DRAG REDUCTION OF A HEMISPHERICAL BODY ADOPTING SPIKE AT SUPERSONIC SPEED

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Abstract

Use of spike on a hemispherical body changes the flow field and hence the aerodynamic drag. Experimental and computational studies have been made to obtain the flow field around a hemispherical body with spikes at a supersonic Mach number of 2. The effect of shape of spike tip and length has been studied. Experiments consisted of shadowgraph flow visualisation and measurement of drag. Computations have been made adopting structured grid and k-ω turbulence model using commercial software Fluent. It is observed that use of a sharp spike itself reduces the drag significantly. However the use of a hemispherical head spike further reduces the drag. Contribution of different components towards drag indicate that the increase in length of a spike do not change the spike contribution. However the flow field on main body is altered which leads to reduction in drag with change in length. Estimated drag generally found to be higher in comparison to measured value, however the trend is almost similar.

Nomenclature

\( C_{df} \) = Coefficient of forebody drag
\( d \) = Diameter of stem of spike
\( D \) = Hemispherical body diameter
\( HS \) = Hemispherical head spike
\( L \) = Length of spike
\( M \) = Mach number
\( p \) = Pressure (N/m\(^2\))
\( p_\infty \) = Freestream pressure
\( P_0 \) = Total pressure
\( Re \) = Reynolds number
\( S \) = Curve length along the surface measured from hemispherical body tip
\( SS \) = Sharp spike
\( X \) = Length along the axis of symmetry measured from hemispherical body tip

Introduction

A blunt body is commonly used in missiles, rockets, reentry capsules, etc., mainly to withstand the aerodynamic heating during the flight at high speed or to maximize the availability of space for larger payload. While travelling at supersonic/hypersonic speeds, the formation of a detached shock wave leads to higher aerodynamic drag and heating. The after effect may be either loss in performance or erosion/ablation of the surface. In order to alleviate these problems, various techniques are being studied, e.g., use of gas jets, energy deposition, breathing nose, spike, etc. Use of spike seems to be a simple proposition and has been studied in details in last few decades. Fig.1 shows the schematic of flow field around a blunt body which gets modified due to presence of a simple spike having sharp tip. The flow field between the tip of spike and the main body will strongly depend on incoming freestream flow conditions, shape of the tip of spike, length and diameter of the stem connecting the spike tip to the body, etc. The presence of spike, leads to formation of a weaker spike shock, separated zone and separation shock due to adverse pressure gradient, recirculation zone, shear layer, etc.. There exist the possibility of separation shock hitting the main body which might result in a reattachment shock on the body. As the body shock without spike gets modified due to presence of spike, it is expected to reduce the drag and heating. Due to the presence of recirculation in separated zone, major part of the
main body will experience lesser pressure and hence reduction in drag. Further enhancement in reduction of drag/heating could be achieved by making use of a aerodisk as sketched in the same figure.

Experimental investigation reported by Crawford [1] at a hypersonic Mach number of 6.8 on a hemispherical body with sharp spikes of different lengths indicated the reduction of drag and peak heat flux, which is probably one of the investigations made few decades back and is being referred by many researchers for validation. Similar studies are reported in Ref [2,3]. Many researchers have made studies to characterize the flow field on a blunt body with spikes of different shapes, lengths and sizes at hypersonic speed adopting experiments and numerical simulations[Ref.4-17]. Ahmed and Qin [18,19], have explained the phenomenon of drag reduction adopting the approach of dividing streamline of shear layer.

At supersonic speed, the flow field on a hemispherical main body with spike could be different due to shock strength and behavior of separation zone between the spike and body in comparison to hypersonic speed. Studies reported in Ref [20-29] gives the details of the flow field on blunt bodies of different shapes at supersonic speed in the presence of different types of spikes. Most of the studies are with sharp spike or blunt spike. Use of aerodisk is limited to Ref [27] only, whereas different shapes of aerospikes have been studied at hypersonic speed [Ref.5,7,10,11,12,14,16,18]. Mostly the computation are made adopting either laminar flow or turbulent flow using Baldwin Lomax turbulence model. A recent review article by Ahmed and Qin [19] gives the details of research conducted on hemispherical body with spike. Studies with aerodisk having spherical tip reported by Ahmed and Qin [18] at hypersonic speed indicated more reduction in drag in comparison to sharp spike. To the best of our knowledge, use of k-ω turbulence model is limited to Ref [16] and effect of a spike with hemispherical tip having flare is not reported.

The present investigation aims to obtain the flow field around a hemispherical body in the presence of either a sharp spike or hemispherical head spike at supersonic speed. Experiments and computations are made to obtain the overall flow field and drag, in the presence of either a sharp or hemispherical head spike having different lengths.

**Geometry**

The geometry adopted in present study is a hemispherical blunt body having overall length of 1.5D. The spike used has basic stem diameter of 0.1D. Two different tips on the spike have been used. One of the spike had a sharp tip having semi cone angle of 20 degrees, whereas other spike had a hemispherical tip having diameter of 0.2D, with a flare angle of 135 degrees. The details are shown in Fig.2. Spike of three different lengths (L/D=0.75, 1.0, 1.5) were used. The nomenclature used to identify the spike is “XX-YYY”, where XX denotes either a Sharp Spike (SS) or Hemispherical Spike (HS) and YYY represents Length of Spike (L/D) which has the values of 0.75, 1.00 or 1.50.

**Experiment**

All the experiments were performed using the blowdown type Supersonic Wind Tunnel at Birla Institute of Technology, Mesra, Ranchi having a test section size of 50 mm × 100 mm. The present series of experiments have been made at a fixed Mach number of 2.0, with settling chamber pressure of about 3.2 x 10^5 N/m^2, which was measured using a pressure transducer (Make Sensym, Model ASCX150DN), and Reynolds number (Re) of 0.6 x 10^6 based on base diameter of the model.

The spike could be fixed on the body with suitable threads. The photographs of the model without spike, with typical sharp spike (SS-0.75), and hemispherical head spike (HS-0.75) is shown in Fig.3. Overall flow field was visualized using standard shadowgraph technique. Forebody drag (C_d) was measured using a sting mounted single component strain gauge balance having a diameter of 8mm. The balance was energized using a DC power supply and the output was acquired using NI DAQ, LabVIEW software and PC based Data Acquisition System. The accuracy of measurement of drag was found to be better than 5%. All the tests were made at zero degree angle of attack only.

**Computation**

Numerical simulations were performed using FLUENT, to capture the overall flow features of spiked blunt body, which uses a finite volume approach to solve compressible Reynolds Averaged Navier Stokes equations. In the present investigation, steady state axisymmetric computations have been made adopting explicit coupled solver and using “k-ω SST” turbulence model. The use of this turbulence model has been arrived at, after making neces-
sary grid sensitivity tests, convergence history and obtaining good comparison with the experimental and numerical results reported in literatures.

Structured grids were made with uniformly distributed quadrilateral cells having minimum spacing near the wall of the order of $10^{-3}$ mm and $y^+$ of 0.4 for hemispherical body without spike. The 1st cell distance was of the order of $5 \times 10^{-3}$ mm and $y^+$ of 1.7 for sharp spike. For hemispherical head spike the 1st cell distance was of the order of $10^{-3}$ mm and $y^+$ of 0.31. A close view of typical grids used in the present investigation is presented in Fig.4. Necessary clustering of grids have been made for better capture of flow field.

The pressure far field boundary condition at the inlet was specified. No slip wall boundary conditions with suitable near wall treatment for turbulent flows were enforced on the hemispherical body and spike. Due to axisymmetry, only half domain with axis boundary condition was applied at the centerline. The overall grid, computational domain and boundary conditions adopted is shown in Fig.5. The residuals of continuity, energy and turbulent kinetic energy along with mass flux between the inflow and outflow and $y^+$ value on the hemispherical body surface were monitored. For faster convergence, 4-stage multigrid was used. In addition, the convergence history for drag was also monitored during the entire solution period. Results were analysed only when it was ascertained that the residuals has converged to the order of $10^{-5}$. A typical convergence history of RMS residuals for hemispherical body without spike is plotted in Fig.6.

Validation

The experimental result reported in Ref [26] on a hemispherical body with a sharp spike having $L/D = 1.0$, and at $M = 1.89$ has been used to arrive at a suitable grid and validation. Computations are made with different grids [Coarse (28,520), Medium (40,595) and Fine (81,000)] and the results obtained are presented in Table-1. It is observed that the difference between the value of $C_{df}$ for medium and fine grid is of the order of 0.01 and hence further computation are made with medium grids having cells of the order of 40,000. The comparison with the reported value of $C_d$ is observed to be good. Simulations were also made for a blunt spike having $L/D = 1.0$ for comparison. Comparison of numerical and experimental schlieren presented in Fig.7, indicate that overall flow features are well captured. The comparison of estimated forebody drag with the measured values reported in Ref [26] is presented in Table-2, which also indicates good agreement. Computational and experimental results on a hemispherical body and with a flat tip spike at $M = 2.23$ reported in Ref [29] is also used for the purpose of validation. The comparison of surface pressure distribution presented in Fig.8 indicates fairly good agreement. These results indicates the adequacy of the grids and turbulence model and hence similar grids have been adopted for present investigation.

Results

Experiments have been made to visualize the overall flow field over hemispherical body with and without spike adopting shadowgraph technique. The photographs shown in Fig.9 indicates a strong detached bow shock wave in front of hemispherical body as expected. With adoption of sharp spike with $L/D = 0.75$ (SS-0.75), a conical shock is observed. In addition, a feeble shock originating at the cone cylinder junction is observed, which could be due to possible separated flow in front of main body. With increase in length of spike ($L/D = 1.0$), the separation shock seems to interact on hemispherical body. With further increase in length of spike ($L/D = 1.5$), the separation shock is clearly visible and originates at a distance of about $(x/D = 0.7)$ and does not reattaches on hemispherical body. The presence of recirculating zone could not be ascertained from these photographs. Shadowgraph observed for spike with hemispherical tip having

<table>
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<th>Grid</th>
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<th>Present Computation</th>
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<tr>
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<td>Hemispherical body with blunt spike ($L/D = 1.0$)</td>
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L/D = 0.75, 1.0 and 1.5 is also presented in Fig. 9. Qualitatively, the flow field has almost similar features as observed with sharp spike.

The measured forebody drag \( C_{df} \) for hemispherical body and with different spikes is shown in Fig. 10. This indicates that, use of any of these spikes lead to substantial reduction in drag. In the case of sharp spike, the drag decreases with increase in length from L/D = 0.75 to L/D = 1.0, however increase in drag is observed with increase in length to L/D = 1.5. For hemispherical head spike, the drag reduces with increase in length from L/D = 0.75 to 1.5. It could be also observed that in general, the hemispherical head spike leads to more reduction in drag in comparison to sharp spike.

Computation has been made for all the cases for which experiments have been conducted. Typical comparison of shadowgraph with the corresponding numerical schlieren is presented in Fig. 11. Overall comparison seems to be good for hemispherical body and as well with sharp spike SS-0.75. Comparison of SS-1.00, HS-0.75, HS-1.00 and HS-1.50 also indicated good agreement. However, the comparison of SS-1.50 indicates some differences in flow field.

Density contour presented in Fig. 12 indicates the flow features for all the spikes. For sharp spike, a weak separation shock and presence of recirculation zone is clearly visible for L/D = 0.75 and 1.0. The flow features have similar behaviour, except the increase in separation zone with increase in length. However with further increase in length to L/D = 1.5, the overall flow field has changed. Another separation shock and a recirculating zone has been formed which embeds about 60% of the length of spike in comparison to 80-90% for other sharp spikes. Such a separation shock is also reported at Mach 6.0 (Ref [18]). The change in the behaviour of flow near the reattachment point on the main body is observed with change in spike length.

For hemispherical head spikes, a bow shock is formed in front of spike. The flow separates at the edge of sphere-flare junction for all the spikes. The separation shock reattaches on the main body and the zone between the spike and blunt body is engulfed by a separated zone. Overall flow features for both spikes seems to have qualitative similarity, except for SS-1.50, where an additional separation shock on the stem of spike is observed.

In order to obtain more details of flow field, the computed Mach contours are presented in Fig. 13. Attempt has been made to indicate some of the values of Mach numbers at few locations. For sharp spikes, the existence of separated zone in front of the main body is observed. For SS-0.75 and SS-1.00, the separation occurs at the junction of cone-cylinder and a recirculation zone is formed. However the formation of another smaller separated zone is also observed. In case of spike SS-1.50, the separation starts at a location \( x/D = -0.9 \) downstream from the tip of spike and also contains a small separated zone. It could be observed that a portion of spike \( x/D = -1.5 \) to -0.9) experiences supersonic flow for SS-1.50 only. The velocity in the recirculating zone till the point of reattachment is almost similar for all spikes. Mach contours with hemispherical head spike (HS-0.75) indicates almost similar behaviour observed with corresponding sharp spike (SS-0.75), except the presence of a small separation zone in the vicinity of cone-flare region. With increase in length, a small separation zone observed on spike has disappeared. The value of Mach number near the reattachment zone has almost similar values. These results indicate the occurrence of different types of flow features with change in shape and length of spike.

The pressure contours for all the cases are shown in Fig. 14 along with typical values of pressures. Pressure is observed to be maximum on the main body in the vicinity of reattachment location for all the cases. For sharp spike, the values are higher than the hemispherical head spike. The effect of length of spike on the maximum pressure on the main body is not very predominant. The velocity vectors for all the cases presented in Fig. 15 gives further more insight of existing flow field, e.g., the separated zone, flow reversal, etc., which compliments the previous observations made from other contours. It is observed that the reattachment of dividing streamline moves down-stream with increase in spike length, leading to reduction in drag. A closer look of velocity vector on all the cases studied, none of them seems to have stagnation point on the main body which is expected due to reattachment of separated flow from the spike. This leads to oscillation of flow as reported in Ref [18,19] and also gives rise to oscillation of drag coefficients.

For all the cases, the computation showed rapid convergence, however a small oscillation continued (Fig. 6). In order to obtain the steady state flow parameters of interest, solutions were further marched for about 5000 iterations and were averaged. A typical oscillation observed for drag coefficient is shown in Fig. 16, which...
indicates the magnitude of oscillation being of the order of ±15%, which is almost similar to the oscillation reported by Ahmed and Qin [18] while making laminar computation. The estimated averaged forebody drag for all the cases along with the measured values is shown in Fig.17 and Table-3, along with the measured values. It is observed that the behaviour is almost similar for experimental and computed results except for sharp spike with longer spike (L/D = 1.5). In general, the computed drag is lower than measured drag, except for sharp spike (SS-1.50). For this case the flow observed is quite different (Fig.12c and Fig.14c).

The percentage reduction in drag (a quantity which is measure of efficiency of spike) due to different spike is shown in Fig.17b and Table-3, which indicates that maximum reduction in drag occurs with adoption of hemispherical head spike (HS-1.50). The total drag consists of pressure and skin friction drag, which could be estimated for all the cases and it is observed that the contribution of skin friction is much less than 5% of total drag and hence it’s contribution is not emphasized.

In order to obtain more details, the pressure distribution on main body without spike and with different spikes is shown in Fig.18. It is observed that major change in pressure on hemispherical body is generally restricted to S/D < 0.5, which contributes for pressure drag. Change in pressure beyond S/D > 0.5 is small and hence it will have lesser contribution towards drag due to its lower value and as well due to the local surface gradient. For sharp spike (SS-0.75) having L/D = 0.75, almost a constant pressure exists upto S/D = 0.2 and further increases to a maximum value of about 3.6 at S/D = 0.35 and further decreases downstream. Similar behaviour is observed with increase in spike length, except that pressure values are lower. It is also observed that peak values has shifted downstream (S/D = 0.4) with increase in spike length. This feature could be also observed through Mach contours (Fig.13).

The pressure distribution on the spike indicates almost a constant value on conical tip of spike and decreases due to expansion. The pressure distribution on the stem of spike have different behaviour due to change in flow field depending on spike length (Fig.14). It may also be noted that the pressure on stem of spike will not contribute to pressure drag. Fig.18b shows the pressure distribution on hemispherical head spikes. This indicates monotonous decrease in pressure on main body with increase in spike length and also gradual shift in the location of peak pressure. The pressure distribution on the spike tip and stem indicates almost similar behaviour with change in spike length. Comparison of location of peak pressure of spikes of same length indicates that for a hemispherical head spike, it occurs at a downstream location in comparison to sharp spike. Using these pressure distributions, the drag of individual components (spike tip, spike stem and main body) could be estimated which is presented in Table-3. It is observed that contribution due to stem of spike is negligible as it experiences only skin friction. The hemispherical tip spike contributes more than sharp spike as expected and the drag value is almost independent of length. The main reduction in drag is due to reduction in pressure drag on the main body with change in spike shape and length. This indicates that further reduction in drag could be achieved by suitably modifying the hemispherical tip of spike.

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Conclusions
Experiments and computations have been made to obtain the flow field on a hemispherical main body at a supersonic Mach number of 2, in the presence of a sharp spike and hemispherical head spike of different lengths. Overall flow features captured through shadowgraph did not show much difference with change in spike length, however it was observed that in general the drag reduces. Computation indicated good comparison with corresponding experimental results. Computational results indicate more details of flow field and the effect of spike shape and length. Flow features indicates the presence of separated zones, reattachment point. It is observed that use of hemispherical head spike having length of 1.5 times the base diameter leads to maximum reduction in drag (60%). Estimation of drag for different components indicate that major reduction is from the main body which gets modified due to spike tip and hence shape and size of spike is of prime importance for reduction of drag.

Acknowledgement
This study is a joint effort of Birla Institute of Technology, Mesra and Defence Research and Development Laboratory (DRDL), Hyderabad. The authors sincerely acknowledge Director, DRDL, Hyderabad, and Vice Chancellor, BIT Mesra for the grant of approval and supports for carrying out the research.

References


Fig. 1 Schematic of Flow Field Around a Blunt Body without and with Spike
Fig. 2 Geometrical Details of Models

(a) Hemispherical body  
(b) Sharp Spike (SS)  
(c) Hemispherical head spike (HS)

Fig. 3 Photograph of Assembled Models

(a) Without spike  
(b) SS-0.75  
(c) HS-0.75

Fig. 4 Grids for Hemispherical Models without and with Different Spikes

Fig. 5 Computational Domain and Boundary Condition

Fig. 6 Convergence of Residuals for Hemispherical Body without Spike
Fig. 7 Comparison of Present Computation with Schlieren for Hemispherical Body without Spike and Body with a Blunt Spike

Fig. 8 Comparison of Pressure Distribution at Mach 2.23

Fig. 10 Measured Forebody Drag with and without Spike

Fig. 9 Shadowgraph on Hemispherical Body with Sharp and Hemispherical Head Spike of Different Lengths
Fig. 11 Comparison of Schlieren Obtained Through Experiments and Computations

Fig. 12 Density Contours with Spikes of Different Lengths
Fig. 13 Mach Contours with Spikes of Different Lengths

Fig. 14 Pressure (kPa) Contours with Spikes of Different Lengths
Fig. 15 Velocity Vectors with Spikes of Different Lengths

(a) SS-0.75  
(b) SS-1.00  
(c) SS-1.50  
(d) HS-0.75  
(e) HS-1.00  
(f) HS-1.50

Fig. 16 Typical Oscillation of Drag Coefficient (SS-1.00)

Fig. 17 Comparison of Computed and Measured Forebody Drag with and without Spike

(a) Drag

(b) Reduction in drag
Fig. 18 Computed Pressure Distribution

(a) Sharp Spike

(b) Hemispherical head Spike