Fundamentals Of Particle And Fluid Solid Processing
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Lecture - 07
Fluid - particle mechanics (Contd.)

Welcome to another class of Fundamentals of Particle and Fluid Solid Processing. Today, we will be looking at the boundary layer. The fundamentals of boundary layer that you have already known from your fluid mechanics background, this will again solve as a refresher slides to your memory.

So, I hope there wouldn't be much difficulty in following these slides, which we will quickly go through to the basics and then we will again see the link that why these knowledges are important in this course.

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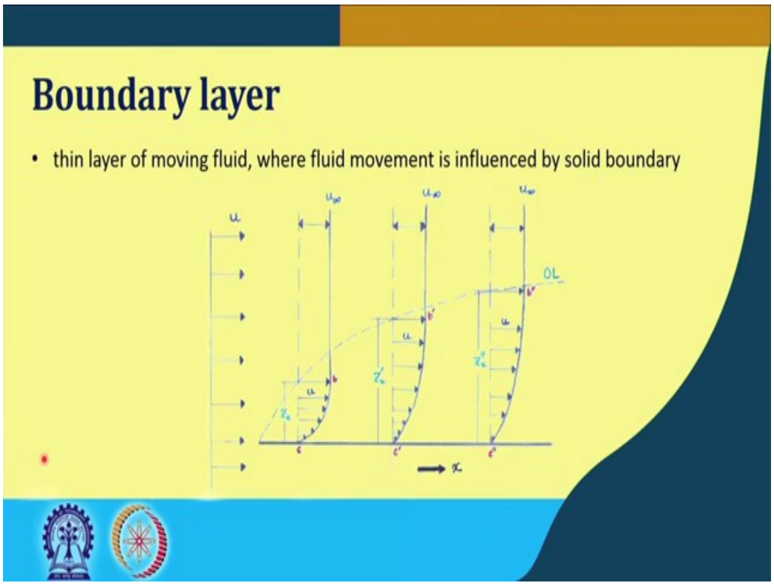

So, when we talk about boundary layer this picture immediately comes to our mind, that how or what is boundary layer or how that forms. So, boundary layer we can call this as a thin layer of a moving fluid, where the fluid movement is influenced by the solid boundary. We can broadly say by this definition, that it is a thin layer of moving fluid attached to the surface of the solid surface, where the fluid movement is influenced by the solid boundary.

So, what happens in this schematic what I have tried to show you is that, let us say this hard line is solid surface. There is object flat plate let us consider the example of a flat plate and there it is approached by a uniform fluid velocity ok. This approaching velocity is uniform and it is coming on to this flat plate. So, when it flows over the flat plate what happens, let us consider for the time being this flow is laminar and has uniform velocity.

So, near to the surface this solid fluid interface, there the velocity of this fluid is 0. And, as we go far from the solid surface, there we see such kind of a velocity distribution ok. Now, these velocity distributions are asymptotic in nation. So, the point is that it achieves the bulk fluid velocity some point far from the solid object.

Now, these points let us say are these imaginary, I mean these points are connected by this imaginary line. So, what happens, that this imaginary line divides this flow domain into two segments basically. One where the fluid velocity is influenced or gradually changes from near surface that is 0, to a velocity that is close to the bulk fluid velocity or we say that as a free stream velocity. And, the other region where we see that the velocity is not influenced or nearly constant or nearly not varying with the distance, that is from the leading edge of the flat plate.

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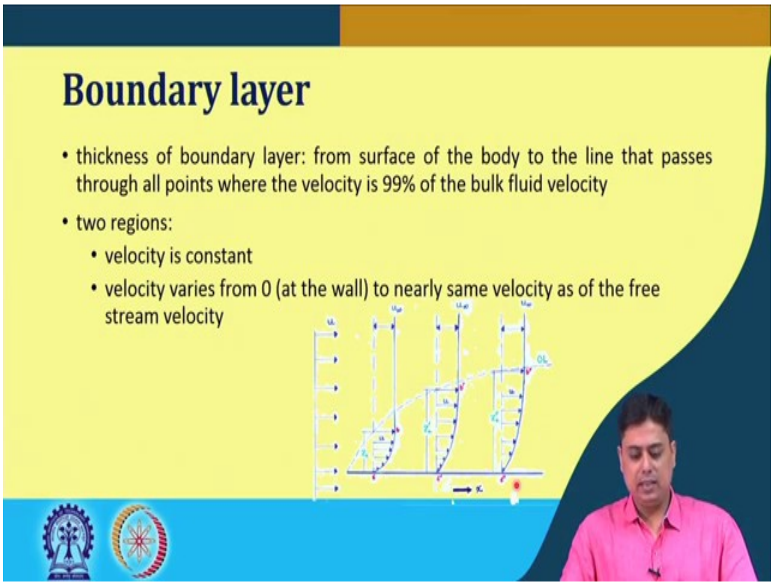

So, what happens? This we this imaginary line we call as the boundary layer and this is the thickness of the boundary layer ok. So, this boundary layer which means basically bisects or not bisects, it is divides this fluid flow region into 2 segments, where velocity varies or influenced by the solid boundary and the other portion, where that is not varying or nearly, in fact, is constant.

So, this thickness of the boundary layer ok, that depends on the type of the body or the object that we are considering here. So, again we stick to the flat plate example, now here we can see the thickness of the boundary layer that we define as a from the surface of the body as I said to the line that passes through all points where the velocity is nearly same to the bulk velocity. Now, as I said this velocity lines are asymptotic in nature. So, it never reaches the actual velocity. So, we typically say that 99 % of the fluid velocity or the bulk fluid velocity whenever that is reached we take those points.

So, in this case the distance from the leading edge to this point so, let us say here the velocity's profile like this and here at this point, the velocity is the 99 % of this bulk velocity or the approach velocity there we select the point. So, similarly from another distance from the leading edge we find out that point, but remember these are all the imaginary points ok. So, when we connect these imaginary points and get this imaginary line, which is designated by *OL* here in this picture we can see it is in a better view.

So, when that happens? This imaginary line we say that this is the boundary layer thickness at a certain distance from the leading edge of the solid flat plate ok. So, this boundary layer divides this region in 2 segments, where the velocity is constant, this is the outer region and inside the boundary layer the velocity varies from 0 at the wall, to nearly same velocity as of the free stream velocity or the bulk fluid velocity.

So, what is that thickness? How do we know that how much is this distance from here surface to this boundary layer as it is varying. ok or what is the overall thickness of this boundary layer when the flow gets fully developed?

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Now, what is fully developed, we will come to that. So, in boundary layer or within the boundary layer there are a few points that you need to remember, that the velocity at the interface or the solid fluid interface is 0, velocity near the surface is essentially laminar, it is of very low velocity flow.

So, that is why we typically consider that the velocity near that plate irrespective of it is approach velocity is laminar. But, sometimes what happens, although, the fluid happens to be laminar in that layer, but sometimes eddies can form. And, that eddies due to turbulence or some obstruction or some influence of the geometry, that creates some eddies are wake, that alters the flow profile in that layer of the laminar flow. And, then what happens? It influences the near wall average velocity profile, but it hardly changes the overall profile at the bulk velocity ok.

So, the point is that the point I am trying to make here is that although we consider the surface near the the near surface velocity is laminar. Sometimes some small eddies or currents can wake happen there and then some local velocity profile change can be observed or can happen. And, that change or the alteration basically enhances several things or significantly alters several parameters like, temperature and concentration. And, sometimes that helps to have a better mixing in fluid, because in mixing, we require turbulence. But far away from the surface flow field can be turbulent and, usually if the approach velocities so, it is definitely turbulent.

So, in between this fully developed turbulent flow or the fully developed turbulent layer and the near surface laminar region, there can be several sub layers ok. Those are listed here that is the viscous sub layer, buffer layer, and then we have the turbulent layer. So, in between this surface and the free stream region or inside the boundary layer we can have viscous sub layer, buffer layer, and the turbulent layer.

So, buffer layer can also be considered as kind of a transition layer, because if the flow changes from laminar to turbulent, there is that buffer or the transition layer is there.

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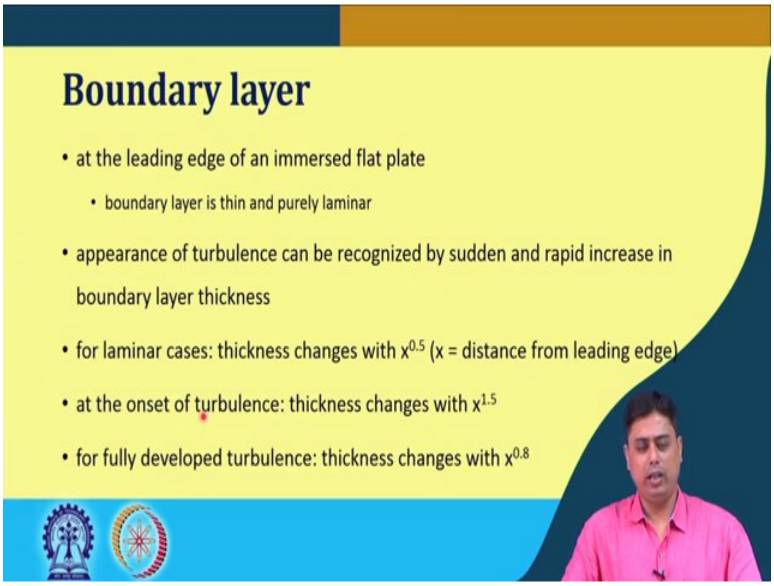

So, at the leading edge of an emerged body, let us say here the flat plate the boundary layer is usually very thin and purely laminar. Now, this appearance of turbulence can be recognized by sudden and rapid increase in the boundary layer thickness. So, if you remember or if you realize this picture here again or the schematic, this near the leading edge the boundary layer is typically very thin. In fact, this whole boundary layer is very thin depending on the scenario and it is mostly exaggerated a picture that we show on any textbook shows.

So, here typically near this leading edge the boundary layer is very thin and it is mostly laminar in nature, but then there can be a sudden increase in the boundary layer. And, that actually dictates that there is the onset of turbulence layer. So, then what happens? And, after that again as we go far from the leading edge of this flat plate, that turbulence sometimes dissipates or sometimes, it is carried away by it is bulk fluid velocity.

So, in laminar cases the thickness of this boundary layer typically varies with the $x^{0.5}$ or where x is the distance from the leading edge ok. So, for laminar case thickness of the boundary layer changes with $x^{0.5}$, with multiplied by certain cofactors of prefactors and those relations are typically suggested by several researchers by their several experiments, but typically it varies by this factor. And at the onset of the turbulence when there is a sudden change in that boundary layer thickness, the thickness changes with $x^{1.5}$. It rapidly changes this indices indicate, that it the rapid change of the boundary layer thickness as we go from the leading edge to the far away to it is tailing end.

So, for fully developed turbulents cases this thickness, then changes with $x^{0.8}$. So, after the onset of the turbulence if the turbulence prevails, then it goes in this manner, or it changes in this manner. So, where again x is the distance from the leading edge to its tailing end the length that we go from that side ok.

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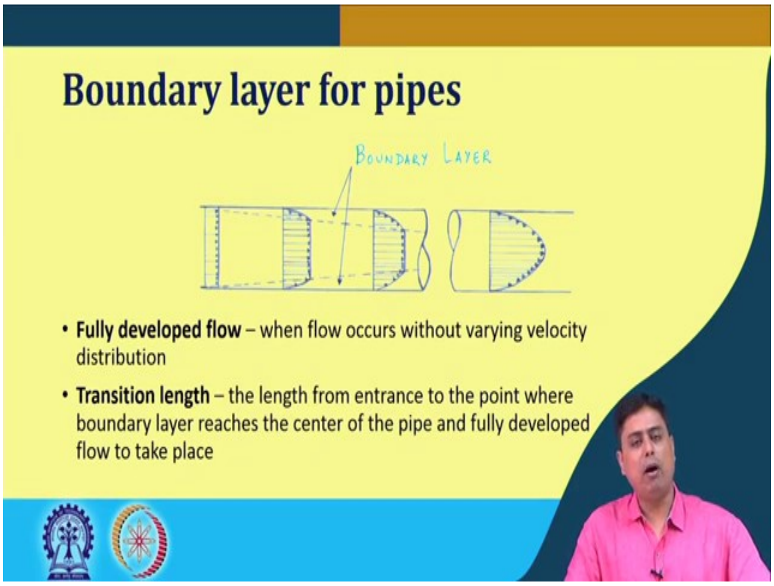

So, now the point is that how the boundary layer develops? Now, this again this concept possibly you have already seen in your previous fluid mechanics class is that when typically this is let us say, the uniform velocity that comes in a pipe or a conduit ok. When it comes in the pipe there is the development of the boundary layer. Now, as soon as it enters the boundary layer starts to form and it is thickness grows.

So, this part let us say the initial part of the pipe or a certain length that is required to develop the boundary layer to a fully developed region. So, what happens is that as soon as it enters the boundary layer starts to develop ok. And, in the developing region the fluid flows like a rod kind of a behaviour, because here the fluid movement is there and here the boundary layer. So, here the flow is very very low as you can see that, we can understand that in the boundary layer we have seen there is a laminar flow or the viscous sub layer buffer layer and then the turbulent flow or the flow of free stream region comes into play. So, there is a substantiate a substantial velocity gradient and here the bulk fluid flows in a rod like manner.

And, after a certain distance this boundary layer basically comes to the center of the this pipe or the conduit and then the fully developed region happens. So, here in the fluid developed a fully developed profile the boundary layer basically coincides at this center plane from both the sides. So, it from this side it goes like this and from the top it comes up like this and it is coincide at the center and then the velocity profile gets like this. So, in fully developed flow when the flow occurs without varying velocity distribution we typically call such scenario as a fully developed flow that is here.

Now, it this profile is then maintained irrespective of it is direction in the; if we consider this as the positive x direction ok. So, the fully developed region, we can say that the where the boundary layer coincides at the centerline of the fluid or in fact, and that is when the flow profile does not vary with its distance from the inlet to the outlet.

So, from that point onward we can say that the flow profile is now fully developed and its flow the velocity distribution it is not changing along the axial length of the pipe or the conduit. Now, quite naturally as we say that this fully developed flow it requires a certain length so; that means, that length is typically characterized by the transition length. The, length from the entrance to the point, where the boundary layer reaches the center of the pipe or the conduit and the fully developed flow takes place ok.

So, till this distance in a pipe we call this is the transition length, this is the transition length that is required to have the fully developed flow.

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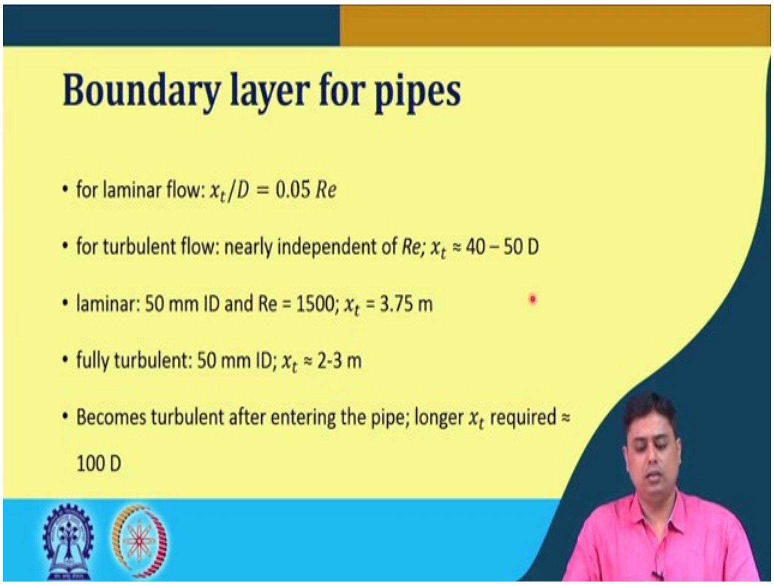

So, this length varies or depends on the flow condition. So, for laminar flow this transition length this x_t as I said the distance from the inlet in a pipe here in this case D is the diameter or inside diameter of the pipe or the conduit it varies as:

$x_t/D = 0.05\Re$ ok. So, for laminar flow this is the transition length required. For turbulent flow it or let us say typically when it goes very higher velocity, the transition the transition and the turbulent flow occurs.

So, where in the fully turbulent cases we see that this entrance length or the thus transition length is nearly independent of the Reynolds number. And, that transition length typically is ≈ 40 – 50 D, where the boundary layer is developing.

So, for example, to give you the numbers so, for a 50 mm ID pipe with a Reynolds number of 500, we see that the transition length by this formula its around 3.75 m. Now, what we expect or intuitively you can think that for possibly turbulent flow, this length will be much more to have the fully developed region, but the point is that in the very high velocity of the turbulent flows or fully turbulent cases this value is around ≈ 2 – 3 m.

Why this happens? We will see in the next slides or in fact, in the other slides that this region this region for this thing why this is happening. So, there can be scenario that the flow becomes turbulent after entering the pipe ok. So, initially there was laminar case or some different condition of flow, but as it enters a pipe it becomes turbulent. So, in that case the transition length required that length required is very higher ok. And, it is in fact, in the range of ≈ 100 D (D being the pipe diameter or the conduit diameter).

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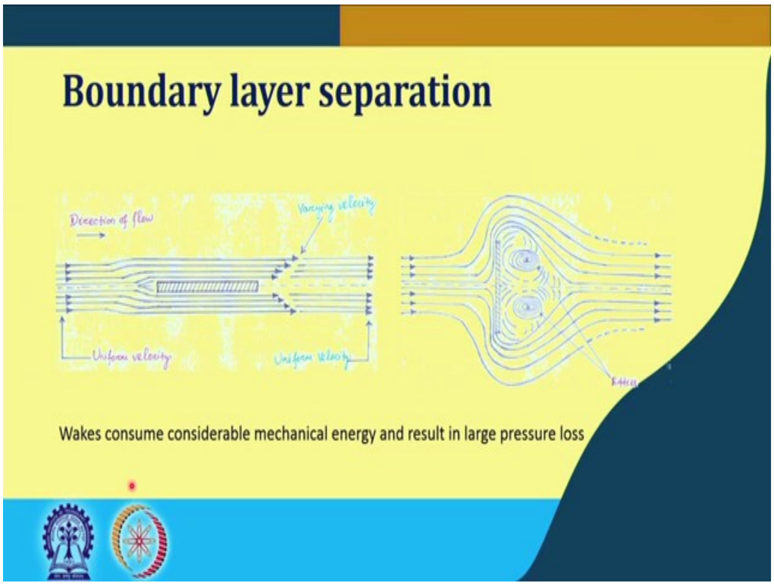

Now, the point is that when boundary layer separation happens. The boundary layer separation happens, say for example, this flat plate the we discussed this thing that the uniform let us say of a velocity is approaching this flat plate. So, we have boundary layer development in both the sides of upper and the bottom of this flat plate upper side and the bottom side. Now, the point is that when that happens and at the end of this flat plate ok. There will be still some gradient in the flow, but we as we go along this distance in the positive direction, we can again have uniform velocity after a certain.

So, this gradient can persist in a certain point, but then again we can have the uniform velocity if the scenario is like this, but now consider this flat plate is perpendicular to the direction of the flow. So, what happens here, that this boundary layer develops at the surface and then there is a sudden due to this momentum of this fluid ok. This boundary layer cannot be suddenly coming to this point and it flows with the momentum of the flow ok.

So, in that case what happens this back portions of this vertical plate sometimes become or in fact, becomes as a backwater kind of a scenario, where decelerating velocities are there and the flow field occurs and this results in a sudden drop in a pressure or the larger pressure drop.

And, it creates the eddies or the wake ok. And, this wake consumes considerable mechanical energy and result in larger pressure losses ok. This formation of wake happens due to this boundary layer separations, because it cannot abruptly come to this point and it flows with the momentum of the flow. In such scenario, the eddies of the wakes forms and that leads to this considerable mechanical energy loss and the pressure loss.

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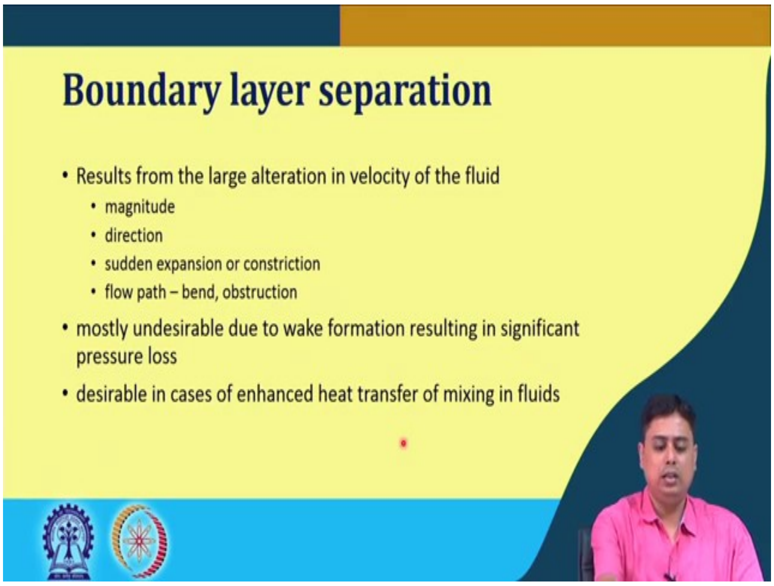

So, this results this boundary layer separation can be resulted from the large alteration of the velocity in the fluid. And, that can be occurred by changing magnitude of the flow field, change in direction of the flow field, it can happen due to sudden expansion or constriction of the flow path, as well as the flow path can be tweaked by bend obstruction or something like that ok.

So, boundary layer separation is mostly undesirable due to this wake formation that results in significant pressure loss, but it is sometimes desirable, in cases where we require enhanced mass transfer or mixing of fluid ok. So, in those cases this kind of wake formation or local turbulences, local wake formations, is helpful or helps us to have the enhanced conditions.

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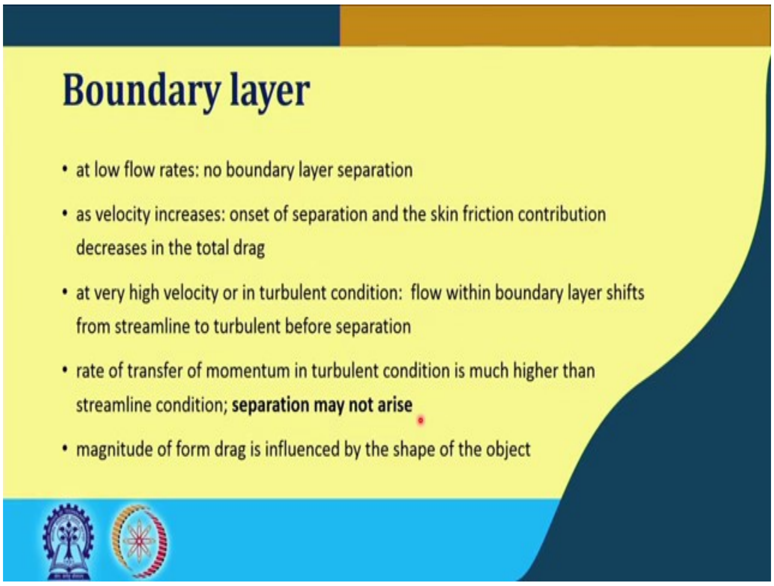

Now, at low flow rates there is no boundary layer separation ok. As the velocity increases we have now understood, the onset of separation happens, the onset of separation is there and the skin friction or the wall friction that we discussed in the last class, contributions becomes lesser and lesser ok. At very high velocity or when there is turbulent condition flow within the boundary layer, initially shifts from streamline to turbulent cases before the separation occurs ok.

So, this is the condition at the very high velocity or at the very high turbulence region for the fully turbulent cases. Now, once that happens that even before the separation takes place if the streamlines change from the boundary layer shifts from the streamlines to the turbulent, then what happens rate of transfer of momentum in turbulent case is much higher than the streamline conditions. So, the separation may not arise ok.

Now, this has this is some interesting feature, that in laminar case that is why we had a sufficient length that was required to have the fully developed flow, but in highly turbulent cases since the boundary layer separation is suppressed by the high rate of transfer of momentum from one point to another quickly that fully developed length can be achieved ok.

Now, the point is that this is interesting point for our case that this fundamentals of particles and the fluid solid processing that when there is a submerged object or let us say a sphere and the smooth sphere ok. And, then what happens the condition is laminar the flow field is laminar, you can understand there will be the change in the change in the flow field or the boundary layer separation will happen ok.

But, if you somehow can tweak the flow field or you can induce turbulence there ok, that can result in a reduced drag or the reduced pressure drop, because then this scenario is much more suppressed.

So, how it has been done by the scientist? In fact, Randall did this by sticking a hoop in front of a sphere, when the sphere is submerged and the flow field was coming. So, at the front end of the sphere, if you create some roughness, then that onsets the triggers the turbulence and the flow field changes. And, the bound boundary layer and all these things gets different than the normal scenario and the drag becomes reduced.

So, magnitude of form drag is basically influenced by the shape of the object and that is our main consideration in this study, because we will be dealing with different types of the material or the particle and the particle shapes will be different or the shapes will be different. So, we will see some examples of this concept boundary layer and the drag in the forthcoming classes, till then I would like you to go through this theory and thank you for your attention.