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Aerodynamics: A Tool to Achieve Glory in Speed Sports

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Abstract

Aerodynamics has a major impact on the performance of athletes and their sports equipment. Sports balls, sports garments and sports equipment- all are affected by aero/hydrodynamics as their speed, motion (position and placement) and ultimately performance are dictated by aero/hydrodynamics. As in all competitive sports, the winning margin is progressively reducing the gain achieved by understanding and utilizing the effect of aero/hydrodynamics has become a paramount. This paper reviews the latest aerodynamics advances in some popular sports including soccer, football, tennis, golf, and cricket, baseball, swimming and cycling.

Keywords: aerodynamics, hydrodynamics, sports balls, sports garments, swimming.

1. Introduction

Enhancement of performance has become a necessity for all speed sports today. Aerodynamics and hydrodynamics, technological advancement of equipment and sports gears, biomechanics, psychology, physiology, natural talent and perseverance- all are playing vital role in augmenting the performance and ultimate outcome [1-3]. Among all, aero/hydrodynamics is considered central in almost every speed sports in which the performance is the result of the optimal motion of the athlete and/or equipment in the air or water. From ball games such as golf, tennis, baseball, cricket, soccer, rugby, American football, Australian football to athletics, alpine skiing, cross-country skiing, ski jumping, cycling, swimming, speed skating, bobsleigh, skeleton, javelin, discus, motor sport and many others, the application of some basic principles of aerodynamic can make the ultimate difference between winners and losers [3-12]. Some exciting moments/finishes in different speed sports are shown in Fig. 1.

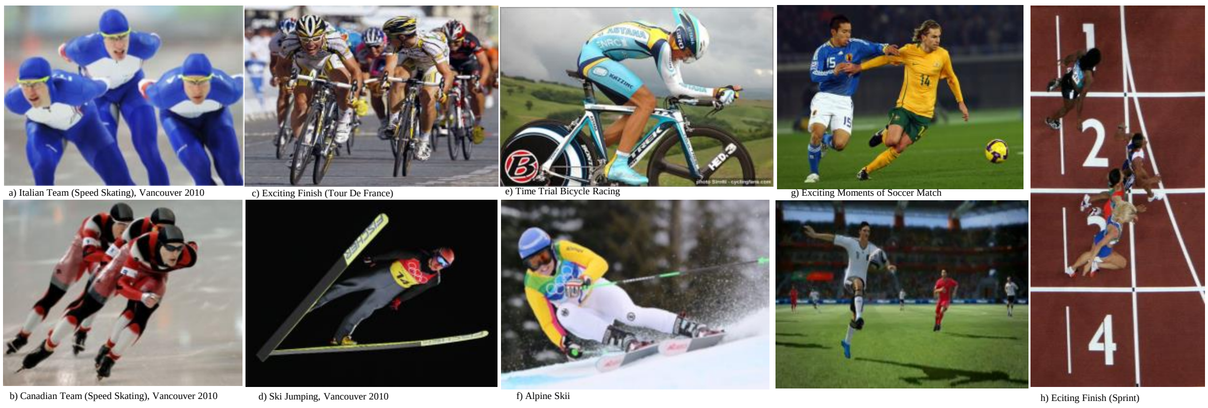


Fig. 1. Exciting moments in various speed sports

In speed sports such as Formula 1 racing, it is highly desirable to have down force at the cornering. This is generally achieved by using aerodynamic effects of spoiler which creates down force thereby enhancing the stability of the vehicle in cornering. Similarly athletes wear skin suits in cycling, swimming, speed skating, skeleton, etc. to reduce aero/hydrodynamic resistance (drag) so that they can conserve their biological energy to enhance performance [1-5]. The idea of 'marginal gains' has been well known in competitive sports since over several decades. An example is the winning story of Greg LeMond in the final stage of Tour de France in 1989. Fellow rider Laurent Fignon had a 50-second lead heading into the stage, but lost to LeMond by just eight seconds (thanks to the superior aerodynamics effect created by cycling gears, helmet and skinsuit), the smallest winning margin in Tour de France history [8]. In 2011, Cadel Evans gained the yellow jersey in the final time trial stage by winning the tour by 94 seconds. Now a day, cycling competition is dominated by aerodynamics. Aero/hydrodynamics is not only vital in endurance sports where it has significant effect but also in sprints where it has marginal gains. A study by Kyle [22] in 1986 showed that by reducing wind resistance/aerodynamic drag by only 2% across 100 m would save a sprinter 0.01s, certainly a marginal gain over a competitor. With modern materials and construction techniques, this 2% is simple to find and athletes can save up to 10%, or 0.05 seconds.

2. Aerodynamics of Sports Balls

The deflection (swing, swerve or curve) in flight of spherical sports balls (soccer, tennis, cricket, baseball, softball, golf, volleyball) and oval shape balls (rugby, American football and Australian football) is well known. The deflection is produced either by spinning the ball about an axis perpendicular to the line of flight or by asymmetric airflow created by seams or surface structures. The aerodynamic behaviour is strongly dependent on the details of the ball external surface structure, spin and speed. In cricket game, the ball is released with the seam angled which creates the boundary layer asymmetry and pressure variation necessary to produce sideway force popularly known as swing. In other spherical ball games (soccer, tennis, baseball, softball and volleyball), the sideway deviation is generally created by the seam or stitch orientation and/or by imparting the spin. Due to this sideway deviation, the balls experience an unpredictable flight path. Additionally, the aerodynamic drag (resistance that slows the ball) can significantly be varied by manipulating the fluid boundary layer (laminar to turbulent or turbulent to laminar flow) around the ball through altering surface structures (roughness, dimples/pimples) and/or speeds. It is mesmerizing to see that a small surface feature such as seams/ stitches on cricket ball, soccer ball, baseball and softball, hairy fuzz and seam on tennis ball, dimple on golf ball can create profound impact on each of these ball’s flight trajectories. Published data have clearly demonstrated these impacts [1-4, 9-14].

2.1. Soccer Balls

The aerodynamic behaviour of a sport ball is considered to be the fundamental for the players, coaches (trainers), regulatory bodies, ball manufacturers and even the spectators. It is no doubt that the soccer (football) is the most popular game in the world. No other game is so much loved, played and excited spectators than the soccer. It is played in every corner by every nation in the world. It is also perhaps the only game that can be played by everyone regardless of player’s socio-cultural and economic background. It can also be played in all climate conditions. Although, the soccer ball among all spherical balls is traditionally considered having better aerodynamic balance, over the years, the ball design has undergone a series of technological changes, in which the ball was attempted to be more spherical and aerodynamically efficient as claimed by the manufacturers by utilising new surface design, joining technique and manufacturing processes [2, 5-6, 20-21]. Adidas has applied thermal bonding to replace conventional stitching to make a seamless surface design and carcass shape by using 14 panels in 2006, 8 panels in 2010 and more recently 6 panels in 2014 FIFA World Cup instead of the traditional 32 panels ball used from 1970 to 2002 FIFA World Cup. A pictorial view of soccer ball design change is shown in Fig. 2.

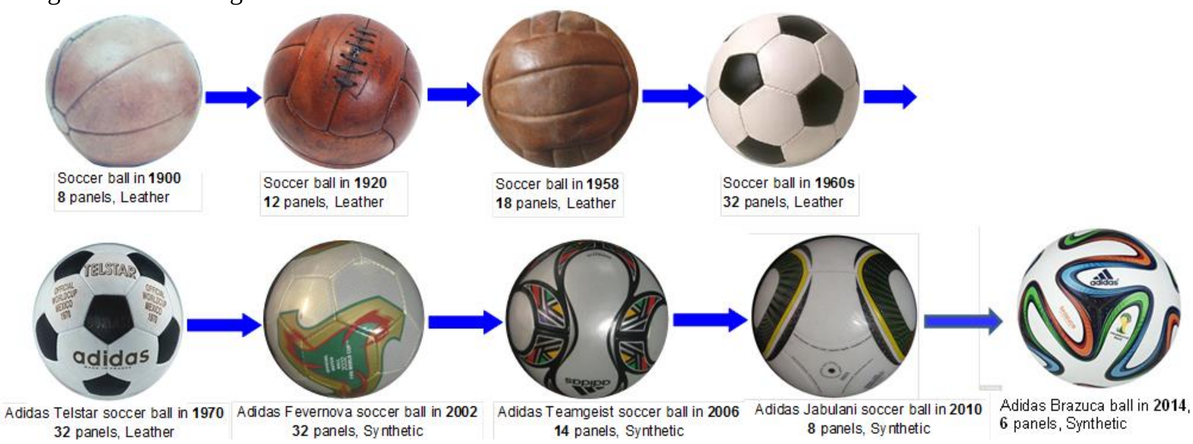


Fig. 2. The evaluation of soccer ball design

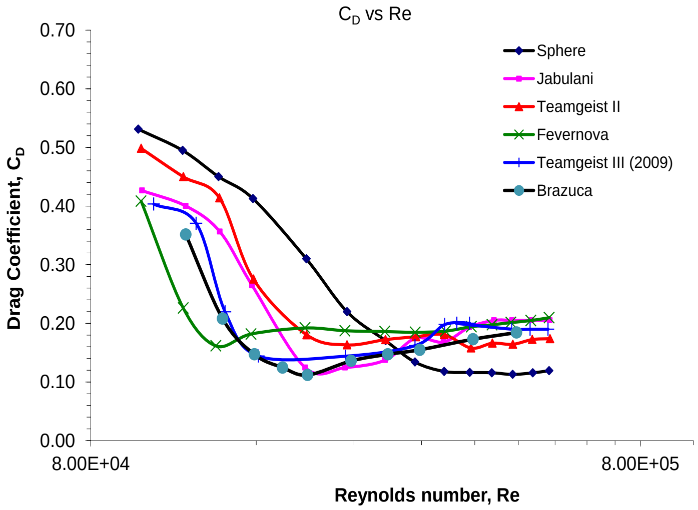


Fig. 3. Aerodynamic drag coefficient variation with Reynolds number for soccer balls

Majority ball manufacturers claim that the newly designed balls are more spherical, aerodynamically balanced and easy to handle. However, studies by Alam et al. [2, 5-6] and Asai et al. [13, 20] clearly demonstrated that newly designed balls are not necessarily aerodynamically better than traditional 32 panels (pentagon and hexagon) stitched balls. A recent study by Alam et al. [5-6] has shown that the aerodynamic behaviour (especially aerodynamic drag) varies notably with the Reynolds number (varied by speed) as shown in Fig. 3. They also reported that the drag coefficient difference between two different sides facing the wind varies from 9% for Jabulani (2010 FIFA World Cup ball – 8 panels), 4% for Teamgeist (2006 FIFA World Cup ball – 14 panels), 3% for Brazuca (2014 FIFA World Cup ball – 6 panels) in comparison to Fevernova (2002 FIFA World Cup ball – 32 panels) ball [2, 5-6].

2.2. Baseball, Cricket ball, Tennis ball and Golf ball

Baseball

It is widely recognised that baseball and softball games are national sports in the USA, Cuba and other Caribbean nations. It is at all levels (professional, amateur, and youth) now popular in North America, Japan, South Korea, Australia, New Zealand and many parts of Asia. Unlike a smooth sphere, baseball and softball are not uniformly smooth but are characterised by the yin – yang pattern of raised approximately 108 stitches for baseballs and 88 to 96 stitches for softballs. The stitches, seams, and their orientations can make the airflow around these balls complex and unpredictable. Although the aerodynamic behaviour of other sports balls have been studied widely, there are insufficient reliable experimental data of baseball aerodynamics available to the public domain except limited studies by Adair [25], Kensrud & Smith [27], Nathan [28] and Alam et al. [1]. Alam et al. [7] undertook an experimental study of baseballs and softballs' aerodynamic behaviour under a range of wind speeds (Reynolds number) and angle of attack. The non-dimensional drag coefficient (C_D) is shown as a function of Reynolds number in Fig. 4 (ii).

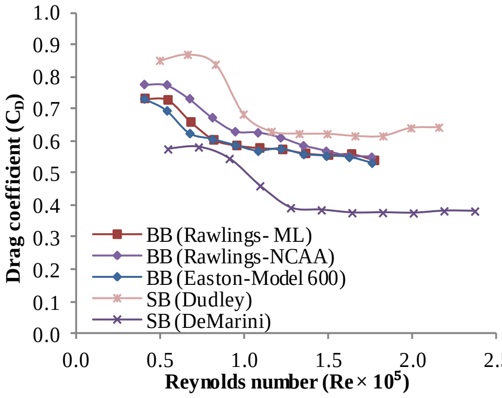
The four seam positions of baseballs and softballs facing the wind are shown in Fig. 4 (i). The average of C_D all these positions are shown in Fig. 4 (ii). The variations between position 1 & 2, and position 3 & 4 are minimal as these two positions are considered to be the mirror image. Additionally, the C_D variations among four positions for each ball are evident at low Reynolds number (below 40 km/h), however, these variations are minimal at high Reynolds numbers ($Re = 1.6 \times 10^5$ or above) which is believed to be due to the elimination or minimization of local flow separations from seams.

The angle of attack has notable impact on C_D value for both baseball and softball. For a smooth sphere, the angle of attack has no effect as the flow is symmetrical regardless the flow orientation. However, the baseball and softball are not fully symmetrical due to their complex seam orientation, seam geometry (height and width) and number of stitches. This asymmetry causes not only drag but also side and lift forces as a function of angle of attack. It was also noted that the average C_D value for three baseballs and two softballs (made by different manufacturers) increases approximately 23% with the increase of angle of attack between 45° and 90°. The average C_D value for a baseball and softball at high Reynolds number (120 km/h and above) is approximately 0.57 and 0.50, however, at low Reynolds number (40 km/h) the value could be as high as 0.70 and 0.67

respectively. Seam orientation and stitches have significant effects on baseball aerodynamics. The average variation of C_D value between sides of baseball facing the wind can vary up to 16%.

a) Baseball seam orientation b) Softball seam orientation

i) Baseball & Softball seam orientation



ii) Drag coefficient for baseballs & soft balls

Fig. 4. Aerodynamic behavior of baseballs and softballs

Golf Ball

The aerodynamics of golf ball draws attention to both golf players and golf ball manufactures as the types of golf ball used in the game greatly affect the flight path of the ball thereby players' performance. The flight trajectory is influenced by the aerodynamic forces exerted on the ball especially due to the variation in dimple geometry and dimple numbers. Most commercially manufactured golf ball dimple not only vary in numbers (between 250 and 500) but also in their sizes, shapes and depths. The published data shows that surface dimple has notable effect on golf ball wind resistance (drag). The dimples alter the critical region (laminar to turbulent flow regime) at a much lower Reynolds number by reducing the drag coefficient by over 50% compared to a smooth (non-dimple) ball. After the critical region, the drag coefficient increases with the increase of the Reynolds number. As the flow regime largely depends on dimple size, depth and shape, a series of experimental studies have been undertaken at RMIT by Sports Aerodynamics Research Group [9-10] to understand the aerodynamic drag behaviour of production and prototype golf balls with varied dimple characteristics. A recent study by the Group has revealed that the increase of the dimple depth ratio shifts the flow transition to a lower Reynolds number and increases the drag coefficient in trans-critical flow regime. The study also reported a positive linear correlation between relative roughness and drag coefficient for golf balls.

Tennis Ball

The game of tennis originated in France in the 12th century and was referred to as 'jes de paume,' the game of the palm played with the bare hand. As early as the 12th century, a glove was used to protect the hand. Starting in the 16th century and continuing until the middle of the 18th century, rackets of various shapes and sizes were introduced [9-10]. One of the centre pieces of tennis is the hairy spherical tennis ball. The aerodynamic behaviour of tennis ball is complex. Some studies on tennis ball aerodynamics have been undertaken in early 1970s. However these findings were contradictory and somehow different to each other. More recently, Alam et al. [34-35] conducted a series of experimental investigations on a wide range of tennis balls used in various tournaments around the world. The primary objectives of these studies were to verify previously published results and also to quantify the effect of seam and spin on tennis ball aerodynamics. Alam et al. [34-35] reported that the average drag coefficient for non-spinning new tennis balls varies between 0.55 and 0.65. These values are slightly higher compared to previous studies [23]. However, recent measurements conducted by Mehta et al. [9] strongly support the findings of Alam et al. [34-35]. The C_D value for tennis ball is much higher than cricket or other spherical balls mainly due to the combined effect of fuzz and fuzz filament orientation. No apparent flow transition is occurred for tennis balls over tennis ball speed range. The seam orientation has negligible or no effect on drag coefficient at high Reynolds numbers. However, some effects have been noted at lower Reynolds numbers (~8% increase of C_D value). The spin has significant effect on drag and lift force coefficients (C_D and C_L). The C_D value generally increases with the increase of spin rate. The average C_D value varies between 0.6 to 0.8 at speeds (60-140 km/h) under spin rate between 8.33 to 50 rev/s) [9, 23]. This is mainly due to the interaction complex rotating boundary layer and hairy fuzz surface structure.

Cricket Ball

Cricket is widely played and watched game in more than 60 countries of the former British Empire (British Commonwealth nations) with a potential viewing audience of over 1.5 billion people. Cricket's popularity has already moved outside the boundary of the British Commonwealth nations. With the participation of China in cricket, the game can become potentially the 2nd most viewed game after the football (soccer). The centre piece of the game of cricket is the ball. As a cricket ball has to be projected through the air as a three dimensional body, the associated aerodynamics play a significant role in the motion thereby flight of the ball. A cricket ball is constructed of a several layers of cork tightly wound with string. The ball is covered with a leather skin comprising 4 quarters stitched together to form a major seam in an equatorial plane. Moreover the quarter seams on both halves of the ball are internally stitched. The seam comprises six rows of stitches with approximately 70 to 90 stretches in each row. The height of the seam can be over 1 mm. The prominence of the seam can vary from one manufacturer to another as there is no standard for the seam geometry. The aerodynamic behaviour of cricket balls can greatly be affected by the prominence of seams, surface roughness and spin. The bowler launch attitude and pitch condition can also play an important role. An asymmetric airflow around the ball is generated due to the seam angle, surface roughness and spinning which creates a pressure difference thereby deviating the ball's flight from its intended flight path. This flight deviation is called swing. In cricket, a bowler bowls the ball to a batsman where the sole objective for the batsman is to strike the ball hard; scoring as many runs as possible, by protecting the stumps. However, the bowler is geared towards tricking the batsman by altering the direction and flight of the ball. This compels the batsman to play an incorrect stroke. Therefore, it is extremely important to understand aerodynamic behaviour of new and used (worn) cricket balls as seam angle to the airflow, spinning, and wear and tear can have major impact on swing and place of landing.

Till to date, the complex behaviour of swing of a cricket ball is not fully understood. Although some studies have been undertaken on new cricket ball aerodynamics, scant information is available on aerodynamics of used cricket balls especially 'Reverse Swing' [10, 14-15]. The reverse swing is believed to be occurred in used balls at a particular wind speeds. Several experimental studies are currently being undertaken at RMIT University and NASA Ames Center in California, USA to understand the mechanism of reverse swing.

2.3. Oval Shape Balls

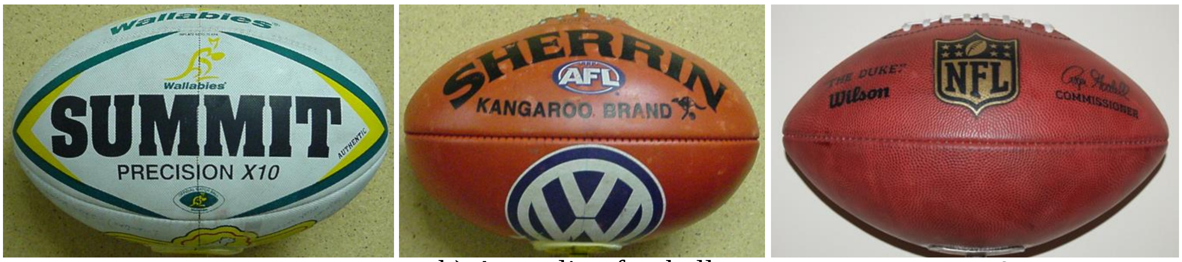
Oval shaped sports balls are Rugby ball, Australian football and American football. The oval shape balls' aerodynamic properties lead to interesting and sometimes highly unexpected flight trajectories. Our present understanding of oval shape ball aerodynamics is limited. Even when the ball is round, as in the case of golf balls and tennis balls, the aerodynamic parameters such as the coefficients of lift and drag, and their dependence on spin rate, are not known a priori, and must be found empirically. The oval shapes of Rugby, Australian and American footballs present additional challenges to the understanding of their aerodynamics, such as the action of two separate spin axes and the possibility of tumbling. The Rugby ball is larger than the Australian and American footballs and its surface is roughened with pimples. The pimples are intended to increase hand traction and minimise the slip during passing. However, they also influence the lift and drag forces and thus affect the trajectory and flight distance. The American and Australian footballs have distinctive features such as laces in contrast to the Rugby ball. The Rugby ball had also laces which were eliminated in the new design since 2004. The American football has also pimples to increase hand traction. However, the Australian football does not have any pimples. Both Australian and American footballs are made of leather panels. Physical properties of rugby ball, Australian football and American football are shown in Table 1.

Table 1. Physical parameters of balls

	Rugby Ball	Australian Football	American Football
Length, mm	280 - 300	270 - 280	280 - 292
Circumference (Longitudinal) mm	740 - 770	720 - 735	711 - 724
Circumference (Lateral) mm	580 - 620	545 - 555	527 - 530
Mass, gm	410 - 460	450 - 500	400 - 430
Air pressure, kPa	66 - 69	62 - 76	86 - 93
Panel Numbers	4	4	4
Panel Type	Synthetic	Leather	Leather
Surface Finish	Rough with Pimples	Smooth	Rough with Pimples
Lace Exposed	No	Yes	Yes
Shape	Oval with Bullet Ends	Oval with Bullet Ends	Oval with Conical Ends

The external shapes of Rugby, Australian and American balls appear similar but they are actually significantly different in terms of geometrical properties. As All 3 balls are made of 4 panels, with leather being used for the panels of Australian and American footballs, and synthetic rubber panels for the Rugby ball. The seams created by joining the panels can also play an important role in the aerodynamic performance of the ball, as is well known from studies of cricket balls and baseballs. The two ends of a Rugby and Australian balls are similar and appear to be bullet head shape in contrast the American football's two ends are conical in shape.

The airflow around a Rugby ball, Australian football and American football is complex and three dimensional as these balls can experience both lateral and longitudinal rotational motion during flight. Due to complex behaviour, the accuracy of long distance kicking/punting by the elite level players to the desired point/goalpost is very low. The accuracy of kicking of oval shape balls is close to 50% and not much improved over the last three decades despite undertaking numerous efforts. A comprehensive aerodynamics study therefore is paramount to understand the balls' behaviours in flight and subsequently build flight trajectory models of the ball for players and coaches so that they can develop better game strategy. However, the work is challenging, time consuming and costly. At RMIT University, a series of aerodynamics studies of rugby ball, Australian football and American football has been undertaken mainly under non spinning condition. The steady-state aerodynamic properties especially drag and side force (or lift) acting on a Rugby ball, Australian football and American football have been investigated and compared. The steady aerodynamic properties were measured experimentally for a range of wind speeds and yaw angles. Pictorial views of oval shape balls are shown in Fig. 5.



a) Rugby ball b) Australian football c) American football

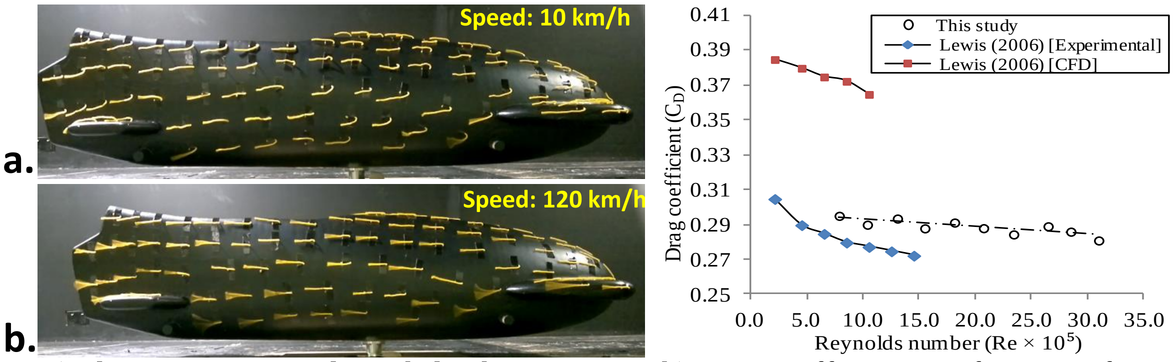
Fig. 5. Oval shape balls

The studies at RMIT University have revealed that the aerodynamic behaviour of oval shape balls is extremely complex even when the ball is not spinning. The airflow around the ball is 3 dimensional and axisymmetric. The average drag coefficients (C_D values) for a rugby ball, Australian football and American football at zero yaw angle are found to be around 0.10, 0.18, 0.20 respectively. The crosswinds have significant effects on drag coefficient and vary with the ball's yaw angles, external shape, surface roughness and other extrusions. The Rugby ball and the Australian football generate more asymmetric drag forces under leeward and windward yaw angles compared to the American football. The Reynolds number dependency in drag coefficient was noted at lower speeds at all yaw angles. However, the variation is minimal at high speeds (e.g. high Reynolds numbers). More details can be found in Alam et al. [3-4]. The coefficients of drag, side and lift forces are important as they are essential for the development of 3D flight trajectory models under a range of conditions including multi axes spin, angles of attack, crosswinds and varied atmospheric turbulence.

3. Bobsleigh

Bobsleighing is one of the most technologically advanced and costly events in competitive sports. The winter sport of bobsleighing involves teams of either two or four to make timed runs down an iced track in a gravity-powered sleigh. The modern bobsleigh design started to take shape since 1950s. The streamlined body shapes of automobiles and aircraft development during 1930s and 1940s started to inspire bobsleigh design. Bobsleighs can attain speeds of 150 km/h and some curves can subject the crew to as much as 5 times the gravitational acceleration. At such high speeds, the importance of aerodynamics is paramount. Prior studies on the bobsleigh aerodynamics have shown that the majority of the aerodynamic drag is attributed to the bobsleigh cowling. This is due to the formation of the wake inside the cavity of bobsleigh. The shape of the nose of bobsleigh can play a critical role in improving the aerodynamic performance at low Reynolds numbers. Although some limited studies have been reported in open literature, the aerodynamic behaviour of bobsleigh is not fully understood. This is especially true in regard to the interaction of airflow with bobsleigh and athletes. Chowdhury et al. [26] conducted an experimental aerodynamics study of two crews bobsleigh at RMIT University.

The airflow around a Bobsleigh model is visualised using wool tuft as shown in Fig. 6(a). The variation of drag coefficient (C_D) with Reynolds number (Re) is shown in Fig. 6(b). The figure also includes the results obtained by Lewis [29] for both Computational Fluid Dynamics (CFD) modelling and experimental values. It can be seen in Fig. 6(b) that the measured drag coefficient (C_D) slightly decreases with increasing Reynolds number (Re). Similar trend is also seen in the work of Lewis [29]. The Bobsleigh model without modelling the crew, runners and runner carriers was found to have an average drag coefficient of 0.289. By adding the drag of crews, the drag coefficient of Bobsleigh and crew can be around 0.314 which agrees well with the findings of Lewis [29], flow visualisation indicated that optimisation of the bumpers, particularly the rear bumpers, may not be significantly effective for reducing the aerodynamic drag. Hence, the aerodynamic performance improvements can be achieved by altering the size and shape of the nose as well as the sidewall curvature.



a) Flow pattern around a Bobsleigh b) Drag coefficient as a function of Re

Fig. 6. Aerodynamic behavior of a Bobsleigh

4. Sports Hydrodynamics

In most water sports (swimming, rowing, sailing, water skiing, sail boats and powerboats), the equipment and athlete are affected by the dual fluid medium of both water and air simultaneously. The athlete body, watercraft and equipment in water sports are fully and/or partially submerged. The forces acting on such objects are similar to those in aerodynamics: thrust, drag, lift, weight with the additional consideration of buoyancy. In addition to aerodynamic forces, hydrodynamic forces are affected by: water waves and spray, ventilation (cavitation), fouling (marine growth on an object's surface), planning, the free surface interface and wind shear. Wave surface deformation occurs for a water surface-piercing body. Water peaks and hollows are formed along the body that creates the wave drag. This water piling can also form water jets, which shoot into the air creating spray drag. In this paper our focus is on swimming and sailing.

4.1. Swimming

Swimming is the movement through water using natural mean of propulsion such as arms, legs or both, whether for pleasure, exercise or sport. It is a popular sport (competitive and recreational) as it involves low-impact aerobic exercise beneficial for lungs, heart and general fitness. The swimming sport takes place in pools or open water (sea or lake). Competitive swimming is the 3rd most watched Olympic sport with varied distance events in butterfly, backstroke, breaststroke, freestyle, and individual medley sports [33]. In swimming each stroke requires specific techniques, and in competition, there are specific regulations concerning the acceptable form for different strokes. There are four different strokes approved by FINA (Fédération Internationale de Natation) regulated world and Olympic competition. These strokes are: a) Freestyle ‘front crawl’, b) Butterfly ’dolphin and power’, c) Breaststroke, and d) Backstroke. Overall, FINA oversees 5 aquatics sports: i) Swimming, ii) Diving, iii) Synchronized Swimming, iv) Water Polo, and v) Open Water Swimming.

In all aquatic sports including swimming, the understanding of hydrodynamics is central. The hydrodynamics play a vital role in athlete’s thrust, lift, drag, design of swimming gears (swimsuits), and swimming infrastructures (pool and lane dividers, etc.). There are four primary forces acting on a swimmer: a) thrust (propulsive forces), b) weight, c) drag, and d) buoyancy. The weight of the swimmer is partially offset by buoyancy. However, the full offset is achieved by creating lift through inclining the athlete body under some angles with the horizontal (angle of attack). This body inclination generates additional form/pressure drag. Thus an optimal angle of attack is desirable to minimise the drag. The athlete hydrodynamic drag consists of form/pressure drag, skin friction drag and wave-making drag. The most dominating is the form/pressure drag (over 85%), followed by wave making drag (~10%) and skin friction drag (~5%) [30]. Form/pressure drag is caused by the exposed frontal area of the athlete body. Hence, the athlete needs to streamline his/her body to reduce the projected frontal area thereby the form/pressure drag. The skin friction drag can be reduced using athlete outfit such as swimsuit. An engineered swimsuit in compliance with the FINA regulations can be developed which will minimise the skin friction drag by utilising the fluid boundary layer transitional effect [16-17, 19, 24, 31].

4.2. Sailing

Research in aero/hydrodynamics of sail boat and power boat is challenging as they have great diversity in sizes, shapes and configurations. Hence the specialised research focuses on specific component such as sails, masts, hulls or appendages. Until recently most studies were experimental type using wind tunnel or water tunnel. However, with increasingly available computational resources, the Computational Fluid Dynamics (CFD) modelling has been widely used into marine sport equipment design (sails, masts, hulls or appendages). Aero/hydrodynamic modelling of marine sports equipment is a tremendous challenge. Realistic results require the modelling of multiple interacting components immersed in air, water or both fluids at the same time, as well as free surface (water wave) effects and wind shear effects. One such complex flow pattern is shown in Fig.7.

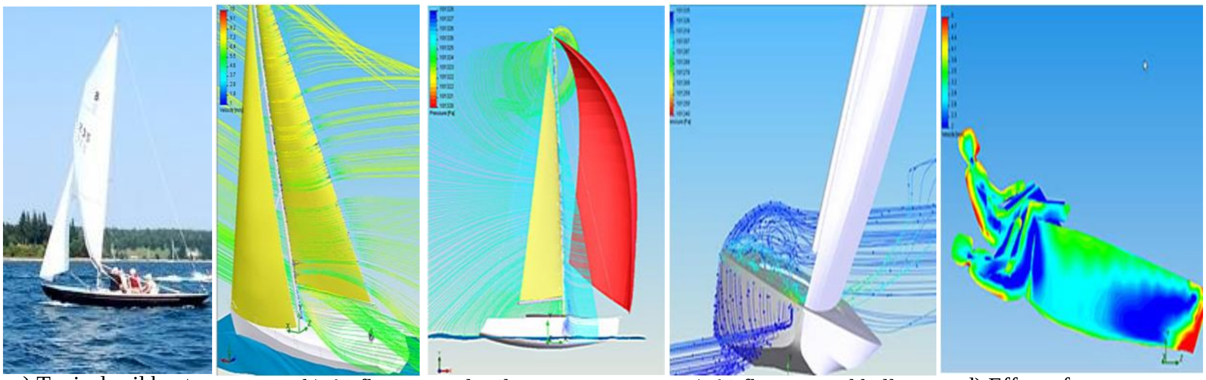
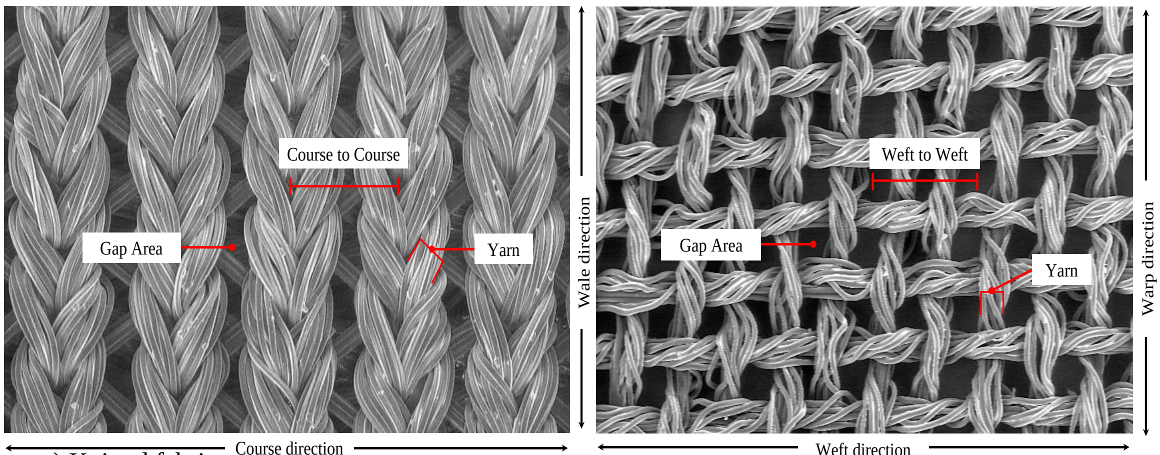

a) Typical sail boat b) Airflow around sail c) Airflow around hall d) Effect of crew

Fig. 7. Airflow around sail boat, adapted from web-sail [32]

5. Textile Aero/Hydrodynamics

Technological innovation, in both design and materials, has played a significant role in sport achieving its current standing in both absolute performance and its aesthetics. Aerodynamic properties play a significant role in athlete outfits (garments) across a wide range of sports including cycling, skiing, bobsleigh, and speed skating. Considerations in this aerodynamic performance include the textile weave or knit, seam and fastener placement and air permeability. Elite competition involves very short winning time margins in events that often have much longer timescales, making aerodynamic resistance/drag and its associated energy loss during the event significant in the outcome. In fact, a two fold increase in athlete velocity results in a fourfold increase in the drag force needing to be overcome.

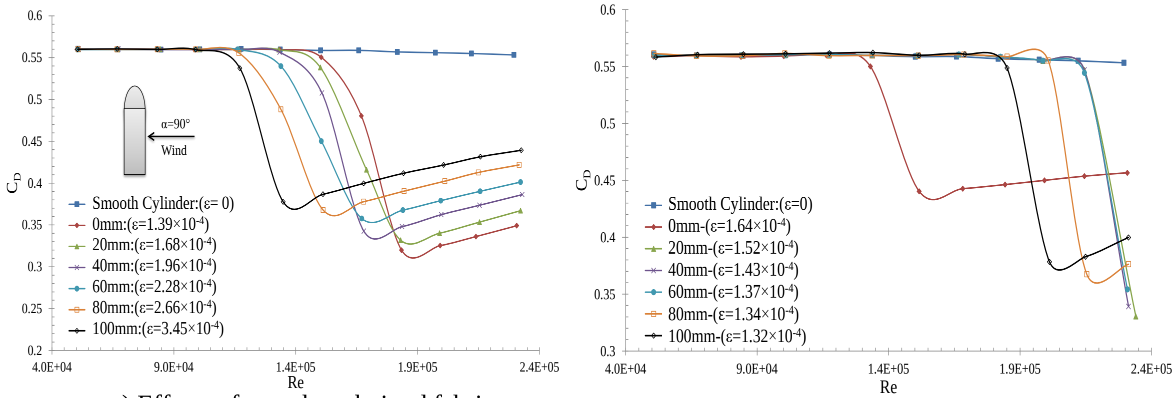
The surface texture of sports fabrics can potentially exhibit subtle yet significant influences on drag and flow transitions. Surface roughness is an important parameter for lift and drag due to the transitional properties at the boundary layer. Sport garments made of textiles represent a wide spectrum of surface topologies and wide boundary layer behaviour. A series of studies to understand the aero/hydrodynamic behaviour of sports textile has been undertaken by Sports Aerodynamics Research Group at RMIT University in Melbourne. Some findings from these studies are shown in Fig. 8 and Fig. 9.



a) Knitted fabric b) Woven fabric

Fig. 8. Surface structure of knitted and woven fabrics

Figure 8 illustrates the significant variation in surface morphology of knitted and woven sports fabrics. This surface variation becomes more complex under tension (stretch). The surface morphological changes cause the aero/hydrodynamic boundary layer transitional effect as shown in Fig. 9. The boundary layer transitional effect can be used to minimise the aero/hydrodynamic drag depending on athlete's body configuration and speed range [16-17, 19].



a) Effects of stretch on knitted fabric

b) Effects of stretch on woven fabric

Fig. 9. Flow regime variation in knitted and woven fabrics under various stretches

6. Concluding Remarks

The aerodynamics and hydrodynamics knowledge is critical in competitive sports. Natural talent, perseverance and hard training are not enough to be glorious unless technological advantages including knowledge of aero/hydrodynamics is utilised in most competitive sports.

Aerodynamics and hydrodynamics in sports is a wide-open research field. Significant enhancement of performance in sports can be achieved through undertaking aero/hydrodynamic research. Aero/hydrodynamics dynamics knowledge will allow determining the optimal body position of the athlete but also enhancing the equipment/sports gear efficiency.

7. Acknowledgement

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11. References

[1] F. Alam, H. Ho, L.V. Smith, A. Subic, H. Chowdhury, and A. Kumar, "A study of baseball and softball aerodynamics", *Procedia Engineering*, Vol. 34, pp. 86-91, 2012.

[2] F. Alam, H. Chowdhury, M. Stemmer, Z. Wang, and J. Yang, "Effects of surface structure on soccer ball aerodynamics", *Procedia Engineering*, Vol. 34, pp. 86-91, 2012.

[3] F. Alam, A. Subic, S. Watkins, A.J. Smits, "Aerodynamics of an Australian Rules Foot Ball and Rugby Ball" In *Computational Fluid Dynamics for Sport Simulation* (edited by M. Peters), pp. 103-127, Springer, 2009.

[4] F. Alam, S. Smith, H. Chowdhury, and H. Moria, "Aerodynamic drag measurement of American footballs", *Procedia Engineering*, Vol. 4, pp. 1877-7058, 2012.

[5] F. Alam, H. Chowdhury, B. Loganathan, and I. Mustary, "A study of aerodynamic drag of contemporary footballs", *Procedia Engineering*, Vol. 147, pp. 81-86, 2016

[6] F. Alam, H. Chowdhury, I. Mustary, and B. Loganathan, "Aerodynamic study of FIFA-approved footballs", *Procedia Engineering*, Vol. 105, pp. 317-322, 2015.

[7] F. Alam, H. Chowdhury, N. Husnia, and L.V. Smith, "An Experimental Study of Baseballs and Softballs", *Procedia Engineering*, Vol. 60, pp. 467-472, 2013.

[8] F. Alam, H. Chowdhury, Z. Elmir, A. Sayogo, J. Love, and A. Subic, "An Experimental Study of Thermal Comfort and Aerodynamic Efficiency of Recreational and Racing Helmets", *Procedia Engineering*, Vol. 2, No. 2, pp. 2413-2418, 2010.

[9] R.D. Mehta, F. Alam, and A. Subic, "Aerodynamics of tennis balls- a review", *Sports Technology*, Vol. 1, No. 1, pp. 1-10, 2008.

[10] R.D. Mehta, "Aerodynamics of Sports Balls", *Annual Review of Fluid Mecha*nics, Vol. 17, pp. 151-189, 1985.

[11] R.D. Mehta and J.M. Pallis, "Sports Ball Aerodynamics: Effects of Velocity, Spin and Surface roughness". In: *Materials and Science in Sports* [eds. F. H. Froes and S. J. Haake], pp. 185-197, The Minerals, Metals and Materials Society [TMS], Warrendale, USA, 2001.

[12] A.J. Smits and S. Ogg, "Golf ball aerodynamics", *The Engineering of Sport*, Vol. 5, No. 1, pp. 3-12, 2004.

[13] T. Asai, K. Seo, O. Kobayashi, and R. Sakashita, "Fundamental aerodynamics of the soccer ball", *Sports Engineering*, Vol. 10, pp. 101-110, 2007.

[14] R.L. Brooy, F. Alam, and J. Watmuff, "New Methods of Initiating Reverse Swing on a Cricket Ball" in *The Impact of Technology on Sports III*, ISBN 13: 978-1-921426-39-1, 275-279, Honolulu, USA, 2009.

[15] A.T. Sayers and A. Hill, "Aerodynamics of a cricket ball", *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 79, pp. 169-182, 1999.

[16] H. Chowdhury and F. Alam, "An experimental investigation on aerodynamic drag coefficient and surface roughness properties of sport textiles", *Journal of the Textile Institute*, Vol. 105, No. 4, pp. 414-422, 2014.

[17] H. Moria, H. Chowdhury, F. Alam, and A. Subic, "Aerodynamic behaviour of stretchable sports fabrics suits", *Sports Technology*, Vol. 4, No. 3– 4, pp. 171-177, 2011

[18] H. Chowdhury, B. Loganathan, Y. Wang, I. Mustary, and F. Alam, "A Study of Dimple Characteristics on Golf Ball Drag", *Procedia Engineering*, Vol. 147, pp. 87-91, 2016

[19] H. Moria, H. Chowdhury, F. Alam, and A. Subic, "Comparative aerodynamic analysis of commercial swimsuits", *Sports Technology*, Vol. 3, No. 4, pp. 261-267, 2010.

[20] T. Asai and K. Kamemoto, "Flow structure of knuckling effect in footballs", *Fluids and Structures*, Vol. 27, No. 5-6, pp. 727-733, 2011.

[21] S. Barber, S.B. Chin, and M.J. Carré, "Sports ball aerodynamics: A numerical study of the erratic motion of soccer balls", *Computers & Fluids*, Vol. 38, No. 6, pp. 1091-1100, 2009

[22] C.R. Kyle and V.J. Caiozzo, "The effect of athletic clothing aerodynamics upon running speed", *Medicine and Science in Sports and Exercise*, Vol. 18, pp. 509-515, 1986

[23] S. G. Chadwick and S. J. Haake, "The drag coefficient of tennis balls", *The Engineering of Sport: Research, Development and Innovation*, pp. 169-176, Blackwell Science, 2000.

[24] L.W. Brownlie, "Aerodynamic Characteristics of Sports Apparel", Ph.D. thesis, University of British Columbia, Canada, 1992.

[25] R.K. Adair, "The physics of baseball", *Physics Today*, Vol. 48, pp. 26-31, 1995.

[26] H. Chowdhury, F. Alam, S. Arena, and I. Mustary, "An Experimental Study of Airflow Behaviour around a Standard 2-man Bobsleigh*", Procedia Engineering*, Vol. 60, pp. 479–484, 2013.

[27] J.R. Kensrud and L.V. Smith, "In situ drag measurements of sports balls", *Procedia Engineering*, Vol. 2, pp. 2437-2442, 2010.

[28] A.M. Nathan, "The effect of spin on the flight of a baseball", *American Journal of Physics*, Vol. 76, pp. 119-124, 2008.

[29] O. Lewis, Aerodynamic analysis of a 2-man bobsleigh, Master Thesis, Delft University of Technology; Netherlands, 2006.

[30] A.R. Vorontsov and V.A. Rumyantsev, "Resistive forces in swimming" In Biomechanics in sport: performance enhancement and injury prevention, Blackwell, Oxford, pp. 184-204, 2000.

[31] S. Ito, "The swimming style and fluid dynamics of swimming", *JSME News*, Vol.15, No. 2, pp. 1-10, 2004

[32] Web-Sail, retrieved on 12 November 2017 from https://cdn2.hubspot.net/hub/209338/news/Ad_aerodynamics/index2.htm

[33] Bleacher Report, retrieved on 30 October 2017 from http://bleacherreport.com/articles/2656664-ranking-the-top-ten-olympic-sports-to-watch.

[34] F. Alam, A. Subic, and S. Watkins, "An Experimental Study of Aerodynamic Drag of a Series of Tennis Balls", *Proceedings of the International Congress on Sports Dynamics*, 1-3 September, Melbourne, Australia, 2003.

[35] F. Alam, S. Watkins, and A. Subic, "The Aerodynamic Forces on a Series of Tennis Balls", *Proceedings of the 15th Australasian Fluid Mechanics Conference*, 13-17 December, University of Sydney, 2004.