Fundamentals of Food Process Engineering
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Lecture - 32
Freezing & Freeze Drying (Contd.)

Hello everyone, welcome to the NPTEL online certification course on Fundamentals of Food Process Engineering. We have started Freezing and Freeze Drying in our last class. So, we will continue with the topic. In the last class we have seen how the freezing phenomena takes place in case of liquid water and also in case of food material and we have also seen the process of nucleation and crystal growth.

Now in today's class we will see one very important thing that is freezing time calculation. So, we know that for food materials in freezing is one of the important unit operation and very effective because this is the only method by which we can preserve the initial texture, structure and quality of the food material.

So, what is the time required for freezing? This is very important. So, the most common method that is used is a Plank equation.

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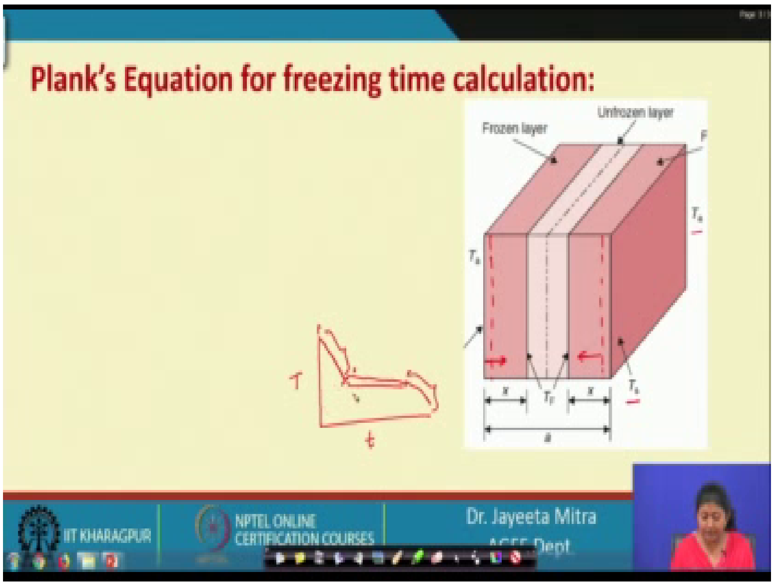

So, Plank's equation for freezing time calculation; what it does in this method is that let us take a block of food material and in that we will consider one direction for the transfer of heat or removal of heat rather and the other 2 dimension maybe of infinite length. So, in this particular figure we are considering this x dimension for transfer of heat. So, if this block is exposed to cold air which is of sufficiently low let us say T a; T a which is sufficiently low temperature and when we expose this block to that temperature from both the side, so, it starts formation of the ice layer; start formation from the ice layer in both the side. And as we move towards the centre the ice front will also come to the middle of the block and eventually we will dry it from both the I mean we can freeze it from both the side.

Now, this in this particular case since the block is exposed from both the side to the low; low air low temperature airstream. So, the freezing can take place from both the side, but it may also happen that from one side is only open to the cold air and the other side is kept on a plate. So, in that case we will consider only from one side heat removal right.

Now, what are the other cases for the Plank's equation? The other cases is that mainly we neglect the sensible heat transfer in this particular case; that means, if you remember; if you remember the temperature with time. So, first we sensibly cool the food material, then there is a super cooling start, then little increase and then decrease or the latent heat removal and then it further decreases, right. But Plank's equation does not account for this to this zone or from this to this zone; it only consider this part that is the latent heat removal because it takes the assumption that the initial temperature of the food sample will be at freezing temperature right.

So, this is one drawback and the other case is when we start the process of latent heat removal and by the time we end the process; there is a huge change in the property of the food. Because the density, thermal conductivity and specific heat will change when we convert it from the water to ice, but in this particular case in Plank's equation they considered all this property to be constant from the start of the freezing process to the end of the freezing process.

However, with this assumption also this method has been used since long time, so we will just see now that how we can come to the final expression of temperature; final expression of relation between the time and the temperature freezing time and temperature relation.

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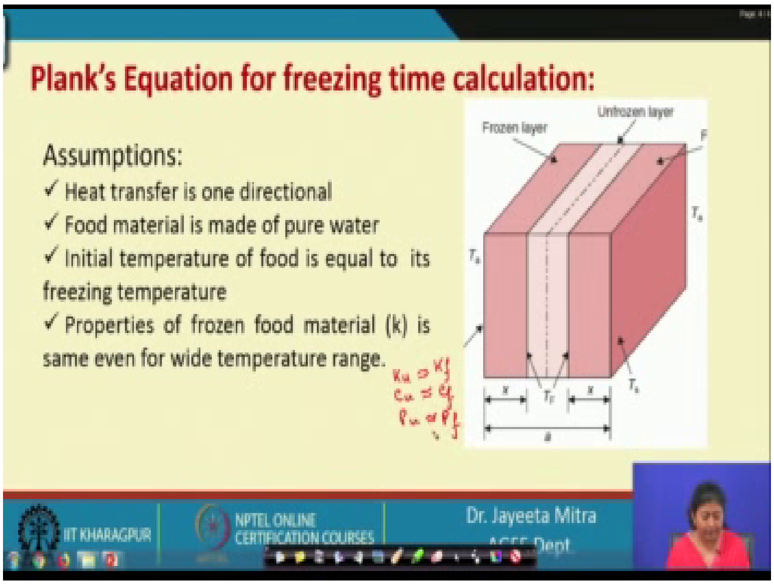

So, first assumption is that heat transfer is one directional, food material is made of pure water. Initial temperature of food is equal to its freezing temperature as I mentioned that; so, it is not considering the sensible cooling phase.

Properties of frozen food material that is in this case thermal conductivity; k is same even for wide temperature range; that means, if you consider, if you consider here k unfrozen they have taken that equal to k frozen. And also the other properties like specific heat unfrozen is equal to specific heat frozen, density unfrozen will be equal to density frozen.

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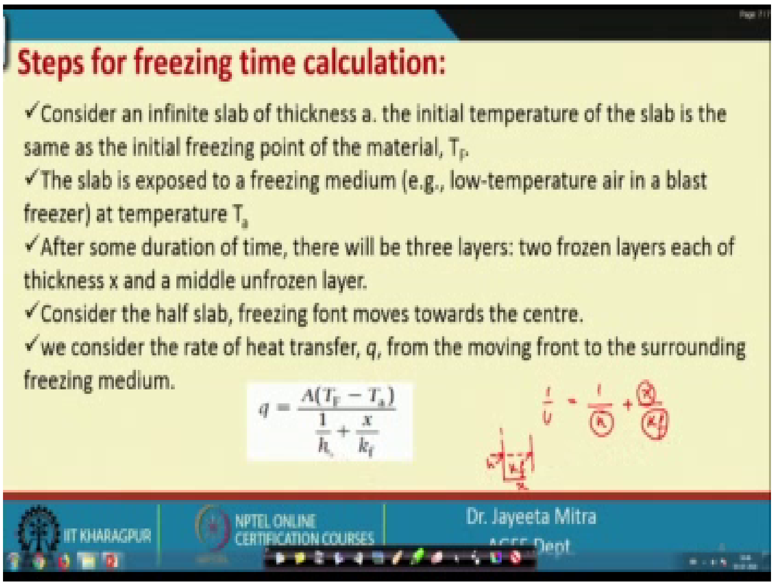

Now, what are the steps for freezing time calculation? First, we have considered an infinite slab of thickness a ok. So, thickness a; that means, we have taken one dimension to be fixed and the other maybe of infinite dimension. The initial temperature of the slab is the same as initial freezing point of the material. So, freezing point T F that we have considered. The slab is exposed to a freezing medium that is low temperature air in a blast freezer at temperature T a. So, the air temperature is T a, which is a blast freezer in which the slab is exposed to this low temperature air. After some duration of time there will be three layers that is two frozen layer each of thickness x and a middle unfrozen layer.

So, if you recall this is the condition like both the side it is exposed to air temperature T a and after certain time both the side x distance we have covered where the whole thickness is a. So, the layer which is already frozen have a temperature T F and the air stream outside have a temperature T a.

Now consider the half slab; considering the half slab; freezing front moves towards the centre ok. So, we consider the rate of heat transfer q, from the moving front to the surrounding freezing medium. So, what will be that? We know that q will be k that is the area cross sectional area through which the transfer is taking place.

The temperature difference that is T by F T F minus T a; T F is the freezing temperature and T a that is the temperature of the air. And this will be if you can remember that overall heat transfer coefficient u we have calculated and the expression of u where 1 by u that is equal to 1 by h plus x by k f. So, h because of convective heat transfer coefficient, k f is the conductivity of the heat through the frozen food and x is the thickness which it has already passed.

So, once the from the; so once the surface is the surface is taking heat in the form of convective heat transfer then this heat has to pass through the frozen material which is of thickness x and k f is the conductivity. So, we know that del x by k f is the resistance and 1 by resistance is your transfer coefficient. So, utilizing this we have put u here. So, the equation become A into T F minus T a divided by 1 by h plus x by k f. So, this is the rate of heat transfer, q from the moving front to the surrounding freezing medium ok.

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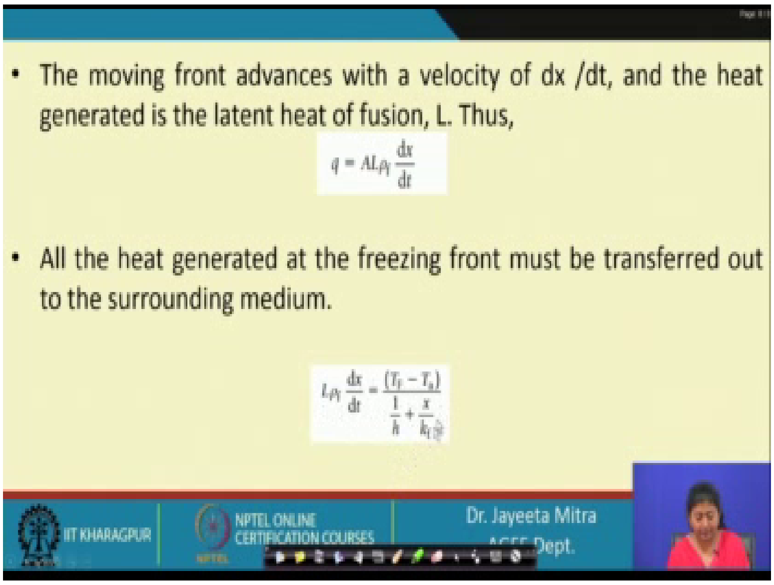

So, the moving front; now we have to remember that normally we when we perform drying, then heat is given to the material. Now, in this case heat is taken out from the material. So, deduction of the heat removal will be from the centre to the towards the direction of the freezing front. So, the moving front advances with a velocity of dx by dt. If we assume that this will be the rate of propagation of the ice front towards the direction of the centre and the heat generated is the latent heat of fusion L. So, whatever heat we are removing that is causing the phase change from the liquid to the ice formation.

So, we can have this expression that the transferred heat that we are taking out that will cause latent heat of that will cause of freezing. So, if velocity is dx by dt multiply the area and that into density that will give us kg per unit time of the conversion into L; that represent the heat transfer needed for this freezing phenomena ok. So, A into L that is the latent heat of fusion into rho f that is the density of the frozen material into velocity dx by dt. So, we are getting this q that we will equate with the heat transfer that has had happened because of conduction first from the; you know frozen layer and then conviction to the air outside.

So, all the heat generated at the freezing front must be transferred out to the surrounding medium. So that means, this much heat we need to extract to freeze the layer. So, we are getting this is equal to that L into rho f dx by dt will be equal to T F minus T a divided by 1 by h plus x by k f a will be cancelled.

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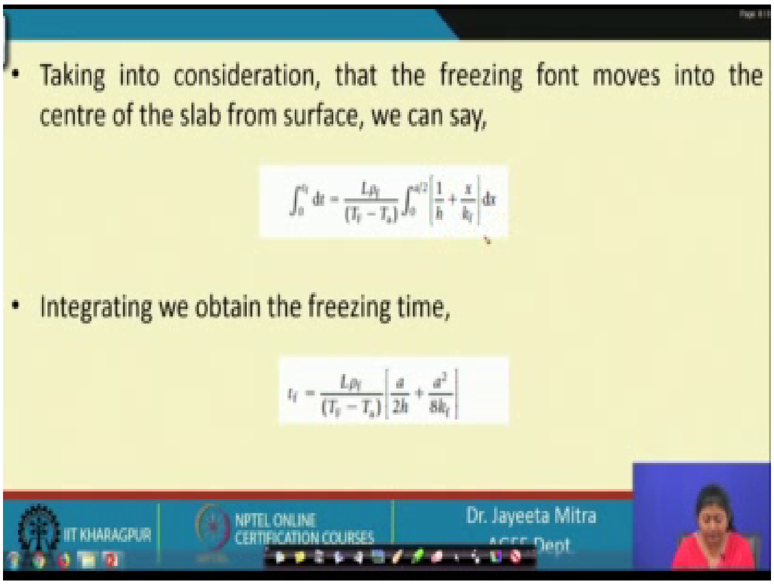

And from this if we consider that freezing front moves into the centre of the slab from the surface; we can say if we integrate this dt from 0 to T F that is when the total material will be frozen. So, 0 to T F will be L into rho f by T F minus T a into integration 0 to a by 2 because the half thickness we need to reach by the time the other half will also be frozen because from both the side this freezing is taking place.

So, therefore, the remaining thing we are getting 1 by h plus x by k f into dx. Now integrating we obtain the expression of freezing time that is T F equal to L into rho f by T F minus T a into a by 2 h a by 2 which is the half thickness a by 2 h plus a square by 8 into k f.

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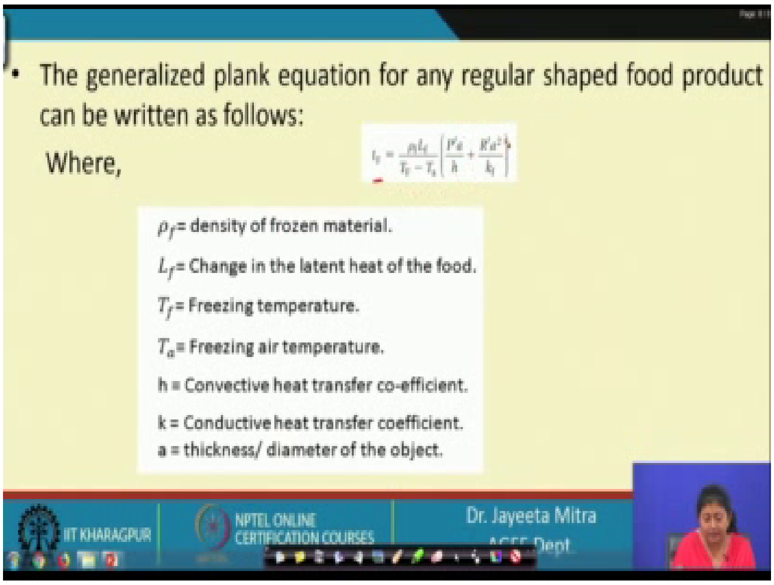

So, the generalized Plank equation for any regular shaped food product can be written as follows that will be T f that is freezing time that is equal to rho f into L f by T f minus T a into P dash a by h plus R dash a square by k f ok. So, a is the thickness of the of the direction to which the we are extracting the heat or removing the heat, h is the convective heat transfer coefficient at the surface, k f is the thermal conductivity of the frozen material. And other things are known to you rho f is the density L f is the latent heat change that is kilo joule per kg.

Now, what will be the value of this parameter P dash and R dash for various geometries? That we will see now.

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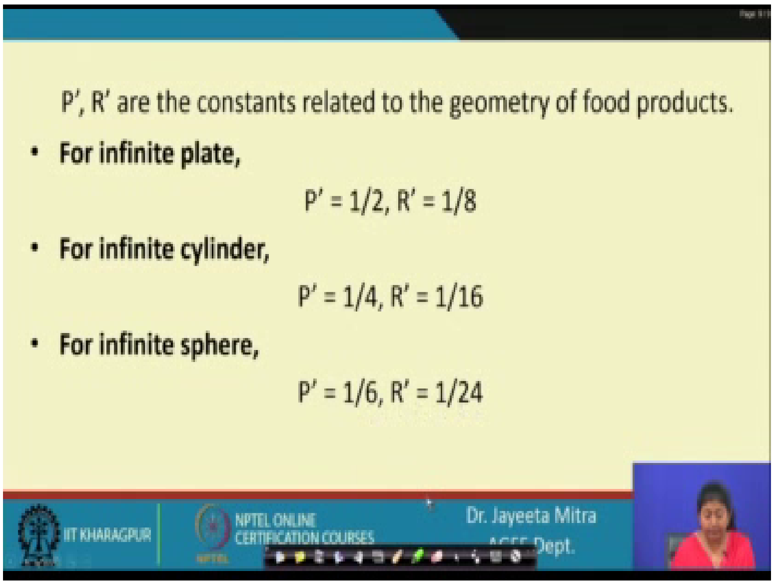

So, for infinite plate P dash will be half and R dash will be 1 by 8; if we go for infinite cylinder, infinite cylinder in the sense the length of the cylinder can be infinite dimension, but radius will be fixed. So, in that case P dash will be 1 by 4; R dash will be 1 by 16 and for infinite sphere P dash will be 1 by 6, R dash will be 1 by 24. So, this will be the representation of freezing time using the Plank's equation.

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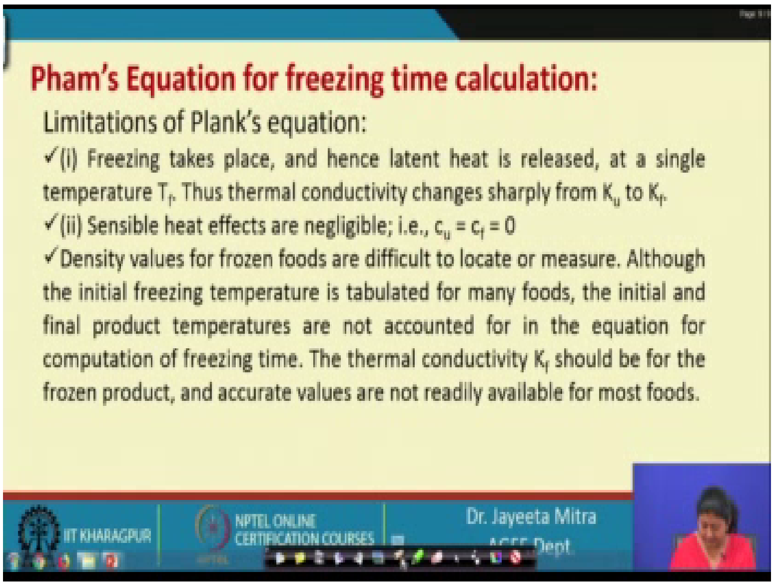

Now, as I already mentioned that there are certain limitation of Plank's equation ok. So, afterwards many experimentation have been have been done on this freezing process to identify the exact freezing time that can you know accommodate both the sensible period, as well as the latent heat removal period. So, one such equation which is developed in 2001 by a scientist called Pham and his equation is very reasonable in terms of calculating this freezing phenomena exact freezing time behavior.

So, let us see how we can we can do this calculation using Pham's method. So, as I mention that in the in the Plank's equation the limitation is we are considering only the latent heat transfer. Because initially we are assume that T f the freezing point was the temperature of the food, we are taking constant property that is specific heat thermal conductivity all we have taken constant.

And also density values for frozen food are difficult to locate or to measure. Although the initial temperature of many food has been tabulated and that are generally lower than 0 degree. So, the thermal conductivity k f should be for the frozen product and accurate values are not readily available for most of the food material.

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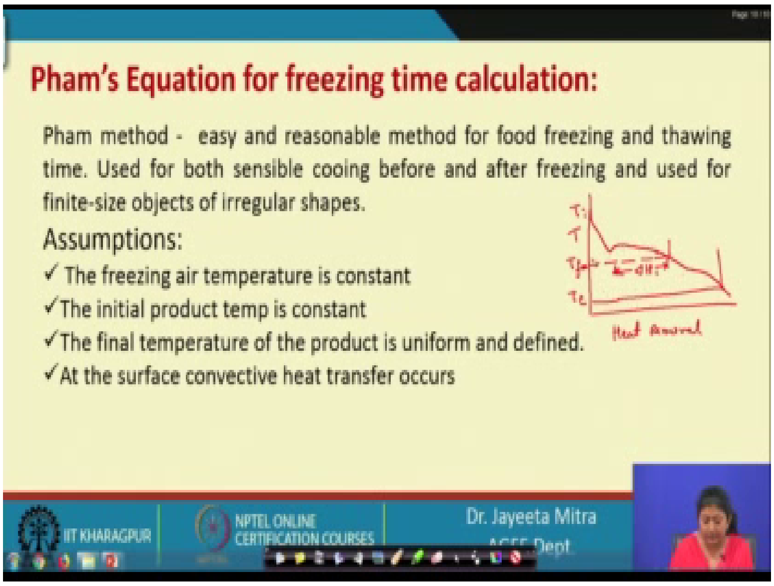

So, for this method what we will do is we apply the Pham's method that is easy and reasonable method for food freezing and thawing time calculation that is the reverse of freezing method.

So, this is used for both sensible cooling before and after freezing and used for the finite size object of irregular shapes and very limited assumptions we need for this method. One is the freezing air temperature is constant ok; so, that is any how we need to consider the freezing air temperature constant. Then initial product temperature is also constant; here we are not mentioning that initial temperature is at freezing temperature, but it should be any temperature a constant temperature right.

Now, the final temperature of the product is uniform and defined. So, up to what extent or till what temperature we need to freeze it that has to be specified. Another surface convective heat transfer occurs; so, this are the assumptions that we need to take and what we found is that if we if we consider Pham's method that temperature and here we are considering heat removal.

So, what we can get initially temperature is being lower; then sensible heat transfer is happened and then further lowering of the temperature. So, if this initial temperature is let us say T I and when the freezing start and it reaches to the minimum extent.

So, we are getting that mean point as T f m that that is called the mean freezing temperature and up to the extent that we need to finally, go that is also mentioned by T c. So, here we can we can measure that when the sensible you know heating starts; what is the removal of heat, till we need to attain the minimum frozen temperature.

And also the additional heat removal that we need to you know extract that also we can calculate and all this 3 temperature T i T f m and T c will be taken in the equation. So, that we can start from the initial to the final not only we are considering the aero sensible heat removal portion.

So, for that we will proceed like this.

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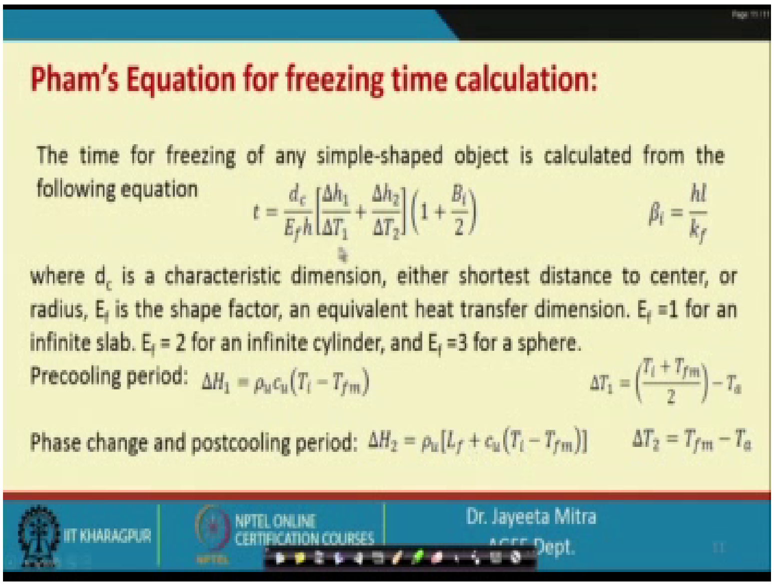

The time for freezing of any simple shaped object is calculated from this equation that is t equal to d c by E f into h into delta h 1 by delta T 1 plus delta h 2 by delta T 2 into 1 plus B i by 2.

And B i is nothing but the Biot number, if you have read this parameter in unsteady state heat conduction. So, Biot number is basically the convective heat transfer coefficient into ok. So, it is a convective heat transfer coefficient into the characteristic dimension of the object divided by the conductivity of the material. So, it is actually the surface convective resistance to the; it is actually the ratio of conductive resistance to the convective resistance at the surface.

So, this is the Biot number that we used here and this is the final expression where d c is the characteristic dimension or shortest distance to the centre or the radius, E f is the shape factor ok. So, an equivalent heat transfer dimension is taken by this where E f equal to 1 for an infinite slab, E f equal to 2 for an infinite cylinder and E f equal to 3 for a sphere.

So, actually this factor states that what will be the time required if we compare a slab with any irregular geometry. So, what we are getting that has been expressed by this sector. So, this is the whole equation and the pre cooling period where freezing has not been done the sensible cooling was occur. So, that time we can calculate the delta H 1 that is rho u c u into T i minus T f m.

So, T f m was our mean freezing temperature T i was the initial, rho u is the density of the unfrozen material and c u is the specific heat of the unfrozen material ok. So, total the change or heat removal that is during pre cooling is this much and phase change and post cooling period. So, we have taken the mean freeze freezing time as the reference and at this point we are considering that all the latent heat required plus after freezing what is the post cooling heat removal.

So, that is delta H 2 equal to rho u into L f that is latent heat of fusion plus c u into T i minus T f m. So, here delta T 1 and delta T 2 that we have used in this equation is also mentioned like this; delta T 1 will be T I that is initial temperature plus the mean freezing temperature T f m by 2 minus T a. So, this will be the gradient T I plus T F m by 2 this is the average temperature of the product has been taken, T a is the temperature of the air to which it is exposed for freezing and delta T 2 will be T f m minus T a.

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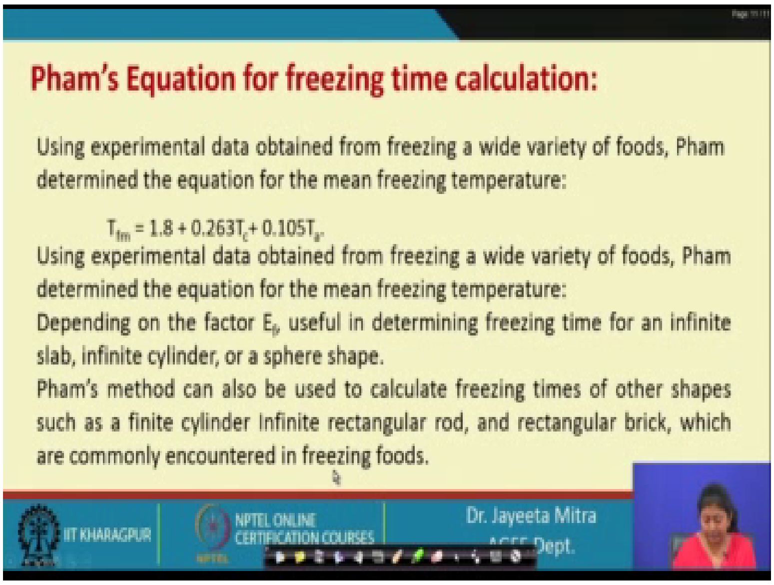

So, using experimental data obtained from freezing a wide variety of the foods, Pham determined the equation for the mean freezing temperature T f m that will be 1.8 plus 0.263 T c that is the temperature to which we need to finally, freeze it or the final temperature final define temperature of the product plus 0.105 T a which is the temperature of the air.

So, using experimental data so, we have we have got this temperature and then depending on the factor E f useful determination of the freezing time for an infinite slab infinite cylinder or a sphere is being done. And it can use for other shapes as well for example, the rectangular rod, rectangular brick which are commonly encountered in the freezing of food.

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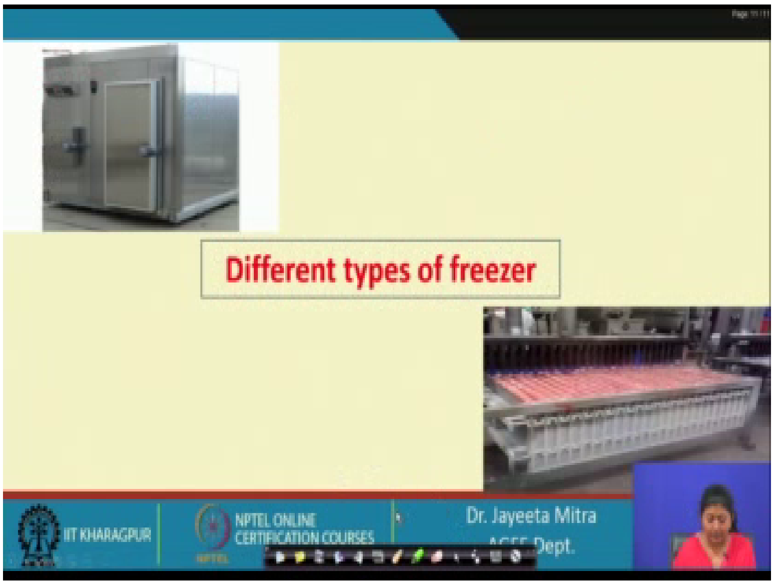

Now, different types of freezers.

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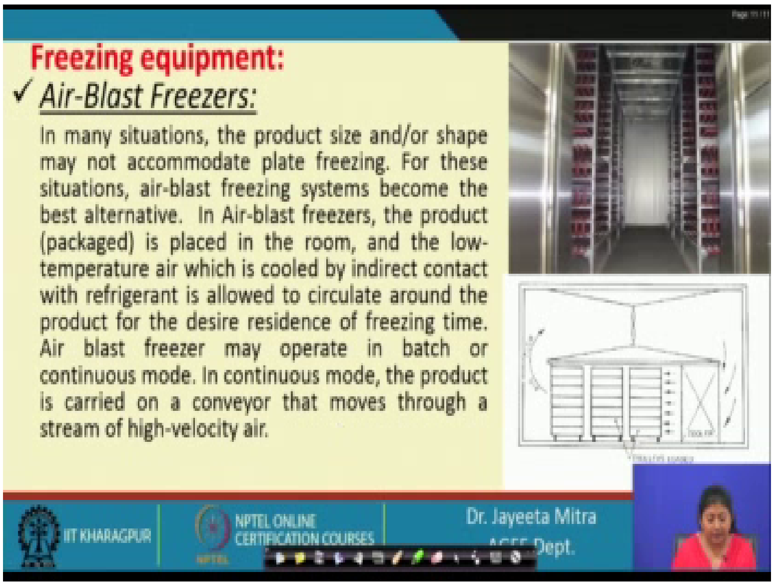

So, let us discuss a few important type of freezer one such is air blast freezer. So, what happen in air blast freezer? We circulate the cold air a very low temperature air over the surface of the food product and while it is while the product is exposed in the blast of the cold air; it will freezes.

So, for this situation air blast freezer when we cannot keep the product on the on the shelf or trace because of the shape of the product. So, then these are placed in the room and the low temperature air is utilized to cool them by cool the product and this air is being cooled indirectly with the contact of the refrigerant and they were allowed to circulate in the room.

Air blast freezer may operate in batch or continuous mode. In continuous mode the product is carried on a conveyor that moves to the stream of high velocity air and that high velocity air is being circulated over the refrigerant. So, the chill chilled air is coming over the over the surface of the material while moving through the conveyor belt and thereby they will frozen.

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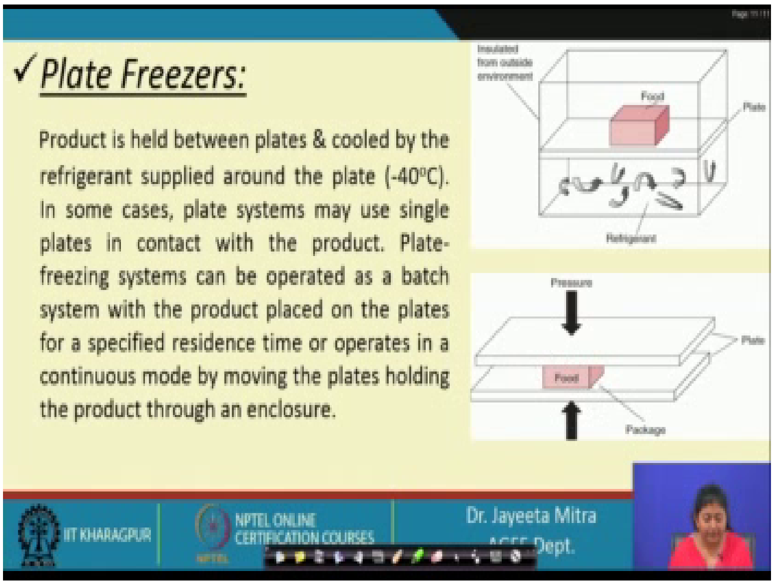

Now, plate freezer which is very common in case of the food industry. So, in that what happen like product is held between the 2 plates and cool by the refrigerant supplied around the plate at almost minus 40 degree Celsius.

In some cases, plate system may use single plate in contact with the product and plate freezing system can be operated as a batch system with the product placed on the plate for a specific residence time or operates in a continuous mode by moving the plates holding the product through the enclosure. So, both the systems are available either you know continuous system or batch system and it is mostly used for the when we need to you know use the regular shape of the product, block of the food to freeze it completely.

So, that time we use this technique. So, if we if we apply the you know heat removal it is takes place from the one side; we will apply the equation for calculating the freezing time and when we use both the both plates and compress the material within that. So, then heat removal will be from the both sides accordingly we need to calculate the freezing time.

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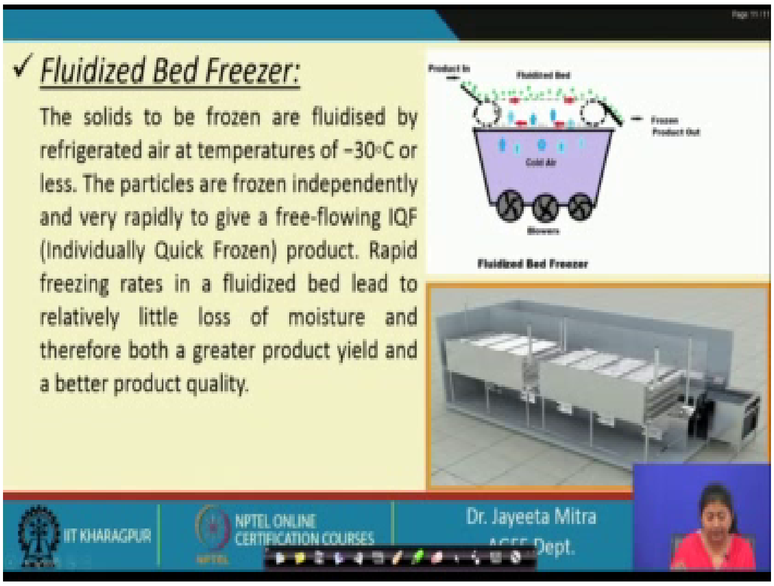

Fluidized bed freezer; so, in this system what we can do is the on the conveyor belt the product is coming in and gradually moving towards the exit section. While the cold air is passing through the perforated plates from the bottom and because of this high velocity air the product will be in a fluidized state and will be exposed to the chilled temperature air or cold temperature air. And while this whole surface is exposed to that it will be it will be frozen and coming towards the exit.

So, for example, we take the food material which has not very heavy in weight very light material for example, pea’s etcetera we can use in this in this method and we can freeze it by fluidized bed freezer. Here is a actual diagram of that where a perforated belt is there in which we bottom of the bottom of that the cold air is placed and that is circulated through the; through a blower because the velocity will be very high.

The temperature is generally minus 30 degree Celsius or less and particles are frozen independently and very rapidly to give a free flowing product that is that is called IQF which is Individually Quick Frozen; individually in the sense one particular food product or one particular you know unit is exposed from all the side to the ambience; so, this is called the individual quick freezing as well.

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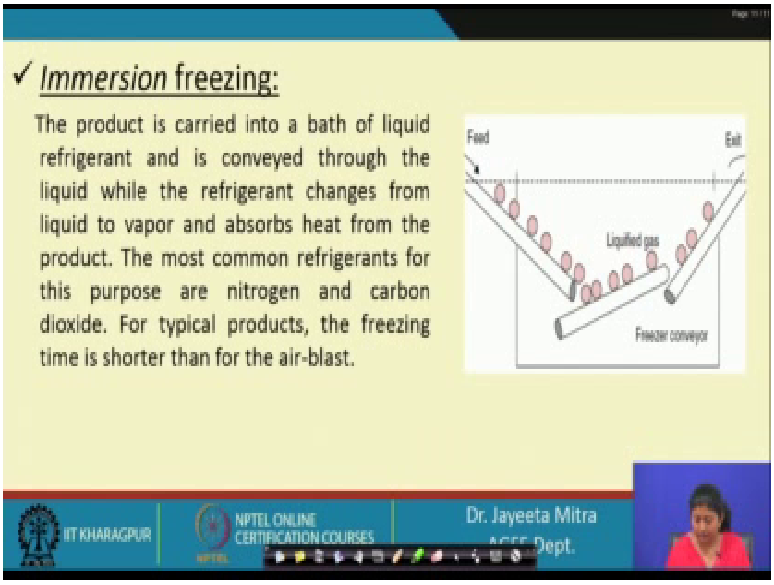

Immersion freezing the product is carried into a bath of liquid refrigerant and is conveyed through the liquid; while the refrigerant changes from liquid to the vapor and absorb the heat from the product. So, the most common refrigerant for this purpose are nitrogen and carbon dioxide. For typical products the freezing time is shorter than the air blast freezer.

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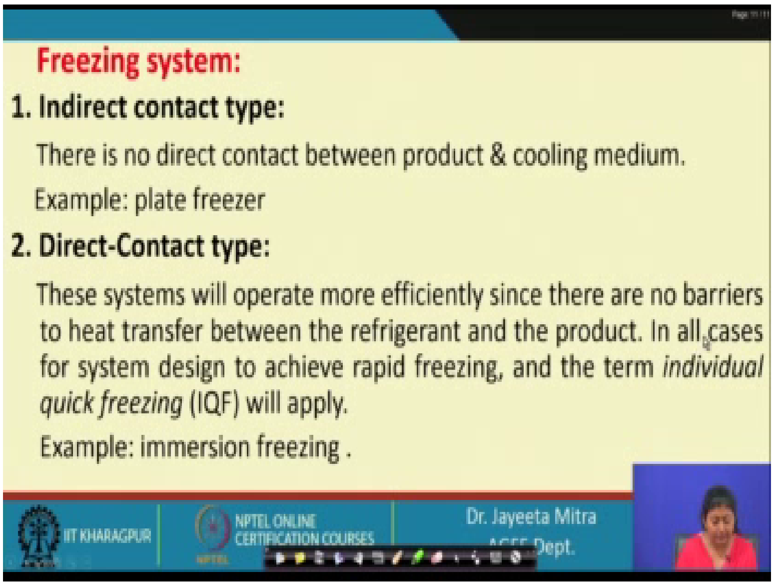

So, freezing system can be of indirect and direct contact type; in the indirect system there is no direct contact between the product and cooling medium; for example, plate freezer.

So, inside the plate we are circulating the refrigerant and the refrigerant is heating I mean lowering the temperature of the plates and then plates in turn the used to lower the temperature of the product. Whereas, the direct contact type systems are those will operate more efficiently since there are no barrier to the heat transfer between the refrigerant and the product.

So, in all cases for the for the system design to achieve a rapid freezing and the term individual quick freezing we can apply. So, for example, immersion freezing; so this is such method where direct contact of the food with the refrigerant is taking place. So, very fast and instant freezing can occur. So, we will stop here.

Thank you.