Downstream Processing
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Lecture - 36
Drying

We have been looking at several downstream, where you are trying to separate solids from slurry and extraction or recovery of the desired product, then we go into the purification of the product. Now, we are approaching the end of the downstream where we are trying to dry the material, generally drying is sort to, if your product is a solid why we need to do drying. There are many reasons why we need to do drying, because when you do drying, the product stability may increase, the quantity or the volume occupied by the product comes down, so it is much easier for you to transport.

And if there is moisture present, you may have bacterial growth, so it may contaminate your product or sometimes the moisture present can lead to hydrolysis of the desired product. So, because of all these reasons, we need to go into drying; drying is also a very important unit operation, because it gives you a certain appeal to your final product, which is accepted by your customer.

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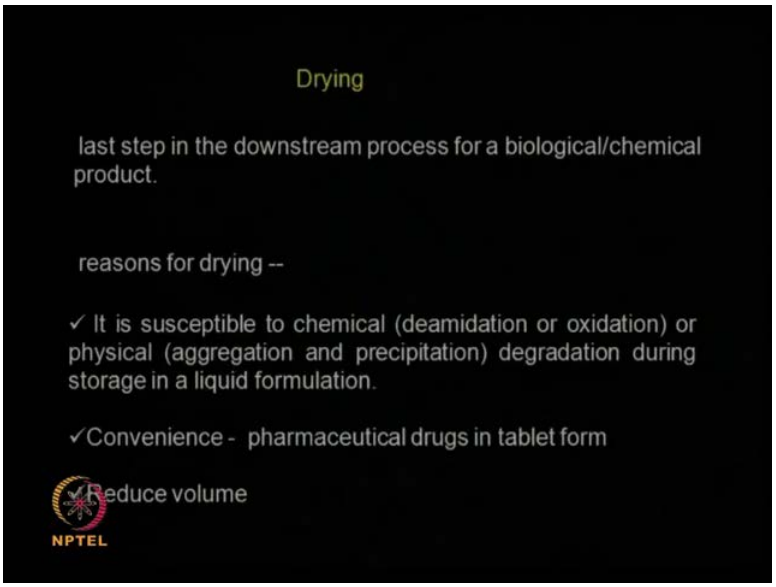

So, this is almost the last step I would say, drying and of course, we also have lifelization where we have again removing moisture, but in the opposite direction that means, we are

using lower temperature there. So, we use drying, because we want to prevent deamidation or oxidation of desired product; sometimes if we have moisture, the product may aggregate or even precipitate, so we would like to dry your product.

And also, if you have a solid material, which you give it to your customer, it may be easy for them to formulate because they can exactly where the material and then use it in their formulation. So, it is more of a convenience and especially in a pharmaceutical drug or tablet manufacture, they would like your product to be in the solid form, and of course it also reduces the volume as I said before.

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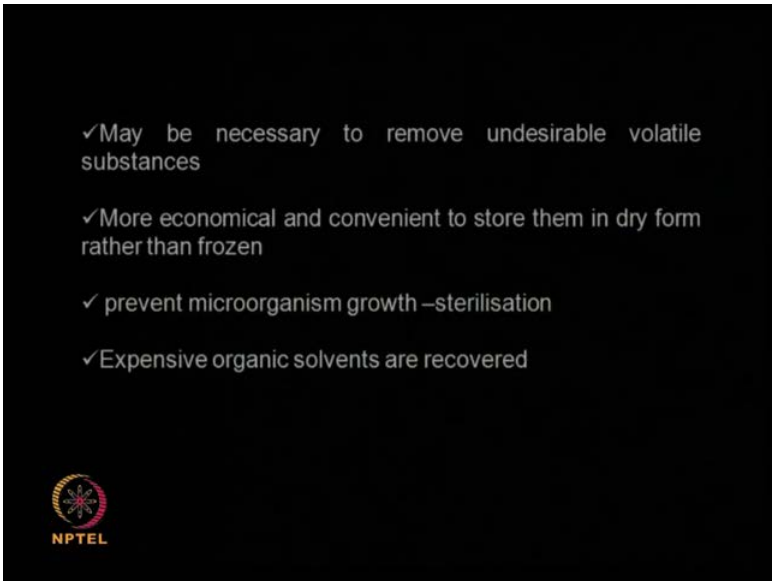

And sometimes, you may like to remove unwanted volatile material, there could be very small amount of solvents present and which you do not wanted to be carried over. Because, when we transport a solid material with some amount of solvent then during the transportation as well as during the storage, the solvent may evaporate and the vapour pressure will be generated by the solvent. And also, it is more economical and convenient to store them in a dried form, rather than in a frozen form.

And then drying also act as a sterilization that means, it kills what are bacteria or micro organisms present. And then if you have very expensive organic solvents, which you have used in the previous step for purification or crystallization then you may be able to recover those expensive organic solvents by doing drying. So, these are many reasons why generally we adopt drying but then one important point we need to keep in mind is

the stability of the material at higher temperature. Especially, if it is a biological product like a protein, so we have to be very careful that, we do not exceed the their stable temperature limits.

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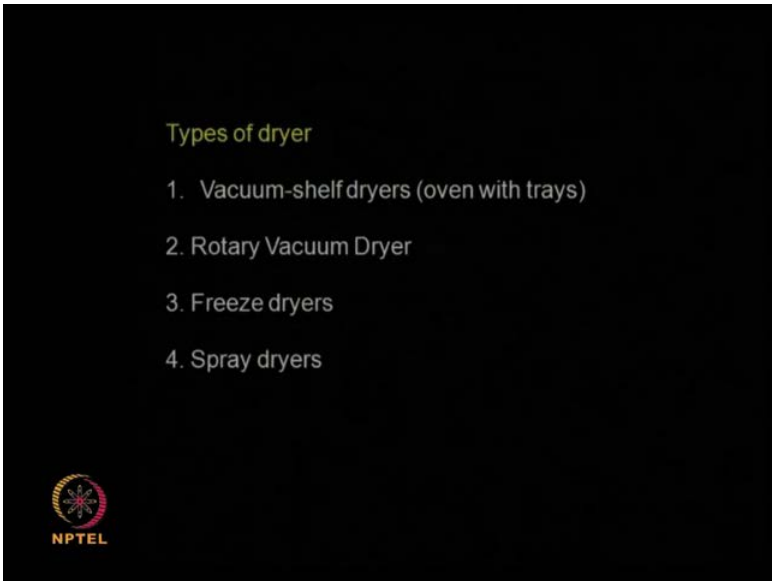

There are different types of dryers, we call it as vacuum shelf dryers or this a oven dryers, you must have seen at your house as well where we have drying carried out in a small oven or even in a small laboratory. If we have flowers or a bottles or plastic ware, you have washed them and you want to remove the moisture then we do it in a oven type of dryer or it is also called trade dryer, so many different names, it is a batch operation.

So, you pack your material in the trace and keep it inside, you apply vacuum or you did not apply the vacuum depending upon the setup and then you raise the temperature, maintaining it for a long period of time, depending upon your protocol. So, the temperature also depends upon the type of solvent you want to remove, how long or how low the moisture contain has to be and so on actually.

The another type of dryer is rotary vacuum dryer so as the name implies, there is a rotary drum which goes round and round, and there is a vacuum applied the drying and then the heat is also applied. So, the vacuum and the heat removes whatever moisture present and then it dries the product. The other type is the freeze drier that means, you are applying a very low temperature, so the water becomes ice that is how it is removed, the solid dry is removed, it is called freeze dryer.

And then finally, the spray dryers like how you make your instant coffee, so you pass the slurry, heat it up, pass it through a nozzle and when it comes out as a spray, the solvent completely operates and you form beautiful small sized fine particles and these particles are non hydroscopic, they are far apart. So, the flow ability is good, appeal is very good and solubility also increases because you have a very high surface area per volume and like a agglomeration or precipitation product.

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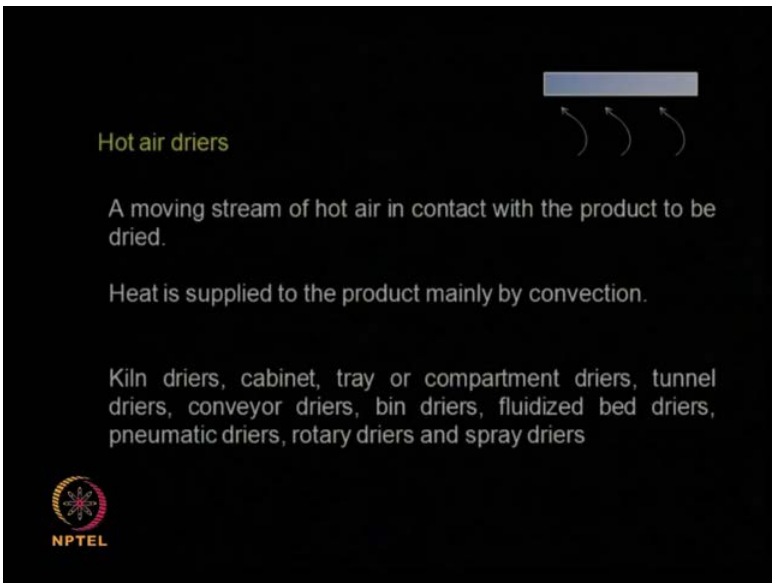

Hot air dryers is basically the material is dried because hot air is flowing and passed it so the hot air is in contact with the solid, which means to be dried. So, the heat transfer is through convection, it is only convection, so there are many types of dryers like your cement kilns, cabinet dryers, tray or compartment dryers, tunnel dryers, conveyor dryers, bin dryers, fluidized bed dryers, pneumatic dryers, rotary dryers and spray dryers. All these are based on the concept of hot air coming in contact with the solid so it carries the moisture away.

So, there is no direct contact between the solid and the heating element so it is only convection. So, convection means, the factors like the fluoride, the factors like and the turbulence that is creating the factors like a difference in temperature, all these govern the rate of heat removal.

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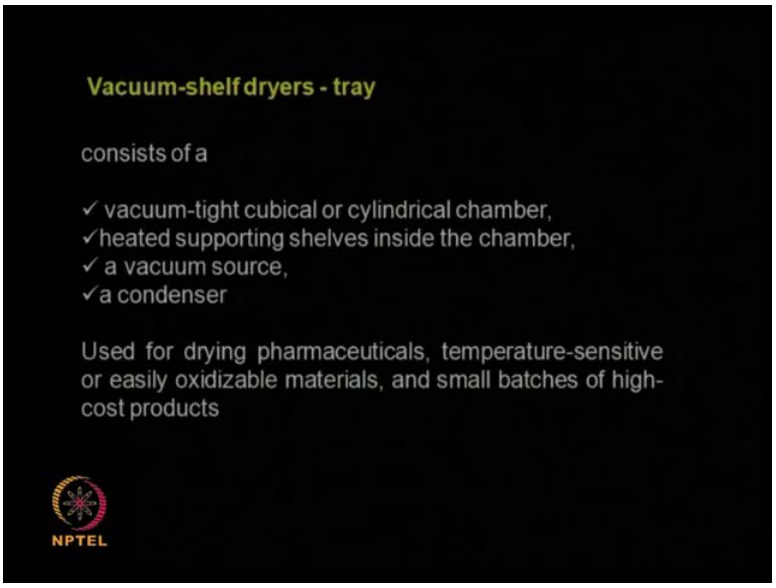

Let us look at vacuum shelf dryers or it also called tray dryers so you have a shelf and you have many trays inside, is a shelf could be a cubical or cylindrical chamber, it is maintain in tight condition. Because, you are applying a vacuum then you have a heating and there is a vacuum source and of course, you need a condenser, if you want to collect a whatever solvent or moisture that is evaporating. So, this is useful for drying pharmaceutical product, even temperature sensitive products is very good and we can use it for oxidizable material.

Because, you are applying vacuum, there is no air inside so there is no oxidization taking place so we can do it in small batches also. So, you have a few trays, you just fill up the trays with the materials that needs to be dried and run it for sufficient period of time and then you discharge all the materials then again you charge. So, it is very useful for small batches and also high cost product also because you have complete control on the drying process.

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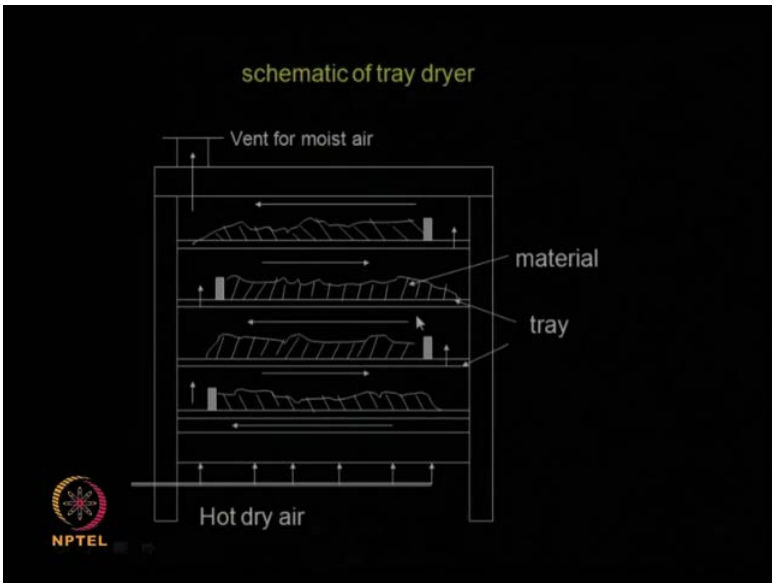

So, there is a typical schematic of a tray dryer so hot air is coming from the bottom so how do you heat air, there could be a external heater electrical or it could be a hot water heating up the air and it could be a dehumidifier. So, this air comes in contact with the solid material, which is placed on trays so the travel through the porous solid material there by carrying the moisture as well as drying the material.

And then it is finally vented out on the other side, you can have condenser here and condense all the moistures or solvent that is present in the solid material, this called a hot air oven. So, this is a batch operation so you need to one such dried remove all the trays, remove all the solid materials, again repack with the wet solid. And again, you start the process so it is a batch operation the loading and unloading can take up quite a lot of time.

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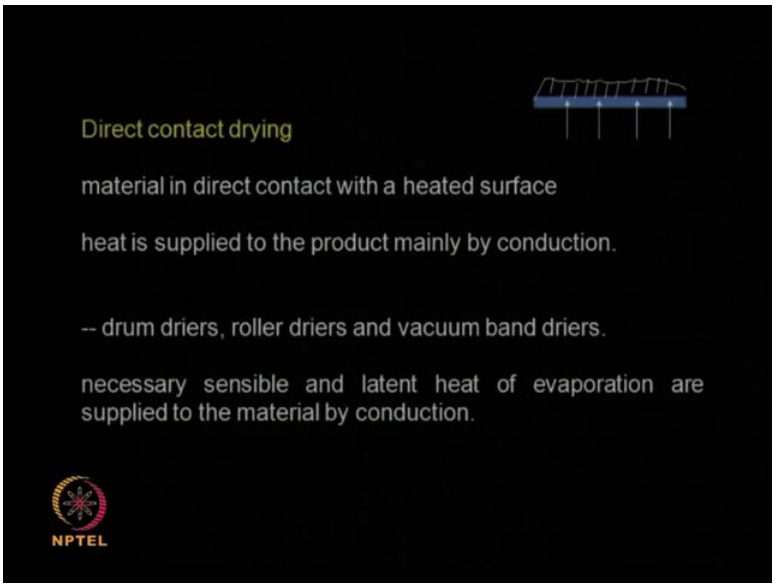

Then, you have the direct contact drying that means, a material which needs to be dried is in direct contact with the heated surface. So, the heat transfer is through conduction so the temperature is very, very high, rate of drying is also very, very high like drum dryers. So, you have a drum, rotating the hot drum the solid wet solid comes in contact with it, it gets dried and solid falls away from these surface of the drum. So, the surface again is clean to take up more metric roller dryers, belt dryers, band dryers all these come under that category, the solid is in direct contact with the heated surface.

So, the conduction process takes care of two things, one is to raise the temperature of the solid to required value and also provide the latent heat of evaporation of the liquid that means, solvent or water present in the solid interact. One thing here we have to be careful is, once the drying has happened and still the solid is in contact with the heated surface so the material should not get charged or over heated. And such a situation, you may have denaturisation, deactivation of the product or you may have a tar formation so the material loses it is activity and also it is texture and appearance.

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So, direct contact drying temperatures are very high, you have to be very careful about heat damage to sensitive food materials. So, you can also carried under low pressure so that, you do not want to apply very high temperatures actually.

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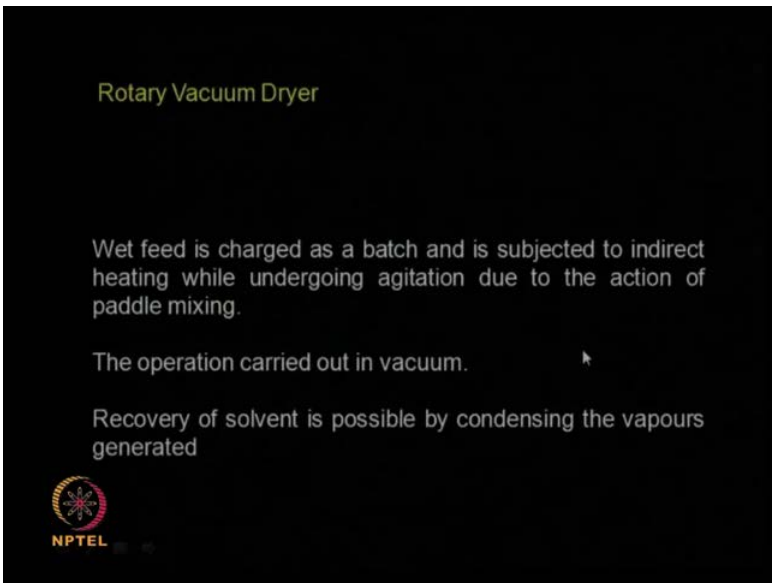

You have the rotary vacuum dryer so you have the drum rotating, there is a vacuum applied inside the drum, the drum surface is maintained at high temperature. So, the wet field is charged as a batch and is subjected to indirect heating and it is undergoing agitation due to the action of the paddle mixing. So here, you can carried out the

operation vacuum, we can recover the solvent by condensing the vapours, as it gets generated actually.

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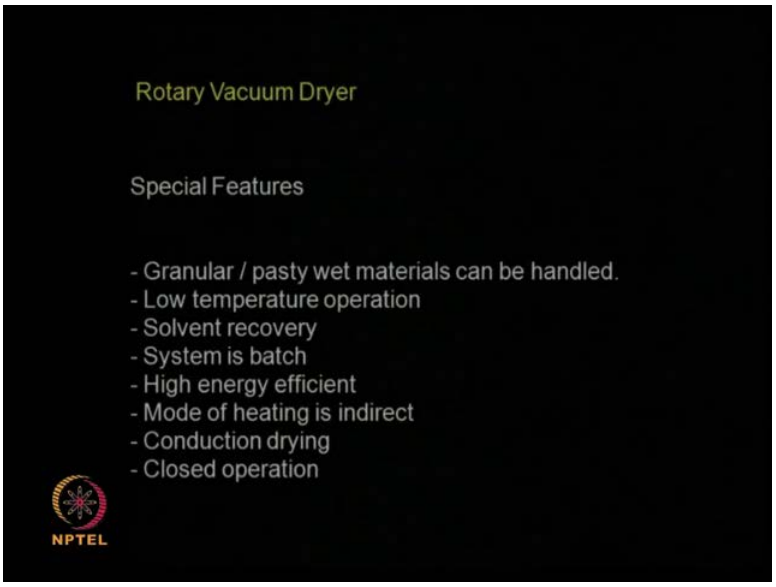

So, this dryer is very, very common, if you go to a pharmaceutical company you may find this type of dryers. It is very good for granular pasty wet materials, it is very good for low temperature operation and it is very good for solvent recovery. And we can do it in a batch and it is also very high energy efficient, the mode of heating can be indirect or it can be even direct.

So, we can heat directly the drum surface, that may it becomes conduction and if the drum surface is heated by some hot air that is flowing inside then it could be a convection and this whole thing can be maintained in a close environment. So, if the solids are various temperature sensitive and air sensitive then this is a very good operation.

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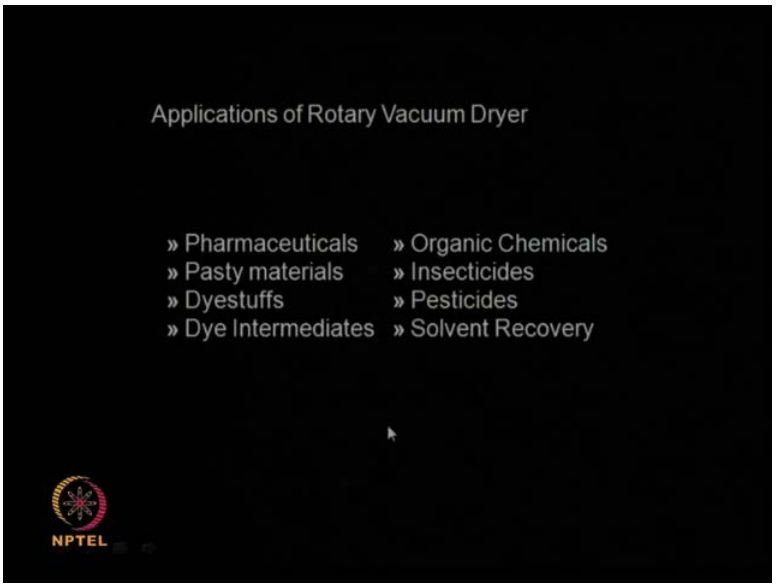

So, it is used quiet a lot in pharmaceutical, organic chemicals, insecticides, pesticides, for pasty materials, dyestuffs, dye intermediates and also for solvent recovery and also for solvent recovery and so on actually. So, this type of dryers, rotary vacuum dryers are very, very common in all these industries.

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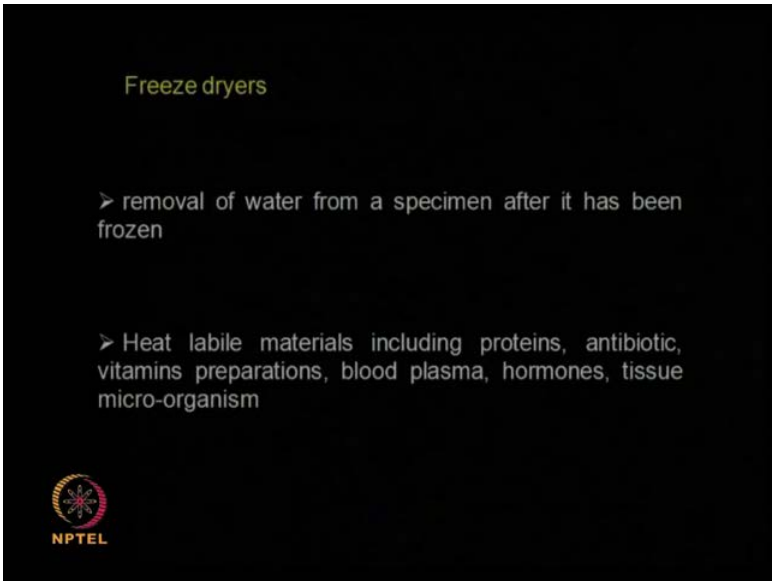

Freeze dryers, now the previous dryers where, you are applying heat or temperature to raise the temperature of the solid and the vapour. Whereas here, you are using the freezing concept that means, you are reducing the temperature so that, the moisture

becomes ice. So, water is removed after it has been frozen, it is very very good for heat labile materials like proteins, antibiotic, vitamins, blood plasma, hormones, tissue, micro organisms.

So, here if you rise the temperature what will happen, the material will totally get deactivated so there is no other way other than using a freeze drying here. So here, what you do is, you reduce the temperature so that, the water becomes ice so it is like a frozen.

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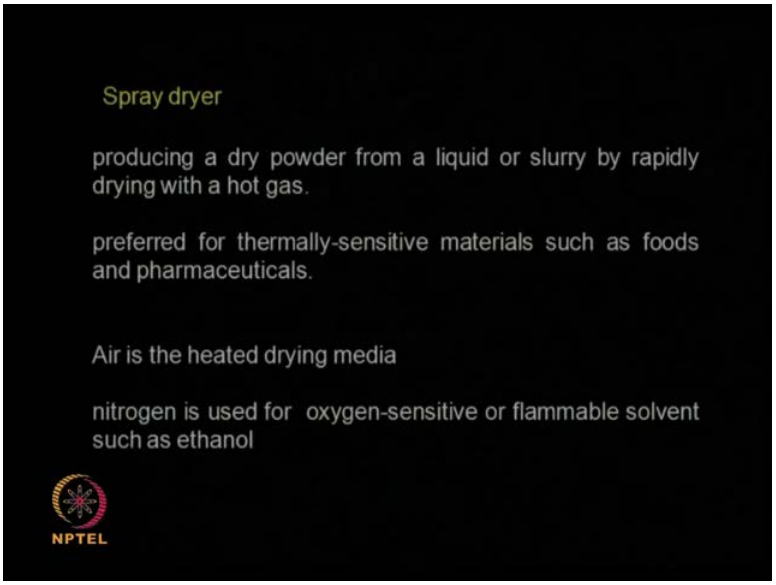

Then, we have the spray dryer, by doing spray drying you are producing a dry powder, completely non hydroscopic. So, you are producing from a slurry by rapidly drying with the hot gas, it is very good for thermally sensitive materials, food products, pharmaceuticals products.

So here, air is the drying medium, we can use nitrogen if you think the oxygen present in the air can lead to flammability or oxidation and so on actually. So, if your solid contains even flammable solvent then oxygen free nitrogen may be used as the heating medium for this material.

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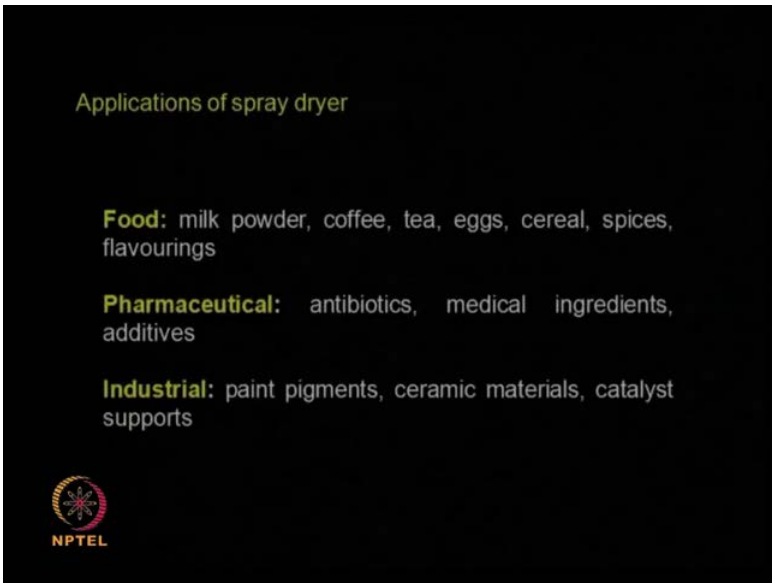

So, spray drying is now a days used in preparation of milk powder, coffee, tea, even egg, spray dried eggs, cereals, spices, flavourings all these are made spray dryers. Even pharmaceutical products like antibiotics, medical ingredients, additives, paint pigments, ceramic material, catalyst support, so all these are made by this concept of spray drying.

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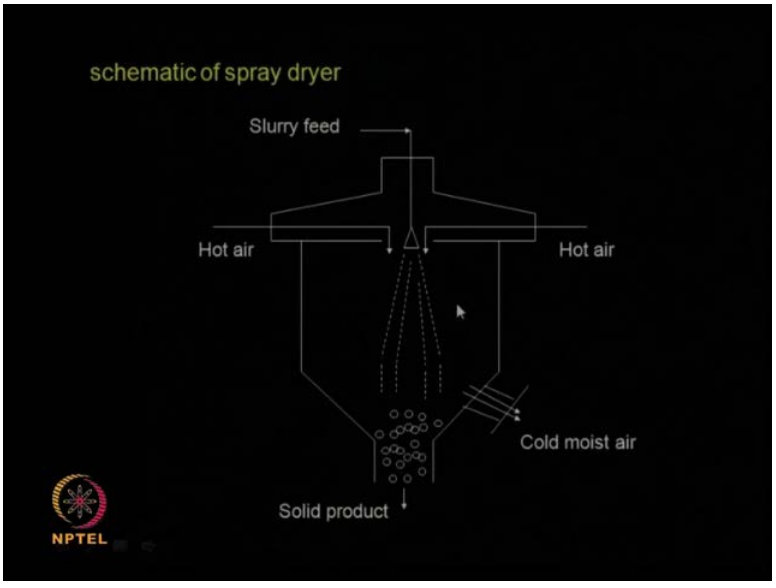

So, how does it look like so this is a typical setup of a spray dryer so you are feeding a slurry to the top, it comes out through the nozzle as a fine spray. We have hot air coming in contact, so your solvent for water gets evaporated, so fine microns size particles are

formed here, which are collected here. Now, the hot air has become slightly colder because it has given the heat here plus the moisture that was present in the solid gets transferred, that is why it has become a cold moist air.

So, this we can do it continuously, we can continuously feed, continuously send hot air and continuously we do the solid product. So, this a very good technique and widely used in food and flavouring industry.

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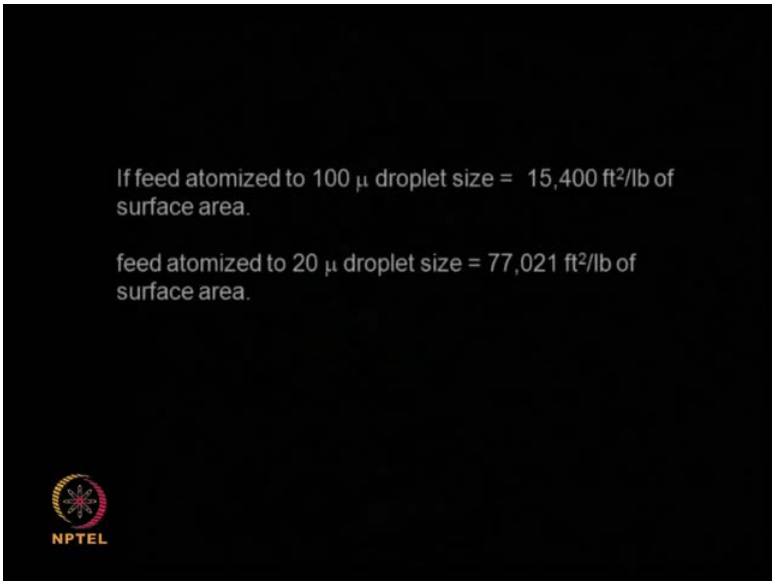

So, the beauty of it is, finer the particle higher will be the surface area per unit volume so higher is the surface area per unit volume what happens, heat transfer is good so drying takes place very fast. And also, if we have this as a product, solubility also increases, because it has got very high surface area to volume. For example, if I atomize it to 100 micron droplet size, the area per pound will be 15400 feet square per pound.

Whereas, if I bring it down that means, I make the particle smaller 20 microns look here, we are almost getting 77000 foot square per pound. That means, you are rising it by almost factor of 5, so that is the main advantage of increase in the surface area or reducing the size of these particles.

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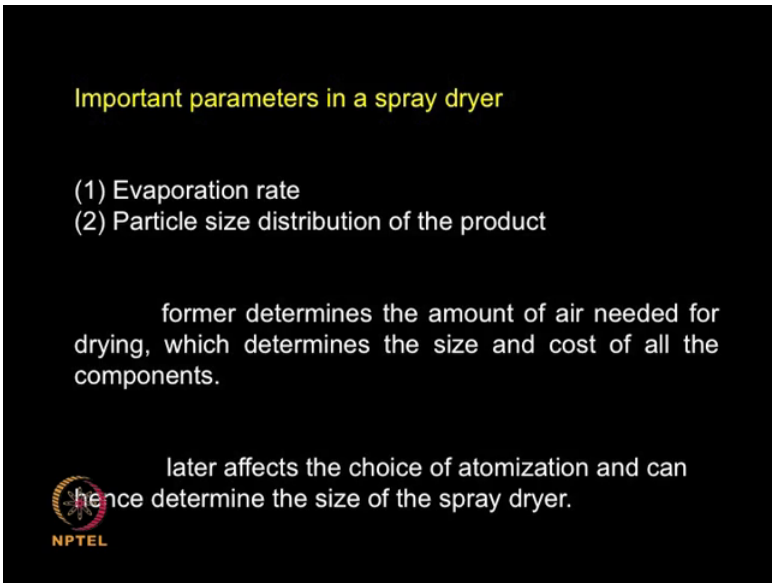

So, what are the important parameters one need to consider in spray drying, evaporation rate that means, how fast this solvent are moisture is evaporating. Because, that determines the amount of air needed, how much air I need to put in to evaporate so many grams of water per minute so that tells me how much air is required. So, when I know how much air is required, that determine the size and cost of all the components. Because, I need to have a air blower or a air compressor to match that particular capacity so that determines the size and the cost.

That is why the operation rate is a very important parameter, what is the other one, particle size distribution of the product. So, do I need very fine particle, do I need very large particle so the particle sizes should be spread out or should be very small so that determines the atomization so that also tells the size of the dryer. So, what should be my atomization design and what should be the size so these are the two important parameters. The operation rate that means, how fast you want the solvent to evaporate, other one is what should be my particle size and it is distribution, that is the product.

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So, for a given evaporation rate, so if I fix my evaporation rate saying that, I want to evaporate so many grams of water per minute. So, if I have a very high temperature difference then I will require less air so if I require less air then my blower can be smaller so the whole system can be smaller so the cost comes down. But then the point is, I need to have high temperature drying force that means, air has to be heated up to a very high temperature.

So, one of the problem may be the material, which I am trying to drive, might be temperature labile that means, it may loose it is activity, if you heated up too much. So, I can try to drive with the high temperature driving force because my setup can be smaller. But, I have to be careful that this material does not get deactivated because of the high temperature so you need to keep that particular point in mind.

So, if I reduce the temperature difference that means, I do not use very hot air but I use medium of hot air then I require more air. That means, my size of the dryer has to be bigger, my size of the blower or compressor, which is pumping in the air also has to be bigger. But then the advantage is, I am not heating it up to very high temperature that means, there is no worry about deactivation of the material because of high temperature.

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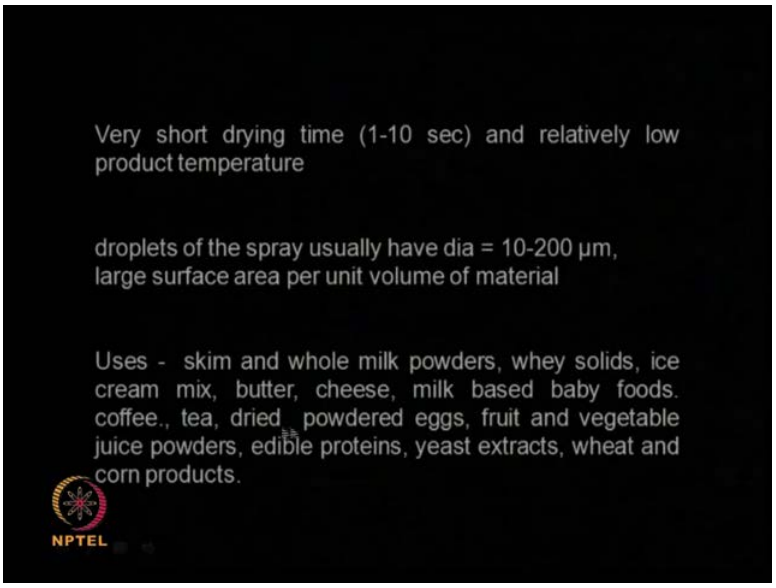

So, I can reach very short drying time and low product temperature using these type of a dryer. So, generally, the particle sizes will be 10 to 200 micron, so I get quiet a good surface area per unit volume of the material. So, we can use it for skim and whole milk powders, whey solids, ice cream mix, butter, cheese, milk based baby foods, coffee, tea, dried powdered eggs so lot of food flavouring type of applications, as I said before.

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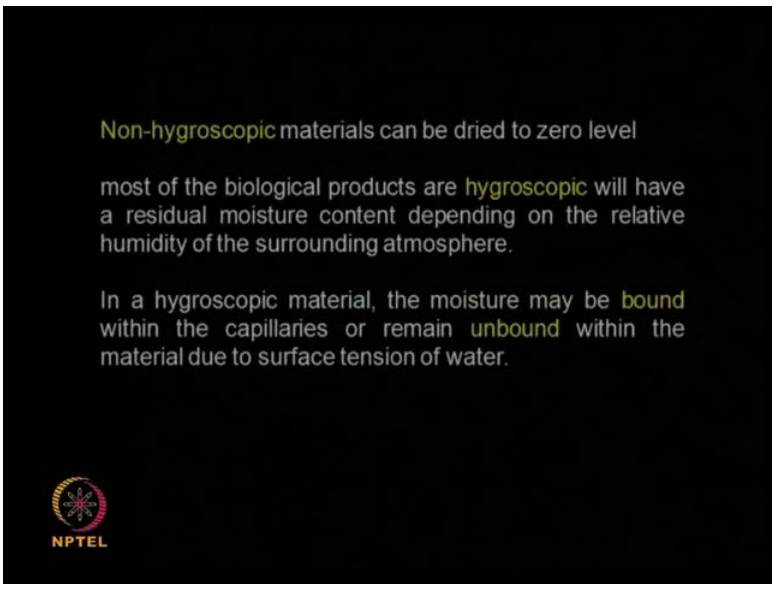

And we can even dry material if it is a non hygroscopic that is, material it does not taking moisture on its own then we can bring down the amount of moisture present to almost 0

value. Now, most of the biological products are hygroscopic so there will always be some residual moisture content, whereas some of the organic molecules can be non hygroscopic.

But, biological molecules are hygroscopic, so there will be some residual moisture even after complete drying, that depends on the relative humidity of the air which we are using.

Now, the hygroscopic material may have two types of water, one is called the bound water and other is called the unbound water. Unbound water is the water, which is present in the material due to surface tension whereas, bound water is, water which is present inside the capillaries of the solid. So, it will be very difficult for you to remove bound water whereas, unbound water can be removed easily.

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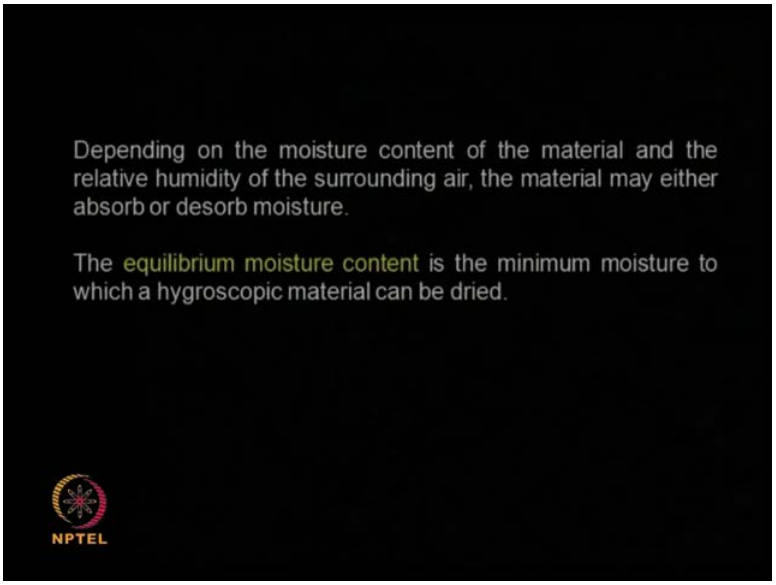

So, you have a solid and it has got certain amount of moisture and you have air at certain relative humidity. So, when you bring them all together both of them, there is a equilibrium that is found. So, the water vapour may evaporate if the relative humidity of the air surrounding it is low or the water vapour may condense on the solid, if the relative humidity of the air is high and the solid is reasonably dry. That means, it does not have much moisture so both of them come to an equilibrium, that calls an any equilibrium moisture content.

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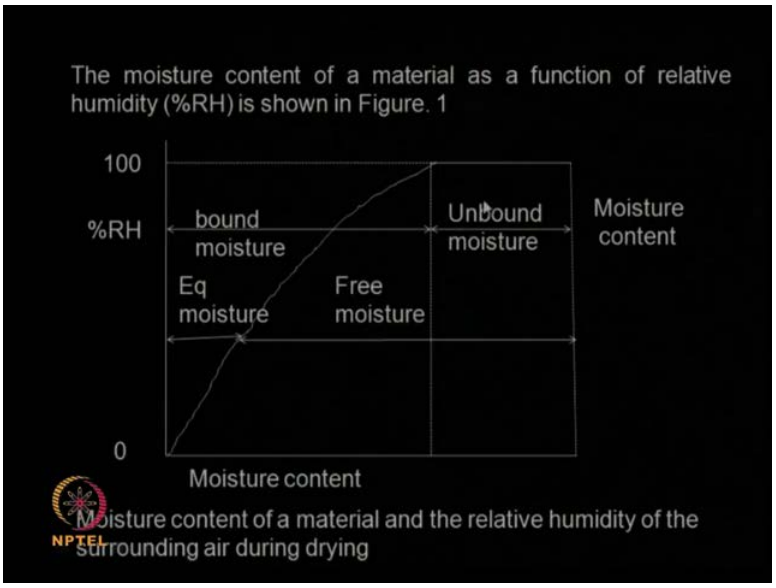

So, you have air, air has some moisture that is determined by the relative humidity and then you have the solid which has got some moisture. So, when you bring both of them together, there is an equilibrium created and the water present in the air may either get observed by the solid or it will get desorbed, depending upon the equilibrium that is formed between the wet air and the solid, wet solid and that is called the equilibrium moisture content.

So, if you look at the diagram between moisture content on the x axis and the percentage relative humidity on the y axis. So, we have something called the equilibrium moisture and then we have something called the free moisture. So, as I said, you cannot dry below the equilibrium moisture for a hydroscopic material now, you also have two types of moisture, one is called the unbound moisture, other one is called the bound moisture. So, unbound moisture is what is the amount of moisture present in the solid is much more easier to remove whereas, it is much more difficult to remove bound moisture.

Now, the moisture content in the solid as I mentioned, depends upon the relative humidity of the air that is surrounding that solid. So, as we can see, if the relative humidity keeps coming down, the moisture content the equilibrium moisture content in the solid also will come down. So, if the relative humidity is very, very high, the equilibrium moisture content in the solid will also be very, very high.

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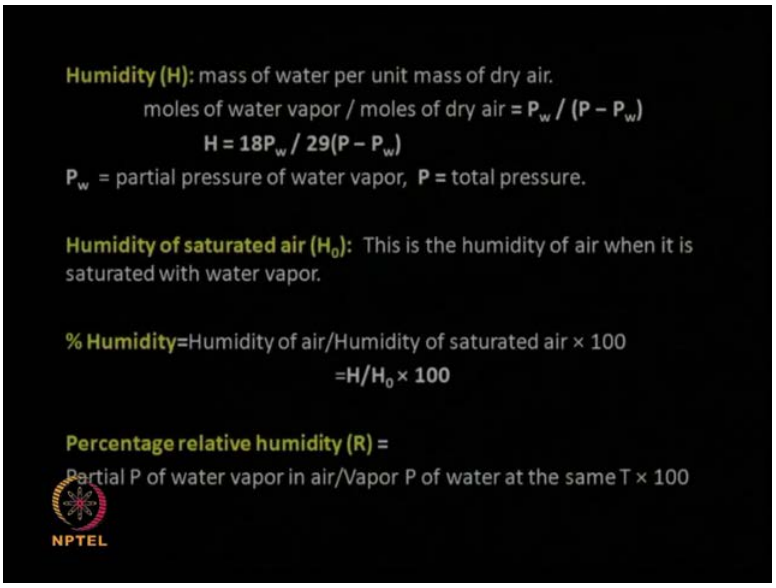

Now, there are certain simple relationships, which connects the humidity, relative humidity, saturation of moisture in air so you need to understand these definitions. What is humidity, humidity is mass of water per unit mass of dry air or it would be moles of water vapour per moles of dry air.

So, if P w is partial pressure of water vapour then P w divided by P minus P w is the humidity, that P is the total pressure. So, humidity is the moles of water vapour divided by moles of dry air so this is P w is the partial pressure of water vapour divided by P minus P w, that gives you the humidity.

Now, if you bring it down instead of moles, we can use for water, molecular weight is 18 and for air, we bring it as 29 so it is still valid, this is the humidity. Now, humidity of saturated air H naught, this is the humidity of air when this saturated in the water vapour that means, at those conditions, temperature and relative humidity. This is the humidity of air when it is saturated with water vapour, completely saturated, it cannot take up any more water.

Now, percentage humidity is the humidity of air divided by humidity of saturated air so obviously, this is H by H naught into 100, this is called the percentage humidity. Now, percentage relative humidity is the partial pressure of water vapour in air divided by vapour pressure of water at the same temperature into 100. So, this is the amount of

water that present in the air and this is the vapour pressure of water at the same temperature, that gives you the percentage relative humidity.

So, if the percentage relative humidity is low that means, amount of water present at that temperature in the air is low, the percentage relative humidity is very very high nearing 100 that means fully saturated, lot of water is present in the air actually. Because, say it is function of amount of water, partial pressure of water in air present and vapour pressure of water in the same temperature, this is percentage of relative humidity.

So, this is a very important term, which tells you how much water that present in air and how much more, the air can take up. So, if the percentage relative humidity is nearing 100 that means, it will not be able to take up any more water. So, these are important terminologies one should know, if one wants to understand the concept of a dry air, wet air, bound moisture, unbound moisture and so on actually.

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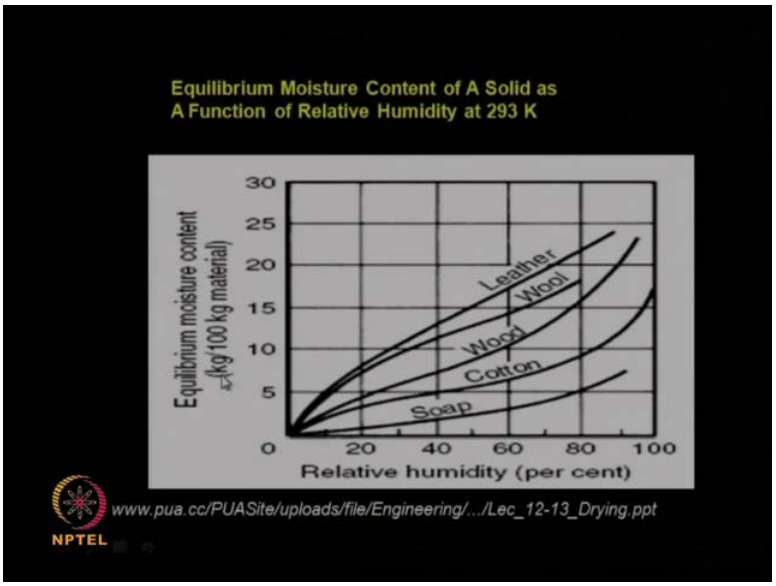

So, each solid has certain equilibrium moisture content depending upon the solid properties, the porosity, types of pores it has and so on, actually. So, this is a picture taken from this particular reference so in this axis, we have the relative humidity that is x axis, percentage and in the y axis, you have the equilibrium moisture content that means, kg per hundred kg of material. So, if you take leather, the graph is going like that so leather can take up more moisture than say, wool than wood, cotton, soap.

So, the same relative humidity, the equilibrium moisture in leather is several times more than soap, as you can see. This is at 293 K, so 293 K is 20 degree centigrade so if I have a graph like this for any material of my interest, I will tell at certain relative humidity what is the minimum I can reach irrespectively the moisture present in that particular solid. So, at a relative humidity of say for example, 40 percent if I take cotton, the lowest amount of moisture I can reach down to is 5 kg of moisture per 100 kg of material.

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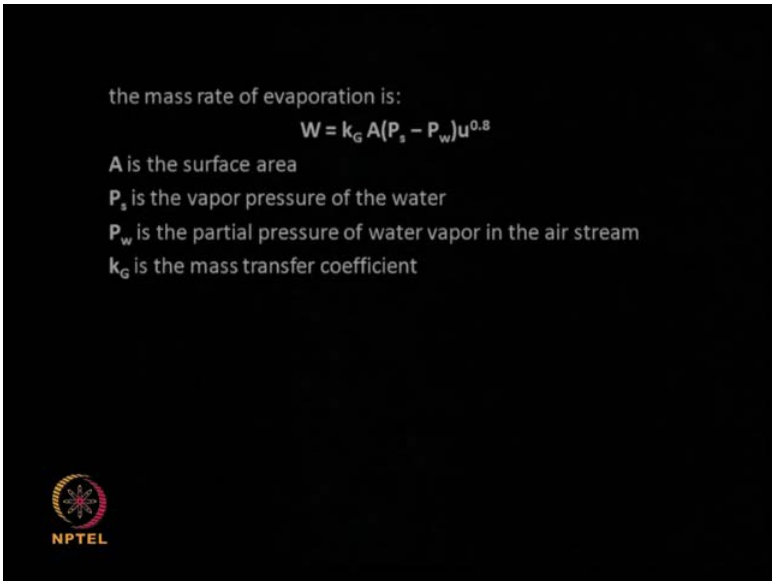

So, the mass rate of the evaporation that means, I am applying a heat so the water gets evaporated. So, here, the mass rate of evaporation, K G is the mass stands for coefficient, A is the area, P s is the vapour pressure of the water, P w is the partial pressure of water vapour in the air, u is the velocity and base to the power 0.8 is the mass rate of evaporation and water.

So, it is the function of area that means, the area exposed to the air, P s is the vapour pressure of water; whereas, P w is the partial pressure of water vapour in the air stream. So, the P s minus P w is the driving force for water to evaporate into the air stream from the solid stream. And u comes in here because there is a turbulence and forces, which increases the mass transfer coefficient that means, transfer of the water vapour from the solid surface to the bulk of the air.

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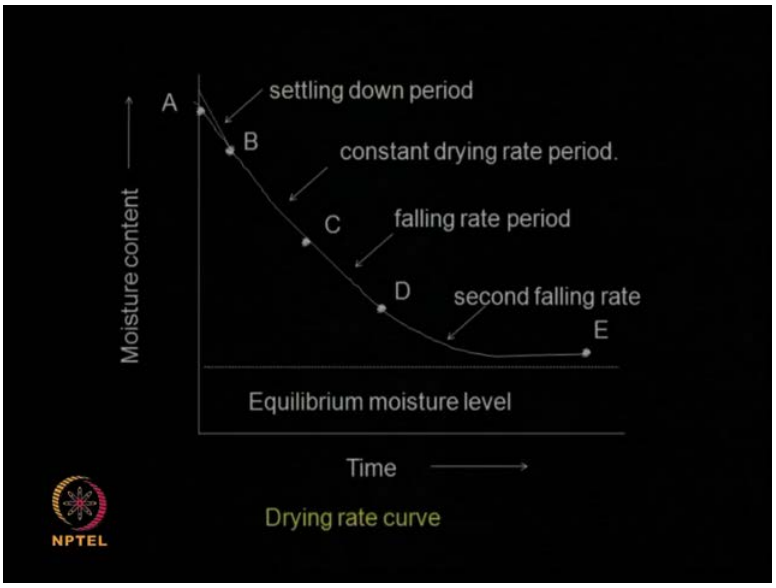

Now, as I keep drying my material, initially there is lot of moisture present so drying is faster, uniformly it is getting dried but after sometime, the amount of moisture goes down and down. So, whatever moisture is present inside some of those interstities or capillaries, has to come up to the surface and then get dried so your rate of drying will keep going down. So, if you look at the drying rate curve that is, x axis is time, y axis is the moisture content so initially, you take a wet solid and leave it in an air atmosphere.

So, initially you call it settling period so some drying takes place after that, for a long time the rate of drying is constant, that is called the constant drying rate period. Here, we have so much moisture present so the amount of moisture present at the surface is not the limiting. So, it is the amount of heat supplied by you, enough for the latent heat of vaporisation that means, your heat is good enough for the water from the liquid state to go into the gaseous state.

Only that is controlling so the rate of drying is constant so this is like a straight line now, after some time, all the moisture on the surface is evaporated. Now, moisture from inside has to come out and then start getting evaporated so here, what do you have is, the diffusion of these moisture which is present inside is controlling. So, the rate of drying goes down, this is called the falling rate period so as time goes on, it become more and more difficult because the moisture present very much inside has to diffuse through the capillaries come out and get evaporated.

So, there rate of drying becomes curve and slowly it peters out like this so initially, you have constant drying rate and then after some time, the rate of drying it is falling down and down. So, if you are looking at designing dryer and if you want to calculate, what should be the drying time or what will be the drying time, you have two types of time, one is the constant drying and another one is the falling rate drying so the constant rate drying period and falling rate period.

So, these two times need to be considered now, as the drying happens and happens, the material cannot give up moisture after some time, this moisture content is called the equilibrium moisture content, which I discussed about few slides back. So, equilibrium moisture content depends upon the percentage relative humidity so the equilibrium moisture content depends on percentage relative humidity as well as the type of material, how hydroscopic it is, how porous it is and so on actually.

For example, I said a leather can take up more moisture so it will have higher equilibrium moisture content than say soap. So, here, you have a content drying rate and then you have a falling drying rate and finally, the moisture content settles down to the equilibrium moisture content, it is called the drying rate curve.

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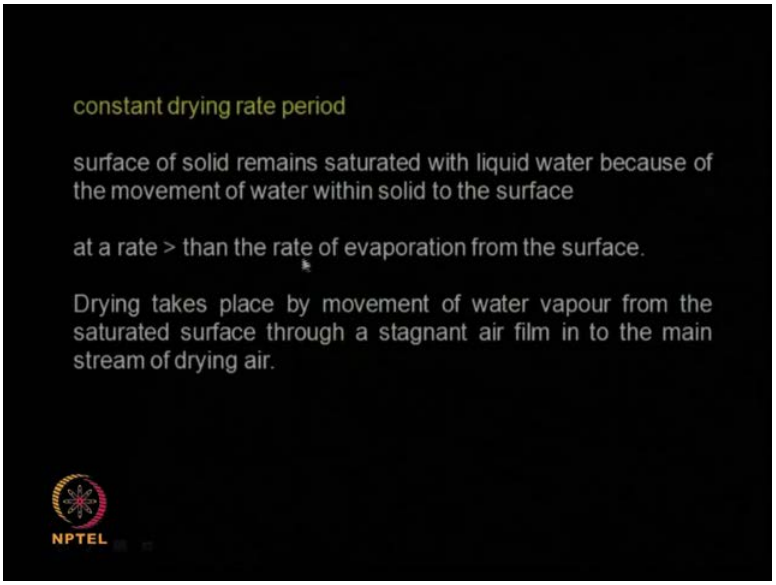

So, the constant drying rate surface of solid remains saturated with the liquid, there is lot of water. So, rate is greater than the rate of evaporation from the surface, drying takes place by the movement of water vapour from the saturated surface through a stagnant air

film. So, there is a stagnant air film, so the water from the surface passes through the stagnant air film and then it gets evaporated and goes to the bulk of the air.

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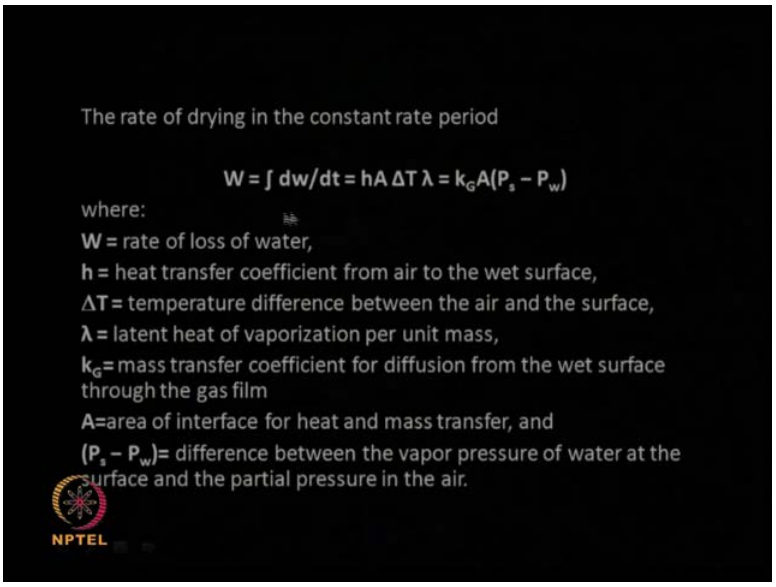

So, here, in a constant drying period the advantage is, we can call the rate of drying, d w by d t is equal to a constant, that is the beauty of this. Now, there are two things happening, one is the vapour is getting evaporated and then the heat is just sufficient for the water to move from the liquid to the vapour state. So, two things are happening, one is related to the evaporation of water, which is given by K G mass stands for coefficient, A is the area, P s is your vapour pressure of water and P w is the partial pressure of water in the air, this is the driving force, this area.

We can put in the velocity also here, if you want to consider the effects of air flow on changes in the mass transfer coefficient. Now, other one is the heat transfer that means, the heat you are supplying is sufficient to evaporate or convert the water from the liquid to the vapour state or water from a liquid to the gaseous state.

So, that is lambda coming in, that is the latent heat of vaporisation and we have the delta T coming here, that is the temperature difference between the air and surface again, we have the area. Then, we may have the heat transfer coefficient coming into the picture because the heat supplied and heat of evaporation coming here. So, many things are happening, you have constant rate drying, in that period the drying force for the water to evaporate from the surface to the bulk of the gas is the P s minus P w. Water is

evaporating because you are supplying sufficient heat for converting liquid to the gaseous state.

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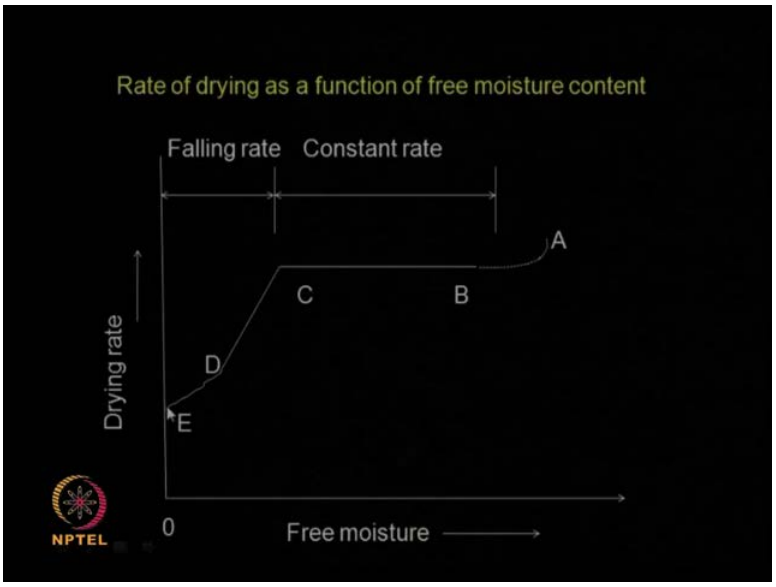

So, this is another the way of talking about the constant rate and falling rate period, if you look at free moisture and drying rate. So initially, we call this as settling down. Then you have constant rate that is why, drying rate is constant so you have a parallel line and then you have a falling rate, two types of falling you can put here 1 falling, 2 falling. So, this region is called the constant rate, this region is called the drying rate or falling rate, this with respect to the free moisture. Now, this is the equilibrium moisture here, below which we cannot and dry your solid.

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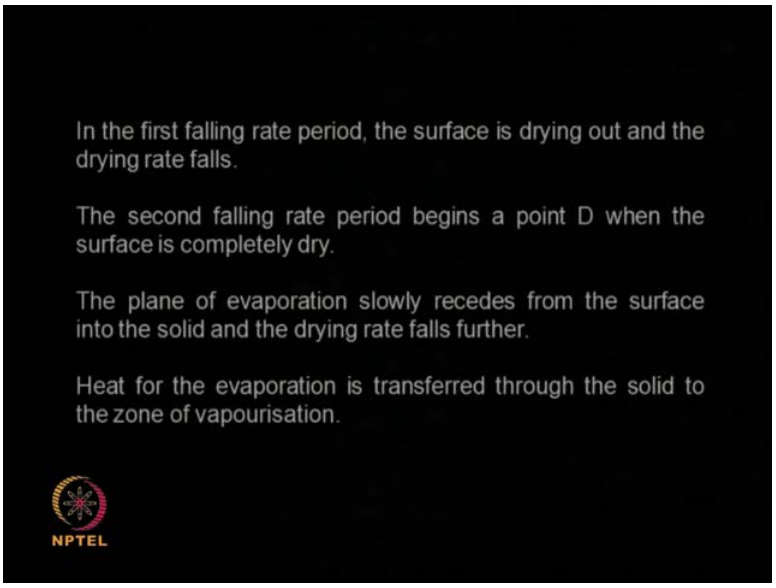

So, in the first falling rate, you have the surface drying out and drying rate fall, the second falling rate may be the surface is completely dry and moisture present indeed, interstities or even capillaries starts drying out. So, the plane of evaporation is slowly slowly going inside the surface actually so there is a zone of evaporation taking place. So, it becoming difficult and difficult for the moisture present in the interstities to get evaporated.

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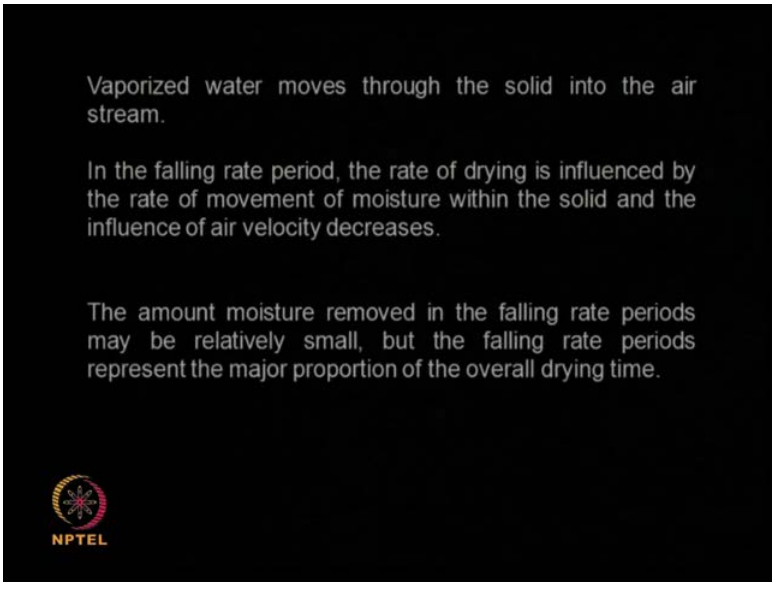

So, in the falling rate period, the rate of drying is influenced by the rate of movement of moisture within the solid and the influence of air velocity decreases actually. So, the air velocity, which is contributing to the drying decreases so it is only the diffusion. So, the amount of moisture removed in the falling rate may be very small but generally, the falling rates are very, very large. So, it is the constant rate may be only say few minutes but the falling rate period could be several hours as well so we need to consider both, if you are designing a dryer.

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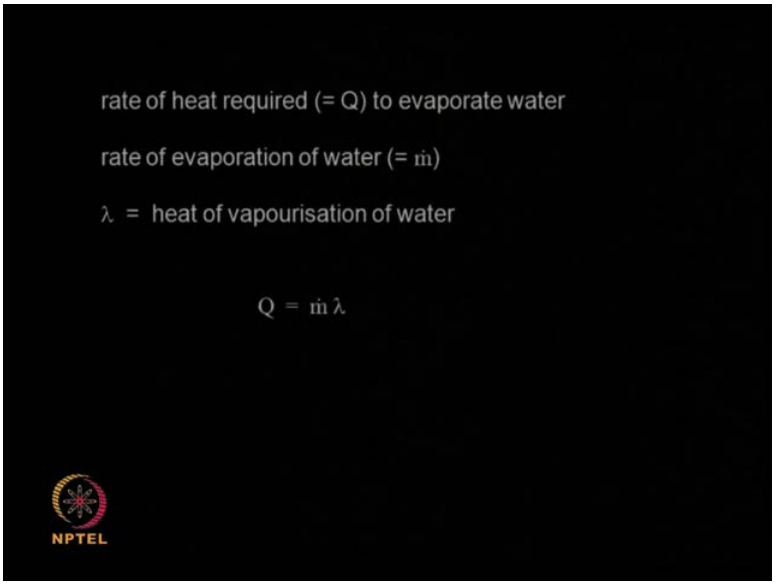

Now, rate of heat required depends upon the amount of water that is evaporating and also the heat of vaporisation of water. So, the rate of heat required Q is equal to m dot lambda, lambda is heat of vaporisation, m dot is the rate of evaporation of water. That means, grams water per minute or kg of water per hour that is getting evaporated during the process.

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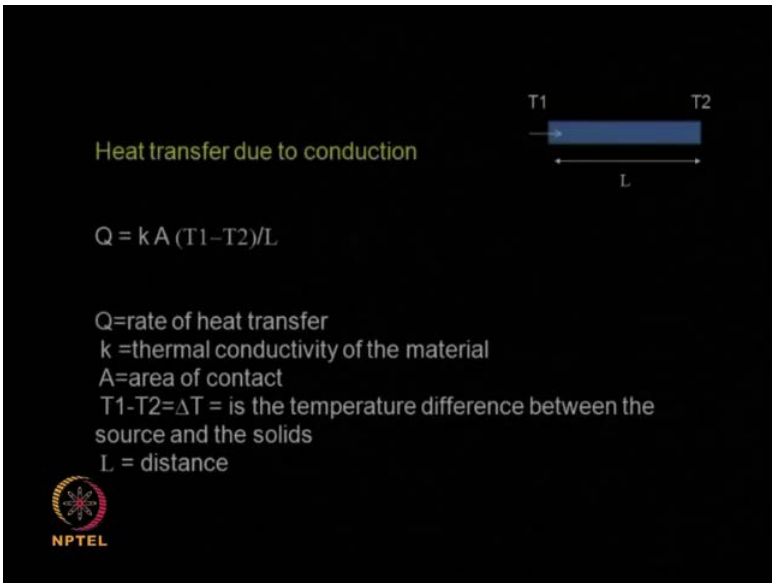

Now, let us look at some simple relationships which we might have done it in our school, the amount of heat transferred during conduction, the amount of heat transferred during convection and amount of heat transferred during radiation. Now, if you have a solid material which is at T 1 at one end and T 2 at another end, T 1 is higher than T 2 so the heat is moving along this direction or the heat is getting transferred.

If the length is L then we can say Q the rate of heat transferred, K is the thermal conductivity of the material, A is the area, T 1 minus T 2 is the driving force in temperature divided by L, this is a very simple equation which we have seen long time back. So, the rate of heat transfer is a function of the thermal conductivity of the material, the cross sectional area of the material and the drying force with respect to temperature and it is inversely proportional to the distance between these two planes.

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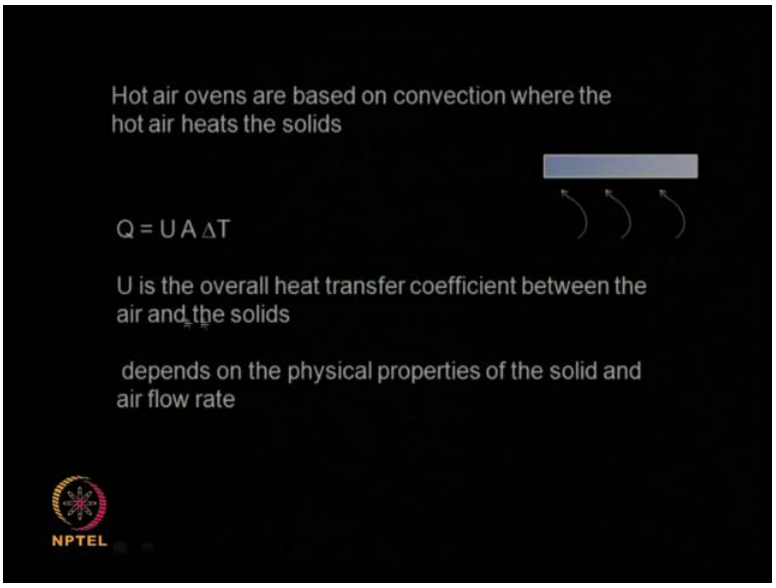

Now, let us look at heat transferred due to convection, this is happening in hot air ovens where, there is no direct contact of the solid with the heating but the air which is hot is transferring the heat. So, here, you have Q is equal to U A delta T, U is the overall heat transfer coefficient between the air and the solids, is called overall heat transfer because it is made up of several resistances. A is again area, delta T is the drying force in temperature that means, T 1 could be the temperature of the hot air, T 2 could be the temperature of the solids.

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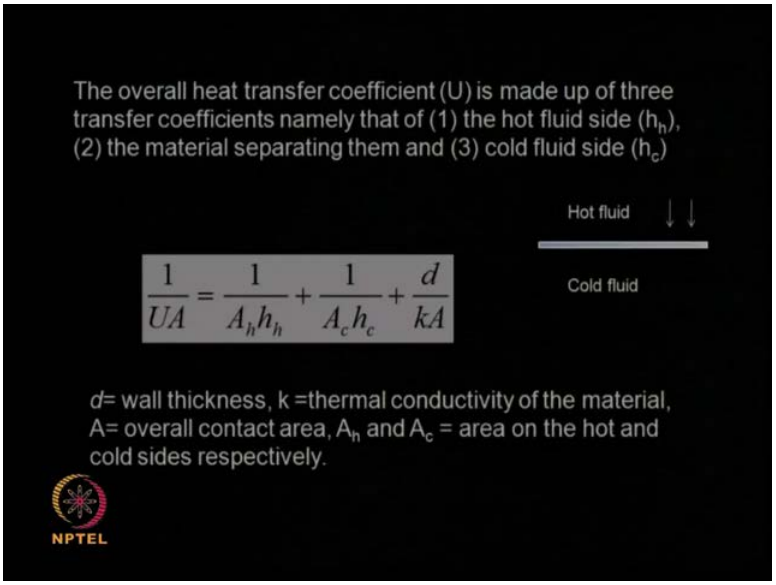

So, the overall heat transfer coefficient is made up of many sub parts because if I take a set up like this, we have some hot fluid flowing outside, cold fluid flowing inside and separated by some material metal. So, heat is getting transferred from the hot to the cold now, the overall heat transfer coefficient is made up of three heat transfer. Because, there is one heat, which transferring heat from the hot fluid side here and then you have made heat transferred through the solid material and then heat transferred in the cold fluid side.

So, you have three heats the hot side, the material and the cold side, that is why the overall heat transfer coefficient has to consider all these three factors. So, if you have heat transfer coefficient h h as the hot fluid side, h c as cold fluid side and then K the thermal conductivity of the material separating these two. Then we have 1 divided by U A, U A is the overall heat transfer coefficient, A is the area equal to 1 divided by A h that is, area on the hot side.

Heat transfer coefficient on the hot side plus 1 divided by A c that is, area on the cold side, h c is the heat transfer coefficient in the cold side plus d, d is the wall thickness, K is the thermal conductivity of the material and A is your overall contact area and look here this A is same as this A. Now, you can have these two areas almost same or you can have very, very small d. So, so many possibilities are there, depending upon the geometry of the heat transfer that is taking place.

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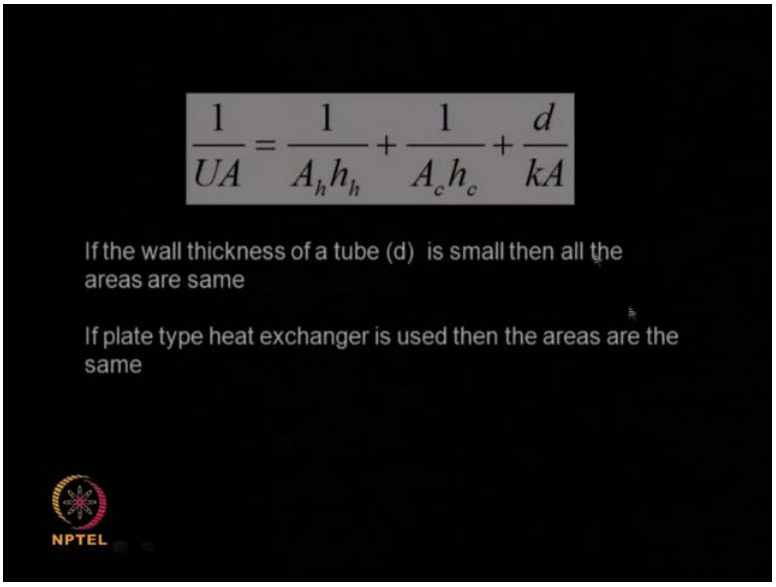

So, if the diameter of the tube is very very small, you can neglect this term or we can have the same A h and A c especially, if you are talking about plate type heat exchangers where, you have plates. Hot fluid flowing, cold fluids flowing on the other side then A h is equal to A c whereas, if you have a tubular concentric tubes where, hot fluid may be flowing outside a tube, cold fluid may be flowing inside the tube then A h is not same as A c.

But then if you have a small thickness material, you may be able to neglect this and if the thickness again is very, very small, A h can be equal to A c. But then normally A h will be different from A c in a tubular type of a heat exchanger designs whereas, A h is equal to A c, if you have plate type of heat exchangers.

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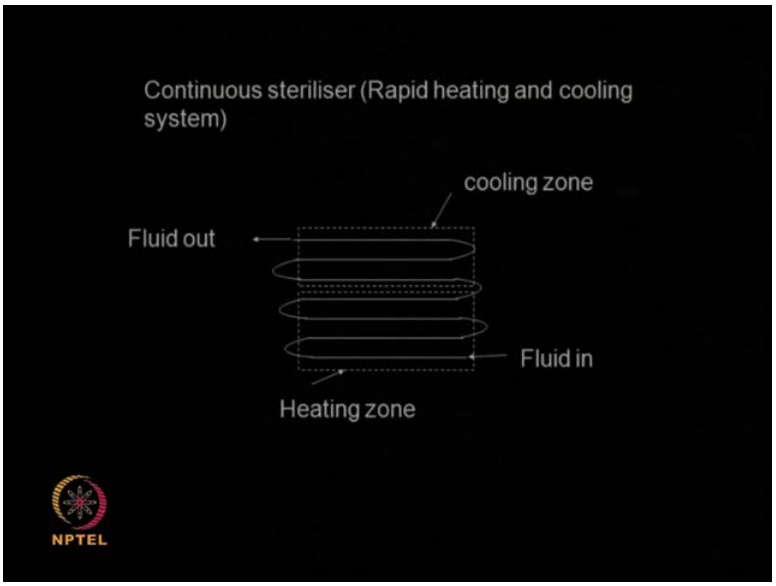

Let us look at the continuous sterilizers so you are having fluid coming in and then it gets heated up and then going finally going out. Here, you may be giving heat, here you may be cooling so you have rapid heating and rapid cooling. So, the advantage is, by rapid heating we are able to sterilize the material that means, you are killing all the bacteria where, rapid cooling what are we doing is, you are bringing the temperature down so fast, that the material does not get deactivated.

Especially, it is very good for biological product, which are thermally labile so this is called rapid heating rapid cooling system where, one side you have the heating zone,

another side you have the cooling zone. And fluids comes in through the tubes, quickly gets heated up and it gets quickly cooled.

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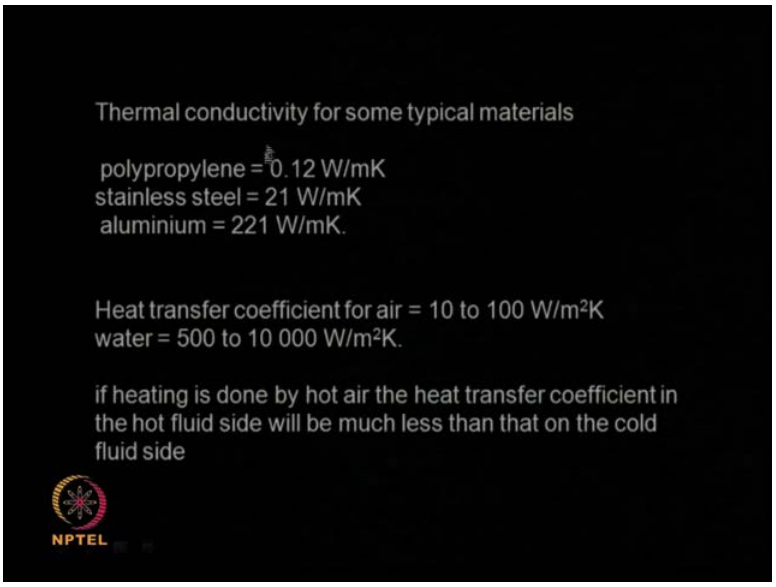

So, let us look at this thermal conductivities of some material for example, if we take polypropylene, it is 0.12 watts per meter per Kelvin whereas, if we take stainless steel, it is 21, it is a big jump. Stainless steel of course, is a metal so it is got a very high thermal conductivity, if you take aluminium it is again very, very high. So, this is the best if you want to conduct but then no body uses this type of thing and then polypropylene is the worst because the heat conductivity are so low, that it offers considerable resistance.

Now, let us look at heat transfer coefficients for air, it is about 10 to 100 watts per meter square per Kelvin whereas, if you go to water look at it, it is a big jump. So, water is high heat transfer coefficient than air so most of the liquids have much, much higher heat transfer coefficient than air.

Air is a very poor heating medium but then that is how it is so if the heating is done by hot air, the heat transfer coefficient in the hot fluid side will be much less than that of the cold fluid side. Because, the hot fluid side has air, cold fluid side may be having water or any liquid, which has got a higher heat transfer coefficient whereas, air is the worst heating medium, it has got very low heat transfer coefficient.

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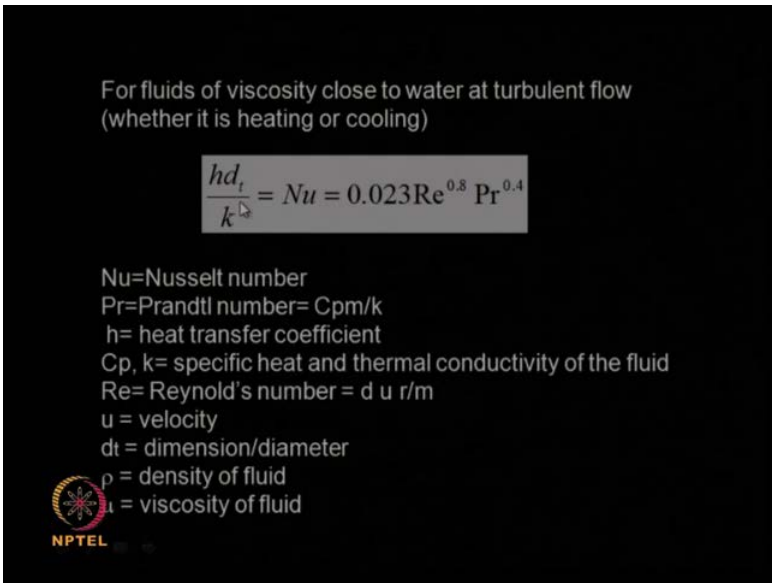

So, if you have fluids of viscosity close to water so when you are using such a fluid at turbulent condition, you can use this type of relationship for calculating heat transfer coefficient. So, h d t is the dimension divided by K is thermal conductivity of the fluid equal to 0.023, this is called Reynolds number, this is called prandtl number. Prandtl number is Cpm by K, C p is the specific heat and the m the viscosity of the fluid, K is the thermal conductivity of the fluid.

Whereas, the R e the Reynolds number is given by dimension d, u is velocity, rho is the density of the fluid, mu is the viscosity of the fluid so that is called the Reynolds number. So, there are many correlation available in literature and which gives you an idea about the heat transfer coefficient depending upon the physical properties of the fluid.

Prandtl number gives you an idea about the physical properties of the fluid and Reynolds number, Reynolds number gives you an idea about the velocity. So, based on those, you can transfer the heat transfer coefficient so using this correlations, if you are using it in your system, we can calculate the heat transfer coefficients.

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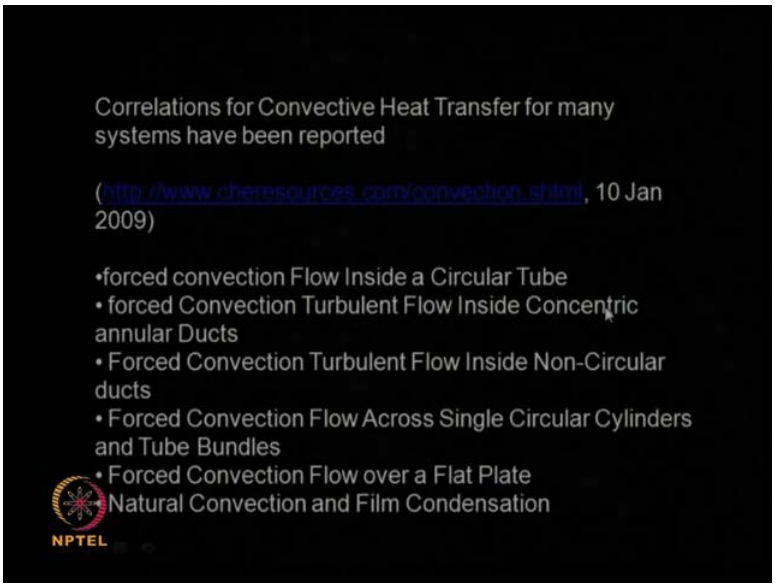

So, there are many correlations available for convection heat transfer for many systems where, this particular reference gives you those correlations. So, if you want to look at force convection flow inside the circular tube, force convection turbulent flow inside concentric annular ducts, forced convection turbulent flow inside non circular ducts, forced convection flow across single circular cylinders, tube bundles, flat plates, condensation. So, for different types of scenarios, for different types of fluids, for different types of shapes of the material, this particular reference gives you some calculation.

So, we can use and depending upon the geometry and the type of system we are studying, we can get the heat transfer coefficient. So, why do we need the heat transfer coefficient, using that we can calculate, what is the heat required to vaporise your liquid from the liquid state to the gaseous state. So, in order to do that, we need to calculate the heat transfer coefficient.

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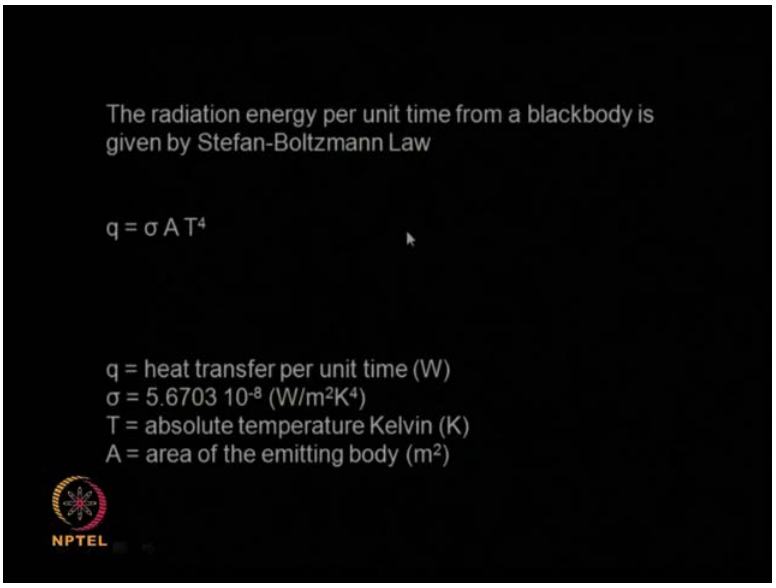

The third one is the, heat because of the radiation, is given by the Stefan-Boltzmann law, q that is the heat transfers per unit time and is a function of a constant sigma, A area, T is the absolute temperature raise to the power 4. Generally in a biological system, we do not use radiation type of energy for heating of an material so and this equation is not really applicable for our studies. Conduction, yes if you are using belt dryers, convection yes if you are using ovens, hot air ovens and so on actually.

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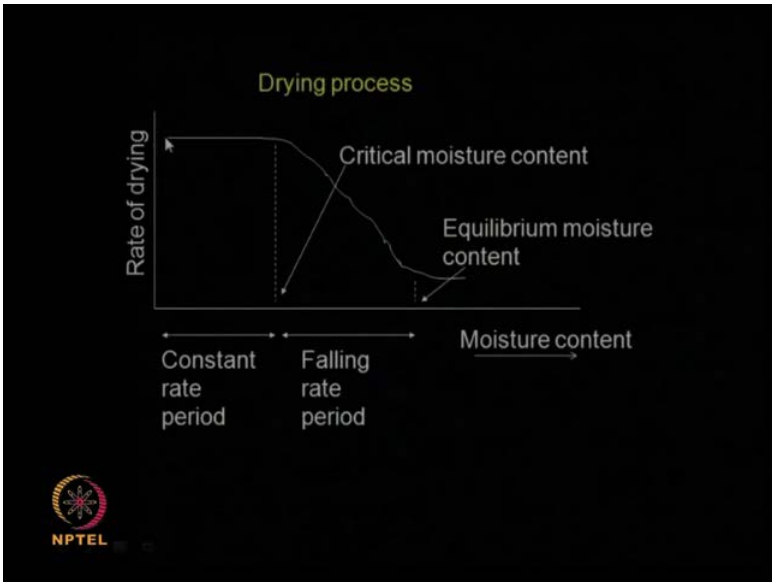

So, once again if you look at this picture of rate of drying on the y axis, moisture content on the x axis so you have a constant rate drying that is, rate of drying is constant. So, you have an straight line like this, then it keeps falling, this is the falling rate period, this is the constant rate period. This is called the critical moisture content that means, the moisture content which divides the constant and the falling rate period and then finally, you reach the equilibrium moisture content. So, this is a typical figure, which describes the drying process, the critical moisture content and the equilibrium moisture content.

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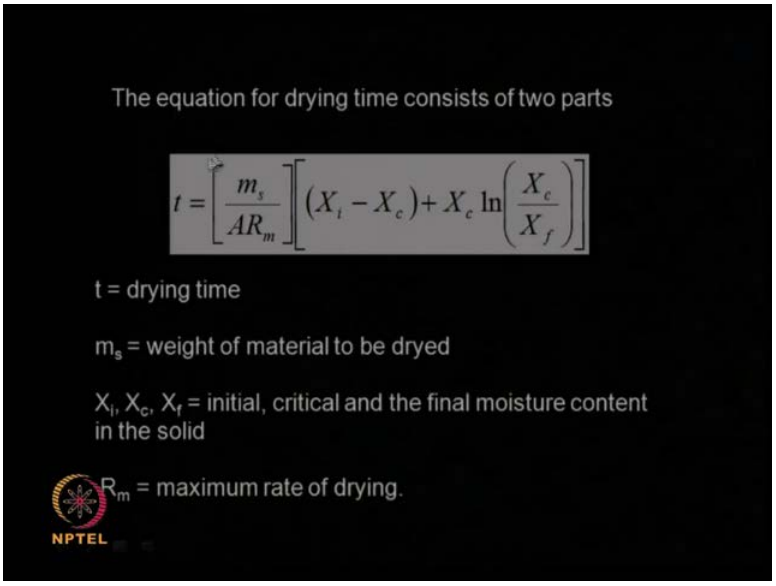

Now, based on that and also we said, that there are two types of regions, one is the constant rate drying and falling rate drying. We have a mathematical relation, which relates the drying time t to many other parameters so t is made up of the weight of the material that needs to be dried, A is the area of the surface area, R m is the maximum rate of drying, X i is the initial moisture content, X c is the critical moisture content, X f is the final or the equilibrium moisture content.

So, this term corresponds to the constant rate, this term corresponds to the falling rate so if I know, what is the critical moisture and the final or equilibrium moisture content of the solid and if I know, what is the initial moisture content of the solid and if I know the mass of the solid as well as area, I can calculate what is time required to dry that material starting from X i going down to X f. X i is initial, x f is the final and critical moisture

comes in between so these equations are very, very useful to calculate the amount of time required for drying.

So, today we talked about drying and the most important downstream for bringing the moisture level to very, very low value and it has got lot of advantages. You can use conduction type of drying, we can use convection type of drying generally, we do not use radiation in biological systems. Then there is something called the equilibrium moisture content or the final moisture content, below which we cannot dry a material. And so there are many equations, which are available which can help you to calculate the entire drying process. So, in the next class, we will still talk more about the drying phenomenon.