Mass Transfer Operations II
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Lecture 06 – Drying Operations

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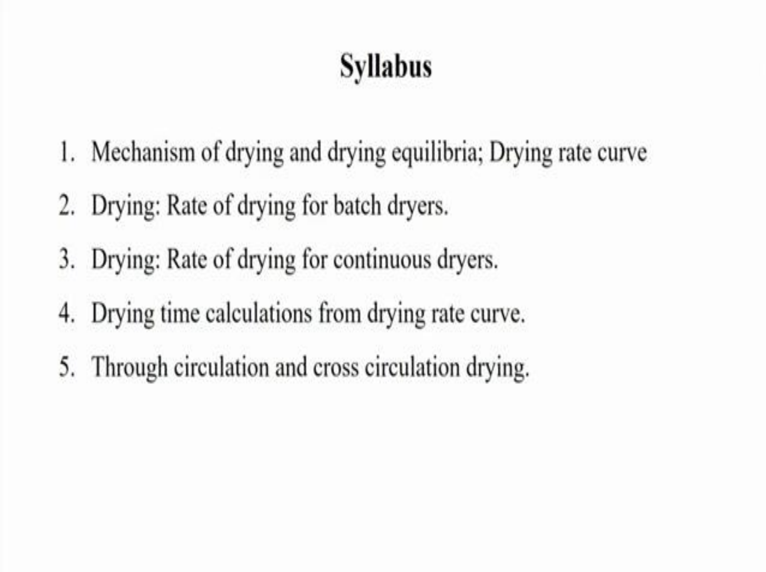

Welcome back to Mass Transfer Operations II course. In this class I shall start discussing the new topic named drying operations. It is very important this one topic in Mass Transfer Operations II. The syllabus is as follows: First point is mechanism of drying and drying equilibrium, then drying rate curve. Then drying, in drying will be discussing on the rate of drying for batch dryers and in another this one class we will be discussing rate of drying for continuous dryers. Then we will be discussing this drying time calculations from drying rate curve.

And finally we will discuss on the through circulation and cross circulation drying. Before the start of this mechanism of drying and drying equilibria, we should know the details about the drying operation. So the drying is regarded as the last operation of so many chemical processes such as this sugar manufacturing and leather manufacturing in the tannery from the leathers. And say for so manufacturing in the humid chamber or milk powder generation from this milk using the spray dryer.

Then we can say sometimes this hit sensitive material drying like enzymes using this freeze dryer that is dried to minus 55 degree Celsius with the help of this labialization. And say some food stuffs also are dried and so many spices also are dried before it goes into the market for the consumers. Like say so many spices ranging from this turcumin to we can say different spices and this there is a difference between this evaporation and drying. If we say that suppose for from the soap like this if we want to make the glycerin then it is called evaporation because the final product is liquid, say from the liquid some amount of water is separated and we are getting this glycerin. So that is evaporation, this is not the drying of say soap like. Like say if we want to make condensed milk then we start with this milk and from the liquid we will be getting another liquid so that we can say evaporation.

But we can say this one whenever we will be talking about say removal of moisture from gases or liquid then that is also regarded as drying process but in this chapter that is in terms of drying operations we will not be covering that part. That is we can say drying of gases and the liquids. Ok.

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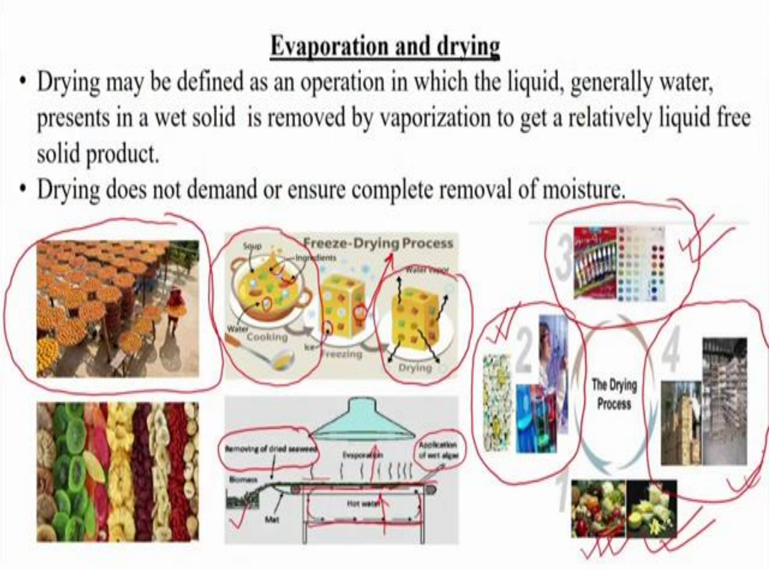

So we will start with this topic like evaporation and drying that I told that say evaporation is to some extent different from drying. In evaporation process, suppose we will start with this liquid and we will be ending with the concentrated liquid but in the case of the drying process in general we can see this one. It can start with any we can say this mostly you can say this one, moist solid or we can say this one anything which is rich in water is converted into relatively liquid free solid.

So we can see drying may be regarded as an operation in which the liquid generally we can see this water presents in wet solid is removed by vaporization to get relatively liquid free solid products. So drying does not demand or ensure complete removal of the moisture. So if so many examples are cited here just like we can see this one in the left hand side, we have shown that so many vegetables or fruits actually are dried here using only sun drying and one example of freeze drying process. We told earlier that which are very heat sensitive material. Let us take one example of this soup. That is nowadays we can get so many ready-to-eat soups are available. Suppose this soup contains say different ingredients. Suppose these ingredients then water also like this. And it is one complete soup.

But whenever we will be freezing this one say whenever it will be converting into the solid product from this liquid mixture then this so much of water also will be converted into ice. Then in the freeze drying process this sublimation will take place. That is, we can see this one whatever the water is there it will be separated from the system or we can say this one solid ice will be converting into vapor in a single stage. So then we will be getting one of freeze dried product that is we can see the soup.

And whenever we have this freeze dried soup in this that is available in the market, so we will bring this one back to our home and we will be adding in the hot water this freeze dried the solid stuff and then we will be getting back the soup with this almost same calorific value and we can say this one same taste and we can say this one with the same color. Another application, suppose wet algae especially we can say so many green blue algae like spirulina, these are obtained from water body. Then it is it is now conveyed through our one conveyor belt like this whereas this hot water bath actually is placed here and this hot water supplies this heat to this wet algae and then evaporation takes place from this wet algae.

So this water will be converting into water vapor here and then whenever it will be leaving this conveyor belt it will be coming as this dried this we can see this one biomass of this spirulina like this and we will be obtaining this one as the dried product and that is used for so many applications like it is used as the food supplement. So many algae are dried in this way also. Now as a whole if we see this drying process, so many vegetables are dried to get the final product. To store for a long period of time so many vegetables are dried and so many fruits also, these fruits and these vegetables are dried like this is one application of the drying process and any another application we say we have also discussed this one that is so many pharmaceutical products are also dried in the controlled condition.

Say suppose humidity is maintained in a particular this one value and it is dried in a long period of time, so this we can say so many drug items are also dried in the drying process. Say whenever we will be talking about any dyes or we can see this one paints et cetera, these are also dried. So and the application of this drying process for the different painting materials and inks or say dyes, they are there in so many this one instances and the fourth one is this say is the drying process as a whole we can see this one different types of dryers are there to dry so many different types of products are there. Ok.

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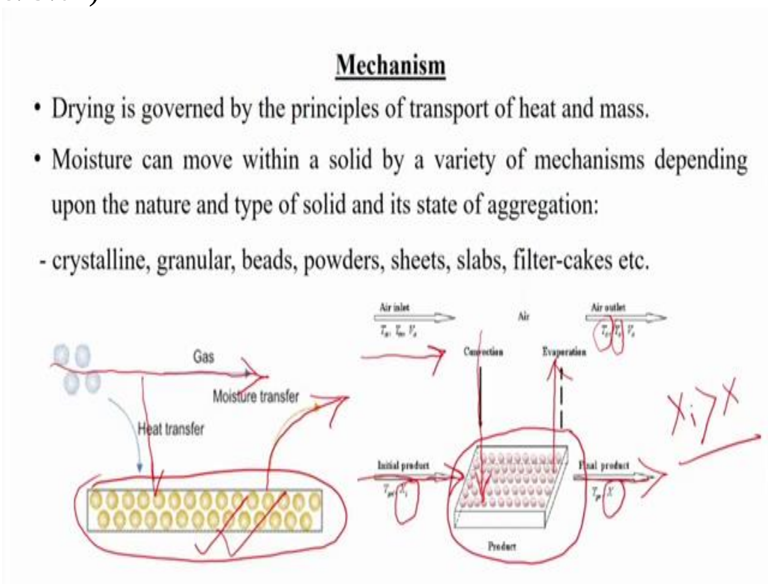

Now we will be discussing about the mechanism of drying process. So drying is governed by the principles of transport of heat and mass that is just like we can say this one humidification operation and dehumidification operation or we can say it is another example of simultaneous heat and mass transfer process. And this moisture can move within a solid by variety of the mechanisms depending upon the nature and type of the solid and its state of the aggregation.

So we will be discussing in detail about the different mechanisms they are there for the drying of different products. Like it is entirely dependent on crystallinity of the material whether it is a granular whether it is a powered material whether it is a bead or whether it is a slit or whether it is a slab or we can say whether it is a filter cake like this. So it is entirely dependent on so many other parameters, also we will be discussing the porosity, pore size distribution everything actually. This one, how the drying mechanism will take place.

So many parameters control the drying process also. Like here schematically it is shown that it is the wet material placed in a tray like this and this hot air is entering and it is actually flown. Then we can say this heat will be transferred from this hot air to the wet solid and then moisture will be transferred through this from the solid body to the gas and then the whatever wet material was there in the beginning it will be converting into the relatively dried products.

Like here actually say this schematically it is shown say one particular product actually we want to get this one, it is placed in a tray and say air is entering with this temperature like TA i that is we can say the initial temperature with the humidity Yi and air velocity is as VA and then due to this convection convective heat transfer, so heat will be transferred from this hot air to this wet solid and this evaporation will take place. Here, actually we have shown that only convection but you see conduction and radiation these also will take place and then say we will be discussing in detail about that the mode of heat transfers from the hot air or heating medium.

It may be direct contact, it may be the indirect contact, we will be discussing in detail and then due this evaporation humidity of air will increase suppose from YA i to YA out and say temperature will decrease. Definitely these temperatures would decrease from TA i to TA O and velocity is assumed as the constant because this is this one devoid of this water vapor. So this we can say this one initial product is entering and then final product is exiting. And if we say this moisture content in the beginning in the initial product is X i and whenever it will be coming from this product that at any time it will be just like X. So that is we can say this one moisture content will definitely decrease from X i to X o. We can say X i will be greater than X because our target is to remove this water vapor is called initial material. And we will be getting relatively less moist solid.

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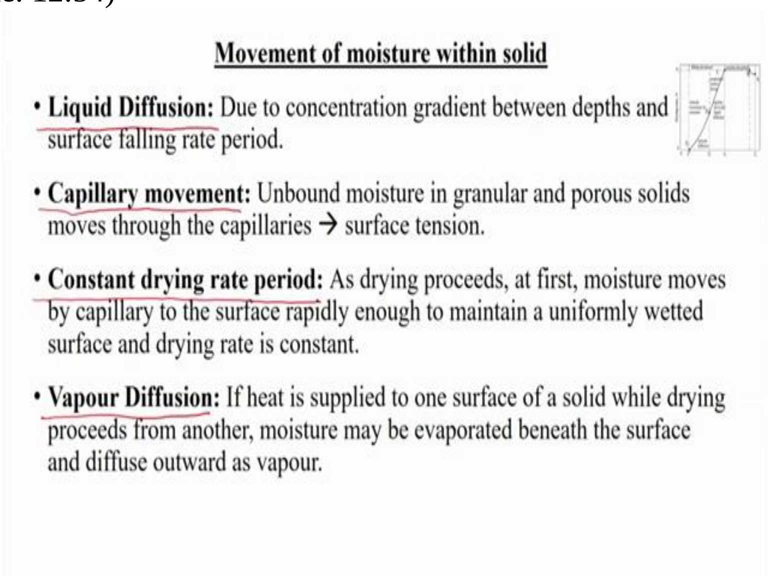

Now we say we will be discussing detail about the movement of the moisture within the solid. So there are four different ways of these we can say this one movement of the moisture in the solid. We will be discussing all the we can say this one diffusion, all the movement mechanism from this wet solid this one and what are the conditions, prevailing conditions required for that type of movement also we will be discussing in detail. The first one is we can say this one this liquid diffusion.

That is due to this concentration gradient between the depth and the surface we can say one falling rate period is there, we can say this one that is liquid diffusion or say we can say this in the beginning we have this wet solid with this huge amount of moisture content and we are applying this heat this one on the wet surface of the wet material and then due to this liquid diffusion from the interior of the solid the we can say water will be vaporized from the top surface of the solid material. So this is we can say it is only due to liquid diffusion.

Ok. Then the second one is called this capillary movement. So whenever we have this unbound moisture in granular or porous solids actually that will move through capillaries. We can say due to the surface tension this water from the interior of this wet solid will be coming out. That is only we can see this one unbound moisture will be dried during and then it will be coming due to this capillary movement. Then we can say this one whenever we will be discussing about the constant drying rate period we will be discussing also in detail about this constant drying rate period what is that say we can see this one as the drying proceeds at first we can see this moisture moves by capillary to the surface rapidly enough to maintain uniformly wetted surface and drying rate remains constant.

So we can say this one say whenever we have a huge amount of moisture content inside this solid so we can say this one moisture will be moving by the capillary to the surface very easily and as we know that this evaporation we can say this it is entirely depend on the surface area from where it is evaporating. So we can say this one in the beginning the wet solid it will not quench also or we can say this one remain as such for a long period of time. So in that condition or in the initial condition this surface area will remain constant and the amount of water also inside this material also will be very high, that is why it will be coming very easily through this capillary and then we can say this one drying rate will be simply proportional to the surface area.

Because this amount of moisture will be very high that is why it will not control the how fast the drying rate will be or how slow will be, so that we can say constant drying rate period. And in fourth the mechanism is like this we can say this one vapor diffusion, so if heat is supplied to one surface of a solid while drying proceeds from another surface then moisture may be evaporated beneath the surface and diffuse outward as vapors. So that we can say this one that is called say vapor diffusion. so that is we can say in one side we are supplying heat and from the another side we can say this one vapor will be the say this one coming out. So in that case we can say vapor diffusion will take place. We will be discussing this also.

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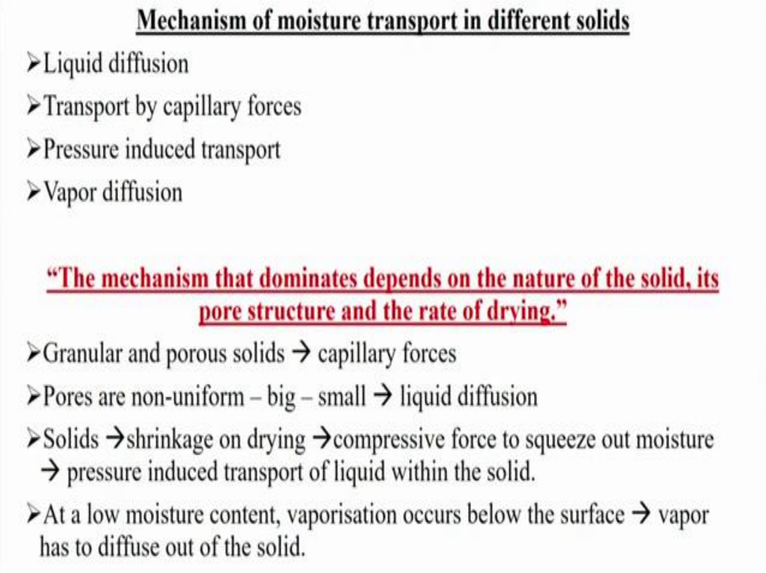

Now see this if we summarize the mechanism of moisture transport in different solids, so we have this suppose one is the liquid diffusion that we can say this one liquid will be coming from this interior of the solid to the exterior of the solid or top surface of the solid as liquid and then from there it will be evaporated. Then we can say this one transport by this capillary forces also, so in some cases we will also show you that say through the capillary the this one water will be transported and it will be vaporized from the top surface. Then pressure induced transport, so we can say this one whenever we will be talking about the constant drying rate period there we will be discussing that say the water vapor will be transporting this one from the interior to the top surface due to this only the partial pressure gradient of this water vapor this one inside this wet material and the exterior of the wet material.

And the fourth one that is the vapor diffusion that we discussed now, that say if heat is supplied from one side and vapor is coming out from another side. But you see we need to remember that on the mechanism that dominates depend on the nature of the solid, its pore structure and the rate of trying. So this is we can say we need to remember this one like we say we can say this one granular and porous solids, the capillary forces will be the guiding transport mechanism. If we say the pores are non-uniform, maybe big, may be small or like these, then we can say there is a liquid diffusion will be the controlling mechanism.

Suppose solids are then it will shrinkage during this drying process then compressive force will be there to squeeze out the moisture from the interior to the exterior surface. Then that we say this one pressure induced transport of the liquid within the solid like this and that low moisture content suppose this drying process is going on, then we can say this one water vapor content inside the solid actually is decreasing, then vaporization occurs below the surface then vapor has to diffuse out of the solid like this. So these are the different we can say this one examples of the different mechanisms in the drying process as well as we this we can say drying materials.

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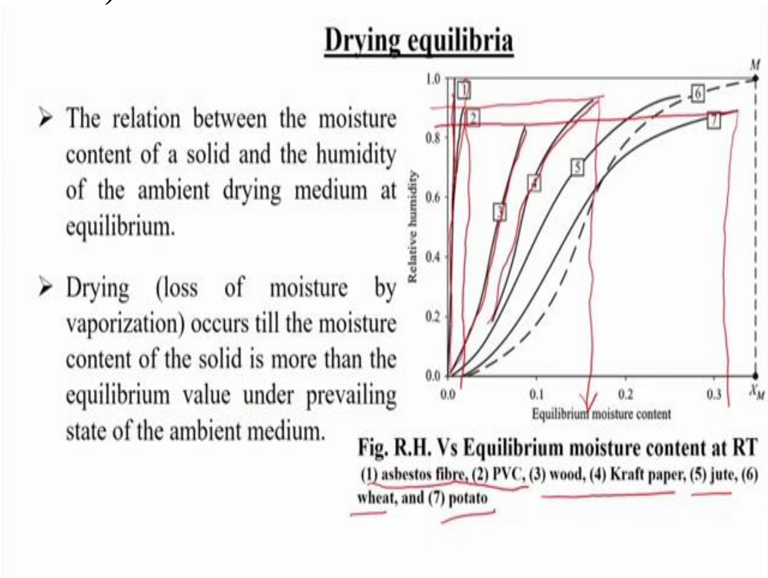

Now we see this one another important term we need to understand that, that is drying equilibria. So we can say this one this is nothing but the equilibrium, this relationship between the moisture content of the solid and the humidity of the ambient drying medium at the equilibrium that is we can say this one drying equilibria.

In the figure if we see the minutely we will find that for asbestos fiber and for PVC, this relative humidity is steeper actually we can say this one for both the cases like this with the equilibrium moisture content. So in the asbestos fiber and PVC we can say this only equilibrium moisture content is very less. So we will be discussing about what is the real meaning of equilibrium moisture content will be discussed in detail. That is equilibrium moisture content means this one in a particular operating condition we can say if we say the temperature or pressure, then relative humidity, then how much amount of moisture will be there inside this solid that cannot be separated by any of the conventional drying process. So that actually is called equilibrium moisture content.

So for we can say this one for asbestos fiber and for PVC the equilibrium moisture content is very less, it is we can say this one 0.001 like this kg dry solid like this. So whenever we will be talking about this wood and craft paper, say this one say equilibrium moisture content actually is increasing gradually with relative humidity. So, we can say this one if we go on increasing the relative humidity of the drying medium, so equilibrium moisture content will go on increasing. So in case of this craft paper you will see this one for a relative humidity of 0.9 like this, so the moisture equilibrium moisture content will be like 0.1, 0.18 or like this equilibrium moisture per kg per kg dry air. But for different jute this one fibers and we can say this one for the wheat also, there are we can say this one whenever we have this more relative humidity then moisture content also equilibrium moisture content value is also very high.

In case of this potato you see this one relative humidity values are we can say this one around 0.32 like this whenever this relative humidity is around 0.85 like this. So we need to know the relationship with the equilibrium moisture content for a particular wet solid drying. So, we need this prior information or relationship between the equilibrium moisture content and the relative humidity to get the drying characteristics. So, we will be discussing that say for time calculation or what type of drying actually is taking place for that type of calculation we need the relative humidity versus equilibrium moisture content relationship. So drying means so we can say the loss of the moisture by the vaporization occur till the moisture content of the solid is more than the equilibrium value under the prevailing state of the ambient medium.

So this whenever we will be talking about this medium or drying medium what is the this one ambient condition means what is the flow rate, what is the humidity, what is the temperature, so all the parameters will control the equilibrium moisture content.

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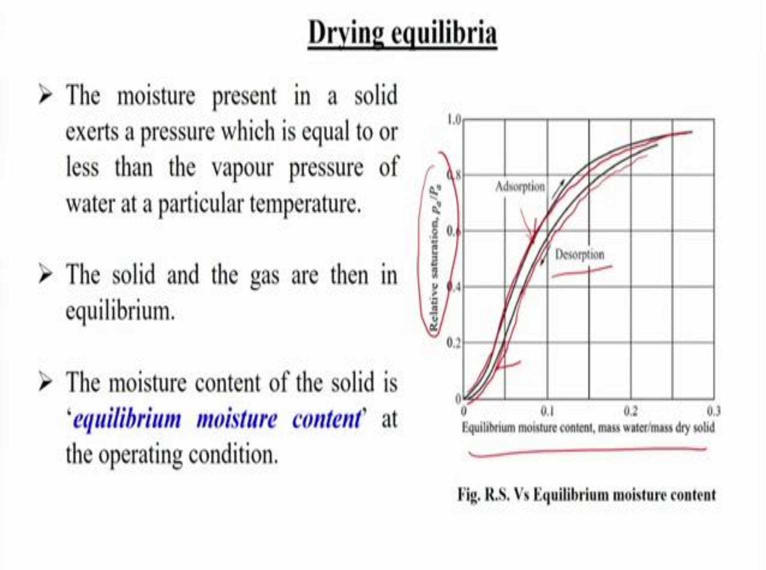

Now the moisture present in the solid exerts pressure which is equal to or less than the vapor pressure of the water at a particular temperature, that will be we can say this one will be separated only. So, if we say this one say adjacent process that is with this relative saturation, this we can see the equilibrium moisture content, the adjacent means we can say this one addition of water here in the dry solid like this. So if we increase the relative saturation of the ambient this one atmosphere, then we can say this one water will be absorbed and we can say this one it will become moist, so it will follow this route like this. But whenever we will be talking about drying process that is our desolation process actually, we say this one if we just decrease this relative saturation and then we can say this one equilibrium moisture content will go on decreasing.

So here actually we see this one whenever this equilibrium moisture content will decrease means desorption, we are this one trying to equilibrate this one with the adjacent as the humidification operation and desorption as the drying operation, so this is we can say desorption is nothing but the drying operation. And the solid and the gas are then in equilibrium we can say this one whenever this drying process is in equilibrium. The moisture content of the solid is equilibrium moisture content at the operating condition. So we will be discussing that also in detail about this critical moisture or equilibrium moisture. Those actually we need to understand those terminologies.

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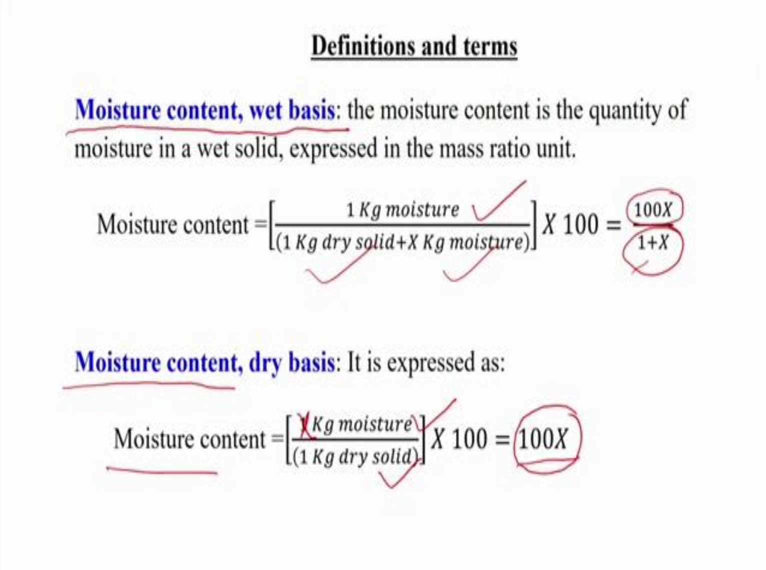

Now we should learn the some typical terms. The first term is that we can say this one, moisture content. So that is we can say this one we have, either we need do it express this moisture content in the wet basis or we need to express the moisture content in the dry basis. In wet basis the moisture content is a quantity of the moisture in a wet solid expressed in the mass ratio unit like this, so moisture content will be 1 kg moisture divided by 1 kg dry solid plus X kg moisture. So we can say in 200 percentage then it is 100 X divided by 1 plus X.

This 1 is this 1 kg dry solid and X is the X kg moisture. Ok. But whenever we will be discussing about this moisture content in the dry basis, so it is expressed as the moisture content like this 1 kg moisture per 1 kg dry solid into 100. So we can say this one, this 100X, divided by 1 means 100X. So that is we can say the dry basis, here this whenever the drying process will be taking place, how much drying is taking place in a wet solid? So this moisture content will remain constant. We can say this one moisture content if we express this one on dry basis, so moisture content in we can say this one wet solid or dry solid will remain always constant. Because you see this one for 1 kg dry solid how much amount of this we can say this one how much amount moisture actually is there.

So this is actually X kg moisture actually is there, X kg moisture per 1 kg dry solid. So X kg moisture means that is the total amount of moisture present there. And we can say this one that is why it is always 100 X. So it will not change for any type of we can say drying operation.

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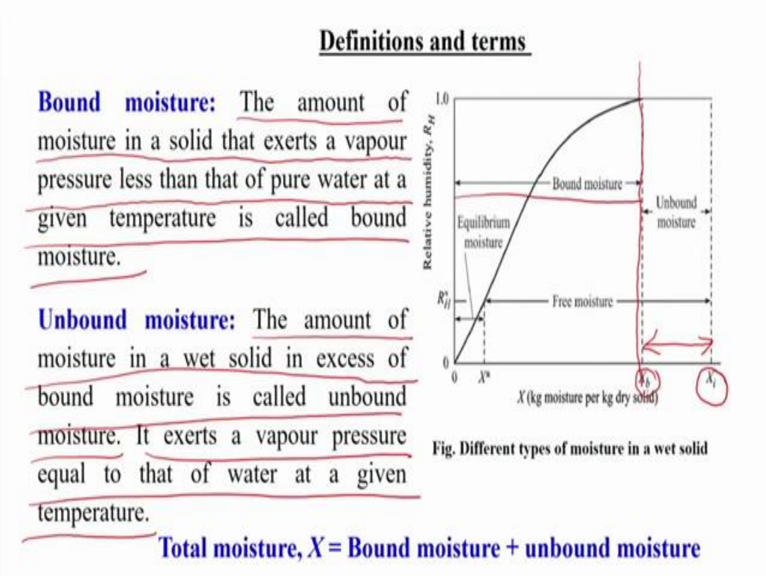

Now there are four different types moisture also we will be discussing. First one it is called bound moisture. So this bound moisture is that we can say this one the amount of moisture in a wet solid actually that exerts a vapor pressure less than that of the pure water at given temperature is called the bound moisture. So if we say this one in the relative humidity versus moisture contents, so we can say this one when we say this amount of the moisture suppose this X be amount, this moisture, this X we can say this one bound moisture. So we can say this one that this amount of the moisture that is present inside this wet solid that exerts vapor pressure less than that of the pure water. Means, we can see this one vapor pressure of the pure water at that particular temperature and pressure.

So that is we can say the bound moisture or in other words we can say this one in a wet solid the amount of moisture that would remain bound with the solid material and that cannot be separated easily or we can say this one if we keep it as such that cannot be separated. Then unbound moisture that is definitely we can say this one the total moisture content minus this bound moisture will give you the unbound moisture. So that is we can say this one the amount of moisture in wet solid in excess of the bound moisture is called the unbound moisture but it exerts a vapor pressure equal to that of the water in the given temperature and pressure.

So in that case we can say this one whenever we will be talking about this unbound moisture, this is we can say this one, the amount of excess this one of the total moisture that is we can say this one, this X i that is actually we can say this one initial moisture content but this difference actually is giving, if we say the total moisture content minus this bound moisture, then we will be getting the unbound moisture. So if the unbound moisture means we can say that is in equilibrium we can say this one the water vapor, vapor pressure of the we can say this one moisture that present inside the solid material and at that particular temperature what is the vapor pressure, both will remain same.

So that is we can say this unbound moisture it will be separated in the particular condition without any we can say this one help of this any drying medium. So that amount of moisture that is unbound moisture if we can say the vapor pressure of this water vapor at that particular temperature pressure becomes equal to the vapor pressure of this water which is present inside this wet solid will become equal, then we can say this one the amount of moisture, this excess amount of moisture over bound moisture will be regarded as this unbound moisture.

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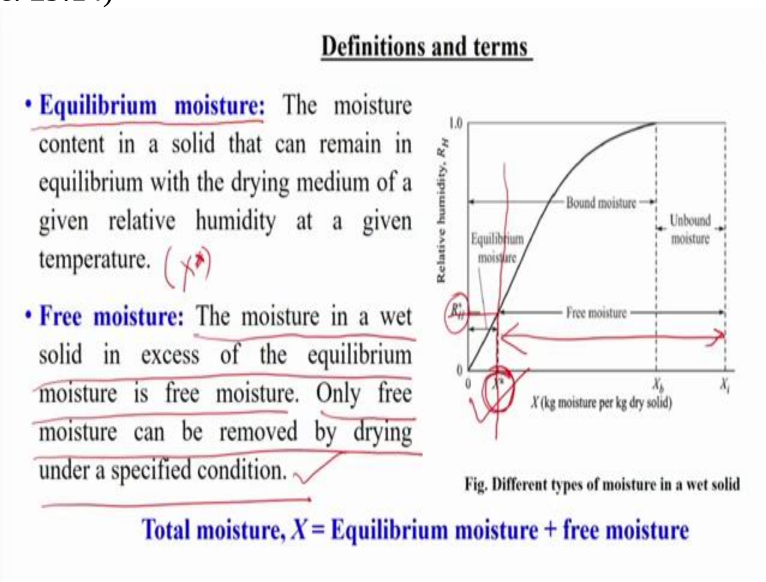

Now the another moisture that we already discussed this one equilibrium moisture, so the moisture content in a solid that can remain in equilibrium with the drying medium of a given relative humidity at a given temperature, so that is we can say this one equilibrium moisture. Let us take one example like this. That condition actually in the beginning also we told that the equilibrium moisture content is not a fixed quantity, so it will be varying with this condition of the drying medium. Let us take, this is the equilibrium moisture content like this, the pressure, temperature, flow rate and relative humidity this one of one particular say drying medium is like this RH is this one and then so we can say this one the moisture content that will remain actually in equilibrium with a drying medium.

So whenever we will be drying that any wet solid because we will be maintaining one drying condition, so in that drying condition whatever the moisture content the minimum amount of moisture content that will remain inside this drying solid, that we can say this one as the equilibrium moisture. So if we change the condition of this drying medium means if we decrease the relative humidity or if we increase the flow rate or we can say this one if we increase the temperature of the drying medium then this X star or equilibrium moisture content, let us say equilibrium moisture content that is we can see this one this X star. So that will decrease, means if we increase this, if we decrease the relative humidity or if we increase the Reynolds number of the flowing air or we can say this one if we increase the temperature, then we can say this equilibrium moisture content will decrease.

And the free moisture, so here also we can say this one, free moisture also we can say the excess of the equilibrium moisture in the total moisture is called the free moisture like this. So the moisture in a wet solid actually in excess of the equilibrium moisture content is free moisture but in technical definition is only free moisture that can be removed by drying under a specified condition, means in particular temperature, pressure and the relative humidity of the drying medium and then we can say this one flow rate of the drying medium, in that condition which amount actually can be separated, so we can say this one free moisture can be separated from the drying process in a particular prevailing drying condition. That we always say this one, which moisture is separated during this drying process?

The answer is that, only the free moisture is separated during this drying processes and this one we can say equilibrium moisture cannot be separated by this drying process. Ok.

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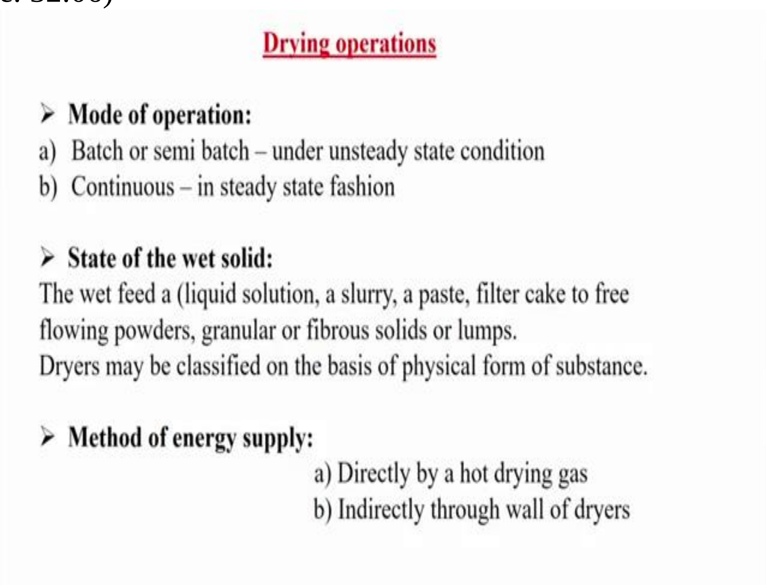

Now this, we will be discussing about the drying operations as a whole. So based on this we can say this one mode of operation we can say this one drying operation may be of two types; one would be the batch or semi-batch process and another one will be the continuous process, like this. Batch or semi-batch process means under unsteady state condition it will be like batch or a semi-batch process. But whenever it is continuous, then we can say these are the steady state fashion. Means, some wet solid is entering in the system and continuously this dry solid is removing the dryer or drying medium like this. And based on the state of the wet solid means so it is a whether it is a liquid solution, whether it is a slurry, whether it is a paste or whether it is a filter cake or it is a free flowing powder or it is granular or fibrous solid or it is a lump, so based on that also there are different types of drying operations are there.

And another one is that method of the energy supply, how this we can say this one drying process will be taking place? Whether directly we will be supplying this hot drying gas or we will be indirectly this one supplying this hot drying gas through the wall of the dryer? Means, from one side of this suppose drying medium we will be supplying heat and from the other side this evaporation of this water vapor will take place or this is indirect what is called power supply or energy supply to the drying medium.

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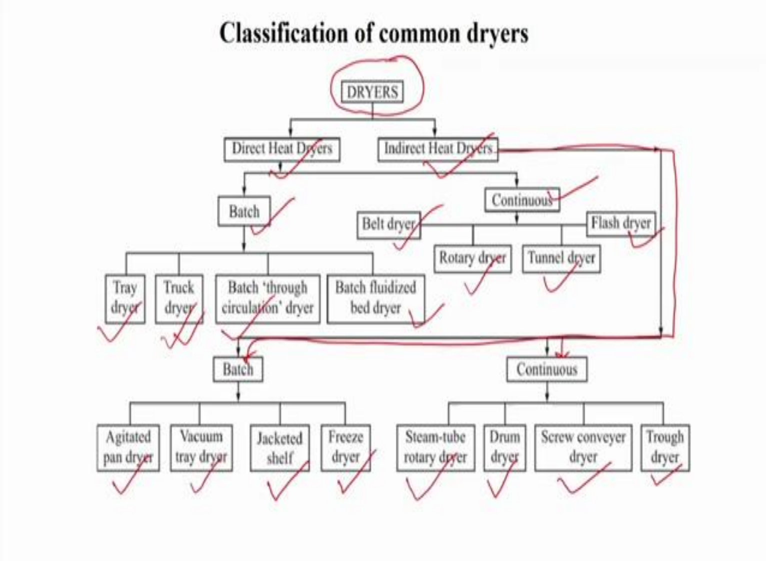

So here you see this, this is a general classification of dryer like this, so say firstly we can say this is direct heat dryer and indirect heat dryer. Say in the direct heat dryer we can say this one batch process is there then continuous process is there. In case of this batch dryers we have this tray dryer, tunnel dryer, truck dryer then we can say the batch through circulation dryer, then batch fluidized bed dryer.

In case of the continuous dryer we have this belt dryer and this flash dryer and as well as this rotary dryer and this tunnel dryer. So, ok so in case of this indirect heat dryer, say we have either batch drying process or continuous drying process. In batch drying we can say agitated pan dryer, then vacuum tray dryer, then jacketed shelf dryer, then freeze dryer. Then in case of the continuous drying process in the indirect heat drying, say steam-tube rotary dryer is there, then drum dryer is there, then screw conveyor is there and trough dryer also is there.

So out of these all the dryers are used for different drying operations, we will be discussing few dryers in detail out of these.

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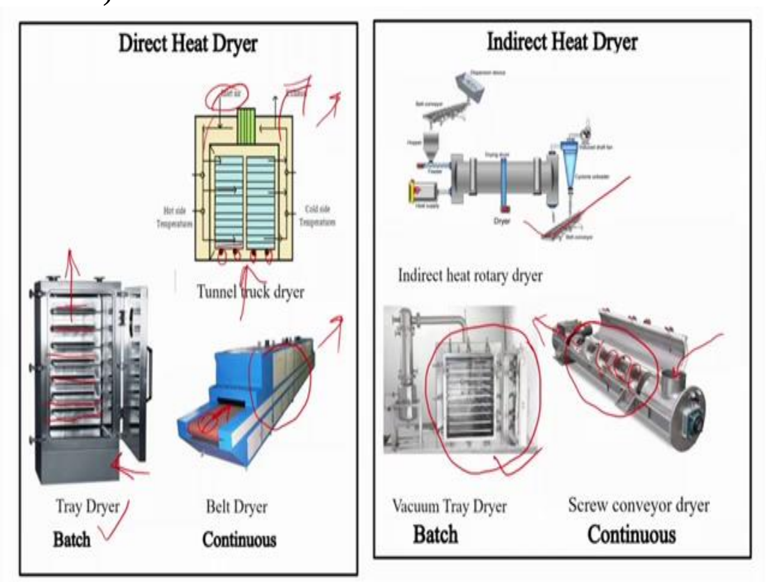

Like few dryers are like this, direct heat dryers we can say this one, one tray dryer is there, so trays are placed you see and heat is supplied from the either from this bottom and this one hot air will be blown and then moist air will be taken out from these top of this tray dryer and a belt dryer means this one say it is the hot chamber, so we can say this one belt will be rotating in this direction. Along with this belt this wet solid will be entering and then from the other side we can say this one dried products will be taken out. In tunnel truck dryer actually you say this one so many we can say this one different rails are there actually, so in the well different dryers will be entering. Inside this we can say this one drying chamber and then it will be coming out. So, we can say this one heat will supplied using this inlet air and from the exhaust we can say this one moist cold air actually will be taken out.

And then final product actually will be taken from through this we can say this one rail from other side of this dryer. And in case of indirect heat dryer we can say this one say one is that we can say the rotary dryer, so it is one of the dryers and vacuum tray dryer suppose the tray dryer is there but a vacuum is created and that is why we say at the low temperature and pressure this some drying also will take place in the batch process and screw conveyor like this, the screw itself will carry the wet solids especially for slurry type material. Suppose this slurry spread from this top and screw will be for conveying the wet solid and during this the chamber, the entire chamber will become hot. These relatively dried solids will be taken out from the other side of the screw conveyor dryer.

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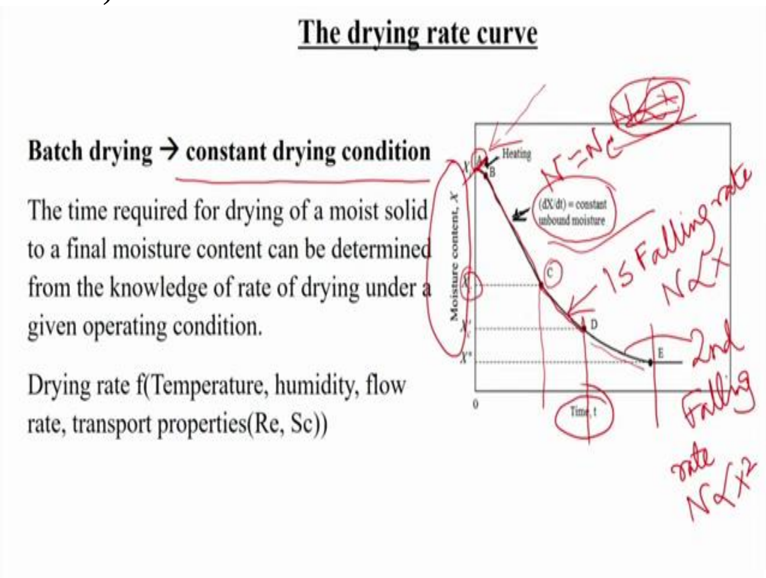

Now we will be discussing about the very important topic that is the we can say the drying rate curve. So we will be first discussing about the batch drying process then for the continuous drying process also we will be discussing but first, we will be discussing about the constant drying condition. It indicates that whatever the drying medium is supplied or is used to dry the wet solid it will remain constant or we can say this one temperature, humidity, flow rate and then suppose Reynolds number, Smith number of the drying medium will remain constant and at the same time also we can say this one the height of the drying medium or we can say this one amount of the material that will remain also constant.

So in that case we can say this one the time required for the drying of moist solid to a final moisture content can be determined from the knowledge of the rate of drying under a given operating condition, we will be discussing in detail about that. So that drying rate will be the function of temperature, humidity, flow rate and this Reynolds number and Smith number of the flowing medium or drying medium.

It does take this graph of this time versus we can say this moisture content. So, in the beginning we have this huge amount of moisture that is X i that is we say this 0.1, point A, so from here to B actually we can say this one when the heating started at the beginning when the heating started, so some initial adjustment takes place. And that is why we can say the moisture content decreases from A to B, a small decrease during this initial adjustment or we can say this one during heating process. Then there is one particular this one period of the drying that is from B to C we can say this one there dX, dt actually will be constant. That is we can say this from B to C where we can say this one only unbound moisture will be removed from this wet solid. And moisture content actually will be decreasing proportionately or linearly with this we can say this one if we say this one drying rate is and, that is we can say this is proportional to X.

So in that case we can say this one in the constant this one what is called drying rate period in general we can say this one, this one the drying rate actually will be may be proportional to that is proportional to the moisture content. So that it for constant we can say this one drying rate period. But from C to D we have this one we can say this first falling rate period. So in that case we can say this one moisture content say maybe this is called say critical moisture content. What is critical moisture content? We will be discussing this one in the constant drying rate period. At the end of this constant drying rate period whatever the moisture content of wet solid that is called critical moisture content. So around this C we can say this one to D that this first falling rate period, this is called the first falling rate period.

First Falling rate, there actually you see this one this N proportional to in most of the cases is proportional to X. Then we can say this one another one is this we can say this one second falling rate period is there, D to E, so that is we can say this one second falling rate. So second falling rate period there you see N is proportional to most of the cases it is proportional to the X square because that time this moisture content it becomes very less and that is why this rate will be proportional to X square. But for this one for constant drying rate period this N actually is equal to NC. Not this N proportional to X.

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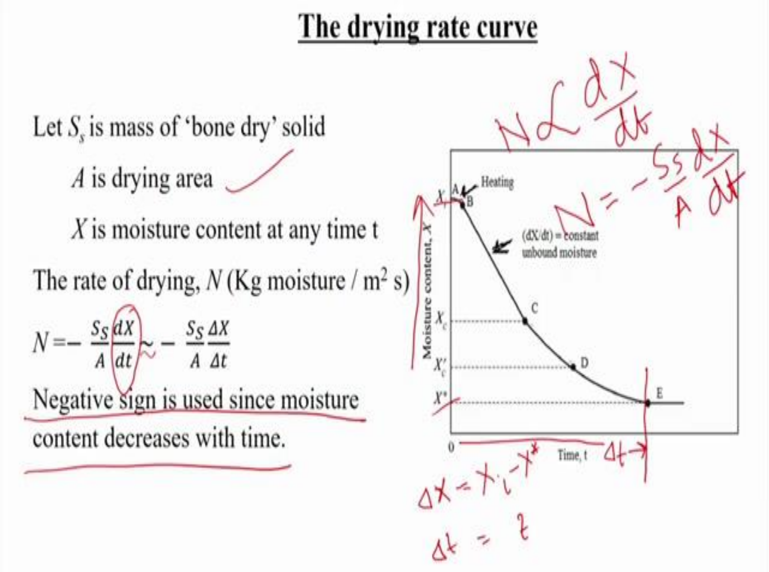

Now this let S s be the mass of this bone dry solid like this, so S s means we can say this one only dry solid is this one amount and A is the drying area that is we can say it is on top surface. That is I told that whenever it is a constant drying condition then we can say this A will not vary or A should not vary. But in reality A actually will go on decreasing because you see whenever the drying operation starts this after especially after this constant drying period over the some dry spots or we can say the hot spots appear and we can say this one and then this solid starts squeezing, so area decreases. So, we can say this one area will not remain constant but for the timing we can say this one we assume that A will remain constant throughout the drying process.

And X is the moisture content at any time like this, in this we can say this one we take this one as the moisture content, so rate of drying process N is proportional to, we can say this one proportional to the amount of dry bone solid and then we can say this one inversely proportional to the area and proportional to the we can say this one drying rate means that we can say this one change of the moisture content with time dX, dt. So, we can say this one N is equal to minus S s by A into dX, dt or simply we can say this one or almost equal to minus S s by A into dX delta X by Delta t.

So for if we start from X i and we reach this X star, so then Delta X will be like this, delta X will be this X i minus X star and delta T will be whatever the time actually we will be requiring from this to this. So, this is the total time, we can say this one Delta t will be this one. So we can say a negative sign is used since moisture content decreases with time, so that say why we have given this one or in general we can say this one, say rate is proportional to dX dt. Ok. From here actually say we have this N is equal to minus S s by A into dX dt.

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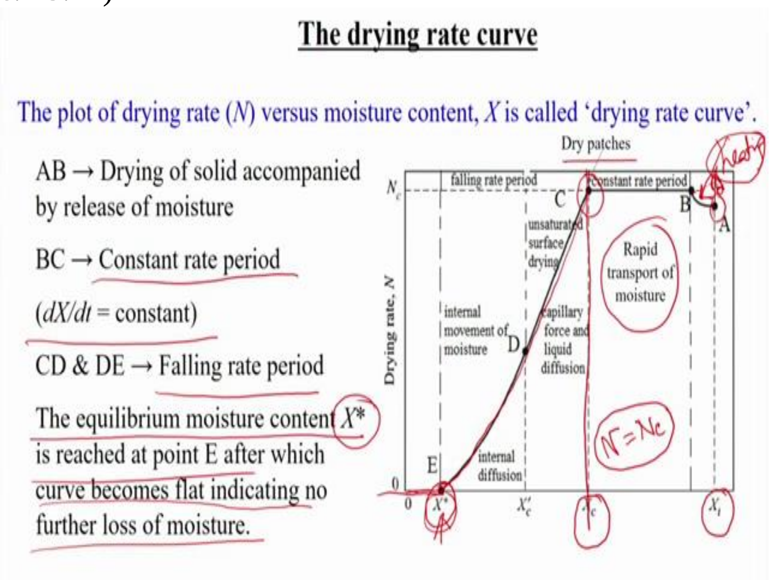

Now this plot of this drawing rate versus this moisture content, X is called the drying rate curve. We need to understand this drying rate curve very precisely because you see based on that we have all the calculations. For this drying rate curve actually we will start from the right hand side that we will start from this A. So this is the initially we can say this one this X i amount of we can say this moisture is there or X i amount of the water vapor is there inside this one.

And this one we have started this heating. So whenever we would do the heating sometimes you see drying rate increases but there are some instances where this drying rate decreases also. So, we can say this one sometimes this A prime also in there say means the drying rate in the beginning also sometimes may decrease depending on the material. So it may start from here also. Anyway this one this is called this heating of this, this one what is called wet solid or from this room temperature to this particular operating condition. This, it is coming from A to B. So A may be here or may be somewhere here also. Then you see this I told earlier also that in the beginning the huge amount of this one water vapor is there inside this wet solid, so rapid transport of the moisture will take place. That is why we can say this one from point B to point C it is called constant rate period that is we can say this one N has become NC.

So it will, it is we can say the time it is not dependent on the how much amount of moisture actually is there in the beginning, it is not this one controlling that and whenever it will be reaching a point, where we can say this one dry patches will actually will appear and then that time we can say this one rate will start falling. So the junction point this moisture content is called critical moisture. So that is we can say this one X C, so this AB we can say this one A to B we can say drying of solid accompanied by release of the moisture or due to this only heating or we can say this one, this is the initial adjustment.

From B to C we can say this one constant drying period that is dX is equal to dX, dt is equal to constant parameter. So it is whether the X i is very high or X i is very low it is not dependent on that. So in that case we can say this one drying rate will remain constant that is in as NC. But whenever the dry patches will appear we can say at the same time we can say this one moisture content inside the solid decreases, then we can say this one the falling rate actually starts. From C to D we can say this one we can say from C to D and from D to E, we can say this one these are called this falling rate period.

So the equilibrium moisture content, this X star we can say this one is reached at point E. So whenever we can say this one any wet solid reaches it X star then equilibrium moisture content then drying process stops. Then we can say this one drying becomes this drying rate becomes 0. So after that if you see this one X star will remain constant and then it will not change also. So if we can change the condition of the drying medium say in terms of we can say this relative humidity in terms of this temperature in terms of this Reynolds number, Smith number then we can say this one X star will decrease or increase depending on the situation. But you see whenever it will be reaching this X star equilibrium moisture content then we can say the drying process will be stopped.

So that is why we can say after that flat become the curve become flat indicating no further loss of the moisture. So, then X star actually there the drying process stops. So if we can keep this one for a long period of time, after this X star also, then there will be no drying only the heating of the dry solid or this one whatever the less wet solid will be there without any drying operation.

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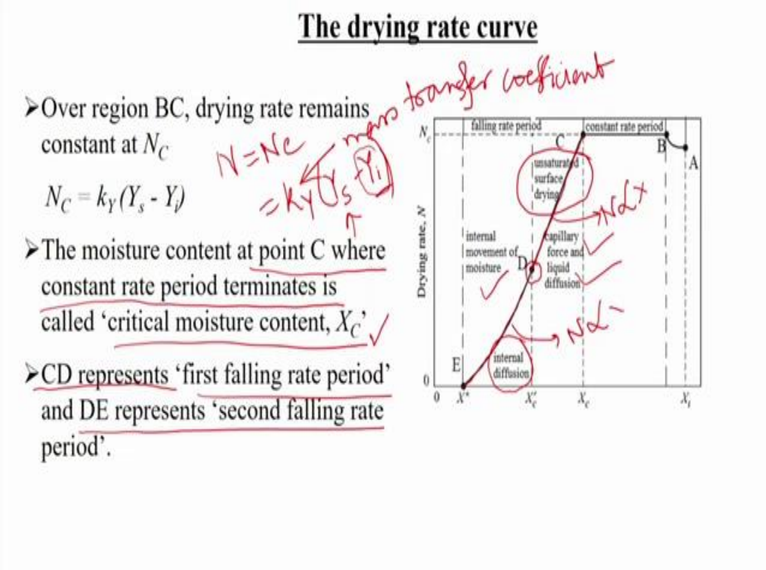

And over the region B to C we can say this one we told that this one N becomes actually NC. So, this N is equal to NC and in that case that is nothing but we can say this one K y into say Y s minus this Y i. Ok. So this Y s means in any time actually we can say this K y this we can say this one mass transfer coefficient. That is K y is equal to mass transfer coefficient and Y i is the initial, this one initial humidity and Y s is the we can say this one humidity at that we can say this one final condition. Ok.

So the moisture content at point C where the constant rate terminates is called the critical moisture content. So, critical moisture content means their constant drying rate period is over and then this one falling rate period starts. So CD represents the first falling rate period and D represents the second falling rate period. So this fast falling rate period DC, we can say it almost linear that is unsaturated surface drying takes place, there these both the capillary force as well as liquid diffusion will take place simultaneously.

But whenever it will be reaching this point D then we can say this one moisture content inside this wet solid actually decreases and then we told that in most other cases this from D to E in the second falling rate period this only internal diffusion takes place. And due to this internal movement of the moisture this drying rate decreases but here from C to D I told that this N in general is proportional to X, here N is proportional to X square.

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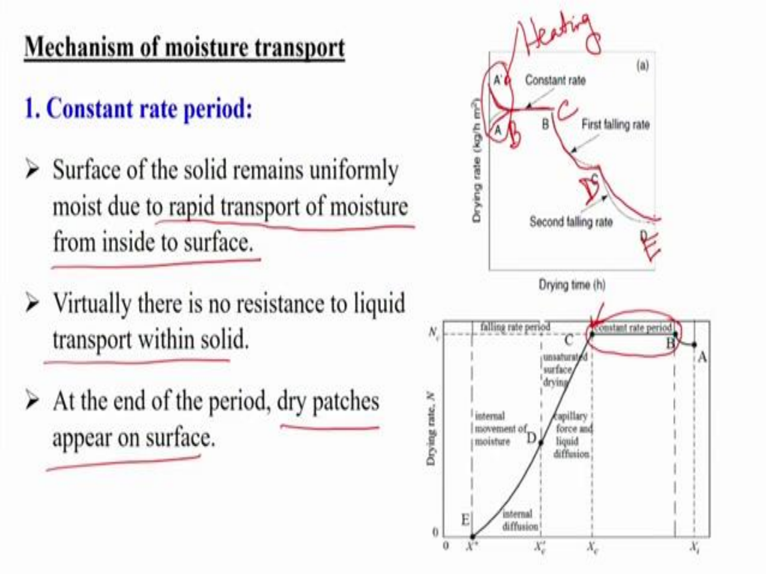

Now you see this in the constant rate period suppose in the constant drying rate period say from B to C we can say this surface of the solid remains uniformly moist due to the rapid transport of the moisture from inside to the top surface of the material. So in that case from B to C we can say this one this is constant drying rate period. And virtually there is no resistance to the fluid transport within the solid because this is huge amount of liquid is there, liquid water is there, that is why it will be coming and this one it will be evaporating from the top surface. So, it is as the surface is empty so we can say this one the drying rate will be constant. Like this so we can say this is NC.

At the end of this period we can say the dry patches I told that here actually dry patches actually will appear on the surface and small amount of the shrinkage of this one what is called the top surface also takes places. So we can say the constant drying period say from here to here I told that say from this point to this may be decreasing or sometimes the drying rate is increasing that is we can say this initial adjustment part I told, that only due to this heating, because you see this one first we need to heat the wet solid.

So due to this heating either drying rate decreases or sometimes drying rate increases also and then it will remain constant up to this. We are talking about this constant period say this one from B to C actually this is constant drying period and this is that is why we can say this one it is actually you can say this one B to C and then C to D actually this is first falling rate period and from D to E that we can say this one second falling rate period.

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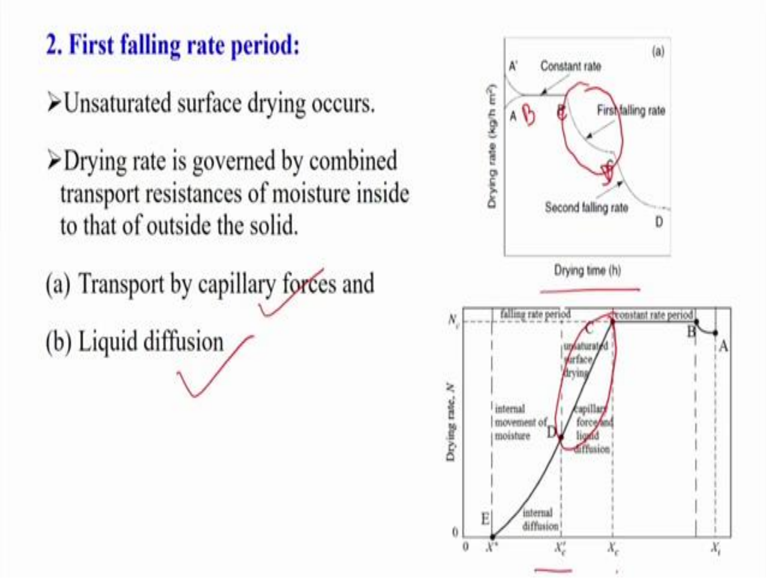

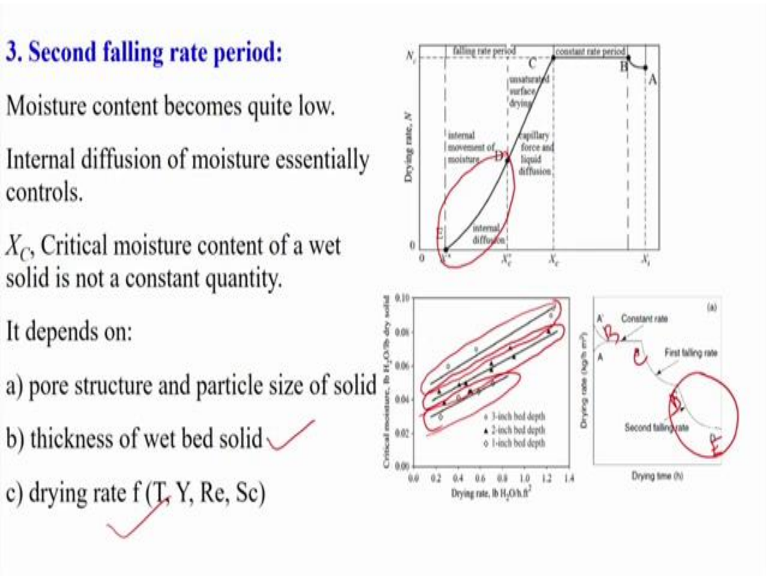

The first falling rate period say from C to D like this from if we say this is C, actually this is C to D, this is first falling rate period that is we can say unsaturated surface drying occurs. Drying rate is governed by this combined transport resistance of the moisture inside to that of the outside of the solid so that we can say this one in the first falling rate period and transport by capillary force and we can say this by liquid diffusion both will be taking place like capillary force as well as this liquid diffusion in the first falling rate period from D, C to D but here also we can say this one for first falling rate period. It is explained in terms of the drying time, it is expressed in terms of the moisture content.

Then for second falling rate period we can say this one now say if we talk about this portion say from D to E, here actually from this D to E that is we can say this one, so from in this period say moisture content becomes quite low and internal diffusion of the moisture essentially controls the drying process and the critical moisture content of wet solid is not constant quantity because I told that it is it can be vary for so many alteration of the different variables like this. Pore structure and particle size of this solid then we can say thickness of the wet bed say whenever the thickness of the wet bed suppose 1 inch this one wet bed has this lower critical moisture content, whenever it is 2 inch wet bed say it is increasing critical moisture content. For 3 inch wet bed again we can say that the critical moisture content also increases.

So, whenever we will be increasing the thickness of the wet bed the critical moisture content also will also be increasing, so that is the thickness or drying rate so we can say this one that is temperature, humidity, Reynolds number et cetera, depending on that also critical moisture content will be different.

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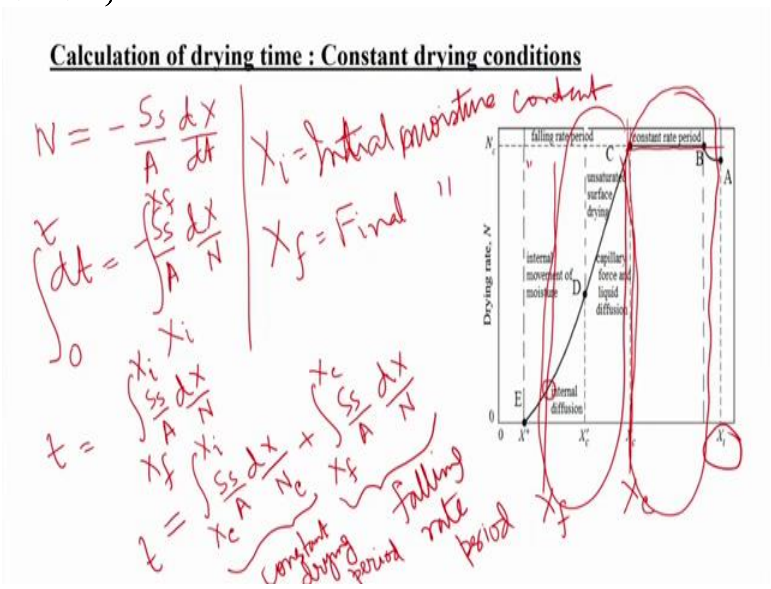

Now we will be doing the calculation. For the constant drying condition I told that is for the constant drying condition we need to maintain the same area, we can say this one humidity of the dry medium then we can say the Reynolds number, Smith number of the drying medium we need to keep constant. So in that case, this is a constant drying condition. For that we will we be getting the drying time for S, so we can say this one for batch drying process like this. So let us take this one for this example like this, we will be we know this one that N is equal to we can say this one S s this by A in to dX, dt.

Later we can say this one X i is the initial moisture content of the say there actually we will take that X i that is the initial moisture content. So this is the X i and we can say this one X f is the final moisture content. Final moisture content. Then we will be taking this one say, we will be rearranging like this from here say dt is equal to say let us take S s by A in to dX by N. Now we say we will be interrogating from time 0 to T, we will be integrating this one from suppose X i to X f. So we can say this T will be equal to, now we will be changing this limit from X f to X i into S s. S s by A dX by N. That will be equal to two different zones.

Let us take this X f is here. X f is somewhere here. So firstly it will be coming like this for the time being. We will start from here. So it is coming to this point. So this is we can say this one from X i to X c so it will be coming like this, so we can say this one so X i to X c, S s by A dX by N plus X f to X c, S s by A dX by N. So this one we can say this one total drying time will be like this. So this is we can say this one for constant drying period this is we can say this one for constant this is called constant drying period. This is we can say this one falling rate period.

So this total time will be like this say if we interrogate from X c to X i S s by A, dX by N plus S s by A dX by N, integrating from X f to X c. So now we have this one divided into these two different parts. Firstly, it will be drying for this zone and secondly we will be drying for this zone. Inside this we can say falling rate period we have this another this one maybe we have two different drying zones. We can say this first falling period then second falling that we can again we can do that manipulation also.

So drying rate will remain constant at N c, so we can say this one N c for this till X c. So this is we can say this one N c, so in that case we can say this one N will be converting into N c. So for that because X i to X c this drying rate will remain constant. Ok. Now say for first falling rate period and for second falling rate period we will be discussing.

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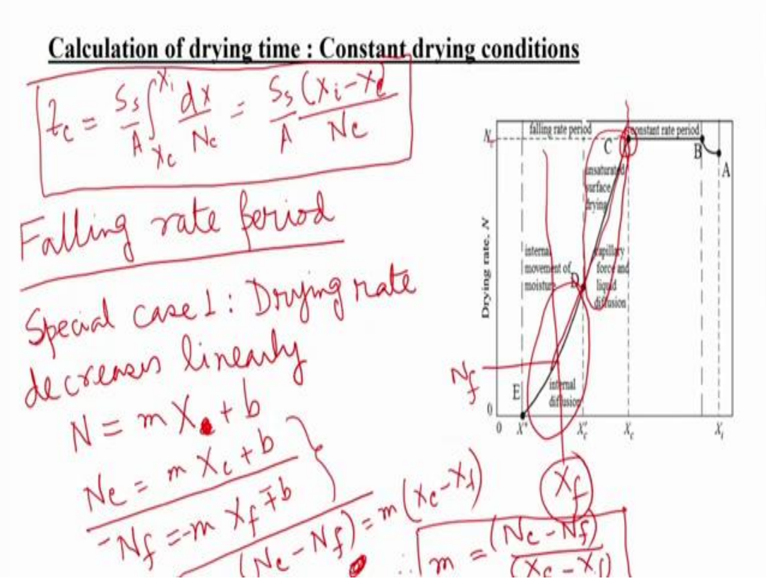

So you see this for constant drying period say we can say this one for t c whatever we have this one S s by A into say X c to X i dX into And c that will be equal to S s by A into X i minus X c by N c. So this is we can say this one t c will be equal to S s by A into X i minus X c by N c. Now we are more interested in the falling rate period. So there in falling rate period I told this in the beginning that for falling rate period say suppose say it is the fast falling rate period then it is the second falling rate period.

Let us take this is X f. In falling rate period so we will be taking this, we will be taking two conditions. Like these two cases actually we will be discussing suppose special case like the special case 1, so we will be taking that drying rate decreases linearly. Like we can say this one N will be like this proportional to X. So we will be taking at N is equal to suppose m X c plus b. We can take this one and in this point let us say in this point suppose let us say with the start of this falling rate period we can say this one, in that point actually say N c will be equal to m into X c plus b. And this is nothing. N is equal to m X plus b. So at constant drying when the constant drying rate stops and first falling rate starts there we can say this one N c is equal to m into X c plus b.

And say whenever it is X f that case I can say this one N f that is we can say this one, so in that case suppose this is N f and this is N c, so in that case it will be equal to m into X f plus b. And then we can say N c minus N f is equal to m c, m X c minus m X f minus this one b. So from these two equations we will be getting N c minus N f is equal to m in to X c minus X f or we can say this one m will be equal to N c minus N f by X c minus X f. So we can say this one slope of this linear, so we are assuming that it is entirely linear like this, so m will be the slope will be this one what is called in N c minus N f by X c minus X f. So we can say this one for falling rate period we can say this one….

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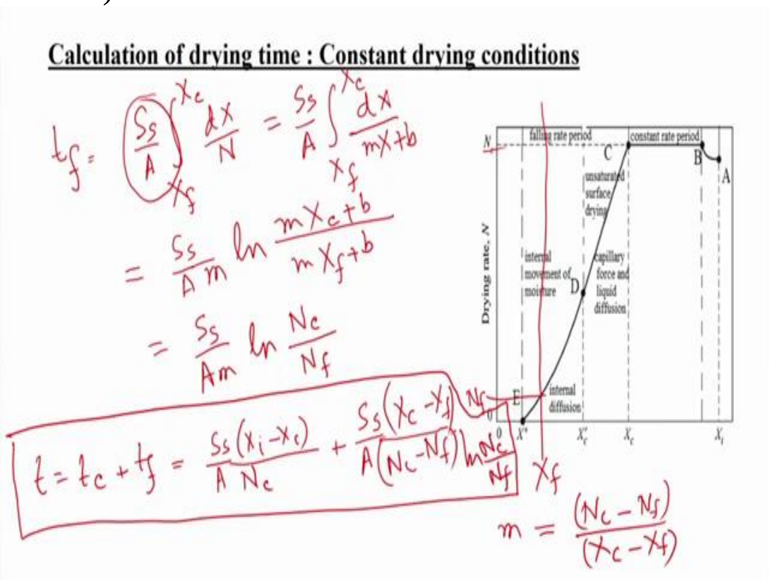

So for falling rate period this t f will be S s by A into X f to X c and dX by N. So there actually we have this in place of this we can say this N we will be writing this S s by A because we have excluded this one from the integration, these are constant this one parameter, then we will be integrating this one except to X c, dX by N is equal to m X plus b.

Now we will be putting this: Now we need to get this t f is equal to S s by A and then m also will be coming and then we can say this one m will be coming whenever we will be integrating this one, ln m X c plus b by m X f plus b. Ok. Now we have this in place of this m, we can put this one and also we can say this one whenever we will be talking about this, this is equal to S s by A into m into ln. That is nothing but N c by N f, whatever the N c is there or say for this X f we have this N f. Ok. Now we say for this condition, first condition when we assume that this drying rate, falling rate actually is linearly proportional to this moisture content then we can say this total time will be equal to we can say this one t c plus t f.

That is we can say this one S s by A into X i minus X c by A into N c plus S s by A. The m actually we find out as m is equal to in the this one just now we have found out that A is equal to N c minus N f by X c minus X f.

So we will be putting this one m is equal to N c minus N f into that is X c minus X f into ln, N c by N f. So this is the total time actually for we can say this one for the drying using this falling rate that is linearly falling. There is only linearly falling then we can say this total drying time will be S s by A into Xi minus X c by N c plus S s by A into this one X c minus X f by A N c minus N f into ln N c by N f. Ok.

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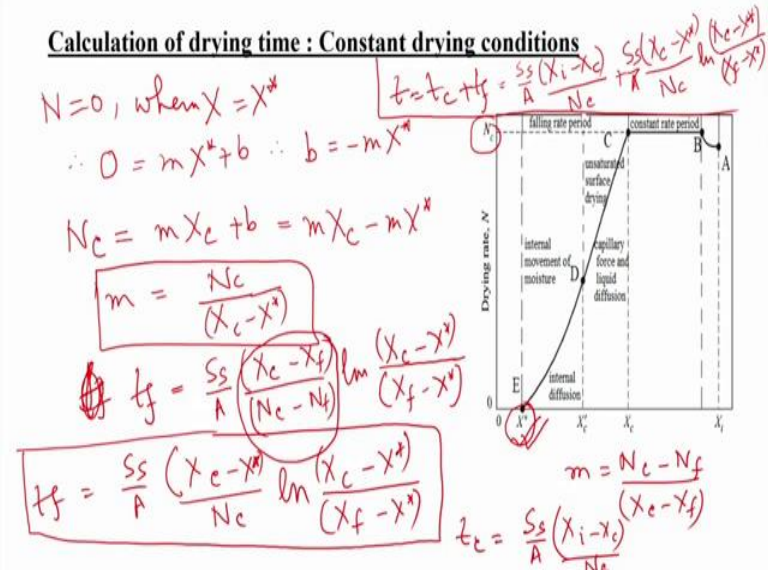

Now whenever it will be reaching this we can say this one X star whenever we have this X star then drying rate will be say we can say this one N will be zero. This one when this X will be X star. Whenever it will be reaching this equilibrium moisture content therefore we can say this one whatever the N is equal to m X plus c b, we have this one mentioned that will be N is equal to m we have into X star plus b. Or we can say this one from here we can say this one b is equal to minus m X star. Ok. And also we know that N c that is we can say this one critical this one what is called constant drying rate. But N c is equal to say we can say this one m into X c plus b. Ok.

So then we can do one thing, in place of b we will be placing this minus m X star. So m into X c minus m into X star. Ok. So from here we can say this one m is equal to N c by X c minus X star. So we have got again another relation. This one for m, is equal to N c by X c minus X star. So whenever we reach this X star or we say the equilibrium moisture content. Now we see this one this whatever the t f actually we have this one this for t for falling rate time t f that is we can say t f that is equal to say whatever the expression we have this one this S s by A into say X c minus X f by N c minus N f into ln say there ln we have this one ln N c by N f, just we will be putting that, N c by N f is equal to X c minus X star by we can say this one X f minus X star. Ok.

So there we will be putting this X c this here actually this X c minus X f by N c this one we have this, again m is equal to N c minus N f by X c minus X f. So we will be putting this one in place of this actually we will be putting 1 by m like this, so t f will be equal to S s by A into we can say this one X c minus X star by N c into ln, we can say X c minus X star divided by X f minus X star. Ok.

So here we have this t f is equal to this one, so whenever it is going up to X star, so we have this t f is equal to 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. So here we can say this one total this one drying time will be this t c whatever we have this t c is equal to again we know that t c is equal to we can say then we know S s by A into say X i minus X c by N c. So, we will be adding this t c and t f and we will be getting this total time is equal to S s by A into X i minus X c by N c plus 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. So we can say for this we can say total time is equal to t c plus t f is equal to S s by A, X i minus X c by N c plus 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. So this is we can say this one total drying time will be like this. Ok.

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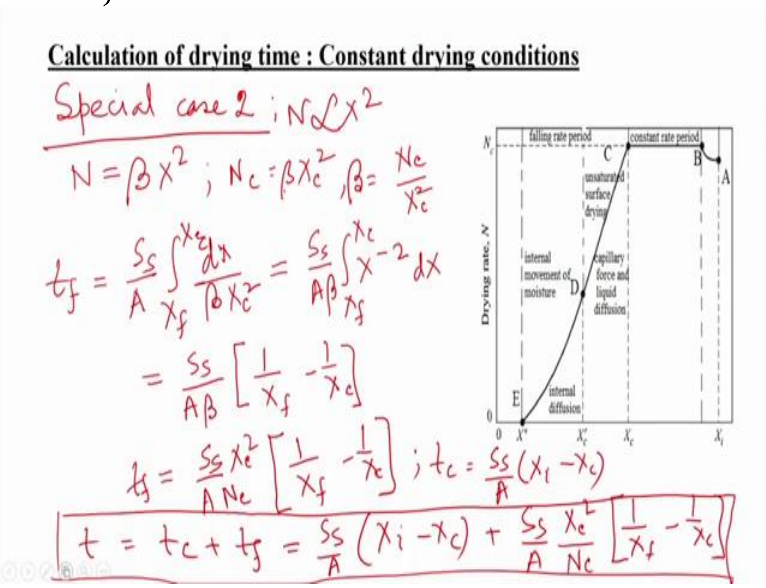

Now you see this one another case actually we discussed this one that for special case II. Special Case II, we can say we told that N is each proportional to say X Square. Like this we can say this one m will be equal to say beta into X square. Ok. Then we can say this one N c will be say beta into X c square. Ok. And then we can say this one beta is equal to we can say this N c by X c square. In that case equal to t f will be like this, falling rate period whatever the expression we have obtained for the case I, we will be putting this beta value there. That is like S s by A. So we will be putting this one say X f to X c say dX by, so we can say this one N c is equal to we can say this one beta into X c square.

That is we can say this ultimately we will be getting S s by A integration X f to this is X c, X c into beta also will be taken out this one what we can say this one will be keeping this one here that is beta here. Beta here X to the power minus 2 into dX. Ok. So then we will be getting this one is equal to S s by A into beta into say we can say this one this is 1 by say X f minus 1 by X c. Ok.

So that will be we can say this one that is beta we can put here like this S s by A. Beta is equal to this N c into X c square and then 1 by X f minus 1 by X c. Ok. So this is t f. And again we know that t c that is we know that S s by A into X i minus X c so total time will be equal to say t c plus t f is equal to we can say this S s by A into X i minus X c plus S s by A into X c square by N c and into 1 by X f minus 1 by X c. So this is the total time actually if we say that it is linearly decreasing. In the falling rate period suppose it is linearly decreasing, so in that case we can say this one the total drying time will be t c plus t f, S s by A into X i minus X c plus S s by A X c square by N c into 1 by X f minus 1 by X c. Ok.

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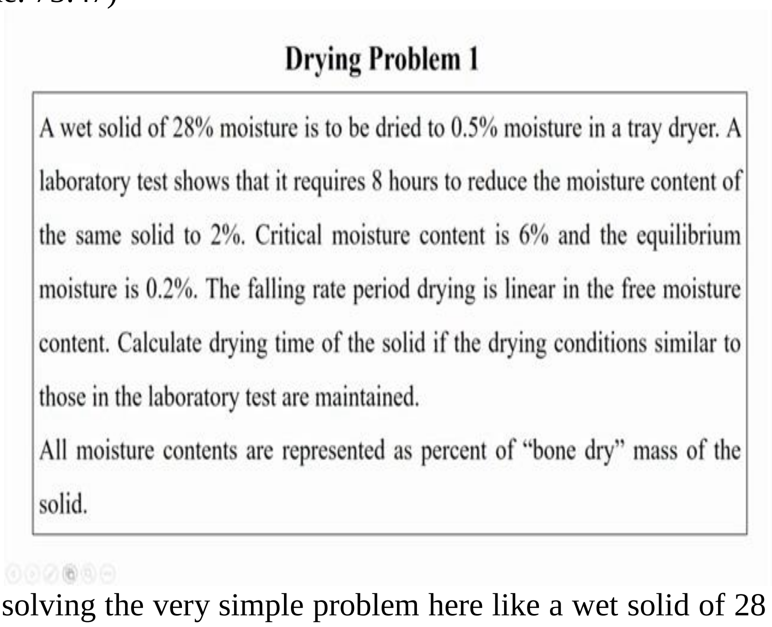

Now we will be solving the very simple problem here like a wet solid of 28 percent moisture is to be dried to 0.5 percent moisture in a tray dryer. Our laboratory test shows that it requires 8 hours to reduce the moisture content of the same solid to 22 percent. Critical moisture content is 6 percent and the equilibrium moisture is 0.2 percent. The falling rate period is linear means this one it is N proportional to N only in the free moisture content and calculating the dry time of the solid if the drying conditions similar to those in the laboratory test are maintained.

All moisture content are the representative of the percent of bone dry, it is at dry basis of the solid. So this is very simple problem, just we need to gather the information only, from there we will be getting the total what is the total drying time.

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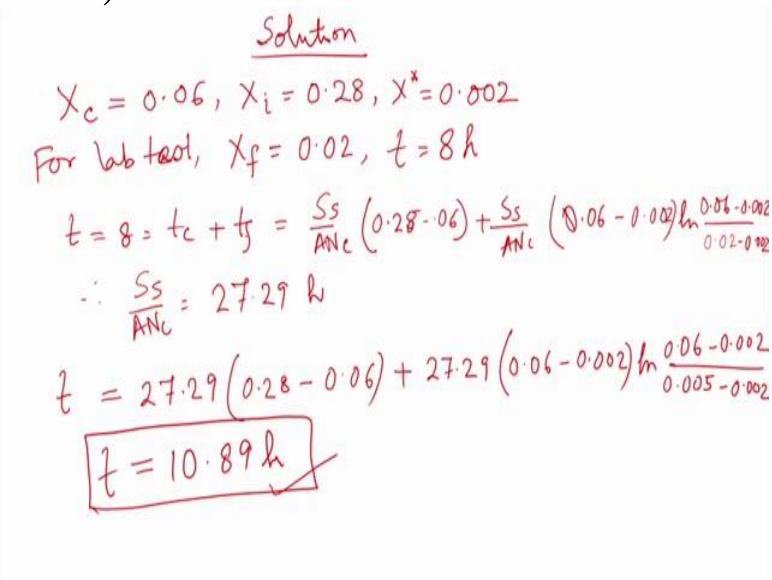

Like say for solving this one very easily we can write this one. Say for the solution we have this we need to write only what is these values actually. X c is equal to 0.06, then X i is equal to say whatever the initial moisture content 28 percent that is 0.28. And whatever the equilibrium moisture content that is given as 0.02 percent. Like this 0.002 and for laboratory test actually we can say this for lab test X f is given as this final moisture content is given as 0.02. And time is given as 8 hours. Because this is required to get S s by A, so these hints are required actually to get S s by A into N c also. Because that constant drying rate actually is not also given in this condition.

So whatever the lab test actually is given from there we will be trying to say total t is equal to 8 is equal to t c plus t f is equal to say whatever we know this one S s by A into N c, then what is called this X i minus X c that is we can say this one 0.28 minus 0.06 plus S s by A into N c into 0.06 minus equilibrium. This one 0.002 into ln say we can say this one X c 0.06 minus X star that is 0.002 divided by 0.02 minus 0.002.

So from here actually we will be getting just S s by A into N c that will be 27.29 hour. Ok. Now you see this time required to dry tools, we need to get this total time required to dry time required t is equal to say we can say this one S s by A into N c. Now, we have this 27.29 into

X i that is we can say this one 0.28 minus 0.06 X c plus S s by A into N c this 27.29 into we can say this one 0.06 minus 0.002, then ln 0.06 minus 0.002 divided by 0.005 minus 0.002. So that is coming out to be as 10.89 hours. So this is the we can say this is the total time required to dry this one what is called wet solid because in this case we have this the total drying condition is similar to that of the laboratory condition.

Hence, total 10.89 hour is required to dry this, whereas, it took only eight hours for that condition.

So in the next class we will be discussing about the rate of drying for batch dryers.

Thank you.