Multiphase Flow
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Lecture No. # 29
Two Phase Flow with Phase Change
An Introduction to Boiling Heat Transfer

Good morning everybody, we are going to learn today Two Phase Flow with Phase Change. So far the earlier teacher has discussed different aspects of two phase flow, but it was two components to phase flow, where there was no phase change. So, basically gas liquid two phase flow or solid liquid two phase flow without any phase change was discussed earlier. Now, today we are going to see and may be a couple of lecture, we will follow after these, where we will consider, where there is a two phase flow with phase change.

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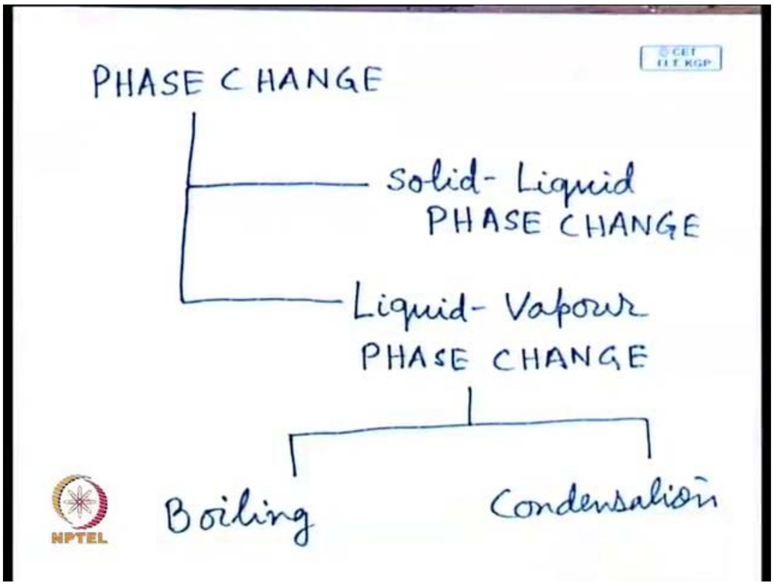

Now, in general, if we consider phase change (Refer Slide Time: 01:02) from engineering application point of view, two types of phase change problems are very important. First one is solid liquid phase change and second one is liquid vapor phase change it goes without saying that, if we consider solid liquid phase change; we are mainly talking about we are mainly talking about melting and solidification. In this kind of phase change, one of the phase is solid phase and another phase is liquid phase, there are many problems where we will find that in this type of phase change application, the motion involved, particularly the motion involved in the fluid phase, in the liquid phase it not very prominent.

So, these are often analyzed as problems of static nature without considering the fluid motion, many problems of sorry melting and solidification, can be can be discussed without taking the fluid motion into combination. On the other hand, when there is liquid vapor phase change then both the phases are fluid phases, so motion is very important.

So, these are typical two phase flow problem, along which the complicacies of two phase flow, the intricacies of phase change phenomena is also involved. So, liquid vapor phase change again they are at two types, one is boiling and another is condensation. So, both boiling and condensation, we will find that these two type of problem they have got many aspects common to your two phase flow two phase flow situation which you have seen earlier.

That means a gas liquid two phase flow two phase flow where a there are different kinds of flow regimes, where there is different distribution of void fraction in a conduit. So, those aspects are there, but another thing that there is a continuous change of the void fraction due to the phase change. So, this also we have two incorporate in our analysis, so that means, along with the fluid flow equation mainly the continuity equation and the conservation of momentum, we have to also consider the conservation of energy.

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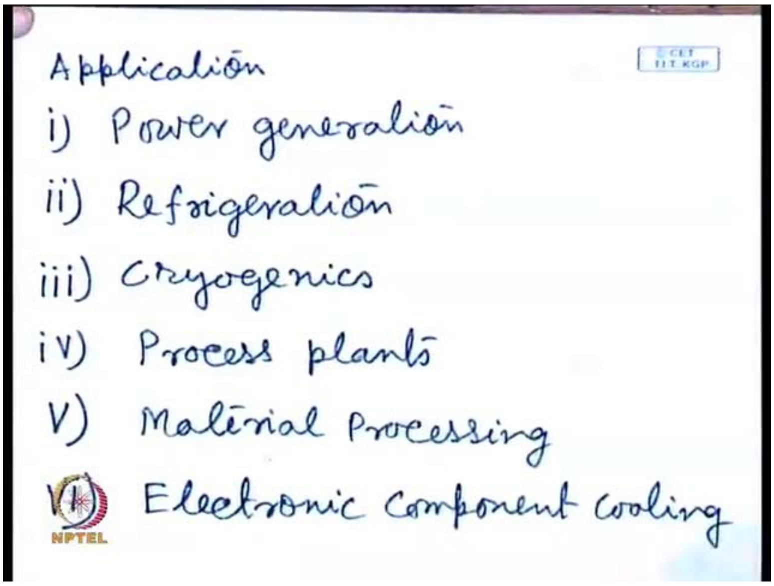

Now, there are many many applications of these two types of two phase flow, the field of applications which we can mention is powered generation, see both in case of fossil fuel type of power plant that means, cool based steam power plant. And the nuclear power plant, where we have to produce steam from water which we will do what in the turbine that involves the process of evaporation of boiling, which is a two phase flow with phase change.

Then we have got refrigeration, a refrigeration cycle is just the reverse of a power cycle, so here also evaporation and condensation both are important, then we have got cryogenics here also phase change phenomena plays a very important role. Then there are different process plants, by process plant I mean, chemical process plant, petroleum processing, refineries etcetera, so here also phase change processes are very important. Then there are other applications like material processing, let say (()), so in (()) phase change phenomena is also important.

So, material processing then a large number of cooling applications, very larger number of cooling application where phase change phenomena is very important; one example, which is very common one can give, that electronic component cooling (Refer Slide Time: 06:33). Now, I like to mention that this least is not an exhaustibly is, there are many more application, where phase change along with two phase flow, that is very important and we have to know how to deal with that.

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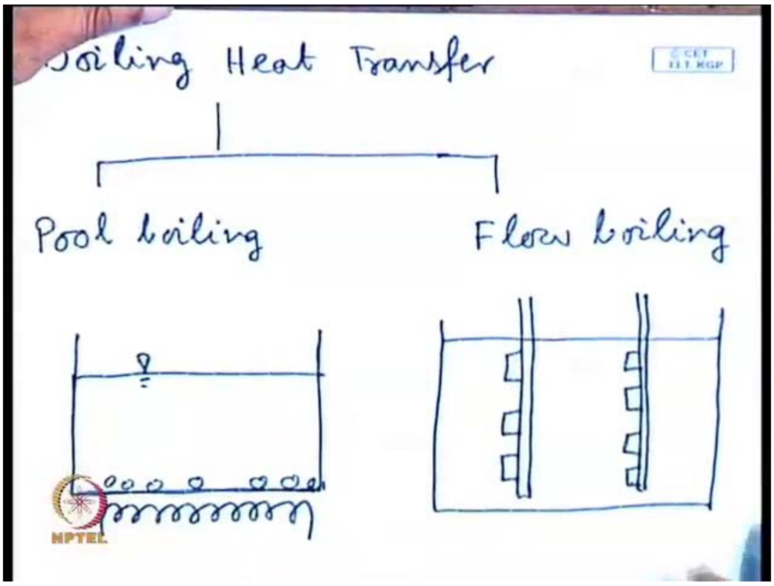

Now, as I have told that there are two main types of gas liquid or vapor liquid phase change process, boiling and condensation, so we will see them in detail and I like to start with boiling heat transfer. So, boiling heat transfer again boiling heat transfer is a very complex phenomenon, and there are different kinds of boiling. So, we can make a good analysis of the boiling process, if we categorize them at the very beginning and then we start discussing them from the simplest case of boiling heat transfer, and then we gradually go to more complex cases of boiling heat transfer.

So, boiling heat transfer the general categorization is like this, boiling heat transfer can be initially categorized like pool boiling and flow boiling. So, pool boiling here the boiling takes place on the external surface, when the object is submerged in a very large bulk of fluid, which is in general motionless, that is what we call as pool boiling. So, there are many example of pool boiling, the most common example of pool boiling which we can which we can sight, that is suppose you are boiling some amount of water in a pan.

So, below there is a heater and the pan is partially filled with water, and then what we will find and as you put on the heater and go on increasing the temperature of the heater, the bottom surface of the pan that is also getting heated up. At one point, it will over suit the saturation temperature of the liquid water, which is resting at the top of it corresponding to the prevalent pressure and then we can find that bubbles are getting generated and of course, with time we will find a boiling and different phases of boiling, so this is a very common example of pool boiling. So, here what we are having, we are having boiling in a pool of liquid.

So, in general the liquid is motionless of course, truly speaking when the bubbles are generated and they are moving of locally they induce some amount of motion, that motion of course, has got a very great influence on the boiling heat transfer. But, in general as there is no established fluid motion due to some prime mover, this is called pool boiling transfer.

So, this is from the domain of our domestic application where we can see pool boiling, but there is many other application in industry where we can see pool boiling or apply pool boiling for our own benefit. Like there could be a scheme of cooling electronic component, so let say these are electronic component which are generating heat and they are immersed in a large cool of liquid. So, here also the transfer will take place due to boiling very large amount of heat transfer will take place due to boiling.

So, this is an application of pool boiling, what is what is used in industrial practice or we can take the example of material processing, that a large chunk of metal is immersed in a cool of liquid of (()), so this is also another application of pool boiling where we can use them in industrial practice.

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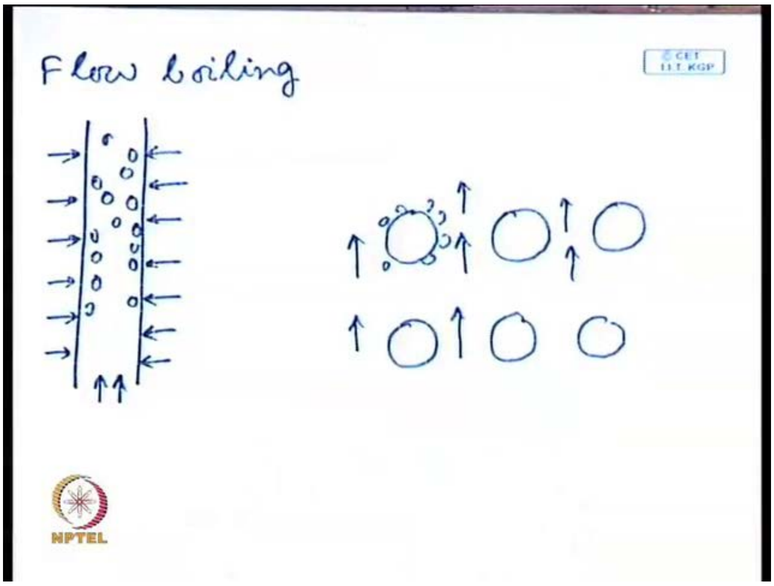

On the other hand flow boiling applications are many more, so flow boiling as the name suggest here, boiling will be over a surface as the surface is heated up, but fast the surface, there is a distinct motion of fluid. And this motion of fluid is not due to the boiling process itself, but it is generated by some prime mover like a pump, there could be other meals also. So, very common example is that that suppose we have got the tube of a boiler, so in this through a feed pump the motion of the fluid is generated.

So, fluid motion takes place through the boiler tube and as it is passing there will be boiling bubble generation will be there on the surface and then of course, there will be developed boiling as we go up and pump. So, it is basically, it is a heated tube this tube is heated may be a combination of convection and radiation heat transfer due to the combustion inside the boiler, and through the heated tube when the fluid is moving with some velocity boiling is taking place.

So, this is the example of flow boiling phenomenon, there could be other example let say we have got salient tube kind of heat exchange and through the tube some hot fluid is passing may be some hot gas is passing, it is it is steam generation by some sort of (()) state and outside we have got the fluid it may be some liquid may be water. So, boiling will take place outside this, but there is emotion of fluid.

So, this is again an example of flow boiling, and it goes without saying that the examples of flow boil or application of flow boiling is many more compared to pool boiling in our industrial practice. But, in then as pool boiling is very easy to analyze and it gives you an over view of all the important processes of boiling, we start our discussion with pool boiling.

So, first we will discuss pool boiling, we will understand different mechanisms of boiling from the discussion of pool boiling, and then probably we will try to see how those understanding could be applied for the analysis of flow boiling situation.

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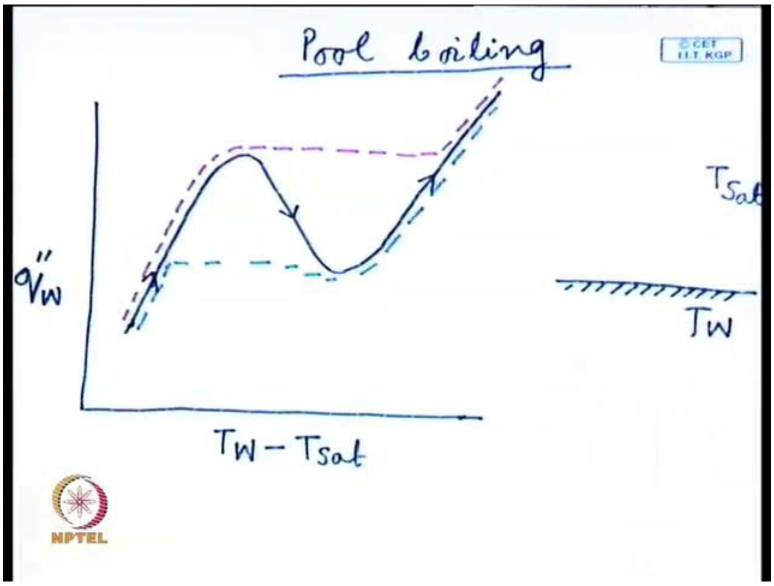

So, now we like to discuss pool boiling, pool boiling conventionally it is discussed in connection with a boiling card, so a boiling card it looks like this, we have got two coordinate one is T w minus T saturated the situation is like this, let us consider this is part of this system, which is experiencing pool boiling. So, this is the solid surface on which boiling is taking place. So, this solid surface has a temperature T 12 denoted by T w and this temperature is is definitely higher than the saturation pressure, saturation temperature of the bulk of the liquid.

So, corresponding to the prevailing pressure, the saturation temperature of the bulk of the liquid is denoted by T z. So, here the excess wall temperature or T w minus T z is used as one coordinate, as a function of this T w and T z, if we plot q w double prime which is the wall heat flux, then we get the pool boiling card. So, pool boiling curve conventionally looks like this, first let us draw the simplest form of pool boiling curve then we will go to different interfaces, so pool boiling curve looks like this (Refer Slide Time: 15:36).

Now, in any operating system, the pool boiling curve can be obtained by two different means, there are two variable T w minus T z or rather T w that could be one variable and q w double prime that is the wall heat flux, that could be another variable. So, either we can vary q w double prime or we can vary T w depending on our method of experimentation; and depending on that we will get a slight variation in our pool boiling curve. The pool boiling curve which I have shown, that is generally obtained when the temperature of the heating surface is independently curve, independently controlled irrespective of the wall heat flux; we will get this kind of a curve.

Whereas, if we try to control the heat flux, what we will get is slightly different suppose we are heating. So, we are heating and gradually we are increasing the wall heat flux, then we will get a curve which is given by this broken red line, but there will be now a difference with the previous curve, we will get a pool boiling curve like this (Refer Slide Time: 17:01).

Suppose instead of increasing the wall heat flux we have started our experiment from a very large value of wall heat flux, and then we are gradually reducing the wall heat flux; then what we will get, we will get a different nature of the pool boiling curve which is given by the broken line in blue colour (Refer Slide Time: 17:35). So, please carefully look into this curve, the black curve shows the pool boiling curve the black curve shows the pool boiling curve, when when the temperature of the wall is independently controlled, the rate curve with broken line shows the pool boiling curve.

When the heat flux is controlled, but heat flux is increased gradually and the other curve that means, the blue curve with broken line that gives the pool boiling curve, when heat flux is decreased from a higher value gradually to do are well as.

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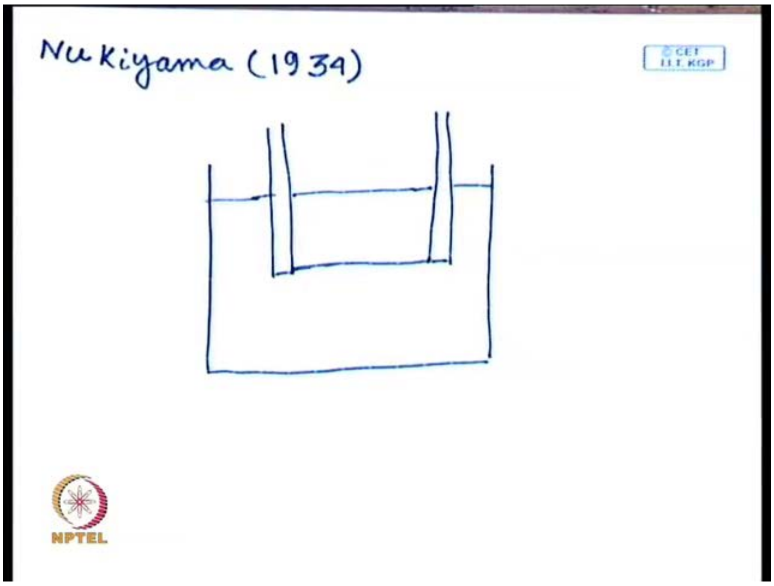

Now, this pool boiling curve which is a very classical one, it was first proposed by NuKiyama (Refer Slide Time: 18:41) in 1934, from his classical experiment. So, NuKiyama experiment was very simple, there is a pool of liquid in this pool of liquid what he has done, he has popped a heater, electrically control heater and this heater was nothing but, a very thin platinum wire.

So, this is the heater on which the boiling will take place, if this heater is heated to sufficient temperature, and what was the ingenuity in this experiment that as you heat a platinum platinum wire its temperature will increase; and its resistance that will also change. So, if you can major the resistance of the wire, you will also get an idea of the temperature which is there on this, which this varies have been.

So, so by this method he could have the boiling curve in a very convenient way where he could get the surface temperature of the heating surface, and at the same time as you was controlling the electrical power he could get the wall heat flux q w double prime. So, with this he could conduct the experiment and propose the conventional pool boiling curve. Now, thing is that again you can understand, that this is a heat flux control kind of experiment, here we will not get all the features of the boiling curve.

So, later on people have done people have devised different method for conducting experiment, where the temperature of the heating surface can be controlled independently; and they get other features which is not possible by the original NuKiyama experiment.

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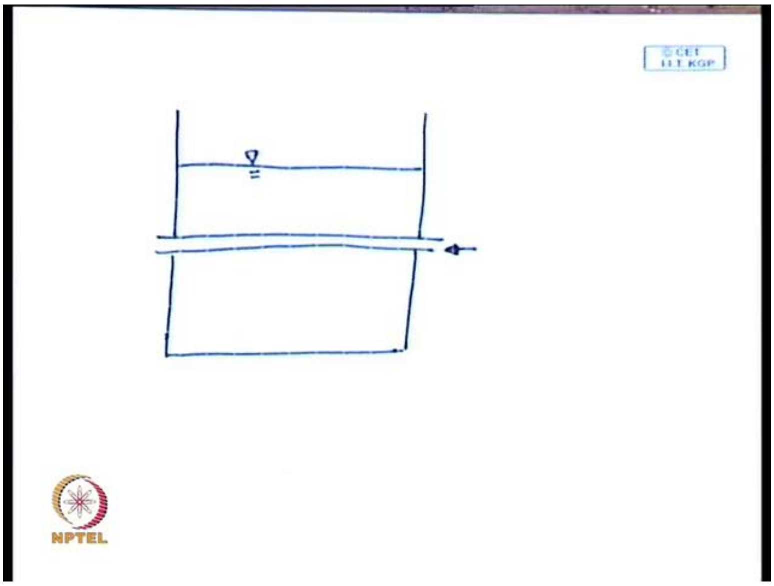

Let me give a very quick version how it can done, though there are different methods by which you can control the temperature, one method could be something like this, that you have got it you which is immersed in a bulk of fluid, bulk of liquid. And through this tube you pass some high temperature vapor, which will heat the surface and then what you can do, you can control the pressure of the vapor.

So, the saturation temperature of the vapor inside the tube will change, so by having different pressure you can independently control the heater surface temperature. And that So, that is how you can get a temperature control condition for experiment, and the curve which I have shown the curve drawn in solid black line, that type of pool boiling curve can be generated.

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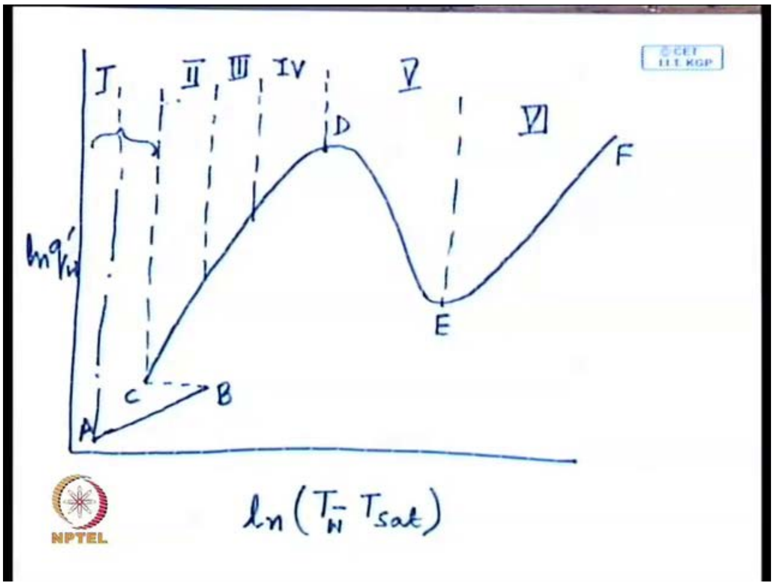

So, now, for our sake of discussion, we will go back to that curve rather I will re draw that curve with greater features and let us see, how does a detail how does the detail of a pool boiling curve under temperature control condition looks like. So, under temperature control condition we have got here T w minus T z conventionally a logarithmic scale is used.

So, here we are having conventionally here also a logarithmic scale is used and then the curve looks like this. So, this curve has got different regimes, let us give some name, let say this is A, B, C, D, E, F, so the different regimes of these curves, let us also give some name to this different regimes (Refer Slide Time: 23:43). So, this regime starts from the heating process, then we have got second regime, we have got the hard regime, we have got the fourth one, then we have got the fifth one, and ultimately we have got the sixth regime.

Here, there are important points which let me tell you, and important regions in this pool boiling curve from A to B this is a natural convection zone, so A to B what we are doing basically, we can imagine one experiment where the pool of the liquid is at the atmospheric temperature, then we are starting the heating process and we start the heating process. Obviously, the liquid temperature is much below the saturation saturation temperature, and no boiling will take place, but definitely heat transfer will take place and the mechanism of the transfer is natural convection, So, that is your regime one. Then regime two we will get the regime of isolated bar, so I think for the convenience I can give you small stage of these regimes.

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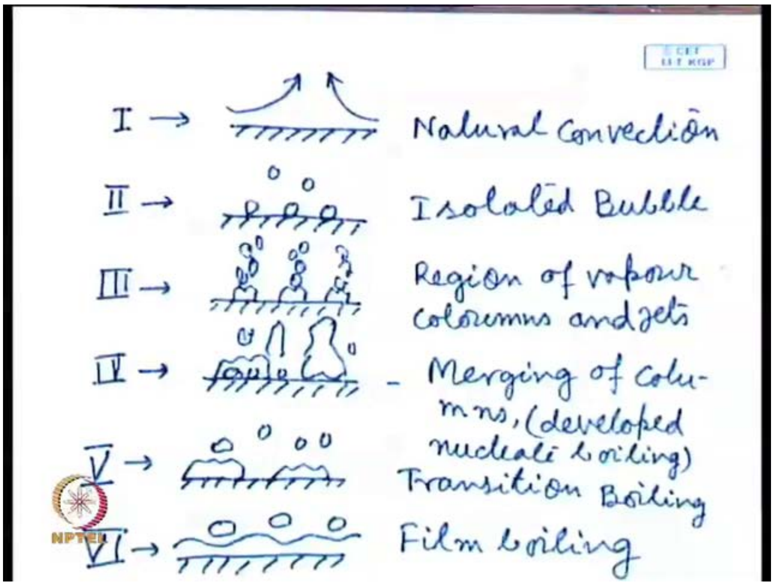

So, this is your natural convection regime one, two is the regime of isolated bubble, so now what has happened now the solid surface temperature is more than the saturation temperature, so bubbles are generating, so this is isolated bubble. The third regime we are increasing the temperature, so what will happen the number of isolated bubble that will increase, the distance (()) into isolated bubble that will decrease, and then the frequency of bubble generation that will also increase. So, instead of isolated bubble what I will get, I will get some columns and jet probably at some distance they will at some gap in between this, so this is region of vapor columns and jets.

In the fourth regime, what will happen this vapor columns and jets, they will try to merge together, they will not completely merge, but they will try to merge together, so something like this they will try to merge together. And this is merging of columns sometimes it is also called developed nuclear boiling.

In the fifth regime what I will find that, this surface is partially blocked by vapor patches and partially it is contacting the liquid, so this is called transition boiling. Ultimately in the sixth regime, we will find that the entire surface is covered by a thin vapor layer, thin vapor film and from that we get the name film boiling.

So, usually we can have theses regimes during boiling heat transfer (Refer Slide Time: 28:58), if we go back to our earlier figure here, we can see A to B that is the natural convection heat transfer regime, C to d this is the nuclear boiling regime. Because, here bubbles are nucleated over the heated surface, and then they are leaving the surface, taking the heat from the hot surface to the bulk of the liquid, so this is called nuclear boiling regime.

And one has to remember that this is a very very effective regime of heat transfer, without many exceptions this is the regime of heat transfer, which is mostly applied for industrial application. Suppose, when a boiler we want to operate within these regime only, then D D is a very important point. So, D is called the maximum heat flux or critical heat flux point, D is called the maximum heat flux or critical heat flux point.

So, here we can see, this is the this is the fool exploitation of nucleate boiling heat transfer, and here we are having the maximum heat flux where pre dominantly bubbles are nucleating over this surface. After that what will happen, after that probably nucleation process will not stop completely, but the heat flux is high enough.

So, part of the heated surface will be permanently block by vapor patches, and in between it will contact with the liquid only, and as the surface temperature increases, the vapor patches the extent of the extent of the vapor patches that goes on increasing. So, here, we will find a very interesting phenomenon and also it is important phenomenon from the (()) of the heater, that here wall temperature is increasing, but heat flux is decreasing.

So, in general wall temperature is increasing heat transfer co efficient is decreasing, so this is a very reverse trend generally, when we increase the surface temperature or we increase the temperature difference, we get an increase or enhancement in the heat flux. But, here the reverse is here the reverse is here, the reverse is seen in this particular volume phenomenon.

So, this D to E this is called a transition boiling regime this is very very unstable regime, many cases we do not find this regime or we cannot record this regime. So, that is why I have shown earlier, if you remember the fool boiling car, if we see and when we are unable to control the temperature, but we are controlling the heat flux. (Refer Slide Time: 32:06) so the transition boiling regime is totally bypass and from nucleate boiling we go to the other side of the car, and here what we find that if we control the heat flux and try to have the boiling phenomenon. So, suddenly up to nucleate boiling heat transfer, there is increase in wall temperature and increase in heat flux.

But, suddenly at the critical heat flux point, we have got a jump in temperature, heat flux value almost remains same, but there is a very sudden change and sudden increase in the wall temperature. So, what does it mean, if my hitting surface is not designed properly then it could mean a failure of the heater surface, but a tube failure it can mean the boiling tube failure, it can mean the failure of other heating surface also.

So, sometimes this critical heat flux point from the application point of view it is also called the burn out point, so here there is a possibility of the of the (()) surface being burnt out. So, one has to be very careful and the prediction of the critical heat flux that should be also very precise for the safety of your many industrial systems.

Now, again if we come back to our earlier diagram that means, from the from the heat flux dominated systems, we are going back the temperature controls system (Refer Slide Time: 33:39). So, here we can have the here we can have the transition boiling regime, which is going from the nucleate boiling regime to the film boiling regime, gradually by the increase of the surface temperature. So, at point E we are having the entire surface offered by a vapor film, so film boiling starts from here, before that we are having transition boiling or even in some text book or some researchers it is a referred by partial film boiling, so after that we get the fool phase film boiling.

So, obviously, in the film boiling, what we get the entire surface is covered by a thin film of vapor, vapor film will have a low heat transfer capability, so the rate of heat transfer will reduce in the film boiling regime. Most of the industrial application we will try to award the film boiling regime, even we will try to award the transition boiling regime, but for our design sake we need to know, how we can analyze film boiling regime also.

Now, you see we are gradually increasing the temperature, so when we reach at point E that is the initiation of fool (()) film boiling. So, already my temperature is high and after that again we are increasing the temperature if we have to cross it in the film boiling regime. So, here along with the conductive heat transfer along with the phase change, another mode of heat transfer becomes very important, that is radiate heat transfer; but in any case this modes of heat transfer are not very effective modes of a heat transfer.

So, always there is a possibility or there is a risk of heater failure, then very interesting thing we can see as this particular region, so A to B that gives the natural convection heat transfer, but from B to C I have joined by a dotted line, so what is this? Now, what happens that natural convection is taking place, so heat transfer from the heat is taken away from the heated surface.

But, at point B, so the wall temperature condition is such that here, boiling can take place, so at this point B we can get two parallel mechanism of heat transfer, one is natural convection and another is boiling. So, obviously, there is an enhanced capacity of transferring heat, so if there is an enhanced capacity of transferring heat, so what will happen, the overall effect will be that there should be an increase in the heat transfer coefficient.

Now, this heat transfer coefficient increase we are getting in an in an experiment where we are controlling the wall temperature separately or independently. So, what does it mean that, it will come back here to indicate that actual inception of boiling is at this point. So, there will be some sort of a by very controlled experiment, one can find out this kind of a temperature sorry this kind of a change in temperature, so that we can get at same heat flux a higher value of heat transfer co efficient.

See, you can understand one thing that here, if we consider this p w minus p sat what will happen this is a higher value of the w minus T sat for the same amount of heat flux it means that heat transfer co efficient is low. But, here what I am telling two different mechanisms of heat transfer is being operated, so from the physics point of view here the heat transfer co efficient, should be high how it can be high keeping, the heat flux same.

If you reduce the temperature then only it can be high, so that is why by controlled experiment one can get a decrease in temperature at this point. Now, different regimes are boiling I have told and one thing is important here, that for we operate in most of the industrial practices, we operate in the nucleate boiling regime and in the nucleate boiling regime also, we can find the errors different sub regimes. First we have get, first we have got the regime of isolated bubbles, then we have got the regimes of bubbles slugs and columns then this slugs and columns they march together and we get some sort fully developed nucleate boiling kind of a thing.

Now, it is very difficult to analyze all these cases, and boiling heat transfer it tilled a it is dependent on a large amount of temperature, we can have the physics in our mind, but from the first law of physics or from the first principle of physics it is very difficult to predict the heat transfer co efficient.

So, what is done people have adopted some sort of a mixture that means, guided by the physics, you try to you try to predict some sort of a law or propose some sort of a law. But, that law will not completely describe the process of boiling heat transfer, then what you do to to minimize the gap you bring in some sort of numerical constants, which are dependent on experiments. So, that how you get the complete relationship for boiling heat transfer.

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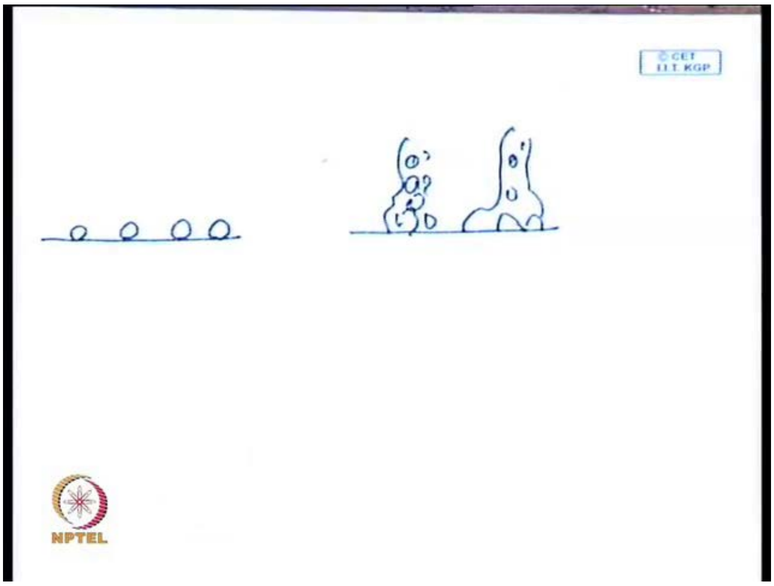

Now, one thing it would be appreciated by you that out of different regimes of boiling what we have seen in nuclear boiling, we have seen there are regimes of isolated bubble, then there are regimes of jets and columns, which are actually due to mergers or bubbles we have got this regimes.

So, obviously, this isolated bubble regimes is much easier to analyze, so many analysis has been done for this isolated bubble regime and then of course, as I have told that different empirical constants have been brought in to get the relationship over the entire nuclear boiling regime. Another thing is important that this isolated bubbles, the generation of isolated bubble is crucial for the process of boiling.

Why it is crucial for the process of boiling, because these slugs and columns they are ultimately coming from these isolated bubble. And isolated bubble there are many physical process involve, if we analyze them properly, then probably the part of the boiling process is clear to us. So, next part what I will do I will try to I mean I will devote some time on the bubble nucleation its growth and collapse.

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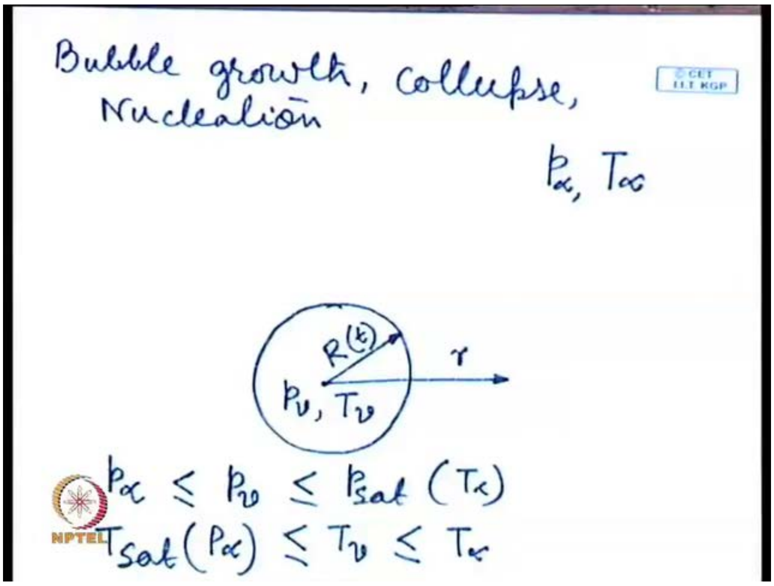

So, chronologically it should have been bubble nucleation growth, collapse, but nucleation part I have intentionally get after the growth collapse. Because, initially it is I mean it is easier to understand the bubble growth and collapse, then if we try to analyzing probably with our knowledge of bubble growth and collapse, we will be in a better position to appreciate that.

Now, for boiling process what we have seen that mostly boiling occurs on a (()) in this solid surface the surface temperature increases and then the bubble appears there bubble grows and then departs or leaves the surface, but initially if we try to analyze from there the analysis will be bit difficult.

So, what we will do, we will try to see the growth of an isolated bubble, this is also not very irrelevant, why it is not irrelevant that in many cases, we can find the growth and collapse of bubble that would be connected to boiling that could be connected to other kind of processes which are equally important, like cavitations. In cavitations what happens, in cavitations we know that in a flow passage if the local pressure comes below the vapor pressure, then nucleation takes place and vapor bubble generates.

So, due to that we will get the growth of the bubble and after that if the bubble moves in the flow field and it goes to some place where the pressure is high. So, it will collapse again a very similar phenomenon is flashing, suppose suddenly, suppose somewhere water is there and or any other hot liquid is there, suddenly the pressure is reduced.

So, what we will find that bubble nucleation takes place, bubble growth take place and depending on this situation probably bubble collapse will also take place. So, this kind of a situation, we are interested two analyze first, so let us consider a spherical bubble, this is your spherical bubble at any instant of time its radius is given by R t, where t is the time and R is the radius of the bubble or in other words what we can see or what we can say that, R is the location of the interface.

So, this bubble is there in a bulk of liquid, so this bulk of liquid are from the bubble as a pressure of p infinity and as a temperature of T infinity, where as inside the bubble we have got the temperature p v and we have got the pressure p v and temperature T. So, basically, what the analysis one can take some sort of a spherical code in it which is having a center of coordinate in a center of the bubble, and r is the co-ordinate with which we can develop the analysis for such type of a bubble for its growth and collapse.

Now, what will happen during the growth or the collapse during the change of the bubble radius r T show the pressure and temperature that will also change, but there is a range within which this pressure and temperature will change. So, what we can write, that the range within which it will change.

So, how this bubble growth can take place, bubble growth can take place only if the temperature T infinity which I have shown that it is far from the bubble the temperature is T infinity, if it is more than the temperature inside the bubble T v, and if it is more than the temperature is at which should be generally at the interface.

So, in other words when this bubble growth can take place bubble nucleation and bubble growth can take place that if we consider that there is a liquid bulk, very large bulk of liquid whose temperature is the infinity. And that is more than this saturation temperature here, if the bubble has to grow how it can grow of course, the pressure field is important, but rather than that, the bubble has to grow due to more evaporation. So, from where the latent theta vaporization will come the latent theta vaporization will come from the liquid bulk extend. So, the liquid temperature has to be more compared to the secretion temperature and that is what has been shown here.

Now, generally what happens that the bubble grows not in one phase, there are different stages of bubble growth or in other words what we can say that, as the bubble grows different mechanism are important. For the initial bubble growth some mechanisms are important, for the intermediate stage of bubble growth some other mechanisms are important. And again for the final stage of bubble growth different mechanism is important that means, if you see the rate of change of bubble radius capital R t which time it will not be having the same flow all through its growth.

Depending on the depending on the mechanism which is prevalent at that particular instant of time, we will have different functional relationship between r T and time alright. Now, what this sake of analysis what we can do, we can take two limiting cases (Refer Slide Time: 49:29).

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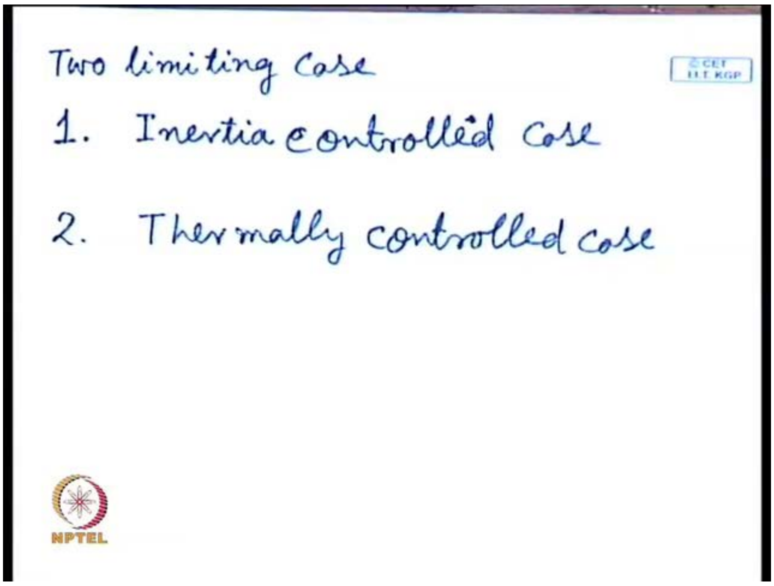

First case is the inertial controlled case. So, this is the initial phase of bubble growth, this is the initial phase of bubble growth, so in the initial phase of bubble growth the bubble growth is controlled by its inertia.

And generally of course, we will discuss more about it, generally at this phase the bubble growth is quite fast, inertia controlled bubble growth means what? It means that the pressure field and the march of the bubble bubble though where very important for the good process. So, this is the initial stage of bubble growth, here generally the growth of bubble is much faster, another limiting case is (Refer Slide Time: 50:51) thermally controlled case, this is again the march later stage of bubble growth.

So, at this stage what happens, at this stage vaporization takes place and what the vaporization to take place, what is needed heat transfer from the bulk of the liquid that has to take place, and that process definitely as heat transfer is taking place, so it is thermally controlled. And this thermal heat transfer process or thermally controlled process is much slower this vapor generation process is much slower. So, here we will get a slower growth of the bubble and this is generally the final stage of bubble growth, after that either the bubble will have a stable size it will move away from where it is going, if it is growing over a surface then it will become, so big that it will detach from the surface, so those kind of phenomenon take place.

So, as I have told that the there are two limiting cases, inertia controlled case and thermally controlled case, so inertia controlled case is just at the beginning of the bubble generation or bubble formation very first growth. And basically here, we have some sort of a pressure equalization and growth of the bubble not much of the evaporation in and not much of increase in its mass. In the final stage, we have got a thermally controlled growth where heat transfer gives rise to more vaporization the bubble size grows, because of its change in mass and these both is slower. I think I will stop here, and next day I will start with the inertia controlled growth of bubble.