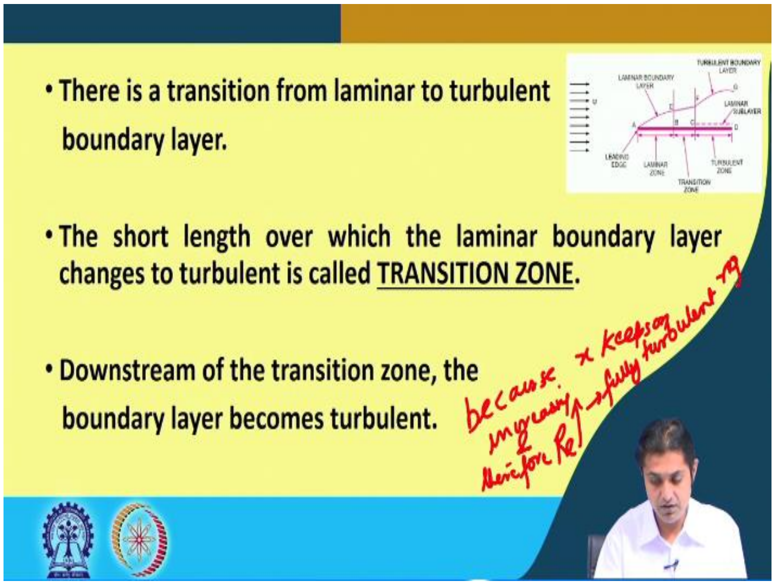

And then there is a transition from laminar to turbulent boundary layer. So, this is the transitional zone here. So, this short length over which the laminar boundary layer changes to turbulent is called the transition zone, indicated by this distance here. Now, the downstream of the transition zone, the boundary layer becomes turbulent because x keeps on increasing and therefore, Reynolds number increases leading to fully turbulent region.

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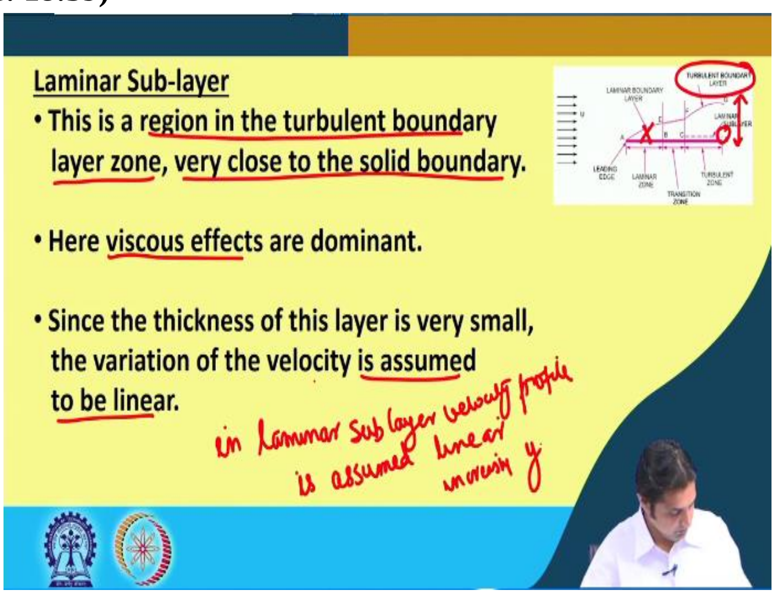

Now, as you see in this diagram, there is something called laminar sub-layer. And what is that laminar sub-layer? This is a region where the turbulent boundary layer zone and it is very close to the solid boundary. So, basically it is a region in the turbulent boundary layer zone. So, this is this does not happen here, but it happens in the turbulent boundary layer and it occurs very close to the solid boundary and here, because viscosity will play an important role.

Therefore, the viscous effects are dominant; they are much more than the other type of forces. Since, the thickness of this layer, as we can see, this is very, very small compared to this, the variation of the velocity can be assumed to be linear. So, in laminar sub-layer velocity profile is assumed linear. Linear with respect to what? With the distance increasing distance linear, that means, with increasing y. And we also assume that there is has a constant velocity gradient. So, the velocity gradient du / dy is constant.

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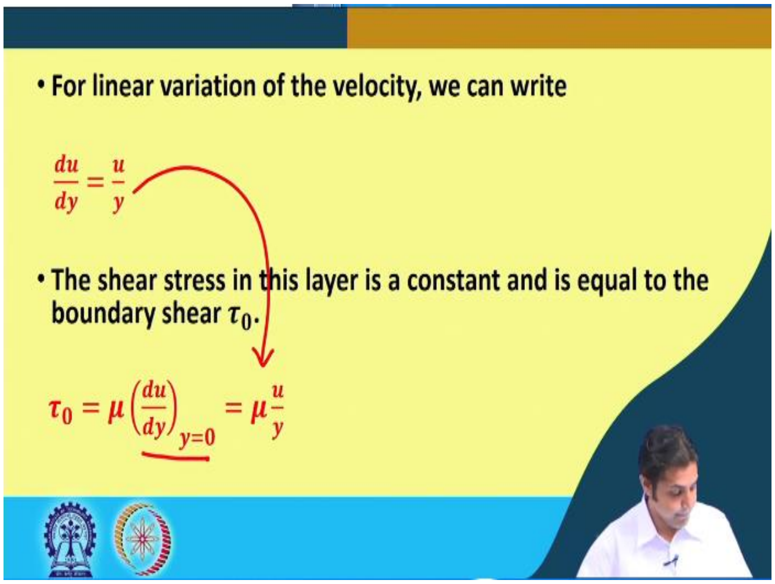

Therefore, for linear variation of velocity, we can write,

$$\frac{du}{dy} = \frac{u}{y}$$

.

Now, the shear stress in this layer is constant and is equal to the boundary shear stress given by tao not, as we have already been using not for the tau not, for the shear stress near the wall this is also is it is like a sort of a wall only this is the boundary. And therefore, we can write

$$\tau_0 = \mu \left(\frac{du}{dy}\right)_{y=0} = \mu \frac{u}{y}$$

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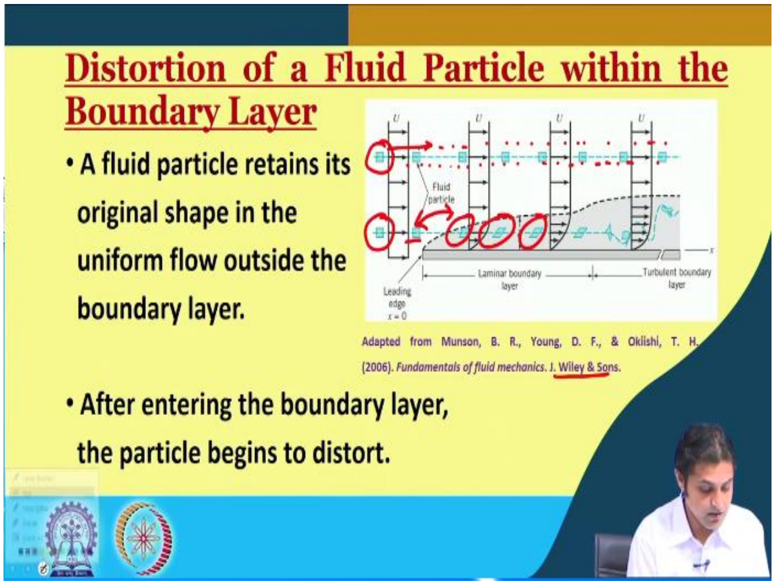

Now, we will talk about another phenomenon, that is, distortion of a fluid particle within the boundary layer. What happens? So, this figure has been taken from Munson Young and Okiishi's Fundamentals of Fluid Mechanics published by Wiley and Sons. So, let me just, so, what it says is that the fluid particle retains its original shape in the uniform flow outside the boundary layer. That is very true, because outside the boundary layer there are no effects and the fluid particle, this is the fluid particle above the boundary layer, this is the fluid particle that is going to be in the boundary layer.

So, when it moves in this direction, there is no problem at all because all the points will have equal velocities. However, this particle here, after entering the boundary layer the particles begin to distort, as you can see. This is where it starts distorting and when it goes it distorts more, it distorts more, depending upon what the velocity gradient but there is definitely is a distortion from this point to this point, as soon as it enters the boundary layer.

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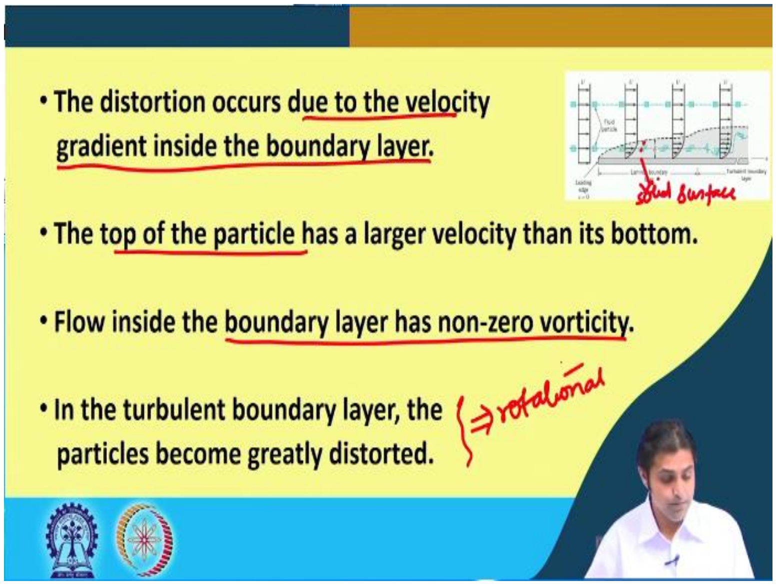

So, the why this distortion occurs? This distortion occurs due to the velocity gradient inside the boundary layer. How? Because the top of the particle has a larger velocity then its bottom. So, this point here, the bottom will have lesser velocity than at the top because this is more closer to the solid surface the lower, the surface which is closer to the solid surface here.

Therefore, the flow inside the boundary layer has a non zero vorticity. Because what does vorticity causes? It causes rotation and this is what we see, the fluid particle will rotate. And this happens because of the differential velocity at the top and the bottom surface. And what we can see is, in the turbulent boundary layer the particle becomes greatly distorted. So, in the boundary layer the flow is rotational.

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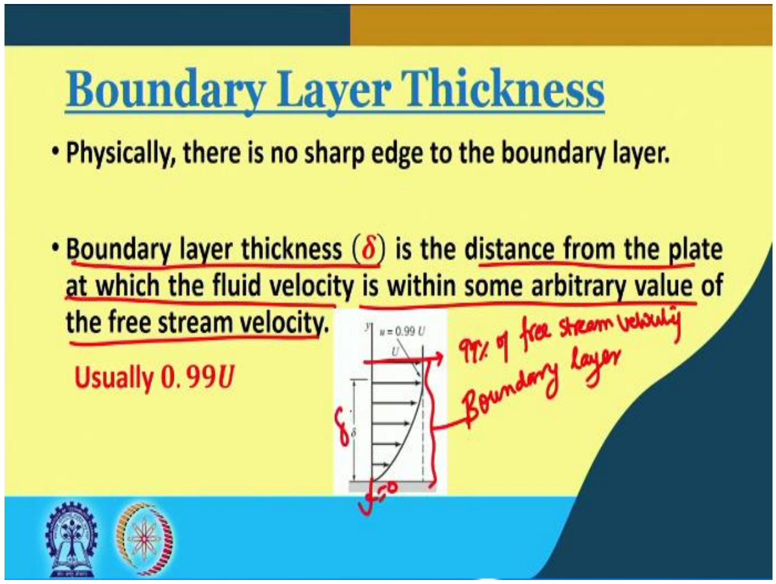

Now, we are going to see, what the boundary layer thickness is. In real sense, physically, there is no sharp edge to the boundary layer. Now, the boundary layer thickness is the distance from the plate at which the fluid velocity is within some arbitrary value of the free stream velocity. So, this is an important term, boundary layer thickness delta. We have seen similar term in some slides before. And what is this boundary layer thickness? It is distance from the plate, the flat plate over which we have considered the flow.

So, distance from the plate at which the fluid velocity is within some arbitrary value of the free stream velocity. Ideally, at the top of this boundary layer, the velocity should be equal to the free stream velocity, normally, at the top. So, this is the boundary layer. So, because of this is the velocity is going to be zero and at one point we have to consider where the boundary layer. And so we assume, when the velocity reaches almost 99% of free stream velocity, the boundary layers cease to exist above that. And that thickness is called the boundary layer thickness.

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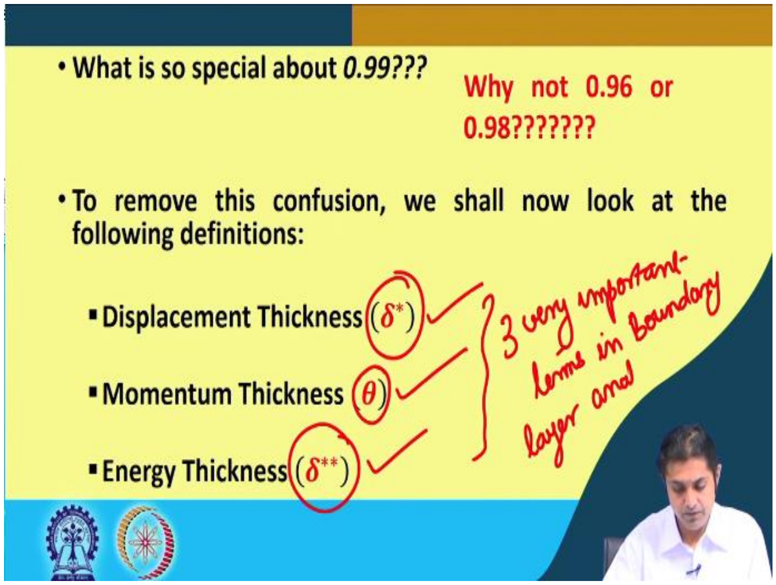

So, what is so special about 0.99? Why not for 0.96 or 0.98? To remove this confusion, we will now look at some of the definitions. Some of the definitions is displacement thickness, given by, delta star, very important term, in this particular module of hydraulic engineering. This is another thing called momentum thickness that is called theta. And then there is something called energy thickness which is given by, delta double star. So, these 3 are very important terms in boundary layer analysis.

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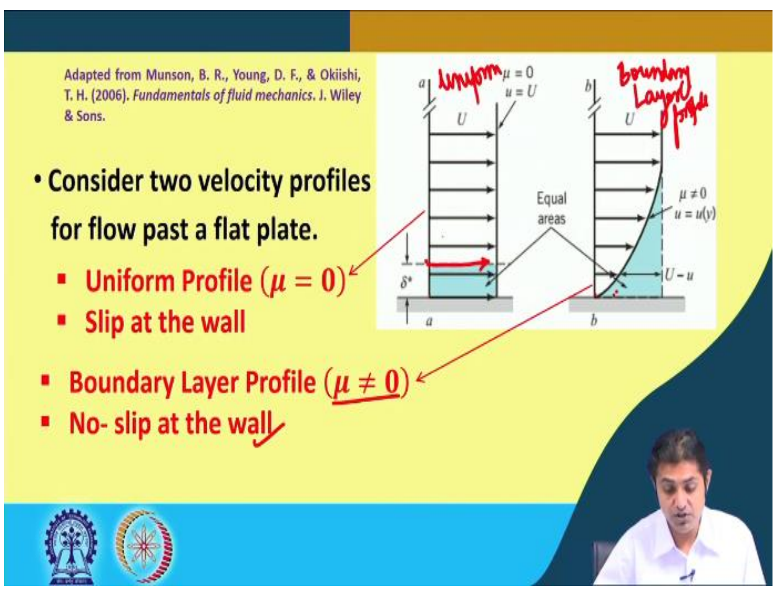

So, we consider 2 velocity profiles for flow past a flat plate. So, this is flat plate here. This is the 1 velocity profile, this is 2 and both has equal areas. And this figure has been taken from Munson, Young and Okiishi Fundamentals of Fluid Mechanics. So, as you can see, I will explain these terms, as it comes. So, this is a uniform profile, where mu is zero. So, there is no viscosity and there is going to be slip at the wall, this place.

It is not, I mean, here, there will be no slip condition. The second is the boundary layer profile, this was a uniform profile and this is the boundary layer profile. Here, there will be some viscosity and mu is not equal to zero and there is going to be no slip at the wall. No slip at the wall means, the fluid velocity just above the plate is going to have the same velocity as the plate. In this case, since, the plate is stationary, the fluid particle just above this, will have a zero velocity.

So, that is why, the velocity profile, you see, it is zero here. In profile, in the uniform profile, at the beginning there exist some, the u is here, there is the uniform velocity u, it is not zero.

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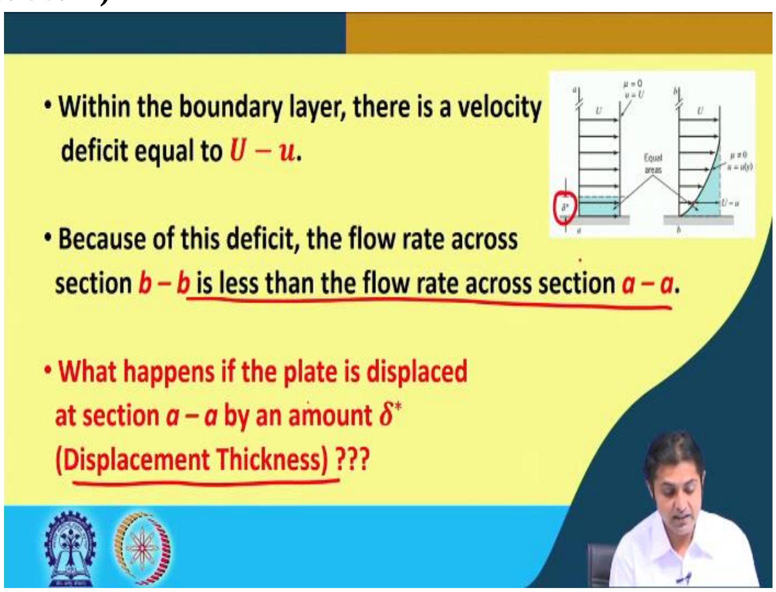

So, within the boundary layer there is a velocity deficit. So, this is the boundary layer. So, U capital U is the uniform velocity profile, here also the free stream velocity is same. But say, at this distance if the velocity is u, then the deficit of the velocity that is, happening is U minus u. u here, is the velocity at a point in the boundary layer. So, this is the velocity deficit equal to. Because of this deficit, the flow rate across the section b - b. So, this is the section b – b. I am going to remove. Sorry.

So, because of this deficit, the flow rate across the section b - b is less than the flow rate across section a – a, that is, correct. Because the velocity here is limited, I mean, less than this U / u. So, the velocity in the boundary layer is lesser than the uniform velocity profile by U minus u. Suppose what happens, if the plate, my question to you is, what happens if the plate is displaced at section a - a by an amount delta dash? So, here, this delta dash is called the displacement thickness. With this we will see in the upcoming lecture.

So, the question at which we are going to end this lecture today is, what happens if the plate is displaced at section a - a by an amount delta dash. So, this is enough for today and we are going to start the next lecture by answering this question. Thank you so much. See you in the next lecture. Bye.