Innovative Techniques of Drag Reduction over Blunt Bodies at varied Angles of Attack in Supersonic Flow

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ABSTRACT

Better thermal management capability of blunt nose body results in a paradigm shift in the hypersonic vehicles’ design. The aerospace vehicles flying at high Mach numbers are intentionally designed to have blunt-nose to reduce the aerothermodynamic heating. However, the advantages of heat shielding due to blunt shape does not stand alone but comes with associated wave drag penalty due to the formation of bow-shock in front of the blunt nose. Different active and passive techniques are employed to deal with this drag penalty associated. A forward facing aero-spike attached to a blunt body is an active control technique and has been found to change the flow field and aerodynamic drag significantly. These forward facing spikes lead to flow separation as well as they also weaken the shock ahead of the blunt nose. Consequently, the dynamic pressure in the recirculation area, and thus aerodynamic drag, is reduced significantly. The capability of spikes in drag reduction varies with their shapes and types. The breathing blunt nose is a passive technique and it reduces the drag on the body by manipulating the high pressure at the nose and low pressure at the base simultaneously. In the present investigation, the flow field computations over a forward facing conical spike, hemispherical aero-disk and flat faced aero-disk attached to the blunt body and over breathing blunt nose have been carried out at Mach 2.0 flow regime. The efficacy of these different configurations on the reduction of drag is numerically calculated and presented through contours and graphs at Mach 2 with angles of attack 0, 2, 5 and 8 degrees. Numerical simulation is carried out using CFD software with SST $k – \omega$ turbulence model adopted. The hemispherical aero-disk configuration attached to blunt nose is found to be more efficient in reducing pressure in the vicinity of blunt nose, while the flat faced aerodisk works more efficiently in reducing peak pressure as compared to other configurations. However, from the plots of lift to drag ratio variation with angle of attack, the conical spike is observed to have highest lift to drag ratio at particular angle of attack and thus can be treated the most desired configuration.

Keywords: Shock wave, Wave drag, Spikes, Blunt body, Breathing blunt nose.

1. INTRODUCTION

The realization of the fact that a blunt body actually results in relatively less heating to the body as compared to the sharp, slender body result in a paradigm shift in spacecraft design. A blunt shape (high drag) causes the effective heat shield. These blunt shape of the vehicle acts as an air cushion and does not let the air to get out of the way quickly enough, thus it pushes the shock wave and heated shock layer forward (away from the vehicle). Since most of the hot gases are no longer in direct contact with the vehicle, thus the heat energy will remain in the gas and simply will move...
around the vehicle to later dissipate in the atmosphere. Thus, the flying vehicles like space planes, missiles, reusable launch vehicles, etc., which fly at high speed generally employ the blunt nose bodies to provide better thermal management. However, this benefit in thermal management comes with a penalty of drag associated with blunt nose configuration. The blunt body in high-speed vehicles results in the formation of the bow shock wave, which compresses the air and thus forms a high-pressure region in the vicinity of the blunt body. The generation of this high-pressure region in the foremost part of the blunt body leads to a high wave drag. Thus, the reduction of drag is one of the major considerations for vehicles with a blunt nose. There are research already done since the 1940s and still going on, to employ a different methodology to reduce drag over the vehicle. The main task is to achieve low-pressure difference between front and the aft portion of the body.

There are different techniques available to reduce the pressure, created by the strong bow shock waves. One of the favorable technique is to attach forward facing spikes to the hemispherical blunt body. These spikes are basically slender body and are attached to the stagnation point of the blunt nose. These spikes work by creating separated flow region adjacent to the spikes, and just forward to the nose. This separated region is created due to the adverse pressure gradient in the boundary layer of spikes’ wall and is associated with low dynamic pressure. One more influence of these spikes is that they replace the strong bow shock wave generated by blunt shape with the system of weaker oblique shocks. The combined effect of the above two helps in reducing pressure in front of the blunt nose and thus helps in reducing pressure drag associated. The separated flow behind the conical shock wave forms a conically shaped re-circulation zone in the vicinity of stagnation region. This recirculation region modifies the shock such that the bow shock moves upstream. Figure 1(a) and Figure 1(b) shows the flow field over a conical and spherical spiked Blunt body configuration.

**Figure 1(a):** Flow over a conical spiked Blunt nose body  **Figure 1(b):** Flow over a spherical spiked Blunt nose body
The effects of the spike length on the nature of the flow field around a Blunt shaped body are experimentally investigated by Crawford [1] at free stream Mach number 6. The results show that the aerodynamic drag of the blunted body is highly influenced by the addition of spikes. The point where the shear layer reattached near the shoulder of hemispherical portion of blunt body show higher pressure. Similar experimental investigation of effects of spikes on aerodynamic drag and heating of blunt body is observed by Motoyama et al., [2] at free stream Mach number 7. They employed different configurations of spikes, conical, hemispherical, and flat faced aerospikes. The effect of the length of the spikes on drag reduction is observed by employing spikes with L/D = 0.5 and 1.0, where L is the spike length and D is the cylinder diameter. They found that L/D = 1.0 has higher drag reduction potential as compared to 0.5. The effect of different spikes configuration is continued and Milicev [3] has done an experimental investigation of the influence of four different types of spikes attached to hemispherical blunt nose at Mach number 1.89 and angle of attack 2 degrees. Wood [4] has done an investigation of the flow over spiked cone-cylinders at Mach 10. Five distinct type of flow was discovered. The occurrence of each is defined in terms of spike length and cone angle. All the above studies provide an overview of the effects of spikes over blunt nose body at zero angles of attack. However, the spike is advantageous for the drag reduction when the spherical body is at an angle of attack. Kalimuthu et. al., [5] has done an investigation of the effect of spike length, shape and angle of attack on the reduction of the drag experimentally at Mach 6. It is observed that the spike with larger length has more potential for the drag reduction. However, spike length larger than some critical length is not effective due to detachment of shock structure from the point of the spike and its reformation as a strong normal shock just upstream of the body. This work is continued by Kalimuthu et. al., [6] to observe the effect of spikes on fluid flow structure and aerodynamic characteristics further. An approximately cone-shaped recirculation region is noticed, using Schlieren flow visualization, between the shock wave and the spike due to the flow separation. Introduction of the spike at the nose of the blunt body is noticed to increase the value of lift coefficient. Recent studies have also shown computational efforts to look upon the effects of a spike over Blunt nose. Sebastian et. al., [7] has analyzed the flow around a blunted body fitted with an aerospike using commercial CFD software at a high Mach number 6 and L/D 1.5 and 2.0, where, L is the length and D are the diameter of the spike. A 20.8% and 26.9% reduction in total pressure is achieved using an aerospike of L/D = 1.5 and 2.0 respectively.
Although employing the spikes over Blunt nose are capable of achieving the low drag aspects, there are penalties associated with this. The additional weight and the generation of undesirable side forces, especially at high angles of attack, limit the use of this technique. At higher velocities, the spike itself suffers from excess heating as well as high structural loading. To deal with these anomalies, a new concept of Breathing Blunt Nose (BBN) was proposed by Imamura et al., [8]. This is a passive method and is capable of drag reduction at higher speeds with treatment for penalties due to use of spikes as well. This method employs a breathing nose at the point of stagnation of the blunt nose body. The nose sucks the air at high pressure, due to the detached shock wave, and ejects it at the rear portion of the blunt body. Thus, the breathing nose technique affects both the high-pressure region at the front portion of the body as well as the low-pressure region at the aft portion of the body. This technique is also expected to weaken the detached shock as compared to simple blunt nose configuration and thus less pressure rise across shock. Hence, this technique of employing BBN has a unique advantage of lowering pressure at the nose as well as increasing the pressure at the base simultaneously.

Vashishtha and Rathakrishnan [9] have done an analysis of reduction of pressure drag of blunt-nosed body by the passive control in form of breathing nose at supersonic Mach number (Mach 1.96). The efficacy of breathing blunt nose technique is investigated by measuring the drag, pressure levels at the nose and the base of the body in supersonic flow regimes. A maximum drag reduction of 21% is obtained. The shock at the nose becomes weaker when the nose hole is open. Similar BBN configurations investigation is done by Watanabe et. al., [10] at hypersonic regime (Mach 7). The drag and the flow field around the blunt-nosed body with and without breathing nose have been computed at Mach 7 experimentally and compared with the CFD results. The breathing configuration is found to cause 5% reduction in drag. The lift coefficient also comes down for the model, but the lift to drag ratio is found to be the same for both the cases. The lift coefficient of NBN model is observed to be higher than that of BBN for the angle of attack greater than 2 degrees. Inside the BBN hole, the flow in some areas is observed to be at supersonic speeds and thus generates internal bow shock just in front of the inner body.

The previous works show the separate studies of different drag reduction mechanism over blunt nose bodies. However, a comparison of the different methodology is not yet done. It is important to find the mechanism with more efficacy and potential in drag reduction. With this objective, the flow field computations have been performed over breathing nose and over conical-spiked,
hemispherical aero-disk, and flat faced aero-disk attached to a hemispherical nosed body at Mach 2.0 flow regime. An attempt is made to understand the effectiveness of different techniques for reducing the wave drag. The effect of spike nose at varying angles of attack is also studied and further compared with that of breathing blunt nose configuration. The angles of attack considered for analysis are 0, 2, 5 and 8 degrees. The ratio of coefficient of lift and drag is also observed and thus the influence of different configurations is investigated to understand the cause of drag reduction and other effects on aerodynamic characteristics.

2. NUMERICAL SIMULATION
Models are discretized using ICEM® and simulations are performed using solver FLUENT®. The solver uses steady, compressible Reynolds- Averaged Navier-Stokes equations with two equation SST k-ω turbulence model. The implicit density-based algorithm is adopted to solve the flow field. The equations are discretized in finite volume form on each of the hexahedral control volumes. The second-order upwind scheme is used in spatial discretization.

2.1. Model
Three different types of spikes with flat-face aerodisk, hemisphere aerodisk, and conical spikes are investigated. In addition to this, breathing blunt nose is investigated. The dimensions of the spiked blunt body are shown in figure 2. All the models are axisymmetric. The main body has a hemisphere-cylinder shape with diameter D as 10mm and the length of the cylindrical portion is 1.25D as 12.5mm. All the spikes consist of a cylindrical part of diameter 0.1D and length 1.5D with different types of nose attached. The flat face aerodisk configuration utilizes a disk on its nose of radius 0.1D as shown in figure 2a. The conical aerospike which consists of a conical part as the nose of the spike is shown in figure 2b. The angle of the cone is 15 degrees. Figure 2c depicts the dimension for hemisphere aerodisk spikes configurations which have a hemisphere attached to the spike with a diameter twice that of the diameter of the spike stem.

Figure 2d represents the information of breathing blunt nose with same dimensions of cylindrical and hemispherical portions as earlier, however, a hole of 2.5 mm is provided at the nose of the hemisphere. The high-pressure air is drawn through the nose hole and passed through the annular gap of 0.5mm, between the outer and inner surface of BBN.
2.2. Computational domain and Grid generation

One of the controlling factors for the numerical simulation is the proper grid arrangement. In order to capture detail flow characteristics near the wall, the enhanced wall treatment is used, and the mesh is characterized by an inflation layer grid to capture boundary layer. Grid independence test is carried out by considering the effects of computational domain and the grid intensity in the axial
and normal directions. To satisfy that the used grid cells will give correct results, the number of grid cells is increased until a steady solution is achieved. Figure 3 depicts an enlarged view of the computational grid and inflation layers over object walls. Details of the full 3D computational domain are presented in figure 4. Relative to the diameter of the cylindrical portion, 10 times the length of the diameter is extended approximately along the directions perpendicular to the flow, 3 times the diameter to the upstream and downstream of the model.

2.3. Boundary conditions

Boundary conditions, as presented in figure 5, are imposed such that it is compatible with the compressible flow. Pressure inlet condition is applied at inlet boundary with Mach number 2, temperature as 300K and the flow angle as required. The ambient region surrounding the model is defined as the pressure far field conditions with Mach number 2 and $P_0 = 101325$ Pa. At the outflow boundary, the static pressure $P_b = 101325$ Pa is imposed and the other variables are extrapolated from the interior. Impermeable, non-slipped and adiabatic wall boundaries are applied on the solid wall of the model. The boundary conditions are such that to ensure zero normal flux of mass, momentum, and energy through the wall. An ideal gas is considered for the analysis.

![Figure 5. Boundary Conditions](image)
3. RESULTS AND DISCUSSIONS

3.1. Flow field visualization and characteristics

*Pressure contours*

Fig 6(a)-6(e) shows the pressure contours of models blunt nose, hemispherical aerodisk, conical, and flat face aerodisk spike, and BBN at angles of attack 0, 5, and 8 degrees respectively. For plain blunt nose, a bow shock can be clearly observed ahead of the model. Further, through the contours the cause of the drag reduction due to employing spikes can be explained. The pressure in the vicinity of blunt nose reduces significantly as compared to simple blunt nose configuration. It can be seen that the conical aero-spike reduces the shock angle and thus the shock considerably weakens compared to the other two configurations. Due to the adverse pressure gradient, the spikes create the separated flow region adjacent to the spikes’ wall and thus the dynamic pressure is highly reduced. In the fore region of the aerodisk or hemispherical cap, the flow decelerates through the bow shock wave and thus reduced Mach number is observed. This reduced Mach number is incapable of forming strong shock wave in the vicinity of the blunt nose and thus the increase in pressure is less. At the shoulder of the aerodisk or hemispherical cap, the flow turns and expands rapidly, the boundary layer detaches forming a free shear layer that separates the inner recirculating region. This separation, thus, additionally helps in reducing pressure. The presented contours also show the deformation of bow shock by the effect of breathing nose. The BBN model weakens the detached shock as compared to NBN model and thus reducing the pressure in the front portion of the blunt body. This breathing nose sucks the air at high pressure, due to the detached shock wave, and ejects it at the rear portion of the blunt bodies. Thus, the breathing nose technique affects both the high-pressure region at front portion of the body as well as the low-pressure region at the aft portion of the body. Hence, provides a unique advantage by lowering pressure at the nose as well as increasing the pressure at the base simultaneously.

(a) Plain Blunt body
Figure 6. Pressure (in Pa) contours for various configurations at Angles of Attack 0, 5, and 8 degrees.
3.2. Surface Pressure Distribution

The nondimensional surface pressure distribution over different spiked blunt body is presented in figure 7. The surface pressure is non-dimensionalized using ambient operating pressure (\(P_a=101325\) Pa) and the axial distance is made non-dimensional using radius of the cylinder of blunt body, \(R\). The \(x/R = 0\) is the spike tip junction. Due to the flow turning and rapid expansion at the shoulder of the aerodisk or hemispherical cap, a sudden pressure drop is observed after the tip of hemispherical aerodisk and flat faced aerodisk. Interestingly, it is to note that the maximum pressure is found at the same location on the blunt body for all the three spike configurations. However, the peak value of pressure is different for different spikes. The plot shows that the peak pressure for the flat faced aerodisk is least and for the conical spike is most among the three.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure7}
\caption{Variation of pressure along different spike body}
\end{figure}

Effect of angle of attack

The change in angle of attack leads to asymmetry flow distribution over the body. The similar pattern is observed through contours as well as through plots. Figure 8-10 shows the effect of angle of attack on pressure distribution over the hemispherical aerodisk, conical spiked, and flat faced aerodisk body respectively. The angles of attack considered are 0, 5 and 8 degrees. The pattern of the pressure distribution remains similar for different angles of attack. However, as expected, the pressure in the lower portion of the body increases and in the upper portion of the body decreases as the angle of attack increases. The difference in pressure at lower and upper surface becomes more significant as the angle of attack increases further and this leads to increase in

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure8}
\caption{Effect of angle of attack on pressure distribution over hemispherical aerodisk body}
\end{figure}
lift generation. It is observed that the peak pressure at the upper surface and the lower surface of the body is observed at the slightly different location. At the upper surface the peak pressure is observed a little upstream and at the lower surface, it is observed a little downstream of the location as compared to the angle of attack 0 degrees.

Figure 9. Effect of angle of attack on pressure distribution over conical spiked body

Figure 10. Effect of angle of attack on pressure distribution over flat face aerodisk body

3.3. Moment and Force coefficients

Figure 11. Lift to drag ratio variation with angle of attack for different configurations

Figure 11 shows the variation of lift to drag ratio with the angle of attack for different configurations used. It is observed that the spike tip shape influences the flow field and thus have
varying lift to drag ratio as well. Due to the flow turning and rapid expansion at the shoulder of the aerodisk or hemispherical cap, the peak pressure is observed to be minimum in the case of flat faced aerodisk as compared to other configurations. But, the conical spike is observed to have the highest lift to drag ratio and thus can be considered most effective configuration among all. At a lower angle of attack, BBN and NBN configurations have an almost same lift to drag ratio. However, at a higher angle of attack, the differences become significant.

![Figure 12. Variation of pitching moment coefficient with angle of attack](image)

Figure 12 shows the pitching-moment coefficient $C_m$ with respect to the angle of attack for the basic configuration and spiked body. In the case of the blunt body without a spike, the pitching-moment coefficient shows a linear variation with respect to the angle of attack. $C_m$ variation is found to be nonlinear with the angle of attack for spiked configuration. Introduction of the spike shows the increasing trend of the pitching moment coefficient. Thus, it shows that the model is going to become more stable. Therefore, more control force is needed to trim the vehicle.
4. CONCLUSIONS

The drag reduction over the blunt body using breathing technique and by employing different spikes have been computationally investigated at Mach 2.0 with angles of attack 0, 2, 5 and 8 degrees. The flow field is found to be significantly varying by employing these active and passive techniques over the blunt body. In the case of the spike, the flow field is found to be a function of the shape of the aero spike. Shock strength is considerably attenuated in the case of a conical spike. However, due to the flow turning and rapid expansion at the shoulder of the aerodisk or hemispherical cap, the peak pressure value is observed to be minimum in the case of flat faced aerodisk as compared to other two spike configurations. The peak value of the pressure is different for different spikes, but the maximum pressure is found to be at the same location on the blunt body surface for all the three spiked blunt bodies. The BBN model weakens and deforms the detached bow shock and thus reducing the pressure in the fore region of the blunt body. A unique advantage of employing BBN is observed. It lowers pressure at the nose and increases the pressure at the base simultaneously. The conical spike has a higher lift to drag ratio as compared to other configurations and thus is more efficient at higher angles of attack. Introduction of the spike shows the increasing trend of the pitching moment coefficient. Thus, the model is going to become more stable. Therefore, more control force is needed to trim the vehicle.

REFERENCES