Principles and Practices of Process Equipment and Plant Design

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Module - 02
Lecture - 40
Design of Mass Transfer Processes (Review)

A good day to you all. Today is basically the last session on our module 2 which covers the Design of Mass Transfer Processes. What we intend to do is basically provide overview of what we have covered so far and introduce you to a new concept. We will see that, let us move on.

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Designing a Mass Transfer Process?

- Process selection
- Equipment selection
- Economics – optimum design

Mass transfer rate =*f*(mass transfer coefficient x area of mass transfer, concentration driving force)

Design approaches

- Equilibrium based
- Rate based

Whenever we are talking about designing any mass transfer process, these are the steps. First, most of the mass transfer processes are basically separation processes. So, we got to select the process; that means, whether it is distillation or absorption, adsorption, extraction, leaching or whatever type of process that we have, that we require in order to make the separation that we have to decide.

Well, in doing that perhaps we need to have some idea about the efficiency of the process that we are going to adopt. The efficiency of the process means the transfer rate should be high and we all know that your mass transfer rate is a function of the mass transfer coefficient multiplied by the area of mass transfer and also the concentration driving force.

So, we will just recapitulate what exactly is the basis of selection of the process and this will be followed by detailing the equipment which is required for this particular separation; that means, what type of equipment. For example, even if we are chosen a process like distillation; it could be continuous, it could be batch, it could be tray, it could be packed whatever type of equipment. We have to decide on this at this stage.

And once we have decided these two, we have to arrive at the optimum design which is basically supposed to be based on economics, but quite often exactly making an economic calculation is not necessary. We make certain other heuristic choice first and among the choices we evaluate the best possible alternative either by economic criteria like either profit, rate of return or cost minimization. Or we decide on a particular technical factor like efficiency of the process or recovery of the process and we arrive at the optimum design.

Quite naturally whenever we are talking about an optimum, there has to be at least two numbers of opposing effects which is going to affect the optimization criteria. And that is what is going to lead to your optimum.

We definitely after doing this, will also be talking about the design approaches, so far what we have been using is the equilibrium based approach, that means, what we tried to do. We tried to find out the ideal number of stages required for the separation and tried to realize it by considering some amount of inefficiency of these stages or the process itself if it is a single stage. And, we have arrived at a practical solution which accounts for the inefficiencies in my process.

The other approach we have not covered. We just had mentioned it in one of the first few classes. It is a rate based approach, this is the new concept which I was talking about. I will be elaborating this rate based concept, this you need to know the fundamental concept and what lies within it; what is the basic principle of the rate based approach to the design.

Remember one thing, rate based process though I am saying here, rate based process is not essentially applicable to mass transfer processes it could be for other types of processes like heat transfer and others as well.

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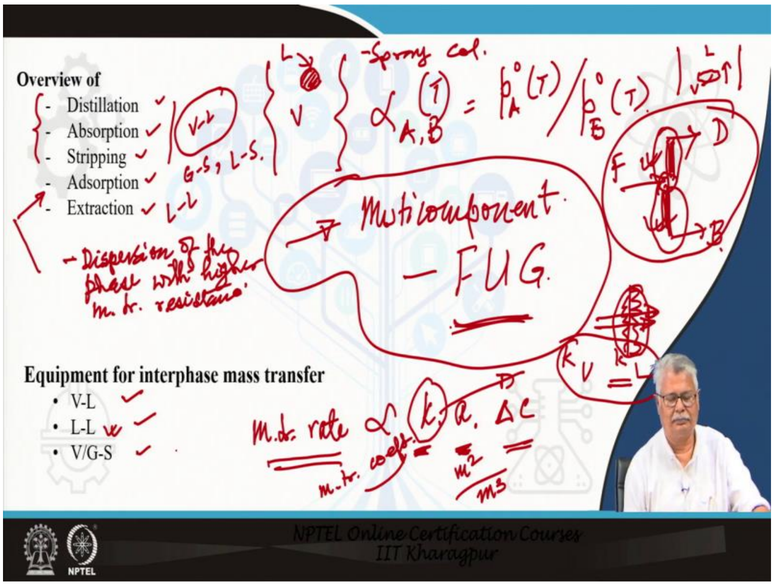

Overview of

- Distillation
- Absorption
- Stripping
- Adsorption
- Extraction

Equipment for interphase mass transfer

- V-L
- L-L
- V/G-S

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If we talk about the mass transfer processes; here is a list what we have covered. We definitely have covered distillation, absorption, stripping, adsorption and extraction. Now, if you have noticed definitely out of these except I mean not the except extraction; extraction is a liquid – liquid process but, distillation and absorption and stripping these are our vapor liquid processes.

In case of extraction what you had? You had a liquid – liquid interaction or these two other phases involved in it. Now, in case of adsorption what happen you have a choice it could be either a gas solid, adsorption or it could also be a liquid solid system. Now, I just have a very quick recapitulation of the distillation.

In distillation, what we do? In distillation, we take care of the principle of separation by looking at the relative volatility of the two components or more than two components or the individual components whatever you say by defining a term which is called relative volatility which is nothing, but; relative volatility A of A with respect to B is the pure component vapor pressure of A at that particular temperature. This is a function of temperature divided by the pure component vapor pressure of B at the same temperature.

Quite naturally the component A if it is having a higher vapor pressure at the same temperature T in relation to B alpha A, B is going to be one and separation should be possible. And, typical separations which are done when you have alpha around say 2.5, 2.8 and higher than that.

We also have to look at and we found out that each of these processes could be conducted either as a continuous process; that means, both the feed stream and any other stream which is coming and approaching the process, they are flowing in continuously and the streams which get separated they also flow out continuously.

We have the other process which is basically the batch 1 where you keep on charging the initial batch. That means, the entire processing feed has to be charged to the equipment in one shot. The processing takes place for a time duration T and then the products are separated or taken out from that particular batch charged equipment.

Now, it is true that you can have other processes also. For example, in case of adsorption suppose I am talking of the gas solid adsorption I will just give you an example or rather before I go there I should make one more detailing about the first three processes.

We have encountered and we have told you regarding binary system separation as well as multi components separation. And, this we have done specifically in case of distillation. If you look at the processes which is there; that means, the separation stage wise there is no basic difference between distillation, absorption and stripping.

What I would like to say here is that each of these processes can be approach with a generalization. For example, if you do a fairly detailed calculation for distillation which has got the stripping section at the bottom and the enrichment section at the top, in that case the calculations are same for the absorption as well as stripping and distillation. In fact, the simulators that you have today for simulating processes of distillation, they use the same set of mathematical routines for simulating, either distillation, absorption and stripping.

The technique that has been told to you regarding absorption and stripping is under a slightly approximation that is only a single component goes from one phase to the other. This is not so in distillation and so, if I take the same approach as distillation it should be possible for us to design absorption and stripping also exactly the same way.

Now, there is some more generalization involved here. In distillation, particularly when we have talked of multi-component distillation we talk we talked about the multi-component distillation here and we talked about the generalized method of Fenske-Underwood-Gilliland. This is for the multi component distillation, but it is also applicable for absorption and stripping when we take that generalized approach.

So, if you wish you can use the FUG approach also for absorption and stripping and you have to think about right now what are the basic differences between these two cases. What I would like to say is, if you look at a distillation column the distillation column typically will have a feed somewhere, the upper portion will be you can consider that this is one distillation column and this is a second distillation column.

That means, this is your feed, this is your distillate and this is your bottoms as if there are two distillation columns which are merged into one, the upper portion is one column and the lower portion is the second column. And, you can apply here the FUG method also. That means, if I can apply here the FUG method here definitely there here the operation is of enrichment and here is that of stripping. So, your absorption and stripping can both be handled this way.

Now, we talk about adsorption. The example of adsorption, the simplest absorption example is basically whenever you have moisture to be removed from air, you pass it either through a bed of silica gel or through a bed of activated alumina. The moisture in the air gets transferred to the solid surface. So, that is the process of adsorption.

Similarly, you can also remove some coloring material which may be present in a liquid stream. For example, in an effluent water and get it adsorbed by passing it through a bed of activated charcoal or activated carbon whatever you may call, charcoal or activated carbon.

Similarly, you can extract from a liquid phase by addition of a solvent one particular component preferentially dissolving into the solvent and that is your process of extraction. Typically, sulfur one of the earliest process of commercial extraction was use of liquid sulfur dioxide to extract aromatics from naphtha and the kerosene fractions. So, aromatic extraction by liquid – liquid contacting of the liquid solvent as well as a liquid feed is already established.

If you go to any refinery which produces lubricating oil you will definitely find one extraction column, most probably using a rotating disc conductor which is removing the aromatics from the lubricating oil base stock. So, what we have here is an overview of these, and we now should focus at the equipment which are involved. We talk about distillation and we have so far focused primarily on vapor and liquid contacting equipment.

We know the rate of mass transfer, basically if I write here mass transfer rate is proportional to the mass transfer coefficient into the specific area into the concentration driving force. Now, what we do is what I say here is if I have to increase the rate, why do I want to increase the rate? Because if I have a higher rate of mass transfer, in that case possibly I will be with the same equipment I will be handling a larger amount of feed quantity per unit time; that is one advantage. Or if my feed availability quantity is fixed, my size of equipment is going to be smaller.

Now, what are the ways you can increase the mass transfer rate you can increase k, you can increase a, you can increase delta c. Delta c is basically decided by what? It is a initial to the final concentration grossly, it is just a conceptual indication of the difference in the concentration that you are going to achieve in your piece of equipment; k is the mass transfer coefficient and a is the specific area through which the mass transfer takes place.

Typically the unit of this could be metre square per metre cube of the equipment volume or equipment active volume whatever you see and, this k is basically the mass transfer coefficient. Now, the mass transfer coefficient is basically depending on what? It depends on quite a few things. The simplest way of having a mass transfer is by diffusion by molecular diffusion.

So, if I can somehow increase the molecular diffusion, the molecular diffusion depends on what? It depends on the diffusivity; diffusivity in the liquid or in the gas phase both are functions of temperature. So, usually the mass transfer rate will go up if you have increased temperature. What else you require? If you can somehow increase the turbulence; that means, agitation is one very common thing.

Now, there is one more thing which is also required in this case. We are talking about the inter phase mass transfer say this side is vapor and this side is liquid, and the transfer is from the vapor to the liquid the component that whose transfer I am talking about. Now, there is some resistance in this side and there is some resistance at the other side also; that means, these two resistances are in series to the mass transfer flux.

Now, it is also possible that one of these resistances dominate. Now, in case of mass transfer, the inverse of the mass transfer coefficient denotes its resistance. That means, out of these phase, the phase which has got a higher mass transfer coefficient has got the least resistance. I repeat the higher mass transfer coefficient refers to least resistance.

Now, what are the ways I can in; ultimately what is going to happen is basically this k is a function of the k of the vapor side and k of the liquid side. The same thing could be k of phase 1 and k v of phase 2. So, this k is a function of these two k individual k’s. Now, say I know that my liquid phase resistance dominates, in that case how will I decide on equipment?

In order to have or facilitate my mass transfer I will normally prefer to have dispersion of the phase with higher mass transfer resistance. What advantage you have? The length through which the transferred mass has to travel becomes less. Now, very a common thing in case of vapor liquid contacting you have various options. One option is what you can have droplet us of liquid in a continuous medium of gas.

Now, when will you have drop when will you generate droplets of liquid and what exactly is this? This one is a spray column this is a spray column. Now, when will you go for this spray column? Naturally, when you know that your liquids phase mass transfer is the controlling mass transfer coefficient; that means, it is the lowest one lower of the two.

Similarly, you could have gone for a bubble column also. In case of bubble column what you have? You have a continuous medium this one is liquid and this is your vapor or gas; whatever you may call. And, in this case what will happen? You will have a continuous medium of liquid and you have a bubble which is rising up; a bubble which is rising up through a liquid medium. So, this is a vapor bubble.

Now, when do you do it? When you know that your resistance lies in the vapor phase. So, you have an idea that depending on which phase the resistance lies that particular phase you are thinking that it should be dispersed, because it will reduce your diffusion length. And that is how you choose your nature of mass transfer equipment. There is another thing which is also there. The mass transfer is not only a function of k, it is also a function of a k into a multiplied together.

So, if we can somehow disperse one into another medium the interface area increases, the smaller the droplets the smaller the dispersion size the specific area increases. So, naturally if you have high a large number of droplets made from this same quantity of fluid the specific area would go up.

There is one more thing which increases k that is agitation. For example, in liquid – liquid, so dispersion is there, but what you require really is a good amount of agitation because in both phases the mass transfer coefficients are not very high. So, in such cases definitely there will be in any equipment there will be dispersion of one phase into the other, the second part of it will be the agitation and for dispersion as well as agitation you need to spend power. So, quite naturally there will be expenses on this particular account.

So, these are the basics of choosing the vapor liquid transfer, the liquid – liquid transfer and the vapor or gas to solid transfer as well.

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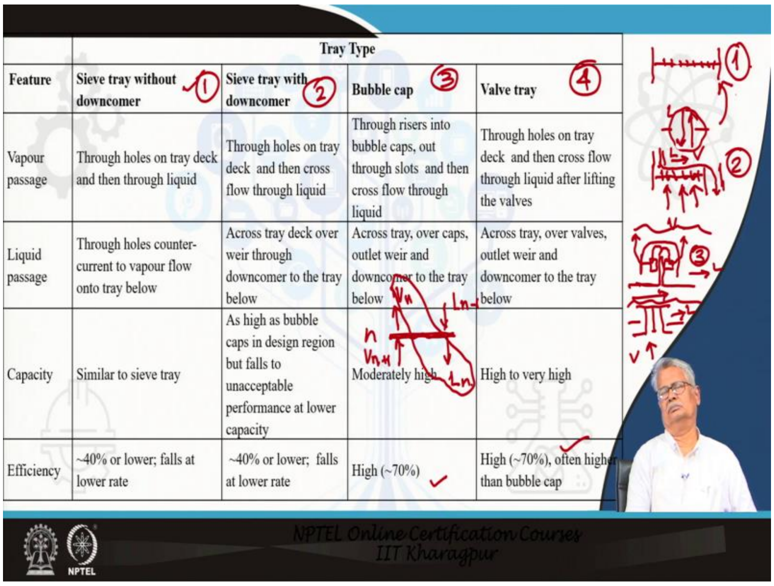

	Tray Type			
Feature	**Sieve tray without downcomer** ①	**Sieve tray with downcomer** ②	**Bubble cap** ③	**Valve tray** ④
Vapour passage	Through holes on tray deck and then through liquid	Through holes on tray deck and then cross flow through liquid	Through risers into bubble caps, out through slots and then cross flow through liquid	Through holes on tray deck and then cross flow through liquid after lifting the valves
Liquid passage	Through holes counter-current to vapour flow onto tray below	Across tray deck over weir through downcomer to the tray below	Across tray, over caps, outlet weir and downcomer to the tray below	Across tray, over valves, outlet weir and downcomer to the tray below
Capacity	Similar to sieve tray	As high as bubble caps in design region but falls to unacceptable performance at lower capacity	Moderately high	High to very high
Efficiency	~40% or lower; falls at lower rate	~40% or lower; falls at lower rate	High (~70%) ✓	High (~70%), often higher ✓ than bubble cap

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Now, we look at the different tray types for vapor liquid contacting. We have so far talked about vapor liquid contracting with respect to adsorption stripping and distillation.

And, while talking about the tray internals we talked about the sieve tray without downcomer; that means, you just have a tray here you just have a tray here which is this with punched hole usually.

The punched hole could be anything like 5-6 millimeters depending on the design that you have. And it is through the same hole in this particular case, the liquid falls and the vapor also goes up the liquid falls and the vapor goes up. And, here you definitely have a good amount of interaction.

Now, let us see the feature of these and what you have in this is the type one which is my sieve tray without downcomer. In case you have a different construction what you have in that particular case it is something similar what is there in other trays also. Here also you have the sieve tray, but you have a downcomer. That means, the liquid falls from here and it falls has it has a cross over and then falls into the downcomer of the sieve tray.

And, what you have here is basically the vapor goes up and this is a cross flow tray. In case of 1, what you have? You have a counter flow tray; that means, you have through the same hole counter flowing vapor and the liquid whereas, in this particular case of the second type of sieve tray with downcomer it is a cross flow tray. In fact, number 2, number 3 and number 4 all are cross flow trays.

On a cross flow tray what you have? On a cross flow tray basically what you have is a disperser; a vapor disperser. In case of sieve tray with downcomer or sieve tray without downcomer what you have is the vapor disperser which is not an external fitting. It is basically the whole acts for dispersing the vapor into the liquid. In case of bubble cap what you have? You have an inverted cap and a riser.

The inverted cap basically covers the inverted cap has got slots and it has on a riser which is the riser is fitted onto a deck. So, what happens is the vapor goes out, it comes out and bubbles out it; goes out comes out through the slots and it comes out like this. So, all these has been told to you and how it is designed and what are their limitations and operations of these bubble cap has also been told to you.

In case of the valve tray what you have? You have a disc. You basically have a disc with three legs which protrude inside a hole and you have the vapor going up and the liquid is cross flowing over this. This is definitely immersed in liquid, this is also immersed in liquid, you have the liquid flow this way, you have the liquid flowing this way. So, basically 2, 3 and 4 are cross flow trays.

Now, let us look at the features of each of these. The vapor passage part we have talked about, we also have talked about the liquid passage. The liquid passage is basically through sieve holes in case of the tray without downcomer and in all other cases it is cross flow and it has got a separate downcomer through which the liquid falls to the next tray.

Regarding the capacity whether you have downcomer or not the sieve trays have similar capacity. Now, if you see here a comparison of the capacity, you will find the bubble cap usually will have a moderately high capacity. The valve tray usually has a capacity which is high to fairly high enough.

Now, efficiency is one term in vapor liquid contacting. In vapor liquid contracting when you are talking about efficiency, in an ideal tray; in an ideal tray and if this be the n-th tray and the liquid falling from this tray is L n the liquid falling to the up from the upper tray number n minus 1 is L n minus 1. The vapor approaching the tray is V n plus 1 and the vapor leaving the tray is V n. So, actually in an ideal tray the vapor and the liquid which is leaving the tray should be in equilibrium.

So, basically what you find is the approach to equilibrium which is achieved in sieve tray because the contacting quality contacting quality is not very good is usually below 40 percent. In fact, the sieve tray without downcomer has got a very limited range of operation and it does not operate very well if your design conditions are violated.

Relative to that you have a fairly high efficiency of bubble cap and the valve trays. You see it goes up to an approach to approach of around 70 percent. Sometimes the valve trays have even higher capacity and definitely the efficiency could also be higher.

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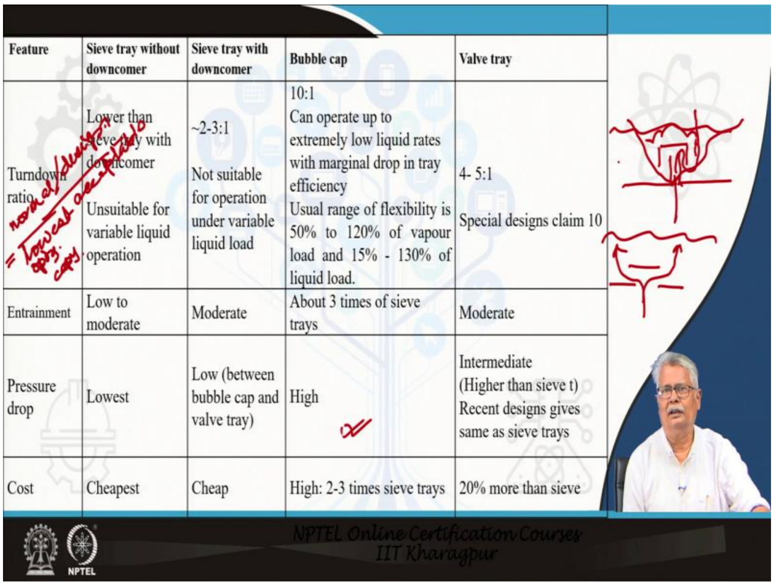

Feature	Sieve tray without downcomer	Sieve tray with downcomer	Bubble cap	Valve tray
Turndown ratio	Lower than sieve tray with downcomer Unsuitable for variable liquid operation	~2-3:1 Not suitable for operation under variable liquid load	10:1 Can operate up to extremely low liquid rates with marginal drop in tray efficiency Usual range of flexibility is 50% to 120% of vapour load and 15% - 130% of liquid load.	4- 5:1 Special designs claim 10
Entrainment	Low to moderate	Moderate	About 3 times of sieve trays	Moderate
Pressure drop	Lowest	Low (between bubble cap and valve tray)	High	Intermediate (Higher than sieve t) Recent designs gives same as sieve trays
Cost	Cheapest	Cheap	High: 2-3 times sieve trays	20% more than sieve

normal/design / = lowest acceptable opg. capy

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Regarding capacity what I am saying here is something very interesting. I have in my last class defined the turndown ratio. The turndown ratio is what conceptually it is basically the normal capacity it is normal or design capacity divided by the lowest acceptable operating capacity.

Now, what is meant by the lowest acceptable operating capacity? Yes, I can operate my plant at a very low capacity also, but perhaps in that case I will even if it is a sieve tray my efficiency will be 15 percent for the trays. So, that is not acceptable. So, the normal design if it is for 40 percent it can go for about 36 – 34 percent of efficiency, but not lower than that.

So, this turndown the higher it is, it is possible to operate that particular piece of equipment to a lower capacity without much loss of efficiency. The figures are given here for the sieve trays in a relative scale. And here the you have one more thing which is there the bubble cap and the valve trays, what you have here in case of sieve trays with diameter with downcomer it could be 2 to 3.

In case of bubble cap it will be roughly about 10 is to 1; in case of valve tray it will about 4 to 5 is to 1. The entrainment affects the capacities largely, you will find the entrainment in a sieve tray without downcomer is the least. The reason is very simple because you have almost the column entire column tray section through which that flow takes place. And, there is ample scope of disengagement of the droplets from the vapor which is going up.

You have a moderate level of entrainment in your sieve trays and in case of bubble cap roughly about 3 times the sieve trays, because in case sieve trays because in case of bubble cap there is something called jet flooding. For example, if you have a bubble cap here with it is riser on the deck and I have a liquid level. If my vapor rate goes up quite often it happens that it blows the liquid over this.

So, definitely we do not want to have this and this leads to a good amount of entrainment in case of bubble caps. In case of valve tray, the entrainment is slightly less than the bubble cap, but it is still there. Regarding pressure drop its lowest in case of sieve tray without downcomer, with downcomer it is also still low and in case of bubble cap you will see that there is a reversal of the gas flow rate the flow direction. So, that entails or leads to a high pressure drop across the tray.

Not only the liquid column has to be pierced, but there is a reversal and direction also. In case of valve tray such a direct or a very strong change in direction is not there, because it basically will enter and go like this the vapor. And here you have a liquid level.

The cost you obviously, would find that the cheapest to make is the sieve tray without downcomer even if you provide a downcomer the cost is not much, because the holes are usually punched and the bubble cap is quite expensive and the valve trays are also quite expensive; in the sense it is about 20-25 percent more than the sieve tray with downcomer. Sometimes we are going for proprietary valve trays, they have a much higher cost.

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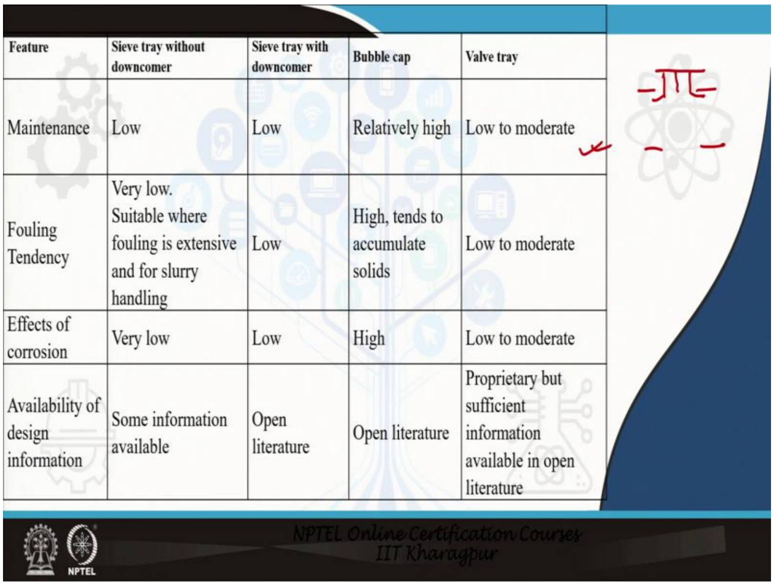

Feature	Sieve tray without downcomer	Sieve tray with downcomer	Bubble cap	Valve tray
Maintenance	Low	Low	Relatively high	Low to moderate
Fouling Tendency	Very low. Suitable where fouling is extensive and for slurry handling	Low	High, tends to accumulate solids	Low to moderate
Effects of corrosion	Very low	Low	High	Low to moderate
Availability of design information	Some information available	Open literature	Open literature	Proprietary but sufficient information available in open literature

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Regarding maintenance obviously, the bubble cap has got more components, it will require the highest level of maintenance. And, valve trays they have a moderate requirement of maintenance very often what happens is the legs are the weakest part. So, often you will find you had a bubble cap here, you have it a bubble cap here with a which was like this, it gets sorry, you have a valve tray here which goes like this. So, it gets blown off.

So, losing this bubble caps it from its position by failure of the weakest part which is it gets bent in fact, under a very high vapor load or a fluctuating vapor load is not uncommon. So, that may require a little bit of moderate level of maintenance for the valve trays.

The fouling tendency is rather low in case of sieve tray and downcomer, because after all since the vapor and the liquid traffic both are happening through the same hole the chance of the hole getting plugged is less in case of sieves. In case of bubble cap again there is a tendency to accumulate solid because what happens is right on the deck. The level the flow rate of the liquid which is cross flowing through it is less and there is a chance of accumulation of solids.

In fact, if you really have to handle some material some liquid which has got little bit of solids in it you will prefer a bubble cap with a long riser and a good amount of skirt clearance, because this will allow a little bit of deposits to remain there. In case of valve trays it is again low to moderate. The effect of corrosion is high in case of bubble cap it is obviously so because the components are more and the complications are in the path is also more.

The last point which is given here is very important regarding sieve tray without downcomer there is information available in the literature the with and without downcomer both are there in the literature. In case of bubble cap; yes, you can refer to that book by B. D. Smith. Design of equilibrium stage processes which gives a fairly detailed way by which this is designed. And in case of valve trays some data is available, but it is mostly proprietary.

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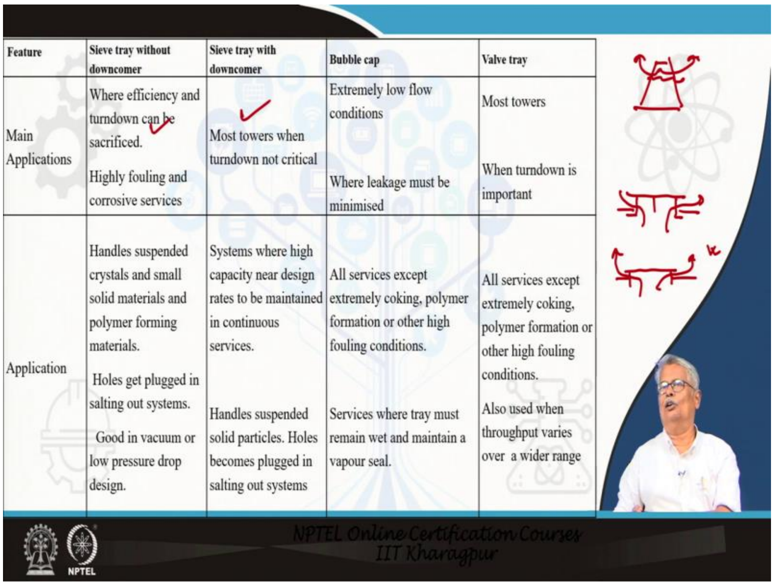

Feature	Sieve tray without downcomer	Sieve tray with downcomer	Bubble cap	Valve tray
Main Applications	Where efficiency and turndown can be sacrificed. ✓ Highly fouling and corrosive services	✓ Most towers when turndown not critical	Extremely low flow conditions Where leakage must be minimised	Most towers When turndown is important
Application	Handles suspended crystals and small solid materials and polymer forming materials. Holes get plugged in salting out systems. Good in vacuum or low pressure drop design.	Systems where high capacity near design rates to be maintained in continuous services. Handles suspended solid particles. Holes becomes plugged in salting out systems	All services except extremely coking, polymer formation or other high fouling conditions. Services where tray must remain wet and maintain a vapour seal.	All services except extremely coking, polymer formation or other high fouling conditions. Also used when throughput varies over a wider range

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This is perhaps a very important point regarding applications. The main application in case of sieve tray is when efficiency really does not matter; that means, you require a few number of stage. So, we can go for a sieve tray with or without downcomer when you really require a few number of stages. So, if you provide 100 percent extra number of stages it really does not matter, the cost is also not much instead of 2 we are going to provide 4 or 5 trays. So, that should be ok and because, it is cheap to make also.

Bubble cap allows very low flow conditions. For example, if you have a bubble gap in which the slots are trapezoidal and you have a liquid depression here and through which the vapor flows out. You will notice that if you have such a design, the area available for the valve to; for the vapor to escape through the slot, changes with the vapor load. So, when your flow rates are less the area is also less because of the trapezoidal section.

This allows extremely low flow conditions. And there is very little amount of leakage which takes place in this type of trays because the riser is quite raised from the deck. In case of valve trays the valve trays can be used with most applications and it is important when the turndown is also important; that you can think of such applications. You have the you have been given the turndown, relative turndown of each of these four types of trays earlier.

Typical applications in case of sieve trays are handling a suspended crystal, small solid material and polymer forming material; that means, you have following systems. And holes get plugged in basically salting out system. Yes, if crystals form there is a chance that they will be plugging the holes.

It is pretty good for vacuum or low pressure drop design because sieve trays with or without downcomer will be having lot of open area through which the vapor can pass and quite naturally the pressure drop in such trays are less. The bubble caps are pretty good except where you have got a large amount of coking or polymerization that can take place. Bubble caps in general are hardy. So, if you have pressure surges normally nothing much happens.

Valve trays in that respect a rather weak. So, the legs may get bent and the valve may be dislodged in case of pressure surges. Obviously, the valve tray should not also be used for extremely coking and polymer forming things; polymer farming systems. And, it is also used when you have a large variation in the vapor throughput, because what you will find here in this case of valve tray also; the valve tray maximum lift is in this position. If it is having a lower; if it is having a lower vapor rate the lift is less.

So, this also the area through which it comes out the area is also lower in this case when your vapor flow is less. This allows almost the same quality and the same size of the bubbles being formed and keeping its efficiency fairly constant over a large overheating range.

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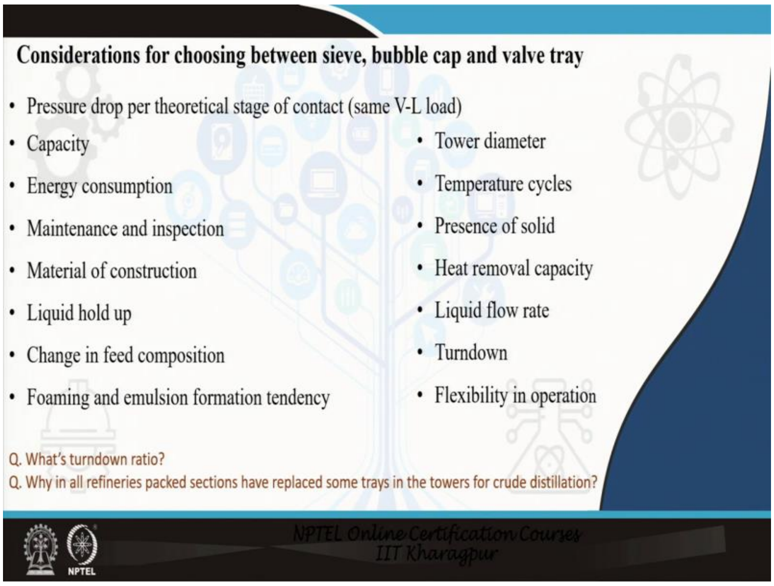

Considerations for choosing between sieve, bubble cap and valve tray

- Pressure drop per theoretical stage of contact (same V-L load)
- Capacity
- Energy consumption
- Maintenance and inspection
- Material of construction
- Liquid hold up
- Change in feed composition
- Foaming and emulsion formation tendency
- Tower diameter
- Temperature cycles
- Presence of solid
- Heat removal capacity
- Liquid flow rate
- Turndown
- Flexibility in operation

Q. What's turndown ratio?

Q. Why in all refineries packed sections have replaced some trays in the towers for crude distillation?

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I think that with this we will stop here today. And I am not going to repeat the choice between the other type of trays. And we will stop here with this. And what we intend to do in the next module is basically start with your heat transfer equipment design. We will start with the basics, then go for the different type of heat exchanger shell and tube, and the typical the simplest one which is the double pipe and so on. I think I will stop here today.

Thank you.