MYSTERY OF SPORTS BALLS

Akshoy Ranjan Paul
Lecturer, Department of Mechanical Engineering.

Abstract:

The article finds what principles of fluid dynamics influence the performance of sports balls. At some point in time, many of us have wondered what puts the curve in Randy Johnson's baseball, the drop in Sania Mirza's S-serve with tennis ball, the flight in Tiger Wood's drive with golf ball or Irfan Pathan's swing with cricket ball. The answers to these questions all share the common principles of fluid mechanics. The fluid mechanics of sports balls directly affect athletic performance. This is vital information for maintaining interest and competitive competency in athletic games.

Introduction:

Sir Isaac Newton[1] in 1672 (Did this person have something to say about everything?) was the first person to describe the curved flight of a tennis ball. Since that time, other scientists have. defined the forces that put the "sport" in sports balls. In 1742, Robins showed that a transverse aerodynamic force could be detected on a rotating sphere. (Hence it is also referred to sometimes as the ***Robin's Effect***).

The first explanation of the lateral deflection of a spinning ball is credited by Lord Rayleigh to German physicist H. Gustav Magnus[2] in 1852, from which the phenomenon derives its name, the ***Magnus Effect***. Rayleigh[3] also gave a simple analysis for a "frictionless fluid," which showed that the side force was proportional to the free stream velocity and the rotational speed. Because deviation from a straight line of flight is central to a sport, Gustav Magnus' original explanation of side force is crucial to explaining a ball's seemingly magical movement. He discovered that lateral deflection is produced by spinning the ball about an axis perpendicular to the line of flight. When a ball spins, the boundary layer of air asymmetrically breaks away from its surface thus causing the ball to swerve from a linear path. This was all before the introduction of the boundary-layer concept by Ludwig Prandtl in 1904.

The more recent studies[4] agree that the Magnus force (Lift) results from the asymmetric distortion of the boundary layer displacement thickness caused by the combined spinning and flow past the sphere. If ρ is density of air, u is the flow velocity of air and Γ is the circulation of the sphere, mathematically,

$$\text{Lift force, } F_L = \rho u \Gamma$$

Likewise, Drag force (F_D) is directly related to both velocity (u) and diameter (d) of the ball and to the density (ρ) of the fluid. Mathematically,

$$\text{Drag Force, } F_D = 0.5 C_D \rho u^2 A$$
$$\text{where, } A = (\pi/4) d^2 .$$

Osborne Reynolds took both of these factors into consideration and derived the ***Reynolds number*** (*Re*), which is a dimensionless value calculated by the product of velocity (u) and size of the object (d), divided by the kinematic viscosity of air (n). It has been found that as the velocity on a sphere is increased in a fluid (such as air), the boundary layer is tripped from laminar to turbulent.

Pre-critical *Re* ($Re<Re_{cr}$) is the term used to define the flow of air on a sphere before the boundary layer has been tripped. After the boundary layer has been tripped, and the drag is greatly decreased, the term post-critical *Re* ($Re>Re_{cr}$) is applied.

The laws of Fluid Mechanics govern the movement of sports balls as they travel through the air. For proper understanding, a few definitions are necessary. ***Viscosity*** is the degree of "stickiness" found in gases and liquids. *Friction* is the resistance to a ball's flight due to the viscosity of air. The ***boundary layer*** is the layer of air on the surface of the ball. It is composed of two regions or states: (1) ***Laminar***, with smooth air layers sliding by each other, and (2) ***Turbulent***, with the air moving irregularly. This turbulent air sticks to the ball longer, allowing less drag and changing the direction of the ball. The velocity at which this occurs is the transition zone.

All sports balls have surface features that which help produce their characteristic eccentricities of flight. The current study has evaluated the role of these surface features using non-spinning balls. Of greatest curiosity is the fact that the surface features have their greatest influence in the speed range where the individual sports are played. Significant deepening of the dimples on a golf ball would greatly increase the amount of drag, shortening its flight. Today, with professional player serving speeds becoming overwhelming fast, there is a move to enlarge the size of the official tennis ball, thereby increasing the drag and slowing the ball's speed. The baseball's raised stitches cause turbulent airflow in an erratic pattern, resulting in the fluttering flight of the non-spinning knuckleball. Roughening the surface of a baseball is so effective in altering its flight path, this practice is now illegal.

Why does a golf ball have dimples?

A golf ball can be driven great distances down the fairway. Study shows that a driver shot in golf can easily make a golf ball carry 250 metres, but the same shot using a smooth ball will only carry about 90 metres. How is this possible? Is the drive only dependent on the strength of the golfer or are other factors at play? As we will see, the aerodynamic forces play a key role in the flight of the golf ball. Consider the aerodynamic drag on a sphere. There are two types of drag experienced by a sphere. The first is the obvious drag due to friction. This only accounts for a small part of the drag experienced by a ball. The majority of the drag comes from the separation of the flow behind the ball and is known as pressure drag due to separation. For laminar flow past a sphere, the flow separates very early as shown in Fig.-1. However, for a turbulent flow, separation is delayed as can be seen in Fig.-2. Notice the difference in the size of the separation region behind the spheres. The separation region in the turbulent case is much smaller than in the laminar case. The larger separation region of the laminar case implies a larger pressure drag on the sphere. The surface roughness caused the flow to transition from laminar to turbulent. The turbulent flow has more energy than the laminar flow and thus, the flow stays attached longer.

So, why dimples? Why not use another method to achieve the same affect? The critical Reynolds number, Re_{cr}, holds the answer to this question. As you recall, Re_{cr} is the Reynolds number at which the flow transitions from a laminar to a turbulent state. For a smooth sphere, *Recr* is much larger than the average Reynolds number experienced by a golf ball. For a sand roughened golf ball, the reduction in drag at Re_{cr} is greater than that of the dimpled golf ball. However, as the Reynolds number continues to increase, the drag increases. The dimpled ball, on the other hand, has a lower Re_{cr} and the drag is fairly constant for Reynolds numbers greater than Re_{cr}.

Therefore, the dimples cause Re_{cr} to decrease, which implies that the flow becomes turbulent at a lower velocity than on a smooth sphere. This in turn, causes the flow to remain attached longer on a dimpled golf ball, which implies a reduction in drag. As the speed of the dimpled golf ball is increased, the drag doesn't change much. This is a good property in a sport like golf.

Although round dimples were accepted as the standard (Fig.-3), a variety of other shapes were experimented with as well. Among these were squares, rectangles, and hexagons. The hexagons actually result in a lower drag than the round dimples. Perhaps in the future we will see golf balls with hexagonal dimples (Fig.-4).

How Golf ball produces lift?

Lift is another aerodynamic force, which affects the flight of a golf ball. This idea might sound a little odd, but given the proper spin a golf ball can produce lift. Originally, golfers thought that all spin was detrimental. However, in 1877, British scientist P.G. Tait[5] learned that a ball, driven with a spin about a horizontal axis with the top of the ball coming toward the golfer produces a lifting force. This type of spin is known as a ***backspin.***

The backspin increases the speed on the upper surface of the ball while decreasing the speed on the lower surface. From the Bernoulli principle, when the velocity increases the pressure decreases. Therefore, the pressure on the upper surface is less than the pressure on the lower surface of the ball. This pressure differential results in a finite lift being applied to the ball.

The dimples also help in the generation of lift. By keeping the flow attached, the dimples help promote an asymmetry of the flow in the wake. This asymmetry can be seen in Fig.-5. In this figure, the smoke shows the flow pattern about a spinning golf ball. The flow is moving from left to right and the ball is spinning in the counter-clockwise direction. The wake is being deflected downwards. This downward deflection of the wake implies that a lifting force is being applied to the golf ball.

Seam and swing bowling of a Cricket ball:

The cricket ball has a raised seam around its equator. In a new ball it is 1mm above the surface and composed of six rows of prominent stitching, with typically 60-80 stitches in each row (primary seam). The seam is along the "equator" of the two-hemisphere ball. Better quality balls are made of 4 pieces of leather so that each hemisphere has a line of internal stitching forming the "secondary seam". The secondary seams of the two hemispheres are at right angles to each other (Fig.-6).

Normal Swing : Fast bowlers make judicious use of the primary seam to swing the ball. Normal swing is achieved by keeping one side of the ball polished smooth and shiny, and delivering the ball with the polished side forward, and the seam angled in the direction of desired swing. The leading part of the ball is covered by a film of fast moving air, called the boundary layer. About halfway round the ball, the boundary layer separates from the surface. On the non-seam side the boundary layer peels away before the halfway mark. But on the seam side the flow is disrupted by the protuberance of the seam, the boundary layer is tripped into a chaotic turbulence and peels away after the halfway mark. The effect is to make the air pressure on the seam side of the ball lower and this pushes the ball towards the seam side, away from the batsman. Fig.-7 shows the standard outswinger; for the inswinging delivery the ball is reversed, with the seam pointing to the leg-side. This delivery requires a different action to the outswinger, allowing the (good) batsman to recognize the deliveries as they are delivered. These deliveries, particularly the outswinger, are the bread and butter of opening bowlers who get to use the ball while it is still new.

Contrary to intuition and popular belief, the swing is not primarily due to the difference in friction caused by the rough and smooth sides of the ball - although it is this difference that helps generate turbulent flow on one side and laminar flow on the other. For a blunt object like a sphere, the main contributor to aerodynamic drag is the point of separation of the boundary layer, and turbulent flow holds the layer on to the surface longer, reducing the pressure on that side of the ball. This is the same principal that allows a dimpled golf ball to fly further than a smooth one. In this case the dimples promote turbulent flow, which reduces the pressure drop behind the golf-ball, thus reducing drag. The ideal ball for normal swing is highly polished on one side with a prominent seam delivered at an angle of about 20° to the direction of flight, and with about 11 revolution/second spin about an axis perpendicular to the seam.

Reverse Swing: Reverse swing is very different to conventional swing. Although the seam is oriented in the same way as for an outswinger and the action is the same, the rough side of the ball is to the fore, and the ball moves in to the batsman like an inswinger. Reverse swing is achieved when the ball is bowled very fast. In this case the airflow will become turbulent on both sides before it reaches the seam (Fig.-8). With a turbulent boundary layer on both sides of the ball, the effect of the seam is reversed. It now acts as a ramp, pushing the turbulent air away from the ball and causing the boundary layer to peel away sooner. That makes the pressure on that side higher, forcing the ball to swing towards the batsman.

To get reverse swing with a new ball, smooth on both sides, experiments show that the bowler has to reach 130-140 km/hour to get appreciable movement. This kind of speed has only ever been achieved consistently by the genuine fast bowlers. At his best, Pakistani left arm pacer Wasim Akram was often credited as the first to produce reverse swing, and he had been followed by other fast bowlers like Waqar Yunis, Shoaib Akhtar, Brett Lee and Irfan Pathan. A scuffed ball however can generate substantial reverse swing at speeds well within the capabilities of any medium-paced bowler.

The ideal ball for reverse swing has one side rough, the other smooth, with a prominent seam in between. The seam should be angled at about 15° to the direction of flight, pointing *away* from the desired direction of movement. The ball can then be swung both into and away from the batsman depending solely on which side of the ball is delivered at the front generating either normal or reverse swing. Because the bowler does not need to change either his grip or his action, the batsman will have no clue which way the ball is likely to move.

There is no simple linear relationship between the speed of delivery and the amount of sideways movement for conventional swing. Up to a certain limit- dependent of the atmospheric conditions and the condition of the ball- the amount of swing increases with the speed of delivery. As the ball's speed increases past this limit however turbulence will start to develop on the shiny side reducing the net side force. This is why medium pace bowlers can often generate more swing than fast bowlers. If the ball is bowled even faster still, the turbulence may begin *before* the seam causing reverse swing! (Turbulence is initiated at the *back* of the ball and moves forward as the speed increases).

A prominent seam obviously helps the laminar to turbulence transition process, whereas a smooth and polished surface on the non-seam side helps maintain a laminar boundary layer.

Study reveals that the two-piece ball is in general found to have better swing properties than the four-piece ball[6]. The secondary seam serves as an effective roughness that helps to cause transition of the laminar boundary layer on the non-seam side. Barton[7] concluded that the ball with a more pronounced seam than average (> 1mm) swung more.

Bentley et al.[8] found that the seam on all new balls is efficient at tripping the boundary layer in the speed range $15 < u < 30$ m/s (i.e., $54 < u < 108$ km/hr). The swing properties obviously deteriorate with age as the seam is worn and the surface scarred. For that matter the spin or rotation of the ball is not theoretically necessary for swing!

[**Note to non-cricket savvy people:** the ball in cricket is only replaced after a minimum fixed number of overs (deliveries if you will) have been bowled. So the wear and tear is a natural consequence of the game. Only "natural" sources like spit and saliva may be used in maintaining the shine on the ball - usually achieved by polishing the ball on clothing. No means of scuffing the ball may be used. Rolling the ball on the ground is legal.]

The two parameters that a bowler can control to some extent are the ball seam angle and the spin rate. The optimum seam angle for $u = 30$ m/s is about 20°. At lower speeds (especially for $u<15$ m/s) a bowler should select a larger seam angle than 30°, so that by the time the flow accelerates around the seam, the critical speed has been reached. It is better not to trip the boundary layer too early (low angle), since the turbulent boundary layer grows at a faster rate and will therefore separate relatively early (compared with a later tripping). At the same time, the seam angle should not be so large that the boundary layer separates before reaching the seam, since this would result in symmetrical separation on the ball and hence zero size force. In a case like this, if transition occurs in the boundary layer upstream of the seam, then the effect of the seam will be to act as a boundary layer 'fence' that thickens the boundary layer even further. This asymmetry would lead to a negative side force for post critical Reynolds numbers. This effect can be produced even at low seam angles by inducing early transition of the laminar boundary layer through an increase of the free-stream turbulence.

Spin on the ball helps stabilize the ball's seam orientation. Too much spin is detrimental since the effective roughness on the ball's surface is increased. This is more relevant at higher speeds ($u>25$ m/s). Barton's results indicate that the optimal spin rate is 5 rev/s, whereas Bentley et al.'s results indicate a much higher rate of 11 rev/s. These anomalies are considered to be due to differences in experimental setups. In practice, a bowler can impart up to 14 rev/s though it is not very easy to control.

Effect of weather conditions : This has got to be one of the most discussed aspects of cricket. It is a common belief that balls swing more in humid weather conditions, but there is no scientific proof of this! The flow pattern around the cricket ball depends on the properties of the air and the ball itself. The only properties of air affected by weather conditions are density and viscosity. These will influence the Reynolds number. However, Bentley et al.[8] found that the average changes in temperature and humidity encountered in a day only affect the Reynolds number to the tune of 2%. Several measurements have been made of the effect of humidity, and even wetness of the ball (due to condensation etc.) and no significant changes have been measured under laboratory conditions. Does the dampness make the ball tackier and hence enable the bowler to impart a better spin rate? This was the untested hypothesis of Bentley et al. This aspect of cricket ball aerodynamics remains a mystery till date.

Baseball:

This is perhaps the hardest pitch to master. Not just for a pitcher, but for an aerodynamicist as well. Some believe that a baseball thrown without any spin will be at the mercy of any passing breeze. And thus, dances through the air in an unpredictable fashion. However, the most likely reason for the 'dance' of a baseball is a very slow spin. Researchers have learned that a slight change in the orientation of the ball with respect to the flow of air results in dramatic changes in the forces acting on the ball. Not only does the magnitude of the force change, but the direction also changes. This is why the ball appears to 'dance'.

The mechanism by which the forces change magnitude and direction is not known. However, one can theorize that the stitches play a key role. The stitches will most likely cause the boundary layer to trip to a turbulent state (Fig.-9). As we know, turbulent flow will stay attached longer than laminar flow. In fact, once the boundary layer becomes turbulent, a separated flow tends to reattach. This reattachment will dramatically alter the forces on the ball. Similarly, as the ball rotates, a region that was turbulent due to the position of the stitches, might now become laminar. The laminar flow will separate earlier than the turbulent flow. This altering of the state of the flow from laminar to turbulent, separated to attached, would cause the forces on the ball to fluctuate as shown by the experiments.

Furthermore, it is important to note that even if the pitcher throws the ball with no rotation, the flow asymmetry will cause the ball to rotate. The flow asymmetry is developed by the stitch pattern on a baseball.

Tennis Ball:

The movement of the air around an object creates lift. On an airplane or a bird, most of the lift is created as air moves over the wing's unique shape. Spinning the sports ball creates lift. The word 'lift' is a little misleading, because one meaning of the word is 'to rise'. Normally, on an airplane or bird that means moving 'up'. Lift is a force, which has a very specific definition and does not always mean 'up'. For example, racecar designers create wing-like surfaces on the car to generate 'negative lift', a downward-directed force. This force and the weight of the racecar, help the driver maintain control on high-speed curves of a racetrack.

A tennis ball can spin in many directions (Fig.-10). Relative to the ball, in ***topspin*** the top of the ball spins forward (top to bottom) into the oncoming air. For backspin the bottom of the ball spins backward (bottom to top). Balls can also have sidespin. Some sports have special terms for different types of spin. For an instance, in volleyball a serve hit with no spin is called ***flat***, while in baseball a pitch with no spin is called a ***knuckleball***. In tennis, backspin is called ***underspin***. In golf and tennis, a ball hit with sidespin is referred to as a ***slice.***

Here are photographs taken in a wind tunnel. A wind tunnel is a device that engineers use to calculate the forces a gas, like air, creates on an object. In this particular test, smoke was blown over a tennis ball and you are able to see the pattern the air made as it moved over the ball.

In the Fig.-11, the ball is not spinning. Look at the wake on the right side of the photograph, which is right behind the ball. Since there is no spin, the wake is not directed up or down - so there is practically no lift!

In Fig.-12, the ball is spinning with topspin. Look at the wake on the right side of this photo. It is seen that the air is moving upwards at an angle. The air is applying an upward force on the back of the ball. Remembering Newton's third law of motion, this means that the ball will be forced down. Topspin pulls the ball down faster - its lift is in the negative direction.

In Fig.-13, the ball is spinning with backspin. The wake on the right side of the photo is directed down. This means the ball will be forced up.

For the athlete this means that a ball struck or thrown with a certain amount of force, the ball with backspin will go farther than a flat or topspin ball. The ball with backspin is lifted up in the air higher than a ball hit with the same amount of force using topspin or with no spin. Likewise, a ball with no spin will travel farther than a ball hit with topspin. Tennis and volleyball players make use of this fact when they serve. To make sure that the ball does not up too far or outside the court lines, they will serve with topspin since it will not go as far as a ball with backspin or no spin.

References

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[6] Mehta, Rabindra D., *"Aerodynamics of sports balls"*, Annual Reviews of Fluid Mechanics, 1985. 17: pp. 151-189.

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[8] Bentley, K., Varty, P., Proudlove, M., Mehta, R. D., *"An experimental study of cricket ball swing"*, Aero. Tech. Note 82-106, Imperial College, London, England, 1982.

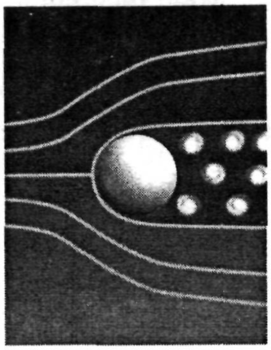

Fig. 1: Laminar flow over a sphere.

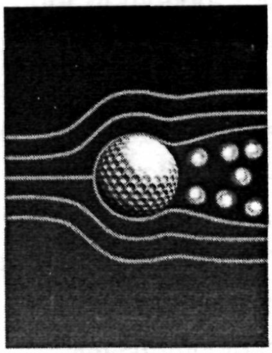

Fig. 2: Turbulent flow over a sphere.

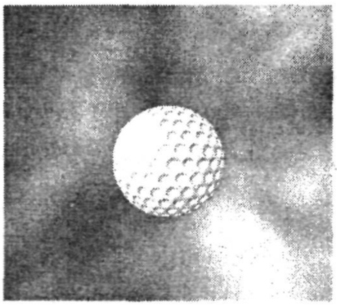

Fig. 3: Golf ball with round dimples.

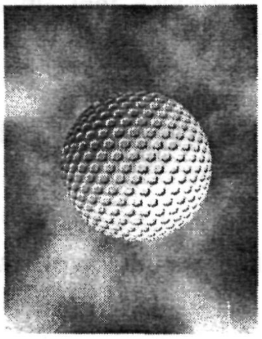

Fig. 4: Turbulent flow with hexagonal dimples.

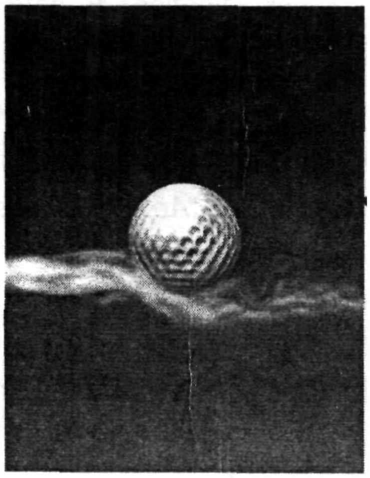

Fig. 5: Smoke flow patterns over a spinning sphere

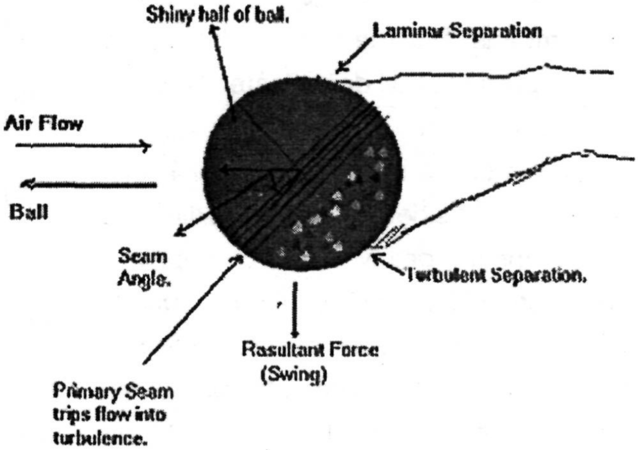

Fig. 6 Movement of a Cricket ball.[1]

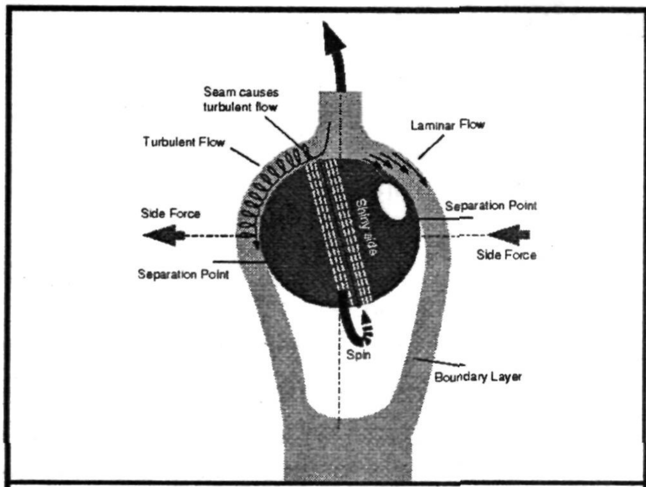

Fig. 7: Normal swing (an outswinger)

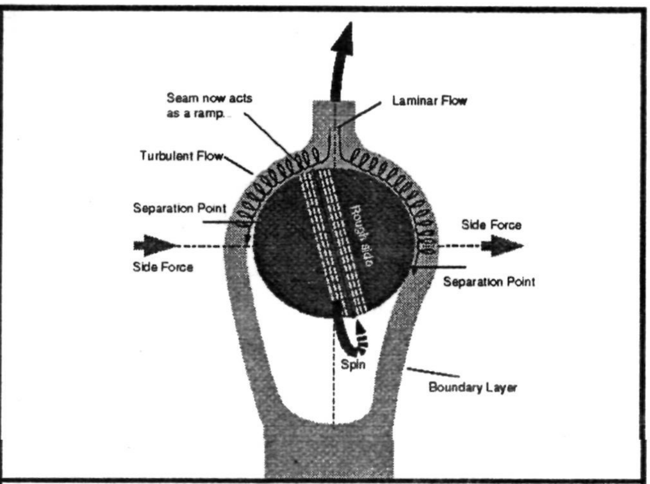

Fig. 8: Reverse swing (an inswinger)

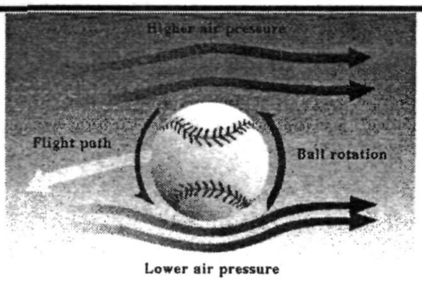

Fig. 9: Flow around a Baseball

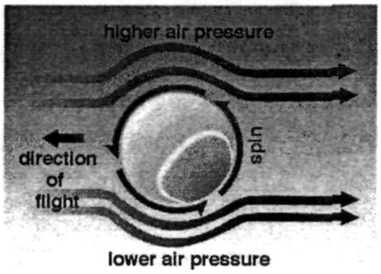

Fig. 10: Spin produced in a rotating tennis ball

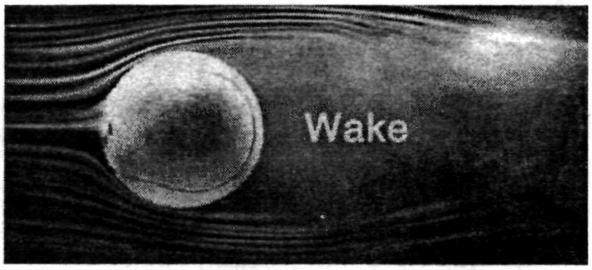

Fig. 11: Tennis ball with no spin

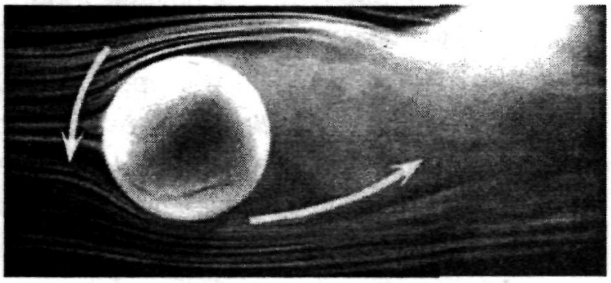

Fig. 12: Tennis ball with topspin

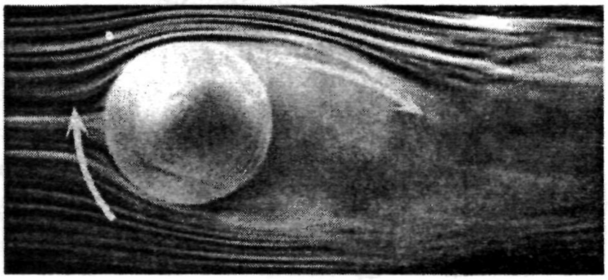

Fig. 13: Tennis ball with backspin (underspin)