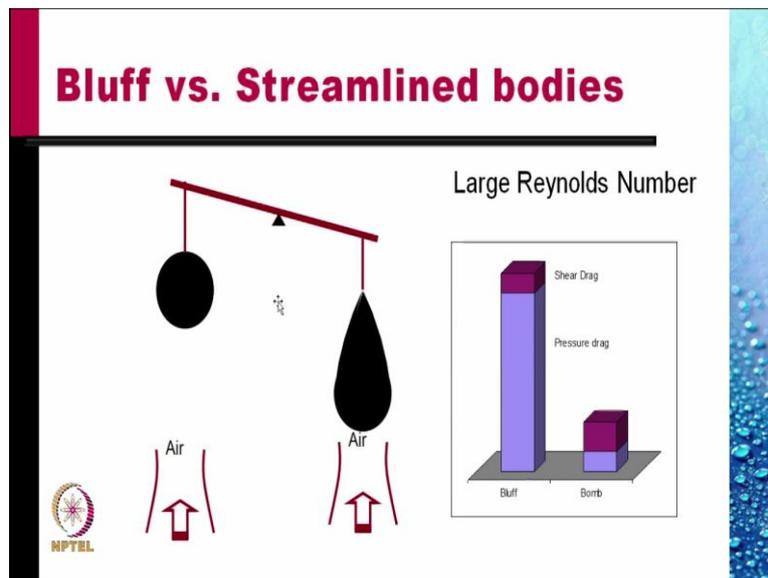


Fluid Mechanics & its Applications
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Lecture 30A
Drag on immersed bodies

Let us now understand some interesting phenomena associated with drags on immersed bodies at large Reynolds number. There are some curious phenomena that take place when we investigate drag on various shaped bodies.

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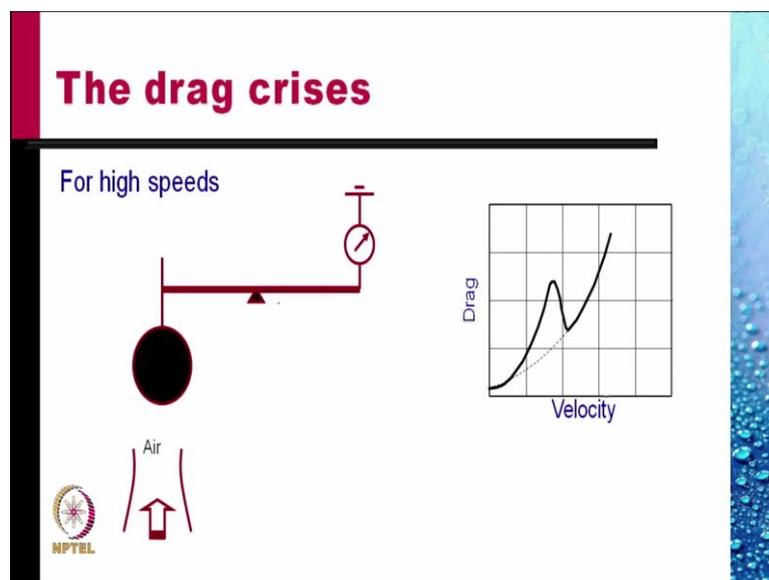
In this first experiment we have shown a sphere and tear-shaped body which we call also a bomb-shaped body, that is a streamlined body exposed to a stream of air at same velocity. And these are attached to a beam at equal distance from the fulcrum. When the flow takes place, we notice that the balance is as shown, indicating that the drag on the sphere is much more than the drag on the streamlined body.

This is what was to be expected. On this streamlined body the boundary layer does not separate very much. If its separate at all, it is near the trailing edge. And so, the pressure on this body recovers as we go down, and the pressure differences in the front and the back are small. Therefore, the pressure drag is small. On the other hand, on the sphere, we have shown just now, the flow separates before the equator, and the pressure at the back of the sphere does not recover to the values in front, and that leads to large drag, drag of the order of the pressure forces.

Of course, on the streamlined body the shear stresses are more, if for no other reason, because the area of the surface is more. For large Reynolds number flows, this bar diagram shows you the relative drags. The light purple color shows the pressure drag for the bluff body, and for the bomb-shaped body.

The pressure drag is much smaller, order magnitude smaller, on the bomb-shaped body, than on the bluff body. Though the shear drag is larger on the bomb-shaped body, because its larger area, it still does not make up for the large difference in the pressure drag. And so the total drag on the bomb-shaped body is much less than the total drag on a bluff body.

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Another interesting phenomenon as demonstrated by Shapiro in his famous set of movies on fluid dynamics of drag. It is a series of four movies made in 1960s that explore the drag phenomenon. It is available on YouTube. You are strongly advised to look them up. They make for interesting viewing.

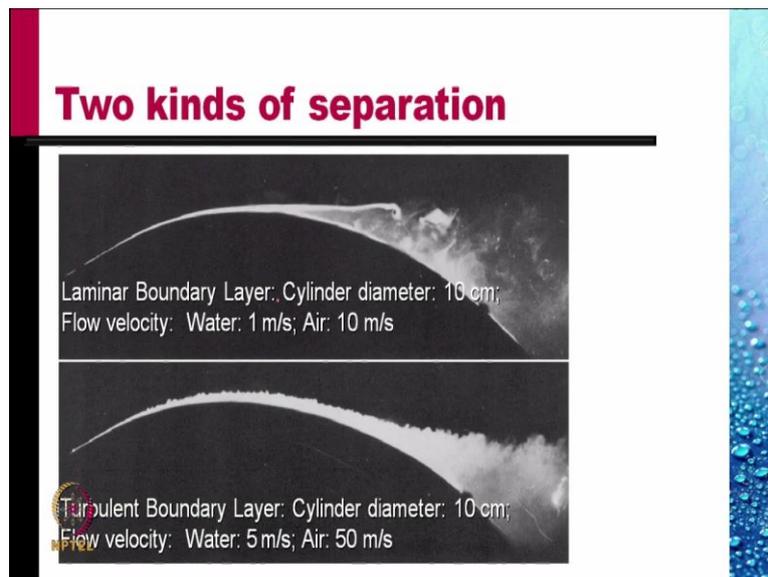
Here is a large sphere which is played on by a stream of air from a nozzle below it. The drag experienced by the body is measured by this spring balance. As the air velocity increases, the drag changes. And we see an interesting change in the drag with velocity. There is shown the velocity as zero in this graph, the velocity is not zero, we start with a fairly large velocity. The corresponding Reynolds number of the order of 1000.

And we see that the drag varies parabolically with the velocity, like the square, signifying that the value of the drag coefficient is constant, because drag coefficient is drag divided by $\frac{1}{2}\rho V^2$

times the characteristic area. In this case, the characteristic area is the frontal area of the sphere πR^2 . So, drag varies like V^2 means C_D is constant.

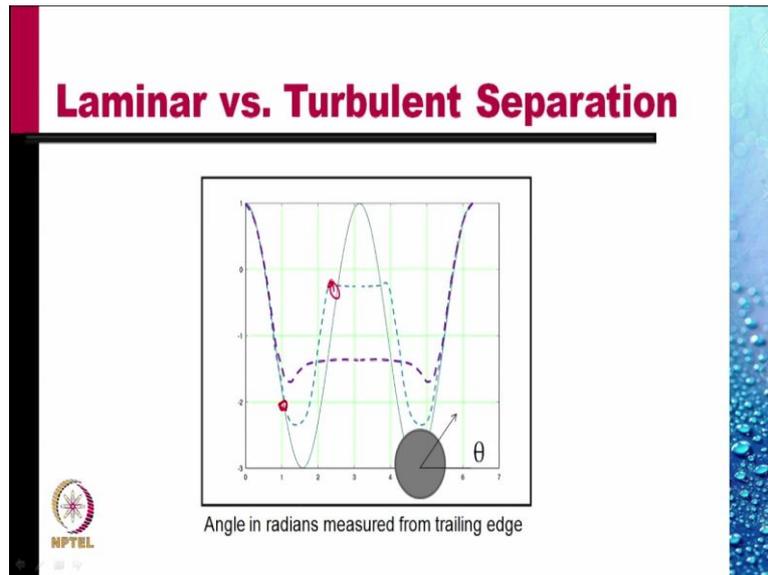
Then at a certain velocity, a fairly large velocity, the drag suddenly decreases. Various authors have termed it as a drag crisis. Drag suddenly decreases, but then starts increasing again, again like V^2 . But this curve is lower than the initial curve. It is again varying like V^2 . That means the drag is the drag coefficient is again constant, but constant at a lower value than it was earlier.

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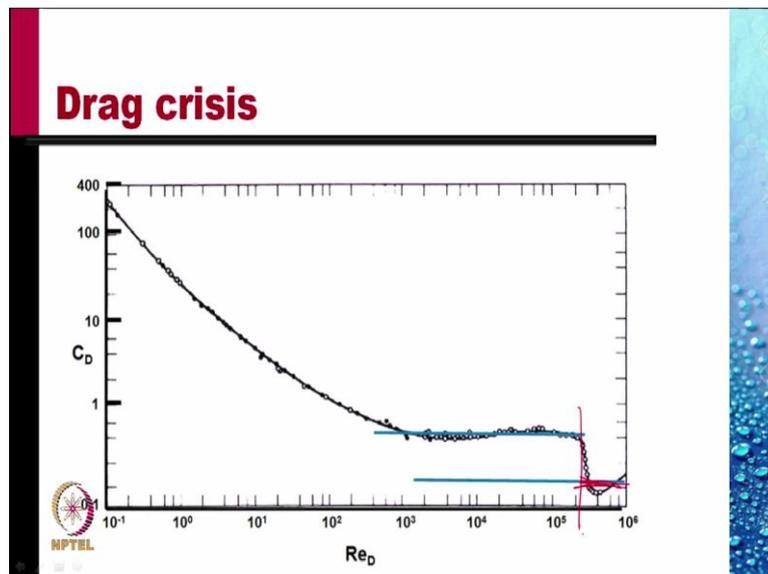
What is happening? What is happening is that there are two kinds of separation. When the boundary layer is laminar, then the separation takes place earlier. In this picture, it is about this case. If the boundary layer is turbulent, because the Reynolds number is larger, then the boundary layer is more energetic, so the velocity near the surface does not reduce to zero till much later down the stream, and the separation is taking place now at a much later location. This delay in separation, when the boundary layer is turbulent, which happens when the Reynolds number is larger, results in a different profile.

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This was the profile of pressure that we have seen earlier. The pressure not recovering at the back of the cylinder. When the boundary layer is turbulent, the recovery is much more than when the flow in the boundary layer is laminar, and the separation is delayed from around here to around there. This results in a narrower wake. The pressure recovery is more than that in the case of the laminar flow, reducing the pressure drag in the case when the separation is turbulent. And this results in a lower drag coefficient.

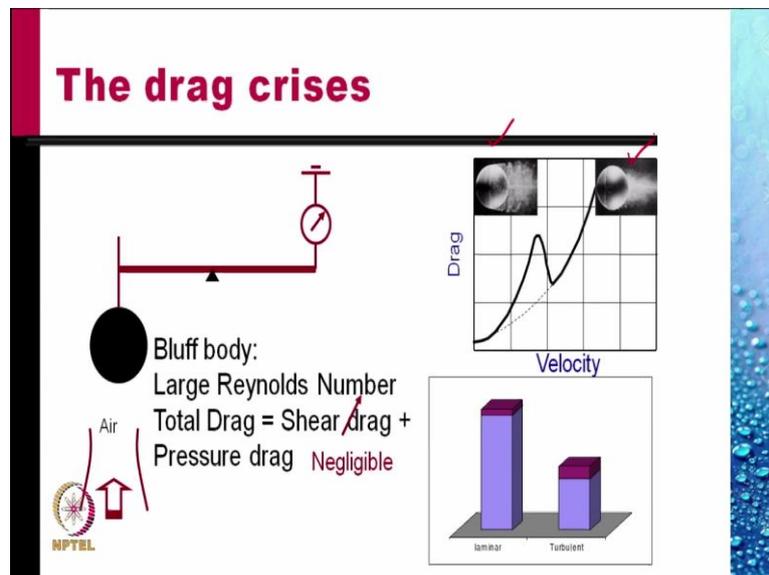
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Notice that this here represents laminar separation, where we can take C_D to be constant, about 0.5. And then later on when the boundary layer becomes turbulent, the separation takes place

at a much down-stream location, and the drag coefficient is order of 0.3 or so. This is about 4×10^5 , Reynolds number equal to 4×10^5 , on a smooth sphere.

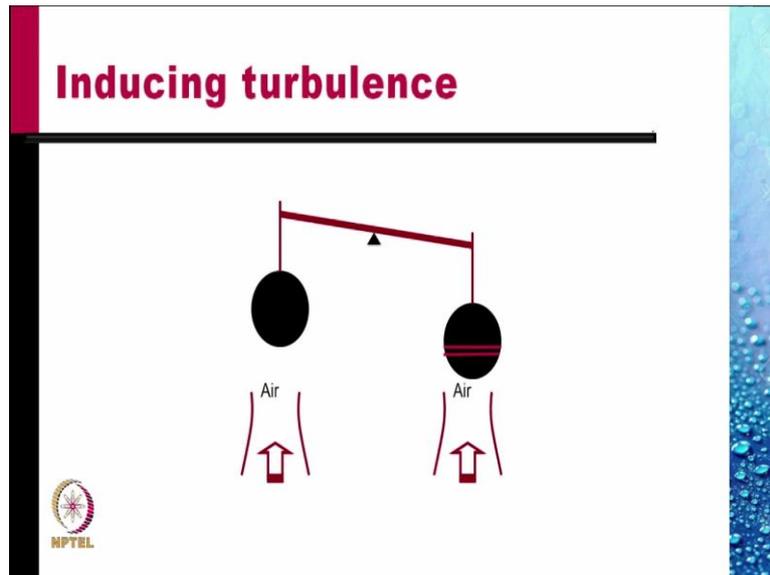
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So, on a bluff body at large Reynolds number, the total drag, which is shear drag plus pressure drag, and the shear drag is negligible. So drag is largely because of pressure drag. And for lower Reynolds numbers, for lower velocities, the separation is like laminar with a wider wake, and for larger velocities, larger Reynolds number, the separation is narrower, with more pressure recovery, and hence lower pressure drag.

So, while the shear drag is larger in the case of turbulent flows, but since the shear drag is a small percentage of the total drag, even increasing turbulence, drag cannot overcome the sharp decrease in pressure drag, because of a larger pressure recovery, and hence, the total drag in the case of turbulent flow is smaller than in the case of laminar flows.

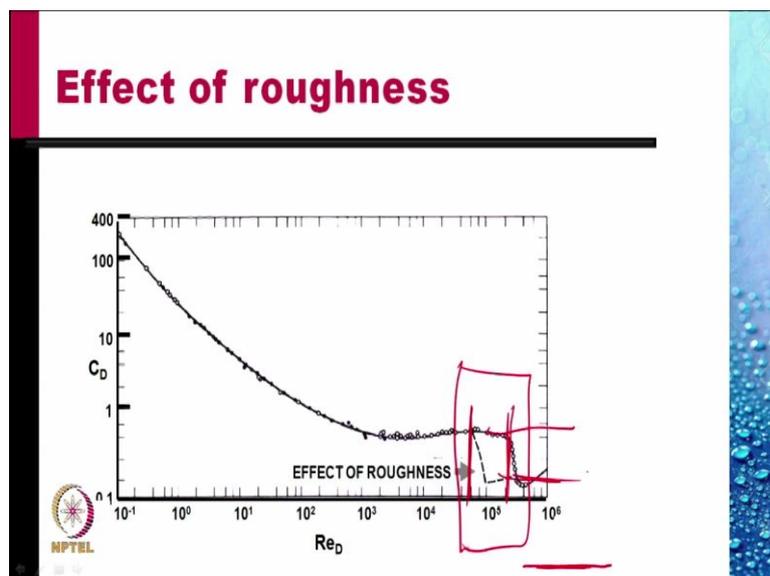
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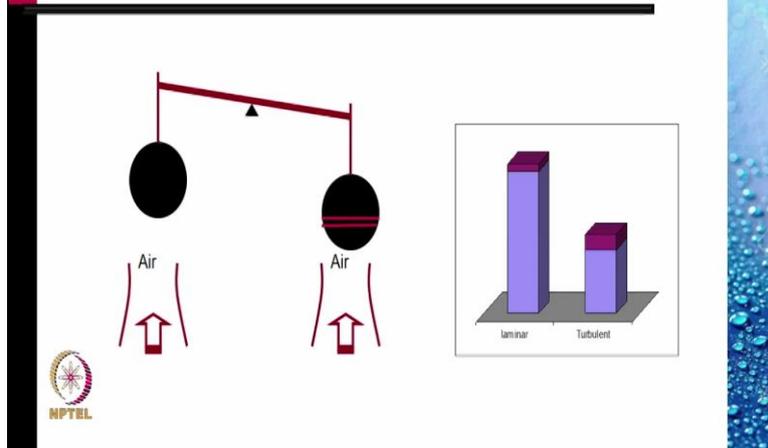
Now in this picture, we have seen, we have two identical spheres except that on the sphere on the right, we have wrapped a wire below, before, the equator. This wire we will call the tripping wire. This makes the boundary layer turbulent. This introduces roughness on the surface, and because of the roughness of the surface, the boundary layer becomes turbulent earlier, that is, at lower Reynolds number, than it would on a smooth sphere.

So, there is a regime of flow, there is a regime of Reynolds number, when the boundary layer on the smooth sphere will be the laminar, while the boundary layer or roughened sphere would become turbulent, leading to a lower drag on the roughened sphere, as is illustrated in this figure.

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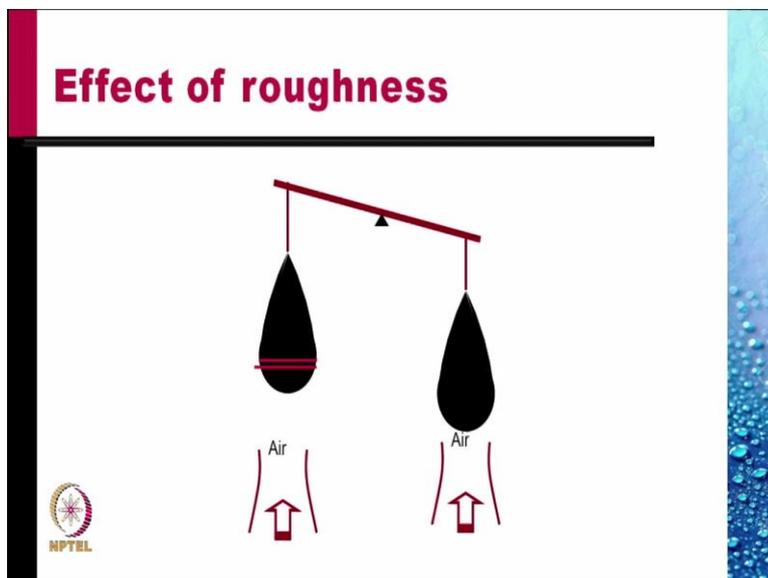
Some Curious Results: Explanation

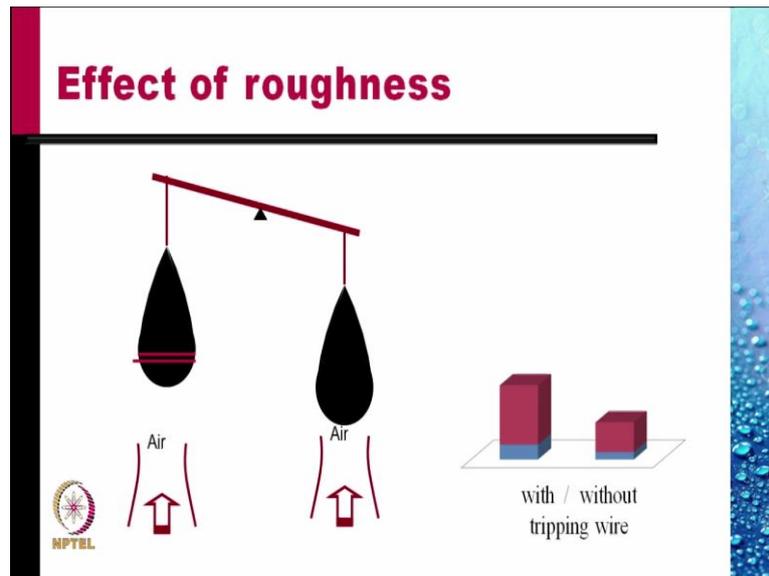


Because of the roughness then, the transition has now shifted from here to here, much earlier transition, and therefore, this is the domain in which the experiment illustrated here would be feasible. In this, the drag on the smooth sphere would be larger than the drag on the rough sphere. As is shown here, the viscous drag, the shear drag, would be more on the rougher sphere, but the pressure drag reduces, and so, the total drag is less.

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Effect of roughness



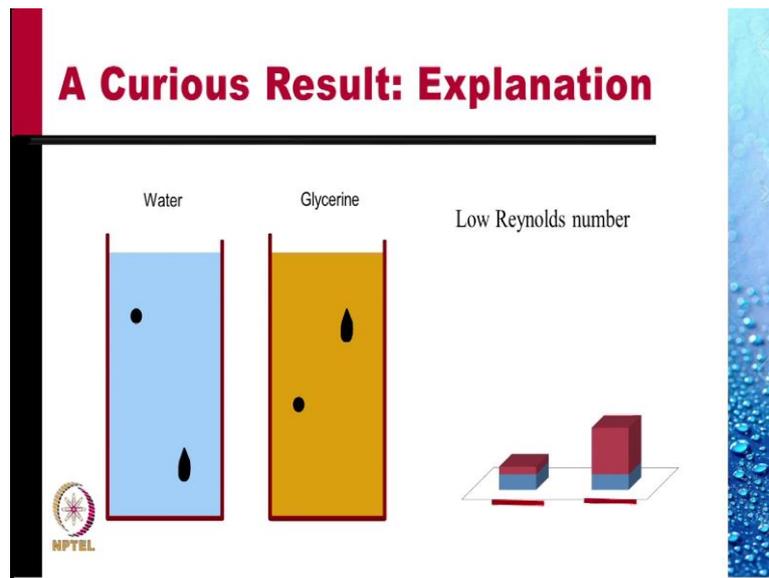


Now, another curious phenomenon in drag is, if we analyze the drag on the bomb-shaped body, the streamline body, and investigate the effect of roughness. Now, when we investigate the effect of roughness on a streamlined body, we see a phenomenon which is directly reverse of what we saw on bluff bodies. Here, for a certain range of Reynolds number, the drag on a roughened bomb-shaped body is more than on a smooth-surfaced body, unlike in a sphere, where smooth sphere had more drag than the roughened sphere.

And why is this so? This is so because there is very little pressure drag to begin with on a teardrop-shaped body, on a bomb-shaped body. The drag is dominated by the shear stresses. So, as the flow changes from laminar to turbulent, the decrease in pressure drag is small, because this drag is itself small, but increase in viscous drag, the shear drag, now dominates.

The shear stresses in turbulent flows are much more, large area, so the shear drag increases, and since it is dominating, the drag on the rough streamlined body is much more than the drag on a laminar streamlined body. That is why attempts are made to keep the flow on aircraft wings, which are streamlined, to be laminar as far as possible. There is a whole class of airfoils, known as laminar flow airfoils, which have been developed for the purpose.

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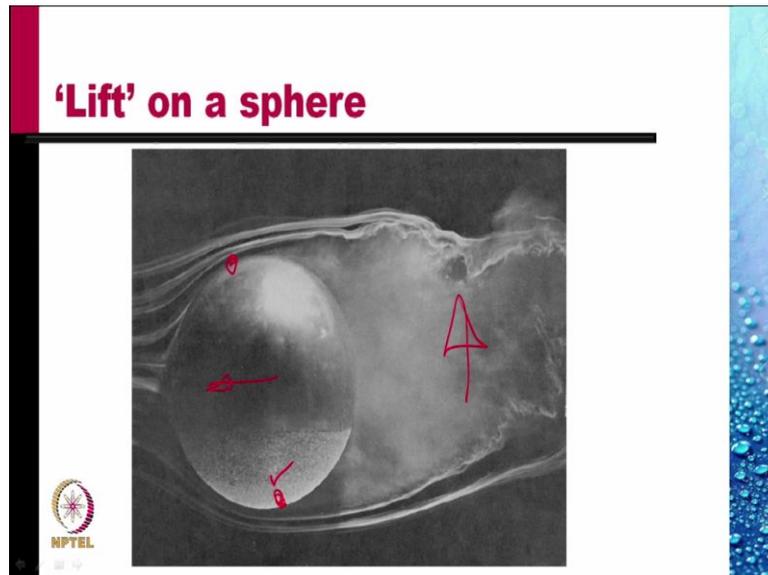
One last experiment to complete the study of drag. Let us have two bodies, one spherical or bluff body, and one bomb-shaped body. The two bodies are designed such that the frontal areas are the same, and the wet weights are the same, that is, the weight minus the buoyancy are equal. So that, while in liquid, the net force accelerating them downwards, they are the same.

Since the density of glycerin is different from density of water, the design of these bodies will be different for glycerin than for water. And when we release these bodies in water, as expected, the streamlined body reaches the bottom much faster, because it has lesser drag, and so, the net force is more, and so it accelerates faster and reaches the bottom faster. This is as per our expectation.

But when we do the same in glycerin, here too the wet weights of the bodies are equal, the frontal areas are equal. And as we see that in this case, when we release the two bodies, it is the bluff body that reaches the bottom earlier than the bomb-shaped or the streamline-shaped body. Why is that difference? And the difference is in a very simple fact. That now we have flow at low Reynolds number in glycerin.

In the glycerin, the flow is dominated by shears stresses. So this shows the drag makeup for the bluff body, and this shows for the teardrop shaped body. Very little pressure drag, no separation, question of separation does not occur. And again, dominated by shear stress, but since there is larger surface area, so the shear stress is more, and therefore, the tear-shaped body moves slower in glycerin than does the bluff body. Very curious results.

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Next presentation

Learning outcomes:

- Aerodynamics of ball games
- Control of boundary layers



In this last picture, we show the lift developing on a sphere. Recall from the very first lecture that we defined lift in a fluid flow as a force normal to the direction of motion of the body. In this case a ball, a sphere, with one side roughened and the other smooth, is travelling in that direction, so the flow is to the right relative to this. The upper surface is smooth, so the boundary layer remains laminar, and because it is laminar, it separates earlier. On the bottom side, the rough part makes the boundary layer turbulent, and it separates much later.

And therefore, a top and bottom asymmetry develops in this flow. The air stream is shifted up a little, that means, a force is being applied on the fluid, or the air, upwards, and the reaction of this is a force on the sphere, the ball which a downward. For this ball experiences a

downward force, a side force, this is a force that is responsible for swinging a cricket ball. More on this in the next lecture, where we will also discuss the control of boundary layers.

Thank you.