Fluid Mechanics & its Applications
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Indian Institute of Technology, Delhi
Lecture - 31
Fluid mechanics of sport balls and control of boundary layers

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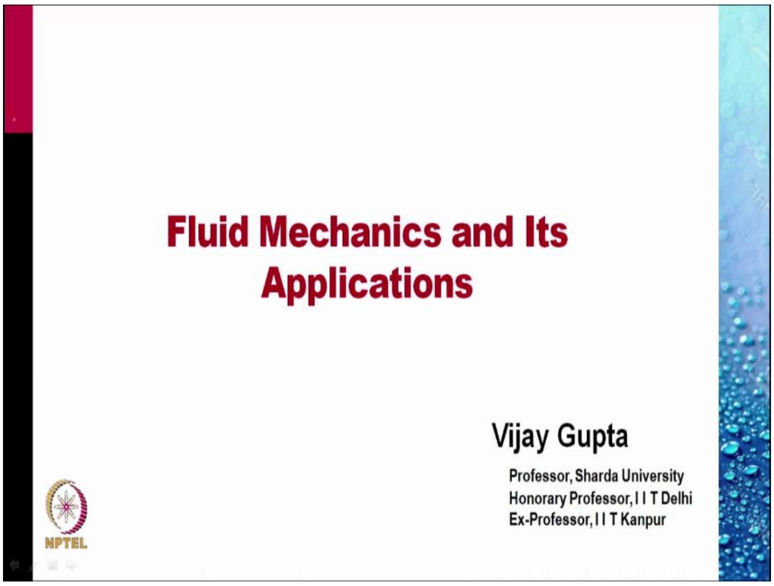

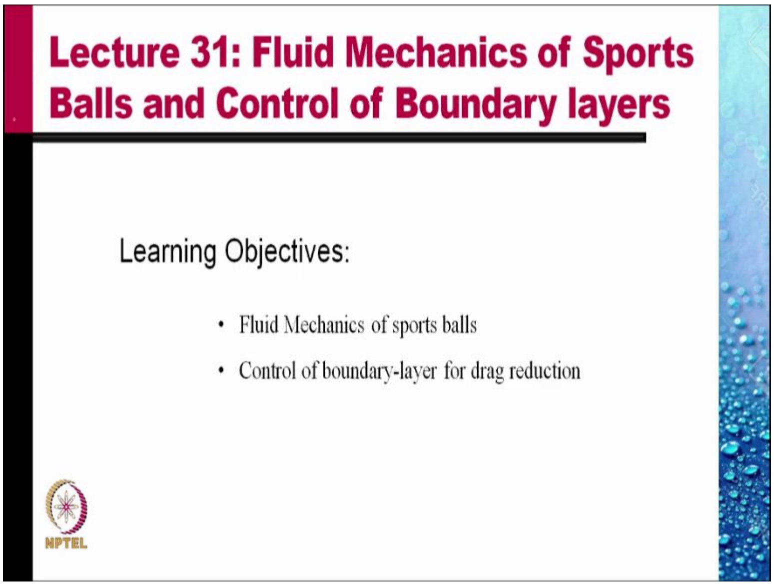

Good morning.

In this lecture, we would apply the principles of fluid mechanics that we learned to the sports balls and to the control of boundary layers.

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Many sports use spherical balls. The spherical balls are different sizes are used in table tennis, golf, tennis, field hockey, cricket, baseball, volleyball, and football. The sizes differ widely, the speed at which they are thrown differ widely too.

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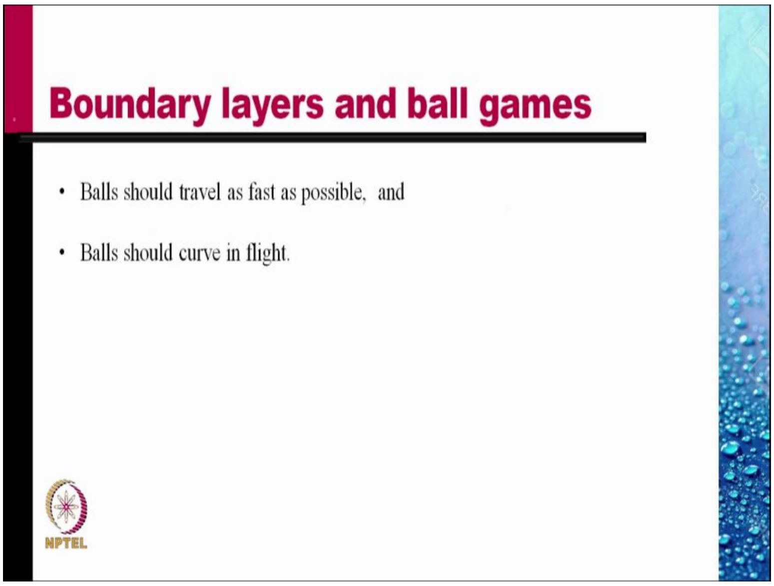

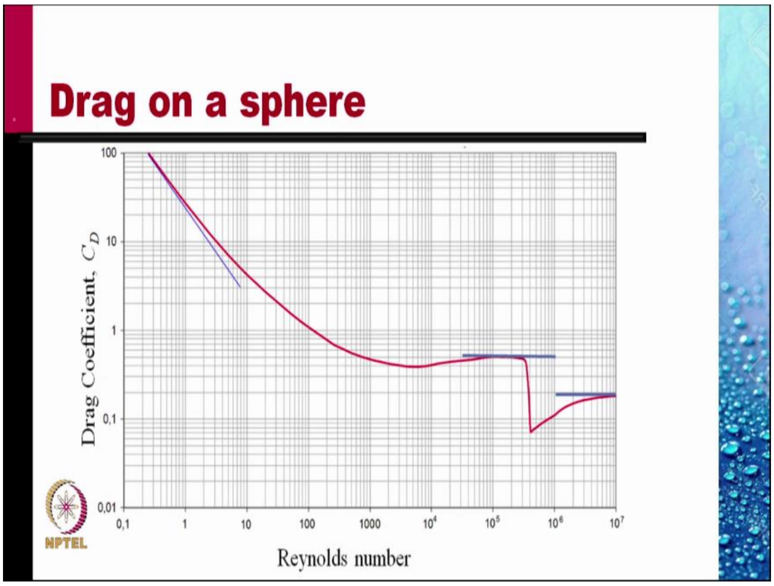

But in every ball game, the ball should travel as fast as possible, and the balls should curve in flight. Only then they can confuse the opponent. If you look at the variation of drag coefficient on a sphere with Reynolds number, this is the curve that best represents it. The interesting thing to note in this is that for large Reynolds number from about 2×10^4 to about 10^6, the drag coefficient can be taken to be constant. So, that the drag force varies like V^2.

Also, for a little higher Reynolds numbers, the drag coefficient is still constant, but at a lower value. Most sports exploit the fact that the drag coefficient decreases when the speed is higher.

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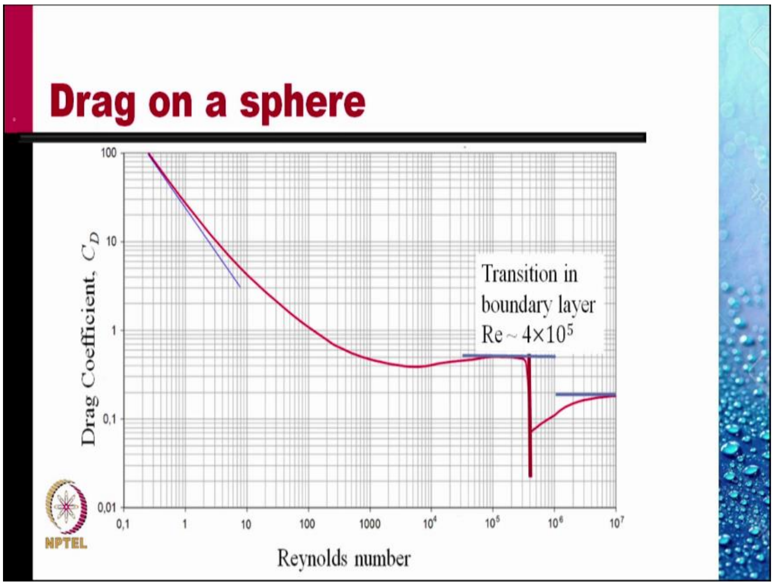

This decrease, as we already know, is because of transition in the boundary layer at about Reynolds number 4×10^5 on a sphere. The boundary layer becomes turbulent, and so it separates later from the body. The wake behind this sphere is narrower, there is a little more pressure recovery, and so the pressure drag reduces. Though of course, as was mentioned in the last lecture, the shear drag or the skin friction drag has increased slightly, but this skin friction does not dominate. What dominates is the pressure drag and so, a reduction of pressure drag leads to reduction in the drag coefficient.

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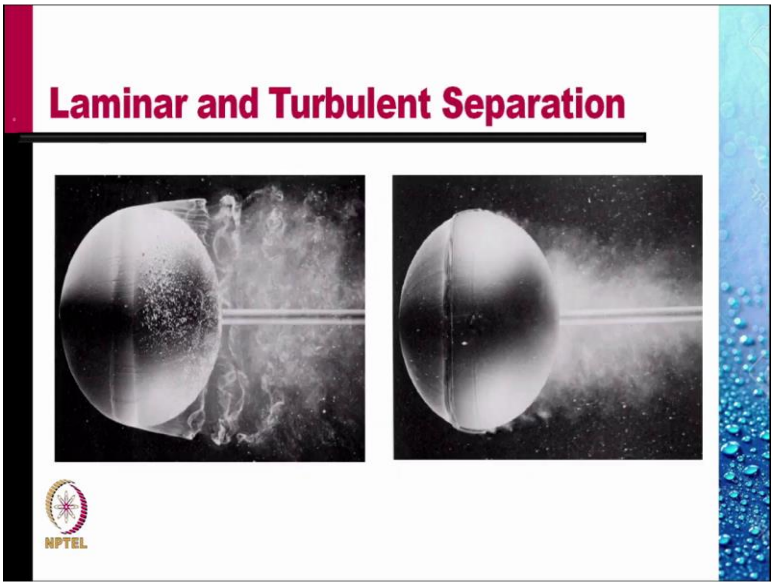

These two pictures demonstrate the behavior of the boundary layer on a sphere. In the first picture, we see the laminar separation of the boundary layer slightly ahead of the shoulder of the sphere. And in the second case, the boundary layer becomes turbulent, and separates much later leading to a narrower wake and lower C_D.

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Speeds required for transition on smooth balls

Ball	Diameter, mm	Velocity (m/s) for Re~4×10^5	Velocity (kmph) for Re~4×10^5
Table tennis	40	155	558
Golf	42	148	531
Tennis	65	95	343
Field hockey	72	86	310
Cricket	72	86	310
Baseball	75	83	298
Volleyball	210	30	106
Soccer	220	28	101

As we said, the transition on a smooth sphere occurs at a Reynolds number about 4×10^5, for the various balls. That translates into velocity in m/s, with a value as high as 155 m/s for the smallest of these balls, the table tennis ball, and the lowest about 28 m/s for a soccer ball. In terms of kilometers per hour these velocities are 558 kmph for a table tennis ball, and 101 for a soccer ball. These velocities are too high. None of these balls travel at velocities even close to these velocities. So, what is going on?

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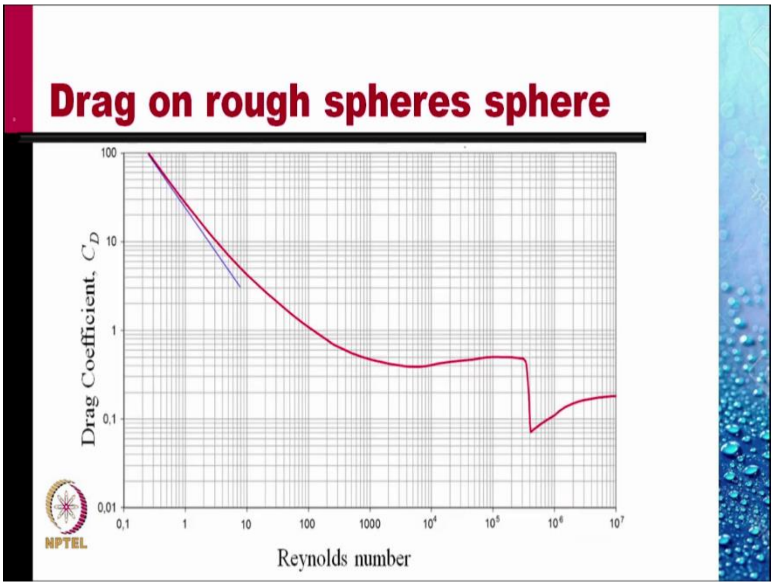

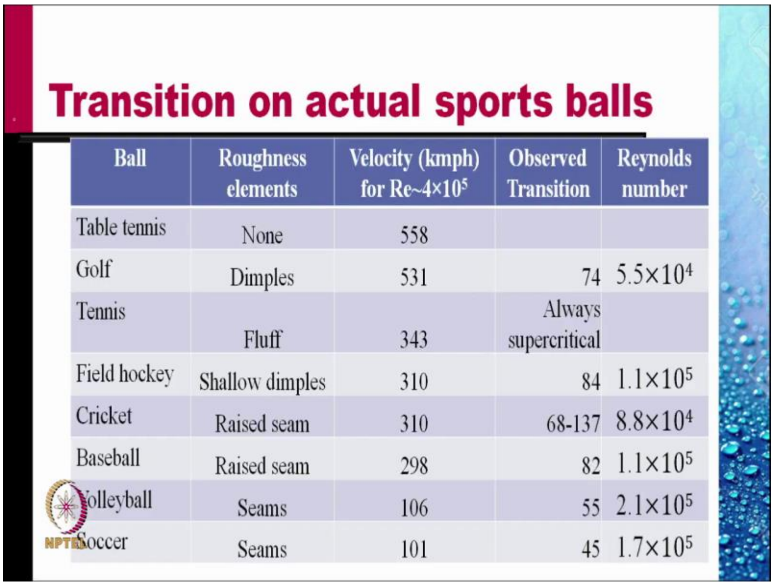

Ball	Roughness elements	Velocity (kmph) for Re~4×10^5	Observed Transition	Reynolds number
Table tennis	None	558		
Golf	Dimples	531	74	5.5×10^4
Tennis	Fluff	343	Always supercritical	
Field hockey	Shallow dimples	310	84	1.1×10^5
Cricket	Raised seam	310	68-137	8.8×10^4
Baseball	Raised seam	298	82	1.1×10^5
Volleyball	Seams	106	55	2.1×10^5
Soccer	Seams	101	45	1.7×10^5

What is going on is the fact that if this sphere is rough, the transition changes by a factor of 5 to 6. It reduces the Reynolds number. And so, the velocity at which the transition occurs is about 6 times lower than what the velocities listed in the last slide. The transition on actual sports ball are listed here. For a table tennis ball, we do not think the transition ever takes place. And on a golf ball, the velocity reduces from a very high value to a value of only 74 kmph, well within the range of good golf shots.

In tennis, the boundary layer is always super critical. And that, I believe, is largely because of the fluff on the tennis ball. In the field hockey with shallow dimples, the transition is at 84 kmph. In a cricket ball with a raised seam, the transition can occur anywhere from 68 to 137 kmph, depending upon the condition of the ball. We will talk about it a little later. Baseball at about 92 kmph. It also has raised seams, but different from a cricket ball. Cricket ball is the only ball with an equatorial seam. Baseball does not have an equatorial seam.

Volleyball, the different patches are stitched together that gives roughness, and the transition takes place at about 55 kmph. Soccer, it is a little lower. And you see the transition Reynolds number has decreased by a factor of about 4 to 7 in various cases. How does it come into play? We will see in the next few slides.

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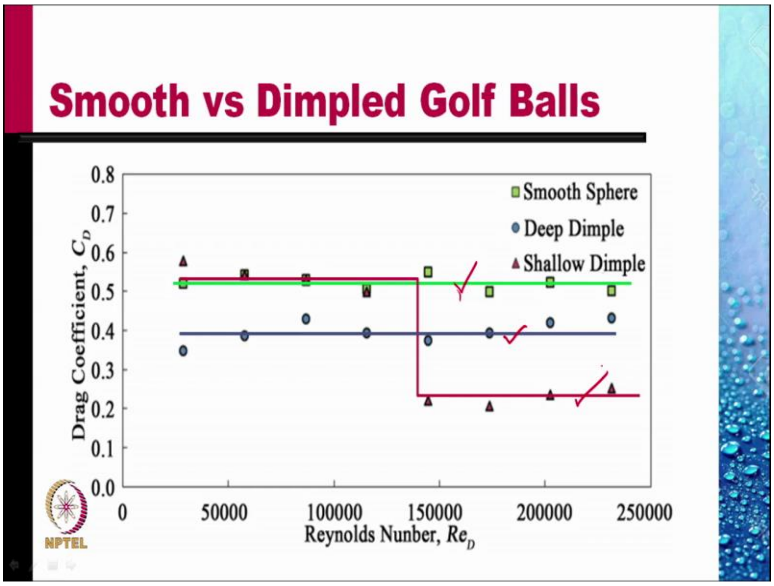

This graph shows the drag coefficient on smooth golf balls versus dimpled golf balls. The green line, this line, shows the drag coefficient for a smooth sphere of the size of the golf ball within the range of Reynolds number from 50,000 to 25,000, 2.5×10^5. So, on a smooth ball, transition does not occur, C_D remains high at more at about 0.5. A golf ball with deep dimples is the blue line, with deep dimples. It appears that transition has occurred below a Reynolds number of 50,000, 5×10^4. So, that is a lower C_D almost everywhere.

But if you have shallow dimples, then the red line represents the C_D curve. And here you see a transition from a higher value about 0.5, to low value of slightly above 0.2. This must be because of the transition in the boundary layer at a Reynolds number about 150,000, or 1.5×10^5, a factor of 3 lower than that on a smooth sphere. The flow on golf balls when they are hit from the tee are largely in the Reynolds numbers higher than that, and so, the drag coefficient is low. That makes the balls go long distances.

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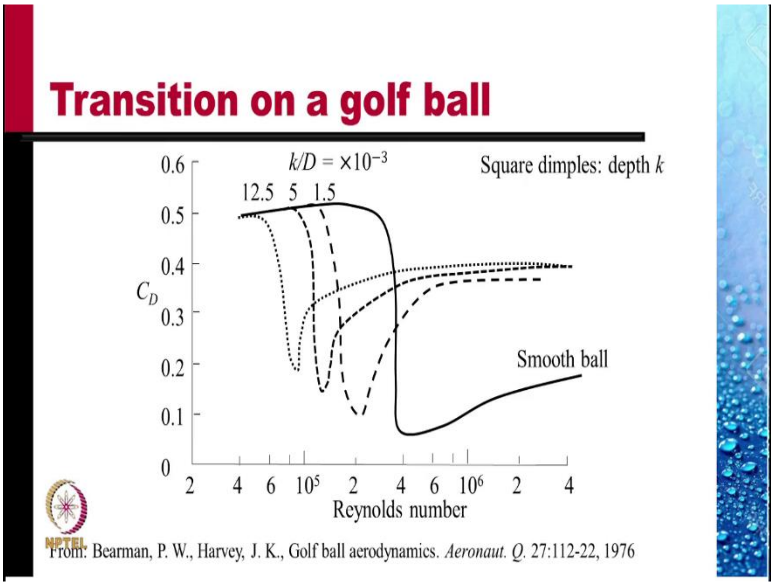

This again is a graph for transition on a golf ball. For a smooth ball, you can see the transition occurs at about 4×10^5. As you increase the depth of dimples, in these experiments were done with square dimples, the depth measured by k, so, k/D, is 10^{-3}. If the dimple was shallow, the transition shifted to something like 2×10^5 or less than 2×10^5. With a little deeper dimples, it shifted down further, and it 12.5 k/D at 12.5×10^{-3}, the transition is occurring at about 8×10^4. So, dimples, the depth of dimples affect the transition point.

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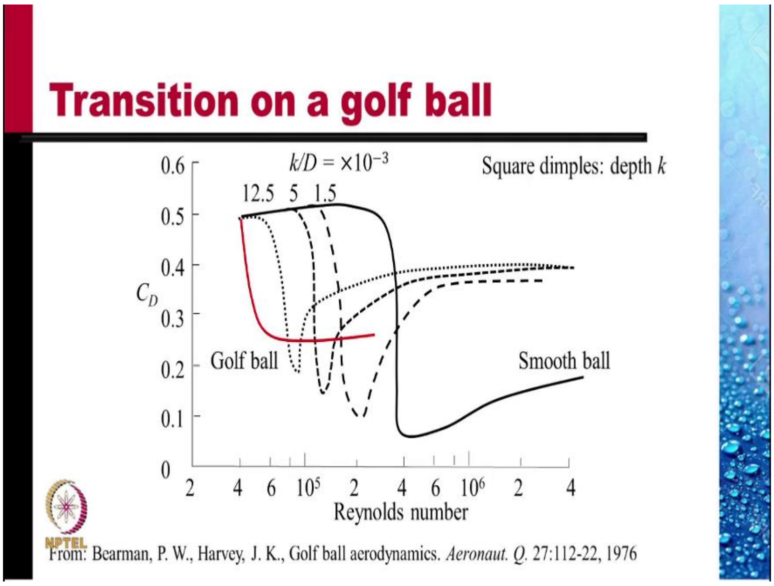

On an actual golf ball, if you measure, the transition takes place at about 4×10^4.

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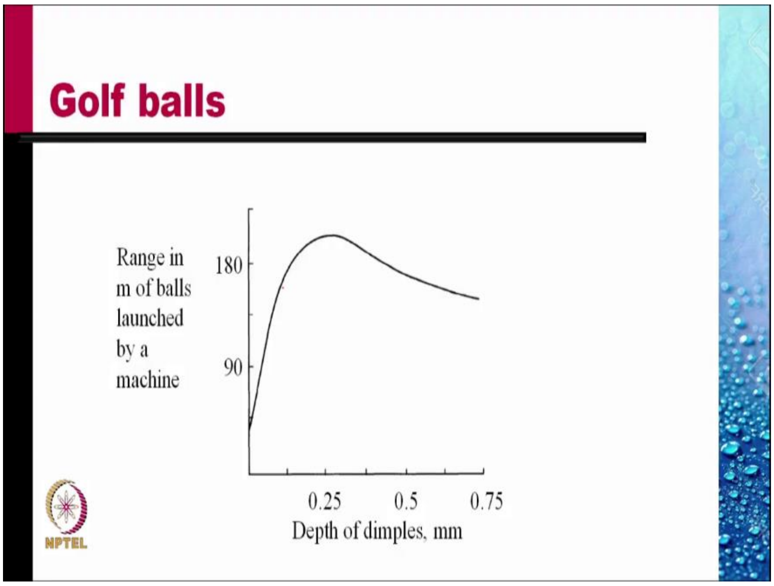

This calculates the range in meters of golf balls launched by a machine at a constant speed, speed large enough to have a value of Reynolds number about 10^5, and we see that we get the maximum range when the depth of dimples in millimeter is about 0.25. Beyond that, the range decreases slightly. I would hazard a guess that as the depth of dimples increases, the transition takes place earlier. But after a depth of 0.25 mm, the skin friction effects come into play. The rougher surface of the dimpled golf ball now causes an increase in skin friction. It then decreases the rage slightly.

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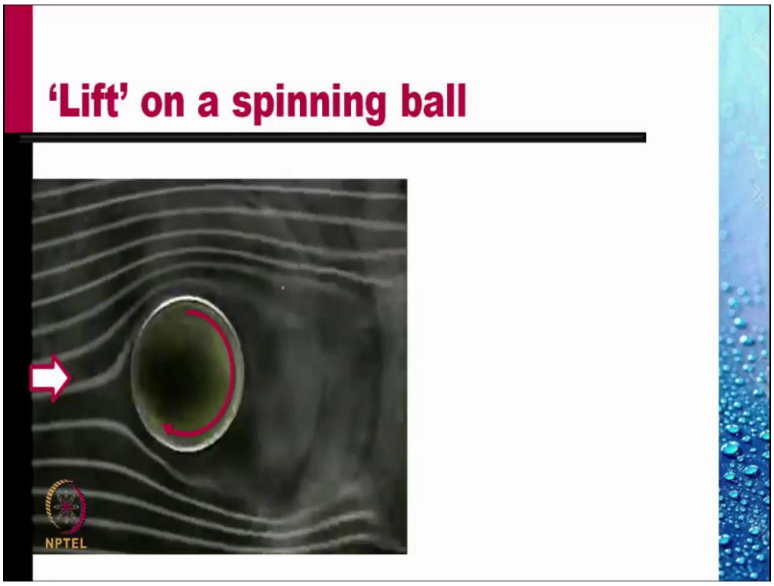

This flow picture shows you the flow approaching a spinning ball, and you see there is no symmetry top and bottom. If the ball is spinning as shown, clockwise with flow approaching from left, at the lower part of the ball, the velocity of the ball surface is in opposition to the free stream velocity, while at the top, the velocity of the ball is in line with the velocity of the approaching airspeed, and therefore, the pressure at the top is less and the pressure at the bottom is more. And because of this, this separation points shifts more to the right on top, and more to the left on bottom. And this gives you a force which is upwards.

This force, termed lift, because it is perpendicular to the direction of motion of the ball moving to the left, is termed as lift, and is utilized in more sports to deviate the path of the ball. This is nothing but what is known as the Magnus force, which was discussed earlier in the chapter of inviscid flows. There is the flow on a spinning ball, and it depends upon the density of the fluid, the velocity which the ball is moving, the angular velocity of the ball, and the radius of the ball.

We have seen that the lift coefficient varies with $\omega R/V_o$. ωR is the surface velocity of the ball, and V_o is the free stream velocity. The lift coefficient varies like I showed. The Magnus force lift coefficient is like this. It explains partly the force.

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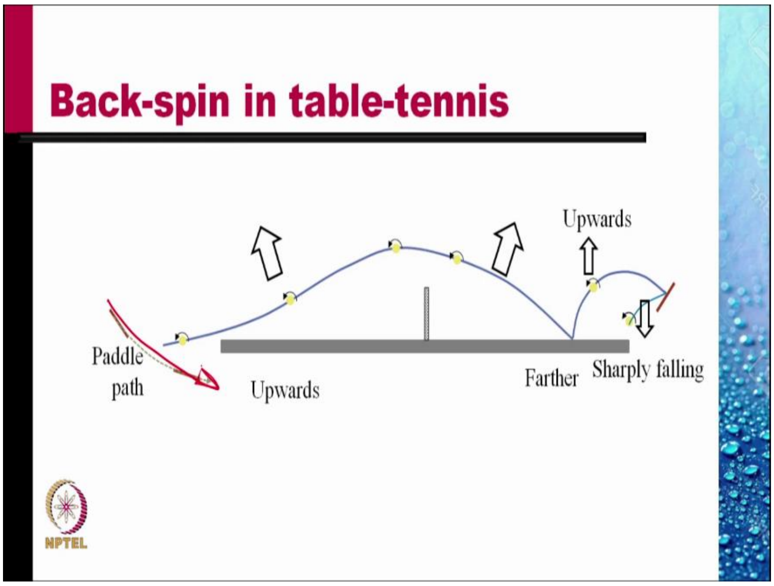

So, let us explore how does the spinning ball affects the trajectory of a ball. Let us look at a table tennis table. A ball is hit by a paddle moving along this arc, and as it hits the ball, the ball is given a rotation in the counterclockwise sense. The surface of the paddle slides along the ball at the lower point, spinning it about an axis perpendicular to the screen, and the ball rotates in a counterclockwise fashion as it travels to the right. Because of this, a lift force develops. This lift force would tend to overcome gravity a little bit and so, the ball instead of following a parabolic trajectory, follows a trajectory that is bent a little upwards from the parabolic trajectory.

When the ball reaches the other half of the table, the lift is oriented like this. So, the ball lands on the table a little further than it would if the ball was not spinning. Thus, if you give the ball a backspin, you have to be careful to control the force so that the ball does not overshoot the table. After impact from the table, the ball is still moving counterclockwise and so, there is a lift force upwards. And this lift force upwards would make the ball go up more than it would go up if the ball was not spinning.

After the ball is returned, by hitting from the paddle, since the direction of travel of the ball is now reversed, it is moving to the left instead of to the right, and spinning in the same anti-clockwise sense, the lift force on the ball is now directed downwards. That is why the return shot dips sharply as it is played.

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On the other hand, in a topspin, as you move the paddle up along this line, the ball is given a spin which is clockwise, and because of this clockwise spin, there is a lift force which is downwards, which makes the trajectory of ball flatter. So, you have to be careful, so that it clears the net at the center, and then the force continues to be downwards, and therefore, the ball lands on the table closer to the net than it would if there was no topspin.

Then on rebound, the trajectory is flatter again, because of the topspin. And on a return shot, since the direction of travel of the ball changes, so the lift force now is upwards, and that will make the ball pop up. All these are exploited by experienced table tennis players. Same thing is used in tennis.

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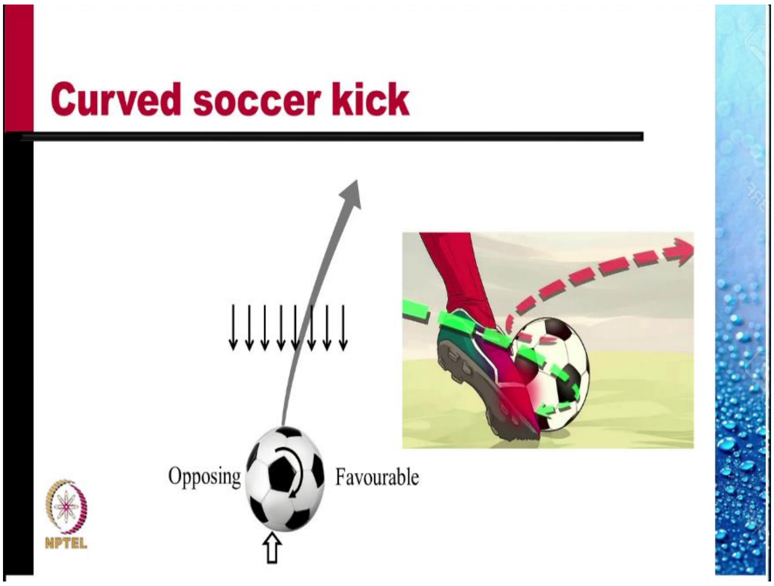

Now, let us look at a soccer kick. When a player wants to curve the ball along the ground, he kicks the ball on the side to impart a spin to the ball about a horizontal axis. So, if this ball is kicked at around this point, the ball travels forward, and is given a spin. Because of the spin and the forward motion of the ball, we have the opposing velocities on the left, and the favorable velocities on the right, and because of this, a ball curves in this manner. Because a force is generated towards right, the lift force generated towards the right, and the ball curves. Hit it, and the ball curves.

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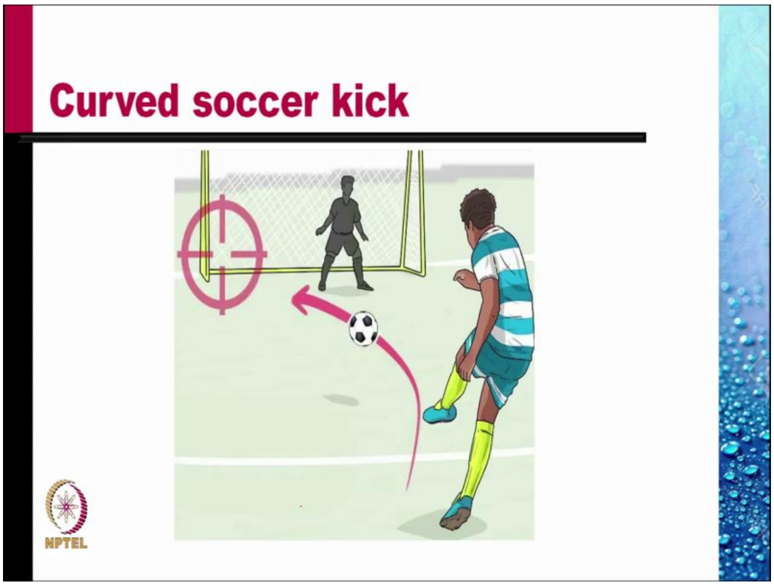

And this can beat the goalkeeper. The ball is taking a trajectory very unlike what would you expect if the ball was hit without the spin. This also is used routinely by football players.

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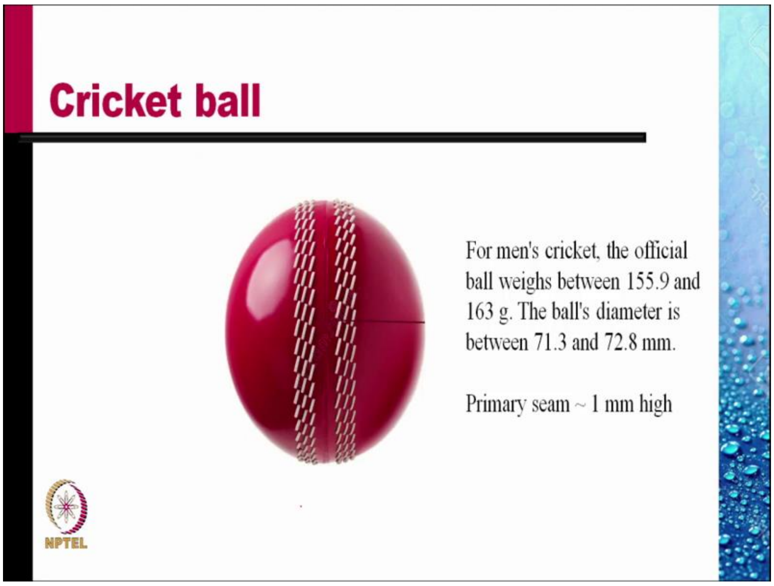

Now, we come to the sport of cricket. As mentioned earlier, a ball used cricket is the strangest ball of all. It has any equatorial seam, six rows of stitches raised. The seam is about one mm high from the surface. There are two secondary seams running perpendicular to these primary seams, but they are of little consequence. What these seams do is, first, when they land on the pitch, they provide a factor which is unpredictable to the bounce back from the pitch, if the ball lands on the seam. The second, this raised seam causes the boundary layer to transit from the laminar regime to the turbulent regime.

And the art of bowling has developed techniques by which the transition occurs on one half of the ball, not of the other half. I will explain this shortly.

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While bowling seamers, the bowler spins the ball about the horizontal axis by rubbing the fingers against the seam as he delivers the ball. The ball is spinning with seam vertical. If the seam is vertical, there is symmetry to the motion of the ball, and the air rushing past this. And so, the ball does not curve in flight. However, when it lands, the seams can make it go in either direction, to the left for a ball seaming in, or to the right for a ball seaming out. But this is not in control of the bowler. The ball could go either way. Neither the bowler nor the batsman can predict where the ball would go.

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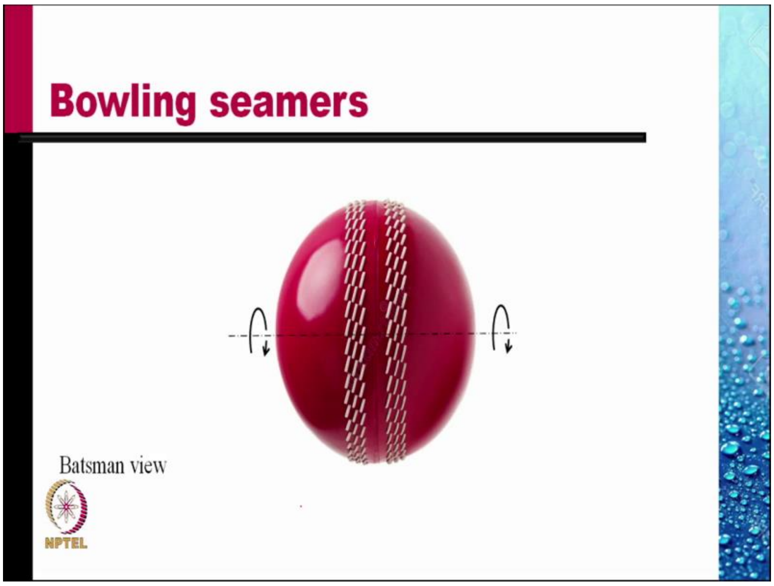

It deviates a little bit in flight, left or right, and only on pitching randomly on pitch.

However, the swing bowling is a different ballgame altogether. Here the ball deviates from its path in flight, and that is due to asymmetric separation. From the viewpoint of the batsman, if the seam is inclined, as shown, towards the right, that is, towards his off stump, the ball is going to swing out. On the other hand, if the seam was tilted towards the left, opposite of what is shown here, the ball would swing in towards his leg stump. Why? We will explain.

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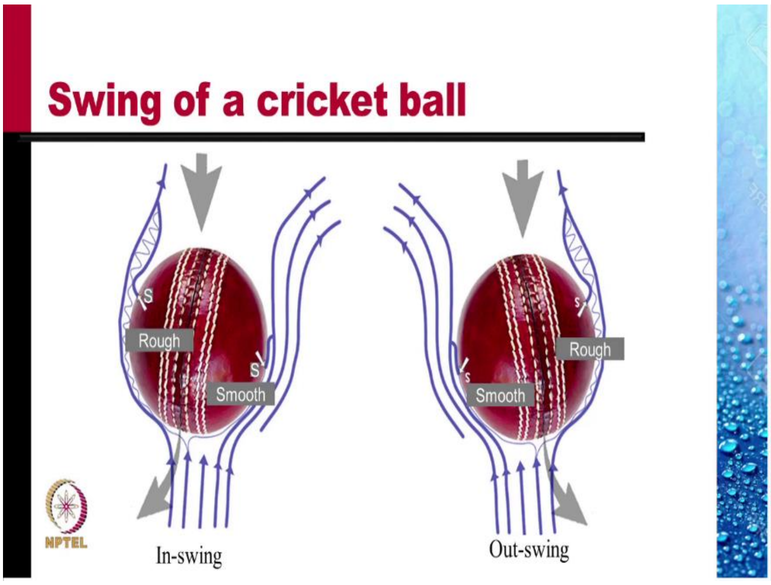

Consider this ball which is held, or which is delivered, with the seam as shown. In this picture, if the ball is traveling down, and so, relative to the ball, the air is rushing up around the ball. On the right side, which is the smooth side, the ball does not meet the seam, and so, the transition does not occur on a smooth side. So, flow remains laminar, and because the flow is laminar, the separation takes place early. However, on the left side, the air has to pass around these roughness elements. This seam provides roughness elements, and because of this the boundary layer becomes turbulent, and once the boundary layer becomes turbulent, the separation point is shifted backwards.

This results in an asymmetric flow, with lower pressures on the left side and higher pressures on the right side. And because of this the ball curves towards the legs stump. So, this is an in-swing ball. On the other hand, if the seam was tilted as shown on the right, this story reverses. On the left side is the smooth side, and we get laminar separation here, while on the right is the rough side. The air passing over the seams and becoming turbulent, and the separation is delayed.

And so now the net force on the ball is towards the right, and it is an out-swing ball, ball moving towards the off stump. It is necessary that the seam of the ball is held stationary, in the sense it is always in the same plane, and that is why the ball needs to be spun to give it gyroscopic stability.

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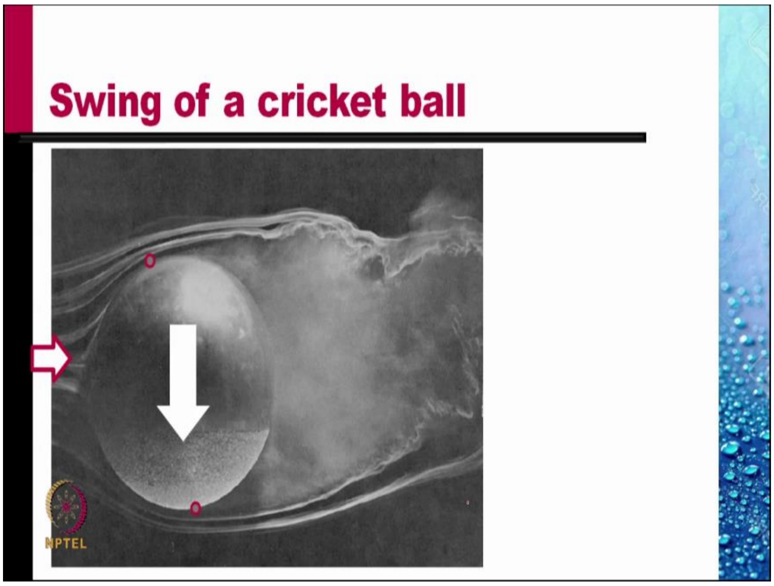

This actual flow picture shows the same phenomenon. One side of the ball has been roughed, and one side of the ball is smooth. So that the air is shifting, given a momentum towards the smooth side, and therefore there is a net force that is downwards. So, this mechanism for swing seems justified.

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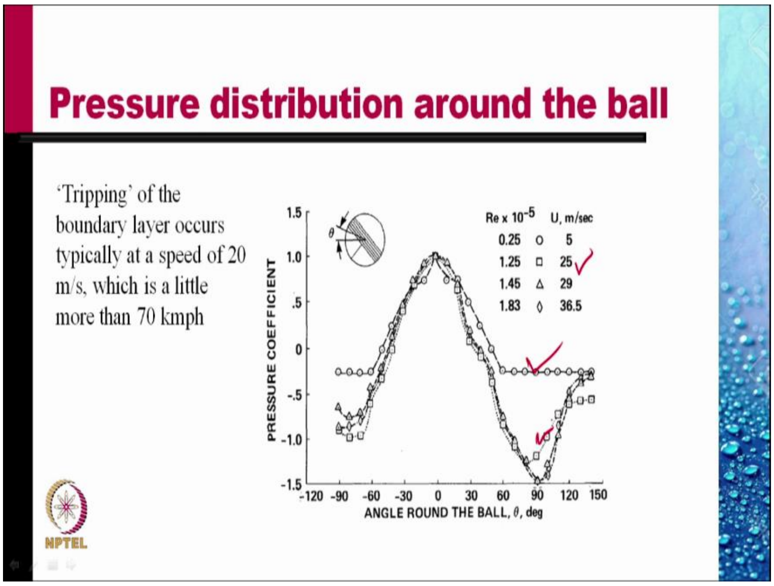

Here are shown some measured the pressure distribution around the ball at various Reynolds number at various velocities of the ball. At 5 m/s, the Reynolds number is 0.25×10^5, and this is the picture. The Reynolds number is so low that even with the seam creating roughness, the boundary layer does not transit. It remains laminar. And so the pressure distribution is the same on the left as on the right, and no swing force results. As you increase the velocity 5 folds to about 25 m/s, the swing force is there. For higher velocities, 29 m/s or 36.5 m/s, the pressure distributions are same.

Tripping of the boundary layer occurs typically at a speed of 20 m/s, which is a little more than 70 kmph. So, there would not be a swing if the speed of the ball is less than 70 kmph. On the other hand, if the speed of the ball is of the order of twice this, that is, about 140 kmph, then the ball is traveling too fast. The boundary layer becomes turbulent even on the smooth side, and if that happens, the swing would again disappear. So, really fast bowlers do not produce any swing in the balls, they kill with speed only.

Another thing to keep in mind is that we need the smooth side of the ball to remain smooth. And that is why all fielders when they get the ball would rub the ball, would shine the ball, and you should notice they always shine on one half of the ball, every one on one half of the ball. It will not affect negatively if they shine the other side as well. But that is a waste of effort. Shining the ball takes quite a bit of energy, and so why waste the energy shining the side where it does not affect. So, everyone shines the ball on one side

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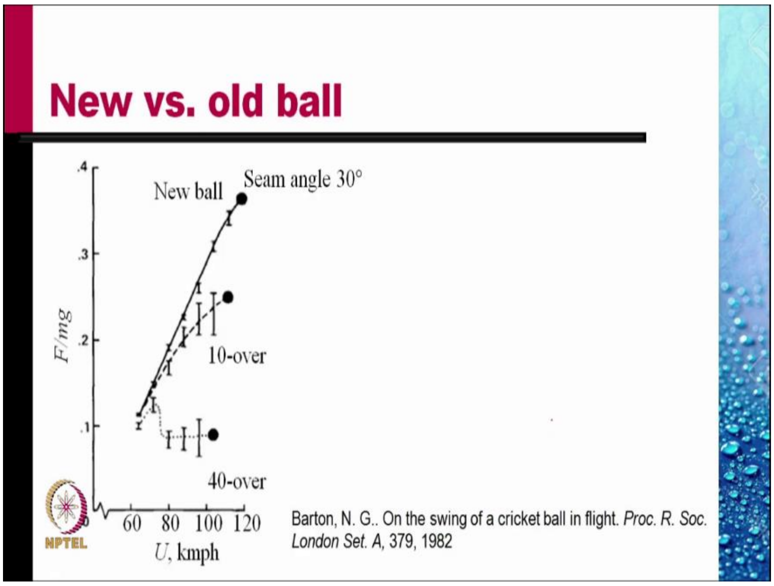

This is also seen in new versus old ball. If the ball gets old, even after shining the surface which we are try to maintain smooth, it is no longer smooth, and so the swing force F as fraction of the weight of the ball decreases as the ball gets older. At about 40-overs ball, you notice that the swing force is very small.

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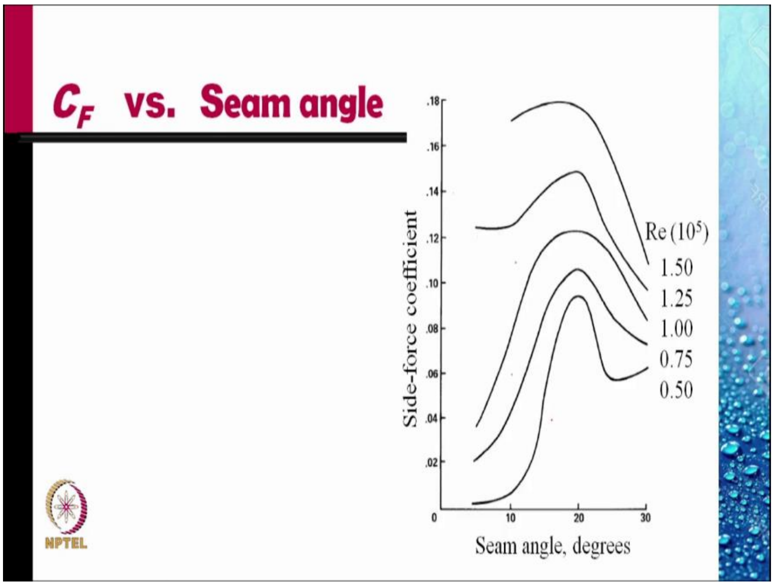

This graph shows you the side-force coefficient versus the seam angle. Seam angle of about 20 degrees seems the optimum for producing the swing.

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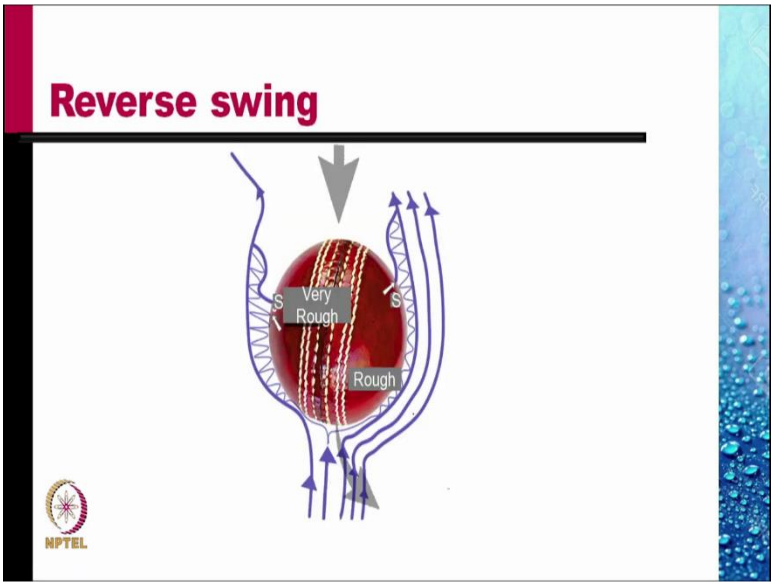

This picture shows the trajectory of the balls at various speeds starting with 16 m/s going up to 20 m/s. These are trajectories calculated from the side force coefficients which we have developed earlier, and the drag coefficients that we know about a sphere. Using those force coefficients and the side-force coefficient, we calculate the trajectories. These square black points represent the trajectory as measured. So, that the theory presented here does explain the swing of the ball, because of a very good agreement that we have with the theoretically calculated results.

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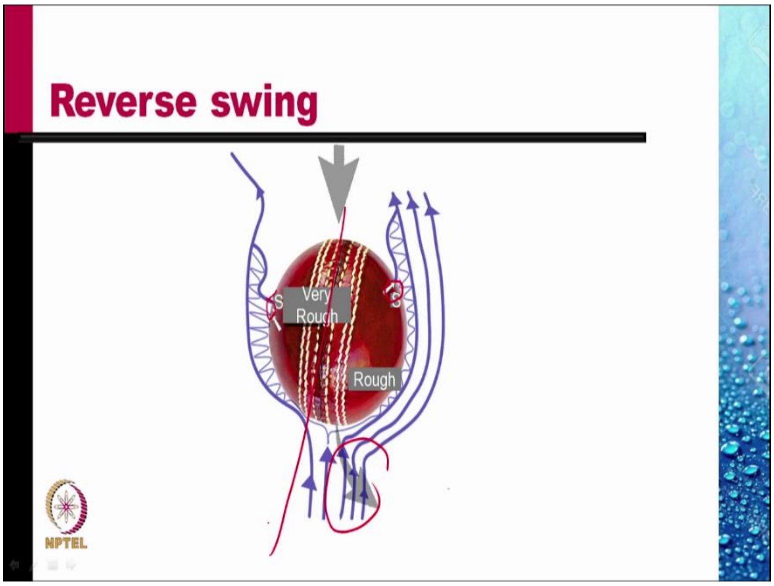

Now, let us look at the phenomenon of reverse swing. In this case, what we are talking about is the ball getting quite old. So, one side is rough and other side is very rough. In this situation, on the rough side the transition does take place, we have separation, here. On the very rough side again, the transition takes place. But on the very rough side, the skin friction is now predominant.

There is a large skin friction, and because of which we get a side force that tends to move the ball in the opposite direction from what you would expect from the orientation of the seam. As I mentioned earlier, that is, in swing bowling you expect the ball to move towards the direction the seam is inclined, from the ball, from the batsman point of view. And so here, one would have thought the ball would swing to the leg wicket. But the ball swings to the off wicket.