Mass Transfer II

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Lecture No. # 35

So, today's lecture, we take up the last unit operation of this course drying alright. So, so far, we had absorption, then we started with distillation, extraction, absorption, and now, we have taken this drying here. So, when we say drying by this unit operation, we mean we have a substance, a solid or could be liquid, and we want to remove moisture out of it. So, we have to supply a heat all right, and then remove moisture to make this substance deplete with the moisture all right. For this course, what we do here? We try to we try to distribute the course contents: first is like we will go through the introductions, some examples all right. Then, we will talk about the characteristics of this drying, and it is very typical of different substances, certain solids will exhibit different type of drying characteristics.

So, one has to do this experiment or a batch experiment for that type of solid, and that type of operating conditions. In other words, if you are trying to scale from a lab to very large scales, some industrial reactor or dryer here. Then one has to ensure that we are having similar operating conditions. So, we will talk about those then, then we will setup the governing equations how long will it take to dry a solid, and batch if you have a continue process, how much is the length require to achieve that, (( )) much of separation here

So, again as we said earlier that drying for this course, for this unit operations. Now, we are restricted, now we are restricting our discussion to drying of a solid which is soap with water. We can have different type of inorganics, we can have organics sometimes we have say benzene all right. So, benzene is a vapor, and it has moisture or water, and then we give heat, then moisture can also be removed by benzene. So, now that is not drying we are interested here, absorptions we discussed, we had a very extensive discussion on absorptions. We have a flue gas or we can have aquas water, we bring in contact with the solid charcoals, and then the solute is transferred from water or from the aquas system or from the gas system to the solid here. So, that is also not drying that is a specifically absorptions.

We will see here, that a certain steps of absorption, desorptions, they also take place in drying very similar, but all right, but otherwise what we mean here is we have to give a supply, we have to give a heat to the solid, which is soap with moisture. And we remove this moisture by certain driving force say partial pressure at the surface, and the partial pressure in atmosphere in the drying air. So, with that introductions let us start this topic here, and let us make a note of few salient points here.

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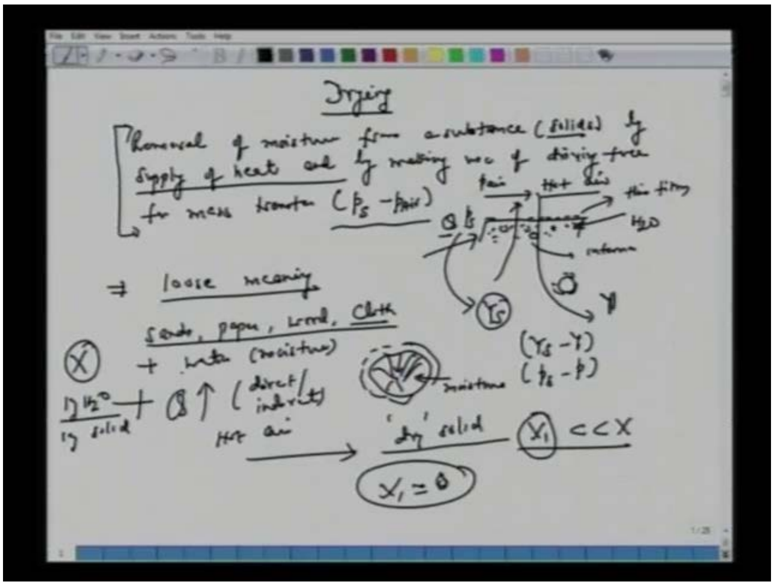

Drying

Removal of moisture from a substance (solids) by supply of heat and by making use of driving force for mass transfer ($p_s - p_{air}$)

⇒ loose meaning

sands, paper, wood, cloth + water (moisture)

So, here we have this drying, this is the last unit operation we have, and a very short definition, could be removal of moisture from a substance, and for this course we will restrict our discussion to solids. So, when we say removal or moisture from a substance by supply of heat. So, we have to give this energy, and by making use of driving force driving force for mass transfer. And this driving force is nothing we will come to this again details nothing, but the partial pressure at the surface, and the partial pressure in the air stream. So, we are talking of solid surface say let say, this is some, sand or some granules, all right and this contains moisture.

So, now when we say that contains water; this moisture could be inside in interior or this could be covered here with some thin film of moisture. So, even one solid it is possible that there is a film of moisture here. So, we supply some heat q either z by radiations or we can have hot air flowing over this or we can pass the hot air right through this. So, we talk about this different method of contact between the hot air, and on the solid here. So, as a consequence of this driving force so, what driving force we are talking here we have this p s. So, partial pressure of moisture in the vicinity of this solid surface and in atmosphere or in this air. So, equivalent to this p s we can think of some y s some kg or moisture per kg of solid at the solid surface and here we can have some y kg of moisture per kg of air here.

So, that is a driving force we can also represent in terms of y s minus y corresponding to this p s minus p. So, essentially we have to supply some heat, that is one thing, and we are talking of removal of moisture from solids . And we said that may be you can note down that this drawing has a loose meaning. So, all right all we mean that we have to be careful that in our context what we are trying to say here that the solids like sands say paper, wood, cloth, you know some carbon fiber cloth, this contains water or moisture, now the type of this moisture, which is (( )) the sands or the solids they could also be different may be this we talked about in case of absorption that there are lot of capillaries or pores within the solids. So, moisture can be imbedded inside all right moisture can be inside, and some mixes moisture can also be on this external solid surface. So, both type of moisture soaped, and now, we want to remove.

So, we supply some heat this could be direct, this could be indirect. So, we will discuss about this most common is that you bring some hot air, and then remove this to make this you dry solid. So, now when we say we have the dry solid here also we have to be careful by saying that well the initial we had the moisture content was x say kg of moisture, kg of water, per kg of solid, and here we have x 1 where x 1 is much much smaller than this x. So, in other words really we will have x 1 very small to 0 it is a rare possibility. We will see lot of limitations limitation by this, because of property of the solid itself limitation, because of air or certain operating conditions.

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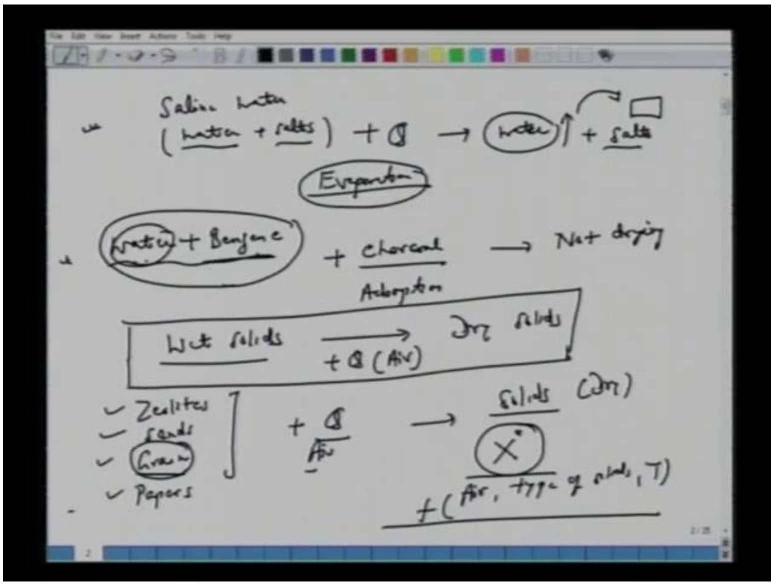

So, talking about this loose meaning here; so, let say we have saline water. So, it contains water plus salt all right. So, now, the salts relatively it is a smaller water is a very large quantity. And if you recall, some unit operations where you supply heat, and then you have this water which all right. So, water will evaporate you take this water contents, and you have some salts left sodium chloride etcetera. Now, this unit operation is evaporations; this is not drying in drying we will see that some step is very close to evaporations.

Similarly, let us take water, and say we have benzene all right. Now, it is possible that we bring this water, and benzene, in some contact with some solid let say we have charcoal. So, benzene contains some amount of moisture. So, now, we want to remove moisture from benzene; we bring in contact with charcoal this is also not dry. So, here we are talking of multi component absorptions. So, this would be your absorption although, we are removing moisture from benzene all right. So, different unit operations we remove water all right, but not necessarily. It is a drying what drying we are doing it here. Again, we are talking of wet solids, and we are making it dry solid by supplying heat through mostly say hot air.

So, this would be the most common scenarios we are going to discuss in this course. Wet solids so, let say we have zeolites, we have sands, we can have grains. If you recall in food industries, moisture has to be grains to improve the longevity or to ensure that grain does not depurate with time. You have a huge dryer where you remove moisture by supply your say hot air. So, zeolites, sands, grain, we have some papers; all of this supply heat through hot air, and then you have this solid, which is relatively less you know wet or it is a dry solid. Now, again where be some amount of moisture in this some x star equilibrium moisture will be left here; which will be a function of what is operating conditions air or even type of the solid temperature of course, has to player major role all right. So, these are different different definitions for drying different application of drying. So, what here now from the mechanistic point of view; this drying is if you are careful you know it is about heat, and mass transfer. So, that is a main difference that is a main difference we had bed between this drying, and the other unit operations all right.

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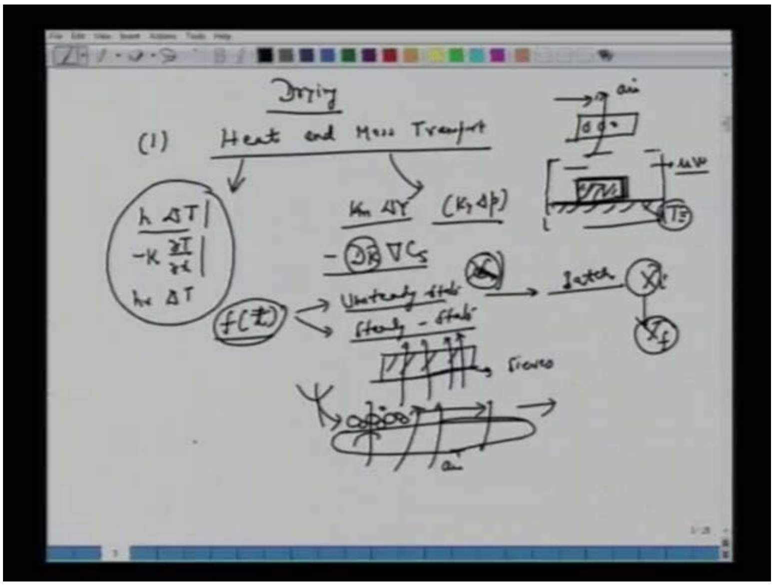

So, if you recall previous unit operations say absorption or we had distillations, absorption, extractions. All of this most of them all three of them other than distillations. We did not have any energy balance or enthalpy balance all right. The process could be non isothermal. That is one thing say absorptions, certain absorption could be exothermic heat may be release or in other case heat may be absorb endothermic all right.

So, in those cases generally we did not have energy balance distillation was one unit operations; where we had very extensively energy balance, enthalpy balance, but if you recall there were two methods: one was ponchon-savarit method, and one was mccabe-thiele; ponchon-savarit method was the one where we made very extensive energy balance, enthalpy balance for the top column, and for the bottom column, but if you the second method which was which we said is much simpler mccabe-thiele methods. It was all based on your species balance the two operating lines for the rectifying section, and for a stripping sections. There is no energy balance, except the q line or the feed line which we had to generate for which we made enthalpy balance all right.

So, by enlarge all this unit operations we did it was extensively based on mass transfer drying is one unit unit operations where you have simultaneous mass, and heat transfer. Because we are saying that we are starting with the solids it has moisture, and moisture is removed. So, we have mass transfer whether moisture from the surface or moisture from the pores inside. So, we have you know surface transport say hot air blows over this. So, we have done mass transfer coefficients there is a diffusion, resistance, moisture is also removed driven off from the pores. So, we are talking of now pore diffusion, knudsen diffusion. So, that is a mass (( )) of it, but also you have simultaneous heat transfer. If you want to dry a solids which is soap with moisture of course, you can bring cold air, which has less you know it is a relative humidity; then what you have corresponding to this equilibrium conditions. So, that will also drive some moisture all right, but that is a very slow process; you require a very use amount of air we will have to wait a long.

So, generally you have air hot air. So, you are talking of now you are heating the solids as well. So, there is a some time delay when the solid surface temperature reaches some equilibrium temperature. You can have radiation heating, microwave heating. So, different types of heating arrangements; you are bringing you are trying to improve enhance your mass transfer by the simultaneously, heat transfer; heat also you rises your vapor pressures all right. So, the temperature is there is a film of liquid over the solid, and if you heat it. Then the vapor pressure will be larger heat content moisture content is the same. So, the you are increasing the driving force from mass transfer as well; if you are increase the solid bulk solid. Then knudsen diffusivity will also has a function on depends on temperature. So, the diffusivity where also increase moisture will be driven off from the pores from the capillaries. So, here we will see that there is very good very good discussion, we will have extensive this heat transfer has to play a role in addition to mass transfer. So, let us again note down here.

So, when we say drying the mechanism here is both heat, and mass transfer. So, when we talk of heat transfer may be we have heat transfer coefficients. So, solids blowing hot air either over the surface or we can have hot air blowing through this. So, this is h del t; we can have microwave heating or let say we have put a plate on which we have put the solid, and this solid is heated to some temperature t. So, by the conductions heat will be transported. In some case, it happens that we do not want to damage the solids specially in the food industries pharmaceutical industries. Now very small amount of heat is required otherwise at high temperature if you want to blow with this hot air then there is risk of decomposing this solid here.

So, here we talking of now minus k del t over del x. So, heat transfer by conductions by convective or we can have radiations. So, we can have microwave heater here all right microwave heater, and then by some radiation heating, we can heat this solid. So, there is a heat transport of course, we have mass transport similar to the h del t we can have k m del c or del y or we can have k y, and we can talk in terms of pressure partial pressure difference what we have in the surface, and what we have in the atmosphere. So, there is a mass transfer the most important mass transfer has to play a role in this knudsen diffusivity.

So, now we are talking of solid it has capillaries, pores. So, this moisture has to be driven from inside the pores to the solid surface. So, now, we are talking of knudsen diffusivity d k into some concentration gradient inside this solid all right. So, of course, both of them will have an independent effect, but in some cases you can see that heat can improve this knudsen diffusivity. So, it has a simultaneous effect also we can have an unsteady state problems function of time. So, if you start with some solid which is cold room temperature now you bring at very high temperature. So, it will take some while before this temperature of the solid become same as this temperature of your heat player.

So, it is a function of temperature we can have unsteady state problem or we can have steady state problem all right. So, unsteady state problem generally, you have in batch how long will it take to drive to bring the concentration level or solid content or moisture content with the solids from x initial to x f. We can have a steady state problem so, we are talking of some dryer like this we have granules we have put on a sieve perforated sieves, and you blow continuously air through this or you can have a belt like this. We have some say certain coals or certain minerals here, and in this belt moves. So, and you have the flow of air through this.

So, it is a continues process by hopper, we are bringing some minerals here we are removing it and you have this hot air. So, we are talking of this steady state continues process unsteady state typically you have in case of batch process all right. So, that is one thing heat role of heat, and mass transfer, number two unsteady state or steady state all right. So, these are very introductory matter on this topic drying you can go through the text book treybal, and you can you can brief (( )) all right.

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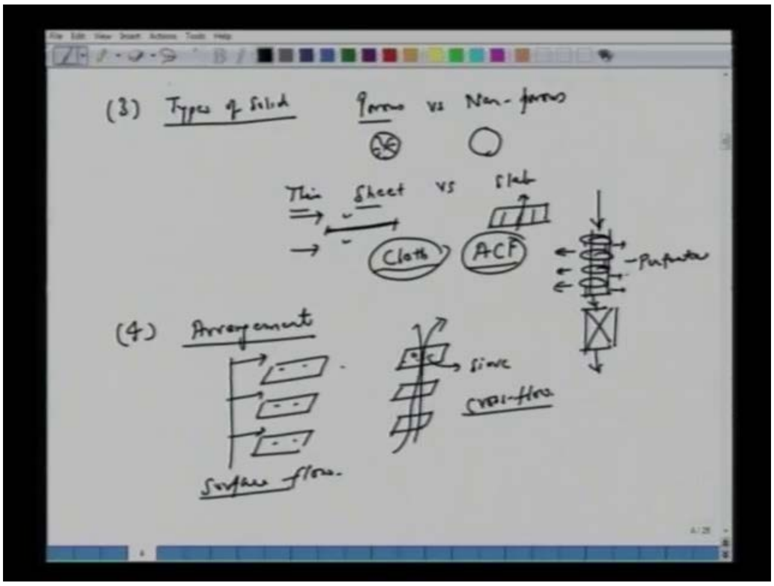

The third thing here is types of solids types of solid also have to play a major role just like we talk to when we are discussion on this absorptions. So, here also we can have porous, and we can have non porous. So, trying to dry a non porous solid is different from a porous solid for the same reason that they have large capillaries. So, it will take longer time. So, when we say drying we can also have a lesser sheet versus you know very thin sheet versus we can have some slab. So, notice here we're talking of drying of this sheet and we are talking of this slab here. So, in addition to this depth through which the moisture has to be driven off.

Now, also we talking of some certain area which has been exposed from both end to hot air. So, the two we have two different scenarios here. So, different type of solids thin sheets, slab or you can have cloth. So, when you want to draw a cloth say activated carbon fiber we talked about when we had adsorptions it contains lot of moisture it can soak into very large poured porous here micro porous here. So, it want to dry a c f may be like to wrap this A C F on some tube right. The tubes could be perforated perforated you close this end allow this hot air to pass through this, and then you have air flowing radially outward all right. Instead of taking this A C F, and making a pack belt. So, two will have a different extent of mass transfer or heat transfer.

So, here we talking of and we said types of solid we also talking of different types of arrangement. So, arrangements of dryers say like in refrigerators you have trays we can have its stack of trays on which you can put solids and then you can think of hot air blowing of pass this in some cases you can have the trays, but this trays would will have some sieves. So, ensure that these solids diameter is larger than the sieves. So, you can have trays like this, and then hot air, can blow through this. So, it is like cross flow, all right and here we talking of say surface flow. So, two same materials, but the drying rate will be different here drying rate will be different here drying rate will be different here.

So, these are the introductory things we talked of mechanism heat, and mass transfer, that is one drying is one unit operations where will have both heat considerations transport of energy, and we have transport of mass, that is one different types of solids. So, porous non porous slab thin plates that is one thing different drying rates may be same solids charcoal, but you have one you have made a pallets, one you have made a something sheets, one you made fiber, different type of dryers arrangements staking, then you have hot airs. In some cases, trays you can have some perforations to allow the air to flow through this. So, it is a different type of thing, then we talked of steady state, unsteady state just like the previous case, it have a batch you have a small amount amount to dry it you can have a continues process. So, you have talking of minerals or coals, sands. So, you have a conveyor belts on which continuously through a hopper this solids they fall on this belt moves, and you have air flowing across this. So, it is a continues process right.

So, you have a different species balance for or energy balance for a continues process. And then, you have different for your batch steady what we do now is the way we have the our approach has been similar in previous cases. Let us, start with thermodynamics equilibrium adsorption, we had the equilibrium we talked about solubility, then we had the distillations. We talked about raoult's law relative volatility. Then, we took up the topic on extractions we talk of solubility immiscible fluids this ternary phase diagram equilateral diagram. Then we started absorptions, we had the isotherms uptake given. So, much of partial pressure in atmosphere or in the aqueous phase milligram per liter or atmosphere how much amount of solute is absorb by the solid. So, langmuir, isotherms b e t isotherms, elovich, freundlich.

So, similarly here in case of drying also we have this some kind of equilibrium isotherms or equilibrium curve what it should be the equilibrium curve. So, now, we are talking of drying of solids. So, we have moisture content. So, we start with 1 kg of solid it has say x kg of water or moisture. Moisture form is also we said is different, we have very excessive moisture. So, it will form just like a layer of pool of thin film of water, and once this moisture on the external surface is dried. And now, we are talking of moisture within the capillaries, within the porous.

So, none the less so, we have moisture content x kg per kg of you know the solid materials. So, that is one x axis, and what else we do now we talk about this partial pressure. So, we are bringing hot air. So, it has a very small relative humidity, and what relative humidity have we have this surface or you know p s y s. So, that is the driving force. So, we need to know what type of operating conditions? We have corresponding to that operating conditions what moisture content we have. Now, look at the difference between the drying, and the previous unit operation. They are thermodynamic alone; you know it qualifies, and gives you equilibrium curve here. We are talking of operating conditions in equilibrium; why because what is the equilibrium moisture content? It depends upon what is the hot air compositions what is the relative humidity of the hot air.

In other previous case, it is an equilibrium it depends upon the solid, and the solutions we have isotherms relative. So, here drying simultaneously also we have some consideration from the operating one type of solid right same charcoals, but it will exhibit different type of moisture content. In one case moisture content could be large; in one case moisture content will be small. We will see depends upon that also heating arrangements drying at (( )).

So, equilibrium we have to establish first, we establish the equilibrium. Then we talk of characteristics of a various important what do we called drying curve how does the drying curve change one has to establish this. So, in case of drying we do not we have some similarity how are approach, but there is a very significant difference here. We want to design a very large dryers for the same solids one has to do this is small experiment, and try to mimic try to have some analogy between the existing operating conditions, and the you know lab experimental conditions. So, let us start with this equilibrium. So, as we said that, if we have solids say let us say some slab like this or we can have some granules like this.

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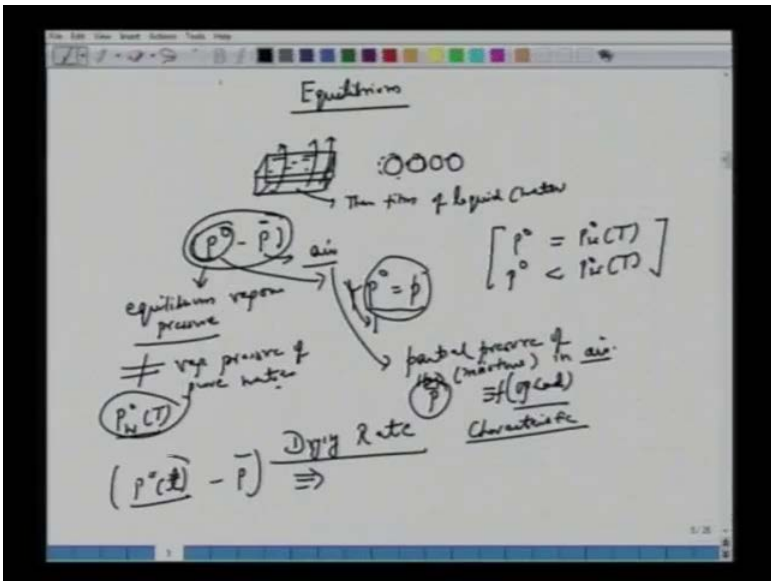

So, on which so, there a moisture you can have thin film. Let us start with thin film of thin film of liquid which is water here solid also, we can have some moisture here like this. So, we are talking of p 0 minus p or p bar. So, what is p 0? This we are seeing that this is your equilibrium vapor pressure all right equilibrium vapor pressure. So, it is a moisture here. And make a note here that this equilibrium vapor pressured need not be the vapor pressure of pure water. So, that is another difference we are having it. So, what we are saying that, if the pure water has a vapor pressure let say p 0 t say water here. It is possible that the vapor pressure at the solid surface need not be p 0 w by t. We will see that the two different ranges: in one case p 0 is same as vapor pressure of pure water, and in most of the other cases or different time this p 0 is less than vapor pressure of pure water. So, p 0 like this, it is all it says equilibrium vapor pressure how much moisture exerts vapor pressure.

So, again we can think of this you know raoult's law like y p 0 into partial pressure. So, y is 1. So, equilibrium vapor pressure is what call here partial pressure minus partial pressure in the air. So, this is what we are going to control is a partial pressure of moisture in atmosphere partial pressure of moisture in air or atmosphere. So, this p bar; that means, it is depended upon what operating conditions? We choose this is not something which is fixed or different different partial pressure in atmosphere different quality of air will give different drying rate. So, we are slowly getting into this design this drying rate. So, it is a characteristics of a drying of a solid here all right.

So, that is the driving force we are talking that is one thing. So, when solid starts now evaporating, now water starts evaporating as a solids are drying this p 0 will now will change. So, this p 0 what we are write in pure pressure of course, temperature is fixed, but now this becomes time depended. And you have p bar assuming that p bar remains constant. That means, the drying rate is a function of your moisture contents. So, we will talk about this how does now partial pressure at the solid surface it changes with times as a solid is getting dried down.

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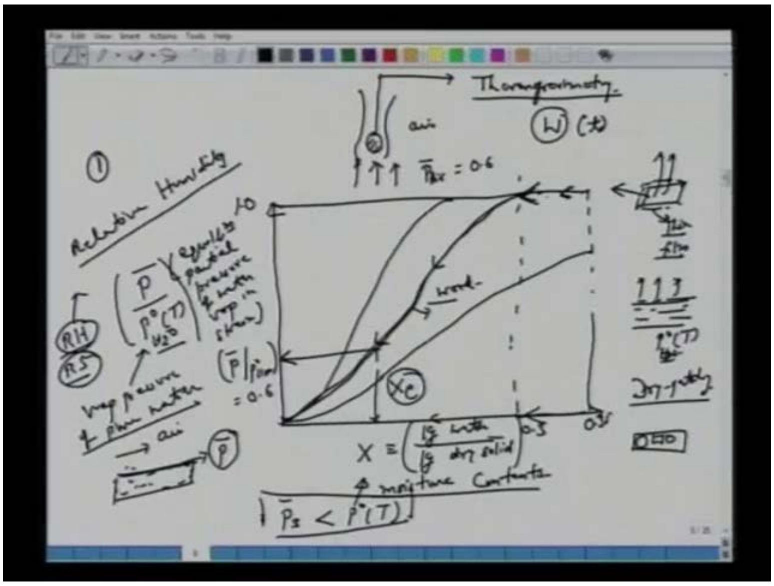

So, what we will do or when you lab suppose, we take a solid suspended very simple experiment and you have hot air flowing pass this. So, you have some kind of velocity profile this solid could be again it could be porous could be non porous you have suspended may be your measuring it is weight by some thermo gravimetric method gravimetric method. So, there are very precise instruments all right one can measure the weight as a function of time.

So, essentially if you we plot all right. So, we are plotting here x, that is the first important and drying curve; you call it we are we have in this drying. So, let us plot x which is nothing, but kg of water, per kg of dry solid. So, in the lateral lecture will talk about the different ways of reporting this moisture content sorry wet basis dry basis. You have some idea earlier moisture contents. So, one is going to measure this here what we want to plot is p bar over p 0 t moisture. So, this p bar is equilibrium partial pressure of water water vapor in stream in stream. And all we have done, we have non-dimensionalize by this vapor pressure of pure water all right. So, this vapor pressure of pure water given temperature is fixed just just one we way of non dimensionalize. So, may be here it is one.

So, we are talking of now p bar equilibrium partial pressure. So, add this surface. So, water evaporates inside or outside at a solid surface what is this equilibrium partial pressure. Now, you will expect that if we start with a very large amount of moisture contents to the extent that the solid is completely filled with the solid. So, there is a thin film. So, when we say thin film of water evaporation rate from this water or the characteristics of this evaporation of water is not different. If you have pool of water, say even lake all right. So, this water which evaporates this will exert vapor pressure p 0 t we said here p 0 is 2 same as you know the thin film of water which evaporates.

So, right now this p bar, and p 0 t, will be the same; that means, we are starting with the very large amount of this x content. We will expect that you are following this line of one equilibrium partial pressure of water vapor at the surface here is the same as vapor pressure of pure water. So, you will move will expect that as a moisture content decreases it is falling one. Then after sometimes when we will see the dry patches, it will start occurring. So, some solid surface maybe some there is a wet; some where there is a dry; some where there is a wet; there is a dry that time typically, if you plot a typical drying curve this curve will go like this. So, this would be your very typical p bar versus p over p 0 versus x curve. So, let us say this is would would has very typical this type of feature that for a long time; it is a soaps lot of amount of lot of amount of moisture here.

So, for a long time you will see that this one will expect, and moisture contents are decrease starting from certain values to say this 0.35 to 0.3. This partial pressure at the surface can be assume to be same as a vapor pressure of pure water, because it is a thin film after that now on the batches starts decreasing. Now, you this goes below one or it means, now the partial pressure exerted by this water at this solids at the surface it has gone below the vapor pressure of pure water all right.

So, decreases then you have all the way till whatever range. So, it is going to decrease will expect that when it reaches certain level of partial pressure in atmosphere. So, now, you are drying with air or you drying with air here. So, this air partial pressure moisture partial pressure moisture content in this is fixed. So, let say this value is 0.6. So, are you plotting p bar over p 0 t shall we call from some other class will other no that is nothing, but relative humidity or it is a relative saturations r h relative humidity or relative saturations all right.

So, what we are saying here that this partial pressure, equilibrium partial pressure at the solid surface will decrease. Then moisture content continuously decreases still it reaches a level where you have this p bar over p 0 h 2 o equal to 0.06. Essentially now, this becomes your air partial pressure when the partial pressure or moisture in solid at the solid surface becomes equal to this. So, now no matter how long you stop you have reached an equilibrium. Some solid surface they can have which adsorb very large amount of moisture they can behave like this certain another type of solid can behave like this. That means, it have very long this extent of moisture; we give certain names here all right. So, we are going to mark certain features or certain terminology we are going to introduce certain terminology here.

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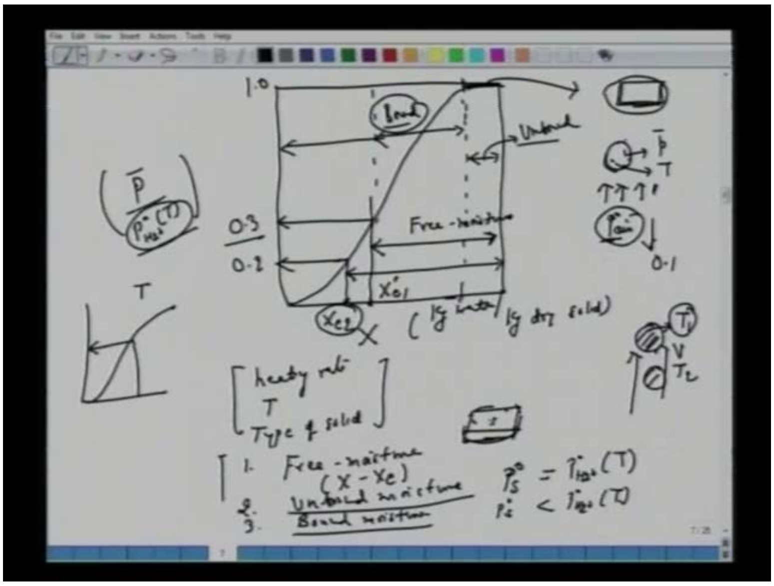

So, let say again this is x; we have kg of water, per kg of dry solid, and let us make one curve it should goes like this. This is one p bar over p 0 h 2 o pure water like this. We reach corresponding air values, and let say, we call it that says 0.3 corresponds to quality of air which has been used to try this corresponding to this. We have x star or x e. So, we can say that no matter for how long we are going to rate this content cannot go below. This, because here you have air and here you have solid surface or inside where you have reach a level of p bar which is same as p zero p of air right.

So, moisture in air, that is the same relative humidity corresponding to what you have surface reaches equilibrium we can call this as free moisture. So, this is the moisture which is free to be removed. Now notice here that, if I reduce the quality of this air from 0.3 to 0.1, I can further dry this. We can come down to this level of 0.2 that means, the free moisture which has been remove or free to remove has increased. All it means, now the equilibrium value has changed equilibrium content as change from say x c 1 to x c 2. So, for this what we are saying that equilibrium concentrations for equilibrium moisture content. It depends upon given the operating conditions p 0, and like in all those isotherms we said that once you fix temperature you have an isotherm ready. So, given this So, much is this.

Here it depends upon your air conditions air quality of air to what extend now it has been. In fact, it depends upon the temperature also same air, but you have the different solid may be you are heating the solid by radiation heating or microwave heating. So, this one case temperature is t 1, another case temperature is t 2, but you have the same quality of air going through this. In this case partial pressure or the vapor pressure of moisture will be larger than this; if the temperature is larger than t 2. So, in all these cases from moisture content will be different. Moisture content at equilibrium in general depends upon your heating rate it will depend upon the temperature, and it will also depend upon type of solid. We will discuss this later right now we have all we have done we have defined equilibrium moisture content, we have defined free moisture, and here we can defined one more which we call it as unbound moisture. And then the remaining we can call it as right from here to here we can call it actually, bound moisture bound moisture.

So, what is unbound moisture till you have the vapor pressure same as the vapor pressure of pure water. So, this is the region where the solid surface is still fill with very thin film of the liquid. So, the water depletes, but only from the external surfaces till the end you have that this range this moisture contents. Still you have some amount of moisture below this. Now we are talking of dry patches occurring so, what we are saying here that to begin with the solid as a film film of water over this. So, the partial pressure is same as the partial pressure of pure water. And then we have this patches of solid patches of you know dry surface they start appearing, and then we have the different type of moisture if you call it is bound moisture.

So, we are we have use the terminology here one is free moisture. So, this would be x start with x, and we have x c that is one when the we talk about unbound moisture. So, unbound moisture where we are saying that the vapor pressure of at the surface is same as vapor pressure of pure water. So, all we are seeing that is still there is a film of moisture film of water, and third we are talking of this bound moisture. So, when you say bound moisture, now the vapor pressure at the solid surface is now smaller than a vapor pressure of pure water. Of course, we have talked of equilibrium moisture equilibrium moisture content x c.

So, will come back to this one very very interesting thing occurs in case of drying of the solid is since we have air pores. So, the rate of drying is different when we have dry solid, and then we are trying to wet; that is one, and when we have the wet solid then we want to dry. So, in other words if you have a solid say the moisture continent is x 1. We dry it we bring down to the level of x 2. In one case we are start with x 2, and then, we start to wet. So, we bring in contact with moisture and we bring from x 2 to x 1. So, between the two levels one is the drying x 1 to x 2, and one is the wet. In terms of incase of this solid on the drying of solid what happens there is a hysteresis all right. So, that means, the path to go from x 1 to x 2 is difference from x 2 to x 1 . So, for the same partial pressure or same quality of air in which solid is the brought in contact you will have you will see that the two different moisture content lives. So, let us try to understand what you are saying here that in case of drying we have this hysteresis will see that why does it occur.

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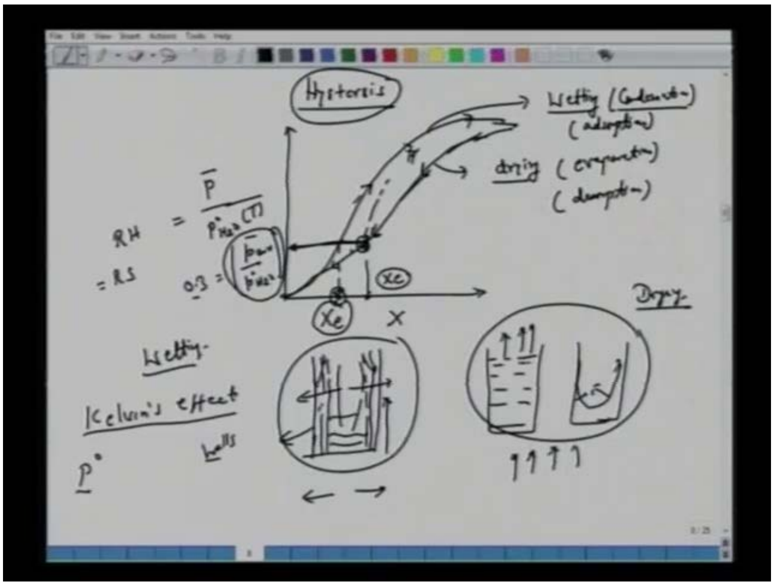

So, what we are saying that, if we plot x what we did earlier versus this partial pressure over partial pressure of pure water which is nothing, but relative humidity nothing, but relative saturations. And then, we say the drying if you see saw this earlier curve. It is like this of course, it will stop when you have this equilibrium concentration x c given this quality of p bar over p 0 is 2 in air. So, let say this number is say 0.3. So, now, when we dry we go like this, and we want to wet, then we have the different path like this. So, this all about hysteresis all right. So, one path for drying moisture content decreases, and one path for wet wetting. This is very similar to say we are saying that see evaporation, and here we talking of condensations. So, it is getting wet or very similar to we are saying that it is desorption there is a desorption, and here we are talking of absorption all right.

So, what is significance here if you have a solid which has been dry to this level of p air, and we have this equilibrium concentrations, no matter how long you wet this concentration is not going to go below this, but when you want to wet. Then, it is not for going to follow this path here now it has a different to follow or for the same quality of air, now look at this equilibrium concentrations now it is difference.

So, for the drying there is a different equilibrium concentrations and for the wetting there is different equilibrium concentration; a solid which has been dry to this level. When expose to same quality of air during the wet will exhibit different type of different amount of moisture content or a solid which has been wetted with this with one quality of air, and now when you want to dry then it will have different equilibrium concentrations. So, this also has some practical applications from mechanism mechnism point of view why does it happen, if we recall some knowledge of this thermodynamics you have this pores all right. So, when the pores are empty. So, we are talking of now wetting what happens the first the films are the walls is start getting fill filled up here. So, there is a adsorptions recall you know (( )) absorption is very similar to what we call condensation or wetting.

So, moisture is starts getting this absorb on the walls of the pores till there is a film then of course, this gets narrow and narrower and you have the film like this also. So, you have the sideways filling to start with then you picks up then the adsorption picks up and the pores get filled up this way. But when the pores are already filled up. So, you have situation like this. Now when you want to dry then you can see that drying takes place from the surface till very very small levels now we have some (( )) like this, and then we can think of sideways of drying here.

So, the mechanism of wetting, and mechanism of drying, in case of pores of is pores solid is different. That results in case of that results in that in hysteresis in whereever we have hysteresis in any context; that means, there is a mechanism of certain you know phenomenon in one path is different from the other path. So, here we have the pore filling which goes sideways when we are drying or desorption it takes place laterally upward. So, the mechanism is different that is why you have two different rate surface called kelvin’s effect. In fact, kelvin’s equations to calculate partial vapor pressure or partial pressure in two cases are different when the pores or film at the adsorption for desorption they are two are different here.

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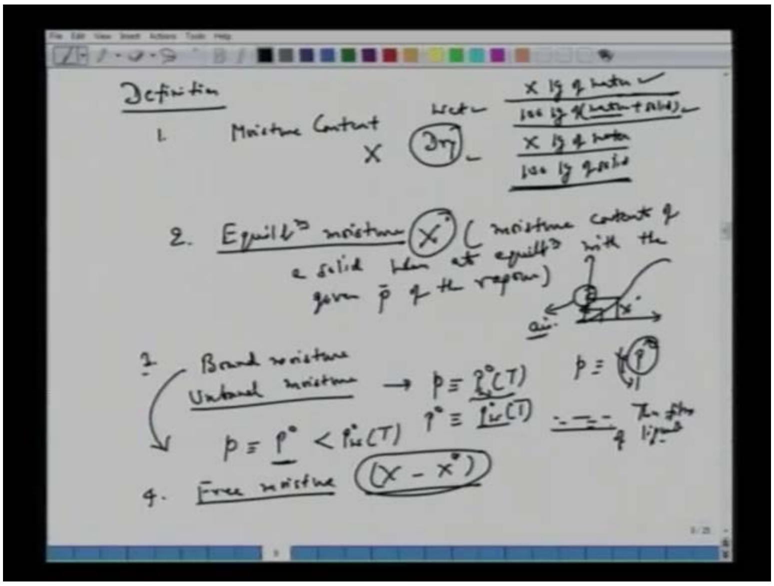

Definition

1. Moisture Content X — Wet – $\frac{x \text{ kg of water}}{100 \text{ kg of (water + solid)}}$; Dry – $\frac{x \text{ kg of water}}{100 \text{ kg of solid}}$

2. Equilib^m moisture (X^*) (moisture content of a solid when at equilib^m with the given $\bar{p}$ of the vapour)

3. Bound moisture
Unbound moisture → $p = p^\circ_v(T)$
$p = p^* < p_w(T)$ $\quad p^\circ = p_w(T)$
Thin film of liquid

4. Free moisture $(X - X^*)$

So, now what we do here after we understand this p versus x diagram we will have some definitions for different ways of the representing moisture contents or different quantities here. One is of course, very important is moisture content how do we represent there are two ways of doing this; one is wet basis one is dry basis. So, when we say wet we are talking of x kg of moisture or water per say 100 kg of water plus solid. So, it is a wet basis, and when we say dry all we have x kg of water per say 100 kg of solid.

So, again you see the advantage often working on this dry solid 100 kg this remain the same denominator remains the same otherwise here this quantities work numerator as well as denominator changes, because high amount of water changes. The two ways: one is the wet basis one is the dry basis we talked of equilibrium moisture. So, when we have equilibrium moisture we denote by x star this like x x star. So, we are saying moisture content, now again this content could be dry basis or wet basis content of solid when at equilibrium with the given partial pressure of the vapor. So, this is the equilibrium concentrations we talked about that drying curve when it goes like this, but you stops at x star why it stops at x star, because now the moisture content of the solid is an equilibrium with the partial pressure of this vapor in the air which has been use to dry this.

So, we cannot go below this you want to go below this one has to have a dryer air which will take you below this range talked of bound moisture, and we talked of unbound moisture. So, may be that is number 3. So, unbound moisture of partial pressure of this moisture partial pressure of vapor at the solid surface is same as p 0 t partial, in this vapor pressure of pure water all right. So, in the words of vapor pressure exerted by this moisture is same as vapor pressure of pure water. So, what here writing here is the partial pressure equal to y into p 0 y is one pure moisture no other species here we have and this vapor pressure what it did exerts it same as the vapor pressure of pure water.

So, that is unbound moisture. So, this will happen when there is a thin film of this liquid thin film of liquid. Once we talked of one the moisture is starts you know the whole surface gets dried up and we talking moisture driven of from the pores or capillaries there it happens that the partial pressure let say this is equal to p 0, but this p 0 will be now, less than vapor pressure of pure water. So, now we are talking of some capillary effect etcetera we talked of free moisture. So, that is moisture which is free for the removal x minus x star, and of course, x star depends upon. So, many things it depends upon type of solids, depends upon drying rate, depends upon quality of air, depends upon temperatures. So, this is the moisture which is available you must now you must understand that solid alone is not good enough you have to specify when the operating conditions when we can say that this moisture is available for remover say it is only free moisture which can be evaporated or it can be removed. And all of these for the last time we draw again this is the first very important curve will typical curve we have where we plot x kg of water kg of moisture per kg of solid.

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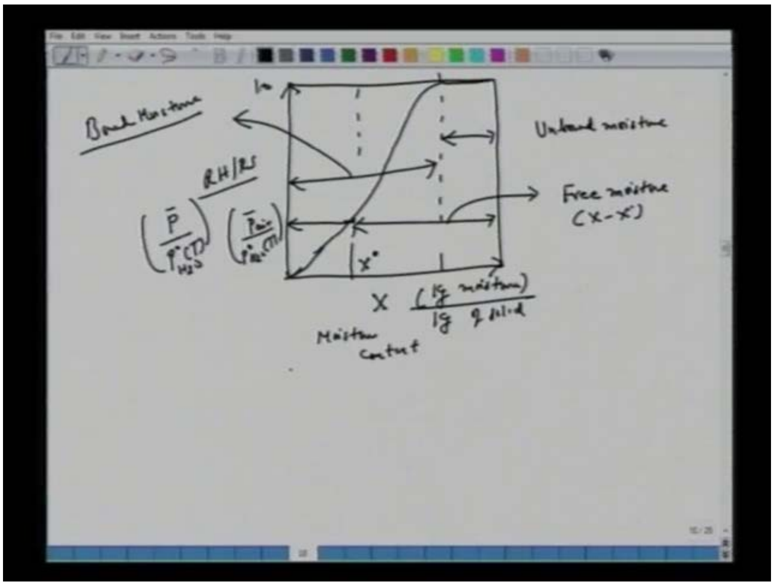

So, this is moisture content. Here, we are plotting relative humidity or relative saturations or partial pressure of water vapor in air over vapor pressure of pure water. So, these are the important things; we have marked here this is the first thing first graph which we need to understand in this drying operations here all right.

Now, let see we have which lets try to understand what happens when we have this unbound moisture all right. So, what happens here when we unbound moisture we are talking of film here water film. So, the mass transfer rate is we can expect this should be equal to k y let say there is air flow here k y into y s minus y. So, what is this k y first this is mass transfer coefficients. So, water evaporates we have done earlier; a moisture on the solid surface it evaporates there is air flow.

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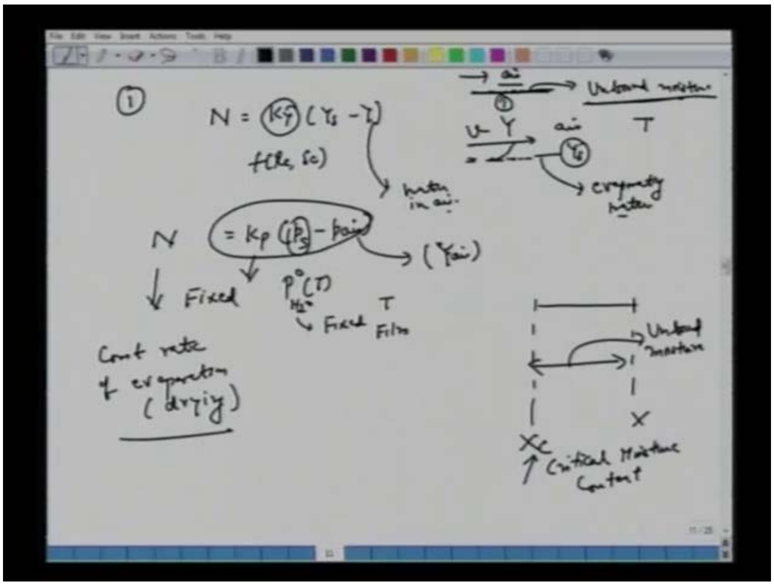

So, they will be some concentration gradient this k y is a function of reynolds number, schmidt number, depends what number what velocity we have etcetera what is y s y is spacing that it is a moisture content in air allright at the solid surface. So, we have pool of the liquid at the top of this water which evaporating. So, this is evaporating water, we have evaporating water, and this y is y here this water content in air.

This is very similar to may be you can say k p, we can say that p at solid surface minus p of air. So, this is at the p at the surface of water this could be equal to for in our case spent the water is solid surface is covered with the film this p s will be nothing, but vapor pressure of pure water. So, it is a constant as long as you maintain this temperature; temperature is fixed as long as there is a water film this p 0 t reynolds number is fixed. So, this also fixed here this also fixed, because temperature is fixed, and there is a film of water. Ensure that, you have continuous supply of air and content in air does not change. So, you have essentially constant rate of evaporations constant rate of evaporation which we are calling at is drying rate.

So, that is a stage one we have address this one, and the rate moisture content decreases from x to certain quantity let say x c let us call it critical critical moisture content. So, this zone over which we have unbound moisture all the time equilibrium vapor pressure is same as the vapor pressure of pure water. Now, we have decrease. So, now, we are talking of the second level where we start decreasing below x c.

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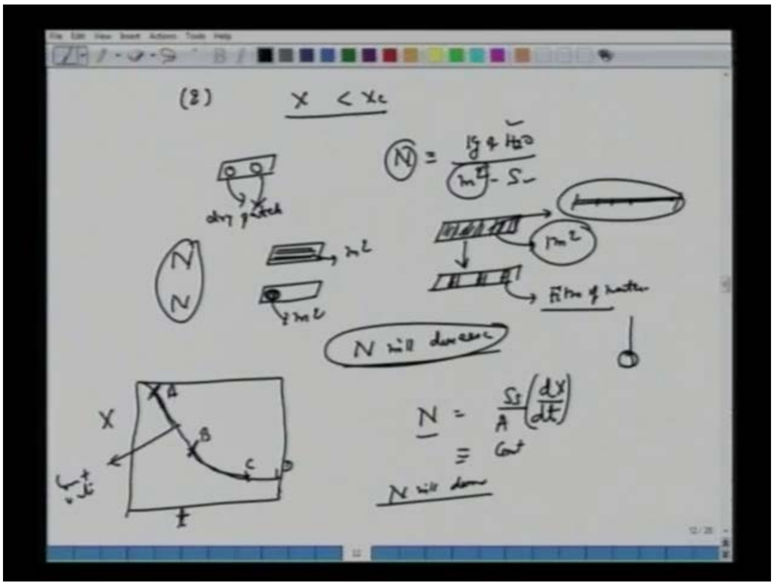

So, now x is less than x c what happens here, now, the solid surface now, there are dry patches dry patch of water. Now here if you look at if you talk of rate as kg of water per meter square of solid surface per second. So, now, we have been careful what meter square we are talking suppose we start with a one meter square of a solid surface is completely filled with water. And after some time when it x as gone below x c now we have certain patch dry patch, but still we are reporting this rate N as per meter square of the total area. That means, from individual those areas regions where there is a film of water. This specific rate will still be the same as what we have here in other words intrinsic rate does not change whether we have full a surface occupied by complete moistures or we just have one solid surface where is a small small amount of water left here if we take meter this meter square, and if we take only this meter square. Then the two rates would be the same all right.

So, still when you measure per meter square then there is a possibility that or then this will happen that n will decrease. So, you have to be careful when we say that when the rate decreases or the rate does not decrease. Because depends upon how your reporting this rate in general; you start with meter square of a total solid surface which fixed. So, even if they are dry patches is still you report your rate how much kg of moistures decreases in one second per one square meter of this. So, in that case N will decrease. So, it is you can say that there is an artifact of reporting here all right. So, what we do here that one curve we will like to continue in the next class. So, if you do this experiment.

You have suspended the solid and measure how does is moisture content decreases, then what you will expect that? Here also you will have several regions where be one region where x will decrease linearly. Then it will slow down then will further slow down. So, next time, when we meet we will mark this points A B C D here, we will call it constant rate, because x changes linearly. So, if N we defined as s s over surface area total surface area as d x by d t since x changes linearly we will expect that this N is constant here.

So, this range this region is called constant rate drying then of course, x changes non-linearly. So, that in that type N will decrease here. So, we will stop here, let just summarize today's lecture, one of we started with a unit operation drying where we are saying that, we are interested in drying of a solid for we contents moisture we want to remove dry of moisture from this solid by simultaneously giving heat, and mass transport.

So, we have dry air, as well as we have hot air. So, there is an effect the both heat transfer, and mass transfer. That is the unit operation drying we are saying of course, it has a loose meaning moisture given of from different substance by this interfusing by mechanical separations does not drying, we are interested. A water - saline water, sea water, You drive of moisture by evaporation very large quantity of water is move that is evaporation’s.

So, that is a definition for drying where interested here, that is one number two we talked about drying is one phenomenon, where you have so many other concentrations, like type of solid; once solid of course, porous non porous, but even the way you make the solid pellets, sheet, slab, that will also affect your drying rate, because the operating conditions external air in contact or with the solid surface plays a major role. What is a reynolds number? What is a quality of air to we have entire re expose to the same amount of air or if you are doing a microwave heating, then does entire surface gets heated. If you have a sheet expose to microwave heating, and if we have granules which are inside deep, you know solid surface may not be get heated by the same may not we receiving the same amount of energy.So, the drying rate will be different although you have the same materials.

Then you talked our trays different ways of heating, it cross flow we have flow over surface (( )). I said earlier, it is recommended you go through the textbook, and see physically or some handbook, and drawings, different type of trays. You may have seen some unit operation in some laplace. Then came we talk to the first characteristic curve of this drying here, when we plotted x or we plotted partial pressure of equilibrium partial pressure of moisture over non-dimensionalize with vapor pressure of pure water verses moisture content. And there we said that we have unbound moisture, and we can have bound moisture, free moisture, equilibrium moisture. Then came the differential for the rate, we have to defined a rate, so rate we defined defined as kg of moisture per second per meter square of the area. What area is this? This area is a total area all right not the area of the wet, because this wet area will change.

So, but you know we are defining it, we are reporting this rate per meter square of your total area. And then, we will see that what does cause the effect in between also we talked about this kelvin effect drying has a very special property, very special characteristic hysteresis. That means, drying is different from wetting; if you want to dry a solid surface, moisture content will decrease. It will take one root, different rate when you start wetting up putting this moisture here, just reverse the conditions, then we will take a different rate. That means, for the same quality of air moisture content in during drying, and moisture content during wetting will be different.

This will have a you can make or this will have a significance; if you trying to say dry or wet certain food packages. So, when you dry one conditions you pack it, but you bring to the same quality of air right, during the wetting. So, you start from lower to the higher will expect that moisture content will change all right. So, that is the introductions on drying next time, we will be meet. We start continue with our discussions on different type of characteristics curve, especially we have drying then we take up some few examples or setup the governing equations for unsteady state process.