Aerodynamics of badminton shuttlecock : Characterization of flow around a conical skirt with gaps, behind a hemispherical dome

Lin, C. S. H.; Chua, C. K.; Yeo, J. H.

2014

Lin, C., Chua, C., & Yeo, J. (2014). Aerodynamics of badminton shuttlecock: Characterization of flow around a conical skirt with gaps, behind a hemispherical dome. *Journal of Wind Engineering and Industrial Aerodynamics*, 127, 29-39.

<https://hdl.handle.net/10356/79761>

<https://doi.org/10.1016/j.jweia.2014.02.002>

© 2014 Elsevier Ltd. This is the author created version of a work that has been peer reviewed and accepted for publication by *Journal of Wind Engineering & Industrial Aerodynamics*, Elsevier Ltd. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at:
[<http://dx.doi.org/10.1016/j.jweia.2014.02.002>].

Downloaded on 26 Apr 2023 18:30:26 SGT

Elsevier Editorial System(tm) for Journal of Wind Engineering & Industrial
Aerodynamics
Manuscript Draft

Manuscript Number: INDAER-D-13-00295

Title: Aerodynamics of badminton shuttlecock: Characterization of flow around a conical skirt with gaps, behind a hemispherical dome

Article Type: Full Length Article

Keywords: shuttlecock; blunt body; flow; aerodynamics; pressure profile

Corresponding Author: Mr. Calvin Shenghuai Lin, B.Eng

Corresponding Author's Institution: Nanyang Technological University

First Author: Calvin Shenghuai Lin, B.Eng

Order of Authors: Calvin Shenghuai Lin, B.Eng; Chee Kai Chua, Ph.D; Joon Hock Yeo, Ph.D

- Comparative analysis of flow around shuttlecocks with and without gaps through CFD.
- Presence of gaps increased air bleed and reduced blunt body effect.
- In all instances, gaps increased the drag over a gapless shuttlecock.
- Velocity plot, wake vector plot, and pressure profile plots were evaluated.
- Experimental data on gapless model shows good agreement with numerical data.

Dear Editor-in-Chief,

Please find enclosed our manuscript, “Aerodynamics of badminton shuttlecock: Characterization of flow around a conical skirt with gaps, behind a hemispherical dome” by Lin et al., which we would like to submit for publication as an original research article in Journal of Wind Engineering and Industrial Aerodynamics.

The flow around a badminton shuttlecock is interesting because aerodynamically, it is the combination of two blunt bodies- a thin wall conical skirt behind a hemispherical dome. However, gaps are required along the skirt of the shuttlecock to fulfill the typical drag characteristics and flight performance associated with a shuttle. This is an unusual case where drag is desired. It is proposed that these gaps reduce the blunt body effect, and result from the work supports this. While there have been previous works that observed the differences between a skirt with and without gaps, none was able to explain the effect of varying the gap sizes. Building on those publications, we were able to qualify and quantify how changing the gap size affects the shuttlecock. To our knowledge, there exists no similar publication on this area of work for a thin wall conical bluff body. Moreover, there has been limited work in the open literature on flow over such blunt body with gaps. Therefore, we believe that this study will be highly relevant to future work in synthetic shuttlecocks and may even be applied to other fields of industrial aerodynamics.

We hope this article will interest the readers of Journal of Wind Engineering and Industrial Aerodynamics. We look forward to your reply. Thank you for reading.

Please address all correspondence to cshlin@ntu.edu.sg

Yours sincerely,
Calvin Lin

Aerodynamics of badminton shuttlecock: Characterization of flow around a conical skirt with gaps, behind a hemispherical dome

C.S.H. Lin^{a, b, #}

C.K. Chua^a

J.H. Yeo^a

^a School of mechanical and aerospace engineering, Nanyang Technological University, 50 Nanyang Ave, Singapore 639798

^b Institute for sports research, Nanyang Technological University, 50 Nanyang Ave, Singapore 639798

[#]Corresponding author: Lin Shenghuai Calvin

Tel: 065-67904192

E-mail: CSHLIN@NTU.EDU.SG

Postal address: 158 Jalan Teck Whye #13-109, Singapore, Singapore 680158

The effects of gaps on flow properties were studied for thin walled conical structure behind a hemispherical dome- badminton shuttlecocks . Computational fluid dynamics was applied to six different profiles with differing gap sizes. The gaps increased the drag force over a gapless conical skirt by up to 45.2% using the design dimensions. This is termed the critical gap size. Below the critical gap size, drag increases with as gap widens. Beyond the critical gap size, larger gaps resulted in reduced blunt body effect, reduced drag, and increased skirt porosity. Bleeding caused the formation of air jets that diminished the recirculation typical in wake behind a blunt body. Analysis of the pressure profiles showed that gaps increased the differential pressure between the inner and outer surface, thereby producing more drag. The gaps also resulted in spikes along the pressure profiles. Some of the numerical results were validated against wind tunnel experiments. The numerical and experimental results showed good agreement.

Keywords: shuttlecock; blunt body; flow; aerodynamics; pressure profile

1. Introduction

The shuttlecock used in a badminton game has the drag characteristics of a blunt body. Aerodynamically, the shuttlecock is equivalent to a semi-porous thin wall cone attached behind a solid hemispherical dome. This property gives the shuttlecock very high deceleration rate, where shuttlecock velocity in the same game can range from 5.5m/s to over 80m/s. Based on the guidelines from Badminton World Federation (BWF 1988), a badminton shuttlecock comprises of a 16 feather skirt attached to a base and weigh between 4.74g to 5.50g. The skirt can be replaced by synthetic materials but flight characteristics should remain similar. Since flight of a shuttlecock is highly dependent on the drag properties, the synthetic skirt must retain the same

drag properties. The synthetic skirt must also weigh as light as a feather skirt to retain the flight performance, especially the trajectory and turnover. The challenge then, is innovating a skirt design that can reproduce feather performance. Through the decades of badminton sports, there have been numerous attempts from the industry at the creation of an alternative to the natural feather shuttlecock. However, none was successful and even till today, feather shuttlecocks remain the top choice. Despite that, the development of a synthetic shuttlecock remains attractive for various reasons. These include the possible increase in consistency from batch to batch of shuttlecock, the decrease in demand of natural waterfowl feathers that can be unpredictable in supply and quality, improved durability, and lowered production cost. The availability of good synthetic shuttlecocks will make badminton more affordable and attractive as a recreational sport because top grade feather shuttles remain a costly consumable in the game.

The first step in development of synthetic shuttles is to understand the fundamental differences between it and the feather counterpart. Numerous previous works explored the differences between synthetic and feather shuttlecocks. Cooke (Cooke 1992; Cooke 1996; Cooke 1999; Cooke 2002) was one pioneer of such works. Her works include trajectory studies to compare the flight path, wind tunnel studies to evaluate flow field differences between synthetic and feather shuttles, and the design process changes required for development of synthetic shuttlecocks. More recently, Alam et al. (Alam, Chowdhury et al. 2009) compared the drag coefficient between feather and synthetic shuttlecocks in the wind tunnel. The average drag coefficient observed for the 10 types of shuttlecocks was 0.61 at flow speed over 100km/hr. It was proposed that the skirt deformation of synthetic shuttles at high speed was the cause in lowered drag. The work by Chan and Rossmann (Chan and Rossmann 2012) reinforced this idea by observing the transient deformation under steady state flow in wind tunnel. It was observed that even with spin,

synthetic skirts are unable to maintain the circular geometry at high speed. In contrast, feather shuttles were able to resist deformation. The feathers shuttlecocks were also observed to have higher spin rate at the same free stream speed. Differences between feather and synthetic shuttlecocks have also been observed through flow simulation. Verma et al. (Verma, Desai et al. 2013) applied computational fluid dynamics (CFD) to evaluate the differences between synthetic and feather shuttlecock. The various planar cuts and plots presented gave insight to local flow conditions around the badminton shuttlecock skirt. Through CFD, the effect of twist angle of feathers was studied. It was found that increasing the twist angle beyond 12 degrees lowered the drag. However, such properties are less relevant for design of synthetic shuttles, because synthetic skirts are typically molded as one-piece design. Study of the effect of gaps on feather shuttlecocks by Kitta et al. (Kitta, Hasegawa et al. 2011) may be more applicable in the design of synthetic skirts. This is because gap designs, which play a critical role in synthetic skirts, are seldom discussed in open literatures. The work compared the drag coefficient of feather shuttlecocks with and without gaps. It was observed that presence of gaps significantly increased drag. Kitta et al. (Kitta, Hasegawa et al. 2011) also observed that spin has no direct effect on drag. The drag change from spin was induced by the skirt expansion under the centrifugal force of spin.

However, none of the work explored the effect of gap dimensions. In this paper, research was carried out to investigate further the effect of gaps. The main objective is to increase the understanding of how different gap sizes affect the skirt porosity and thus, the degree of similarity to blunt body aerodynamics. In addition to drag estimation, changes from varying gaps dimensions were explained through study of the wake, bleeding through the skirt, and pressure profiles along the skirt. Six simple shuttlecock models were studied in the numerical experiment:

a gapless cone model and five other cone models with varied gap dimension. The baseline result of the gapless cone model was then compared through physical experiments. This reinforces the validity of the CFD simulation. While the Reynolds-averaged Navier-Stokes (RANS) simulation that was carried out may be the averaged values, it improves understanding of conical thin walled bluff bodies which are much less studied than other solid bluff bodies. Moreover, the work will serve as a foundation for subsequent shuttlecock development, especially in virtual prototyping and transient simulation with Unsteady RANS (URANS) and Large Eddy Simulation (LES).

2.1 Numerical Analysis

The reference bluff body, profile A, consists of a thin wall gapless conical cup (skirt) attached to a solid hemispherical dome (cork) shown in Figure 1. Dimensions of the cork and skirt were referenced from Verma et al. (Verma, Desai et al. 2013). To investigate the effect of gaps around the skirt, 5 models (profile B to F), each with a different gap dimension, were constructed. Each profile had 15 triangular gaps of X/mm width and H/mm height that extend downward along the skirt beginning from 35mm behind the cork. External dimensions remain the same as profile A. The various dimensions of cut, including the surface area reduction by virtue of the gaps, are given in Table 1.

Numerical analysis was applied to the six simple shuttlecock profiles using ANSYSTM suite. Through ANSYSTM design modeler, the CAD model of each profile was enclosed in a cylinder of diameter 310mm, as shown in Figure 2. Flow inlet is 135mm upstream from the model, while outlet is 500mm downstream. In defining the case in CFXTM, velocity inlet was applied to the inlet, 0Pa static pressure for the outlet, free-slip wall at the cylindrical wall, and no-slip wall on

the shuttlecock profile. Simulation was conducted using the shear stress transport turbulence model (SST).

Unstructured mesh in the fluid domain within the cylinder was generated through ICEMTM. By comparison of numerical drag forces at 50m/s between the applied mesh and a finer mesh setup, a mesh of 3.5 to 4 million elements was observed to be sufficient for grid independency.

Presented in Table 2 are the numerical drag forces after 100 iterations for each profile and mesh setup. Such grid requirement is also similar to what was obtained by Verma et al. (Verma, Desai et al. 2013). Drag forces obtained through the two meshes had differences of 0.7-5.8% for the six profiles. At 0.7%, the gapless shuttlecock model A had the smallest difference in drag predicted by the two meshes. Despite the higher magnitude of 5%, differences in numerical drag between the applied mesh and refined mesh for profile B, C and F are still of acceptable level.

2.2 Experimental validation of numerical data

The numerical drag forces obtained were validated through wind tunnel analysis of physical models of the profiles. The hard models were manufactured through ObjectTM Eden 350V on FullCure 720 model material and FullCure 705 support material. This validation work was presented in (Lin, Chua et al. 2013). Due to resource limitation, only profile A, C and E were fabricated. Profile A was chosen because it presents a baseline value that is comparable against previous works on a gapless conical skirt, such as (Cooke 1992; Kitta, Hasegawa et al. 2011; Nakagawa, Hasegawa et al. 2012; Verma, Desai et al. 2013). Profile C and E were chosen because their drag coefficients are close to that of a speed 76 feather shuttlecock. Moreover, numerical drag forces of profile C and E fall on an interesting trend in study of the effect of gap on drag. At gap size of profile C, increasing the gap size increases the resultant drag. However,

drag reduces with further increase in gap size from that of profile E. Thus, physical models of these two profiles were reproduced to validate the trend.

Numerical pressure on the skirt of the gapless shuttlecock was validated with experimental data.

The pressure profile on the outer wall was validated against the experimental data by Cooke (Cooke 1992). Since no inner pressure profile of a thin wall gapless conical skirt was found in the open literature, a fourth physical model consisting of a gapless cone with attachment for silicon tubing was manufactured to validate the inner pressure profile. This physical model, as presented in Figure 3, was manufactured through the same rapid prototyping process as the physical models for drag validation. The only difference is the fittings for pressure measurements that were integrated into the skirt, and then fabricated as a one-piece design. The fittings are located at 30mm, 40mm, 50mm, 60mm, 70mm, and 80mm aft of the tip of the cork. Static pressure measurement was carried out using a MPXV7002DP differential pressure sensor.

All measurements were conducted in a closed loop wind tunnel commissioned by STEM ISI ImpiantiS.p.A with a test section measuring 780mm (W) x 720mm (H) x 2000mm (L). Drag forces were recorded through a calibrated load system comprising of a Sseed Studio 500g load cell (SEN128A3B) and a Vishay P-3500 strain indicator. Drag force measurements were only conducted at 15m/s, 30m/s, and 50m/s. No experimental drag data was collected for 6m/s because the load system was not designed for the small load involved (0.05N).

3. Results and discussions

Effect of the gaps was investigated through study on the drag forces, discussion of the wake behind the blunt body, and analysis of the coefficient of pressure. Flow simulation was conducted at velocities of 6m/s ($Re \sim 0.26 \times 10^5$), 15m/s ($Re \sim 0.66 \times 10^5$), 30m/s ($Re \sim 1.3 \times 10^5$), and

50m/s ($Re \sim 2.2 \times 10^5$). These velocities were chosen because 6m/s is the terminal velocity of various feather shuttlecocks tested, 15m/s and 30m/s allow for comparison with many shuttlecock experimental data in the open literature, while 50m/s is the high Reynolds number flow that is of interest in recent literatures on badminton shuttlecocks. Having the same diameter and test conditions, the six profiles investigated have the same Reynolds number at the same flow condition. Therefore, the results are discussed with respect to free-stream velocity (m/s) for easier comparison with the local velocities in the velocity plots.

3.1 Drag coefficient

Drag coefficients of the profiles at various airspeeds are shown in Figure 4. The presence of gaps increases the drag experienced by the shuttlecock model, but little variation is seen within each shuttlecock profile at different airspeed. The consistent drag coefficient with respect to airspeed suggests that the shuttlecock models remain in sub-critical flow regime throughout the operating airspeed that was investigated. This observation agrees with previous work such as that in (Cooke 1999; Alam, Chowdhury et al. 2010; Kitta, Hasegawa et al. 2011; Chan and Rossmann 2012). In those publications, changes in drag coefficient observed through wind tunnel experiments were attributed to changes in skirt diameter due to combination of shrinkage by high speed flow and expansion from centrifugal force of spin.

Comparison between profile A and B shows that introduction of gaps on the skirt resulted in an average increase of drag coefficient by 18.8%. The largest average increase over a gapless conical shuttlecock was observed on profile D at 45.2%. Comparing the drag forces on the various profiles at the same flow rate further demonstrated the effect of gap size on drag. This is seen in Figure 5 where drag forces of the various profiles at 50m/s flow are tabulated. It was

observed that the gapless conical model has the lowest drag force. As exhibited by the numerical data of profile B and C, drag on the shuttlecock increased as gap size widened. Drag peaked at profile D, with approximately 18% surface reduction. Further increase in gap size, as seen in profile E and F, caused reduction in drag force. This is attributed by the increased bleeding with larger gap size, thereby reducing the blunt body effect. In this case, profile D may be termed as the critical gap size.

For a blunt body such as a sphere or flat plate, pressure drag is the dominant component of drag force (Bertin and Cummings 2009). According to Cooke (Cooke 1999), the drag regime of a shuttlecock is similar to that of a blunt body, and the numerical data obtained in this study agrees with that. Contribution of pressure drag summarized in Table 3 shows pressure drag to be the dominant drag component throughout typical operating speeds of the models. Dominance of pressure drag over viscous drag increases with increasing airspeed in all profiles. Variation in gap dimensions has less significant effect. The significance of pressure drag indicates the importance of understanding the pressure profile along a shuttlecock model. The impact of gaps on bleeding and pressure coefficient along the six profiles will be further explored in subsequent sections of this article.

The trend observed in Figure 5 demonstrates that drag first increases with growing gap size and then subsequently decreases when gaps are larger than the critical gap size. This is an important aspect in the design of synthetic shuttlecocks because it allows for the balance between the various design specifications and the resultant drag force. Figure 5 shows that for a desired drag force, there exists two possible design points, one before and one after the critical gap size. Since flight trajectory of a shuttlecock is heavily influenced by the drag force (Cooke 2002), these two design points may represent two designs that have very different physical properties, but similar

flight performance at the same overall weight. For instance, the design curve in Figure 5 shows that a drag force of 3.7N can be achieved by a skirt profile with gaps that reduce the surface area by either 12.5% or 27.5%. For application in a synthetic shuttlecock, the skirt design with gaps of 27.5% surface area reduction will be desired because of inherent difficulty in substitution of lightweight natural feather with synthetic material. Moreover, the larger gaps may increase stability by virtue of a more forward center of gravity and changes in inertia of moments. However, the design curve in Figure 5 is design specific. That is, a new curve is required for gaps of other order or arrangement.

Drag measurement with physical models of profile A, C, and E shows good agreement with drag predicted through numerical method. The results, as presented in Table 4, suggest that the simulation results are reliable. Average percentage difference between numerical and experimental drag coefficient is 3.11% for profile A, 8.50% for profile C, and 5.25% for profile E.

3.2 Effect of gaps on wake

When the gaps are small or not present, such as in profile A, B and C, recirculation of air is seen in the immediate wake region of the model, as per Figure 6. This pair of counter rotating vortices seen in the plane is located directly behind the skirt within an area of the largest diameter of the skirt. Due to the counter rotation, it was observed that the near field wake around the core region have a tendency to curl inward. Vector plot of the wake also shows reverse flow near the core region of the skirt. The above is similar to a typical blunt body, such as a square cylinder as depicted in (Hu, Zhao et al. 2012) or a blunt body with rounded edges, as studied by Chok et al.

(Chok, Parameswaran et al. 1994). This observed wake pattern is same as the wake observed for a shuttlecock through physical experiment by Cooke (Cooke 1999).

As gap size increases, intensity of the recirculation and reverse flow decreases. Vector plot of the wake of profile D, also in Figure 6, exhibits much lower reverse flow velocity as compared to the other profiles with smaller gap sizes. Beyond the critical gap size, as on profile E and F, recirculation and flow reversal is no longer observed on the velocity vector plot. Instead of the medium intensity (16-32m/s) reverse flow observed from profile A, B, and C, or the low intensity (0-15m/s) reverse flow observed for profile D, high speed air stream is seen in the immediate wake of profile E and F. It is likely that the high velocity stream forming in and exiting through the skirt is due to the increased bleeding. As observed from Figure 7, amount of air bleeding through the shuttlecock skirt increases with gap size, thereby increasing the overall skirt porosity. It is likely that the increased dominance of gap is reducing the blunt body effect.

When the gaps are small, as seen on profile B and C, small stream of high velocity air is formed only within the skirt around the gaps. The jet of high velocity air grows in coverage and intensity as gap size increases, eventually going beyond the skirt and into the wake as seen in the velocity plot from profile E and F in Figure 7. Indeed, this stream of air was also observed in physical experiments on flow visualization by Cooke (Cooke 1992; Cooke 1999) and Kitta et al. (Kitta, Hasegawa et al. 2011). Cooke (Cooke 1999) termed this stream as “air jet”, and on basis of the work by Calvert (Calvert 1967) proposed that such bleeding increases the drag of a 3-dimensional bluff body over a gapless conical skirt. Kitta et al. (Kitta, Hasegawa et al. 2011) presented experimental result of a shuttlecock with gaps and with its gaps covered. It was concluded that gaps increase drag of a shuttlecock. Moreover, bleeding from the gaps reduced the flow over the outer surface of the skirt.

3.3 Coefficient of pressure

Surface pressure profile obtained from flow simulation for the gapless profile A was validated with experimental data. In general, comparative analysis between experimental data and simulation results show the simulation method to be reliable.

Outer surface pressure coefficient was validated against experimental data adopted from wind tunnel measurement by Cooke (Cooke 1992), as given in Figure 8. The pressure profile behind the cork follows closely to that obtained by Cooke (Cooke 1992) in the wind tunnel. Three observations were identified. Firstly, numerical data shows a small first peak at location of approximately 25mm, which is the region directly behind the leeward wall of the cork. In contrast, the experimental data has no peak in pressure immediately behind the cork. This is possibly due to the difference in lip area of the model that was used by Cooke (Cooke 1992). Interestingly, this peak and dip between the 25mm to 30mm chord location was also observed in the numerical data by Verma et al. (Verma, Desai et al. 2013). Secondly, it is noticed that the second pressure peak (between 30mm to 40mm along the chord) occurred earlier in the experimental data. This is because the gapless profile used in the numerical method was 85mm and thus, was 4mm longer than the model used in the experimental study. Lastly, it was noticed that unlike on the numerical result where pressure dips, experimental data shows that surface pressure rises towards the end of the skirt profile. This could be due to the difference in shuttlecock model where the physical model is a solid wood cone, while the numerical model is a thin wall hollow profile.

Numerical pressure coefficient of the inner surface was validated through experimental data obtained from the wind tunnel. In comparison with the numerical coefficient of pressure for

inner surface from Verma et al. (Verma, Desai et al. 2013), the result using the SST turbulence model shows larger negative pressure on the inner side of the gapless shuttlecock. Experimental result from measurement with physical model agrees with general trend and values that were observed with the flow simulation in this work. Comparison of the numerical and experimental results is presented in Figure 9. The increase in negative pressure after the 80mm point was also captured in experimental data.

3.3.1 Effect of gaps on the coefficient of pressure

Numerical pressure profiles of the six models at fully developed flow of 6m/s and 50m/s are presented in Figure 10, Figure 11, and Figure 12. These pressure profiles were obtained from both the inner and outer surface of the models. By comparison, strong positive pressure was observed along the outer surface of all models. Positive pressure on the outer surface increases drag force acting against the shuttlecock by resisting forward motion. Strong negative pressure was observed along the inner surface of the models. This negative pressure on the inner surface creates suction effect in the direction against the flow, thus increasing drag. As described by Verma et al. (Verma, Desai et al. 2013) , difference in outer and inner surface pressure creates the resultant drag.

Comparing the upper pressure distribution of the six different models show that gaps along the skirt has two significant effects. Firstly, the introduction of gaps resulted in an increase in the magnitude of the first pressure peak that occurs at the 20mm point on the plots. Although this pressure peak was already present in the gapless skirt, the introduction of gaps on the skirt with shuttlecock model B, C, D and E resulted in increased magnitude. The gaps also resulted in this peak occurring at an earlier point along the chordwise direction of the skirt. Interestingly, the

largest gaps, as seen in shuttlecock profile F, diminished the increase of the first pressure peak. This is likely contributed by the larger gaps that resulted in more bleeding through the skirt at the same chordwise position. The second impact of gaps on the outer surface is the increase in mid-chord pressure with growing gap size. It was observed that with increased gap size, the second pressure peak that occurs at approximately 43mm on the plot increases in magnitude. Moreover, pressure between the first and second pressure peak also increased significantly. This is the effect of gaps because such was not observed on the gapless profile A. Formation of the second pressure peak also resulted in elevated pressure on the outer surface after the gaps. This contributed to the increased drag that was observed over a gapless conical shuttlecock. With the exception of profile B, little variation was seen between the 50m/s plot and 6m/s plot of each model on the outer surface. Upper coefficient of pressure for profile B was observed to be lower at flow speed of 6m/s than at 50m/s.

Analysis of the inner pressure profiles showed three significant observations. Firstly, gaps on the skirt resulted in higher overall negative pressure in all instances. Drag increase with the presence of gaps was contributed by larger negative pressure on the inside of the shuttlecock model, in addition to the increased outer pressure. This is critical because drag characteristic of shuttlecocks is dominated by pressure drag. Secondly, formation of the two pressure dips (negative spikes) was noticed around the locations where the two positive pressure spikes were seen on the outer pressure profile. Similar to the outer pressure peaks, intensity of these two pressure dips increases with gap dimensions. However, unlike the outer surface where the first pressure peak was not the sole effect of gaps, both pressure drops on the inner pressure profiles were attributed by the gaps. This is because no spike was observed along the skirt on the inner side of the gapless profile A. The last observation is the rise in negative pressure towards the end

of the skirt. This was only observed on profile E and F, suggesting this to be an effect of the air jet that resulted from increased skirt porosity.

3.3.2 Further discussion on pressure profile

The pressure coefficient (50m/s) with respect to the chordwise position on the skirt of model E is plotted in Figure 13. Three distinct regions labeled 1, 2, and 3 are discussed. Dashed lines symbolize the cut plane of pressure plots. The first region occurring 28mm behind the tip of the cork (labeled 1), corresponds to an area of low negative pressure. This dip was observed on all the profile models, but to varying magnitude depending on the gap size. This phenomenon is akin to the low pressure region at the leeward back wall of flow around a blunt body, such as that observed by Stathopoulos and Zhou (Stathopoulos and Zhou 1993) , and Gomes et al. (Gomes, Moret Rodrigues et al. 2005). In (Gomes, Moret Rodrigues et al. 2005), flow fields around irregular shapes were studied. On faces in the leeward side, low negative pressure was recorded. Such was also observed in the region of the skirt directly behind the cork. A pressure plot in the X-Z plane corresponding to 28.3mm behind the tip of the cork is presented in Figure 14. Despite the presence of gaps, pressure plot shows that negative pressure around the vicinity of the outer side of the skirt remains consistent. Going outward in the radial direction, pressure increases rapidly beyond the diameter of the cork, suggesting the validity of treating the region to the immediate behind of the cork as similar to the wake behind a body. The lack of positive differential pressure between the inner and outer surface in this segment suggests that no drag is produced by this section of the skirt. This dip may not be observed if there is no lip located at the intersection of skirt and cork.

After the dip, magnitude of inner and outer pressure rises rapidly along the chord length of the skirt, reaching a peak after 34mm from the tip of cork. This large rise corresponds to region 2 in

Figure 13. This arises from the higher velocity flow, deflected by the cork, being incident onto the stems of the skirt. This is in contrast to region 1 where the free stream velocity is shielded by the cork. This is observed through the vector plot of the velocity flow field in Figure 15. The pressure plot in X-Z plane, given in Figure 16, shows the high pressure region to be concentrated around the stems between the gaps, while pressure between the gaps is much lower. This means that air bleed through the gap, increasing the overall skirt porosity of the model, as also observed in Figure 15.

Surface pressure on the outer surface remains high between region 2 and 3 of the surface pressure plot. Pressure difference between the inner and outer surface at this section of the skirt is large, contributing significantly to the pressure drag that is dominant for a blunt body, such as the shuttlecock model. Towards region 3, pressure increases along the chord of the skirt on the outer surface, peaking at the edge of the gap on the skirt, as seen in Figure 13. Pressure plot before (Figure 17) and at the end of the gap locations (Figure 18) showed localized high-pressure region around the stems. This suggests that blockage effect of the stem continues to be significant. As seen from the pressure profile, outer pressure peaks at region 3 where the gaps are discontinued on the skirt. This is likely due to the sudden increase in blockage when the air has to choose between a path that goes inward into the skirt or outward around the skirt. The effect is similar to an angled plate in a free stream, almost like a second stagnation point albeit to a smaller magnitude. Such pressure peak is not observed on a gapless cone because the full blockage earlier upstream resulted in the formation of a lower velocity layer that follows the contour of the skirt, similar to a viscous sub-layer along a plate. Beyond region 3, little difference is observed from a gapless skirt.

4. Conclusion

The numerical approach to evaluate the drag characteristic of shuttlecock models with gaps was conducted with SST model. This was achieved by comparison of five profiles with gaps and a reference gapless shuttlecock. To understand further the fundamentals, the wake vector plots, pressure profiles, and velocity plots were studied. Numerical results of the gapless shuttlecock were validated against experimental work to substantiate the simulation method. Major findings include:

1. The gapless skirt has lower drag than the average badminton shuttlecock. The presence of gaps along the skirt increased drag force significantly, even beyond that of a standard shuttlecock. The largest drag increase that was observed was 45.2% over a gapless shuttlecock. For gaps larger than the critical gap size, drag force decreases with increasing gap size. It is likely that this is due to the increasing skirt porosity that is reducing the blunt body effect. Pressure drag remains the dominant drag component regardless of gap sizes.
2. The gapless shuttlecock exhibited a wake similar to a blunt body, where recirculation vortices and flow reversal are observed. Key features of the wake reduce in intensity with the introduction of gaps along the skirt. Beyond the critical gap size, formation of air jet was observed instead of the recirculation effect in the wake of a blunt body. This again is due to the increased skirt porosity, reinforcing the idea that beyond the critical gap size, blunt body effect is significantly diminished.
3. Comparative analysis of the pressure profiles shows the fundamental effect of gaps. A flat line inner pressure was observed for the reference gapless profile A. Introduction of gaps resulted in spikes at various locations that were discussed. Magnitude of pressure on inner and outer surface also increased with larger gap size despite the increased bleeding.

It is possible that the gaps prevented the formation of a lower velocity sub-layer that adheres to the contour of the gapless skirt, as observed on the velocity plot.

References

- Alam, F., H. Chowdhury, et al. (2010). "Measurements of aerodynamic properties of badminton shuttlecocks." *Procedia Engineering* 2(2): 2487-2492.
- Alam, F., H. Chowdhury, et al. (2009). "Aerodynamic properties of badminton shuttlecock." *International journal of mechanical and materials engineering* 4(3): 266-272.
- Bertin, J. J. and R. M. Cummings (2009). *Aerodynamics for engineers*. Upper saddle river, NJ, Pearson Prentice-Hall.
- BWF (1988). "Badminton World Federation equipment approval scheme (shuttlecock)." Retrieved from <http://www.bwfbadminton.org/file.aspx?id=473031&dl=1>
- Calvert, J. R. (1967). *The separated flow behind axially symmetric bodies*. PhD thesis, Cambridge University.
- Chan, C. M. and J. S. Rossmann (2012). "Badminton shuttlecock aerodynamics: synthesizing experiment and theory." *Sports Engineering* 15(2): 61-71.
- Chok, C., S. Parameswaran, et al. (1994). "Numerical investigation of the effects of base slant on the wake pattery and drag of three-dimensional bluff bodies with a rear blunt end." *Journal of wind engineering and industrial aerodynamics* 51: 269-285.
- Cooke, A. (1999). "Shuttlecock aerodynamics." *Sports engineering (International sports engineering association)* 2: 85-96.
- Cooke, A. J. (1992). *The aerodynamics and mechanics of shuttlecocks*. Doctor of Philosophy, University of Cambridge.
- Cooke, A. J. (1996). *Shuttlecock design and development*. Sports engineering- Design and development. S. J. Haake. Balkeman, Rotterdam, Blackwell Science.
- Cooke, A. J. (2002). "Computer simulation of shuttlecock trajectories." *Sports engineering (International sports engineering association)* 5(2): 93-105.
- Gomes, M. G., A. Moret Rodrigues, et al. (2005). "Experimental and numerical study of wind pressures on irregular-plan shapes." *Journal of wind engineering and industrial aerodynamics* 93(10): 741-756.
- Hu, L. H., X. Y. Zhao, et al. (2012). "An experimental investigation and characterization on flame bifurcation and leaning transition behavior of a pool fire in near wake of a square cylinder." *International Journal of Heat and Mass Transfer* 55(23-24): 7024-7035.
- Kitta, S., H. Hasegawa, et al. (2011). "Aerodynamic properties of a shuttlecock with spin at high Reynolds number." *Procedia Engineering* 13: 271-277.
- Lin, C. S. H., C. K. Chua, et al. (2013). "Design of high performance badminton shuttlecocks; virtual and rapid prototyping approach." *Journal Virtual and Physical Prototyping* 8(2): 165-171.
- Nakagawa, K., H. Hasegawa, et al. (2012). "Aerodynamic Properties and Flow Behavior for a Badminton Shuttlecock with Spin at High Reynolds Numbers." *Procedia Engineering* 34: 104-109.
- Stathopoulos, T. and Y. S. Zhou (1993). "Numerical simulation of wind-induced pressures on buildings of various geometries." *Journal of wind engineering and industrial aerodynamics* 46 & 47: 419-430.
- Verma, A., A. Desai, et al. (2013). "Aerodynamics of badminton shuttlecocks." *Journal of fluids and structures*.

Figure 1 Graphical description of the conical model without gap and model with gap. All dimensions are in mm.

Figure 2 Cylindrical fluid domain enclosing the shuttlecock profile.

Figure 3 Gapless shuttlecock profile A fabricated through rapid prototyping method.

Figure 4 Numerical drag coefficient recorded for the profiles at various airspeeds.

Figure 5 Effect of gap on the resultant numerical drag force at 50m/s flow speed. A design curve that can predict the drag characteristic of gaps.

Figure 6 Vector plot of the wake of the various shuttlecock profiles that were studied. Free stream velocity is 50m/s.

Figure 7 Effect of gap size on skirt porosity. Increased bleeding through the skirt is observed as gap size grows. Shown is the planar view of velocity plot under free stream velocity of 50m/s.

Figure 8 Comparison between experimental and numerical data of outer surface pressure coefficient along the gapless shuttlecock.

Figure 9 Numerical and experimental inner pressure coefficient along the gapless profile A.

Figure 10 Plot of numerical pressure coefficient for profile A and profile B. The upper line is the outer surface, while the bottom one is for the inner surface.

Figure 11 Plot of numerical pressure coefficient for profile C and profile D. The upper line is the outer surface, while the bottom one is for the inner surface.

Figure 12 Plot of numerical pressure coefficient for profile E and profile F. The upper line is the outer surface, while the bottom one is for the inner surface.

Figure 13 Skirt pressure profile with respect to the distance behind the cork for model E at 50m/s. The chord distance scale has been superimposed onto the shuttlecock diagram for visual representation and is representative of the actual chord location on the skirt.

Figure 14 Pressure plot of flow field around the shuttlecock at 28.3mm behind the tip of the cork, corresponding to position 1 on the pressure plot. Clip plane was set to 29.2mm.

Figure 15 Velocity vectors showing the deflection of airflow around the cork.

Figure 16 Pressure plot in X-Z plane at 34.3mm behind the tip of the cork, corresponding to position 2 on the pressure plot. Clip plane was set to 35.1mm.

Figure 17 Pressure plot in X-Z plane at 57.3mm behind the tip of the cork, approaching the edge of the gap. Clip plane was set to 57.5mm.

Figure 18 Pressure plot in X-Z plane at 59.8mm behind the tip of the cork, where the gap pattern terminates and pressure peaks on the outer surface.

Profile	Width X/mm	Height H/mm	Surface area/mm ²	Surface area reduction
A	N.A.	N.A.	8420	0.00%
B	2	20	7865	6.59%
C	2	40	7551	10.32%
D	4	40	6910	17.93%
E	6	40	6268	25.56%
F	7.5	40	5784	31.31%

Table 1 Dimensions and areas of gaps for the various models.

Profile	Applied mesh	Drag force(N)	Refined mesh	Drag force(N)	Difference %
	Number of elements		Number of elements		
A	3.50mil	2.61	5.95mil	2.63	-0.77
B	4.04mil	3.08	6.02mil	3.26	-5.84
C	4.02 mil	3.39	5.99mil	3.56	-5.01
D	4.08mil	4.04	5.83mil	4.14	-2.48
E	3.99 mil	3.80	5.61mil	3.72	2.11
F	3.86mil	3.49	5.56mil	3.31	5.16

Table 2 Comparative analysis of numerical drag force to check for grid independency. Drag forces were recorded after 100 iterations.

	Pressure drag as percentage of overall drag force at each simulation flow velocity			
	6m/s	15m/s	30m/s	50m/s
Profile A	94.3%	95.8%	96.7%	97.1%
Profile B	94.3%	96.2%	97.0%	97.7%
Profile C	93.5%	95.6%	96.7%	97.2%
Profile D	93.8%	96.0%	96.9%	97.4%
Profile E	94.1%	96.4%	97.4%	97.8%
Profile F	94.7%	96.8%	97.7%	98.1%

Table 3 Pressure drag as a percentage of the overall drag force acting against the various models at each simulation speed.

Profile	Airspeed		Wind tunnel (experimental)
	(m/s)	CFD (numerical)	
A	15	0.509	0.501
	30	0.513	0.497
	50	0.514	0.491
C	15	0.665	0.612
	30	0.667	0.611
	50	0.667	0.606
E	15	0.739	0.658
	30	0.743	0.714
	50	0.734	0.728

Table 4 Coefficient of drag obtained through numerical and experimental methods.