Conduction and Convection Heat Transfer
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Lecture - 57
Condensation - I

Good morning to all of you. Today onwards, we will discuss boiling and condensation. So far, we have discussed convective heat transfer both forced and free, and there we have seen that heat is being transferred between a fluid and the adjacent solid, when the fluid is in motion. And this motion may be caused by external agency. That is known as forced flow, where we prescribe it as forced convection.

And this motion may be generated due to buoyancy. Buoyancy driven flow where the convection is termed as free convection. But in both the cases the fluid medium is homogeneous and there is no change in phase. It is either liquid or gas, but in many practical applications in this type of convective heat transfer, the fluid medium changes its phase, which means it may change from liquid to vapour phase or from vapour to liquid phase.

Vapour is a gaseous phase as you know close to saturation state. The term vapour is a gas phase of a liquid close to the saturation state. So, either liquid to vapour or vapour to liquid, few examples I tell you so that you will be encouraged to study this boiling and condensation phenomena.

For example, the condenser of a steal power plant, you know the steam after expansion from the turbine where we get mechanical work comes or enters into the condenser and it flows over the surface of number of tubes, where the cooling water flows inside the tube. And the cooling water takes the heat from the steam and steam gets condensed.

Similar type of things happens in the condenser of a refrigerator, the working fluid known as refrigerant, which after leaving from compressor at high temperature and pressure, flows inside a, inside number of tubes and it is condensed by dejecting heat to the atmospheric air, which flows past the tubes. In this case the condensation takes place at the inside surface of the tube, unlike that at the outside surface of the tubes in case of the steam power plant condensation.

Now the other direction phase change from liquid to vapour takes place in the water tube of a boiler. As you know, the boiler receives high pressure water from the fit pump and as the water flows to the water tubes of the boiler, heat transfer takes place from the compression product known as true gas at high temperature, which flows surrounding the tube and transfers heat to the water, which in course of its flow is converted into vapour.

Now this type of processer convective heat transfer, because there is a transfer of heat to or from solid surface, that means heat transfer between the solid and the fluid where the fluid changes its phase either from liquid to vapour or from vapour to liquid. So therefore, it is a convection process associated with phase change and known as boiling and condensation depending upon the phenomena, whether it is boiling or condensation.

Now how does it differ, this thing differs from the convection without phase change. This is because of two things, number one is that as we know the condensation or boiling takes place at a constant temperature, when the fluid takes heat or dejects heat and changes its enthalpy. For example, when the steam condensed water, there is a change in enthalpy from its saturated vapour state to the saturated liquid state.

And a large difference of enthalpy is there and the difference of enthalpy becomes equal to the heat rejected by the steam. And this thing happens this conversion from steam to water, just as an example, at a constant temperature and pressure. Similar is the conversion from liquid to vapour, that means water to steam. So, this phase change was always takes place at a constant temperature and pressure.

But is associated with a large change of enthalpy, which we tell as enthalpy of vaporisation in case of boiling that is from liquid to vaporisation vapour, or enthalpy of condensation that is from vapour to liquid. And sometimes we tell it as latent heat of vaporisation or latent heat of condensation. So therefore, if a small temperature difference is created that can sustain this process.

For an example, if we have steam at atmospheric pressure we know the saturation temperature is 100 degree Celsius. Steam is ready to condense if it is cool little bit, that means if the steam is brought into contact of any surface whose temperature is little less than 100 degree Celsius, for example 90 degree Celsius, condensation will take place. And there is a huge change in the enthalpy.

That means a high heat transfer will take place, a rate of heat transfer will take place at a very small temperature difference, for which the heat transfer coefficient in phase change processes, condensation and boiling is much higher than those of free and forced convections. In sequence, the heat transfer coefficients are very low for free convection, because the heat transfer rate is low because of small flow due to buoyancy.

And forced convection is much higher and phase change process is much, much higher. This is one characteristic feature another characteristic feature is that, in a phase change process the flow is dominated by buoyancy, because of the change in density between the vapour state and the liquid state. And sometimes, surface tension plays a major role, for example in case of boiling, when liquid changes into vapour.

For example, water changes into steam in a water tube, then what happens? When the boiling is initiated that I will describe later on vapour bubbles are generated. Now the growth of the bubble, the collapse of the bubble, the movement of the bubble, that creates the flow field in such a way that heat transfer is affected depends to a large extent on the surface tension property between the liquid and vapour of that particular material, or the particular fluid.

So therefore, surface tension also makes a major contribution along with the buoyancy forces which are not common in convection without the phase change. So, these are the characteristic features which makes these two phenomena, though convective heat transfer, but little different from the pure convective heat transfer without phase change. With this, I will start first the condensation, then the boiling.

So, with this in background, let us first consider a simple case to understand the condensation heat transfer. Now before that, I have to explain again the condensation, we will start with the condensation. As I have told that a vapour, if you consider a vapour at saturated state comes into contact with a solid surface whose temperature is little less than the saturation temperature very easy to conceive that consider steam at one atmospheric pressure at 100 degree Celsius comes into contact to a plate whose temperature is lower than that.

For example, 60 degree or even 90-degree Celsius steam condenses. So now condensation takes place in two ways, how? If the liquid after condensation wets the surface, which depends upon the relative wettability characteristics between the surface and the liquid. Then what happens the drops of liquid, which are formed they spread they collies and finally a thin film, which smoothly glides over the surface and is drained out.

This is known as film condensation. But in case where the surface is such, which does not become wet by the liquid in that case what happens the liquid, the vapour after condensation forms the liquid drops, which do not spread and collies and make the film, rather the number of drops are formed and in random fashion and they are ultimately drained as the flow of drops over the surface. This is known as dropwise condensation.

So therefore, condensations are of two types, you write this, I am not writing on the board, one is film condensation where a thin film is formed when the surface is wet by the liquid, another is dropwise condensation where the film is not formed drops are formed in a random fashion and is drained. Now in film condensation it obviously apparent that this thin film does not allow the vapour to come in contact with the bare solid surface at low temperature.

That means in other way that the liquid film provides a thermal resistance or barrier to the vapour to make the heat transfer with the solid surface by coming to direct contact. There is a temperature gradient that exist in the liquid film and the vapour gets condensed at the interface between the liquid film and the vapour. So, it does not get an opportunity to be in contact with the bare surface of the solid. It is always blanketed by a liquid film.

So therefore, in this case the heat transfer rate and the condensation is relatively smaller as compared to dropwise condensation, where the vapour gets contact gets an opportunity to come into contact with the bare liquid surface because of the empty space where the drops are not there. If there are number of drops at the location of the drops the vapour cannot come into contact with the solid surface.

But when the exposed solid surfaces are there, where the vapour can come into contact. So that the rate of heat transfer and rate of condensation will be definitely more since vapour can come into contact with the bare solid surface. But, unfortunately, we have found in all practical surfaces the wettability characteristics is such if the surface is exposed or operation is made for a long, surface becomes wet by the liquid and a thin film is formed.

The effort has been made by putting coatings, adding coatings on surface by adding vapour additives to decrease the wettability characteristics but it has not been made to it a success, so that in almost all practical purposes we come across with the film condensation.

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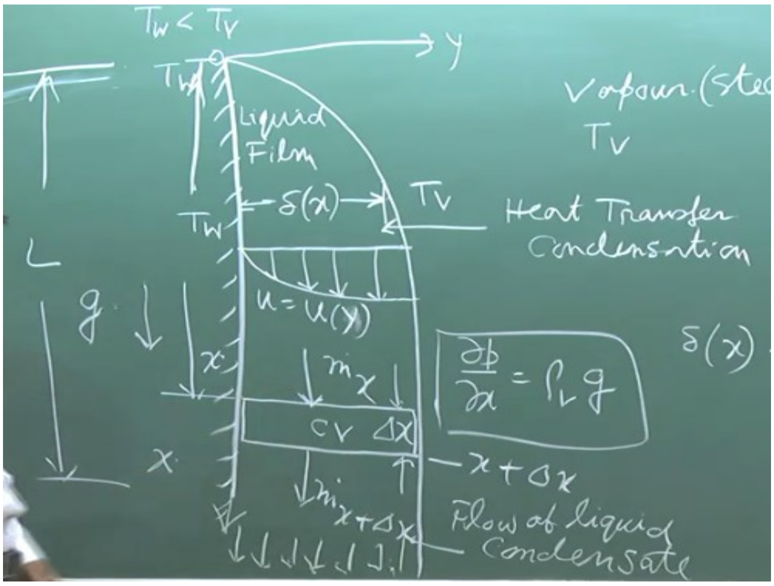

So, to understand film condensation let us consider this ways so that we can have a clear understanding. A simple case of a vertical flat plate, let us consider a vertical flat plate, which is at a temperature Tw and there is a vapour at saturated state, vapour at saturated state, whose temperature is Tv. Now this vapour you can consider as steam and if it is one ambient, one atmospheric pressure as the ambient pressure.

Then this Tv will be 100 degree Celsius. Just to understand, that means saturated vapour at a temperature Tv and the wall is at a temperature Tw, where Tw is less than Tv to enhance or to initiate the process of condensation, okay. So, what happens because of the condensation as I have told and the wettability characteristics of the plate in practice, that there is a thin film, which forms and grows in the vertical direction, downward and in a very amplified or a exaggerated to a, I am drawing this.

This is the thin film of liquid and this film grows, that means the thickness of the film increases in the direction of the flow. This is because of the condensation of vapour, more condensation. So, this is the liquid film and finally, this is the flow of liquid, this is the, this is the flow of liquid which is known as condensate, flow of liquid down the vertical plate. If I just make an axis like this, this is y and this direction for convenience of my analysis x.

Now the film has a thickness at any distance from this origin, the leading edge is zero, let us consider this as the film thickness at this location, delta which a function of x, increases with x. This is the film thickness which increases with x, why, this is because the heat transfer takes place here. Here the temperature is Tv vapour and here the temperature is Tw. So, there is a temperature gradient, Tv is greater than Tw, heat transfer takes place.

And by which it is a saturated state vapour gets condensed into liquid, sticks to the surface and makes a liquid film, which grows and flows along the surface. The thickness increases because of the more condensation, that is heat transfer, and condensation takes place, this is the physical picture. Now this liquid glides, film glides over the surface slowly, the velocity is extremely small.

But it has some velocity, and do expect that within this delta, that is within the film there is a velocity distribution. So qualitatively we can express this velocity like this, there will a no-slip condition at the surface from zero if we draw the velocity profile. So, velocity profile will be like this, u as a function of x. So, which will satisfy the no-slip condition and at the same time at the free surface, it will have a zero siestas condition.

This is a free surface this is a flow of liquid and this is vapour, because of the very low of viscosity on the gas side or vapour side, usually we impure the zero siestas, the interfacial tangential stress become zero. So, for a free surface flow the interface boundary condition is the zero siestas, so that the velocity gradient becomes zero at the free surface, which flows with some definite velocity.

So therefore, a qualitative picture of the velocity profile is like this.

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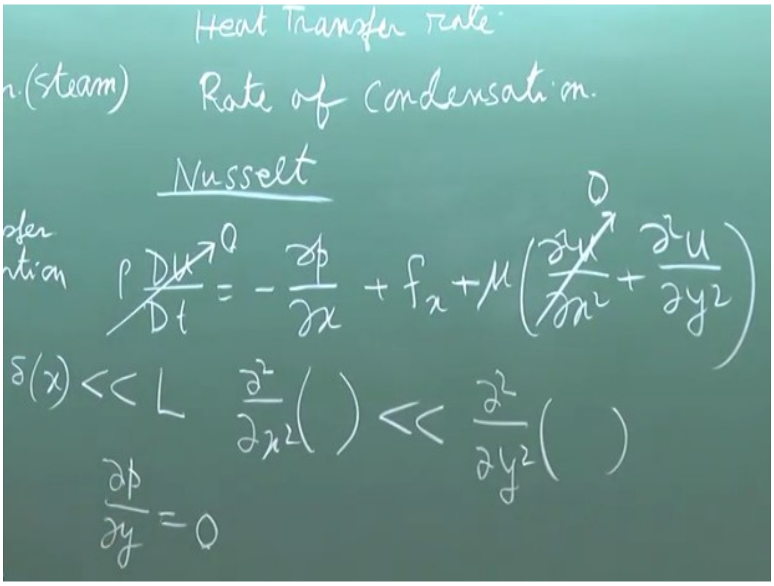

Let us first find out this velocity profile first, our main objective is to find out the heat transfer rate, our main objective is to find out the heat transfer rate, and the rate of condensation. If we know the heat transfer rate, so rate of condensation is just divided by the enthalpy of condensation. They are equal with a scale factor that enthalpy of condensation, that means if we extract heat at a certain rate from a vapour at saturated state.

So, you can find out the rate of condensation is the rate of heat transfer divided by the enthalpy of condensation, true. So therefore, the two things are almost same, we are interested in this two. Let us first, how to do that, Nusselt was the first person who derived this, and this is the classical solution, Nusselt solution of this condensation over a flat vertical surface, okay.

If you have any question you can ask me, you please, what do you want to know, do you have something to ask me, you can ask, you, do you want to ask something to me, hello, now what you are asking him, regarding this, regarding our, why do not ask me, okay, do not ask, because you will get ample opportunity to ask your friend outside, I told you at the beginning of the class. But if you have got any query please ask me, okay.

So, let us first derive the expression for velocity profile. How do you derive, if you take this co-ordinate x and y, this is the direction of gravity, I write the Navier–Stokes equations, consider a two-dimensional flow, then the x direction. This is the Navier-Stokes equation, considering the flow to be two-dimensional means what, that means flow velocity is taking place only in the x direction.

There is no y direction flow, but this in theory is a function of both x and y coordinate. Now, first of all we see that from this x direction equation of motion, what we get. The flow is extremely small, so this is zero, this is zero. We consider the flow is so small, it is a creeping flow type of assumption, probably you have been taught in your fluid mechanics class, where the inertia force can be neglected as compared to the viscous force.

Now, since the delta at any length x is always much, much less than the length of the plate, if we consider the plate has a finite length L. If we consider that the plate has a finite length L, then always one can argue with this geometrical configuration like our boundary layer approximation, where boundary layer is very thin, that is why sometime this approximation is known as boundary layer type approximation.

That the film thickness is very less than this, we can write del square by del x square of any parameter is much less than del square second derivative of y square of any parameter. Why, this is because, this is in the order of y square, and this is in the order of x square and y direction the order is delta, the scale in the y direction is delta, where the scale in the x direction is L.

So therefore, this quantity is lower by order of magnitude, by delta square by L square. This already you have done in your boundary layer approximation. So therefore, I can cancel this term compared to this term, clear. Now next part is the y direction equation, y direction, sorry this y direction, yes y direction equation zero is equal to zero. This is because there is no flow in the y direction.

And actually, the y direction gives you the boundary layer type of approximation, that del p/del y is zero. That means if you write the y direction equation rho D Phi Dt is zero, and this viscous force are totally zero, because there is no flow in the y direction. So, this gives rise to del p/del y is zero. Similar results as you got in boundary layer analysis, which is told in our language.

That pressure outside this film or in case of boundary layer, outside the boundary layer is imposed on the film. That means, if I find out the pressure gradient del p/del x, which is existing here in the outside of the film that is seen within the film since del p/del y is zero.

That is the language probably Prof. Suman Chakraborty told. We always tell the pressure in the free stream is imposed on the boundary layer, pressure in the potential flow is imposed on the boundary layer, because del p/del y is zero.

So therefore, this thing is zero, this thing is zero, I can write as dp/dx. Now our next job is to find these two term, so fx is, therefore zero is minus del p/del x plus fx. Let us find out this del p/del x, when I write this separately in the Navier-Stokes equation, where fx is the body force per unit volume. This pressure gradient pressure is the static pressure. I told you the Navier-Stokes equation is written usually without any body force, because we consider there is no any external body force filled.

But gravity we cannot neglect, but what we do tactically that gravity we taking into pressure itself and we tell that okay this is the Navier-Stokes equation. So, there is no body force, gravity is considered into the pressure, where the pressure is defined as piezometric pressure. But if you decompose it in terms of pressure gradient and the body force, then this pressure gradient is static pressure gradient.

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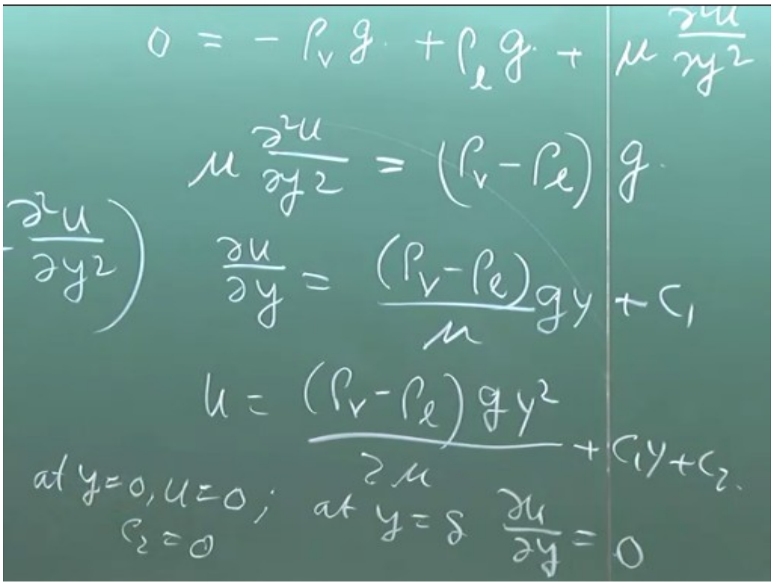

Now static pressure radiant in this vapour, vapour is stationary, so hydrostatic equation of pressure will hold good. So, del p/del x will be rho g, rho v, rho v is the density of the vapour, because we know del p/del x, it is because of the wet. This you know from your fluid mechanics knowledge the pressure filled in a hydrostatic. The pressure changes in the direction of the gravity.

So, it decreases vertically down in the direction of the gravity increases, decreases in the vertically upward. Since my x x is positive is downward, so minus sign is not there, del p/del x is rho v into g, okay. It is a linear variation, and it increases in the vertical direction in hydrostatic pressure distribution and since del p/del y is equal to zero, boundary layer type of approximation. So, this del p/del x will be imposed here.

So, I can write del p/del x as rho v into g with a minus sign, what is the body force per unit volume, fx, it is simply rho l is the density of the liquid into g. That is the wet per unit volume plus mu del square u del y square. So up to this the concept of fluid mechanics is over.