A Comparative Study on Aerodynamic Drag Reduction of a Blunt Nose Body using Aerospike and Aerodisk – Numerical Approach

Senthilkumar S*, Aarohi Anmol Mudholkar and Sanjay K J
Department of Aerospace Engineering, SRM Institute of Science and Technology, Kaatankulathur, Chennai, India – 603203.

*E-mail: s.senthilms@gmail.com/senthils7@srmist.edu.in

A spike attached to a hemispherical body drastically changes its flow field and influences aerodynamic drag in supersonic and hypersonic flow. It is, therefore a potential candidate for drag reduction of a future high-speed vehicle. The effect of spike nose configuration and angle of attack on the reduction of drag is studied. The studies show that the aerodisk is superior to the aerospike. The aerodisk of appropriate length, diameter and nose configuration may have the capability for the drag reduction. Design criteria is studied and the aerodisk attached to the blunt nose body are designed using CATIA. Numerical solutions are obtained using a commercial CFD software ANSYS-Fluent. Flow observations on the blunt body with a conical, hemispherical aerodisk and flat-faced aerodisk are carried out at Mach number of 2. The flow fields show different flow features between the conical spike, the hemispherical aerodisk and the flat-faced aerodisk. The effects of the aerospike and aerodisk on the lift and drag coefficient are studied. Finally, it is found that A forward-facing spike attached to a hemispherical body alters significantly the structure of the flow field and serves to reduce drag by the formation of a recirculation region around the stagnation point of the blunt body. The flow field, immediately behind the aerodisk shows a complex flow field due to back-disk geometry as compared to the conical spike. To take advantage of the forward-facing spike for more efficient drag reduction, the reattachment point of the shear layer on the body should be moved backward by choosing the optimal spike length with suitable geometrical configuration of the nose.

1. Introduction
Aerodynamic drag reduction in supersonic vehicles has been achieved through various techniques in order to enhance aerodynamic performance for safer flight and to reduce fuel consumption. Several research studies have been devoted to use aerospike which a kind of needle like body attached at the tip of the blunt nose bodies. Aerospikes of different shapes with a disk is attached at the tip of the spike. In all these cases, the drag was reduced through two mechanisms as follows:

1. Replacing the strong detached bow shock ahead of the blunt body by a much weaker oblique foreshock.
2. Encouraging separation of the flow downstream of the foreshock and creating a recirculation
zone that screens a large portion of the main body nose surface.

The effects of forward-facing spike at hypersonic speeds have been studied since the late 1940’s. It was found that spike geometrical parameters such as length, head dimensions, forward body geometry and spike diameter have significant effects on drag characteristics. The research on this area got a great attention due to its practical importance in several application in both the supersonic and hypersonic vehicles such as re-entry capsules etc. There have been several studies performed experimentally (Bogdonoff and Vas [1], Peter Reding et al. [2], Maull [3]) Milicic et al. [4], Stadler J R and Nielsen N D [5], Wood C [6]) and numerically (Yamauchi et al. [7]) in order to understand the flow unsteadiness, adverse pressure gradient, shock/boundary-layer interaction and drag reduction mechanisms by changing the aerospike geometrical parameters and configurations namely aerospike and aerodisk for various Mach numbers and Reynolds numbers.

Figure 1. Flow field over a blunt body with conical spike (Left) and a blunt body with aerodisk (Right) at zero angle of attack [8].

Kalimuthu et al. [8] have experimentally studied the aerodynamics characteristics of different spike configurations at a Mach number of 6 for three angles of attack (α = 0° - 8°). They presented the schlieren flow patterns showing recirculation zone formation, interaction between bow shock and reattachment shock and explained the mechanism behind the drag reduction. They also found that the drag reduction mechanism is different for aerospike and aerodisk configurations and that it changes with the angle of attack.

Crawford D C [9] performed experiment to study the flow and heat transfer over aerospiked geometry for a Mach number of 6.7 and found that the changing the length has a significant effect on heat flux where it doesn’t have any influence on drag reduction when the length exceeds by roughly four times of the blunt body diameter. Motoyama et al. [10] have performed experiment to investigate both the flow and heat transfer characteristics of different aerospike and aerodisk shapes for a Mach number of 7 with angle-of-attack ranging from 0° to 8°. They found that the aerodisk having length to diameter equals to 1 has a superior drag reduction capability as compared to the other configurations. Wysocki et al. [11] carried out an experimental study of a wave drag reducing device at slender bodies by means of a self-aligning aerospike. The self-aligning aerospike was allowed to pitch freely around its mounting axis and aligned itself automatically with the oncoming flow direction with the help of two vanes. This revealed that the total drag of the blunt-nosed slender body had been reduced by up to 30% at the highest Mach number M=2.2 and zero angle of attack. The results of the two lower Mach numbers (M=1.4 and M=1.8) show smaller drag reduction rates (about 22-25%). However, both static and
dynamic test results show that the spike was able to reduce the wave drag over a wide range of angles of attack. Kobayashi et al. [12] conducted supersonic and hypersonic wind tunnel experiments on fixed geometry aerospikes to evaluate the effects of geometric parameters like spike length and number of disks on telescopic aerospikes. Two separate variations were carried out. For the fixed length aerospikes, the angle of attack was varied from -6° to 14° and the test models had variations that included configurations such as an aerospike with no disk, single disk, three disks and six disks tested at Mach numbers ranging from Mach 1.5 to Mach 5.1. For the second test including the telescopic aerospikes, the spike length could be changed by 50mm to measure the variations across Mach numbers from 1.5 to 3.0 and angles of attack ranging from 0° to 4°. The main conclusion to be drawn from this was that adding disks was an effective measure for decreasing zero-lift drag and induced drag. To explain the mechanism of drag reduction caused by a spike on a blunt nose by analyzing the interactions between oblique shock, separation shock and re-attachment shock and to assess the impact of varying the spike length (L/D = 0.5, 1.0, 1.5), angle of attack (up to 10°) and Mach number (up to M=3), Khan et al. [13] carried out a numerical modelling. They found that the spike reduces drag up to 42% (for L/D=1.0 and at zero angle of attack). For higher angles of attack, the drag reduction effect is not very useful. Interestingly, the drag reducing efficiency of the spike depends largely on the spike length; however, the length does not influence the aerodynamic coefficients after it exceeds the blunt body diameter ratio of 1.0. Menezes et al. [14] attempted to study experimentally the effectiveness of different types of aerospike/aerodisk assemblies at hypersonic flow regimes over highly blunted cones as retractable drag-reduction devices. It was found that spikes without aerodisks did not result in a noticeable reduction in drag while a drag reduction of around 40- 55% was measured for 120 deg apex-angle blunt cone for small angles of attack at Mach 5.75. There was also an observation made about heat transfer rate fluctuations that finally indicated the oscillatory behavior of the separation bubble. A similar experimental study was done by Kulkarni et al. [15] as a continuation study to Reference [14]. This study evaluated the flat-disc-tipped aerospike configuration’s effect on drag of 120 deg apex-angle blunt cone under various total enthalpy conditions (lower enthalpies of 1.1 and 1.5 MJ/kg and higher enthalpy of 5 MJ/kg). The testing revealed that the configuration consistently reduced the wave drag on the cone by about 57% for various freestream stagnation enthalpies. Hence, the effectiveness of the aerospike configuration used for reducing drag was independent of stagnation enthalpy. The effects of aerospike geometry on the drag reduction and heat transfer rates were investigated by Srinath et al. [16] on a large-angle blunt cone flying at hypersonic Mach numbers of 5.75 to 7.9 for different angles of attack. It was found that telescopic aerospike is effective in drag reduction at higher angles of attack and that the heat transfer rates, though decreased with the help of aerospike, need to be studied further. Deng et al. [17] carried out a computational study using the RANS equations of aerospike and counterflowing jet as the drag-reduction approach of a hypersonic lifting-body model from Mach 8 flow at various angles of attack (0° to 4°) focusing on an unstable oscillation phenomenon of the counterflowing jet – LPM. The results showed that the counterflowing jet proved to be more useful as compared to the aerospike when it came to decrease in shock- wave amplitude and pressure values of the nose. The drag reduction for the nose with the aerospike and the counterflowing jet was 70% and 66% respectively at zero angle of attack, while it is 7.25% and 8.8% respectively at 6° angle of attack. Due to the parameters of reusability and heating, the counterflow jet was considered to be more suitable for passive flow control while in active flow control, the counterflow jet was the clear winner. Kalimuthu R and Rathakrishnan E [18] carried out experimental studies on blunt nose body with and without spike at Mach 6 for bodies with varying L/D ratios – 1.5 and 2.0. For these configurations, a drag reduction of 63% and 78% respectively was noted when the spike was used. They were found to cause an increase in lift and pitching moment which led to better stability for the vehicle. It also gave an advantage of non-linear drag reduction at varying angles of attack (from 0° to 8°). Ryizhov et al. [19]
studied, numerically and experimentally, the interaction between transonic and supersonic flows and investigated the wave drag and flow field independence on fan-shaped-jet (FSJ) intensity, the location of FSJ on aerospike, the length of the spike and the angle of incidence. It was found that the FSJ were capable of about 30% drag reduction and in combination with the aerospike, showed vast protentional for transonic drag reduction.

From the literature review, it is understood that there is no comparative aerodynamic numerical study available between blunt body with aerospike and blunt body with aerodisk configurations for a Mach number of 2. Hence the objective of the present study is to numerically study the aerodynamic performance of these configurations and to find out a better blunt body configuration when the Mach number equals to 2. Numerical studies are performed to predict the aerodynamic characteristics of blunt body with a conical aerospike and flat-faced and hemispherical aerodisks configurations for a free stream Mach number of 2 with three angles of attack (from 0° to 8°).

2. Numerical Methodology

2.1 Design and Mesh Generation
The design process is carried out using the 3D design software, CATIA and the computational domain is shown in Fig. 2. The four models are designed along with the domain, namely blunt body, blunt body with conical aerospike, blunt body with hemisphere aerodisk, and blunt body with flat-face aerodisk., as shown in Fig. 2. The main blunt body has a hemisphere-cylinder nose and the spike has both the conical part and cylinder parts. The cylinder shape of the spike has 0.1D times diameter of the main blunt body and its spike length is 2.0D.

The cone angle of conical spike is 15°. The aerodisk type spike configuration has a disk at the tip of the spike with a node radius of 0.1D. Similarly, the radius of the aerodisk is 0.05D. The diameter ‘D’ is taken as 20 mm. It is known that in order to simulate high speed external flows over bodies, a closed and large computation domain is required with the pressure far-field boundary conditions on the outer domain as depicted in Fig. 3. Thus, the length of the domain is chosen as 24C and the width as 20C, where C is the length of the model. Non-orthogonal mesh size of around 0.25 million is used for discretizing the computational domain as shown in Fig. 4.

2.2 Numerical Analysis
The governing equations for the present turbulent flow simulation include the 2D, steady, continuity, momentum and energy equations along with the equation of state and turbulent kinetic energy (k) and turbulent dissipation rate (epsilon) equations. For turbulent modelling, two-equation RNG k-epsilon closure model is used. Numerical simulations are performed via coupled solver and the temperature dependent viscosity is calculated through the Sutherland formulation. Air is used as the fluid with ideal gas fluid property assumptions. Non-orthogonal mesh size of around 0.25 million is used for discretizing the computational domain. The pressure far-field boundary condition and no-slip boundary condition are used for the outer domain and walls of the computational model, respectively. The residuals for solving the discretized governing equations in all the simulations are set to $1 \times 10^{-5}$. The simulation is carried out for three angles of attack ($\theta = 0^\circ, 5^\circ, 8^\circ$) for the Mach number of 2.
Figure 2. Computational Domain

Figure 3. Computational Models: (a) Blunt body (b) Blunt body with conical aerospike (c) Blunt body with hemisphere aerodisk (d) Blunt body with flat-Face aerodisk
3. Results and Discussion

The static pressure and Mach number contours are captured to visualize the flow field patterns for different shapes of spike such as conical, hemispherical disk and flat-face spikes and to understand the mechanism of the drag reduction. The variation of drag and lift coefficients with the angles of attack are measured for different spike configurations and the results are present in this section.

3.1 Prediction of Flow Field

The flow fields are depicted in terms of the static pressure and Mach number contours over the surface of the models at three angles of attack ($\theta = 0^\circ, 5^\circ, 8^\circ$) in Figs. 5 to 14. In the contour plots reveal the flow field and the formation of shock waves clearly in both the upper and lower sides of the models. At higher angles-of-attack, the flow separation is more which causes increase in drag. The captured flow fields over the designed models at 0° angle-of-attack in supersonic Mach 2 are shown in Figs. 4 -11. It can be seen that the flow field is symmetric around the model in all the configurations for 0° angle-of-attack. However, the flow fields are very different between the aerospikes of conical, hemispherical aerodisk and flat-faced aerodisk as seen in the contour plots.
Figs. 12 and 13 show the contours of the static pressure and Mach number for $5^\circ$ angle-of-attack and $8^\circ$ angle-of-attack, respectively. It can be observed that the flow becomes asymmetric for all the cases when the flow is exposed to the non-zero angles of attack which induces lift force over the models as predicted in Figs. 14-16.

**Figure 6.** Left: Mach number contours for blunt body at $0^\circ$ and Right: Zoomed view

**Figure 7.** Left: Static pressure contours for blunt body with conical aerospike at $0^\circ$ and Right: Zoomed view

**Figure 8.** Left: Mach number contours for blunt body with conical aerospike at $0^\circ$ and Right: Zoomed view
Figure 9. Left: Static pressure contours for blunt body with hemisphere aerodisk at 0° and Right: Zoomed view

Figure 10. Left: Mach number contours for blunt body with hemisphere aerodisk at 0° and Right: Zoomed view

Figure 11. Left: Static pressure contours for blunt body with flat-face aerodisk at 0° and Right:
In the conical spike case, the shock wave emanating from the spike is conical in shape due to the spike nose. Figs. 6, 7, 12 and 13 clearly show the flow pattern including the separated shear layer and shock wave from the reattachment point on the shoulder of the blunt body.

In the aerodisk case, the bow shock wave is standing far away from the blunt body. The bow shock wave pattern changes with the angle-of-attack for the same blunt body configurations. From Figs. 8, 9, 12 and 13, it can be seen that the recirculation zone created in front of blunt body starts behind the aerodisk and reattaches on the shoulder of the blunt body. It is observed that a separation shock wave is formed between recirculation zone and bow shock and that there is an interaction between the reattachment shock developed from the blunt body and bow shock. The interaction between the bow shock and the shock waves produced by the hemispherical aerodisk is significantly different with that of the conical spike. It is evident that the flow fields including the separation mechanism, the recirculation zone formation and the interaction between bow shock and reattachment shock are changing with respect to the shape of aero spike. The changes in the size of the recirculation alters the drag values substantially and the drag is reduced as the size of separation region over the aerodisk type spike increases. This can be attributed by a fact that the pressure at the stagnation point is reduced due to the recirculation formation which is evident from Figs. 4,6,8,10, 12 and 13.

The geometrical effect of spike configurations can be observed through the decrement in drag value from Table 1 that flat- faced aerodisk has more reduction in drag as compared with other cases which is due to the fact the cap radius of the flat-faced spike is larger among all the cases. (see Table 1). The recirculation zone size is also increased as the radius of the aerospike cap increases which is evident from the contour plots of pressure as shown in Figs. 6-13.

The present results are qualitatively consistent with those of experimental study performed by Kalimuth et al. [8]. The flow field observations are in similar patterns that in the fore region of the aerodisk, the fluid is decelerating through the bow shock wave and at the shoulder of the aerodisk or aerospike, the flow is expanding rapidly. It is also found that there is a boundary layer separation behind the aerodisk or spike which causes a shear layer formation that separates the inner re-circulating flow region from the outer inviscid flow field. And also, the flow becomes asymmetric as the angle-of-attack increases which is responsible in changing the aerodynamics characteristics. The lift coefficient increases (see Figs 14-16) and the drag coefficient decreases with the increase in angle-of-attack as listed in Table 1.
| Model                      | Static Pressure Contour | Mach Number Contour |
|----------------------------|--------------------------|---------------------|
| Blunt Body                 | ![Static Pressure Contour](image1.png) | ![Mach Number Contour](image2.png) |
| Blunt body with conical aerospike | ![Static Pressure Contour](image3.png) | ![Mach Number Contour](image4.png) |
| Blunt body with hemisphere aerodisk | ![Static Pressure Contour](image5.png) | ![Mach Number Contour](image6.png) |
Blunt body with flat-face aerodisk

Figure 13. Contours of static pressure and Mach number for various blunt body models kept at 5° angle of attack.

| Model                          | Static Pressure Contour | Mach Number Contour |
|--------------------------------|-------------------------|---------------------|
| Blunt Body                     | ![Static Pressure Contour](image1) | ![Mach Number Contour](image2) |
| Blunt body with conical aerospike | ![Static Pressure Contour](image3) | ![Mach Number Contour](image4) |
3.2 Aerodynamic Characteristics

The lift and drag coefficients are calculated for various blunt body configurations with three different angles of attack. The plots shown in Figs. 15-17 show the increment in lift coefficient is obtained after attaching a conical aerospike, hemisphere aerodisk and flat-face aerodisk. However, this effect is more pronounced in the case of conical aerospike as compared with aerodisk configurations for all angles of attack. This can be attributed by a fact that the size of high-pressure region on the lower side of conical aerospike is bigger and increases with the angle of attack as shown in Figs. 13 and 14 which causes the increment in the lift value where this high-pressure region is smaller in the aerodisk cases.

Figure 14. Contours of static pressure and Mach number for various blunt body models kept at 8° angle of attack.

Figure 15. Lift coefficient variation for conical aerospike
Figure 16. Lift coefficient variation for hemisphere aerodisk

Figure 17. Lift coefficient variation for flat-face aerodisk
| Body\Angle of attack (deg) | Drag Coefficient | 0      | 5      | 8      |
|---------------------------|------------------|--------|--------|--------|
| Blunt Body (Baseline)    | Cd               | 0.03213| 0.03199| 0.03332|
| Blunt Body with Conical Aerospike | Cd               | 0.02209| 0.02283| 0.02138|
|                           | Drag Reduction (%)| 31.23  | 28.64  | 35.82  |
| Blunt Body with Hemispherical Aerodisk | Cd               | 0.01553| 0.01562| 0.01569|
|                           | Drag Reduction (%)| 51.66  | 51.15  | 52.89  |
| Blunt Body with Flat Face Aerodisk | Cd               | 0.01464| 0.01515| 0.01564|
|                           | Drag Reduction (%)| 54.43  | 52.64  | 53.06  |

From Table 1, it can be observed that there is major decrement in drag after attaching the conical aerospike, hemisphere aerodisk and flat-face aerodisk. However, as in comparison of aerodisk with aerospike configurations, it is clearly visible that, the aerodisk is better than aerospike. In all the cases, the flat-face aerodisk produces better results than conical aerospike. Hemisphere aerodisk also reduces the drag to the same extent as flat-face aerodisk does. The aerodynamic drag reduction would eventually help in reducing the fuel consumption of aerospace vehicle at supersonic speed conditions.

4. Conclusion

A combative study is carried out numerically for a supersonic flow over the blunt body with a conical aerospike, hemispherical aerodisk and flat-faced aerodisk with three angles of attack. The flow patterns are presented in terms of pressure and Mach number. It is found that flow field has substantially affected by the shape of the aerospike configurations and angle of attack. The effects of the aerospike and aerodisk on the lift and drag coefficient are studied. It is found that when the flow becomes asymmetric due to increase in angle of attack, the lift coefficient is increased. The reduction in drag is also increased from plain blunt body to flat-facing aerodisk.

Hence, the flat-facing aerodisk attached to the blunt body has the highest drag reduction capability among all the configurations considered in the present study which can be attributed by a fact that the recirculation region formed behind the spike is bigger in size for this case which causes more pressure reduction at the stagnation point of the blunt body which in turn reduces the drag.

The reduction in drag through these aerodisks configurations would help to achieve better fuel consumption for high speed aerospace vehicles. This study can be extended to 3D analysis to get more
insights into flow physics and understand the effects of dimensions on flow features which are coupled with drag reduction mechanism.

References

[1] Bogdonoff S M and Vas I E 1959 Preliminary Investigations of Spiked Bodies at Hypersonic Speeds, *Journal of the Aerospace Sciences* vol. 26, pp 65-74
[2] Peter Reding J, Guenther R A and Richter B J 1977 Unsteady aerodynamic considerations in the design of a drag-reduction spike *Journal of Spacecraft and Rockets* vol. 14, pp 54-60
[3] Maull D J 1960 Hypersonic flow over axially symmetric spiked bodies *Journal of Fluid Mechanics* vol. 8(4), pp 584-592
[4] Milićev S S, Pavlović M D, Ristić S and Vitić A 2002 On the Influence of Spike Shape at Supersonic Flow past Blunt Bodies *Facta Universitatis series: Mechanics, Automatic Control and Robotics* - 55317418 (facta.junis.ni.ac.rs/macar/macar2002/macar2002-06.pdf)
[5] Stadler J R and Nielsen H V 1954 Heat transfer from a hemisphere cylinder equipped with flow- separation spikes *NASA Technical Report Server* 19930083996, NACA-TN-3287
[6] Wood C 1962 Hypersonic flow over spiked cones *Journal of Fluid Mechanics* vol. 12(4), pp 614-624
[7] Yamauchi M, Fujii K and Higashino F 1995 Numerical investigation of supersonic flows around a spiked blunt body *Journal of Spacecraft and Rockets* vol. 32, pp 32-42
[8] Kalimuthu R, Mehta R C and Rathakrishnan E 2008 Experimental investigation on spiked body in hypersonic flow *The Aeronautical Journal* vol. 112(1136), pp 593-598
[9] Crawford D H 1959 *Investigation of the flow over a spiked-nose hemisphere- cylinder at a Mach number of 6.8* (Washington: National Aeronautics and Space Administration)
[10] Motoyama N, Mihara K, Miyajima R, Watanuki T and Kubota H 2001 Thermal protection and drag reduction with use of spike in hypersonic flow *10th AIAA/NAL-NASDA-ISAS International Space Planes and Hypersonic Systems and Technologies Conference* (doi.org/10.2514/6.2001-1828)
[11] Wysocki O, Schülein E and Schnepf C 2014 Experimental study on wave drag reduction at slender bodies by a self-aligning aerospike *Notes on Numerical Fluid Mechanics and Multidisciplinary Design* vol. 124
[12] Kobayashi H, Maru Y and Fukiba K 2007 Experimental study on aerodynamic characteristics of telescopic aerospikes with multiple disks *Journal of Spacecraft and Rockets* vol. 44, pp 33-41
[13] Khan S A, Asadullah M, Fharukh Ahmed G M, Jalaluddeen A and Baig M A A 2018 Flow control with aerospike behind bluff body *International Journal of Mechanical and Production Engineering Research and Development* vol. 8-3, pp 1001-1008
[14] Menezes V, Saravanan S, Jagadeesh G and Reddy K P 2003 Experimental Investigations of Hypersonic Flow over Highly Blunted Cones with Aerospikes *AIAA Journal* vol. 41, pp 1955-1966
[15] Kulkarni V, Menezes V and Reddy K P J 2010 Effectiveness of aerospike for drag reduction on a blunt cone in hypersonic flow *Journal of Spacecraft and Rockets* vol. 47, pp 542-544
[16] Srinath S and Reddy K P J 2010 Experimental Investigation of the Effects of Aerospike Geometry on Aerodynamic Drag and Heat Transfer Rates for a Blunt Body Configuration at Hypersonic Mach Numbers *International Journal of Hypersonics* vol. 1(2) (dx.doi.org/10.1260/1759-3107.1.2.93)

[17] Deng F, Xie F, Qin N, Huang W, Wang L and Chu H 2018 Drag reduction investigation for hypersonic lifting-body vehicles with aerospike and long penetration mode counterflowing jet *Aerospace Science and Technology* vol. 76, pp 361-373

[18] Kalimuthu R and Rathakrishnan E 2008 Aerospike for drag reduction in hypersonic flow *44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit* (doi.org/10.2514/6.2008-4707)

[19] Ryizhov E, Yuriev A and Tsvetkov O 1999 Interaction between trans- and supersonic flow and fan- shaped jets injected from nose aerospike *9th International Space Planes and Hypersonic Systems and Technologies Conference* (doi.org/10.2514/6.1999-4950)