Conduction and Convection Heat Transfer

Prof. S.K. Som
Prof. Suman Chakraborty
Department of Mechanical Engineering
Indian Institute of Technology- Kharagpur

Lecture-59
Boiling

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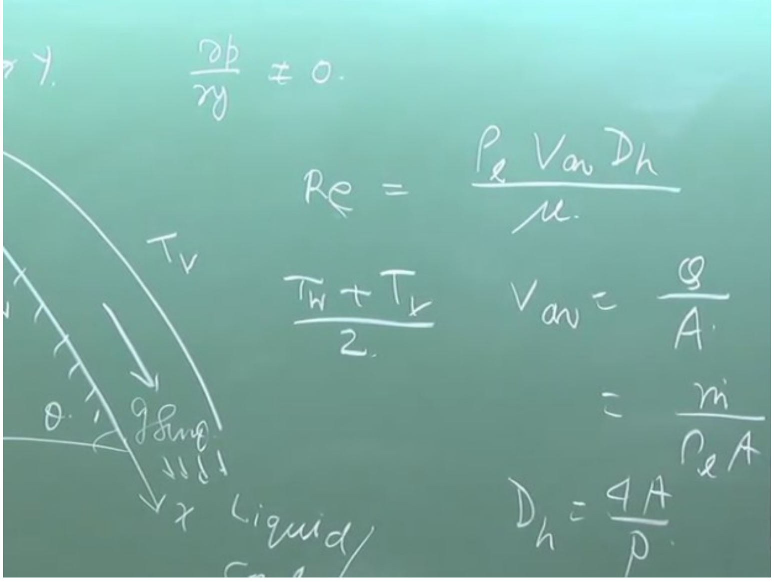

Now I will tell you, something just before closing this discussion. This flow takes place like that and there is a Reynolds number for condensate flow, you know this is condensate flow, this is a liquid film, liquid film flows, liquid which is known as condensate, which is known in the practical terminology as condensate.

There is a Reynolds number of condensate flow, which is defined as density of the liquid. The average velocity, the hydraulic diameter divided by the liquid viscosity and in all such expressions, the liquid density viscosity everything, here I am not putting l, because viscosity is only for dill liquids. Since the density of the vapour comes into question, so I am denoting it as rho l and rho v.

So, all the liquid properties are usually evaluated at a mean, arithmetic mean temperature of Tw and Tv, that means Tw + Tv/2 and this is known as, in our language film conditions. Sometimes we tell, the properties are evaluated at a film conditions means, the arithmetic average, all properties are evaluated at a temperature, which is arithmetic average of the surface and the vapour temperature.

So, this is rho l mu evaluated like that and v average/ definition, you know fluid mechanics; it is the volumetric flow rate/ cross sectional area**,** that means one can write that m./rho L*A and these h is the hydraulic diameter which is 4 area/perimeter, that is enough. But some information I gave you, we will not go for any other analysis, that this Reynolds number definition is important.

Because beyond the Reynolds number Re greater than 1800, instability occurs at the thin film interface and the flow becomes turbulent and these instability onset takes place with the formation of ripples at the surface. In practice, it has been found even at a relatively much lower Reynolds number than 1800, sometimes the instability occurs. Because these depends not only on the Reynolds number.

Sometimes on the surface condition and other properties of the liquid apart from the rheological property mu and rho. So, therefore this is just for an information that a thin film flowing pass the plate may become well; may become turbulent depending upon the situation whether Reynolds number is high or low. In practice, it is not always that a plate will be there for condensation.

Usually tubes are there, yesterday at the beginning I told you the example, where the liquid, one of the fluid is flowing through the tubes. For example, the power plant condenser, the condenser of the refrigerator, the water tube in a boiler, so usually the flow takes place to tube and usually the tube cross section is circular but various cross sections are tried to enhance the rate of heat transfer.

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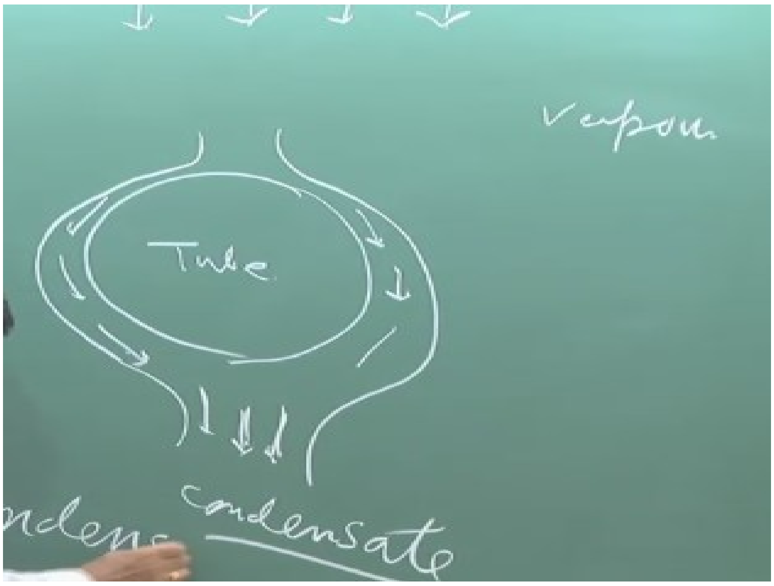

Just I tell you certain things that in the circular tube, usually what we use, it looks like that. If tube is horizontal like this a horizontal tube and if the vapour flows like this either push vapour or vapour flow, flow with a gentle velocity, then what happens it looks like this, the film grows; the picture is like this and tickles down the surface of the; this is the tube, tickles down the surface; this is the film, tickles down the surface of the tube.

Now the rate of heat transfer will be increase, if we can decrease the film thickness, like our decrease a thermal boundary layer. If you decrease the film thickness, you know the temperature gradient will be enhanced, delta T/ thickness of the Tw, Tv-Tw/delta. It is just like the reduction of thermal boundary layer. So, in any condensation problem, our motto will be to drain the condensate this is condensate; to drain the condensate this is the terminology to drain the condensate as fast as possible, so that the thickness of the film at any location is small

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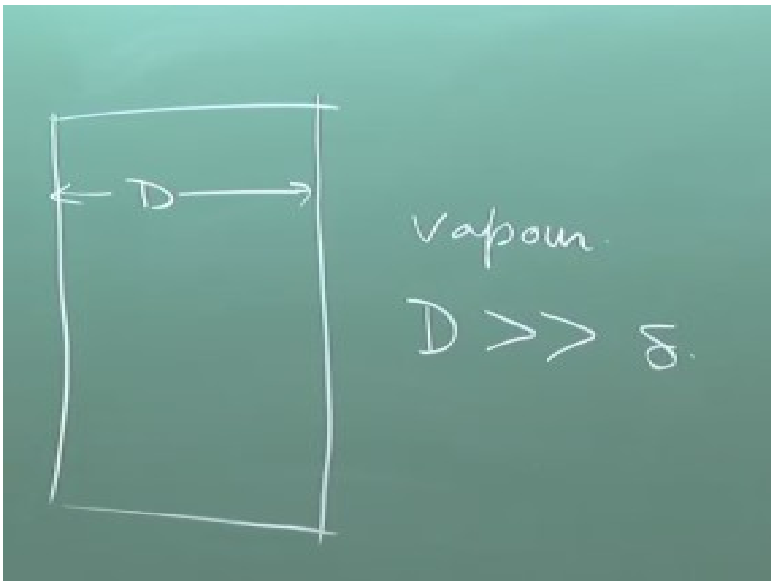

So therefore, different cross-sectional shape has been considered which keeps an effective gravity move, so that this can make the drainage of the condensate faster. Now in case of a vertical cylinder, the information is like this; in case of a vertical cylinder, condensation outer surface in the vertical cylinder, vapour is there. We can use the expression for vertical flat plate provided the diameter of the cylinder is much higher than the thickness of the liquid film, then we can use it.

This is another information, today everything will be informative, no deduction nothing, just for your information. Another information, I tell you because of the turbulence, it has been found experimentally without going for any analytical result. The expression developed in the laminar flow for heat transfer coefficient is getting enhanced by a factor of 1.2 to 1.3, that is going to 30%.

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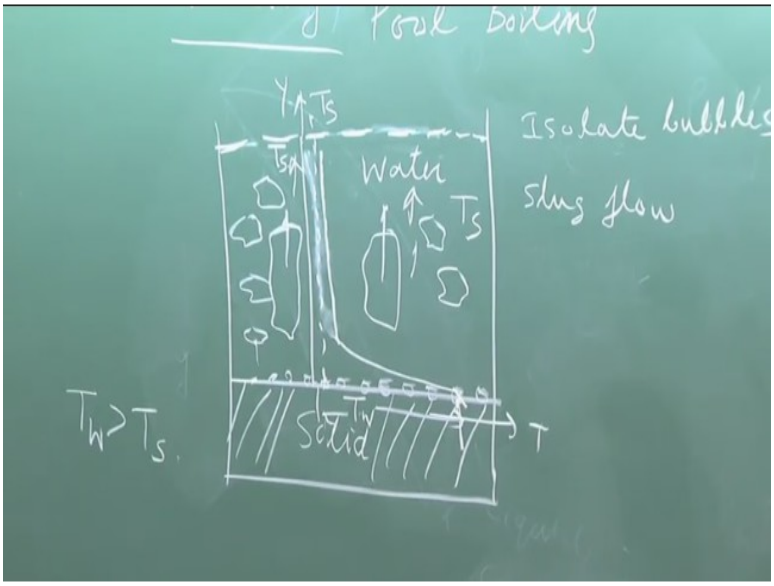

So sometimes in industry, they give this allowance to evaluate the heat flux and design the condenser (()) (11:17) and with this, I will end this discussion on condensation. Now we will move to boiling heat transfer. Now I will discuss the boiling heat transfer, now boiling is the very complicated hear transfer phenomena both from fluid dynamical and heat transfer point of you. This will you understand, when I will explain this.

So, only a qualitative picture of the boiling heat transfer and some pertinent information will be given in this class and frankly speaking the analysis of boiling heat transfer is very tuff. It is much beyond these scope of pure syllabus and scope of your studies now. Now boiling is just the opposite of condensation, here what happens, if a liquid at saturation temperature comes into contact with any hot body whose temperature is above the saturation temperature, the boiling starts.

One example, if we consider liquid water at one atmospheric pressure and 100 degree Celsius; as you know 100 degree Celsius is saturation temperature corresponding to one atmospheric pressure. If you give a certain amount of heat to the water, it will start boiling and the boiling will take place, so long you supply the heat, until and unless the entire water will be converted into steam at 100 degree Celsius.

The reverse that happens in the condensation. So therefore, in the boiling, one has to have a temperature source whose temperature is greater than the saturation temperature. Now this boiling is usually complicit in practice by having a heating surface or the source which is submerged in a pool of liquid and that is known as pool boiling. Now to explain the pool boiling, let us have a very simple figure like this.

Let us consider a surface like this and let us consider some solid which is the heat source, whose temperature is Tw and this liquid. Let us consider water for our; these are the free surface, easy understanding water**,** for example atmospheric water, so Tw has to be greater than the saturation temperature in an atmospheric pressure, water saturation temperature is 100 degree Celsius, it has to be more than that Tw.

Now there may be 2 options, the bulk of the water may be at saturated temperature 100 degree Celsius or may be at a temperature lower than these saturated temperature, but this surface is higher than that. So, in 1 case, when it is a saturated temperature, it is known as saturated boiling. I am not writing everything on the board, you just write saturated boiling and when the temperature is below the saturation temperature.

As you know the terminology use in thermodynamics, the supple state. So therefore, it is known as supple boiling. So, let us consider a saturated boiling case, where the water is at the saturation temperature. My drawing is not that good, so this line is straight, free surface. So, water is at saturated temperature Ts, now what happens, the water near to this having a temperature more than the saturation temperature.

So, the nucleation or the initiation of the boiling takes place at the surface and how does it takes place? It takes place to the formation of small very tiny vapour bubbles, steam bubbles and the places where this takes place a small tiny bubbles, is known as nucleation sign and this nucleation of small tiny bubbles depends not only on the temperature requirement; temperature is the necessary condition as to be higher than saturation temperature.

But depends upon many other condition. So, one of the condition is that impurity in the liquid, the type of surface which enhance the nucleation. So, therefore this surface and liquid characteristics and the liquid impurities, these actually guides the formation of nucleation signs. But we are not going into all those deep thing, we are just studying grossly the qualitative wave here. The nucleation of small tiny bubbles takes place.

Then what happens, big bubbles of different size grow and move toward the free surface. Now moves toward the free surface. What happens? That when the bubble nucleation takes place, it is detached from the surface. Now the bubble may grow, may collapse before reaching to the surface. There are 2 options, now whether a bubble will collapse, let us consider individual bubbles; individual bubbles are flowing.

Whether the bubble will collapse or the bubble will growing sides and go to the free surface and ultimately it will collapse. This all depend upon the pressure temperature and the surface tension property of the vapour and liquid, How I will you tell you? Let us now appreciate that the temperature profile is like that, if you draw this side is y axis and this side is temperature; so this is Ts at the surface, Ts sorry Tw, this is Tw at the surface.

From Tw, it aesthetically reaches, this is Ts, this aesthetically reaches to Ts, this is Ts rather I should draw this way. This is the value of Ts, I am drawing it in exaggerated manner, this Tw is not much above the Ts, but it shows like that, this is Ts. So, it goes from Tw aesthetically to Ts; saturation temperature. So, what happens the liquid near the surface and even above the surface is always at a temperature higher than the saturation temperature.

This is a metastable state, you understand that this surface is at, for example 110 degree Celsius, this is done in a very exaggerated or amplified manner and this is 100 degree Celsius. So liquid temperature here is always more than 100 degree Celsius, that means liquid at superheated state, this is metastable state. Now what happens a bubble which is form or a vapour bubble as you see, which is form whether it will grow or collapse depends upon the heat transfer.

Now because of the surface tension, the pressure within a bubble is higher than that of the liquid outside, because of the surface tension flow. You know that for a bubble it is 4 sigma/r, if you consider the bubble to be the spherical one. Now at that pressure, the temperature is higher, the steam temperature should be higher than that of the saturation, that means, if you consider that water has to be at saturation temperature for a given pressure.

For example, atmospheric pressure 100 degree Celsius is a saturation temperature but this pressure is more than 1 atmosphere because of surface tension. So, steam temperature is more than 100 degree. Now depending upon the superheated metastable state of the water, heat will either come into the bubble or go out of the bubble, that means if the steam temperature or the vapour temperature is more than the outside the liquid temperature.

Then the heat will go out and the vapour will condense and the bubble will collapse but if it is other way That is why I told it depends upon the surface tension characteristics, it depends upon the temperature and pressure of the liquid; try to understand. If it is other way that liquid temperature at this metastable superheated state is still higher than the temperature of the vapour, then the heat will go to the vapour, a bubble will go bigger and bigger.

And ultimately it will burst. Because as it grows bigger, the pressure inside falls, because the surface tension force will be reduced, because of the higher radius of curvature. This is the very lucid explanation, very few books you will get this explanation. So, this is the basic explanation for which the bubble will grow or collapse but this is not the main picture; picture is that number of bubbles will generate with time and ultimately what happens?

Bubble collides each other and they flow in a random manner with random size, different sizes. As you go on increasing this temperature, you will see number of bubbles collides together and comes in the form of wet sorry, jets and columns of bubbles and that create a big chunk of bubble to flow and that is known as slug flow. So, there are various regimes, one is isolated bubble flow, isolated bubbles, then jet; vapour jet, all these things appear, vapour jet and creates a slug flow.

Therefore, the entire flow becomes heterogeneous, 2 phase heterogeneous flow, where liquid is there, number of bubbles with randomly moving different sizes, they collides, they collapse, they form ;sometimes the bubble ejects in the form of jets, they form a big chunk of bubbles and make slug flow and this entirely a discipline which people are perusing in research in 2 phase flow where it is relatively easier to capture that by high speed photography that different regimes of these heterogeneous two phase bubbly flow.

To explain the different regimes physically but theoretically it is very tuff. But still we do it theoretically with the aid of CFD. because analytical treatment cannot be applied here in such a heterogeneous 2 phase flow. So therefore, you can understand very much it is not that easy of a free convection or force convection flow over a flat plate or flow through a simple duct. So That is why the theory in boiling heat transfer is so difficult. But what happens?

This typical 2 phase flow makes a agitation in the liquid and makes a better mixing and creates turbulence for which the rate of heat transfer or heat flux at the solid surface is enhanced and this boiling heat transfer with this thinking, pure background can be explained in a much better way so the very classical and popular curves known as boiling curves, which I will show you now. This is the pointer.

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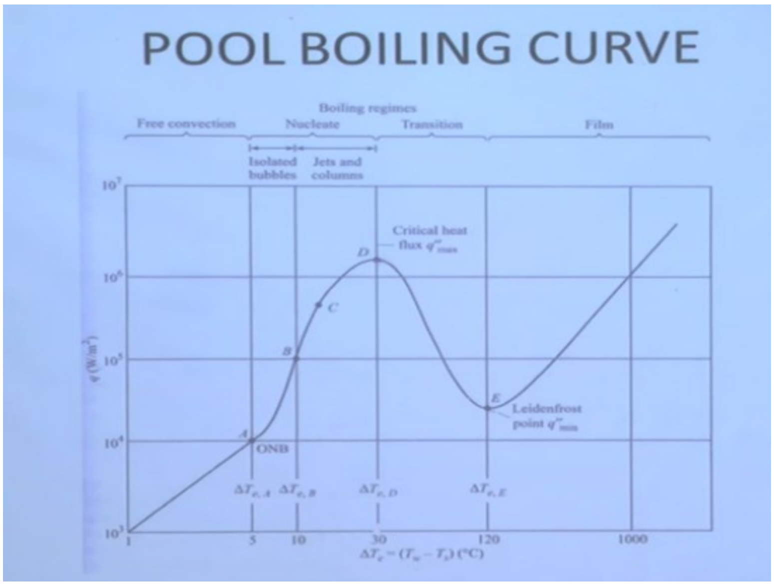

POOL BOILING CURVE

Now this is the standard boiling curves, what is meant by boiling curves? These question will be asked, I tell you, nobody will ask you to make scale analysis and derive the exact form, exact solution at the possibly velocity distribution or the Nusselt number 4.36, 48/11, but employer will ask you this question, what is the boiling curve? There will be something which will be useful for you. Because these curve is used in the practice.

Now what a boiling curve means? So, all these things you know that boiling phenomena, that this is a such a complicated phenomena, we know qualitatively how does it takes place and it is very difficult to make a theoretical analysis. This is the boiling state, liquid at superheated condition, heat transfer takes place. Let us see what is a boiling curve? boiling curve is a curve where in the (()) (26:00), we put the excess temperature.

Now the excess temperature delta Te is defined in case of boiling as the difference between the solid surface temperature which initiates the boiling Tw – the saturation temperature and these definition remains as it is even if the boiling is subtle boiling, that means whether the bulk of the liquid at saturated temperature or subtle temperature does not matter, the excess temperature is defined like that.

Ordinate, we have the heat flux, watt per meter square, this is the heat flux. Now what happens is that these curve, see this is in the (()) (26:40), will be explained with the excess temperature that is delta T as the independent variable and we will see how the heat flux, this is experimentally obtained curve, how heat flux is changing? Now initially these actually quantitative data, this is plotted in a log-log graph.

So, this quantitative data, it is not written in the figure, it is for water at 1 atmospheric pressure otherwise the quantitative figures have got no meaning, this will vary from liquid to liquid. So, so log the excess temperature is up to 5 degree that means, 105 degree Celsius. There are very insufficient bubbles generated not at all, there is no nucleus and at the surface usually.

There is no trace of bubble and the liquid is heated simply by free convection as it happens for any fluid that it is heated at the bottom, cold at the top, so it will go rising and there will a free convection loop, free convection current takes place. So, it is free convection and the heat flux verses delta T follows a power law model in free convection which appears to be linear in a log-log plot.

As you know there are certain things we have to know readily, because your employer will ask this question, nevertheless theory is the most important thing, is the necessary condition you must know the theory in depth. But at the same time, noted the cost of certain practical information, then those people will tell that you do not know anything. Convective heat transfer, there is a thumb rule, that the free convection, if the flow is laminar, heat flux is proportional to delta T to the power 5/4.

Because heat transfer coefficient is proportional to delta T to the power of 1/4, that you have already come into picture that we have seen, it has come into picture that Nusselt number in free convection is always proportional to Grashof number to the power of 1/4, laminar free convection, that means heat flux is proportional to delta T to the power 5/4. Similarly, in turbulent flow, heat transfer coefficient is proportional to delta T to the power 1/3.

This is for information just and the heat flux is proportional to delta T to the power 4/3, so therefore if somebody ask you, you can tell that the slope of this, slope of this curve depends upon laminar and turbulent, these appears to be a straight line so from origin to a, this is a free convection flow. Then point A represent ONB, that is onset of nuclear boiling. Now this boiling with the nucleation side that means with the vapour generated at the surface is known as nuclear boiling.

The boiling is nucleated, nuclear boiling. So, this nucleation starts (Oh! what is happening in my - that is the problem with me) so nucleation starts and what happens? the isolated bubbles are generated more and more bubbles are generated so as you increase the delta T, the heat flux increases sharply. Now, the point B is retained to de-market this region from A to B, which is specified by this temperature delta T, change from 5 to 10 degree, which is the isolated bubbles regimes.

These are the different regimes, which is the free convection regime from origin to A, then A to B part is the isolated bubbles which grow in number. They collide, they collapse, but the flow is governed by the formation and movement of isolated bubbles. Then from B, what happens? I told, the number of bubbles are so much that it is ejected from the surface in the form of jets.

This enhances the heat transfer much more by creating more mixing and turbulence in the fluid and these regimes B to D is the jet and column regime; this B to D, but there is an interesting fact within these jets and column regimes, a point C is an inflexion point. What is that inflexion point? This inflexion point represents that these C the curvature is change. That means, the heat flux still increases but with a decrease in rate.

The slope decreases, which means in terms of heat transfer coefficient, if you see up to these point, heat transfer coefficient increases with delta T, but beyond C, heat transfer coefficient decreases the delta T. So, the heat flux increases with delta T, not in the same proportion are increase in the delta T. That means, the slope decreases and we will see that there is a less decrease with delta T, which is flattened out after C.

This is the inflexion point where the slope changes its sign and curvature changes its sign from increasing to decreasing trend and at D, incidentally it reaches the maximum heat flux which corresponds to 130 degree Celsius for water at one atmospheric pressure. Here it is the maximum heat flux after which a very interesting feature is found that it drops, that means as we go on increasing the surface temperature, increasing the delta T, excess temperature, this is drop.

Why the heat flux drops? The reason is that after sometime the number of bubbles that in the nucleation side collides together and makes just like a film condensation, a thin film of vapour and the heating surface is blanketed with a vapour, film of vapour and that film of vapour produce a additional thermal resistance and the thermal conductivity of vapour is much lower than that of the liquid. So, after the formation of the vapour, what happens?

Suddenly, the thermal resistance increases for which the entire picture changes from here, the nucleate boiling changes to a regime, which is known as film boiling. This is a transition zone, I will explain, that means at this point onwards the film boiling start, that means the blanket of vapour takes place. This is not just number of nucleated bubbles but a continuous vapour which puts an additional resistance.

Because of its low thermal conductivity in the rate of heat transfer for which the heat transfer or heat flux gets reduced with the increase in delta T and reaches the point minimum, which is known as Leidenfrost point, after which it again increases. I will tell you afterwards but why this part is known as transition? That during within the regime, where the nucleate boiling just is converted to the film boiling at delta T.

Up to delta T 120, the film becomes transitions, it happens in all natural phenomena. Transition means sometime it is nucleate, sometime it is film, that means, sometimes if you observe, it has been observed in experiment. I will show you the experimental set up, I am sorry that I cannot show you the video, it would have been much better that sometime there is a continuous vapour blanket, sometimes it disappears number of tiny vapour bubbles.

Again, the blanket, again the vapour bubbles which starts, which happens even in the transition from laminar to turbulent. You know that the transition takes place in a pipe flow at 2000 Reynolds number. But between 2000 to 2500 Reynolds number, the flow becomes sometimes laminar, sometimes turbulent. This is the peculiar or typical characteristics of a transition zone.

That is why this is known as the transition film boiling, after which when the delta T is more than 120, there is no transition, there is a stable blanket of vapour film and the boiling takes place through this vapour film, bulk of the liquid is boiled and there after what happens; obviously the temperature increases from the minimum point, again it goes on increasing and at some high temperature, radiation heat transfer will come into picture.

So, it is a monotonically increasing trend. But in practice, we do not go to that range. So, this is a typical boiling curve with different regimes, the onset of nucleate boiling, this is the isolated vapour regime, this is the jet regime and this regime, the heat flux increases tremendously in steep rise after C, the rise is not that steep, there is an inflexion point where the heat transfer coefficient decreases, heat transfer decreases at a slower rate than that in delta T, after reaching that, this is dropped.

Because of film boiling starts, it is the onset of film boiling and this maximum heat flux point with the onset of film boiling is known as the critical heat flux. What is critical heat flux? You must tell this is the critical heat flux, sorry, critical heat flux and then, after that this drops and these becomes the transition regime within these delta T after which these goes increasing and this minimum point is known as Leidenfrost point.

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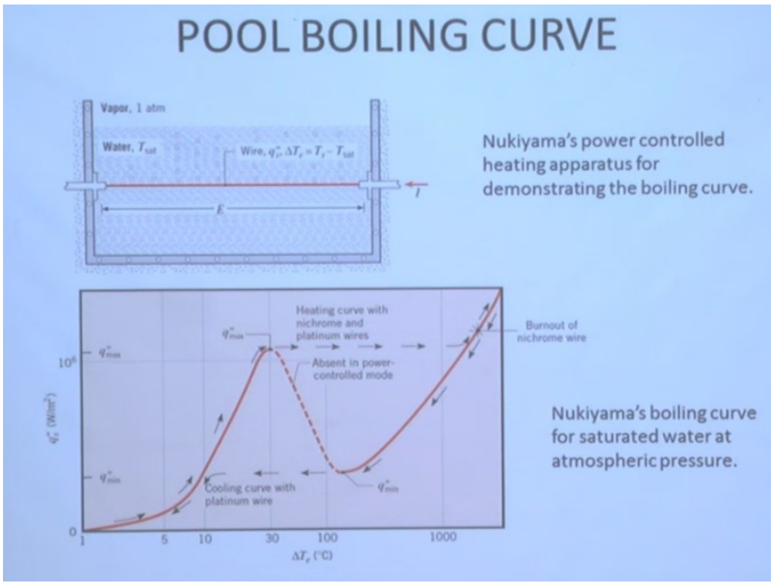

POOL BOILING CURVE

Nukiyama's power controlled heating apparatus for demonstrating the boiling curve.

Nukiyama's boiling curve for saturated water at atmospheric pressure.

Now the most interesting part which is asked to many students even in many experts, they cannot answer that if you make an experiment in the laboratory, which was there in our heat transfer laboratory also, I do not know whether you have done the experiment with these with or not, which was first done by Nukiyama, that is known as power control heating apparatus. What is that? He made an experiment to determine the boiling curve. What he did?

He gave a nichrome wire here for heating, this is the end where he applied a voltage E, potential difference by electrically heating the nichrome wire and he slowly varied the power, so that it is known as power control method and measure the temperature of the nichrome wire by a thermal couple and plotted the value of delta T. He kept this water at a temperature of T saturation and measure the heat flux by an instrument.

So, what he observes in his curve, which everybody observes, do you observe in our Student day and you have observed in your student days. I do not know whether you have done this experiments or not. The similar experiment was there in our laboratory that after this curve, here maximum heat flux, this part of the curve and this part of the curve, this is giving by a dotted line to show the transition nature is missing.

That mean when we go and increasing the temperature, we see cool leaded heat flux is increasing. We are very happy and we are relax and taking tea and readings, we are taking from the temperature indicator and the heat flux indicator so we will see that this part, but after reaching this point suddenly you see where is melted, circuit is broken. The entire experiment is stop why you add this melted?

This is because sorry, this is because that the temperature we found after reaching this point suddenly jumps up to the very high value, even if I do not change the power, even if I do not change the power at all by dimmerstat or variac, we control the power those of you have done the experiments you know, but suddenly heat changes to a very high value jumps, which is more than the melting temperature of the material. Why it happens?

Because of the formation of the thin film of the vapour, there is a drastic increase in the thermal resistance, heat flux. So therefore, at this temperature, so this power; for example, at this power, which creates this temperature because of this immediate deduction in heat transfer coefficient, temperature jumps. We cannot have any control. So, the question come said then how? how then we can generate these curve?

Yes, you think from your physical understanding. These curve to generate, you have to make an independent control of temperature, not by a power control. Here the; That is why sometimes very intelligent employer were literal theoretically bias, not like a routine employer. They ask that why this particular experiment in known as power controlled experiment.

This is because we control the temperature by controlling the power, so that we do not have any fundamental grip over the temperature. You read my book, it is written in a very lucid explanatory manner that it is not control like that, but when we reach that particular power which gives this temperature corresponding to this maximum heat flux, immediately the instantaneously heat transfer coefficient is reduced.

Because of the formation of the vapour and immediately vapour blanket jumps to a very high temperature. But if you put up control over the temperature which numerically can be done and can make an infinite small; horrible, and if we can make an infinitely small resolution of temperature variation from here, we could have obtained this part of the curve. Similarly, in the cooling side, there is a hysteresis that after this is suddenly jumps here at lower temperature.

So, this curve, experimental curve, where we miss the part and have the hysteresis is solely due to this power control method of doing the experiment. Because there is no other way out by which we can make the experiment by an independent control of this source temperature which we can vary at that point, the very small resolution. Is it clear to all of you? I think that these ends our discussion on boiling.