Mass Transfer Operations II
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Lecture 07 – Drying: Rate of drying for batch dryers

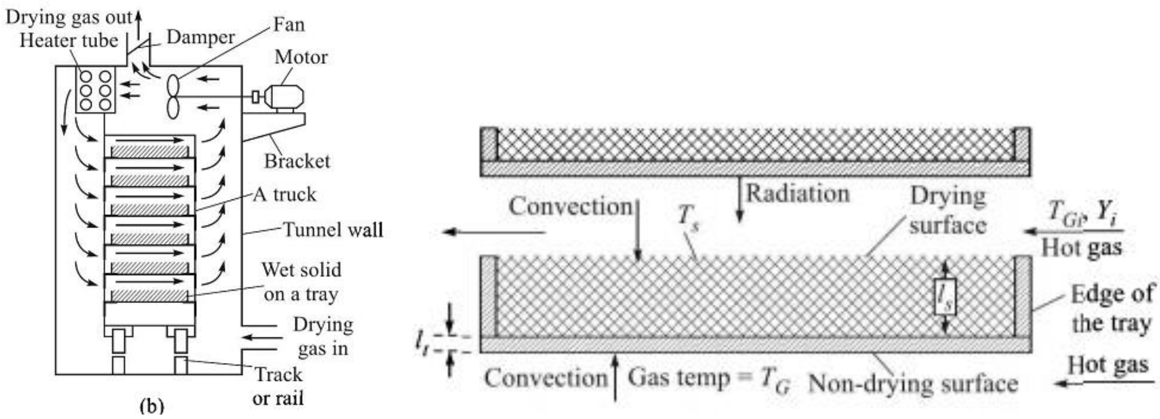
Welcome back to Mass Transfer Operations II, we were discussing on drying operations. In the previous class we discussed about the drying operations then some important terminologies, then drying rate curve, then drying equilibria and in today's lecture we will be discussing on the rate of drying for the batch dryers.

Mechanism of batch drying

Desired final moisture can be calculated (i) N_C (ii) $X_{C,} X^*$ and (iii) nature of dependence of the falling rate of drying are known. Now we discuss the application of basic heat and mass transfer principles to drying calculations and design.

Cross – circulation drying

Flow of drying gas over the wet material on the trays in a tray dryer is called cross flow.



Dry bulb temperature of drying gas at inlet: T_G; K

Humidity of drying gas at inlet: Y_i Kg/Kg dry air

Temperature of solid is T_S K

Thickness of wet solid layer is $L_{S,}$ m

Thermal conductivity is k_S, w/mK

Thickness of tray is l_t $,m$

The rate of evaporation and the surface temperature can be obtained by a heat balance. If q represents total heat receiving at the surface, then

$$q = q_c + q_R + q_K$$

<u>Case I</u>: <u>temperature and humidity of the drying gas remain constant</u>

The heat received at the surface by convection is controlled by the appropriate convection

$$q_c = h_c(T_G - T_S), \quad h_c \ is\ convection\ heat\ transfer\ coefficient$$

Heat received by radiation, $q_R = h_R(T_R - T_S) = \varepsilon(5.669\ X\ 10^{-8})(T_R{}^4 - T_S{}^4)$

$$\sigma(\text{w}/m^2)\ stefan\ boltzman\ constant$$

heat received by conduction

$$q_K = U_K(T_{Gi} - T_S)$$

$$\therefore q = q_c + q_R + q_K = h_c(T_{Gi} - T_S) + h_R(T_R - T_S) + U_K(T_{Gi} - T_S)$$

$$N_C = k_Y(Y_S - Y_i) = \frac{q}{\lambda_s} = \frac{(h_c + U_K)(T_{Gi} - T_s) + h_R(T_R - T_S)}{\lambda_S}$$

If we neglect the heat required to superheat the evaporated moisture the gas temperature and consider only latent heat of vaporization.

Then $N_C \lambda_S = q$

$$\frac{(Y_S - Y_i)\lambda_S}{\frac{h_C}{k_Y}} = (1+\frac{U_K}{h_C})(T_{Gi} - T_S) + \frac{h_R}{h_C}(T_R - T_S)$$

$$U_K = \frac{1}{\frac{1}{h_c}\frac{A}{A_U} + \frac{L_t}{k_M}\frac{A}{A_U} + \frac{l_s}{k_s}\frac{A}{A_m}}$$

A $\rightarrow$ Exposed surface area m^2

$h_c \rightarrow$ convective heat transfer coefficient at tray bottom (w/m^2K)

$k_M \rightarrow$ Thermal conductivity of tray material(w/m^0C)

$k_s \rightarrow$ thermal conductivity of drying solid(w/m^0C)

$A_U \rightarrow$non-drying surface area m^2

$A_m \rightarrow$ average surface area of drying solid m^2

the quantity $\frac{h_c}{k_Y}$ is equal to C$_H$. The equation has two unknowns (T_S *and* Y_S). It can be solved in connection with the saturation humidity and temperature relation for water graphically.

$t_C = \frac{s_s(X_i - X_c)}{A N_C}$ where $N_C = k_Y(Y_S - Y_i)$

$$t_f = \frac{S_S}{A}\frac{X_C - X^*}{N_C}\ln\left(\frac{X_C - X^*}{X_f - X^*}\right) = \frac{S_S}{A}\frac{X_C - X^*}{k_Y(Y_S - Y_i)}\ln\left(\frac{X_C - X^*}{X_f - X^*}\right)$$

$$t_f = \frac{S_S}{A}\frac{\lambda_S(X_C - X^*)}{(h_c + U_K)(T_{Gi} - T_s) + h_R(T_R - T_S)}\ln\left(\frac{X_C - X^*}{X_f - X^*}\right)$$

t = t$_C$ + t_f + t_d [t_d is down time for loading and unloading]

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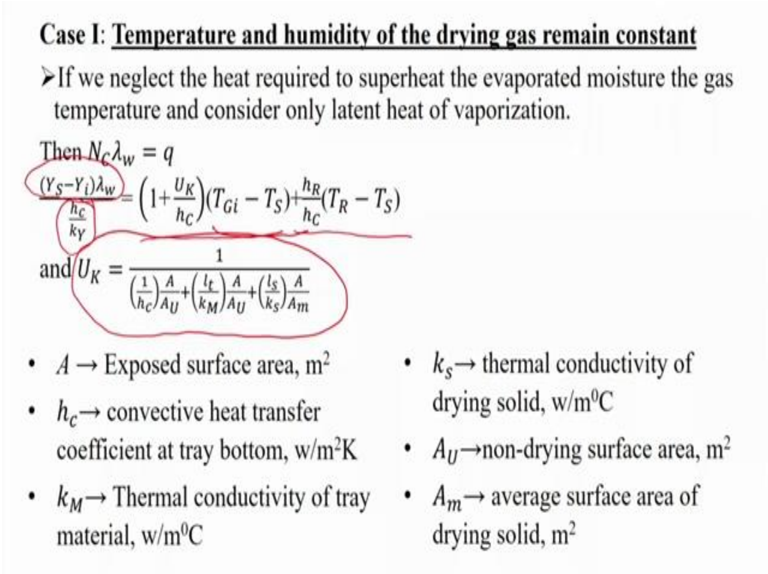

Now see if we neglect the heat required to superheat the evaporated moisture the gas temperature and consider only latent heat of vaporization such that we need to just we are considering this one or this initial adjustment part actual we are not considering.

So then we can say this one N c into lambda w is equal to q and from there if we just do the manipulation we will be getting suppose for this Y S minus Y i into lambda w by h c by k Y, so we will be getting this one just by manipulation we will be getting 1 plus UK by h c into TG i minus T S plus h R by h c into T R minus T S. only, to get this one say and say UK is equal to this one we know this one for average we can say the surface area and say for non-drying surface area we will be getting this one where h c that is nothing but the convective heat transfer coefficient at the tray the bottom and k M is equal to the thermal conductivity of tray material and whereas this case is the thermal conductivity to the drying solid, so that we have this one.

Now say the quantity that h c by k Y actually that is nothing but equal to the CH this we can say this humid heat, so this and we have already derived in this during this humidification operation that CH is equal to h c by k Y and so now this equation has these two unknown parameters like this T S and Y S. So it can be solved in this connection with the saturation humidity and temperature relation for this water that we can do by graphically.

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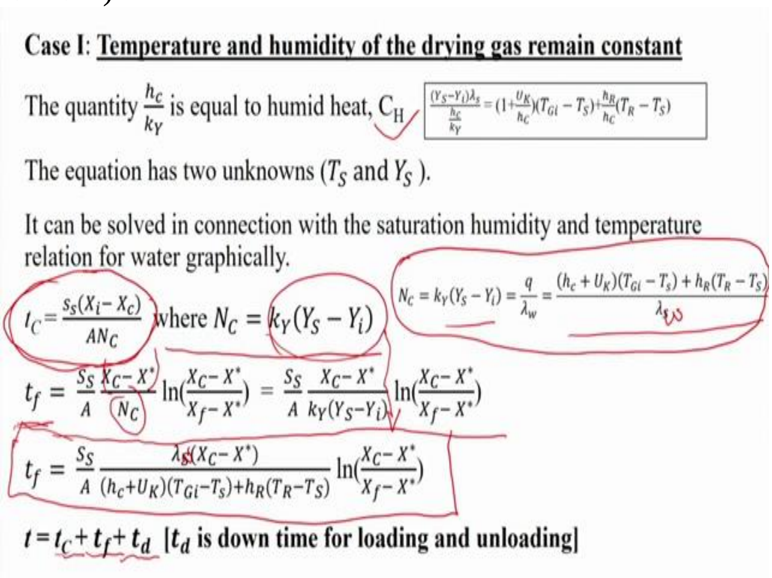


So and we know this one that now we have this derived this N c is equal to this k Y into Y S minus Y i that is equal to q by lambda w and that is we can say this one we will be getting by adding all this heat this one transfer units divided by lambda w and say where this N c is equal we can say this one (kc) k Y into Y S minus Y i and for that condition we can see say whatever the time at the constant drying period, so we can say this drying time at the constant drying time drying period that is we can say S S into X i minus X c by A into N c.

That we have already derived this one in the previous class for this falling rate period. So we are assuming this one that is following the linear relationship, so in that case also we have already derived this equation also for this condition. What we will be doing, so this one S S by A into X c minus X star by N c into ln X c minus X star by X f minus X star, that is nothing but just by manipulating this one because you see this one in the falling rate period also we already discussed this one in the falling rate period the first point, that is the we can say this one last point of that constant drying period.

So there actually we can say this one that we can get this N c, N c part whatever the N c part is there from we will be getting this k Y into Y S minus Y i, we will be putting here and then we will be getting this S S by A into we can say this lambda w into X C minus X star by A into h c plus UK into TG i minus T S plus h R into T R minus T S into ln X c minus X star by X f minus X star, so this is we can say this one for falling rate period.

If the falling rate period is we can say this one varying, square of this we can say this one moisture content, then the expression will be to some extent different. But the total drying time for we can say this one for cross-circulation drying we can say the total drying time will be the drying time in this. So, we can say the constant drying period then we can say the falling rate period and another part also is there that is we can say t d that is we say this one down time for loading and unloading.

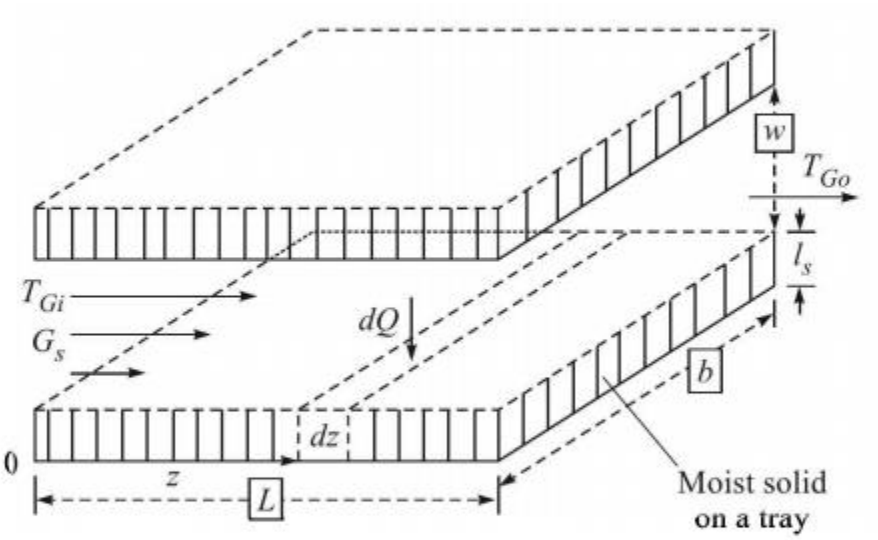
Because you see this one we started the discussion on the batch drying, so in the batch process also we whenever we will be talking about the total drying time then loading and unloading also time also we will be considering. But there is no this one formula for this down time calculation but that is actually obtained from the regular practice.

Case 2: the temperature and the humidity of the gas vary along tray

A theoretical analysis of the changing drying rate along a tray is done by making a different heat balance over a thin strip of the solid layer on a tray.

Let "*b*" be breadth of tray and "*w*" be gap between two adjacent trays for gas flow. Cross Section for gas flow is *b.w*.

Total gas flow rate over a tray is $G'_S.b.w$ (Kg/s) where, G'_S (kg/dry air/m^{2}s)



Now the second case we have this one that temperature and the humidity of gas will vary along the tray. So that theoretical analysis of the changing drying rate along a tray is done by this making a differential heat balance over a thin strip of the solid layer on a tray. Like this we will be taking one thin strip like suppose this is the tray we will be taking this thin slice like this, so this is the dz we can say this one. The length of this we can say this tray we have taken as L so and the thin strip is taken as dz and say let us b be the breadth like this b is the breadth and say w is the we can say this one gap between these two adjacent tray for gas flow.

This is the w means this we can say this one from the top layer of the solid material to the bottom of this tray, that is we can say this one the opening through which this we can say this hot drying AR actually is entering and we can see this one cross-section of the gas flow will be definitely this b into w. So through this cross-section suppose through this cross-section so we can say this one gas, drying gas actually will be entering.

And total gas flow rate actually over a tray it will be GS prime into b into w, so that is we can say this one where GS prime is equal to we can say kg moisture per kg dry air or we can say this gas flow rate and z actually we told that it is a local distance in the L direction and TG is the local temperature of the gas. In any place we can say this one if I say this is gas temperature that is will be TG and we told that in the entry this is TG i and at the exit it is TG o, that is the outlet temperature is TG o and TS is the surface temperature.

So TS actually is the surface temperature of the solid and Ls is the thickness, so Ls actually is the thickness of this material actually is Ls, so that is the thickness of the solid material or wet solid.

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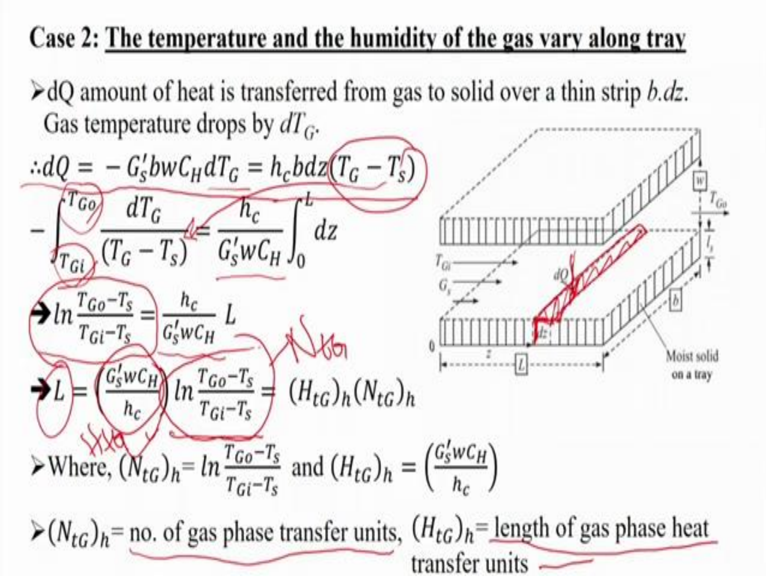

So dQ amount of heat actually is transferred from the gas to solid over a thin strip, we can say this one b into dZ because b is like this this length and dZ is equal to this one because you see through this area we can say this one dQ amount of heat actually is transferred. So there actually we can say this one so this is say this area where dQ amount of heat actually is entering, so that dQ amount of heat actually will be, we are taking this one as a combined amount of the heat received at this slice.

So we can say this one just by this doing this dQ is equal to minus GS prime into b into w into CH into d TG that is nothing but h c into b into dZ into TG minus TS. We are assuming that due to this convection actually this part is there but say this one due to this radiation that conduction part that is we can say very negligible part is there. So if we do the manipulation by, so we can say this one dt by this one d TG by TG minus TS if we bring this one it will be like h c by GS prime into w into CH and into dZ.

So there actually just by integrating from inlet to outlet, so we can say this one at any point actually this is suppose in this point say how much amount is there if we integrate this one for a small slice and if we just extend this one for the entire length, so we will be getting for the entire length we will be getting like this ln, TG o minus TS by TG i minus TS is equal to h c into GS prime into w into CH into L we will be getting for this entire length.

So from 0 to L actually we can say this one that will be TG i to TG o, so then just by manipulation we say this one L will be GS prime into w into CH by hc into ln TG o minus TS by TG i minus TS. So this out of this we have this one ln TG o minus TS by TG i minus TS that is nothing but Nt G that is and GS prime into w into CH by h c that is we can say this one height of this H tG, height of the transfer unit.

So we can say this, so Nt G that is we can say the number of gas phase transfer units and H t G is the height or length of the gas phase transfer heat transfer unit. So now also here just like see if we recall that for humidification chamber also, we got the total height of this cooling tower as H that was nothing but the multiplication of these number of gas phase transfer units into the height of the gas phase transfer units. Here also we have got the similar type of total length of this we can say this wet bed is in the form of this number of transfer units, heat transfer into gas phase transfer units into the height of the gas phase transfer units.

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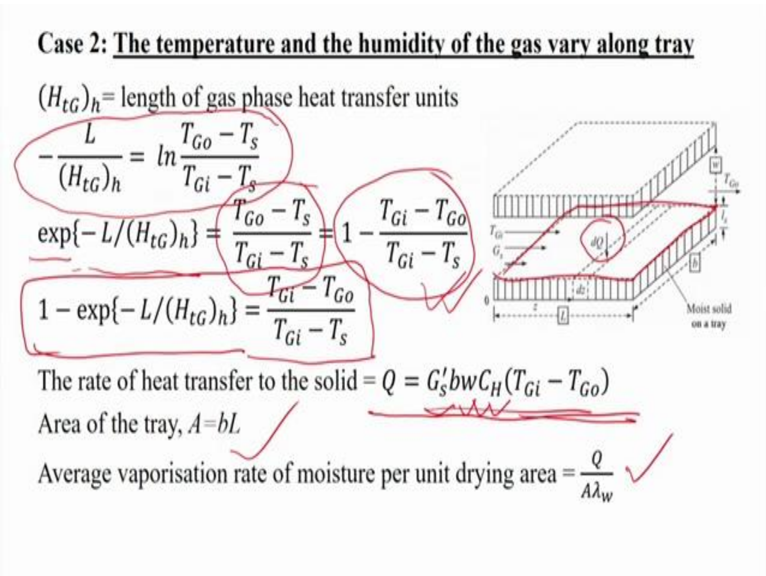

Now you see this one just by manipulating this one L in the form of this we can say this one L in the form of H tG, so we will be getting this one from this previous this one equation, this minus L by H tG is equal to ln TG o minus TS by TG i minus TS, so if we take this one the exponential of these two sides there will be getting this exponential of this minus L by H tG will be equal to this TG o minus TS by TG i minus TS. Just by manipulating this one we will be getting the just we will be doing this one in the form of this TG i and TG o with this TS that is just by manipulation one minus TG i minus TG out by TG i minus TS.

So we are now incorporating all these temperatures means inlet temperature of the drying gas, outlet temperature of the drying gas and we can say this one temperature of the wet solid.

So again by manipulation 1 minus exponential of the minus L by H tG that is we can say this one TG i minus TG o by TG i minus TS and now the rate of heat transfer to the solid the total we can say this one whatever the dQ we have assumed that it is coming that is now we are tagging that is equal to GS into b into w into CH into TG i minus TG out.

So this we are now getting this whatever the total heat actually is Q that is we are getting now in the form of this and area of the tray will be like b into L, because area of the tray that is we can say this one this length and this can be the breadth, so the total area will be like this, b into L. So we can say this one the average vaporisation rate of the moisture per unit drying air will be Q by A into lambda w.

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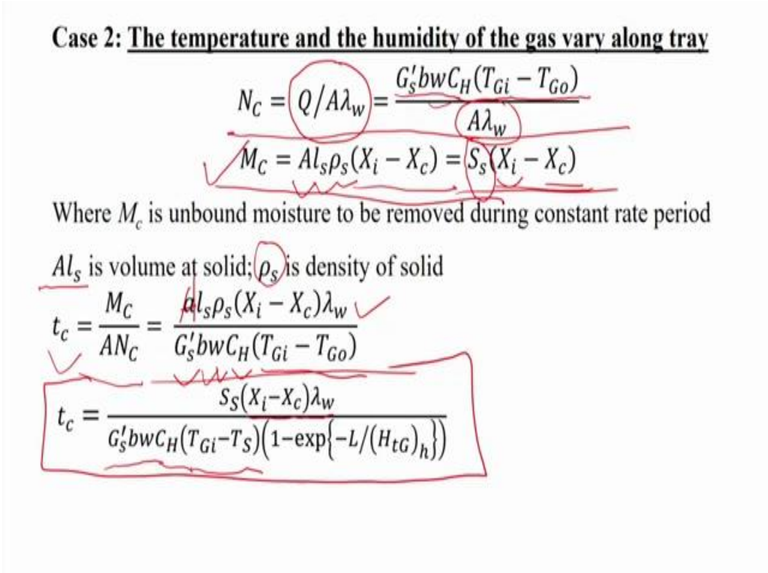

So then in that case we can say this one we will be again calculating this what is called the rate of drying in the constant drying rate period, that is Q by A into lambda w that is we can say whatever Q actually we have got this one that is GS prime into b into w into CH into TG i minus TG out by A into lambda w.

We can say this amount of this unbound moisture that is removed actually during this constant drying rate period, that is M c will be nothing but we can say this A into l s into rho s into X i minus X c, that also we have already derived this one, it is nothing but S S into X i minus X c, this is S S means the how much amount the this wet solid actually we have, that is we can say this one X i minus initial moisture content minus the critical moisture content.

Now we can say this A into l s, this A is the we can say this one top area and the l s is the height of this wet bed, so that is we can say A into l s is the volume of the solid and now we assume that the density of the solid will be the rho s, so now we can say t c is equal to M c by A into N c which is nothing but we can say this one A into l s into rho s into X i minus X c into lambda w by GS prime into b into w into CH into TG i minus TG out.

So finally we will be getting like this one, t c is equal to just by manipulation, manipulating this one say we can say this N c part actually we have this one N c in the form of GS prime into b into w into CH into TG i minus TG out by A into lambda w, we will be putting here, there actually we can say this A will be this one strike out from numerator and denominator and then we will be getting this t c is equal to S S into X i minus X c into lambda w by GS prime into b into w into CH into TG i minus TS into 1 minus exponential L minus L by H tG. So, that is we can say this one for constant drying time for the constant drying rate period.

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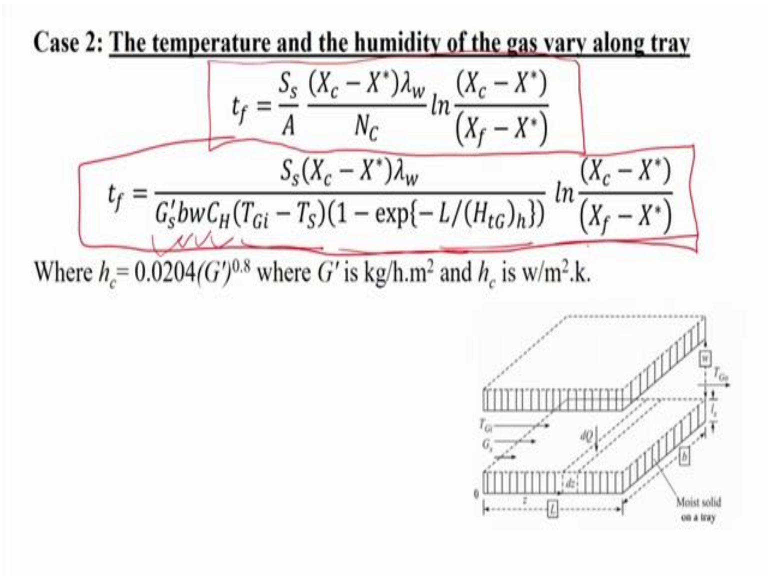

Then for falling rate period then we will be following the same this one whait is called formula where this N c we will actually writing in this form, this t f is equal to S S by A in X c minus X star, that is X star I told that it is nothing but the equilibrium moisture content which will be at the end, into lambda w by N c into ln X c minus X star by X f minus X star, then that is why by just putting this N c we will be getting this formula for this time for this falling rate period, it is t f is equal to S S into X c minus X star into lambda w divided by GS prime into b into w into CH into TG i minus TS into 1 minus exponential of minus L by H tG into ln X c minus X star by X f minus X star.

Where this h c value there is this one generally used formula or frequently this is used as this point 0204 into G prime to the power point 8 where G prime is the kg moisture per hour into meter square and h c is in watt per meter square Kelvin.

Problem 2: A granular wet solid is taken on a tray (1 m x 0.6 m) and dried in a stream of hot air (120°C: humidity -0.02 kg/kg dry air; velocity, u=4.5 m/s). The initial moisture content of 28% (dry basis) is to be reduced to 0.5%. From laboratory tests it is known that the critical moisture content is 12% and the equilibrium moisture is negligible. The falling rate of drying is linear in the moisture content. If the solid loading (dry basis) is 35 kg/m^2, calculate the drying time. Assume that the air flow is large and its temperature drop across the tray is small. (Cross circulation drying)

Now we will be solving one problem like this very simple problem. Granular wet solid is taken on a tray. The dimension is given that 1 meter into 0.6 meter and dried in a stream of hot air, there actually 120 degree Celsius and humidity is 0.2 kg dry air and velocity of the dry air is 4.5 meter per second. The initial moisture content of 28 percent is to be reduced to 0.5 percent. From laboratory tests it known that the critical moisture content is 12 percent. This X is equal to point 0.12 and the equilibrium moisture is negligible, so we can say the X star is equal to 0. The falling rate of the drying we can say this one that where we will be calculating this t f, that is we can say the linear in the moisture content.

So it is directly proportional to the moisture content, so if the solid loading is 35 kg per meter square, so calculate the drying time. Assume that the air flow is large and its temperature drop across the tray is very small. So from this we can say this statment, we can assume that it is nothing but the cross circulation drying. So now we need to solve this problem and we need to calculate the total drying time. So the solution will be like this:

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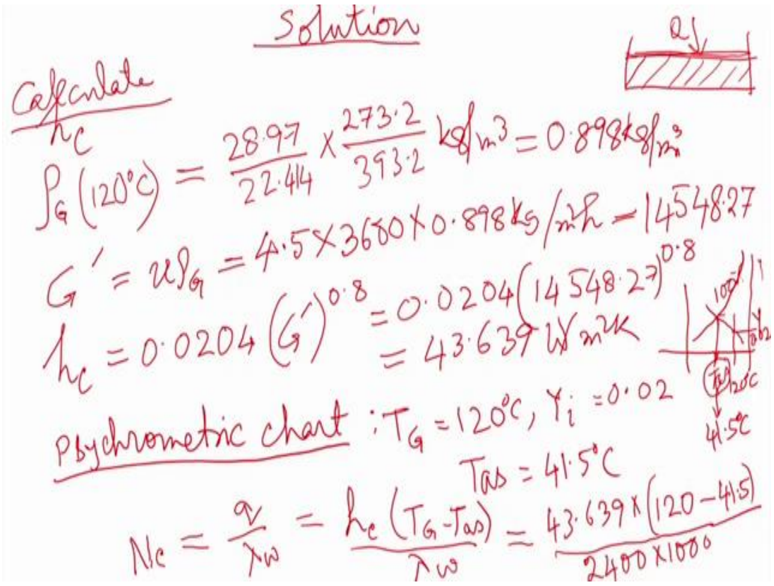

It is assumed that the this one heat transfer and drying occur at the top surface only, no conduction or radiation. So, we are assuming that only convection is taken place. Suppose, this is the try and say the solid material is here, say only due this convection this heat whatever this Q is entering that is due to convection only and from the top surface this drying is taking place. So convective heat transfer actually we will need to we need to calculate first h c, so for that we can say this one we need to calculate this one.

So we need to calculate h c. For that we need to first, we need to calculate the density of we can say this one density of gas, drying air we need to calculate this one say at that is at 120 degree Celsius because it is there in the problem that it is supplied at 120 degree Celsius, will be nothing but this 28.97 divided by 22.414 into 273.2 divided by 120, means 393.2 kg per meter cube.

So we are assuming that it is behaving as the ideal gas, we do not have this density value. If the density value is known then we do not need to do the calculation, there will be a small we can say this one error maybe in that calculation, we are assuming this air as this ideal gas. So, ultimately it will be coming as 0.898 kg per meter cube and so this mass flow rate that is we can say this one G prime that will be nothing but U that is the flow rate of this gas, drying gas into rho G. So, that is flow rate is given as say 4.5 into 3600 in terms of we can say this one hour and into 0.898. So, ultimately it will be coming as kg per meter square hour. So it is coming out to be as 14548.27 kg per meter square hour.

Now we will be getting this h c, that I told that the h c actually it is following this formula, in general we use this one 0.0204 into G prime to the power 0.8, so we will be putting this one 0.0204 into 14548.27 to the power 0.8. It is coming out to be as 43.639 watt per meter square Kelvin. Now we see this temperature of the solid in the constant drying rate period we can say this one is adiabatic saturation temperature, so we will be getting now what will be the we can say this adiabatic saturation temperature. For that we need because you will see the humidity is given and dry bulb temperature is given.

So we will be taking the help of the psychrometric chart, so from the psychrometric chart actually we will be getting this one. So, let us take the for psychrometric chart say TG is equal to 120 degree Celsius and Y i is equal to 0.02. So we have this one just we say this is the 100 percent saturation line and say this is we can say this one Y then for 0.02 and for suppose 120 degree Celsius, so we will be taking this adiabatic saturation line will be moving from this, we can say this 0.02. This is 120 degree Celsius then we will be reaching this 100 percent saturation line.

Then from here whenever we will be reaching this one that will be said we can say this one T a s, so from if we use this psychrometric chart we will be getting T a s is equal to 41.5 degree Celsius this is actually 41.5 degree Celsius. Now we will be getting this N c value, what is this? We can say this one drying rate at the constant drying period. So that is we can say this one q by we can say this lambda w, so that will be we can say this one is equal to h c into TG minus T w or T a s whatever we say this one divided by lambda w, so this will be like this: h c is equal to say 43.639 watt per meter square Kelvin into the TG is equal to 120 degree and T a s or T w that will be say 41.5 degree Celsius divided by this lambda w is equal to we can say this one latent heat of vaporization this 2400 into 7000.

So that will be coming out to be, that is we can say this one it will be equal to…..

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$$N_c = 1.427 \times 10^{-3}\ kg/m^2 s = 5.138\ kg/m^2 h$$

$$X_i = 0.28;\ X_c = 0.12;\ X^* = 0;\ X_f = 0.005,\ \frac{S_s}{A} = 35\ kg/m^2$$

$$t_c = \frac{S_s}{A}\frac{(X_i - X_c)}{N_c} = \frac{35(0.28 - 0.12)}{5.138}\ h = 1.09\ h$$

$$t_f = \frac{S_s}{A}\frac{(X_c - X^*)}{N_c}\ln\frac{(X_c - X^*)}{(X_f - X^*)} = \frac{35(0.12 - 0)}{5.138}\ln\frac{0.12-0}{0.005-0}$$

$$\boxed{t_f = 2.6\ h}$$

Total drying time, $t = t_c + t_f = (1.09 + 2.6)\ h = 3.69\ h$

So N c will be equal to 1.427 into 10 to the power minus 3 kg per meter square second. Now you see we need to get that, that is nothing but we can say this one in terms of hour if we just do this one we will be multiplying with this 3600 then it will be like (5.) Just we can say 5.138 kg per meter square hour. So now we have this N c is equal to 5.138 in kg per meter square hour.

Now we have this you see X i we have that is point 0.28 then X c we have 0.12 then X star that is equilibrium moisture content is negligible, so we take this one as 0 for the calculation and final moisture content actually is given as this only 0.5 percent, so 0.005 and this S S by A actually this is we can say this one this loading actually is given as 35 kg per meter square that is already given.

So we can say this one during this constant drying period we can say this one t c that is we have this S S by A into we can say this one X i minus X c divided by N c that will be like this. S S by A actually we have this 35 then X i is 0.28 and X c actually this X c critical moisture content is 0.12 divided by, we can say this one N c we have got this one as we can say 5.138 that we can say this one, so it will be coming in terms of hour because the TG in terms of hour also N c.

So it is nothing but we can say this one 1.09 hour, so that is we can say this one the time required to drive this in the constant drying period is 1.09 hour and now we see this one the falling rate period actually is linear with the we can say moisture content. So in that case the formula will be like this S S by A into X c minus X star by N c into ln X c minus X star divided by X f minus X star, so now we will be putting all these values like this 35 this S S by A is 35 into X c that is 0.12 minus X star is equal to 0 divided by N c is equal to that 5.138 into ln this X c is equal to 0.12 minus X star is equal to 0 divided by X f that is 0.5 percent, 0.005 minus X star is equal to 0.

So this is equal to 2.6 hour, so now you see the initial time in the constant drying period is only 1.09 hour where this time in the constant falling rate period is 2.6 hour, so total time actually we can say is total drying time, so total drying time will be we can say this one t is equal to t c plus t f that is equal to 1.09 plus 2.6 hour, that is nothing but 3.69 hour. So, here you see the time required in the falling rate period is much more higher than or more than two times than the constant drying period.

So total drying time but here we have not included this down time, that is we can say loading and unloading but say whenever we have this information we can add this the total drying time will be 3.69 hour plus t d.

Movement of moisture within solid:

Liquid Diffusion: Due to concentration gradient between depths and surface falling rate period.

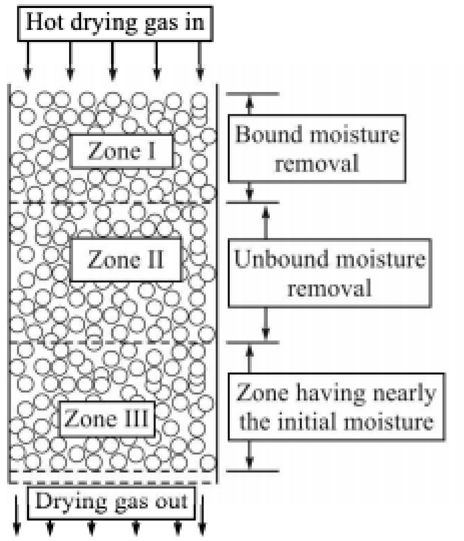
Capillary movement: Unbound moisture in granular and porous solids moves through the capillaries→surface tension.

Constant drying rate period: As drying proceeds, at first, moisture moves by capillary to the surface rapidly enough to maintain a uniformly wetted surface and drying rate is constant.

Vapor Diffusion: If heat is supplied to one surface of a solid while drying proceeds from another, moisture may be evaporated beneath the surface and diffuse outward as vapour.

Through Circulation Drying

In through circulation drying, hot drying gas flows through a shallow bed of wet solid.



As flow of hot gas status, a region near entry (zone I) loses moisture quickly and after sometimes this region will have bound moisture only.

Since the gas entering zone II is already loaded with considerable amount of moisture picked up from zone II, drying rate is lower.

There will be little or no evaporation of moisture in zone III at beginning.

Here, we shall develop simple equations for the determination of drying rate and drying time for through-circulation drying of bed.

Consider a thin slice of bed of unit cross-sectional area and thickness *dz*. If increase in humidity of gas is *dY* as it passes through thin slice of bed. Solid is at adiabatic saturation temperature of drying gas. Now we will be discussing about the another batch drying process that is we can say this is through circulation drying, so in through circulation drying hot drying air flows through the shallow bed of this wet solid. So what is happening in cases of through circulation drying? The total drying this wet material actually is placed in a we can say in the column and hot drying air enters from the top and say this one through this the wet solid this hot air will be entering and then it will force this moisture to be removed from this wet solid and then the cold moist air will be coming out from the bottom of the we can say this one bed.

As the flow of hot gas starts a region near the entry zones, we say this one in the entry zone that is zone I that is we can say this one loses moisture very quickly and after some times this region will have bound moisture only, so that we can say only whatever the unbound moisture actually is there and so only bound moisture will be there, so we can say this one and then this since the gas entering this zone II is already loaded with some considerable amount of the moisture picked up from this zone I, so we can say this one drying rate actually become slower, so this is point.

So from zone I this whatever the moist air so it is entering into the zone II, so there will little or no evaporation of the moisture in the zone III at the beginning, so, we can say this on zone III now this moisture is we can say this again the drying air is we can say this one more with this moisture, so drying rate will be very less, so zone having nearly the initial moisture. So here we assume that the drying is very slower, there will be no drying also at all.

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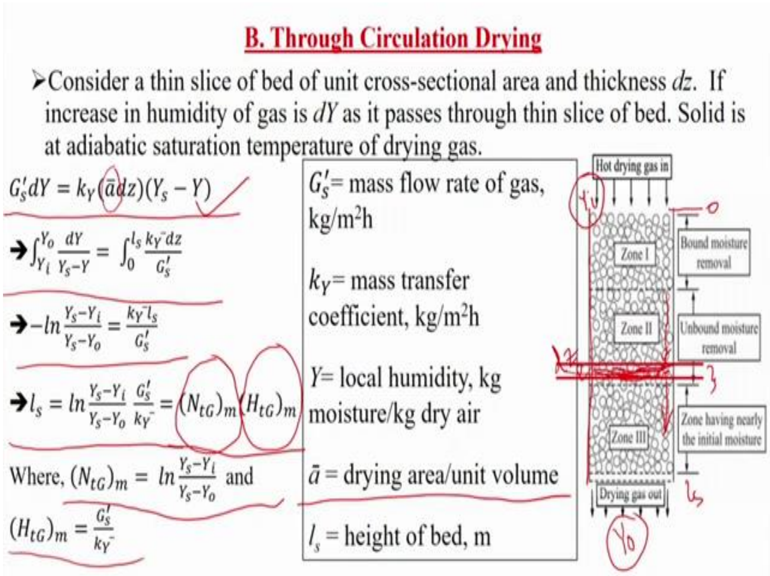

So now we need to consider a thin slice of we can say this one suppose this is the bed and then through this bed actually we are taking one this one slice of dz. So that will be assuming that dz actually this slice we have assumed, the thickness of dz. If the increase in humidity of the gas is dY, so in this direction suppose it is entering here and it is exiting from this the humidity increase will be dY across this thickness and as it passes through this thin slice, so solid we can say this one at adiabatic saturation temperature of the drying gas.

So then we have this one GS prime into dY for this slice actually we are doing this one GS prime into dY is equal to k Y into A prime into dz into Y s minus Y where this A prime actually is nothing but we can this one drying area per unit volume and dz we can say this one the thickness of the slice and Y s is the we can say this one humidity of the solid and Y is this local humidity at any point we can say this one. Just by manipulation, manipulating this equation and integrating from this Y in to Y out, we can say this one this is we can say this one Y in and this humidity of the drying air and Y out actually Y o is actually the humidity of the exit drying gas.

So that is if we this one integrate and suppose l is equal to or dz is equal to 0 here and here actually this one l s, so then we can this one this total length, so this one we can say this one if we integrate this one we will be getting minus ln, Y s minus Y i by Y s minus Y o is equal to k Y into l s by GS prime, so this l s will be nothing but we can say this one from this actually we will be getting ln into Y s minus Y i by Y s into Y 0 into G s by k Y prime.

So here also see this one whatever the length of this we can say this one packed column, we will be get here also, that is also the multiplication of this number of gas phase transfer unit into the height of the this one gas phase transfer unit, so there N tG is equal to we can say this one ln Y s minus Y i by Y s minus Y 0 or Y o and H tG will be G s prime by k Y prime.

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$$\boxed{\rightarrow l_s = ln\frac{Y_s-Y_i}{Y_s-Y_o}\frac{G_s'}{k_Y'} = (N_{tG})_m(H_{tG})_m}$$

Where, $ln\frac{Y_s-Y_i}{Y_s-Y_o} = (N_{tG})_m$

$$\rightarrow \frac{Y_s-Y_o}{Y_s-Y_i} = \exp[-(N_{tG})_m]$$

$$\rightarrow \frac{Y_s-Y_i+Y_i-Y_o}{Y_s-Y_i} = exp[-(N_{tG})_m]$$

$$\rightarrow 1-\frac{Y_o-Y_i}{Y_s-Y_i} = exp[-(N_{tG})_m]$$

$$\rightarrow \frac{Y_o-Y_i}{Y_s-Y_i} = 1-exp[-(N_{tG})_m]$$

$$\rightarrow \boxed{(Y_o-Y_i) = (Y_s-Y_i)(1-exp[-(N_{tG})_m])}$$

Now this l s actually we are writing this one ln into Y s minus Y i by Y s minus Y0 or Y o into G s prime by k Y prime that is again we have written this one and again we are just manipulating this N tG in terms of we can say this one ln into Y s minus Y i by Y s minus Y 0, from there just by manipulation we will be getting this we can say this one, we are trying to get this relation between this we can say this one enthalpy, the humidity of this drying gas in the exit and at the entry, so inlet minus outlet that is just by manipulation we will be getting that is equal to Y s minus Y i into 1 into exponential minus N tG.

So that actually we are getting, so we are trying to get the relation between this humidity at the entry and exit, with the humidity we can this one of the solid and with the number of gas phase transfer units, then let say this one constant drying period and falling rate period these two this one zones and from there we will be getting to drying times.

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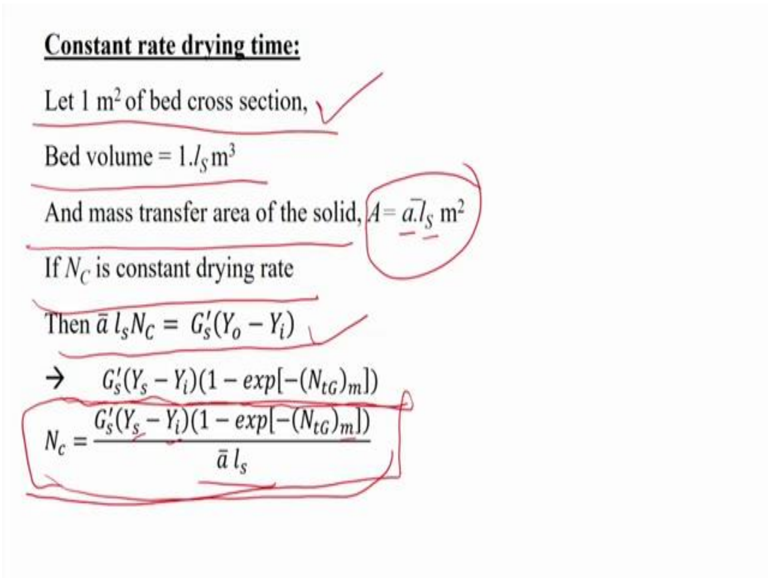

Let 1 meter square of the cross section area, say in place of this 1 meter square we can assume any area also. For simplicity, we have assumed this one and then bed volume is 1 into l S meter cube and the mass transfer area of the solid we can say this one A is equal to a prime into l S and then we can say this one this if N c is the constant drying rate then a prime into l s into N c is equal to G s prime into Y minus Y i that we know this one and say this one we will be putting this N c there. That is, we can say this one from here we will be getting this N c is equal to G s into we can this one Y s minus Y i into 1 minus exponential of minus N tG by a prime into l s.

So that will be we now have got this N c in the form of the known parameters like this G s prime then Y s, Y i then N tG we will be calculating then we will getting exponent of this N tG by, so specific surface area means surface area per unit volume into l s means the thick of the this height of this wet solid.

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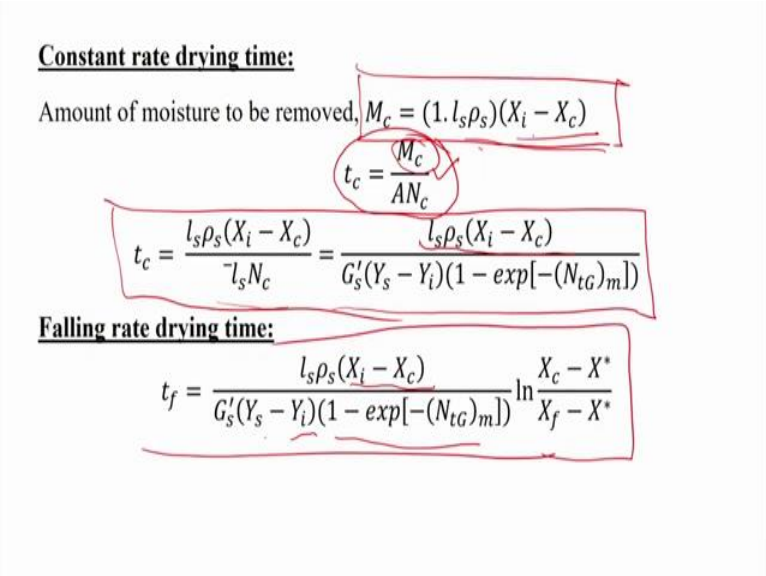

Now you see this one we need to calculate the drying time for this constant drying period, so we know that already know that how much amount of say unbound moisture actually is removed that M c is equal to 1 into l s into rho s into X i minus X c and we know this one also that total time of drying if the constant drying period that is M c by A into N c, so we can say that that will be just by putting this M c in this equation, we will be getting just in place of the this M c we are putting this 1 into l s into rho s into X i minus X c, we will be getting like this one, t c is equal to l s into rho s into X i minus X c by l s into N c. That is nothing but if we put this N c value in this expression then it will be l s into rho s into X i minus X c divided by G s prime into Y s minus Y i into 1 minus exponential of minus N tG.

So that is we say that for constant drying period we have this expression, for falling rate period we have this we can say this one the expression is like this: l s into rho s into X i minus X c and this divided by G s prime into Y s minus Y i into 1 minus exponential minus N tG into ln X c minus X star by X f minus X star, so from there we will be getting this total drying time that is t c plus t f.

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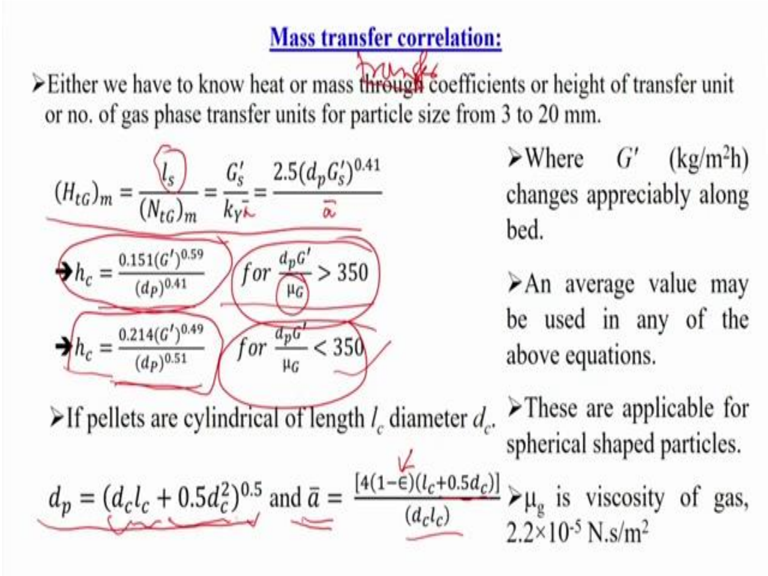

Now we need to consider some mass transfer correlations for different condition like this whenever we have this one wet solid in a packed column, so either we have to know the heat and heat or mass transfer coefficients or height of the transfer unit or number of gas phase transfer units for particular size from 3 to 20 millimetre.

So H tG this one we have got already l s by N tG because the l s is the total length of this or height of this tower, the we can say packed material. So, from there we will be getting like this G s prime divided by k Y into we can say this one k Y prime, k Y prime into H tG which is equal to l s by N tG is equal to G s by k Y prime into k Y into a prime that is we can say is equal to 2.5 into d p into G s prime to the power 0.41 divided by this a prime.

And h c is equal to 0.151 into G prime to the power 0.59 divided by d p to the power 0.41. For d p into G prime by mu G that is greater than 350 where this mu G is equal to viscosity of the drying gas and heat transfer coefficient value will be 0.214 into G prime to the power 0.49 by d p to the power 0.51when we have this d p into G prime by mu G that is less than 350.

So for this d p into G prime by mu G whenever it is less than 350 then we will be getting h c using this formula, when it is d p into G prime by mu G is greater than 350 we will be getting h c using this formula0.151 into G prime to the power 0.59 by d p to the power 0.4. Now if the pellets are cylindrical in nature and the length is l c and diameter is r c then we can say this one d p will be diameter of this we can say this one pellets will be d c into l c plus 0.5

into d c square to the power 0.5 where this and a prime actually will be 4 into 1 minus epsilon that is we can say this porosity.

This is actually mostly for we can say highly porous materials especially the catalysts like this, into l c plus 0.5 into d c by d c into l c. So here we can say this one G prime is this we can say this one in kg per meter square hour and changes appreciably around this one bed and average value may be used in any of the above equations, we can say this one whatever the G s prime G prime actually we have assumed, so we can get this one as the average value. And these are appreciable, applicable for this spherical sphere particles and this viscosity of drying gas in generally we can say this one it is 2.2 into 10 to the power 5 Newton second per meter square.

So in the next class we will be discussing about the rate of drying for this continuous dryer.