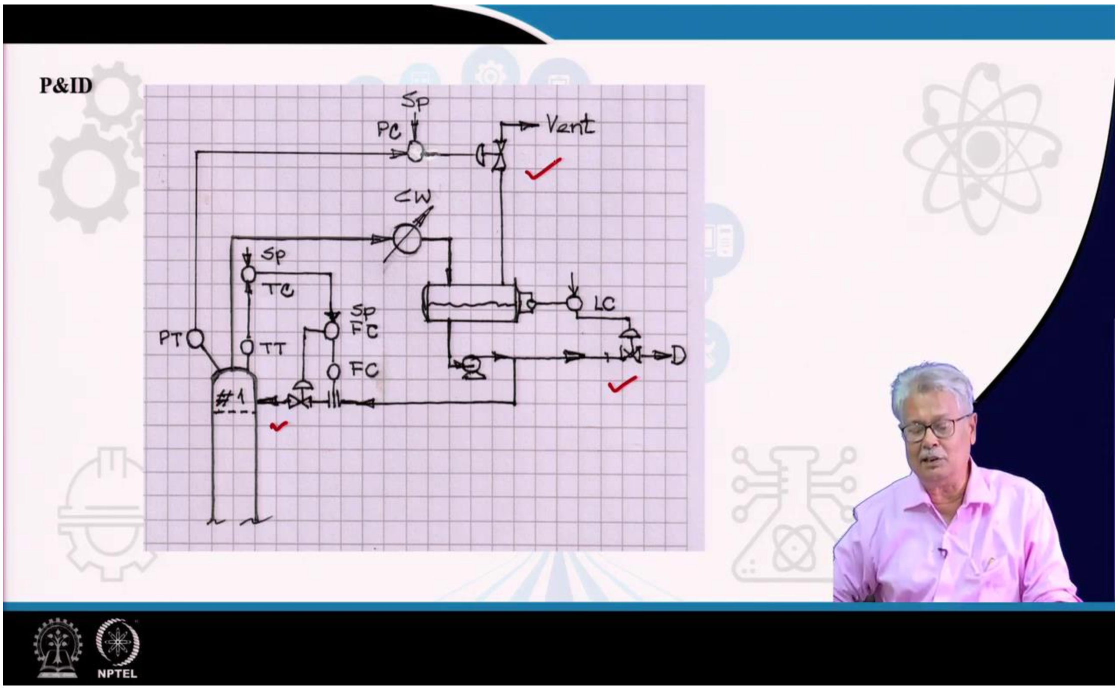

P&ID

Here is the upper section. The upper section definitely shows streams which is the reflux which is controlled. The level is controlled by the distillate, this has been told to you by while teaching in the other class. The pressure is controlled by the venting. This is the basic arrangement that you have in the P and ID. But here I exactly do not call it cannot call it a P and ID, because it does not include the piping details. It only shows the control scheme.

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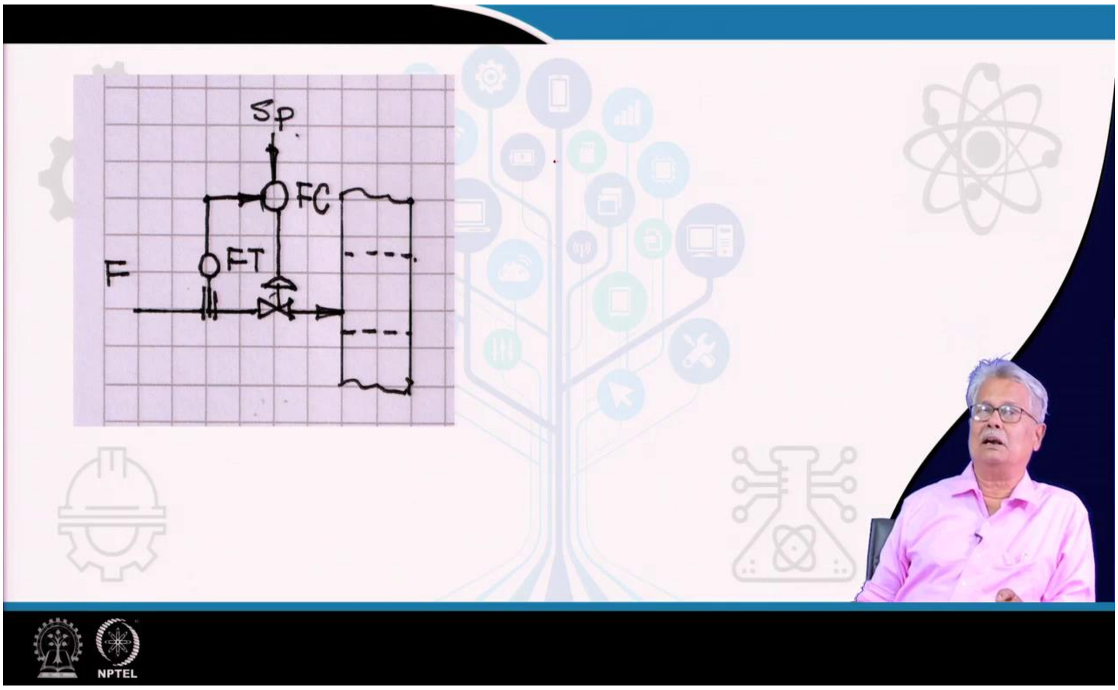

Similarly, a question possibly will be coming up that how do you control your feed? Normally, the feed rate is controlled and is an independent parameter for which your process is being designed. And it is nothing but, a flow control valve in your feed line. So, this is basically the control scheme for your feed.

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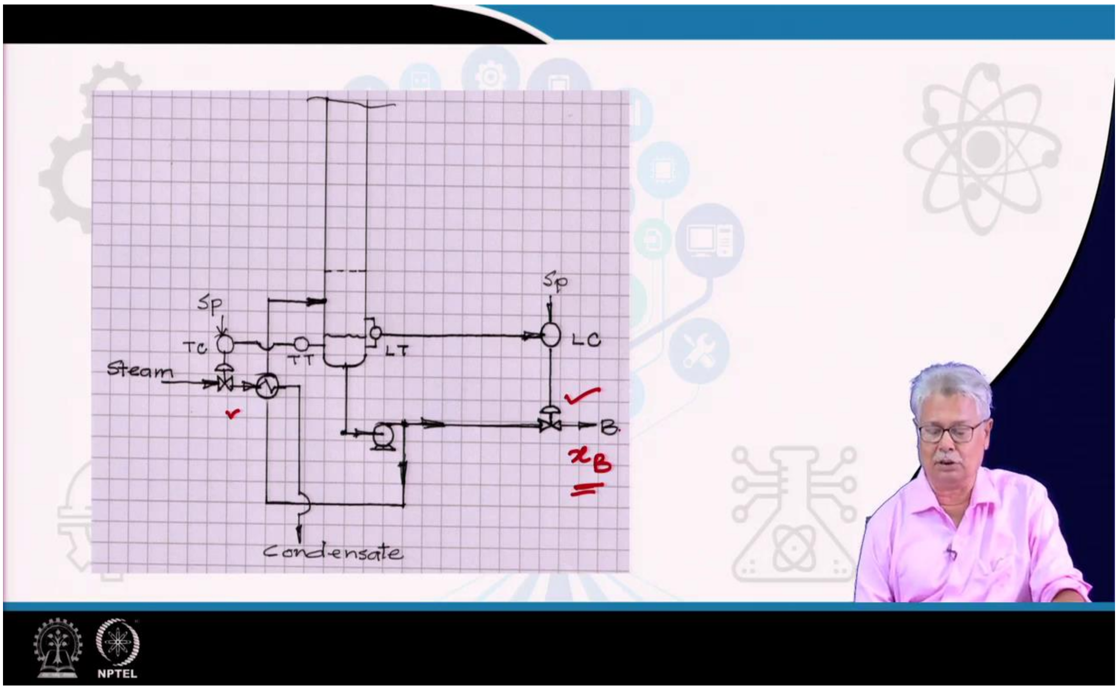

If you look at the column bottom section, what you have is certainly the level control which also has been talked about. You have to control the column bottom temperature because that decides the value of the x_B. That is controlled by controlling the steam or the heating fluid input or the heat input to the reboiler.

So, this is your reboiler. And the reboiler heat basically generates sufficient temperature, and your steam flow or the heating fluid flow is manipulated to control T_B which in turn fixes your x_B. The level naturally decides the flow rate of the column bottom.

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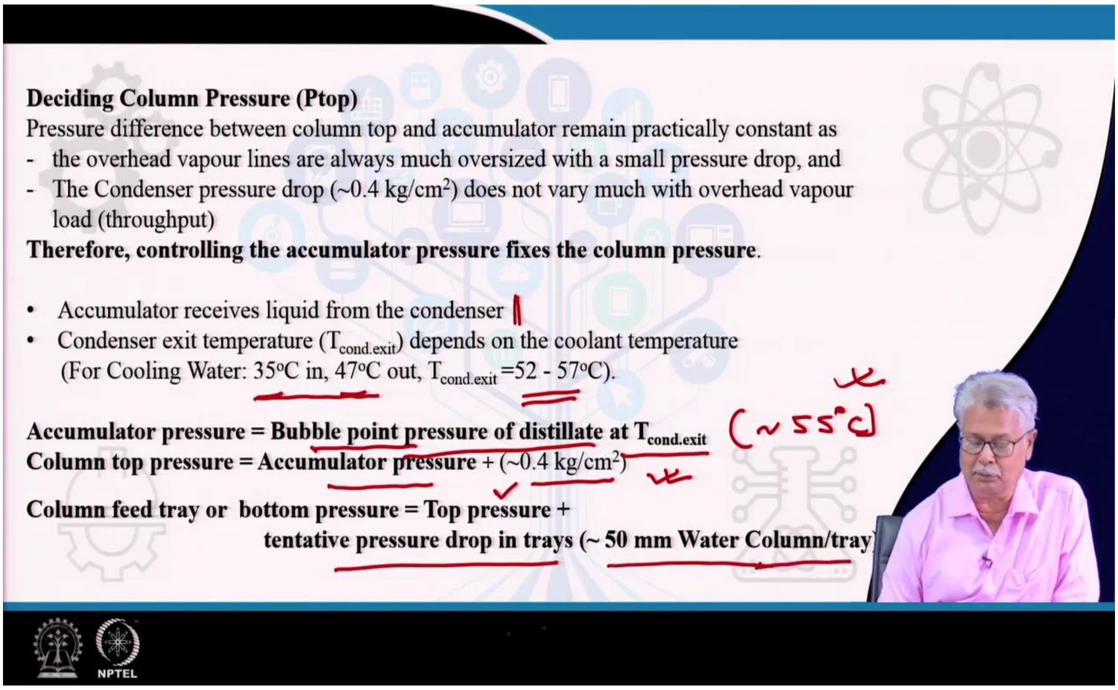

Deciding Column Pressure (Ptop)
Pressure difference between column top and accumulator remain practically constant as
- the overhead vapour lines are always much oversized with a small pressure drop, and
- The Condenser pressure drop (~0.4 kg/cm^2) does not vary much with overhead vapour load (throughput)

Therefore, controlling the accumulator pressure fixes the column pressure.

- Accumulator receives liquid from the condenser
- Condenser exit temperature ($T_{cond.exit}$) depends on the coolant temperature (For Cooling Water: 35°C in, 47°C out, $T_{cond.exit}$ =52 - 57°C).

Accumulator pressure = Bubble point pressure of distillate at $T_{cond.exit}$ (~55°C)
Column top pressure = Accumulator pressure + (~0.4 kg/cm^2)
Column feed tray or bottom pressure = Top pressure +
tentative pressure drop in trays (~ 50 mm Water Column/tray)

Regarding the column pressure, I already have told you that the column pressure is decided primarily by a very interesting point which is that the column receives the liquid from the condenser and the liquid in the condenser after the condenser is at a particular temperature which is decided by the coolant in the condenser.

A typical example for this is if it is cooling water typically in Indian condition, it will be entering at 35 and it will be leaving at 47. We have an adequate pressure adequate temperature driving force, which means if my hot side is between the temperature of 52 to 57 °C. So, if you are going to use cooling water possibly, you will have a condensate exit temperature which will be anything between 52 and 57 which the designer has to decide.

Now, that means, inside your accumulator that is going to be your temperature. The accumulated pressure is the bubble point pressure of the distillate at the condenser exit which is anything around say 55 °C if your temperature of cooling water is 35 °C and 47. So, that is something to note that ultimately your accumulated pressure is decided by the coolant temperature.

Now, the column pressure has to be higher than this particular pressure. So, naturally, the column pressure is going to be accumulated pressure plus the pressure drop in the piping in the overhead which normally is highly oversized and the pressure drop in your condenser. So, your column top pressure normally is found out by adding around 0.3 to 0.4 to the accumulated pressure which has been found at a temperature of around 55 °C using cooling water.

Now, I have already said this. The column feed tray or the bottom pressure will be the top pressure plus the tentative pressure drop in trays. We do not know the exact number of trays yet, but we can always make a guess. Assuming 50mm of water column per tray, we can estimate the column bottom pressure as well.

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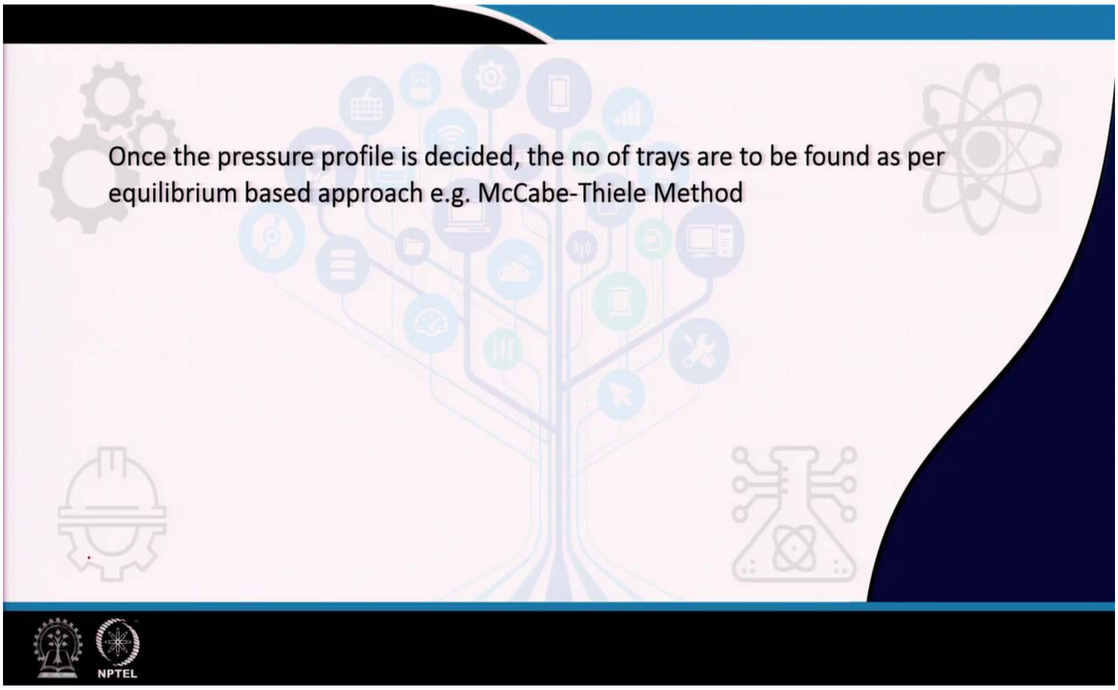

Once the pressure profile is decided, the no of trays are to be found as per equilibrium based approach e.g. McCabe-Thiele Method

So far what we have decided is the design output, and the basic steps, and the principle based on which certain process parameters can be found out. So, the next thing should be finding out the details of the number of equilibrium stages that are required above the feed tray that means in the enriching section, and below the feed tray which is the stripping section.

At the same time, we are also to note that the requirement of the number of trays depends on the reflux ratio. So, quite naturally we need to have a procedure which is a McCabe-Thiele procedure which relates the number of tray requirements for these two sections as well as a reflux ratio for its specific equilibrium system, may be benzene-toluene, it could be alcohol-water or any such equivalent thing.

With this, I think I will stop here. The next input shall be on the McCabe-Thiele method of estimating the number of stages, and the reflux ratio relationship, and what exactly it should be in your design case.

Thank you.