Fundamentals of Food Process Engineering
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Lecture - 16
Evaporation and Concentration

Hello everyone, welcome to NPTEL online certification course on Fundamentals of Food Process Engineering. Today we will start a new chapter on Evaporation and Concentration.

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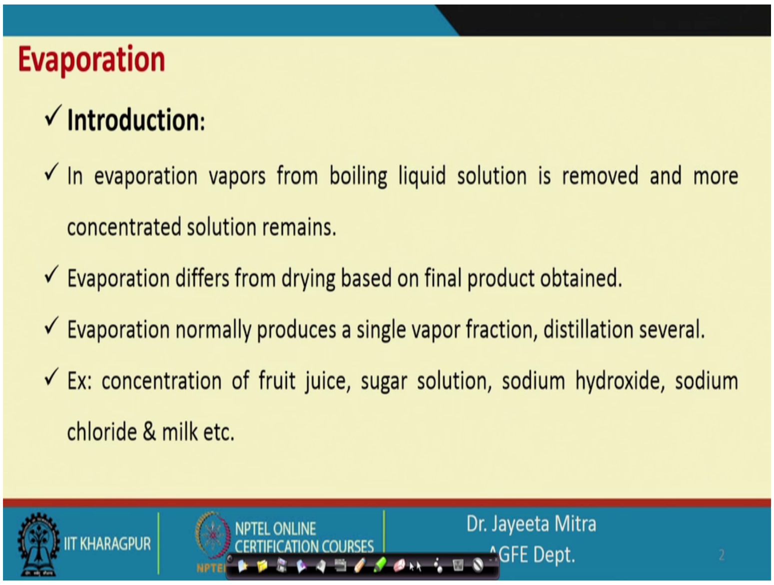

So, evaporation it is very important unit operation and we perform this for many food processing application, where we want to concentrate the product from very dilute solution and also crystallization. And there are many other applications where some processing part of some processing can be done utilizing the evaporation phenomena. So, we will see first what is evaporation? So, in evaporation vapors from boiling liquid solution is removed and more concentrated solution remains; that means, if we compare it with the drying where we also perform moisture removal.

So, the difference is basically in the final product development, evaporation give us final concentrated liquid where as drying give us the dehydrated product, which is basically a solid product having certain amount of moisture content which is definitely lower than the evaporated liquid that we are getting finally And if, we compare it with distillation evaporation normally produces a single vapor fraction where distillation produces several vapor fraction. The evaporation can be done for concentration of fruit juice, sugar solution, sodium hydroxide solution, sodium chloride and for milk.

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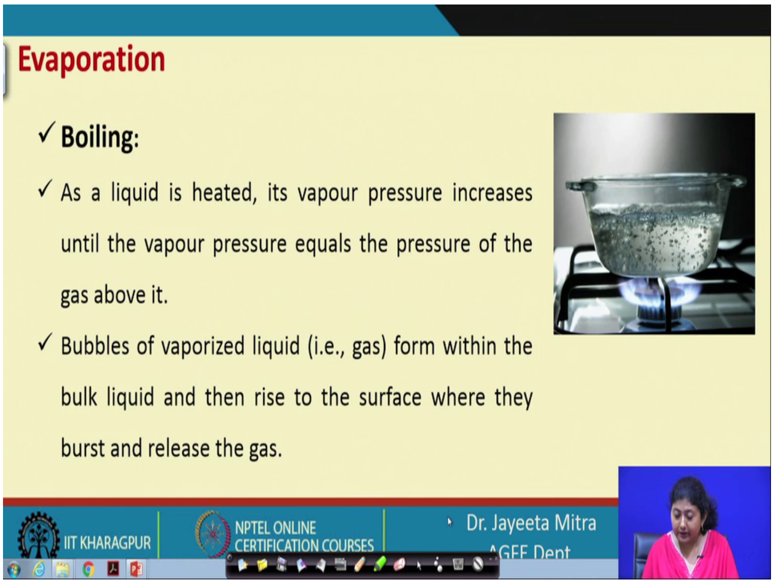

Now, first we will see that the evaporation phenomena. Evaporation as we are talking about that it is a boiling we perform the boiling of the dilute solution and we make it concentrated by evaporation of the liquid.

So, that is why I feel it will be very beneficial to express few things about boiling and also of the condensation phenomena, because these two are very important in terms understanding the evaporation. So what is boiling? As a liquid is heated ok, so its vapor pressure increases, until the vapor pressure equals the pressure of the gas above it ok. And then bubbles of vaporized liquid that is the gas form within the bulk liquid as we can see in this figure rise to the surface were they burst to the atmosphere and release ok. So this is the phenomena of boiling that happen while we heat dilute liquid.

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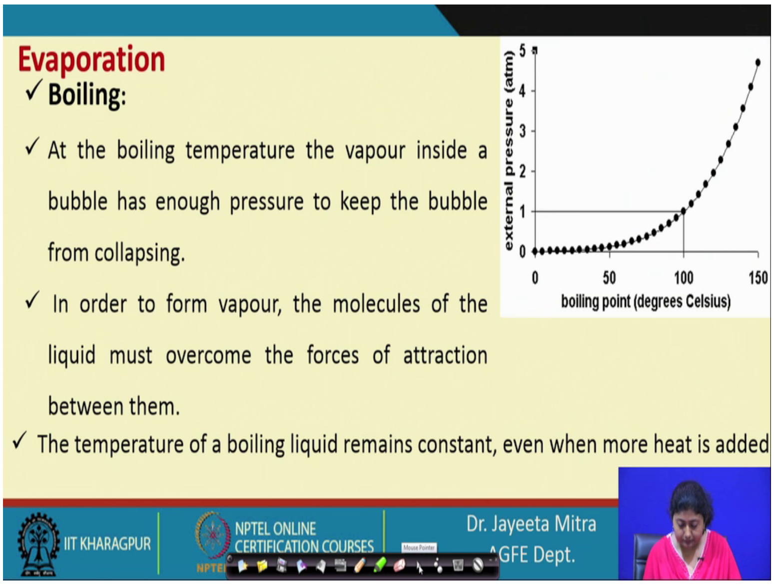

And also if we perform boiling at different temperature, we can observe that the external pressure also increases; that means, if we want to perform the boiling of pure water at 100 degree Celsius the external pressure will be maintained at one atmospheric pressure.

However, if you want to increase the temperature of boiling, we need to definitely increase the pressure as well ok. So, at the boiling temperature the vapor inside the bubble has enough pressure to keep the bubble from collapsing. In order to form vapor the molecules of the liquid must overcome the forces of attraction between them ok. So when they get enough heat so they you know they get that force to overcome the attraction force between them from the vapor and try to come up through the liquid. The temperature of a boiling liquid, remain constant throughout the process, even when more heat is added to it.

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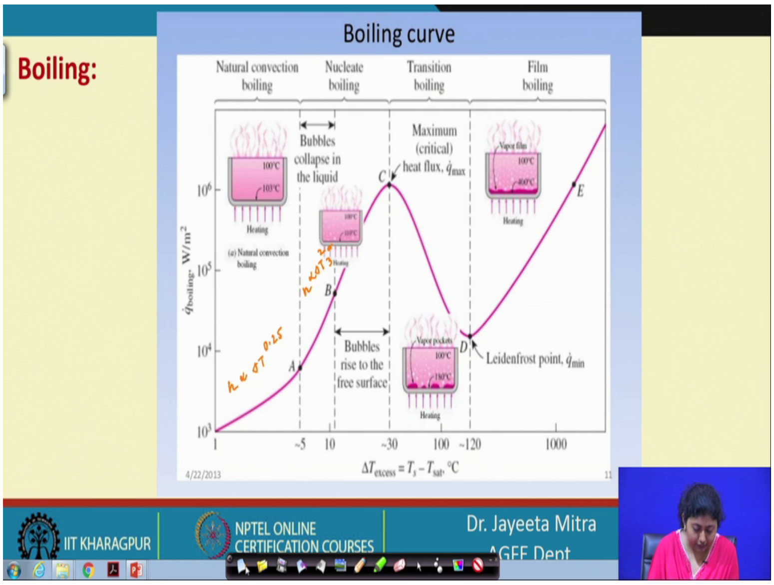

Now, if we try to understand the phenomena of boiling, what happen the boiling is happen across a heat exchange surface or if we want to immerse the you know immerse any tube or any vertical surface through which the steam is being given to the dilute liquid and the liquid is being heated for boiling. So, the heat transfer across the surface of that tube of the vertical surface or any you know any surface through which we are providing the heat that can be represented as the rate of heat transfer per unit area ok.

So, watt per meter square and that watt per meter square if we want to plot against the delta T of the surface and the boiling liquid. Then we can get a curve of this kind which is called the boiling curve. So, this is a typical boiling curve where this delta T excess that signify the T s that is the you know the surface temperature across which we are providing the heat to the boiling liquid. And T saturation is the temperature of the boiling liquid that is in equilibrium with the pressure prevailing in the chamber. So initially when there is a little difference between the hot surface and the boiling liquid ok. So, as a delta T starts building the liquid in the in the liquid if we see you know look into this zone, if we look into this zone from the starting point of the plot to point A so in this zone we observe the natural convection in the liquid level ok.

So, there is a temperature difference very less we can see here around 5 to 3 degree Celsius different temperature is there, it is being shown here by this plot where surface is at 103 degree and the liquid is at 100 degree Celsius at ok. So, here we are providing heating and natural convection taking place, so the heat transfer coefficient will start increasing followed by the natural circulation of the liquid inside the medium right. So, heat transfer also try to increase and so it is for the watt per meter square that is the rate of heat transfer q also increases ok. However, there is not any kind of bubble formation or very less amount of bubble formation may consider may come up here. Now, if we consider the next section if we consider the next section that is from A to B ok, so here again the delta T starts increasing and the bubble form inside the liquid will start collapsing in the liquid and with the bubble the liquid will also try to move at a faster rate in the in the liquid material.

So, the rate of heat transfer is further increased and when the bubbles rise to the free surface that is the condition B to C when bubbles rise to the free surface. So, it further enhances the movement of the liquid and there is a there is a you know high velocity mixture that will initiate in the liquid and that cause the heat transfer increase ok. So, therefore, here we are getting a higher curve, the curve is increasing constantly up to a certain point where the critical point can be observed, that is the maximum heat flux maximum heat flux we can observe at this point ok. Now, here what happened that the temperature in this zone that is A to C the surface temperature was around 110 degree and the liquid since the boiling has to be there at a constant temperature under atmospheric pressure, so it is 100 degree Celsius.

Now, beyond that what happened that the vapors start depositing on their surface and acting as an insulating layer ok. On the surface of the heat exchange surface so that the temperature difference between the heating surface and the liquid the boiling liquid will eventually increase to a very high value ok. So delta T increases high value because of this insulating layer the heat flux does not increase rather it drops drastically ok. So this condition is called the transition boiling, first we have observed from 0 to A section 1 to A section. Here we have observed the natural convection boiling because the convection happened because of the natural convection movement of the water.

Then we have seen the nucleate boiling where because of the bubble formation the movement of the liquid was very fast and the heat transfer increased. In the third zone that is transition boiling heat flux reduced to point D which is the Leidenfrost, that is the lower heat transfer rate we can observe here. And after that what happened that the difference in delta T is being so high around you know the surface temperature has reached to 400 degree Celsius, where the liquid temperature is 100 degree still. So the difference of delta T is so high that the radiation phenomena starts developing here and radiation heat is going to going to you know we generated from the heating surface to the liquid media and that the heat transfer will drastically increase again ok. So this condition is called the film boiling, so because of this insulated air film the gas bubbles film that that is being continuously cover the surface the radiation heat transfer predominants and increasing the heat transfer to the boiling liquid.

So, in general case we may offer this is the typical curve, but in certain cases practically we may move on to C to continuously to the increase section that is the film boiling section. So in the heat transfer you may get the detailed more detail understanding of various kind of this heat transfer phenomenon. But I feel that it will be helpful for you to understand the boiling phenomena here, so that you can analyze or understand the performance and mechanism of evaporator better.

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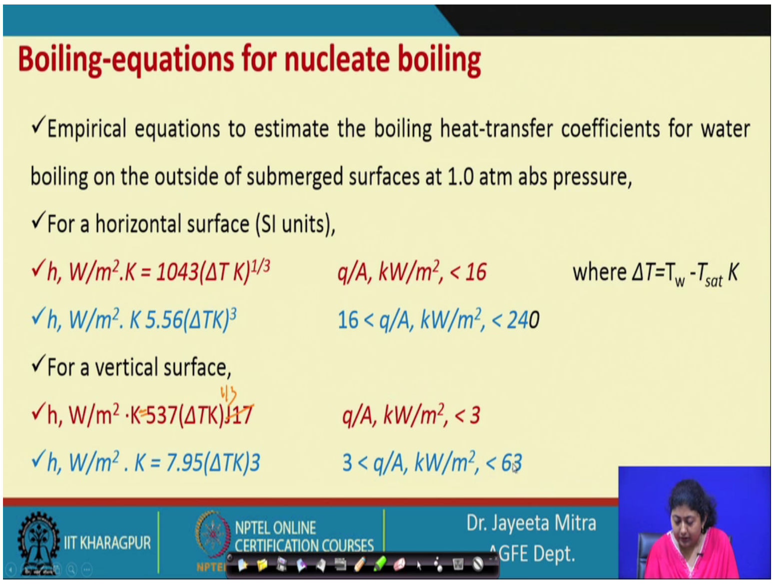

So, empirical equations are there to estimate the boiling heat transfer coefficient for water boiling to the water boiling on the outside of submerged surfaces at 1 atmospheric absolute pressure.

Because most of the cases when we deal with evaporators the submerged phases either tubes or surfaces those are there in the in the liquid material that we want to evaporate or the water we want to evaporate from that. So for that purpose we will see a few equation that has been developed for first is for horizontal surface that is h heat transfer coefficient in watt per meter square Kelvin that is 1043 into delta T Kelvin to the power 1 by 3 delta T is again the difference between the heat transfer surface to the boiling liquid. And this is valid this equation is valid where you are the rate of heat transfer across the unit area that is q by A will be less than 16 kilo watt per meter square. If the rate of heat transfer across an unit area is between 16 to 240 kilo watt per meter square then the heat transfer coefficient will be equal to 5.56, this will be equal to 5.56 into delta T Kelvin to the power cube ok.

So if we want to see the if you want to see the previous plot once again this has been device based on you know this section from new natural convention to then nucleate boiling natural convection. Since, the h is very low h generally varies with respect to delta T to the power 0.25 ok. Here h now, then in the nucleate boiling section generally h varies with respect to delta T to the power 2 or 3 right. So most of the cases we are considering about the nucleate boiling and film boiling because that is most predominant in the cases where the surface is submerged in a boiling liquid. And for a vertical surface when q by A is less than 3 kilo watt per meter square h will be equal to 537 delta T 537 delta T so this will be I think this will be 1 by 3.

So, here we can write this as and again when q by A will be in between 3 to 63 kilo watt per meter square then k will be 7.95 into delta T Kelvin to the power cube. So this will be cube right so you please take this equation as k will be equal to 7.95 into delta T k to the power 3 and the this the above equation is k equal to 537 delta T Kelvin to the power 1 by 3.

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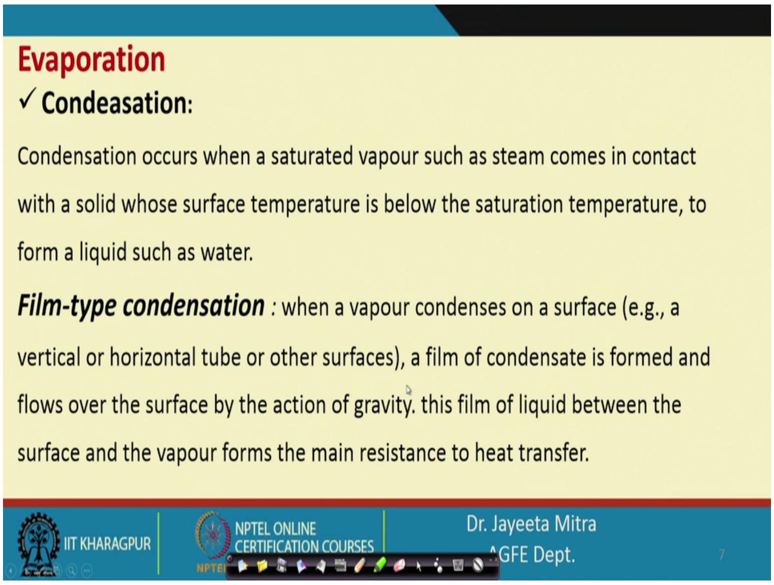

So, next is condensation, so why condensation is important in the context of evaporation? Because we evaporate the liquid and make it concentrated liquid by evaporating the water from it and the heat that we needed for this purpose is taken from the steam ok.

So, we generally take a saturated steam and we condense the stream outside the you know the surface of if it is a steam jacketed type evaporator, then it is inside the jacket or if it is a you know horizontal tube kind of thing. So, inside the tube we send this steam we will discuss in detail the configuration of different evaporators. So, there the condensation occurs right and condensation is needed, so condensation occurs when a saturated vapors such as steam comes in contact with a solid whose surface temperature is below the saturation temperature to form a liquid such as water.

So steam condense to water when it touches the lower temperature surface. So, most common is two kind of condensation that is one film type of condensation another is the drop wise condensation. In film type condensation vapor condenses on a surface as for example vertical or horizontal tube or other surfaces of film of condensate is formed on the surface and flows over the surface by the action of gravity.

So this film of liquid between the surface and the vapor forms the main resistance to heat transfer, so this film type condensation is most common. Another is that the drop wise condensation occurs and when the more and more drops will condense then the drops will collapse with each other and then gradually because of gravity they fall down. So, in that case the whole surface is in covered by the drops in at a processing time, so film type condensation is the most common method the we often observe in case of the heat exchanger that we often use in the evaporation process.

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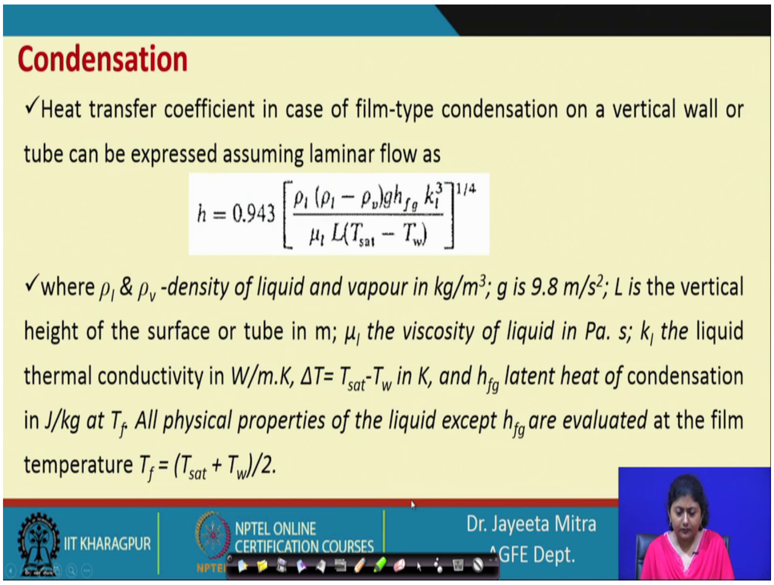

So, for condensation again we will see one equation as we have seen certain empirical equation for the boiling. So, heat transfer coefficient in case of film type condensation on a vertical wall or tube can be expressed assuming laminar flow, that we are assuming that the film which is falling down on the surface of the you know heat exchange surface that is in laminar flow. So, heat transfer coefficient h will be 0.943 rho l into rho l minus rho v g into h fg small h small fg is the suffix k l q divided by mu suffix l capital L into T saturation capital T saturation minus capital T w to the power 1 by 4.

So here rho l and rho v is the density of the liquid and the vapor in kg per meter cube respectively, g is acceleration due to gravity in 9.8 meter per second square L capital L is the vertical height of the surface or tube in meter that is being submerged or on which the film condensation is taking place, mu l is the viscosity of the liquid in Pascal second k l is the liquid thermal conductivity in watt per meter Kelvin. Delta T is the T saturation minus T wall that is in Kelvin and h fg which is the latent heat of condensation in joule per kg at T f that is the film temperature which is taken as T saturation plus T w by 2.

In fact, all the physical properties of the liquid except that h fg because h fg is the latent heat of condensation that has to be fixed at the temperature at which the condensation occurs. So at saturation temperature, but all other properties like the viscosity of the liquid and you know the k l all this we need to calculate at film temperature that is T saturation plus T wall by 2.

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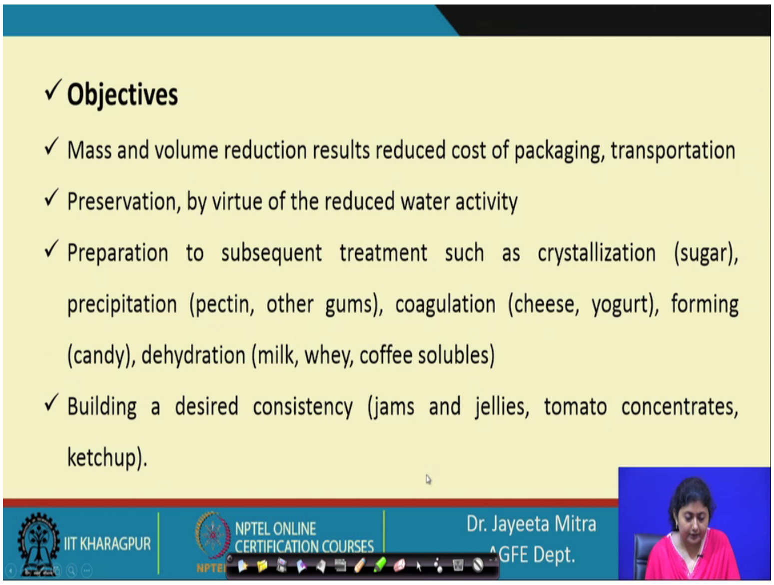

So, coming to objective of evaporation first is mass and volume reduction results reduced cost of package and transportation. So some time we need to do you know such processing using evaporation, so that the bulk volume and the mass can be reduced and the transportation will be benefited.

Then another thing is preservation because by lowering the water activity by evaporation we are lowering the water activity we are evaporating the water. So, free water available to the you know activity of the microbes are for enzymes enzymatic activity that is being reduced, so this helps in the preservation of food material. Then preparation to subsequent treatment such as crystallization, because if we make an you know concentrated solution by evaporation that will help in crystallization and less energy will be involved in the crystallization step. So for sugar crystallization evaporation is used then precipitation like pectin and other gums, coagulation like cheese, yogurt and forming like candy, then dehydration like milk whey, coffee solubles etcetera.

So, for example, milk if we want to dehydrate normally you know spray drying is the mechanism by which normally we perform the drying of milk, to maintain the quality in an efficient way. Now, before sending it to the spray dryer the milk is being concentrated in evaporator and generally around 50 percent of you know this concentration is being done and thereby we can reduce the energy requirement in the spray dryer as well. So, building a desired consistency is also a parameter sometime when we want to prepare jams and jellies, tomato concentrates, ketchup etcetera. So, all such are the primary objective with that we will move on to different evaporation processes.

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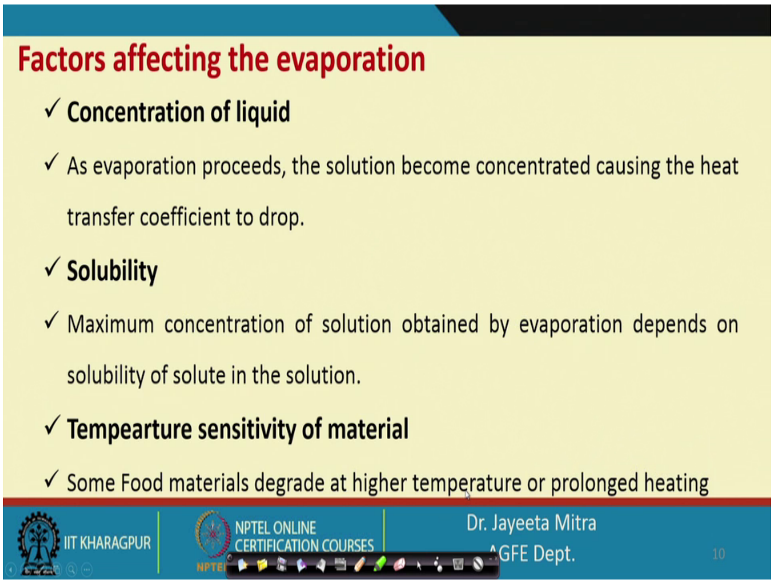

Now, we must have to see the different factors that can affect the evaporation process, first one is the concentration of liquid. So, we know that we use the dilute solution and to evaporate them to make it concentrated solution. So as we concentrated or as the evaporation process moves on the liquid will become viscous and the heat transfer across them is very difficult, because the concentration is increased. So that you know that causing the heat transfer coefficient to drop and to overcome this we may provide some kind of agitated or some kind of motion into it so that heat transfer rate can enhance.

Now solubility is another factor, maximum concentration of solution obtained by evaporation depends on solubility of the solution and the solubility again has some you know interdependency with temperature because some time with increasing the temperature we can increase the solubility. Temperature has also effect with the sensitivity of a material, some food material degrade at higher temperature or prolonged heating, foaming or frothing that is very interesting phenomena that some solution produce foam or froth during boiling, this foam accompanies the vapor coming out of the evaporator and also certain liquid and that causes the entrainment losses. To overcome this several baffles are attached at the in the evaporator at the exit section of the vapor.

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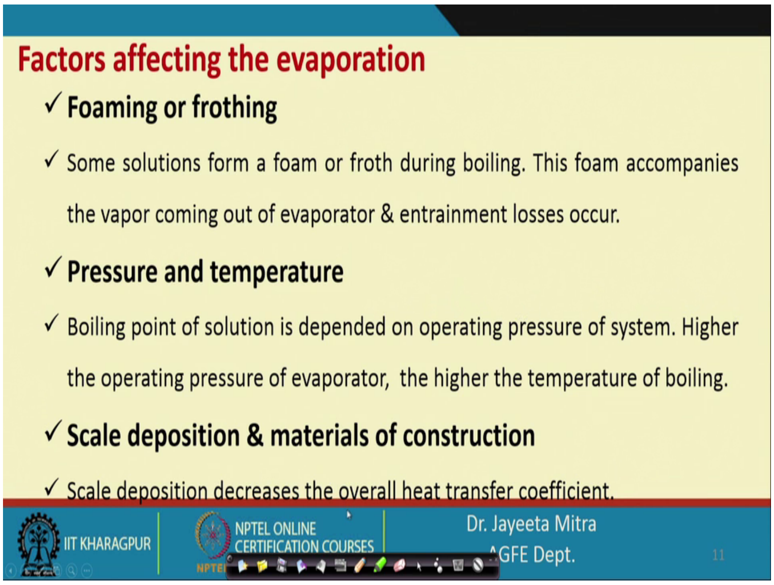

So, that the entrainment loss can be minimized pressure and temperature as I have already mentioned that if you want to increase the temperature of the boiling we want to increase the pressure that prevails above the liquid level as well. Boiling point of solution is dependent on operating pressure of the system. Scale deposition and material construction, scale deposition as it is very common in case of any kind of you know heat exchange surface where we provide the heat exchange by an exchange surface.

So, it may happen that the impurities in the water may deposit on the on one side or the inner side of the tube. And it may also happen that the scale deposition may happen in the liquid side that we want to concentrate because sometime the some composition fat or some composition of the food material may be sticking to the wall of the surface and that may degrade the heat transfer coefficient because that deposited scale will offer resistance to heat transfer. So, the overall heat transfer coefficient will drop.

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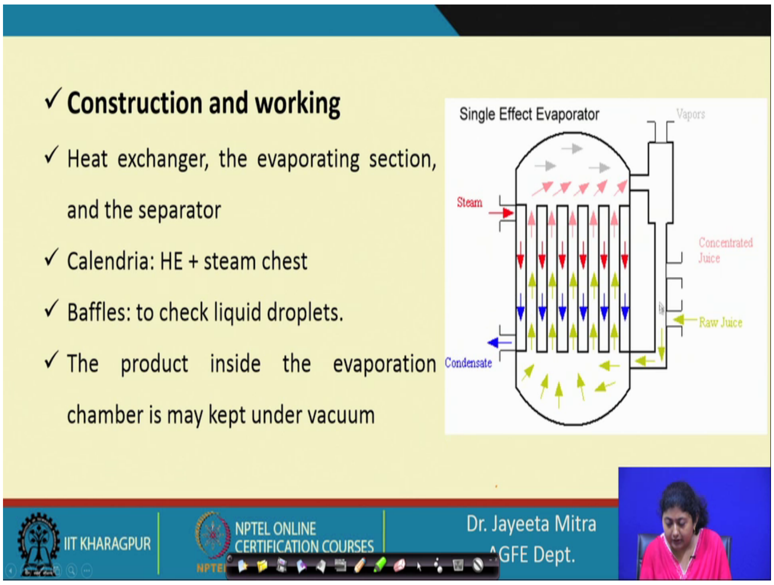

Finally the construction and working, so simply this is the constitute of heat exchanger the evaporating section and the separator. Heat exchanger plus steam chest that is together can be termed as calendria. There is also baffles at the exit to check the liquid or droplets that may cause entrainment losses. In this figure we can see that the feet which is raw juice that is entering from the bottom side and that is entering in the shell where as the steam which is entering in this short particle tubes. And this steam while coming through this you know tubes this is getting condensed and the latent heat of condensation that it leaves that is being taken by the raw juice and it becoming concentrated. And it leads to this section where this is called the stream chest where vapors is separated from the liquid and the concentrated juice is coming from the bottom while vapors are leaving from the top.

So, the steam when it comes to the surface which is having the lower temperature it gets condensed. So, we have seen that it is you know start moving and then vapor development takes place along with the liquid so vapor will separated here and the liquid will come and concentrated juice will come out and some part maybe re-circulated with the raw juice. So, the product inside the evaporator chamber may kept under vacuum for heat sensitive material, because in that case we want to we want to cause the evaporation at lower temperature and as we know the temperature and pressure has a direct relationship in case of the evaporation process. So, if we want to lower the temperature we have to lower the vacuum level inside the chamber as well.

So, we will stop here we will continue in the next class.

Thank you.