Mass Transfer II
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Lecture No. # 38

So, in the previous lecture, we had discussion on batch cross flow draw. So, what we had? A pan, a metallic pan on which, we had kept certain quantity of sand or any material which we want to dry and we brought this solid in contact with the hot air. So, there is a flow of air over the solid surface. The water evaporates and moisture content in the solid decreases. Essentially, it is a batch dryer, and in industries, you do have several batch dryers extensively used, especially in pharmaceutical industries or you have food industries.

Today's lecture: we have discussion on continuous dryer. So, what do you expect here very similar to rotary kiln. So, you may have seen may be in the summer training. So, you have a very huge dryer which rotates at a certain rpm and solids, limestone, minerals, which you want to dry; you bring in from one end. So, you have a hopper, and these solids through some chute, they flow into this rotary dryer. The dryers may be slightly inclined to ensure that this solids they flow along it and hot air flows in the opposite directions.

So, you have a countercurrent rotary dryer which is continuous. So, continuously solids are fit from end and the hot or the dried solid is drawn from the other end. Air flows in and leaves from the other end; so, it is a continuous. You can also have a co-current arrangement, in which case, a certain solids like organics, gypsum, which are prone to damaging at high temperature. You will like, you will prefer co-current. So, in other words, both the solids and the air - hot air - they enter the dryer from one direction.

So, this is just like an heat transfer. In a countercurrent, we have a large driving force. So, we have very extensive heating or relatively more heating than in the co-current. So, in those cases, where are we do not require that much of heating. We are afraid of temperature rising above the certain level and the solids getting damage on might prefer co-current.

So, nonetheless we have today in our discussions trying time in a continuous countercurrent dryer, so, very similar to this rotary kiln. Now, there are several types of dryers; one of them is very common, just spray dryer. For our course, this spray dryer is excluded from the syllabus.

So, spray dryer is also well popularly used. Here, you make use of atomizer. So, essentially you have a solution which you want to dry, slurry, some paste. So, what you will do you? Will feed it from a top and with the help of certain nozzle into small droplets and the moisture will come out to of it. Essentially, you have hot air also flowing in the opposite directions. So, spray dryer is also popular. Today's lecture, we confined our discussion to this continuous countercurrent dryer.

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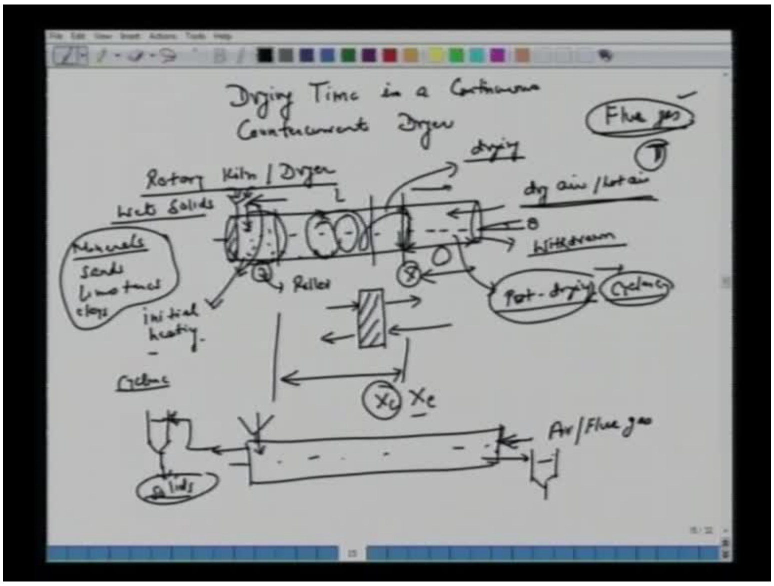

So, let us begin with this. So, what we have here is drying time in a continuous countercurrent dryer. So, as we said on the most common example would be like rotary kiln or dryer. So, let us say we have some inclined, say cylinder like this, but long and may be from one end, you bring solid through some hopper. So, you have a solid or wet solid which we want to dry. So, it is fed from one end and this is kept at certain angle. So, maybe there is a difference, may be 4 to 5 degree very small inclined so that the solids, they flow through this, and so, this end is closed like this, and here, from this directions dry air or hot air.

Now, it is blown with some blower air in opposite directions. So, the solid and this rotary kiln or dryer is kept on some roller; so, it rotates and this chi also rotates sub directions. So, in fact, we are saying that on the solids which drop into this cylinder, they uniformly distributed. So, there also lifted by this rotations and according they move like this. So, all the time, we can, from the qualitative, from mathematical point of view, we can think of entire cross section fill with the solid which moves in this directions and hot air moves in the opposite directions, and then, the solids are withdrawn from other end.

So, this is, now from the other end, now you again here you will expect that, you know, one can defined or one can divide this entire length of the rotary into certain regions. We can say that may be the certain lengths where there is initial heating. Then we can have certain range in which there is a drying. So, we can talk of bound moisture or unbound moistures in this region and then will third region where oppose entire solid has brought down certain to moisture content level, but still we like to further heat it.

So, we can expect certain length over which, we have post drying. So, these are just the optional arrangements, not necessarily where we said the certain solids make damage by this heating. So, in that case, this length will be almost 0 or very small quantity. Similarly, we will not be required preheating zone. There is also possible. So, there is loose definitions of all these three regions different text book, they have different definitions for this regions here.

So, let us note down certain examples here. So, this type of this rotary kiln or dryer essentially is have good for sieves lot of minerals, sands, limestone's, clays. So, these are on the materials. One prefer here sending to this dryer here. You must also not forget that these materials, when they move along or they rotate, they might be broken. So, in that case, one has to put some cyclone downstream to separate the small particles from the large particles. So, that type of different arrangements you have. Again the heating we said dry air, but in some cases, we can have flue gas.

So, generally, we are talking of certain industries where very hot flue gas at certain temperature is already available. So, not necessary we have to think of bringing some dry air, because dry air also require certain compressor one has to heat it. So, generally, in industries, power plants, you may have certain flue gas coming out of certain equipment which has a very high temperature of this temperature of this air can be fed into this rotary kiln here. So, that different options we can always discuss here, that is, the range is a heat drying zone, where the moisture contain may decrease to X c some critical contains or it can further go down to this equilibrium concentration, it come back to this.

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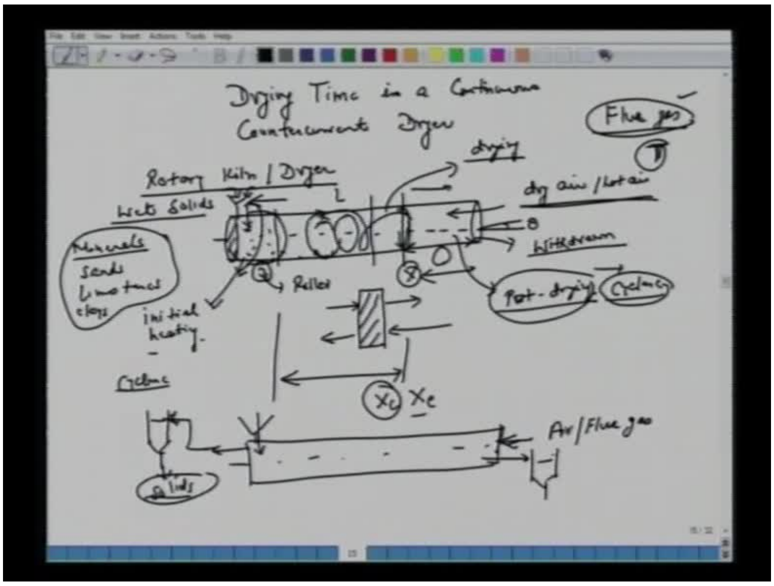

So, generally, as we said, it is recommended that you through certain text book and see a very clear better representation of this hot dryer. Essentially you will have a cross section like this, which is inclined just like the ever. We will have a hopper here to fit the solids. Air will come through this, air or hot flue gas. One can say that we can have, when the hot air comes out of this, we can like we can have a cyclone.

So, this air can be fed into this cyclone, because is going to pick up solids. So, one to have solids and the solids which have been picked up by this hot air will be removed from here. So, similarly, solids which come out from here can also be same to a cyclone. So, these are the different arrangements one can make here.

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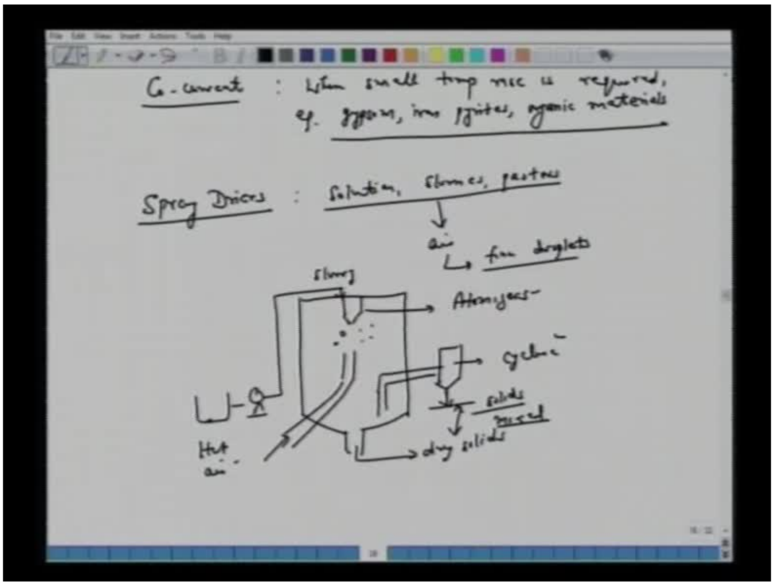

We also said that if we have certain chemicals which are prone to damage at high temperature, one would pray for co-current instead of high temperatures. So, we can make a note here that when a small temperature rise is required, for example, an in case of gypsum, iron pyrites, organic materials. So, in that case, on would prefer co-current. You can also have you know, we said that very popular these days - spray dryers. So, essentially spray dryers prefer to dries to a solution say slurries, pastes. So, essentially we bring this material in contact air. You have very fine droplets; so, the moisture's, so, you make use of certain atomizer.

So, we can think of schematic like this. We have arrangement. So, let us say certain, this is atomizer and we have slurry tank have a pump here, one can feed this. We can put the pump here also. So, this slurry is fed to this atomizer, and then, we have drops. The drops of this material air can be brought in, so, like this. So, hot air comes from one end, and again, we can take over this hot air and put this to some cyclones. So, some cyclones can be put here so that we recover whatever the solids which have come through this. So, solids can be recovered from here. So, this atomizer cyclone hot air, from here, we can also have the dry solids. Two solids can be mixed may be same to another cyclones to separate the air.

So, as we said in this, we said earlier in this lecture, we have discussion on countercurrent continuous dryer. Previous class, we had a discussion on batch and cross flow. Here, we have this solid which also moves and the air also moves. So, one has to make this balance, energy balance, heat balance or this material balance, species balance for moisture in both the streams. In the previous lecture, we were more worried or we have more concerned about how does the moisture content decreases. Here the two things are coupled. So, we have to make energy balance species, balance in the moisture as well as in the air.

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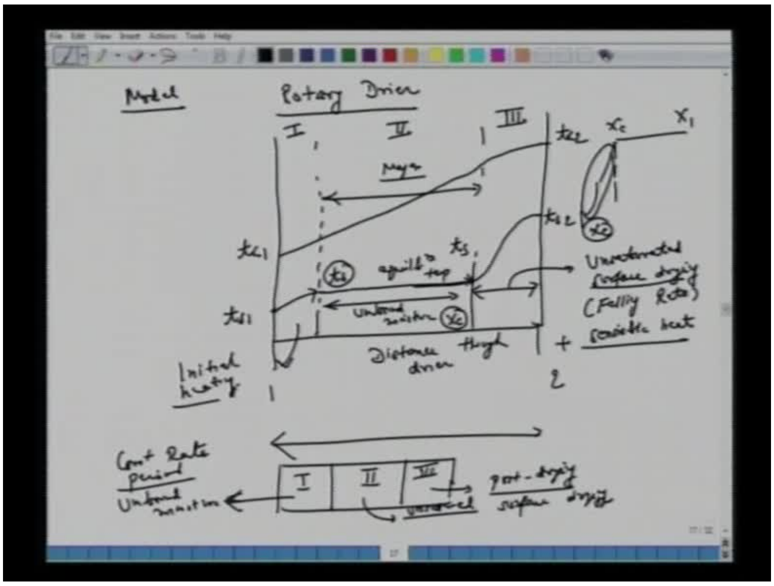

So, again, we have some kind of model here, some kind of approximations. So, if you look at rotary dryers, so, if you have a rotary dryers, then one can think of certain regions. So, let us say this is the distance through these dryers. So, we can think of certain say region like this, solid comes at temperature. Let us say t s1 let gets heated. So, this is your initial heating. May be this length is negligible in some dryers, in some applications; we do not require this (( )).

So, there is initial adjustment. Then, we will expect that there is a huge length, very significant length where the temperature is a constant. Let us say at t s which is the equilibrium temperature. So, at this equilibrium temperature, recall the previous discussions, we have mostly unbound moisture. So, this mode of a model along the length take some measurements is possible that temperature slightly increases.

So, maybe we are saying here that now the temperature has decreased to critical X c. So, recall our previous graph. You start from some X 1 and the moisture content decreases to X c before we have a falling rate region and we have these capillary effects. Then, after this X c, then we will expect that the temperature of the solid surface in the falling rate region.

Now, I starts increasing; so, it will increase like this till it reaches, let us say t s2. So, it is more of a r convenience here that from t s, the temperature has increase to t s2. Now, we are talking that this is a region where we have this unsaturated surface drying that is the region. We also said there is a falling rate. See, in addition to this, unsaturated surface drying is also possible that solid mind also be get further heated.

So, there may be some component of sensible heat, and what happens to the air? Air enters at temperature t c2 let us say. So, this is zone 2; this is zone 1, it decreases. So, we have third region here. We have 2, we have 1, temperature decreases. So, there is some decrease and then may be different slope that keeps on decreasing at a range say t c.

So, essentially, this is the major region where we have this drying at a constant temperature. Here also moisture content goes below X c to all the way to till X e, but in addition to this, there may be some further heating. So, it is one model where we are saying that this length is divided into three regions – one, two, three. Again, we said that these are all very loose. In some cases, one can say that this length is negligible and we start with unbound moisture one region. We can have bound moisture region number 2 and we can have a very small number 3, where we have this heating post drying.

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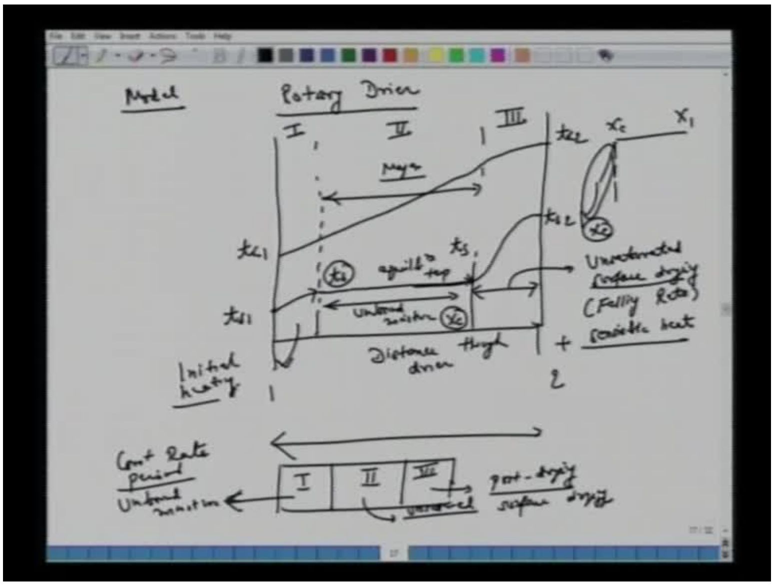

So, may be the first reason is constant rate period. We have unbound moisture that is very much possible, and the second reason is the one we are talking here, that is unsaturated reason, unsaturated surface drying. So, this is the another way of classifying this. So, again, this we can have different types of regions depending upon our applications for the certain drying. So, what do we do now? We make an energy balance; you also make this mass balance or a species balance.

So, let us try to understand that we have a certain meter of length say 5, 3 to 5 meters of length. Some solid is brought from one end. So, it has a moisture content. At certain temperature, it is brought in contact with air in the opposite direction. So, it is a countercurrent of operations. You want to make use of large driving force for heat transfer.

So, the air enters at certain temperature t c2, it has a humidity. Humidity is independent of the temperature. So, the air has certain quality that is a given by certain moisture content based of which, you can calculate the enthalpy. So, the two streams, they are brought in contact. We can have different type of regions - initial heating region or we can say that forget initial heat is very small, negligible. Let us have a region of unknown.

So, for our mathematical treatment to make an estimate, how much distance, time one has to careful? Solid has certain flow rates x kg per second or it has a velocity. So, based on that velocity, how much distance time you have to give so that the, when the solid enters or leaves from the other end and then its moisture content has been reduce to certain level whatever is our decide values.

So, here, it is a continuous process, there is no time. Time comes through distance. Time it is not the batch time. In the batch time, we have a solid and we say that it takes 5 minutes, 10 minutes, 3 hours for a solid to dry from one level to another level. Here, it is continuous process; it takes a certain resistance time over which the moisture content decreases from X 1 to certain levels.

So, for our mathematical purpose will keep, we said earlier also that one region which is unbound moisture, where the evaporation rate is a constant. With the surface temperature is a wet bulb temperature. In most of the cases, if you neglect radiations, that is the region one can do lot of calculations.

The region where the capillary effects become effective. Now, level rate decreases and we have to have very rigorous mathematical analysis. So, in that cases, we make an approximation that we are still, it is a linear falling rate. So, all we are saying that in this today's lecture, we will make a simple calculations and approximations that there are three regions - one region unbound moisture. Then, we have bound moistures. Then, we have a slightly small length where there is a post heating. So, with these three, we can now make a calculations.

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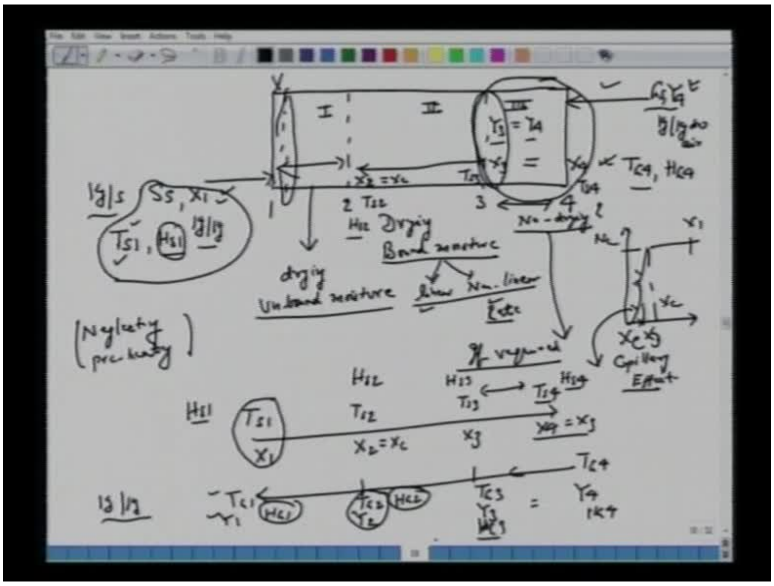

So, let us say we have taken a cross section of a dryer here. So, solid is brought from one end. So, let us mark this end as 1; this end as is 2. Solid we call the same nomenclature S s; this is your kg per second. So, that is your feet flow rate. Now, the solid has certain moisture content X 1, so, this is kg per kg of solid so much kg of moisture per kg of solids. This has a certain temperature T S1. So, based on this T S1 X 1, we can calculate H S1. So, mind you this H S1 enthalpy joule per kg it is a dependent variable. knowing T S1, knowing X 1 other properties, one can calculate H S. We take some data and to make calculation for a specific heat, sensible heat, etcetera.

So, all we are saying that the quality of the solid with that from the mass transfer point of view or from heat transfer point of view is known to us. Now, it enters and the air enters in the opposite directions, that is, a countercurrent. Now, the flow rate of air is G S, this also has certain humidity. So, let us make it Y here. So, Y is kg of moisture per kg of dry air.

So, what we do here? Let us make a note here. Let us make this is reason is 4. Here, we will come back to this. So, we have Y 4 at temperature of this air is T G4. So, based on this Y 4 moisture content and this temperature, we can calculate the enthalpy which is H G4. Now, we can track the air. Now, we can track the solids. Let us see the solid is wet here some moisture content. So, and we have divided this dryer into 3 regions – 1, 2 and 3. Let us label the inter-phase of 1 and 2 as 2, 2 and 3 as 3, and then, we have this 4.

So, as solid moves in these directions, it is going to get dried here. This region 1, we say this is region of drying of unbound moisture. So, if you recall from the previous slide, you have neglected the region where there is a neglecting, preheating. Solid is getting heated here also that is all, but we are saying that we are neglecting certain regions of that length. So, this is the region 1 where we have unbound moisture. We have this moisture content at certain level, but the rate is a constant here. So, if you have recall previous moisture character is this curve like this and then we have like this, going all the way till X c. This is x t; this is X c, corresponding rate is N c and we start with some X 1. So, always we should keep this characteristics covered the solids in the mind here.

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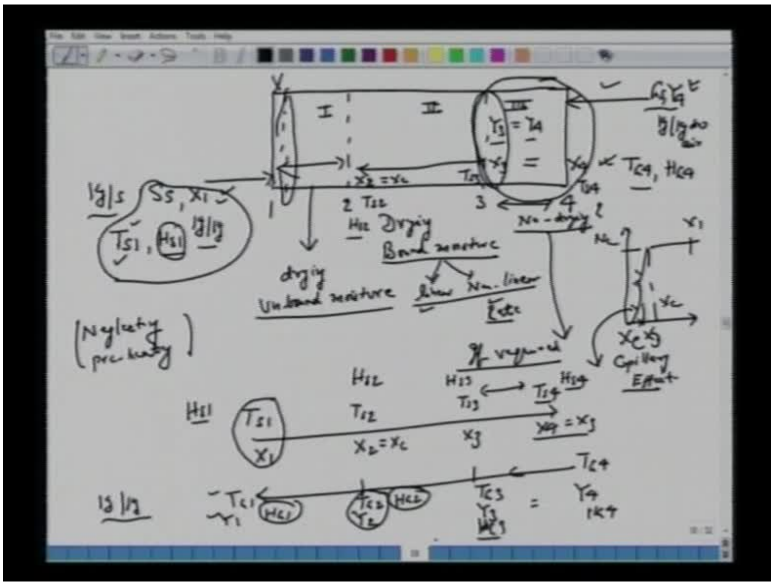

So, unbound moisture, then we have certain region where we have this drying also, but for this is for bound moisture. Now, we have said X 1. Here, the moisture content has decreased to X 2, but this has decreased all the way till X c. So, that is an end of your unbound moisture. So, the inter-phase of 1 and 2 region is a unbound at bound moisture.

So, from previous discussion, now this X c. Temperature will also be T S2. We have H S2 similar convention we are following here, and then, may be in this region, we have both at certain length that solid has dried to certain concentrations. Let us say x t beyond which, now we have this capillary effect taking place. So, what we say that let us, for the timing, let say that this region is here X 3, which includes moisture content has decreased from X 2 X 3. That includes bound moisture whether it is a rate linear rate falling or it is a non-linear rate.

So, will come back to this and we will see some and discussion there on. Right now it is a region of between 2 and 3 where you have the drying of this bound moisture. Now, after this, now there is no drying here. So, as we said that 3 to 4 is no drying and we put this exclamation site here, a question here. If it is required, you can have this.

So, as we said here, the certain solids which have prone to damage because of heating. So, in that case, this third region made become redundant. So, as soon as the moisture content has decreased, certain level or the temperature has reached T S 3. You will like to withdraw this solid. So, this length becomes redundant. Nonetheless we say that here, we have a general case from 3 to 4 moisture content remains the same. So, when you have X 4, X 3 equal to X 4; temperature is of course T S 4.

So, let us write here T S1, T S2, T S3, T S4. So, solid temperature it gives on increasing; moisture content decreases from X 1 to X 2, but X 2 equal to X c. It decreases to further X 3. It may be here; it may be here it may be all the way till equilibrium, and after that, it remains the constant. So, X 4 equal to X 3. So, all the temperature has increase but there is no heating; there is no drying here. What happens to the air? Air will also, one can also track air is now flow rate is G S and your moisture content is Y 4 kg per kg drying. Now, since it is a nondrying region but temperature will decrease, but the moisture content Y 3 will same as Y 4.

So, the way we have made it here, you can also have a similar argument for the gas. Let say the temperature here is T G4, so, T G4. Now, the temperature decreases for air T G3 for since there was no drying in this region, the humidity of the air is Y 4 and Y 3 the same here. So, same argument moisture content is a same and humidity is same. So, we will see will make a material balance or species balance in the 2 phases. Whatever is the lost in the from the solid is gain by this air phase, and again, the temperature will decreased T G3 to T G2 and then here decreases to T G1. We have corresponding Y 1, Y 2 and Y 3 in the humidity kg per kg of dry air corresponding to all this T G1 and Y 1.

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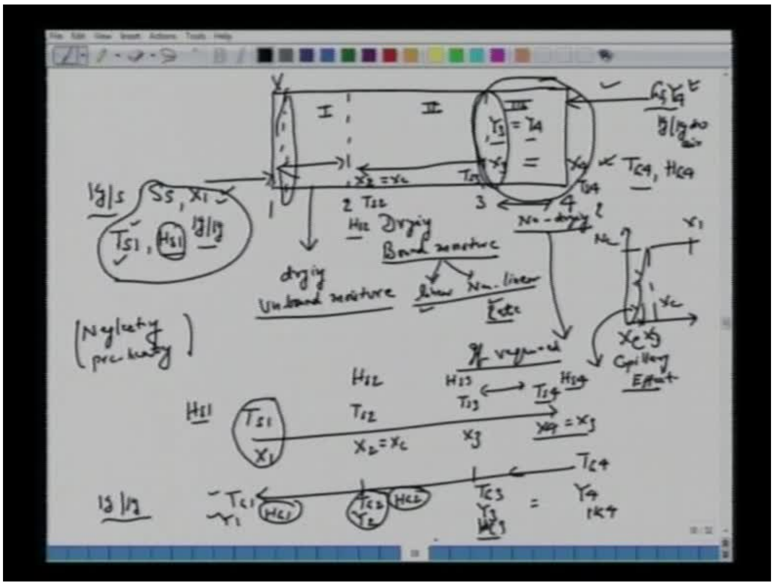

So, once we fix the temperature and humidity, you must recall that enthalpy is also fixed. Once you fix the solid temperature and its moisture content, you fix it H S1 enthalpy. So, corresponding to this, we have H S1, H S2, H S3, H S4. Mind you here, moisture content has not changed but since the temperature changes enthalpy will also be take out.

Similarly, here, we have H G4 moisture contents same but the temperature decreases. So, we have H G3 different from H G4. So, similarly, here, we have H G2 and we have this H G1. So, we should keep this in mind this argument that last region is a one region which is redundant. Here, moisture content either gas phase or the humidity in the moisture content in gas phase or the solid phase remains the same. So, humidity will also be the same Y 3 equal to Y 4 and the region 2 consist a both is a drying bound moisture, but it may have linear and non-linear rate of drying.

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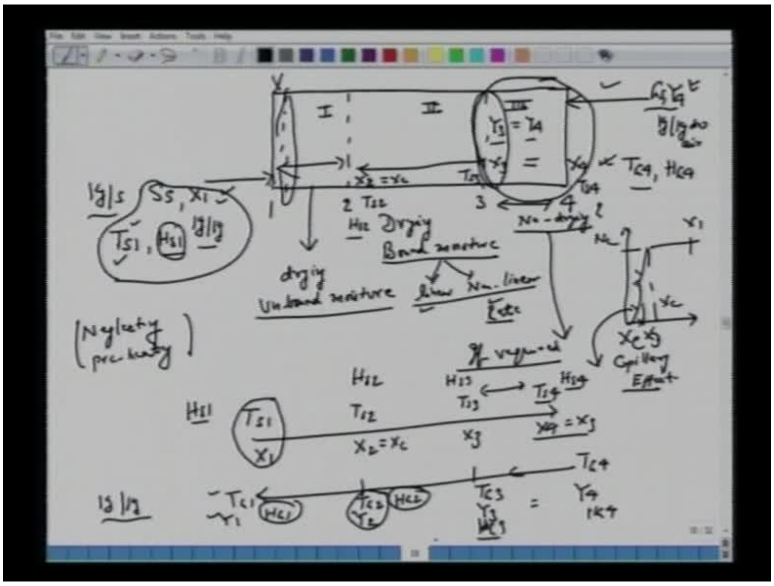

First region is the unbound moisture. Now, of course here is schematically we have shown like this is the region 1 which is a smaller than 2 but in it all depends up on the moisture content heat of drying. This length can be larger; this length can be smaller. Generally, the last length is very smaller and we said that we also have a some length. You can have where there is a solid is cold, it can be heated to desired level before the appreciable amount of drying takes place. So, we have neglected that length also. Now, before we make any energy balance, let us discuss what is the status of your solids surface temperature after or it during this bound moisture.

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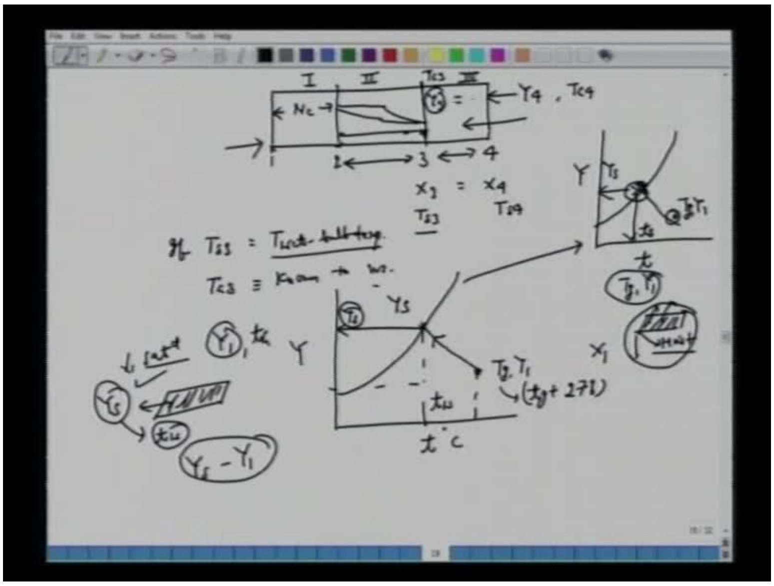

So, when we make this, now let us make an energy balance here. So, let us just draw, redraw it with just mark the region here as 1 4 2 and we have this 3. It is a qualitative. More important to note here is this is Y 4 and this Y 3 each are same; X 3 equal to X 4. So, T S4 and T S 3 they are different, and T G4 and T G3 are different. If you recall, we said in the earlier class that when we refer to the psychrometric chart, we said that if you plot saturated humidity and the temperature, we have the curve like this. So, there we said that if you fix quality of air, which means the temperature and it is humidity and bring this quality of air on to a solid surface its say moist solid.

If there is no radiation effect but there is no conduction effect, then this temperature of the solid will decrease; eventually it will reach a wet bulb temperature. So, it will take this line and follow this adiabatic saturation line, you will reach Y s and you will reach T S. We had an example in the previous lecture, you talked about this. So, let us see, we can also have a similar situations here at this temperature is assume that the solid which is drying here. Now, it has reach the wet bulb temperature.

So, if you fix this T S 3, then we can say that Y 3 is also fixed here. So, we will like to make a note here that if T S 3 is wet bulb temperature, so, if T S 3 is a wet bulb temperature, then T G3 is known to us. So, we are again we are referring to the same graph here. Let us have another discussion here. If we plot temperature and if you follow, we have the psychrometric chart here, which is your saturated humidity versus temperature. If I take certain solid, it has moisture content to start with X 1. I bring in contact with air temperature which is T G and the humidity is Y 1.

So, mind you these two are independent. So, I have this T G and Y 1. So, this coordinate is marked here. Temperature T G is nothing but small temperature T G centigrade plus 273 kelvin. So, I marked this coordinate. Now, the solid temperature will decrease by cooling as moisture evaporates. Ultimately what happens that if a neglecting all those radiation effect, final temperature achieved by this solid. It follow this line here and we have this wet bulb temperature t w, corresponding to which, Y s is fixed.

So, the solid surface under steady state, an over, an equilibrium, here we have very close to the solid surface. Humidity is Y s which corresponds to the saturated humidity. So, it is a saturated humidity corresponding to this t wet bulb temperature.

So, this is your wet bulb temperature, and here, we have the water, this moisture humidity which is Y. So, we have mass transfer driving force as Y s minus Y. So, what we said here that we fix this Y 1 and air temperature and allow this solid to cool. The equilibrium temperature would be the wet bulb temperature corresponding to which, we have this Y s fixed. So, very important discussions, we are going to make use here solvent for this different coordinates moisture content or the enthalpy of the temperature.

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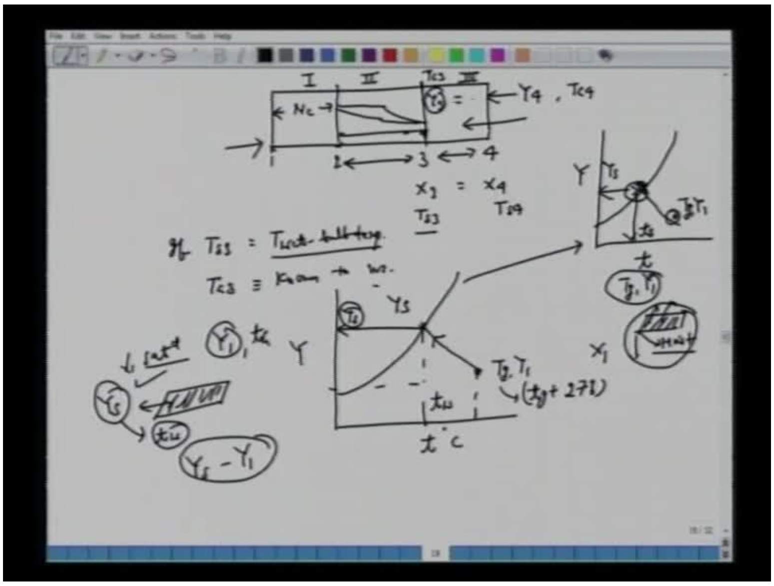

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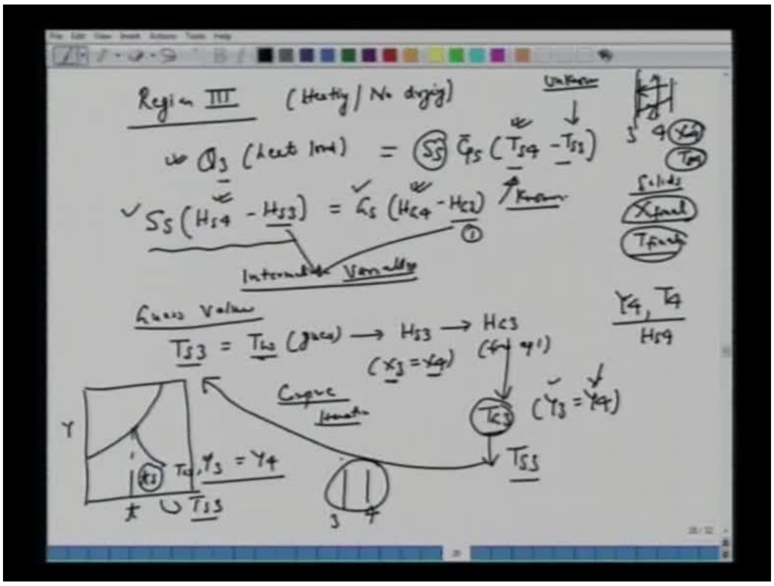

So, I just make a note here that we have N c is a rate at which, we have rate of unbound moisture. Then, the rate decreases. We do not know, may be it is a linear to some extent. Then, again, it changes the slope because of capillary effects. So, that is the second 2 to 3 where we have this bound moisture, and after that, we have this sensible heating. Now, we can make energy balance. Let us see we can again start with 1, 2 or 3. For our convenience, it is better that we start from third region 3. We will see the advantage of making energy balance. From this direction, the solid enters like this, air enters like this. So, let us say we have region 3, which is the region where there is heating, only heating, there is no drying.

So, we are talking of just sensible heat. So, what is the heat load? If we say that heat load 3 for region 3, heat load in this region this nothing but S s that is the flow rate of kg per second of the solid. Certain average a specific heat temperature changes and have a rise in the temperature from T S 3 to T S 4. So, the last region 3 here and the 4 here, temperature rises like this.

So, there is the heat flow T S4 minus T S 3 and your T S4 is known to us, because we want to bring the solid temperature to T S4. It is very important that the quality of a solid is not only specified by it. What should be its final moisture content? X final, but you should also, what should be its temperature, because they are certain solids, organics, especially gypsum, certain chemicals which get damaged at high temperature.

So, when if you want to remove but want to bring this solid to a very small level, you have to be worry, you have to careful this temperature also; temperature must not exceed certain limit. So, essentially, this T S4 the temperature here or this (( )) X 4 here. These are known to us; T S 3 is unknown.

So, this is T S4 known to us. T S 3 is unknown to us. We just talked about that certain approximations, when we can say that T S 3 is a wet bulb temperature. We will come back to this. So, nonetheless, if you know T S 3, we can calculate Q 3. Now, let us a make another balance - solid temperature increases and air temperature decreases. So, whatever is the heat loss, energy loss, we can make a balance here assuming that there is no other heat loss, this a adiabatic drying. So, S s solid kg per second H S4 minus H S3. So, whatever energy is gain, heat is gain by the solid is lost by gaseous, so, G S H G4 minus H G3. So, the enthalpy here is larger. Let us see what are the things known to us. We know S s; we know G s; we know H S4 which, that is the quality of air here.

So, if we know the quality of air which is Y 4, what hot air we have T 4. You can calculate H S4. So, this is known to us. H S4 is a solid; so, H S4 is known here. H G4 is also known to us. H G3 and H S3 these are the intermediate variables which are not known to us.

So, we are running short of one equation, but by making the previous argument that, if we allow, we, if there is no radiations but no conduction effects, it is only of because of convections. The solid temperature at T S 3 can be assume to be wet bulb temperature. In other words, let us assume we have to make certain iteration here. So, our guess value, let said T S 3 equal to T wet bulb. So, it is a guess value. We assume that surface temperature has reached a wet bulb temperature. What temperature we do not know but will see that or we can come back at correct it.

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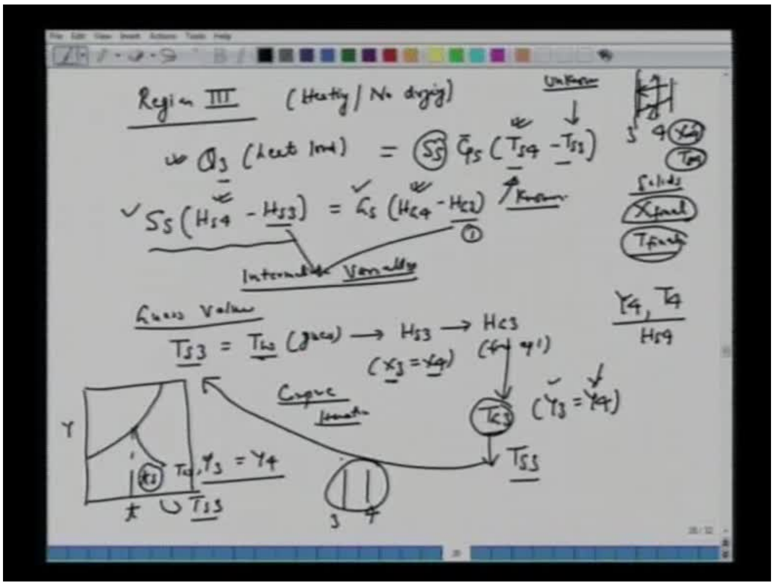

Once we know T S 3, we know H S3. Why? Because the moisture content does not change. So, whatever is X 3 same as X 4, so, X 4 is known to us; X 3 is known. So, mind you if you know the T surface temperature in the moisture content, we can calculate enthalpy. Once we know H S3, now we can go back and calculate H G3 from this equation and let us say equation 1, and once we know H G3, what is H G3? The enthalpy here, we can calculate T G3. Why? Because we know that humidity does not change here. So, Y 3 equal to Y 4. So, if you know Y 4, you can calculate Y 3; Y 3 is same as Y 4.

Just like here X 3 equal to X 4. Now, we know T G3, but mind you what this T G3? This nothing but the saturation temperature. Go back to the previous discussions. This T G3 from this, we can calculate now T S 3 and compare and do the iterations. So, let us come back to this. Once we know T G3, so, this is what we were saying earlier that once we know this T G3, so, this is psychrometric chart here Y versus temperature. If we know this T G3 and Y 3, the surface temperature will be given by this t s, small t s or capital T s.

So, this is what we said here. Once we know T G3, we know this Y 3 which is Y 3 is same as Y 4. You can calculate this t s and we said we can check whether this T S 3. What we have calculated here is same as your guess values. So, it requires certain iterations to mark this or to calculate the zone 3 and 4 here.

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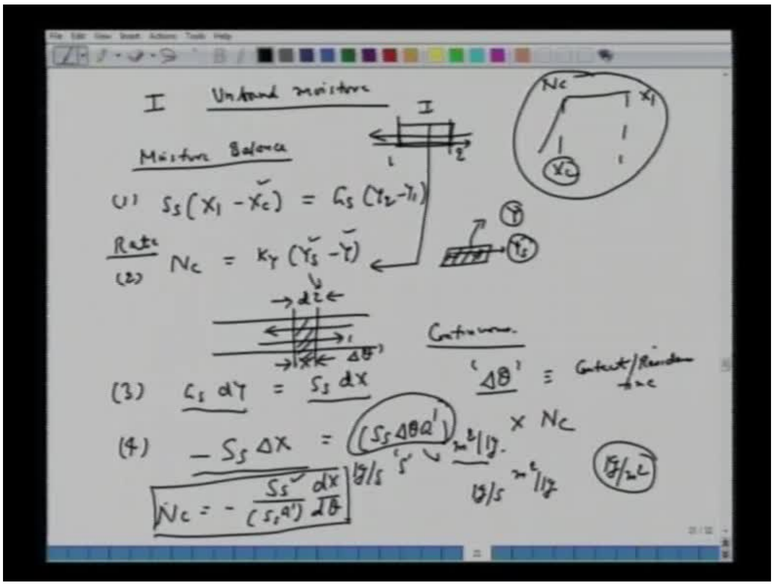

So, now, let us come to this region. Now, 1, so, we had 3 first. For some reason, you will see convenience. We come to this region 1 which is a very simple to solve here. This is unbound moisture or we are talking of this constant evaporation rate here. So, from the moisture content point of view, now we are talking this X c decreasing from X 1 the rate is N c. So, it is a very simple calculation. First, you will like to make the moisture balance over this region 1. So, S s we know the flow rate. Moisture contents is X 1, it decreases to X c. This X c here this again is known to us, because we said earlier that we have to do this experiment here in a laboratory scale to calculate to characterize this solid here.

So, let us say, we have S s X 1 X c known to us. This will be equal to G s. So, whatever moisture is lost, this gain by this a 4. So, we have Y 2 minus Y 1. So, we are talking of this region. First region says 1 and this is 2; solid going like this and gas air flowing in the opposite directions.

Now, what is the rate here? Recall, let us talk of this rate now. What is the rate of drying here? N c constant heating zone here which equal to K y and we have Y s minus Y. So, this Y s we are assuming that it remains constant over this (( )) which is true. The solid surface we have thin film of this moisture which evaporates. So, the surface you immediate, you in close contact with the solid surface is Y s and the moisture humidity is Y. So, we have this region where you can write K N c equal to K y Y s minus Y; Y of course changes between Y 1 to Y 2. We will come back and will see the integrations. So, at any region between 1 and 2, we have written this balance here K y Y s minus Y.

So, this is one equations; it is a second equation. We can also choose a differential elements. So, let us choose a differential elements solid goes like this, gas goes like this. We can write G S dY change in the humidity same as decrease in this moisture content. So, what this small length of dz? We have made this valiancy number 3, number 4 here.

Now, we have written the rate N c as K y S s minus s. You should think here that is a still difficult to integrate it, because we do not know how does the humidity changes along this length here. So, what we do now. Now, again, over this del X dz, say the moisture content is X. This is a continuous flow here but we can think of a certain analogy that over this contact time let us say del theta is a contact time or it is a resistance time. So, what this contact or resistance time?

Suppose solid moisture content decreases by del X. So, minus S s del X you can think of this should also be equal to how much solid we have. We have S s kg per second into del theta. So, del theta is a resistance time. So much solid essentially is getting dry just like a batch conditions multiplied by a time, a prime, which is let us say this is your… Here, we have meter square, some effective area for drying here. So, this is meter square per kg. So, what we are writing here? We are trying to make an analogy between this continuous drying with this is batch drying over a very small distance T z over which, the resistance time is del theta.

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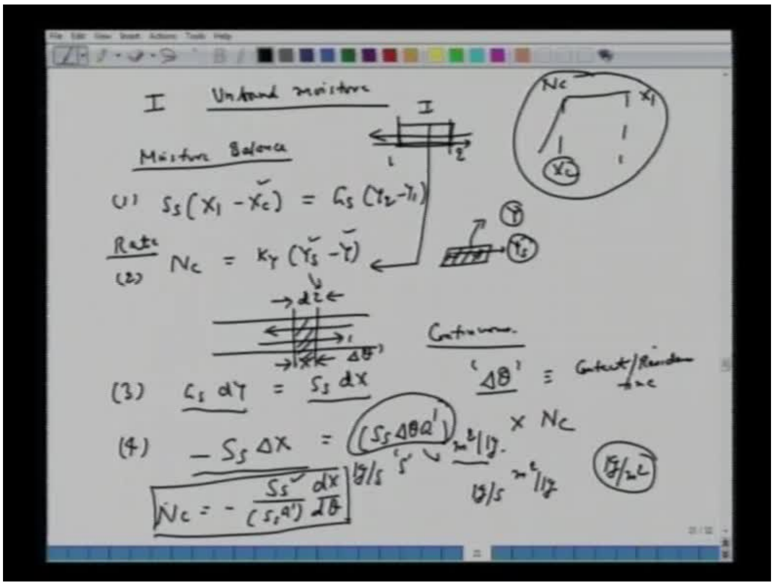

So, when that moisture content decreases for the solid S s to del X, essentially we have certain amount of kg. So, this is kg per second. This is second and this meter square per kg. So, certain amount of solid is getting dried at a rate N c.

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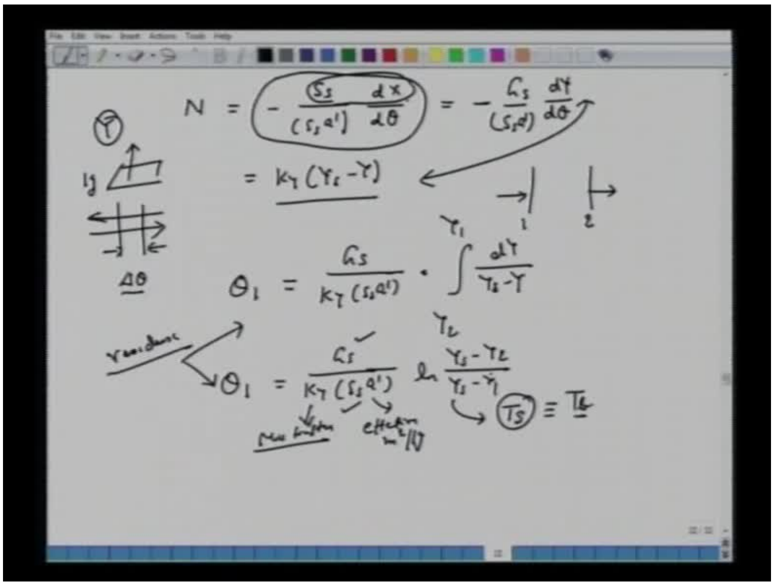

So, this is very close, very similar. If you write down N c as minus S s over S s a prime dX over d theta, so, compare this to your batch a very similar this expression. We have very similar to this batch experiment where we had this amount of the solid, it was kg. Now, we have this kg per second, and here, we have S s a dash which is kg per second and we have meter square per kg. So, we are talking of certain kg over meter square. This whole term is like kg per meter square very equivalent to this. So, we have one more expression N c which is same as this. Now, we can do the integration. So, how we will write? We will write N as minus S s. Let us rewrite like this S s a prime. We have dX over d theta this is equal to K y Y s minus Y. Now, this also equal to minus G s S s into dX is G s into dY. So, all we have done if you have replace S s dX as G s dY, and here, we have S s a dash.

Now, we can integrate these two quantities, so, Y changes. So, over essentially we have gone from the length wise to this time wise t theta is minus; it is not a batch time. So, this is an expression for the batch. As if we have a solid surface of kg and we were heating it or drying it in atmosphere at the humidity was Y. In our case, we have this continuous process solid gets in and solid like this and air pull that, but by this balance here, they have shown that over this del theta, we can also have another expressions. At what rate can dry this or how long will it take or how much is the resistance time one has to give for a solid to decrease from certain one humidity to another humidity. So, essentially, we replace this moisture content with terms of here. Now, with these two, we can integrate to obtain this theta 1. So, if integrate, theta 1 is very simple. Now, we G s K y S s a prime into integral Y 2 to Y 1.

So, this is 1; this is 2 dY Y s minus Y. Now, we know how much is the resistance time, contact time we require to give for the region 1, where we have this unbound moisture which is equivalent to G s K y S s a prime ln Y s minus Y 2 over Y s minus Y 1. What is Y s? We can also say that this is equivalent to this. This is corresponds to this saturation temperature where we can equate this saturation temperature as wet bulb temperature.

So, there is some kind of approximation here other as well, but this is best estimate. One can get for this resistance time or contact time for the region 1. We know the gas flow rate; we know the solid flow rate; we know this effective drying area in terms of meter square per kg. It is a mass transfer coefficient. We have seen earlier come back and take this example 1.

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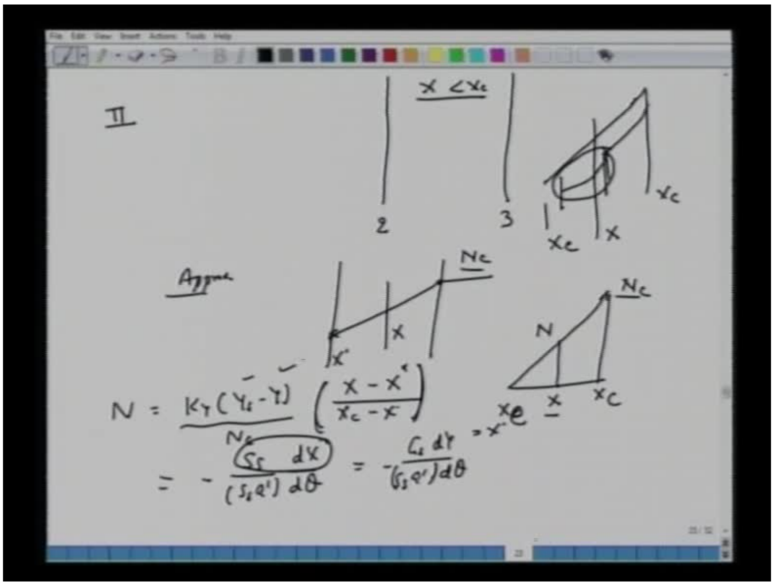

So, this ln Y is to minus Y. Let us come back to this region 2 on we are talking of this region 2. So, here, we have region 2 and this a region 3. Now, this a region where X is less than X c get. So, this a falling rate could be like this or could be like this, so, where the capillary effects to start taking this. So, this X c and these all the wet l may be X c anywhere we have this X.

So, here, what is the rate? Of course one has to make again approximations. We can have the range like this where there is a capillary effect, but then, it becomes very regress mathematical calculations. One has to make these approximations in the region between 2 and 3, the rate falls linearly from N c. So, the rate forms falls like this, which means now, we can write N as K y Y s minus Y. So, this is a rate. We had for N c which we have calculated, but since it is a linear, we can linearize here or we can take forgetting at any moisture content.

All the way till, let us linear till let us X star, we can write X minus X star X c minus X star. So, let us, what we are trying say here? Let us redraw here. We have 3 triangles X c or X star. We have X and we have X c. Rate here is N c. This a general rate N. So, whatever N c we have calculated, now it is a linear. So, we can use of the property of this triangle here to write K y Y s minus Y. It is now in the same proportions, it at any X between X c and X c, we can write like this, and again, this can be equivalent. This can be equated on the batch considerations or batch analogy as S s a prime dX by d theta.

Again S s dX can be written as G s dY. So, again, you say that we are converting all the time from this Y into this X to Y.

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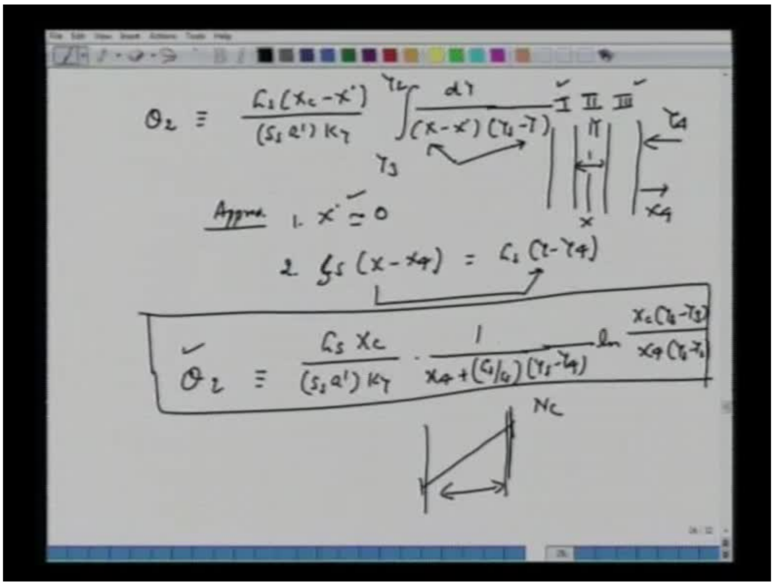

So, G s dY S s a prime d theta. Now, let see if we integrate, mind you X also changes and Y also changes. So, the integral time of the time theta 2 contact time will be G s. You can take of all the, all the parameters which are constant. Critical moisture content, equilibrium moisture content, we have this S s a prime K y, but in the integral, now we have Y 3 Y 2 dY over X minus X star into Y s minus Y.

So, is all X and Y, both are varying between this region. So, what we do? The best of one certain more approximations one can have which is quite reasonable equilibrium concentration. Let say moisture content is very small, very 0 quantity, that is 1. Now, one can make another balance here whatever is last solid phase, so, this S s X minus X 4 will also be same as G s Y minus Y 4.

So, this another balance here. So, whatever is enters here, this is your X 4 and this is your Y 4 and we are talking of this one region, another region and another region, so, 1, 2, 3. So, first, we started with of the region 1; that was first. We started with region 3. Then, we want, now, we are looking at this number region 2 where we have this bound moisture.

So, we can also make a balance, some arbitrarily moisture contents like X and the air humidity Y here. So, we can write like this. Now, we can replace X in terms of Y to obtain this theta 2 contact times, how much time we have to give? The solid G s as G s X c S s a prime K y into 1 over X 4 plus G s by S s. So, it is a very simpler algebra here. We are replacing X in terms of Y 4 X in terms of Y. So, we have X 4 plus G s by S s Y s minus Y 4 these are all known to us ln X c Y s minus Y 3 over X4 Y s minus Y 2. So, that is an expression one can have by approximations assuming that number 1 moisture content is 0 and number 2, we have all the rate it is a linear rate, which should falls all the way from N c in this region 2 which is bound moisture region.

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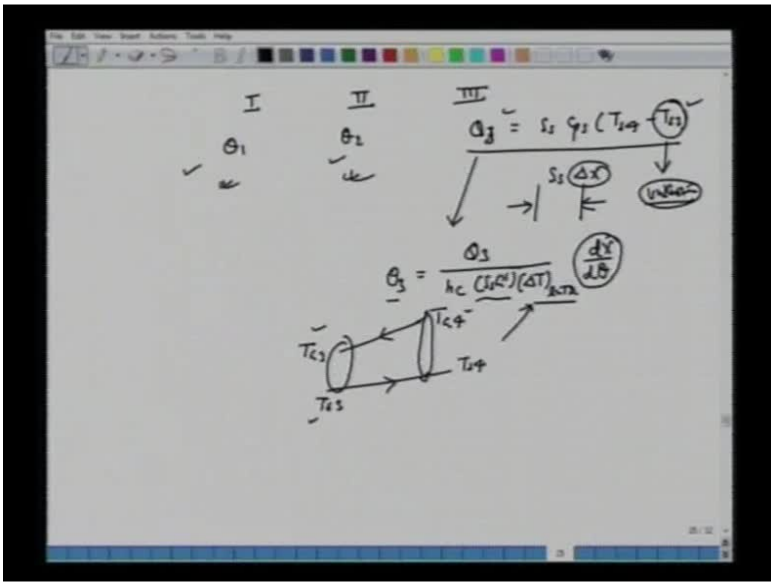

So, it is all linear area. There is no capillary effect. We can make that approximation to be to calculate theta 2 here also. So, what we did here? We have three regions - region 1, region 2, region 3. Remember, we started with this region 3 here where we wrote expression for Q 3 equal to S s c ps T s4 minus T s3. We had theta 1; we had theta 2. Now, based on the same argument, that we have this batch of solid over this S s and we have the moisture content decreases by a del X.

We came out with the expressions or batch time dX by d theta in terms of the mass transfer coefficient. Based on the same argument, we should be able to convenience yourself that even this region 3, one can also come out. What is the heating load? How much contact we require as theta equal to Q 3 over h c S s a prime? So, this where we are saying that now kg per second is equivalent to certain kg over a time theta equal to this del T lm T d. So, in the reason 3, let us make note here that the temperature gas decreases from T G4 to T G3 and the solid temperature increases from T S3 to T S4.

So, you have lm, you can write down this driving force balancing terms of your difference between the gas temperature and the solid temperature to obtain this lm T d del T; this will also give us theta 3. So, today's lecture, what we have done? We have got this some idea or to make an estimate for different time contact. First we started with theta 3. We had the heat balance, sensible heat balance; there we have to make some estimate to obtain certain quantities. Once we have that, we can calculate theta 3.

So, it is the main problem here. If you recall T s3, surface temperature was unknown, so, one has to make by iterations that exercise we did. Once we know T s3, we can calculate theta 3. Then we went back and we did theta 1 and then we did theta 2. So, today's lecture let sum up before we take an example in the next class. We talking of these continuous dryers solid feed from one end and the gas feed from the other end. We said that we can have different regions, different text book, they have the different differential for the regions as well. For our mathematical calculation, we said that we have one first region where we have this unbound moisture evaporation.

So, it is a N c very similar to of the drying characteristic curve where the initially the rate remains constant. You can also have initial heating or heating at adjustment tray or length for the initial heating or initial adjustment; you have neglected. So, we have now constant rate unbound moisture. Then you have the bound moisture, then there is a post heating. Post heating can also be negligible or may not be desirable in some context where the solids may not get heated, because there is a risk of in the solid getting damage by heating so that length can also negligible, but we had 1 to 3 regions and they were the way we had, they approach that all the 2 domains, we knew from the overall energy balance or from the given conditions, we know the solid temperature; we know the solid enthalpy; we know the air temperature. Air humidity is quality of the solid which has to be withdrawn from that overall balance, we know all the 4 boundaries. The problem comes at the unknown at the inter-phase.

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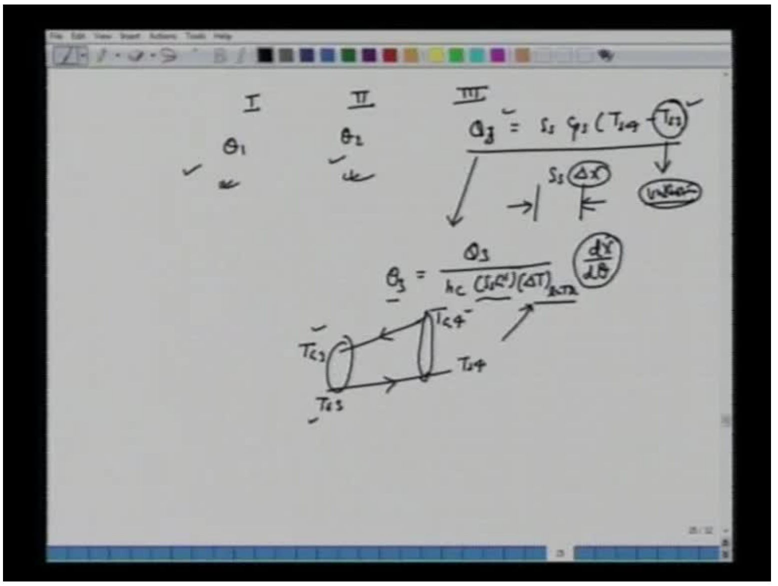

So, there we have to make a balance at the inter-phase between 2 and 3. So, there write on the energy balance. You will see that we require certain iterations. We assume that is all it temperature is same as the wet bulb temperature. We go back, check the psychrometric curve and then we have that iterations. Once we had this region, T S3 was known to us, then all the other quantities like theta 1, theta 2, theta 3, how much is the resistance time we require for a solid to get heated or to lose its moisture from X 1 to some other level. In this case also most important to note here is that we wrote down this energy balance over the differential as well as we also try to making some analogy. How we can make use of this batch rate expression?

So, we have kg instead of kg per second, and the same expressions, we could write in terms of your resistance time. If we think that if we take a differential, you have a del theta del X del Y. Over that, we wrote this differential balance to obtain the expression for your theta 1. So, the next lecture, when we meet, we will like to conclude this or discussion on drying by taken one example.