Process Equipment Design
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Lecture –45
Design of Packed Column-3

Hello everyone. This is the 5th lecture of 9th week of the course Process Equipment Design and here we are going to design the packed column. So, as far as last two lectures of this week is concerned that are basically devoted to the packed column where we have discussed the application of packed column, different type of packing etcetera and here we are going to design the packed column.

So, as far as design of packed column is concerned that you should understand that we are going to calculate the height as well as diameter of the packed column and further we will decide the column internals and when I am going to calculate the height and diameter of the column it will depend on the type of packing. So, all that point we will consider in this method.

So, let us start the design of packed column. So, first of all as we have discussed that we have to calculate the bed height.

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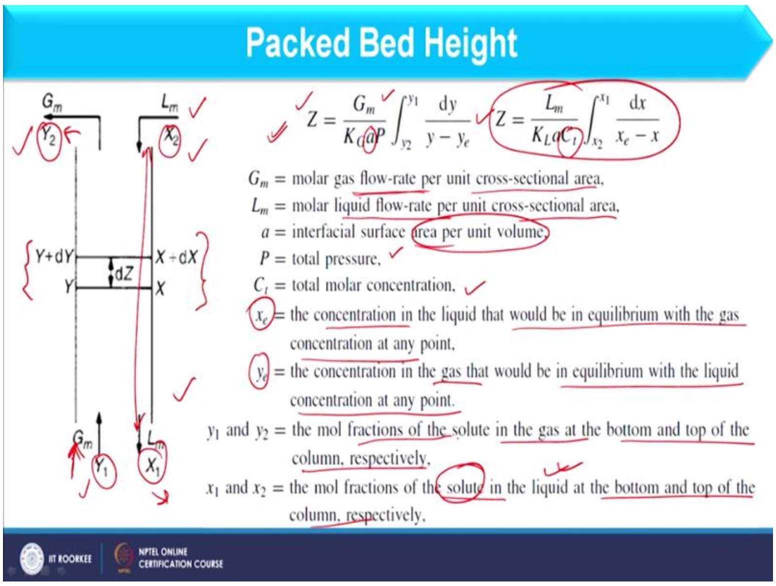

So, to calculate the bed height we should consider schematic of the packed column as it is shown here. So, if you consider this packed column this is basically the packing and here we have consider some section along the length and that should be Y + Y d and Y when I am considering the concentration in gas phase. And similarly I am having X + d X and X. So, usually we have counter current movement of liquid and gas.

So, liquid enters from the top and exits from the bottom. Similarly, gas phase enters from the bottom and exits from the top. So, corresponding concentrations I can consider in gas as well as liquid phases. So, as far as this schematic is concerned this schematic you have already considered in mass transfer course. So, I am not going into detail of derivation of the packed bed height and I am assuming that you already know this.

So, as far as the expression is concerned this is basically given by these expression that is the total bed height is represented by Z and that should be equal to G m / K G a P and integration from y 2 to y 1 d y divided by y – y e and similarly that is the expression when I am considering the liquid phase. So, as far as this expression is concerned the derivation of this expression you must have read.

And here we have different parameters such as G m that is basically the molar gas flow rate per unit cross sectional area and L m is that molar liquid flow rate per unit cross sectional area a is basically the interfacial area and it will depend on the type of packing and P is the total pressure and C t is the total molar concentration. So, along with this we have some other parameters such as y 1 and y 2.

And these are basically the mol fraction of the solute available in gas phase at bottom and top of the column as you can see in this schematic also. And similarly x 1 and x 2 are mol fraction of the solute which we have to recover from gas phase to liquid phase. So that solute available in liquid phase can be represented by x and that is at the bottom and top of the column as we can see the schematic also.

So, along with this we have some other parameters that is x e as well as ye. So, x e is basically the concentration in the liquid that would be in equilibrium with the gas concentration at any point. So, that is basically concentration of solute. Similarly, y e is basically concentration of solute in gas phase that would be in equilibrium with the liquid concentration at any point. So, in this way you can consider different parameters.

And I believe that all these parameters you know very well and I believe that all these parameters you know very well and then we will start calculation of bed height beyond this expression. Whatever is there before this expression that I believe that you have already read. So, let us move further.

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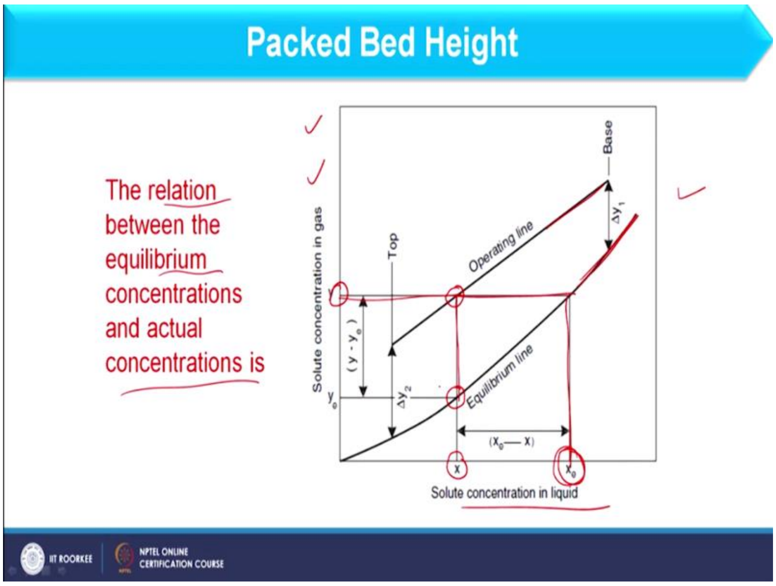

Now, as far as different in concentration in gas phase as well as liquid phase is concerned for that we can consider this graph and this graph is basically showing the relation between the equilibrium concentration and actual concentration. So, when you focus on this graph this is basically solute concentration in gas phase on y axis and here I am having solute concentration in liquid phase on x axis.

So, we have two lines. First is for the equilibrium line and then second is basically the operating line. So, difference of these two will basically speak about the total driving force. So, if I am considering y axis here I am having concentration y. So, when I consider that is at the operating line so corresponding to y we can have concentration in liquid phase as x. So, what is the concentration of liquid at equilibrium condition?

To consider that we extrapolate this line up to the equilibrium line and here you can find the concentration in liquid phase at equilibrium condition. In the similar line, when I consider concentration in operating condition. And similarly we can consider the concentration at equilibrium position when I move vertically downward. So, in this way you can relate the concentration at actual condition and at equilibrium condition.

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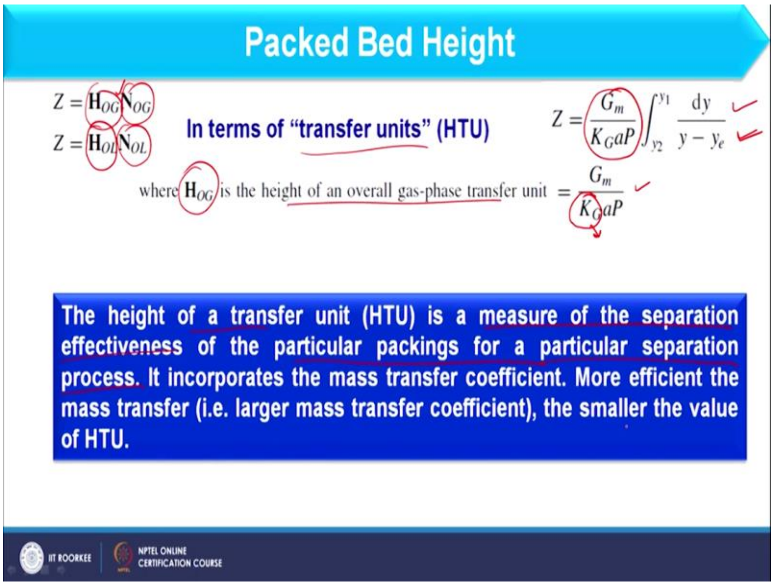

So, let us start the calculation of bed height and here we will focus on calculation of bed height based on transfer units that we consider as HTU. So, here you see we have this expression which we have discussed previously also. And this equation we can represent in terms of transfer unit as Z is equal to H O G and N O G. So, as far as these H O G and N O G values are concerned that value we can extract from this expression only.

So, where H O G is basically height of overall gas phase transfer unit because here I am having G and similarly I can consider H O L and N O L that is the height of overall liquid phase transfer unit. So, let us focus on H O G first. So, as far as this H O G is concerned this is basically the first term of expression Z and here it is equal to G m / K G a P. So, what is this height of overall gas phase transfer unit?

So, for that we consider the height of transfer unit which is a measure of the separation effectiveness of a particular packing for a particular separation process. So, it is basically showing the separation effectiveness because it includes the mass transfer coefficient based on gas phase. So, as we have more mass transfer coefficient we require less and less H O G value and we can consider that the mass transfer becomes more efficient.

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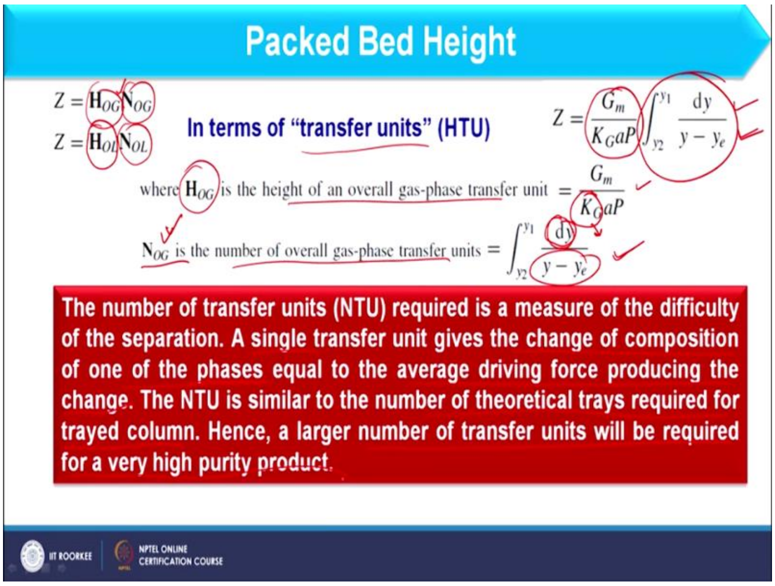

Next, I am having N O G which is basically the number of overall gas phase transfer unit and that can be equal to this term. So, it is showing over here also. So, if you see here we have integration from y 2 to y 1 and that will be d v divided by y minus y e. So, in this way we will integrate and find the N O G value. So, how we can define this number of transfer unit that we consider as NTU.

So, this is basically representing the difficulty in separation. So, here a single transfer unit shows the change of composition of one of the phases equal to average driving force producing the change. So, you can consider that if we consider this N O G that is basically gives the change in composition. So, here I am having change in composition like this where average driving force is produced so this d v is nothing, but the driving force.

So, when we consider this it should be equal if I am having a single N O G value. So, NTU is similar to number of theoretical plates required for the trade column or the plate column. Hence, a large number of transfer unit will be required for very high purity of the product. As we require more and more number of plates in plate column and when we have increase number of plate we can achieve more pure product.

In the similar line, when I am having higher NTU value or when I am having larger NTU value we can have more pure product. So, if you consider this H O G and N O G these are basically overall values.

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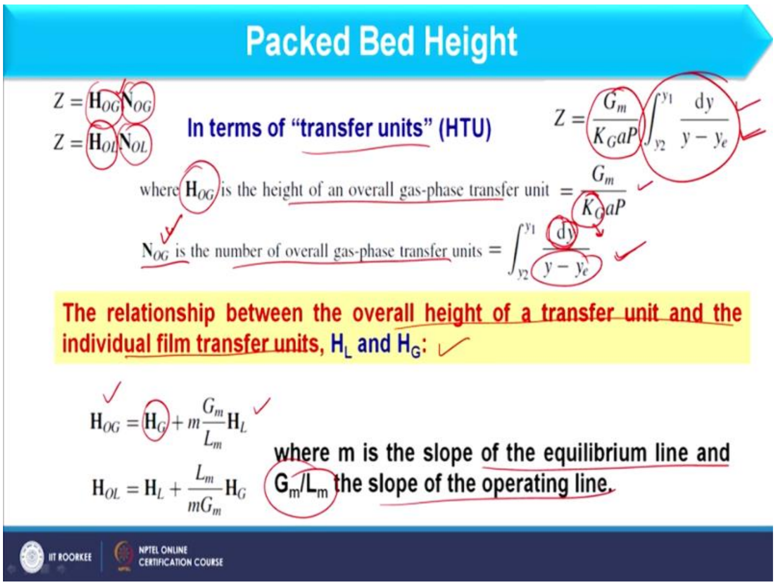

Now, we will relate this with the individual values. So, the relationship between overall height of transfer unit and individual film transfer unit that is H L and H G that relation is basically H O G = H G + m G m / L m into H L. So, to find out H O G we need to find out H G and H L and for that we should know m G m / L m. So, what is m? M is basically the slope of equilibrium line at a particular concentration at G m / G l is the slope of the operating line.

So, in this way you can consider m G m / L m and you have to find H G and H L separately to find out H O G value. So, first of all if you consider the Z calculation in this we need H O G and N O G. So, first of all we will focus on N O G then H O G and for that we should consider H G and H L values.

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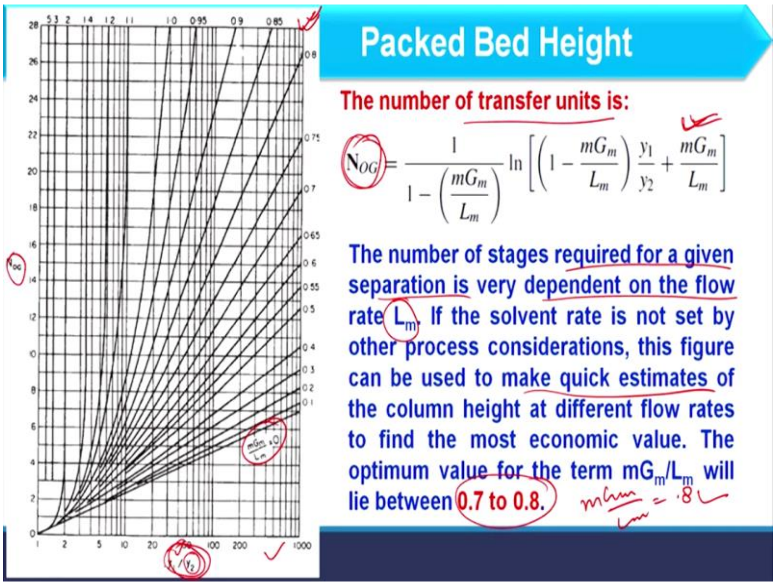

So, let us discuss N O G value first. So, that is basically the number of transfer unit and to calculate the number of transfer unit that is N O G we consider this expression. So, this is the empirical correlation and given in the design book also that is Richardson Coulson Volume 6. So, here you can consider N O G value based on this graph also. You can use this equation as well as you can use this graph. So, here if you see on x axis I am having y 1 and y 2.

So, y 1 is basically the concentration of solute in the gas phase at inlet condition and y 2 is the concentration of solute in the gas phase at exit condition. So, depending upon the y 1 and y 2 value and m G m / L m. Usually, slope of the equilibrium line is known to you and Gm and Lm are basically molar gas and liquid flow rate. So, these are also known to you so you can calculate m G m / L m you can use this graph or you can use the equation.

Now, the point is if I do not know any of this parameter then what I have to do? So, in that case the number of stages required for the given separation is dependent on the flow rate of liquid that is L m. So, usually liquid flow rate that is the solvent flow rate is given to us or that is the known quantity, but if it is not known we can make the balance to gas side as well as liquid side and then we can obtain L m value.

However, if any condition is there where Lm value we cannot obtain then how I can choose m G m / L m value. The optimum parameter or we can consider the optimum range of this is given by the researcher that is the (()) (14:56). And he has mentioned the optimum range of m G m / L m between 0.7 to 0.8. So, when we consider the larger value of m G m / L m we can have more and more separation and so we can have less and less value of solvent.

So, in that case we consider m Gm value should be equal to 0.8. However, you can choose any value from 0.7 to 0.8, but when you are choosing 0.8 you can deal with least flow rate of solvent. So, if value is not given to us then m G m / L m should be equal to 0.8 that you can choose and it is basically the quick estimate of the column height once I am fixing this value. So, if you are fixing this you can simply calculate N O G value from this equation or from this graph because y 1 and y 2 will definitely be given to you.

Now, once I am having the N O G value next is you have to find out H G and H L that is the individual parameters to calculate the height of transfer unit. So, to calculate that we can have two different methods the first is the Cornell's method and second is the Onda's method. We will discuss these methods one by one.

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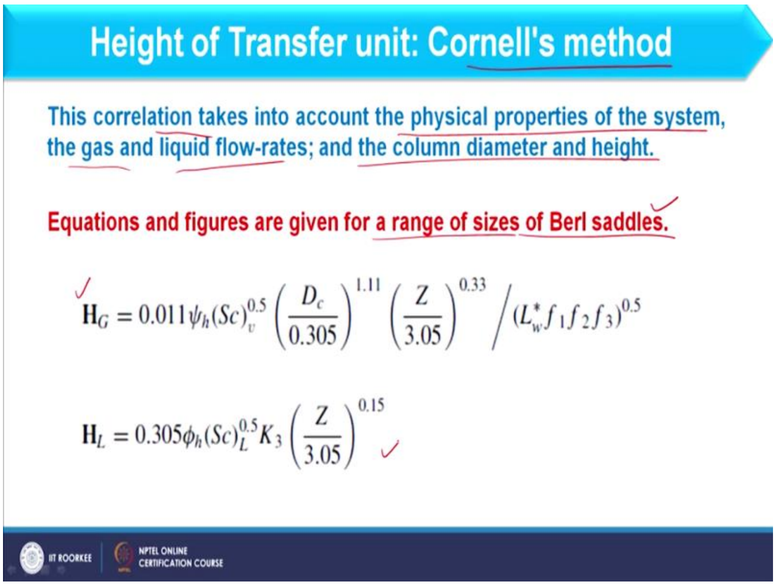

So, first let us focus on Cornells's method. So, as far as this method is concerned this correlation that is proposed by the Cornell's it considers the physical properties of the system, the gas and liquid flow rates and the column diameter and height. So, whatever correlations are given for H G and H L value these are basically for Berl Saddle packing. So, we can consider for a range of sizes of Berl saddle.

And only this type of packing will be used and this is the expression given by Cornell's for H G value and here I am H L value. So, you can see that these correlation or these empirical equations are considering different parameters. So, let us see these parameters one by one.

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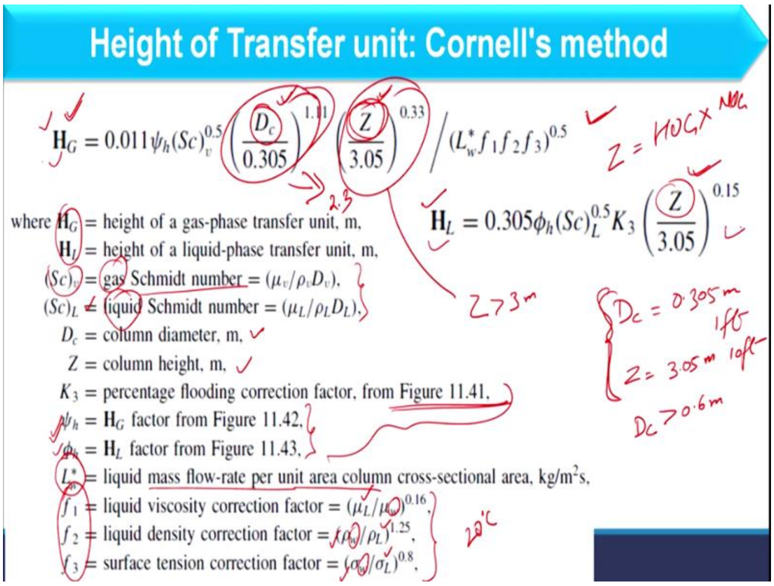

So, here again I am having the equation of H G as well as H L. So, you can consider different parameters as H G and H L are known to you so that is not the point to discuss. S c v and S c L are basically Schmidt number corresponding to gas and liquid and you can obtain from this expressions. D c is the column diameter Z is the column height. And K 3 is basically percent flooding correction factor and that you can obtain from figure 11.41.

And psi h as well as phi h these are basically H G factor and H L factor and can be obtained from figure 11.42 and 11.43 respectively and these figures are basically given in Richardson Coulson Volume 6 and these are available in 4th edition of that book and further we can have L w star. And that is the liquid mass flow rate per unit area and here I am having other parameters like f 1, f 2 and f 3.

And these will the correction factor according to the properties. So, here you see we have mu L / mu w rho w / rho L and sigma w / sigma L. So, all these w are basically properties of water at 20 degree Celsius and mu L rho L and sigma L are basically the properties corresponding to the liquid. So, this f 1, f 2, f 3 will be used when you have solvent other than water.

If it is for water you can consider all these value as equal to 1. So, once you have these value you can obtain H G as well as H L. So, here we should consider the K 3, phi and psi value, but before that let us focus on the expressions. If I consider H G expression here it depends on the diameter as well as height. So, this diameter is also not known to you and this height is not known to you.

Basically what you are doing you are calculating H G and H L to calculate H O G. N O G you have already calculated and multiplication of this will give the Z value. So, what is the meaning of this? It means that you need to calculate Z based on H G and H L values. However, these values require Z value also. So, this is basically the iterative method. Further, if we focus on this expression.

This expression is given by the Cornell’s when he consider diameter is equal to 0.305 meter or 1 feet. And similarly Z he considered as 3.05 meter or 10 feet. So, based on this experimental setup he has given these equations. So, what you have to do further that if your column diameter is more than 0.6 meter. So, the whole expression of this should be replaced by 2 / 3. Whole expression means this power factor also. So, that you can replace by 2 / 3.

On the other hand Z factor that is this correction factor you should consider if your Z is more than 3 meter. And Z is what? Z is basically the height of packing not the height of column because there are some arrangement you have to do for putting the packing support for putting the liquid distributor and some space for movement of gas and liquid at the top as well as at bottom.

So, that Z is only representing the height of the packing and D c is the height of the column. So, based on these guidelines you can apply H G as well as H L value, but here you should understand that all these calculations are iterative in nature. Now, let us see how we can find out K 3 value, phi h value and psi h value.

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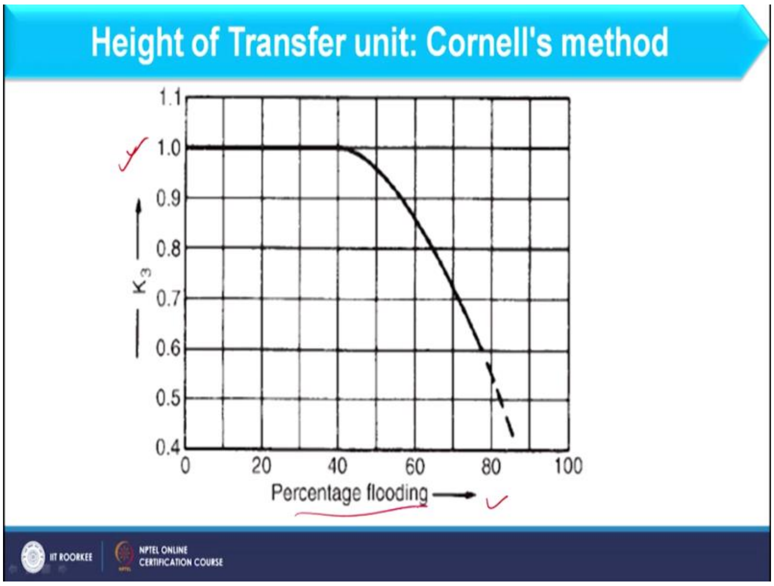

So, as far as K 3 is concerned that we can find out based on percentage flooding and you can use this graph. What is percentage flooding that we will discuss?

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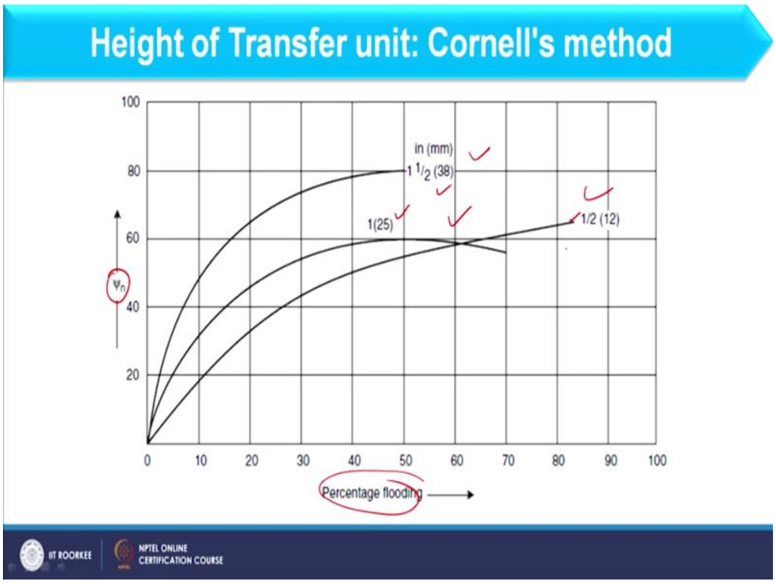

Similarly, you can obtain phi h value depending upon the percentage flooding and different types of packings. These packing are basically Berl saddle and having different sizes. So, in this way you can use this graph.

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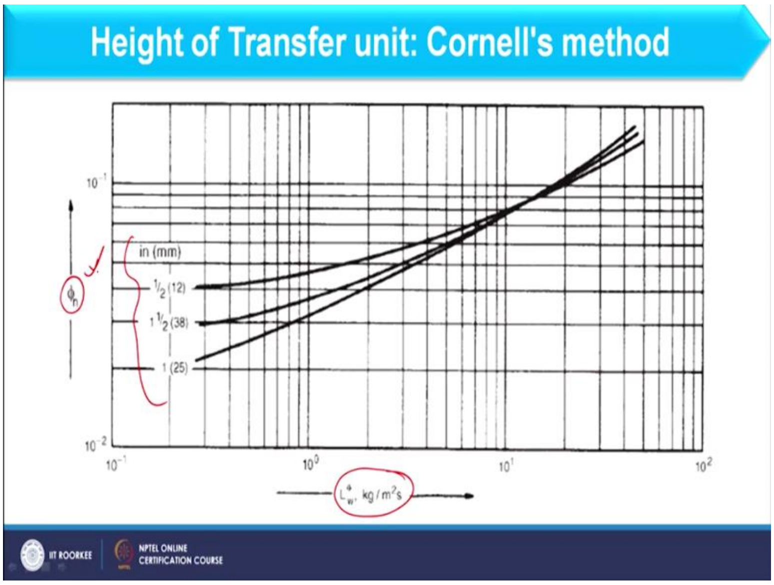

And now we have the graph of phi h. So that can be calculated based on Lw star and this value you can obtain once you know the column diameter. So, depending upon the size of Berl saddle you can find the value of this parameter. So, in this way you can obtain K 3, phi h and psi h value, but that require again a parameter that we consider as the percentage flooding.

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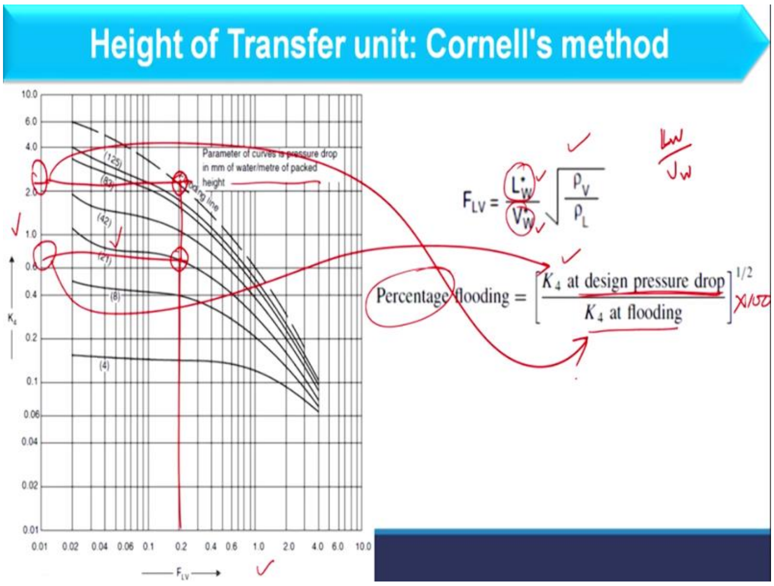

So, percentage flooding you can obtain by this expression and this graph. So, here I am having percentage flooding as we can find out K 4 parameter at design pressure drop and K 4 at flooding condition power 0.5 into 100 because this is basically the percentage flooding. So, if you consider this here on y axis I am having K 4 value and on x axis we have FLV value and FLV value you can obtain from this.

So, here I am having L w star and V w star that is the liquid flow rate that is the liquid flow rate per unit cross sectional area and vapour flow rate per unit cross sectional area. Here, I am considering per unit cross sectional area in both so that should be cancelled out. So, it can be replaced with L w / V w simply the mass flow rate of liquid as well as gas phases. So, once you have the FLV value.

Let us say your FLV value is falling over here you will be known that what is the pressure drop in the column. So, let us say it is 21 mm of water per meter of packed height and accordingly you can find out the K 4 value and this value will be corresponding to value over here and once I move further we can find K 4 value at flooding condition. So, this value you can consider here.

In this way you can use this graph to find out percentage flooding and so you can find out different parameters and so the H G as well as H L value and here we have some points regarding the Cornell's method and these points I have already discussed and now we have the Onda's method.

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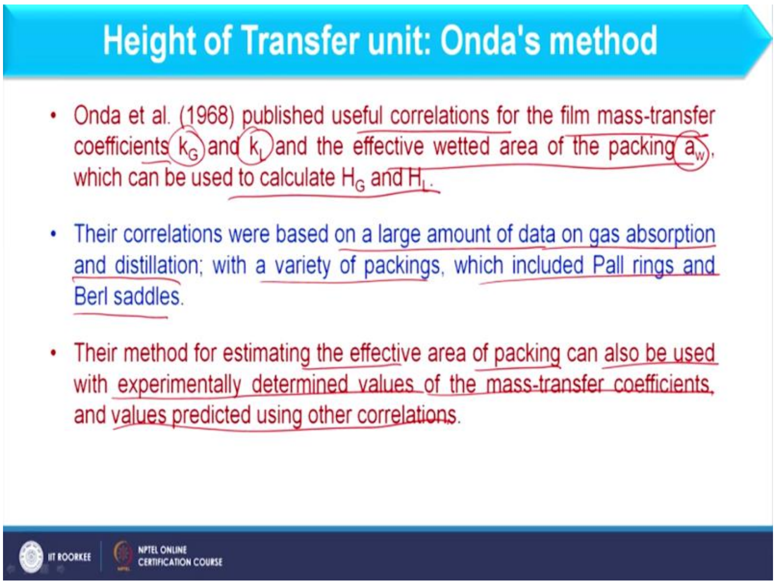

So Onda has given the correlation for the film mass transfer coefficient that is k G as well as k L. And effective wetted area of the packing that is aw which can be used to calculate H G as well as H L and their correlation are based on large amount of data on gas absorption and distillation with variety of packing which include Pall rings as well as Berl saddle. However, Cornell's correlation is basically used for Berl saddles.

So, the Onda's method for estimating the effective area of the packing can also be used with experimentally determined values of mass transfer coefficient and values predicted using other correlations. So, that is the flexibility of this method.

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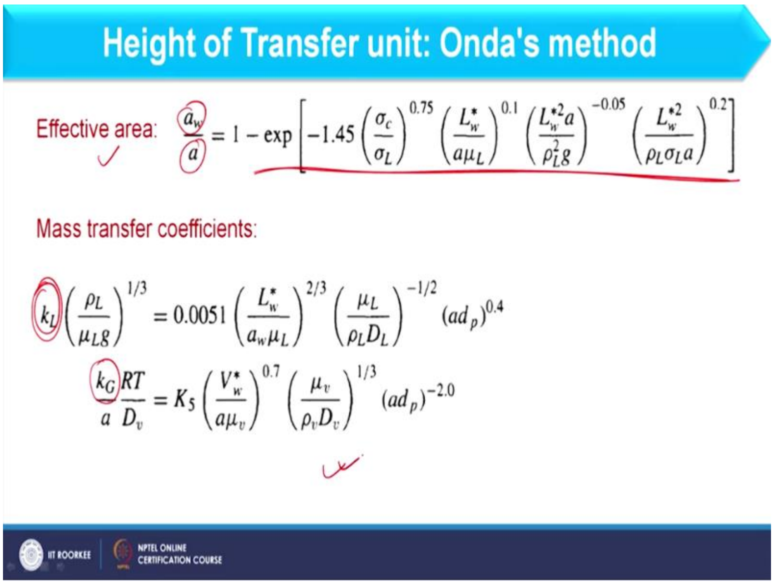

So, let us see the expression of this method. First of all, we have the effective area and that is aw / a. A is basically the interfacial area which you can see from the table and this is the whole expression and further we have k L as well as k G expression which you can use over here.

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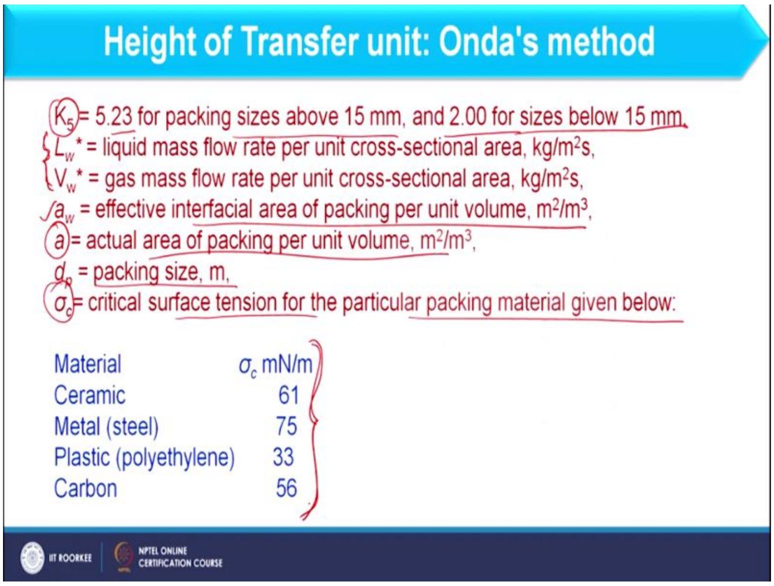

Now as far as parameters are concerned here I have to consider K 5 you can see here I am having the value of K 5. So, its value is equal to 5.23 for packing size above 15 mm and 2 for the packing size below 15 mm, L w star and V w star we have also discussed in Cornell's method aw is the effective interfacial area of packing per unit volume and a is the actual interfacial area of packing per unit volume.

D p is the packing size and sigma c is the critical surface tension for a particular packing depending upon the material. So, you can refer this data to find out sigma c value.

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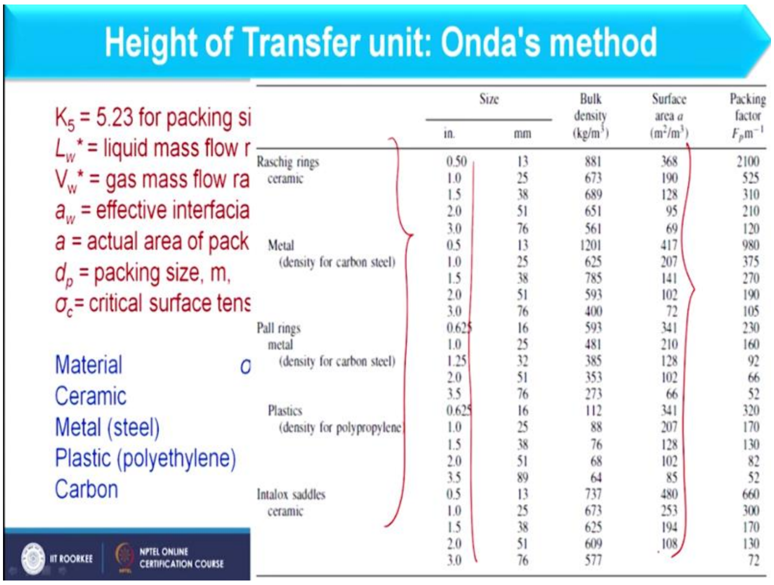

	Size (in.)	Size (mm)	Bulk density (kg/m³)	Surface area a (m²/m³)	Packing factor F_p m⁻¹
Raschig rings ceramic	0.50	13	881	368	2100
	1.0	25	673	190	525
	1.5	38	689	128	310
	2.0	51	651	95	210
	3.0	76	561	69	120
Metal (density for carbon steel)	0.5	13	1201	417	980
	1.0	25	625	207	375
	1.5	38	785	141	270
	2.0	51	593	102	190
	3.0	76	400	72	105
Pall rings metal (density for carbon steel)	0.625	16	593	341	230
	1.0	25	481	210	160
	1.25	32	385	128	92
	2.0	51	353	102	66
	3.5	76	273	66	52
Plastics (density for polypropylene)	0.625	16	112	341	320
	1.0	25	88	207	170
	1.5	38	76	128	130
	2.0	51	68	102	82
	3.5	89	64	85	52
Intalox saddles ceramic	0.5	13	737	480	660
	1.0	25	673	253	300
	1.5	38	625	194	170
	2.0	51	609	108	130
	3.0	76	577		72

And here I am having the complete table of the packing and you see depending upon the size that is basically d p value you can find out area from here. So, in this way you can consider the parameters which are related to the Onda's method.

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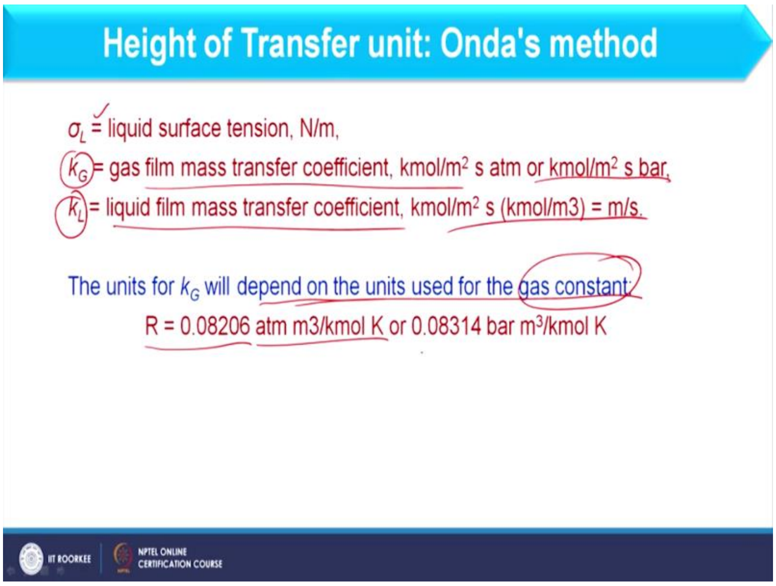

And further we have some points about the Onda's method as sigma L is given as the liquid surface tension. K G and k L are gas film mass transfer coefficient and liquid film mass transfer coefficient and these are the units of these parameters. The unit of k G will depend on the units used for gas constant and the gas constant should be equal to 0.08206 atmospheric meter cube per kilomol Kelvin and you can consider this value also.

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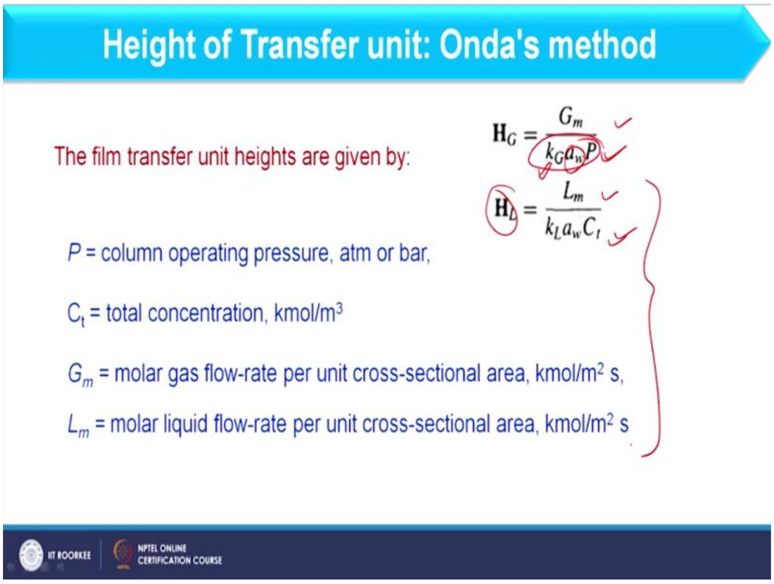

So, once you have the value of mass transfer coefficient in gas and liquid phase Onda's method relates it with the H G and H L value as H G is basically G m / k G a w P. This is the previous expression when we have considered the Z expression however that is based on effective area as well as gas phase mass transfer coefficient and similarly I am having H L value that can be given as L m / k L a w C t.

So, I think all these parameters you know very well. So, in this way you can calculate height of the packed column considering Cornell's method as well as Onda's method. And now we can calculate the column diameter and that is irrespective of these methods.

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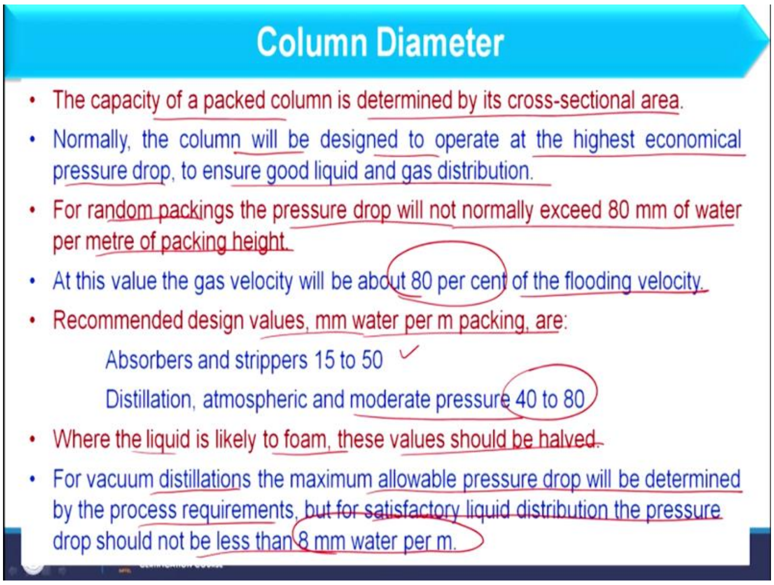

So, as far as column diameter is concerned the capacity of the packed column is determined by its cross sectional area normally the column will be designed to operate at highest economical pressure drop to ensure good liquid and gas distribution. Further, for random packing the pressure drop will not normally exceed 80 mm of water per meter of packing height.

So, when I am considering this value the gas velocity should be around 80% of flooding velocity. I think flooding you understand when liquid is not able to pass from the column liquid is continuously start accumulating in the column and therefore instead of moving down it moves up because from top continuously liquid is coming, from bottom it is not getting proper means to exit.

So, in that case complete column is filled with the liquid and therefore we call that as column is flooded. So, the velocity of gas because gas will also ensure whether liquid will pass from the column or not because it will continuously pushing the liquid upward. So, we can put the bar on gas velocity that it should be 80% of the flooding velocity. Flooding velocity means flooding velocity with respect to gas.

So, actual gas velocity should be 80% of that velocity at which flooding will occur. So, recommended design values that is mm water per meter of packing are for absorption and stripper 15 to 50 mm and distillation atmospheric and moderate pressure it is 40 to 80 mm. Further, where the liquid is likely to foam these value should be halved. So, when we have froth and foam formation in the liquid accordingly we should choose this value.

And for vacuum distillation the maximum allowable pressure drop will be determined by the process requirement, but for satisfactory liquid distribution the pressure drop should not be less than 8 mm water per meter of packing. So, these are some guidelines based on which you can calculate the column diameter.

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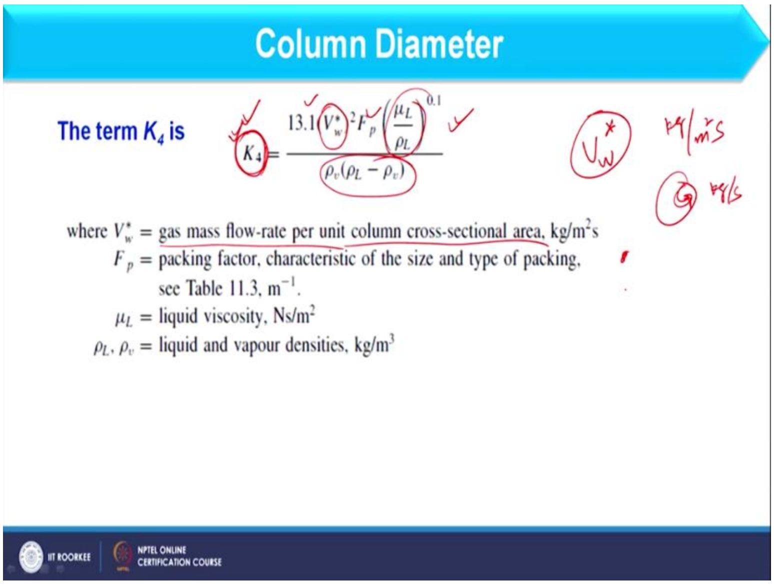

Now see how to calculate the column diameter. To find out that we will consider K 4 because K 4 is the parameter which is corresponding to the flooding condition. So, this K 4 is the parameter when we can obtain it at desired pressure drop. So, the expression is like 13.1 V w star power 2 F p and this is the and this is the physical property and here also we have the physical property of liquid as well as gases.

Now in this case this K 4 you can obtain from the graph. This V w star is basically the gas mass flow rate per unit cross sectional area. So, from this expression we can find out V w star value because I already know the K 4 value. Now once you have this you can obtain in kg per meter square second and gas mass flow rate is already given to you so that is basically in kg per second.

So, when we divide this with this we can find out the cross sectional area of the column and so you can find out the diameter of the column and here we are using the parameter F p that is the packing factor.

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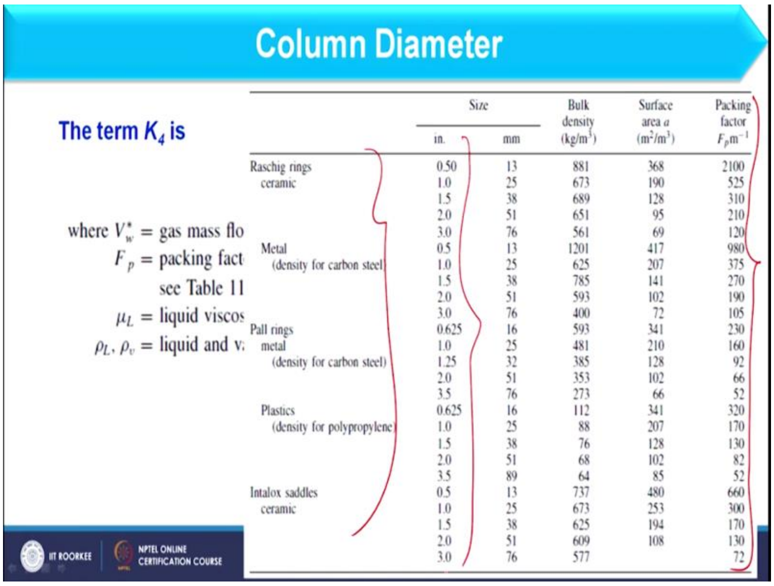

	Size in.	Size mm	Bulk density (kg/m^3)	Surface area a (m^2/m^3)	Packing factor F_pm^{-1}
Raschig rings ceramic	0.50	13	881	368	2100
	1.0	25	673	190	525
	1.5	38	689	128	310
	2.0	51	651	95	210
	3.0	76	561	69	120
Metal (density for carbon steel)	0.5	13	1201	417	980
	1.0	25	625	207	375
	1.5	38	785	141	270
	2.0	51	593	102	190
	3.0	76	400	72	105
Pall rings metal (density for carbon steel)	0.625	16	593	341	230
	1.0	25	481	210	160
	1.25	32	385	128	92
	2.0	51	353	102	66
	3.5	76	273	66	52
Plastics (density for polypropylene)	0.625	16	112	341	320
	1.0	25	88	207	170
	1.5	38	76	128	130
	2.0	51	68	102	82
	3.5	89	64	85	52
Intalox saddles ceramic	0.5	13	737	480	660
	1.0	25	673	253	300
	1.5	38	625	194	170
	2.0	51	609	108	130
	3.0	76	577		72

And that you can obtain from this table depending upon the type of packing so here you see I am having the packing factor depending upon the size of the packing. So, in this way you can calculate the diameter of the column and height of the column. So, height of the column that is H G and H L value you can calculate once you calculate the column diameter. So, this calculation of column diameter should be considered before the height of the packed column calculation.

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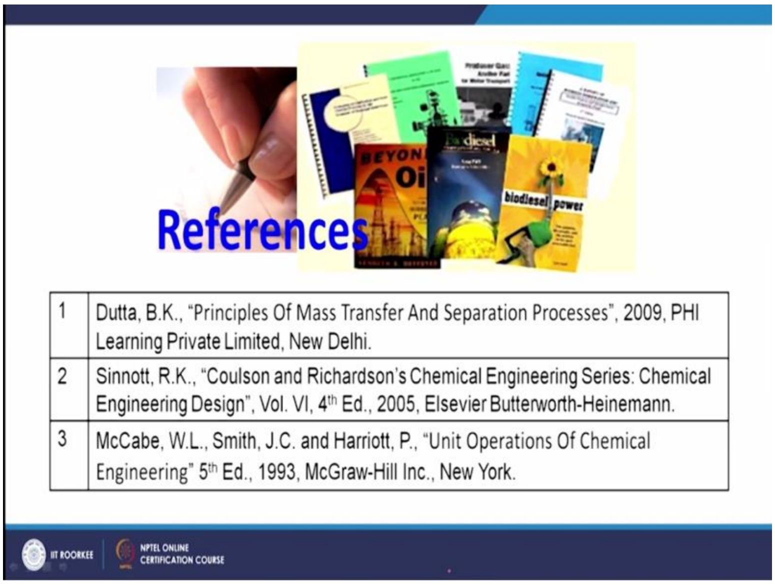

So, here we have some references which you can go through.

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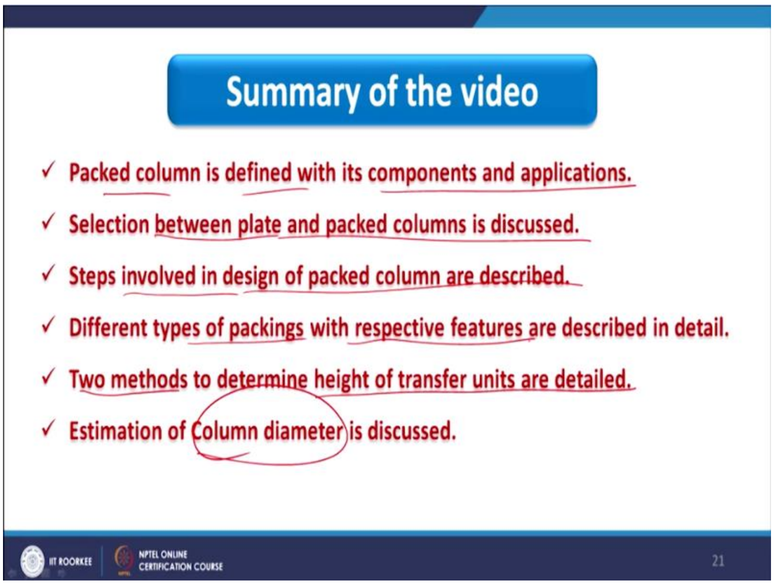

And now we have the summary of the video and this is the summary of the video of 3rd, 4th and 5th lecture of this week where we have covered the packed column. So, let us see in these lectures packed column is defined with its components and applications, selection between plate and packed column is discussed. We have discussed steps involved in design of packed column.

And we have described different types of packing with respective features and along with that we have discussed two methods to determine height of the transfer units that is the Cornell's method and Onda's method and then we have a discussion on how to calculate the column diameter. So, that is all for now. Thank you.