A CONCISE REVIEW OF MODERN RESEARCHES INTO AERODYNAMICS OF SOCCER BALL

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Review paper

Abstract

A concise review of a recent research on the aerodynamics of soccer ball is being presented here. In this review we are going to take a glance at the most important studies done by the best and prominent researchers. This review is useful for students who are interested in sports engineering and are just beginning careers in sports aerodynamics. Basic aerodynamic principles and methods, some of the important factors, knuckling effect and aerodynamic drags of different soccer balls are going to be discussed here.

Key words*: Aerodynamics, soccer ball, wind tunnel, trajectory analysis, flow visualization, knuckling effect.*

Introduction

It is no surprise that the world's most popular sport is soccer which owes its popularity to needing only inexpensive and simple equipment to play. Soccer is played in every corner of the world with every kind of weather condition or culture and everyone can play it from all walks of life. Because of these reasons there is a financial strength in soccer. Therefore all factors of this sport hold a significant level of importance such as the field, soccer ball, shirts, gloves etc. In soccer, the flight trajectory of a ball is the center piece of the game and it's under the effect of its aerodynamic properties (Alam et al., 2014). This ball among all sport balls has better aerodynamic properties and balance (Alam et al., 2011) and has undergone a lot of technological changes since 1970's. In recent years modern balls with lower panels replaced conventional balls with 32 panels and their structures completely changed. All of these evolutions are just to promote the technical level of soccer. Therefore with due attention to the evolution of the soccer ball especially within the past four world cup competitions, many researchers have done a lot of studies on the aerodynamics of a soccer ball and wrote some useful reviews such as the newest review of Goff (2013). There are also two general and fruitful books (Wesson, 2002; Nørstrud, 2008; Goff, 2010) available for students who has just begun their research on soccer ball. The purpose of this review article is to acquaint students and researchers with some of the important studies about soccer ball aerodynamics and give comprehensive conclusion remarks to them. This article is organized as the following: Section 2 introduces the basic principles of smooth sphere and a soccer ball. Sect.3 belongs to some important factors about panel designs and panel orientations. Sect.4 belongs to the knuckling effect and aerodynamic characteristics of different soccer balls are being discussed in Sect. 5 and in Sect. 6 article finishes with conclusion remarks.

Basic principles

The first step in order to understand the aerodynamic behavior of a soccer ball or any spherical sports projectile is to understand the fundamental aerodynamics of a smooth sphere. In 2001, Froes and Haake edited a review on the sports ball properties which has a simple language to understand and also included a rich definition on basics in smooth sphere (Mehta & Pallis, 2001). So let’s take a look at the aerodynamic characteristics of a sphere through the air. As the flow accelerate around the front of the sphere, the surface pressure decreases until a maximum velocity and minimum pressure are achieved half way around the sphere. At the same time the reverse occurs over the back part of it so that the velocity decreases and the pressure (adverse pressure gradient) increases (Mehta & Pallis, 2001). The boundary layer (A thin region of air near the surface of a sphere) cannot negotiate the adverse pressure gradient and it will "separate" from the surface (Mehta & Pallis, 2001). The pressure becomes constant once the boundary layer has separated and a drag force generates due to the pressure differences between the front and back of the sphere (Mehta & Pallis, 2001). Note that the boundary layer has two states: "laminar" and "turbulent" (Mehta & Pallis, 2001). The turbulent layer has higher momentum near the surface compared to the laminar layer. Therefore it's better able to withstand the adverse pressure gradient over the back of the sphere and separates relatively late compared to a laminar layer (Mehta & Pallis, 2001). This results in "wake" behind the ball and thus less drag (Mehta & Pallis, 2001). There is also a book (White, 2011) that is perfect for understanding the basic fluid mechanics principles. The "transition" from a laminar to turbulent boundary layer occurs when a critical Reynolds number is achieved (Mehta & Pallis, 2001). The Reynolds number is a qualitative comparison of a fluid's inertia to its viscosity (Goff, 2013). The Reynolds number, R_e, given by Goff (2013).

$$R_e = VD/v \quad (1)$$

Where V is object's speed for sport balls, D is simply the ball's diameter and v is the kinematic viscosity (Goff, 2013). The flow over a sphere can be divided into four regimes that are shown in figure 1 (Mehta & Pallis, 2001).

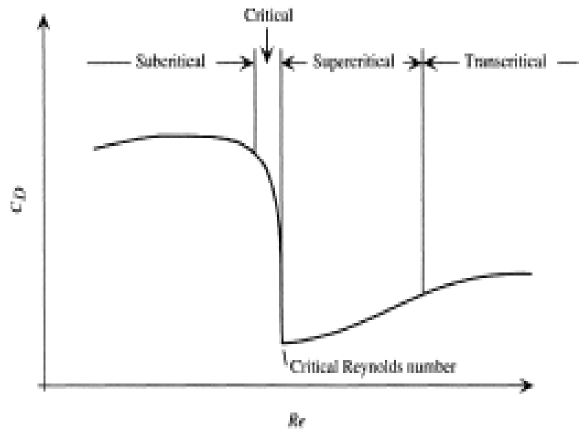

Fig. 1. Flow regimes on a sphere (Mehta & Pallis, 2001).

Earlier transition of the boundary layer can be induced by "tripping" the laminar boundary layer using a surface roughness (Mehta & Pallis, 2001) such as the panels on a soccer ball. It can be concluded that the critical Reynolds number decreases as the surface roughness increases. Fig.2 shows how panels (surface roughness) can change the manners, and also indicated that the aerodynamic characteristics of a soccer ball were intermediate between those of a smooth ball and a golf ball (Goff, 2013).

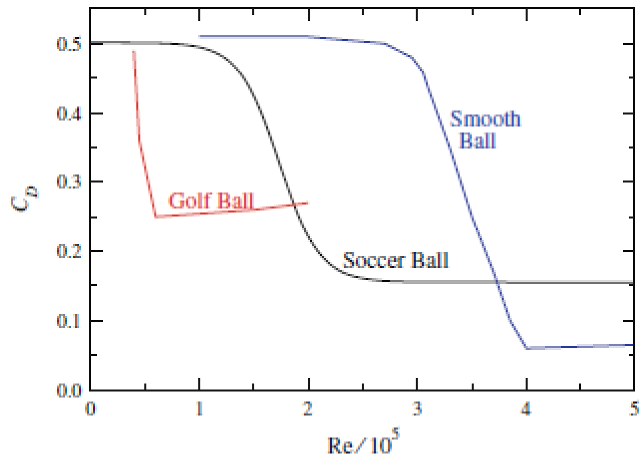

Fig. 2. C_D as a function of R_e for a smooth sphere, a soccer ball and a golf ball (Goff, 2013).

The drag force is one of the important factors of the aerodynamic behaviors. It can slow down the sphere and should be measured in the experiments as a first effort. The magnitude of drag force is given by Goff (2013).

$$F_D = \frac{1}{2} C_D \rho A v^2 \quad (2)$$

Where C_D is the dimensionless drag coefficient, ρ is air density (1.225 kg/m^3 at 15 C at sea level), A is the projectile's cross-sectional area and v is the projectiles speed (Goff, 2013). For the smooth sphere, the C_D in the sub-critical regime is about 0.5 and the critical Re of about 400000 the C_D drops to a minimum of about 0.07, before increasing again in the super-critical regime (Mehta & Pallis, 2001). As mentioned before, with increasing the surface roughness such as the panels on a soccer ball, C_D and Recrit, both decreases. Therefore we can see that the panels and their designs are so important in the flight of a ball. In the soccer ball experiments with the exception of the F_D and Reynolds number, some other forces and parameters should be measured. While spinning, the ball causes the air to asymmetrically whip down off the back side of the ball (Goff, 2013). According to Newton's 3rd law, there is an upward force component called the Magnus force or lift force. F_L is given by Goff (2013).

$$F_L = \frac{1}{2} C_L \rho A v^2 \quad (3)$$

Where C_L is the dimensionless lift coefficient. But there is a problem with this equation. Lift coefficient like C_D, depends on the projectile's speed, spin rate and surface properties (Goff, 2013). Whereas the eq.3 is useful for the study of fixed objects such as air plane wings, the effect of the rotation, which is what gives rise to the Magnus effect, is hidden in C_L. Some researchers like Asai et al. (2007) prefer to have the projectile's spin rate. This is done by defining a new dimensionless lift coefficient as Goff (2013).

$$C_L' = \frac{Cl}{Sp} \quad (4)$$

Where the dimensionless spin parameter is given by Goff (2013).

$$S_P = \frac{r\omega}{v}$$
(5)

r is the ball radius. The alternate lift equation then becomes Goff (2013).

$$F_L = \frac{1}{2} C_L' \rho r \omega A v$$
(6)

As mentioned, in the soccer ball or any sports projectile studies we should measure these parameters.

In the soccer ball, when the boundary layer undergoes the transition from laminar to turbulent flow, a drag crisis occurs whereby the C_D rapidly decreases (Asai et al., 2007). A study by the Japanese group, showed a visualization of the flow around a soccer ball in non-spinning and spinning states. They also measured the *Recrit* of soccer ball ranged from 220000 to 300000 with wind tunnel testing (Asai et al., 2007). As a result, they found that the *Recrit* of the soccer balls were lower than the smooth sphere (350000 to 400000) (White, 2011). With their visualization experiments, they found that in the non-spinning and spinning soccer balls, the wake varied over the time (Asai et al., 2007) and in both states, C_D drops in the super-critical region and the separation point shrank (Asai et al., 2007). Note that they have done their study on a conventional ball (Adidas Fevernova), and modern balls (Adidas Roteiro, Adidas Teamgeist).

Fig.3 shows a ball that is in flight in the sub-critical region. Whereas after the high velocity kick in fig.4, the ball is in flight in the super-critical region. They also visualized a vortex path way of a non-rotating soccer ball using titanium tetra chloride (Asai et al., 2007). In fig.5 we can see a large scale undulation in the no-rotating ball vortex.

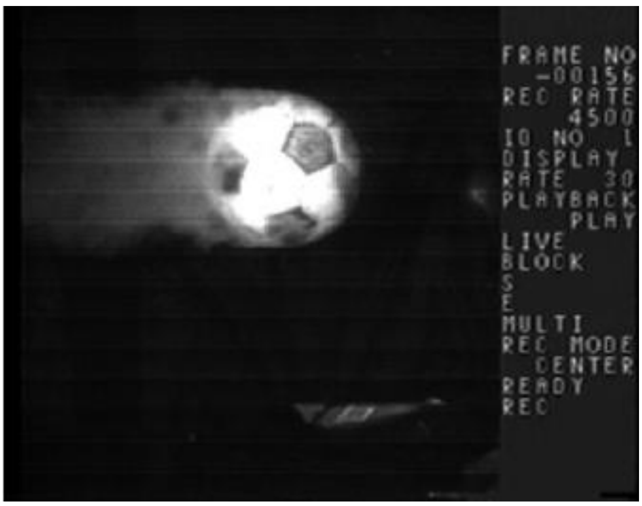

Fig. 3. Visualization of the flow around the ball after a low velocity kick (5m/s).the boundary layer separation point was ~90 from the front stagnation point (Asai et al., 2007).

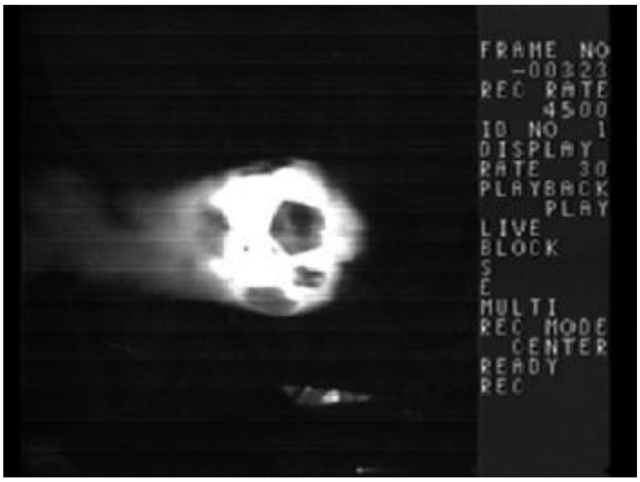

Fig. 4. Visualization of the flow around the ball after a high-velocity kick (29m/s).the boundary layer separation point receded to ~120 from the front stagnation point (Asai et al., 2007).

Fig. 5. Vortex path way for a no-rotating ball viewed from a wide angle (Asai et al., 2007).

According to the wind tunnel experiments, they found that the C_D in the no-rotating ball was about ~0.43 in the sub-critical regime and ~0.15 in the super-critical regime. This experiment also showed that the C_D and C_S (side force) both increased as S_P increased (Asai et al., 2007).

As mentioned before, we considered two important methods, wind tunnel testing and visualization experiment. These approaches besides the trajectory analysis are really vital and also useful for the study of a soccer ball, but they have their own difficulties especially in wind tunnel testing, such as: their relatively large size requires a large wind tunnel with a sensitive force balance; their pressurized air-filled state results in mounting difficulties, especially at various orientations in different ranges; the small details of their surface geometry require very accurate measurements (Barber et al., 2007). Furthermore visualization experiment needs high speed video cameras. In recent years, improvements in computer power, has allowed researchers to study about a soccer ball or any object that moves through the fluid, such as finite-element method or CFD method. Finite-element method is quite new and has not made significant strides into sports research (Goff, 2013). In recent years CFD method has become a major research tool for those interested in aerodynamics in sport because of its available commercial codes (Goff, 2013). Researchers can determine aerodynamic coefficients like C_D and C_L and they also can visualize flows (Goff, 2013). Small budget is one of the important advantages of the CFD method. Sometimes building an appropriate wind tunnel is very expensive and is not possible. In the other sections we consider some studies using CFD methods. Note that a soccer ball analysis with CFD needs high computational skills and in some aspects this method depends on progress in software.

Effects of panel designs and panel orientations

What follows is a concise review of a recent research on aerodynamic of a soccer ball. Therefore with this paper, young investigators and students can access references for more details. A study has been done by a group in 2008 (Barber et al., 2007) in order to measure the effects of surface geometry and orientation on the flight trajectory using wind tunnel tests and oil flow visualization. They tested different Reynolds numbers and soccer balls in their study. Actually they tried to present a new method for the detailed aerodynamics study of a soccer ball. As a result, they found that a ball with smooth surface and fewer seams would travel faster at high *Re* and suddenly changes the path of the flight and a ball with smaller, bonded seams travels far and fast when kicked with a mid-range R_e. As well as the ball with significant surface roughness like old balls with 32 panels, experiences the trans-critical region and would slow down more than the other balls because of their higher C_D in this region and therefore travel less distance. One of the most important findings of this study is the seam alignments and their proportions.In other words more seams alignment cause the ball suddenly to drop towards the end of flight and less alignment causes the ball to have a low C_D at high R_e , besides greater proportion of aligned seams caused the ball to move faster at high R_e. Recent works (Asai & Seo, 2013) have been done on modern balls in order to recognize the effects of the surface roughness in the flight of a ball. They also measured the aerodynamic drag of modern balls using wind tunnel and also the flight trajectory simulation. They tested four different soccer balls. The main purpose of this study was to measure the extended total distances of panel bonds using a curvimeter. The number of ball panels and the extended total distances of the panel bonds were: Adidas Roteiro: smooth surface with 32 pentagonal and hexagonal panels, 3840 mm; Adidas Teamgeist II: small protuberance with 14 panels, 3470 mm; Adidas Jabulani: small ridges with 8 panels, 1980 mm; and Adidas Tango 12: small grip texture with 32 panels, 4470 mm. with these measurements, high correlation was observed between the extended total distance of panel bonds and the critical Reynolds number. Fig.6 shows a correlation between these parameters.

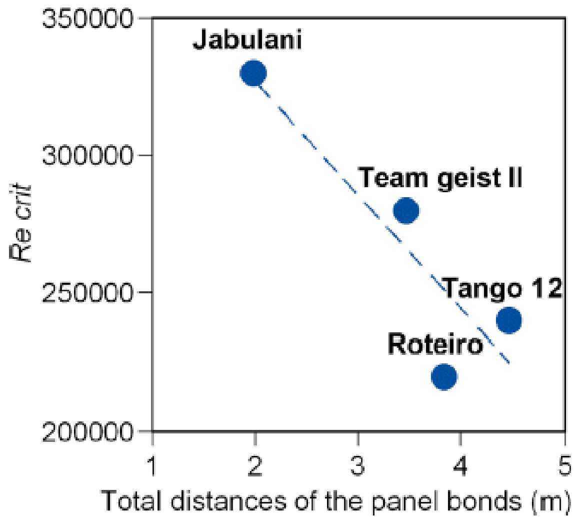

Fig. 6. Correlation between the extended total distances of the panel bonds and the critical Reynolds number (Asai & Seo, 2013).

We know that the critical Reynolds number decreases with increasing the surface roughness. In this study researchers found that the critical Reynolds number for the Roteiro (*Recrit* ~ 220000) was lower than the Jabulani (*Recrit* ~ 330000) despite the panel surface of the Roteiro being relatively smoother than that of the Jabulani. Therefore they concluded that the "small designs" on the soccer ball panels play a small role and the critical Reynolds number depends on the extended total distance of the panel bonds. Fig.7 shows the surface of soccer balls used in the experiment. In the sect.5 we are going to consider the other findings of this study.

Fig. 7. Photographs of soccer balls. (a) Adidas Roteiro with 32 pentagonal and hexagonal panels. (b) Adidas TeamgeistII : small protuberance with 14 panels. (c) Adidas Jabulani: small ridges with 8 panels. (d) Adidas Tango 12: small grip texture with 32 modified panels (Asai & Seo, 2013).

Following studies in this regard, an experiment was done in 2014 (Hong et al., 2014) which led to important findings. The group has done their study in more details compared to the formers, using wind tunnel tests and also kicking robot. In this study they considered different soccer balls with different panel shapes and numbers. Their focus was to clarify the influence of the panel shapes and orientations in the flight of a ball. Fig.8 shows the soccer balls used in this study with different orientations. In this experiment one of the newest balls named Cafusa with 32 modified panels was one of the experimental subjects.

Fig. 8. The soccer balls used in the test panel orientations of respective soccer balls. (a,b,c) Adidas Cafusa: small grip texture with 32 modified panels; (d,e) Adidas Jabulani: small ridges or protrusions with 8 panels; (f,g) Adidas Teamgeist II: small protuberances with 14 panels; (h,i) Molten Vantaggio (conventional ball): smooth surface with 32 pentagonal and hexagonal panels (Hong et al., 2014).

Aerodynamic forces were measured when the panel orientation was changed by rotating the same panel. And also the flight characteristics of the balls were investigated by the points of impact on a goal net using the impact-type kick robot. Their results divided into three sections. First of all they measured the drag force of the soccer balls with various panel orientations in the wind tunnel. With this test they found that the drag variations of the Cafusa and Jabulani balls changed when their panel orientations were varied. In fig.9 we can see how panel orientations of the balls affect the drag coefficient.

After that they measured the side and lift force of the balls when the panel orientation was changed. The results indicated that the irregular fluctuations increase as the flow velocity increases from 20m/s to 30m/s even when the ball panel orientation was changed. The irregular fluctuations were observed more or less in all balls. Fig.10 shows scatter diagrams of the lift and side forces with changing the panel orientations.

Analyzing the impact point of the balls in the kicking robot was the third part of the study. In this part, actual balls were launched by the robot and the points where the balls hit the goal net are plotted as the points of impact in fig.11. The results indicated that the conventional ball showed relatively regular flight trajectory. While the modern balls like Cafusa, Teamgeist and Jabulani whose panel shapes vary drastically depending on the panel orientation relatively showed irregular flight trajectories even in the Cafusa ball having the same number of panels as the conventional ball (32 panels).

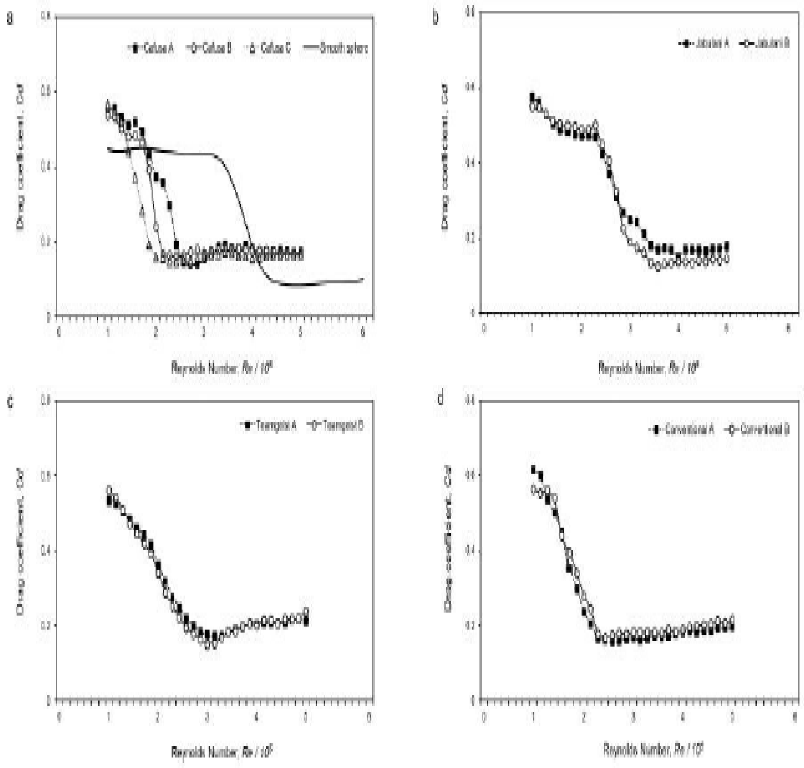

Fig. 9. Drag coefficient variation by balls and their panel orientation in modern soccer balls. a (Cafusa A,B and C); b(Jabulani A and B); c(Teamgeist A and B); and d(Conventional A and B) (Hong et al., 2014)

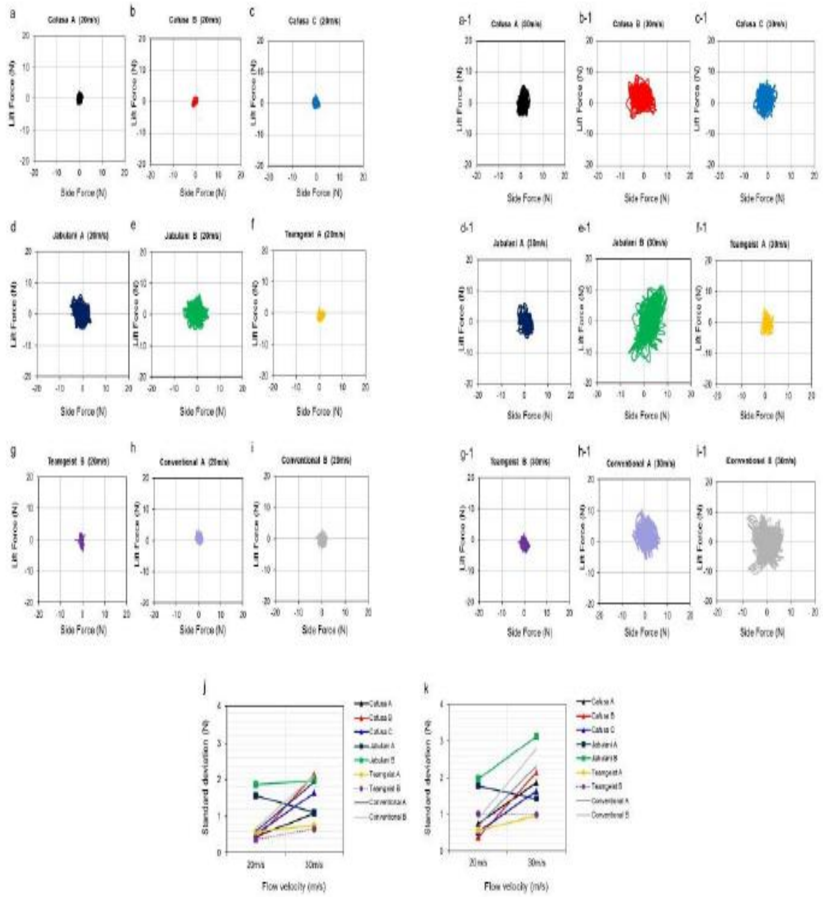

Fig. 10. Force scatter plots of the side and lift forces for the soccer balls. As the flow velocity increases from 20m/s (a-i) to 30m/s (a-1~i-1), the irregular fluctuations of the side and lift forces increase (Hong et al., 2014).

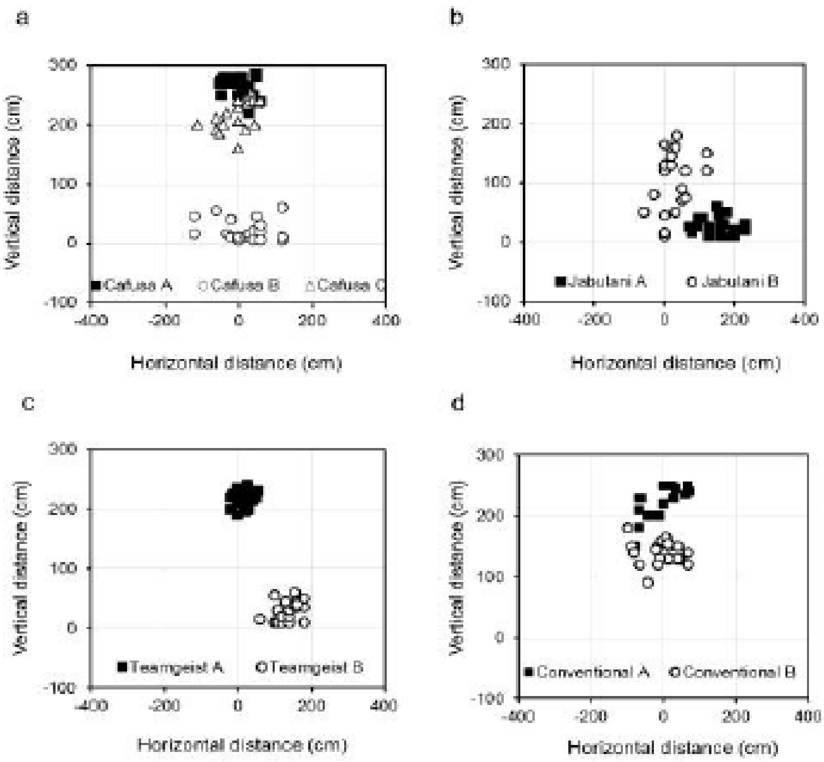

Fig. 11. comparison of flight characteristics (point of impact) by ball and their panel orientation in modern balls. a(Cafusa orientations A,B and C); b(Jabulani orientations A and B); c(Teamgeist orientations A and B); d(conventional ball orientations A and B) (Hong et al., 2014).

Therefore the group found that the panel shapes and orientation dramatically affect the ball trajectory rather than the number of panels on the ball. In 2015, a study was carried out in order to glean information about the influence of panels on the flight trajectory of the soccer balls. The group chose the Cafusa ball with 32 developed panels as the subject (Hong et al., 2015). The experiment has focused on the flow visualizations applied to the soccer ball through its three orientations by 2D-PIV. The kicking robot test was also one of the methods. Results of the kicking robot test showed changes in the flight trajectory of a ball in different panel faces. Therefore the group found that the orientation of a soccer ball can produce extreme changes in the flight trajectory of the ball and significantly affect its flight characteristics. However, the important finding of this study obtained from wind tunnel testing is the importance of considering the velocity vectors on the suction of the soccer balls that is shown in Fig. 12. The results showed that the separation point varied greatly depending on the orientation of the panels even in identical soccer balls. Also the type of seam on the surface of the soccer ball (such as the position, number and spacing) changes the air flow around it and affects the flight trajectory of the ball.

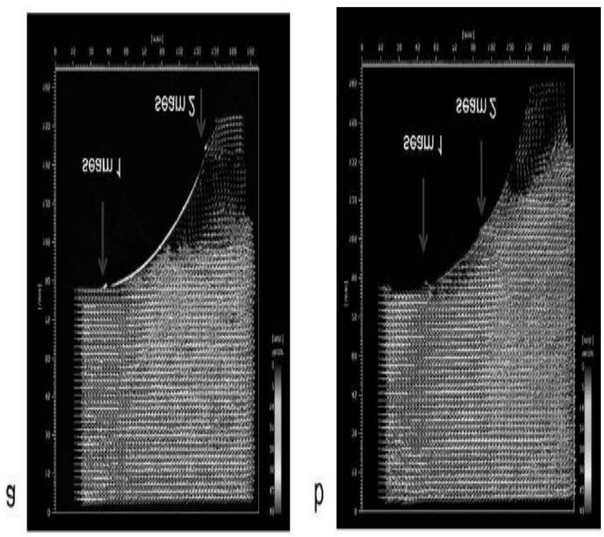

Fig. 12. Velocity vectors on the suction side of the soccer ball (Hong et al., 2015).

In 2016, researchers focused on the seam structure of the new generation of soccer balls. Therefore the main objective of their study was to understand the effects of the seam depth and seam height on the flight trajectory of four new soccer balls specially: Kopanya, Cafusa, Tango12 and Brazuca (Alam et al., 2016). The group also measured the aerodynamic drags of these balls using wind tunnel. Selected methods of the study were manual measurement (A rope for the seam length and plasticine for the seam depth) and 3D scanning technology. A variation between numerical and manual method in the measurement was observed. However, the group found that Brazuca and Kopanya have the minimal differences in C_D with different panel orientations at high speeds. This value was %5 for the Brazuca, %6 for the Tang12 ball, %9 for the Kopanya ball and finally %13 for the Cafusa ball. These results indicated that the Brazuca ball will have more stable flight due to its lowest variation in C_D and the the Cafusa ball can have unstable flight path due to its highest C_D variation. Also the Cafusa ball has the lowest aerodynamic drag at high speeds and it's suitable for long distance passes. However the group found that the seam depth and seam length affect the aerodynamic characteristics of soccer balls especially aerodynamic drag. With a larger seam length and depth, the flow around a ball becomes more complex because a larger seam and depth increase the surface roughness. More recently researchers have done a study on aerodynamic effects of dimples on soccer ball surfaces using wind tunnel experiment (Hong & Asai, 2017). Therefore the aerodynamic properties of different types of soccer balls (including different panel number and shapes and also different surface forms) were studies. They also conducted a 2D flight simulation to compare the effects of the drag coefficient of dimple-type ball and dimple-less balls on their flight distance and flight trajectory. The results showed that the pattern of the surface of a soccer ball is an important factor in aerodynamic properties of the ball in addition to the shape and number of panels. Because the aerodynamic force acting on the ball vary greatly depending on the dimples on the surface of the soccer ball. They also found that creating dimples on the surface of the soccer ball makes it possible to control the irregular movement of the ball in different directions to some extent. In the same year, a study was carried out by a group in order to determine the temperature effect on the body and performance of a soccer ball using ANSYS workbench (Rahman et al., 2017). They also determined the effects of stitching pattern of the ball on its flight. This study revealed that the temperature changes the behavior of the material properties of the soccer ball. Thus the stiffness of the ball materials decreased as the temperature increased and so does the maximum deformation. On the other hand, the ball is more rigid at colder temperature and so delivers a greater force at the surface of contact. Also, the investigation of the ball in flight showed that whether there is spin or not to a ball, where the foot comes in contact with the ball experiences a lower pressure than that of the opposite side which experiences a higher pressure. So the harder the ball is hit with curve the lower pressure causing the ball to fly through the air causing the ball to spin more in the direction it is moving. Again in a study was conducted in 2018 (Naito et al., 2018) focusing on the effects of seam characteristics (length, depth, and width) on critical Reynolds number in soccer balls using wind tunnel. In this experiment 10 most recent soccer balls were selected. The results of this research showed that the drag characteristics of a soccer ball is under effect not only by the panel shape but also the length, depth, and width of the seams. So they found that seam characteristics are important indicators of the ball surface roughness and have an important effect on critical Reynolds number, especially for depth. Thus these parameters may be important in predicting the critical Reynolds number of soccer balls.

Knuckling effect

Understanding the flight trajectory of non-spinning or slowly spinning balls is necessary in the modern games because they may fluctuate in unpredictable ways and affect the game and thus change its outcome. Therefore in this section we are going to discuss one important phenomenon that occurs in the non-spinning or slowly spinning soccer balls named "knuckling effect". One study was done in 2008 (Asai et al., 2008) about knuckling effect. Their focus was to discuss the magnitude and the frequency of the side force of non-spinning flight soccer ball by analyzing the high-speed video images of ball flight using the real place kicks. They were using the direct liner transformation method for obtaining three dimensional coordinates of ball position. Note that in this test, the group divided the kicks into two categories as the following: curve kicks due to the Magnus effect and knuckle balls due to the no-spinning balls. Their results indicated that the ball fluctuation occurs due to the knuckle effect around X=10~15m with a fluctuation amplitude of about 0.03m but there were no major fluctuations clearly on the flight of a curve ball under the influence of the Magnus effect. They also measured the side force on a ball experiencing the knuckle effect and found that the magnitude of the side force in real flight ranged from 1 N to 8 N. Note that the side force is one of the factors contributing to the knuckling effect. Next step was to measure the frequency of the side force in real flight. So they found that the frequency of this parameter in real flight ranged from 1.0 Hz to 3 Hz. The group also showed the variations in the side force and lift coefficients during flight in the Fig. 13. From the figure it's clear that the side force and lift coefficients exhibit a wider range of variation under the influence of the knuckle effect compared to the curve ball.

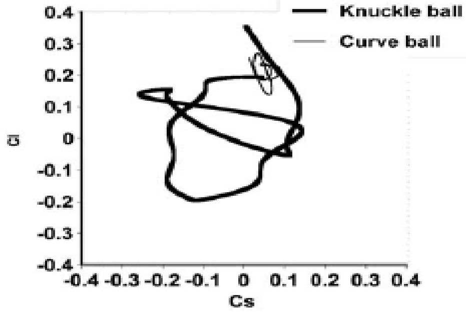

Fig.13. An example of unsteady side force coefficient versus unsteady lift coefficient during

flight on a knuckle ball and a curve ball (Asai et al., 2008).

There is also a study that has been done by a group (Asai et al., 2007) using CFD method. Their focus was to discuss the aerodynamic characteristics of soccer ball and visualization of the vortex structure around the real flight soccer ball in high Reynolds number. Actually they wanted to elucidate the knuckling effect with CFD approach. Because the knuckling effect is fundamentally a non-stationary phenomenon, they therefore analyzed the dynamics of the wake of no rotating soccer balls by non-stationary CFD using a combination of Large Eddy Simulation (LES) and a fluid visualization method using titanium tetrachloride in order to visualize the flow around the ball during flight. Results of the CFD method revealed that the lateral force coefficient has irregularly changed reaching a maximum of about 0.1, from about 0.1 s when the drag coefficient value began to stabilize (Fig.14).

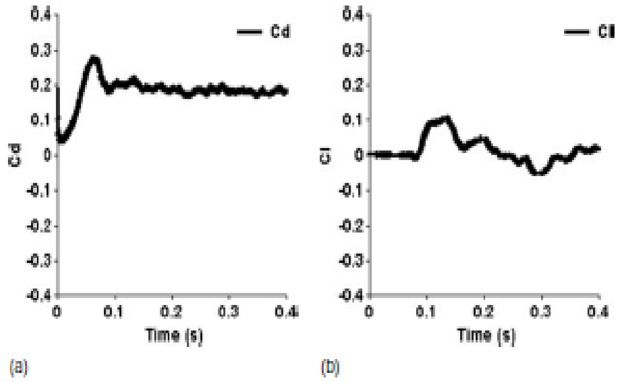

Fig.14. Drag coefficient vs time (a) and lift coefficient vs time (b) on CFD (Asai et al., 2007).

The examination of a high speed VTR camera image of non-rotating ball while in flight also revealed a slightly irregular vortex blob in the path of the ball. So the group calculated the Strouhal number and also from an image having a broad angle of view, the number of blobs was countered per unit of time. At the end of the study the group found that when the flow from the ball to a point in short distance away was examined, a near wake was observed but the slightly separated far wake was reduced. They also concluded that on the basis of calculating the frequency from a vortex blob, such as a vortex ring, directly after it occurs and the St is then estimated, the likely outcome would be a high mode value of about 1.0. Also after balls flight under effect a knuckling effect, large scale fluctuations of the vortex trail were observed when the St was between 0.1 and 0.01. There is a useful paper that is available in terms of the CFD method (Barber et al., 2009) and also a book (Barber & Carré, 2009) that has described CFD simulations in all sports. The soccer ball aerodynamics section is very comprehensive in this book. However, a study carried out in 2010 (Hong et al., 2010) in order to analyze the unsteady aerodynamic force on a soccer ball under the influence of the knuckling effect. The group has chosen the flight trajectory analysis using a high-speed video camera and the flow visualization using a smoke agent in order to investigating the dynamic behavior of the vortex in the trajectory. Note that in this test the knuckle balls compared with normal straight balls due to the instep kicks. They also measured the spin parameter (S_P) and the Strouhal number (St). Results included a number of important things: in the case of displacement, the change in the flight trajectory of knuckleball was evident and it was observed at the second half period of the ball flight. In terms of velocity, the knuckleballs showed an increase in the velocity forward to the lower direction. Also they found that the acceleration of the knuckleballs was affected by the gravity and it showed a large scale undulation. Comparison of the drag force and vortex lift force between the knuckleballs and straight balls showed that the knuckleballs have larger changes in their values (Fig.15).

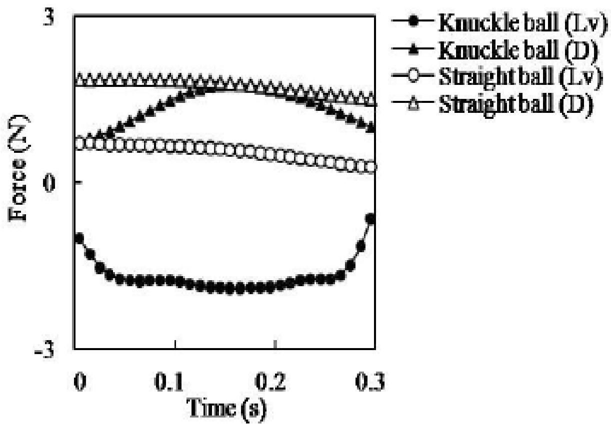

Fig.15. An example of lift and drag force acting on a knuckleball and a normal straight ball (Hong et al., 2010).

The drag coefficient of the knuckleballs also represented changes in their values. In addition, the lift coefficient of the knuckleball showed a larger value than the straight ball. Comparison of the vortex street of the knuckleballs and straight balls showed a large scale undulation in the knuckleballs but a small scale in its level of the straight ball trajectory. Visualization of the vortex using titanium tetra chloride allowed us to see differences between knuckleballs and normal straight balls (Fig.16).

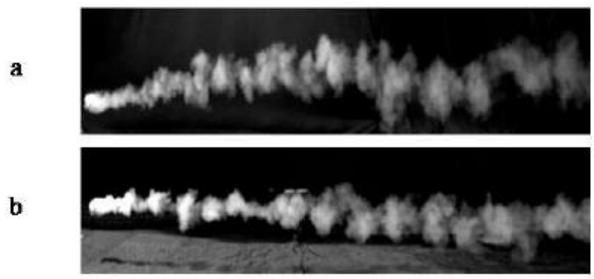

Fig.16. Comparison of the vortex street of a knuckleball (a) with that of a normal straight ball (b). A large scale undulation is evident in the knuckleball (Hong et al., 2010).

The last finding of this study belongs to the frequencies of the vortex lift force. The examinations showed that an average frequency of the vortex lift force was approximately 3.5 Hz. Also, a comparison of this frequency with the frequency of the vortex undulation indicated that these frequencies tended to act in unison with a high statistical correlation. As a general rule, note that in the case of the knuckleballs, the large scale fluctuation is evident that generates irregular forces applied to the soccer balls. Recently in 2016 (Goff et al., 2016) a group tested five non-spinning soccer balls (Brazuca, Cafusa, Jabulani, TeamgeistII and Vantaggio) in different panel orientations using wind Tunnel. Trajectory analysis was also carried out. The group reported a complete aerodynamics profile for two orientations of non-spinning soccer balls which are shown in figures below. The group found that the new panel texture of soccer balls helps roughen the surface enough to ensure a drag crisis consistent with older balls, the reduction in total seam length leads to a greater chance for asymmetric boundary layer separation, which means greater side and lift forces. But there is the exception that the Jabulani has a drag crisis at higher speeds than other balls. This experiment in non-spinning balls showed that the inclusion of side and lift forces creates lateral deflections in flight trajectories. This value obtained %10 of the horizontal range for the A orientation of Vantaggio and about %10 for the B orientation of Jabulani. All balls also showed range changes as large as about %10 for various launch speeds and orientations.

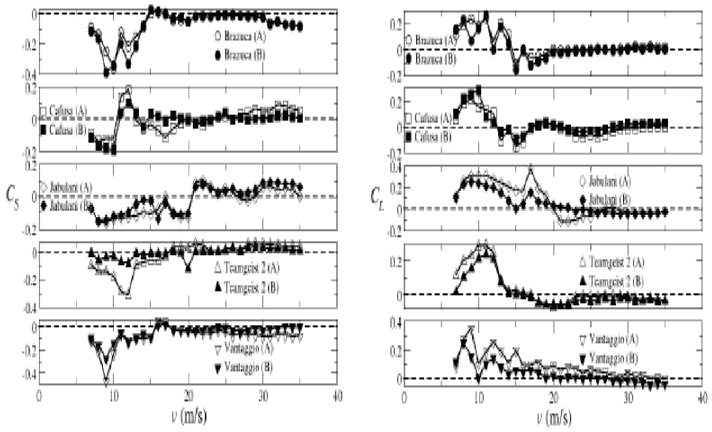

Fig.17. Speed-dependent side (left) and lift (right) coefficients for each of the two orientations of the five balls tested. Horizontal dashed lines show where C_S and C_L change sign (Goff et al., 2016).

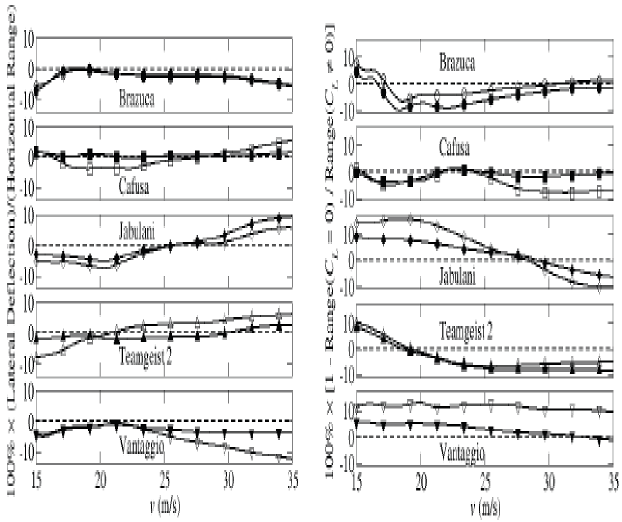

Fig.18. Lateral deflection as a percentage of horizontal range (left) and percent change in horizontal range for C_L = 0 (right) for each orientation of the five balls tested. The launch angle for all kicks was $\theta_0 = 25^{\circ}$. All vertical axes on the left run from -14% to 10%; those on the right run from 11% to 17% (Goff et al., 2016).

In 2016 (Hong et al., 2016) another study was carried out to measure the aerodynamic force on a soccer ball which is spun in wind tunnel test. The group specially prepared two types of spinning soccer balls (air and motor types) to measure the drag and side forces on a soccer ball in the wind tunnel and also examined the aerodynamic characteristics of the spinning soccer balls from the obtained aerodynamic force data. Afterwards, they compared the aerodynamic force on the two types of spinning soccer balls used in the tests and examined the validity of each measurement model. Results were divided into five sections that reported drag and side coefficient under spinning and non-spinning conditions for motor and air types. Although the drag values of the air and motor type spinning balls differed, the group found that this value linearly increased as S_P increased for both methods. But they obtained that the side force decreased in the low speed regions. Furthermore, in the case of the motor type spinning ball, they found that the side force in the medium speed regions displayed negative values. The methods of the tests used in this study showed that the results were greatly affected by the gap in the air type ball and the axle behind the motor type spinning balls. So the group couldn't compare these methods and just confirmed the individual characteristics of them. Recently in 2018 (Asai et al., 2018) a research has been done in order to investigate the aerodynamic characteristics of spinning and non-spinning soccer balls and analyze the dynamics of their vortex structures, using CFD and the Lattice Boltzman method which are developed recently. The results showed that the large scale fluctuation of the side force on the spinning ball is smaller than that for the non-spinning ball. Thus the spinning ball produces a more stable trajectory than the non-spinning ball.

Aerodynamic drag of different soccer balls

So far, we tried to take a look at the most prominent studies to explain the important factors of soccer balls. Although other sections referred to the characteristics of different balls frequently, this short section belongs to some studies that specially compared aerodynamic drag of different soccer balls. A study has been done (Alam et al., 2010) in order to compare two type of balls made of 32 panels (conventional ball) and 14 panels (modern ball) using wind tunnel and the flow visualization. The results showed that the C_D for the conventional ball has more fluctuation compared to the C_D value of the modern ball because of its more spherical characteristics than the conventional ball. Also they found that the C_D of a no-rotating ball is about 0.40 at low speeds and 0.23 at high speeds. Last finding of this study was that the conventional ball (32-panel) has slightly higher drag at high speeds compared to the modern balls. After that, a study was carried out in 2011 (Alam et al., 2011). It was focused on the Fevernova (32-panel), Teamgeist (14-panel) and Jabulani (8-panel) using wind tunnel. The average C_D values were measured as follows: Fevernova: 0.15; teamgeist: 0.19 and Jabulani: 0.21. It was found that the Fevernova and Teamgeist ball have an earlier flow transition compared to the Jabulani and smooth sphere. Also the Jabulani has a lower C_D value at high speeds over 60 km/h compared to the Teamgeist. C_D value for the Teamgeist is relatively lower at the medium-speeds (30-60 km/h). In addition they concluded that the variation of C_D value of two sides of Jabulani is around 5% and 7% more than the Teamgeist and Fevernova balls respectively. A study in 2012 (Asai et al., 2012) showed differences between the Jabulani with 8-panel and the Tango12 with developed 32-panels using wind tunnel. This experiment indicated that the high speed regime of the Tango12 is slightly lower than that of the Jabulani (A study only focused on these two balls). But in 2013, a study was done in more details with more balls (Asai & Seo, 2013) and several findings, one of which was referred to in Sect.3. In this test, the critical Reynolds number and the C_D were measured for each ball as follows: Roteiro (32-panel): 220000, C_D: ~0.12; TeamgeistII (14-panel): 280000, C_D: ~0.13; Jabulani (8-panel): 330000, C_D:~0.13; Tango12 (32-panel), C_D:~0.15; In addition they compared Jabulani ball with Tango12 ball and they found that the Tango12, has less air resistance in the medium-speed region than the Jabulani and can easily gather speed in the frequently used medium speed range, therefore this is relatively suitable for a passing-based game of soccer. One of the most recent studies with the subject "comparison of aerodynamic drag measurements" was done in 2014 (Alam et al., 2014). Their focus was to determine the aerodynamic drags of some balls which are less known and compare them with the modern world cup balls using wind tunnel test and the field trial. The selected soccer balls were as follows: Adidas Cafusa 2013, Mitre Ultimax 2012, Umbro Neo 2012, Nike Maxim 2012/2013, Adidas Jabulani 2010, Nike T90 2010, Adidas Teamgeist 2009, Adidas Teamgeist 2006, Adidas Fevernova 2002. Wind tunnel test results and measuring the C_D and Recrit for each ball indicated that the Adidas Cafusa maintains a lower C_D than the other balls and it possesses less surface disturbance because of its thermal bonding. Adidas Cafusa also has a lower C_D at trans-critical region than the Nike Maxim. The Mitre Ultimax has the lowest C_D prior to the super-critical region because of its complex surface roughness and also displays the similar behavior to that of the Cafusa after super-critical and trans-critical regions. The Umbro Neo has a highest Reynolds number than the other balls due to its relatively smooth surface. Also the Nike T90 has an earlier flow transition due to its additional surface roughness. The group chose the field test to understand the player's perception about the balls and found that the Umbro Neo ball is relatively consistent and players can anticipate targets but most players prefer Adidas Cafusa and Nike Maxim as match balls because of their easier control and better stability. As the latest, in 2014 (Alam et al., 2014), researchers conducted a study on the aerodynamic drag of modern balls since 2002 using wind tunnel. They specially compared the Brazuca with other modern world cup balls. One of the attractions of this study was to evaluate the effects of altitude on the flight trajectory of the soccer balls. Results of the wind tunnel testing showed that the transition for Brazuca ball occurs shortly before Re=90000 and the flow becomes fully turbulent at Re=200000. They also found that the variation of drag coefficient between two sides of Jabulani is around 9% whereas the Brazuca ball has only 2% to 3%. In other words, the Brazuca ball will have a more predictable flight in calm air than its formers like the Jabulani and Teamgeist III balls. Also because of the 40% longer seams in the Brazuca than that of the Jabulani, the air flow becomes turbulent creating an early transition thus less aerodynamic drags at low speeds. In terms of the effects of altitude the study indicates that high altitudes will have significant effect on the balls aerodynamic drag in-flight speed because at high altitude, the air pressure, air temperature, and so the air density are lower and affecting the drag and lift of the ball. Therefore the ball can travel at a 5% higher speed on average in high altitudes compared to see level cities. However for obtaining more details about comparing the aerodynamic drag of the Jabulani and the Brazuca you can consider the 2014 paper (Goff et al., 2014) in this field.

Conclusion remarks

A concise review of the recent research has led to the following conclusions:

- The range of the critical Reynolds number for the smooth sphere is from 350000 to 400000 and the *Recrit* for the soccer balls ranged from 220000 to 300000.
- Increasing the surface roughness like panels on the soccer balls results in decreasing the *Cd* value and the *Recrit*.
- The C_D value of the no-rotating soccer balls in the sub-critical and super-critical regions is about 0.43 and 0.15 respectively.
- The C_D and C_S (side force) of the rotating balls depend on the S_P (spin parameter) and increases with increase of the S_P.
- A ball with smooth surface and fewer seams would travel faster at high *Re* and suddenly changes the path of the flight, while a ball with smaller, bonded seams travels far and fast when kicked with a mid-range R_e.
- An old ball has a higher C_D in the trans-critical region and slows down more than the other balls and travels less distance.
- More seam alignment causes the ball to drop suddenly toward the end of the flight, while less seam alignment causes the ball to have a low C_D at high R_e.
- The *Recrit* depends on the extended total distance of the panel bonds compared to the small designs on the panel surfaces.
- The panel shapes and orientations dramatically affect the ball trajectory rather than the number of panels on the soccer balls.
- The pattern of the surface of a soccer ball is an important factor in aerodynamic properties of the ball in addition to the shape and number of panels.
- Creating dimples on the surface of the soccer ball makes it possible to control the irregular movement of the ball in different directions to some extent.
- The separation point of the air around the soccer ball had a large variation depending on the position, number and spacing of the seams on it .This had an effect on the force applied to the ball and its flight trajectory.
- The seam depth and seam length affect the aerodynamic characteristics of soccer balls especially aerodynamic drag.
- With a larger seam length and depth, the flow around a ball becomes more complex because the larger seam and depth increases the surface roughness.
- Seam characteristics are important indicators of the ball surface roughness and have an important effect on critical Reynolds number, especially for depth.
- The new panel texture of soccer balls helps roughen the surface enough to ensure a drag crisis consistent with older balls, the reduction in total seam length leads greater chance for asymmetric boundary layer separation, which means greater side and lift forces.
- High altitudes affect the aerodynamic drag of soccer balls because the air pressure, air temperature and the air density are lower at high altitude compared to the sea level areas and thus causing the ball to travel higher and faster.
- The stiffness of the ball materials decreased as the temperature increased.
- In the knuckleballs large scale fluctuation is evident that generates irregular forces applied to the soccer balls, while there is no major undulation in the flight of a curve ball under the influence of the Magnus effect.
- The large scale fluctuation of the side force on the spinning ball is smaller than that for the non-spinning ball.
- The magnitude of the side force on a no-rotating balls (that generates the knuckleballs) ranged from 1 N to 8 N and its frequency ranged from 1 Hz to 3 Hz.

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