Aerodynamic Shaping of Base Region of a Multi-Body Launch Vehicle

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Aerodynamic loads on nozzle can be critical for nozzle actuator design for any launch vehicle. The present work deals with the shaping of base region of a typical launch vehicle configuration, with the objective of reducing the aerodynamic loads on the nozzle. Various boat-tail shapes are considered in the aft segment, to provide a smooth reduction in diameter from the propellant tankages to the nozzle. Lower acoustic levels on the boat-tail and least impact on overall aerodynamic coefficients of the vehicle were other design considerations. Aero loads on the nozzle could be decreased by preventing flow re-attachment on the nozzle, which is achieved by providing a step ahead of the nozzle base. Shallow ogive boat-tail is seen to be the most preferable option, as it delays the occurrence of transonic shock and results in less pressure variation along the length of the boat-tail, apart from the benefit of least drag.

Keywords: Boat-tail, nozzle load, flow re-attachment, shock, ogive, drag

Nomenclature

C_A: Coefficient of axial force
C_N: Coefficient of normal force

Introduction

Multi-body launch vehicles are common today to achieve large payload capacities. A common configuration in multi-body launch vehicles is the one with two strap-ons and core, like in JAXA's H2-B, SpaceX's Falcon Heavy etc. For such a vehicle, if the central body is not powered-on at lift-off, aerodynamic load on the central nozzle may cause a critical problem in some configurations. Vehicle considered for the present study has two strap-ons mounted on diametrically opposite sides of the core/central body. Flow over the core will re-attach on the central nozzle. This will lead to oscillatory force on the nozzle and can cause problems for nozzle actuator design. Hence, proper shaping of the base region is very essential.

Design considerations:

The aft-end of the core that is subjected to aero-shaping is after the propellant tanks and houses the engine components (Figure 1). The core vehicle diameter is 'D' whereas the diameter at the nozzle base is 'd'. A length of 1.15 D is available from the propellant tank end to the nozzle base for aero-shaping. The objective of the study is to arrive at an optimal boat-tail shape, while taking care of the following aspects:

1. Lower nozzle load
   - In the initial stages of flight, only the two strap-ons are fired and hence the core nozzle is idle. The flow from the core-stage can separate at the core base end and impinge on the nozzle, resulting in high loads on the nozzle actuator. To reduce the actuator loads, it is preferable that the separated flow from the core does not re-attach on the nozzle.
2. Lower acoustic levels
   - Flow re-attachment on the nozzle will lead to high levels of pressure fluctuations resulting in high acoustic levels. Hence, it is preferable to prevent flow re-attachment on the nozzle from acoustic point of view also.

- Flow expansion on the boat-tail can give rise to transonic terminal shock. More-over, at supersonic Mach numbers, shocks may develop on the boat-tail. The presence of shocks increases the unsteady pressure levels that can have a detrimental impact on the engine components inside. Hence, it is preferable to prevent the occurrence of shocks on the boat-tail.

3. Least impact on overall aerodynamics of vehicle
   - Base is a major contributor to the total drag of the launcher. Hence, least influence on overall drag and normal force are important considerations while attempting aero-dynamic shaping of the core base.

Design approach:

Total 11 candidate configurations have been selected for aero-shaping by varying cone angle, shape and base diameter. Some of them are shown in Figure 2. Flow simulations were carried out over the complete vehicle at M=0.95, 1.10 and 1.20, at 4^0 angle of attack. These Mach numbers are chosen as the vehicle faces maximum dynamic pressure in this regime and the aerodynamic coefficients also peaks at this range of Mach numbers. Flow simulations have been carried out using in-house RANS solver code - PARAS-3D [1,2] . The simulations were carried out till the total force and moment coefficients converged within 1%.

Simulation Details:

'PARAS-3D', an in-house developed CFD software, is used for flow characterisation. It solves the Reynolds Averaged Navier-Stokes (RANS) equations. The discretisation scheme is explicit and second order accurate in space. Wall treatment is done using modified wall functions. Turbulence is modelled using k-ε turbulence model. The time stepping is done for each cell based on local CFL criteria. Flux computation is by means of an approximate Riemann solver.

The software uses Cartesian grid and adaptive mesh refinement techniques to modify the grid as the solution progresses. In this process, more cells are added at regions of high flow gradients, whereas cells are removed from regions of low flow gradients. For the present study, an upstream domain of 57 D and downstream domain of 86 D is considered. All the remaining sides are considered as 57 D. The size of the initial grid was approximately 17 million, which after flow refinement increased to 20-45 million. Upwind boundary condition is used for inward flow and supersonic outflow/pressure outlet condition are used for all remaining surfaces depending on the Mach number being studied.

Results and Discussion:

Preliminary configurations:
4 configurations were chosen for preliminary studies by varying the boat-tail angle: 10^0, 20^0 and 30^0 as well as an ogive boat-tail equivalent to 10^0 boat-tail (Figure 2). The diameter at nozzle base (d) was kept as 0.61 D, the minimum allowable limit, a constraint set for interfacing with other mechanical systems. These angles were chosen with the following logic:

- For lower boat-tail angles (10^0 and ogive), flow is expected to follow the contour of the boat-tail, which will guide the flow away from the nozzle.
- Larger boat-tail angles (20^0 and 30^0), on the other hand, can lead to separation of the flow from the boat-tail, and the nozzle will be in wake of the separated flow, thereby preventing flow reattachment on the nozzle.

Flow simulations show that for 10^0, 20^0 and ogive geometries, flow is always attached on the boat-tail as expected (Figure 3). Even though the geometry of these boat-tails (tangent) would have guided the flow away from the nozzle, it is observed that the flow re-attached on the nozzle for all the configurations at M=1.20.

Towards the aft-end of the boat-tail, a curved thermal boot is present, which turned the flow towards the nozzle, leading to flow re-attachment on the nozzle.

30^0 boat tail is selected for study with the expectation that the flow will separate from the boat tail after formation of shock and clear the nozzle without any reattachment on it. Initially the flow follows the geometry, after which it is seen to separate, with the formation of a shock (at supersonic Mach numbers). Because of the short length of the boat-tail, the location of the shock is very close to the nozzle. This leads to flow re-attachment on the nozzle. Moreover, presence of shock can lead to higher unsteady pressure loads on the structure. In this case also, the thermal boot is seen to turn the flow towards the nozzle, which is undesirable.

The above analysis shows that for all these shapes, flow reattaches on the nozzle. To estimate the merits and demerits of these configurations, impact of these boat tail shapes on overall aerodynamic is evaluated. In Figure 4, overall axial force and normal force coefficients are compared for these four configurations. It is observed that as the boat tail angle increases, the drag of the vehicle also increase with ogive shape having the least drag. About 10% increase in the overall vehicle drag is noticed for 30^0 boat tail as compared to ogive. 20^0 boat tail faces slightly lower drag than 30^0 which is still higher than the 10^0 cone and ogive configurations. 10^0 boat tail is having the similar drag as that of the ogive case. The centre of pressure location shows up to 1.5m difference for these configurations. Overall normal force is highest for 30^0, whereas the ogive and 10^0 boat tail are having the least normal force value. Hence, ogive and 10^0 cone base are seen to be better than the other two configurations.

Shallow cone/ogive boat-tails:
Because of drag penalty and the presence of strong shocks close to the nozzle, boat-tail options with higher angle (20^0 and 30^0) were ruled out and only the shallow cone and ogive options were considered for further studies. Also, a step was provided at the thermal boot (Figure 5a), to prevent the flow from turning towards the nozzle. This demanded an increase in the diameter at nozzle base (d). Two different diameters, d=0.7 D and d=0.75 D were tested for both conical and ogive boat-tails. This resulted in equivalent boat-tail angle of 7.7^0 and 6.5^0 respectively.

The addition of step at the thermal boots and the increase of nozzle base diameter made the flow to glance past the nozzle. The zone of re-attachment was drastically reduced but could not be completely avoided (Figure 5b). The reduction in zone of flow re-attachment is expected to reduce the nozzle loads considerably.

From the above studies, no clear advantage is noticed between the conical and ogive configurations. To analyse the relative merits and demerits of these geometries, CFD simulations were carried out for Mach numbers 0.70, 0.80, 0.90 and 0.95 at 0^0 angle of attack, as typical angle of attack encountered in flight is close to 0. The objective of the study was to check for supersonic pockets or transonic shocks at the cylinder boat tail junction for M<1 as these may lead to higher acoustic levels. Analysis of the flow field data show that for conical shape, an expansion corner is formed at the cone-cylinder junction (Figure 6). It is not seen in ogive boat-tail configuration, as the expansion is gradual. Sudden expansion can lead to the formation of terminal shock in transonic Mach numbers. This will lead to marginally higher acoustic load for conical boat tail as compared to ogive shape. Hence, ogive shape is more preferable from aerodynamic point of view.

Boat-tails with cylinder at aft-end:
From the flow field analysis of direct ogive/cone, it is clear that none of these shapes are enough to prevent the flow from reattaching on nozzle. It may be due the fact that the curvature of the shapes studied so far allows the flow to turn towards nozzle. Hence, a cylindrical shape is selected and added at the end of the boat tail so that it directs the flow in a straight line (i.e. parallel to the vehicle axis), resulting in 0^0 boat-tail angle near the end. For this purpose, three cone/ogive-cylinder boat-tails were studied (Figure 7).

For these configurations, the flow nearly cleared the nozzle. However, they did not offer a large advantage by completely avoiding flow reattachment (Figure 8). It is noticed that all these configurations produce load and axial force similar to the simple cone/ogive configurations (Figure 9). The variation is within 2-4%. From this aspect, simple cone/ogive as well as the cone/ogive-cylinder configurations are equally preferable.

Pressure palette on the boat tail is shown in Figure 10 for the cone/ogive-cylinder configurations along with simple conical and ogive configurations. A shock is formed on the boat-tail of all configurations. Because of more flow expansion, the shock strength and hence the pressure variation is more for the cone/ogive-cylinder configurations in comparison to the simple ogive/cone configurations. Ogive boat-tail is seen to be the most preferable, as it results in much less pressure variation along the length and delays the formation of transonic shock.

Conclusions:

11 different configurations have been studied to identify a suitable geometry for base region of a multi stage launch vehicle. The main objective of the study was to arrive at a configuration that would prevent flow reattachment on the nozzle and have least impact on overall aerodynamics of vehicle and least unsteady pressure loads. By varying the configuration dimension and shape, the re-attachment point on the nozzle could be moved downstream but not completely eliminated in majority of the configurations. Aerodynamically, direct ogive/cone or ogive-cylinder configurations were seen to be more favourable from flow reattachment point. However, ogive boat-tail is seen to be the most preferable, as it results in much less pressure variation along the length.

References:

1. V. Ashok and Thomas C Babu,“Paralisation of Navier -Stoke Code on a Cluster of Workstations”, Procedings of the 6th International High Performance Computing Conference.
2. R Balu, Thomas C Babu, V. Ashok, Pradeep Kumar and Dipankar Das, “Development of low cost parallel computing platform for CFD applications”, 3rd Annual symposium of CFD division of Ae. S.I., Aug.11-12, 2002PARAS

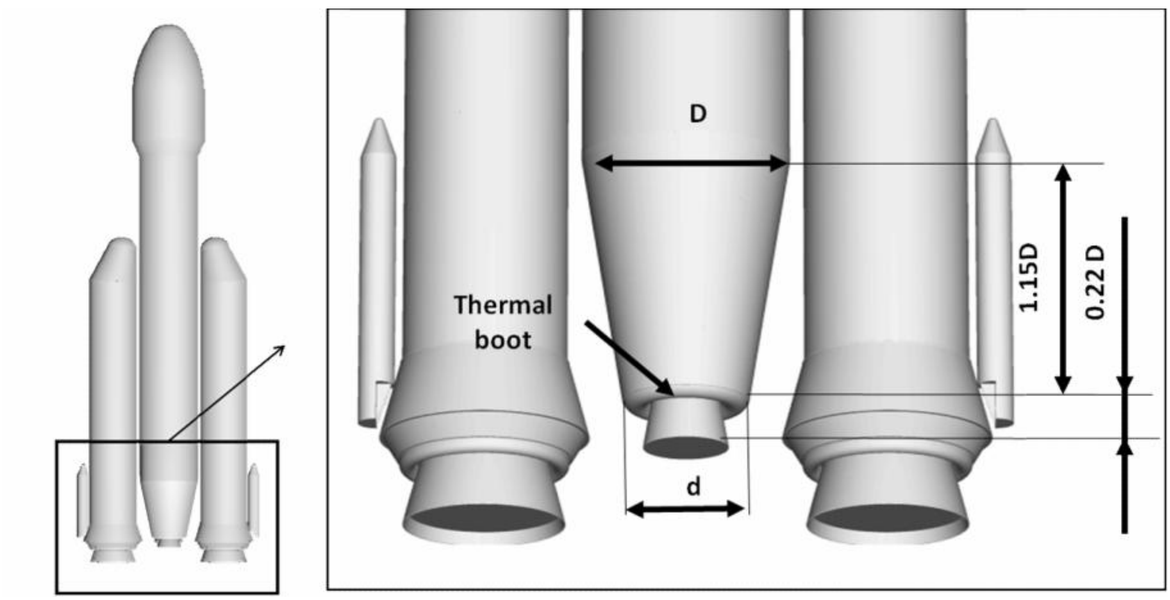


Figure 1: Vehicle configuration and dimensional details of the base region of the vehicle

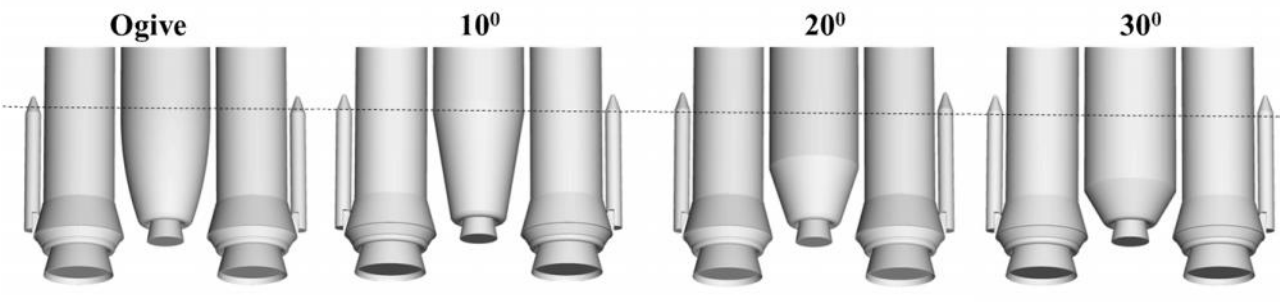


Figure 2: Four preliminary boat-tail configurations studied

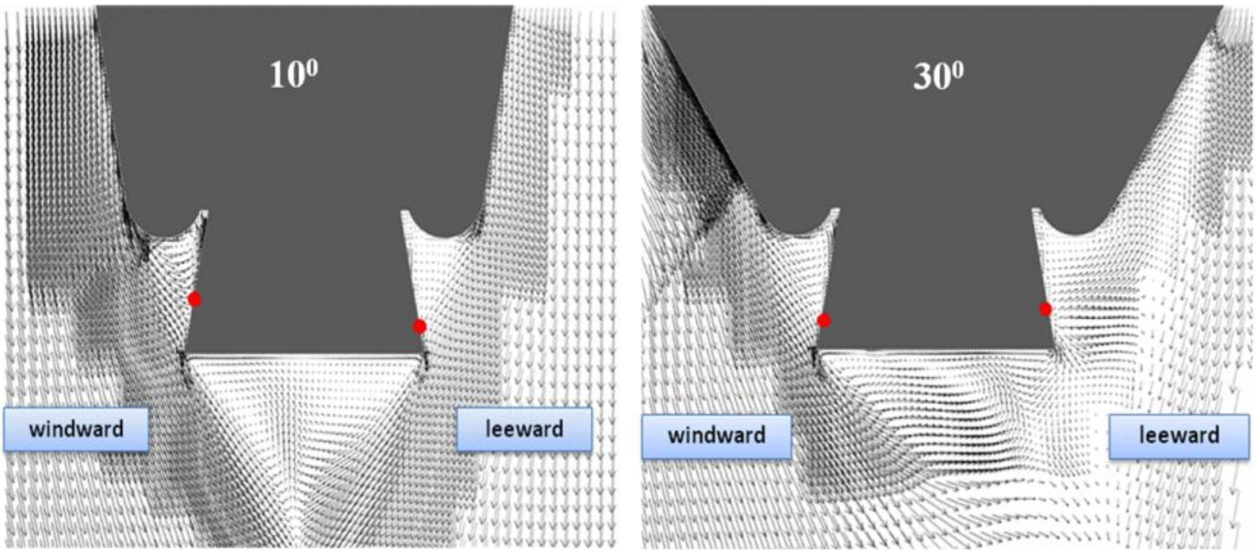


Figure 3: Flow field around the boat-tail at M=1.20

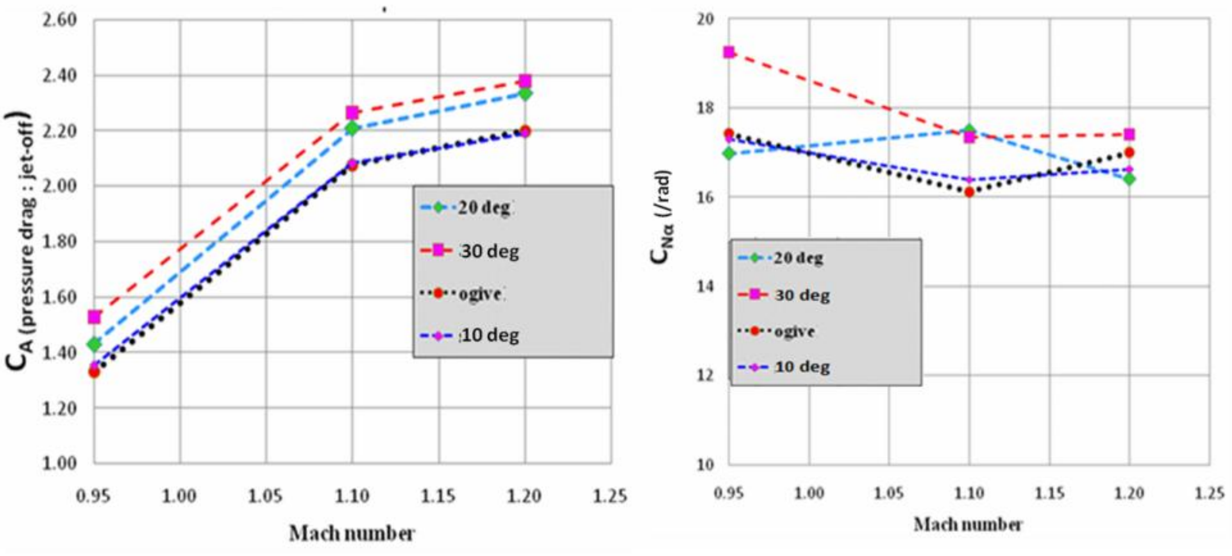
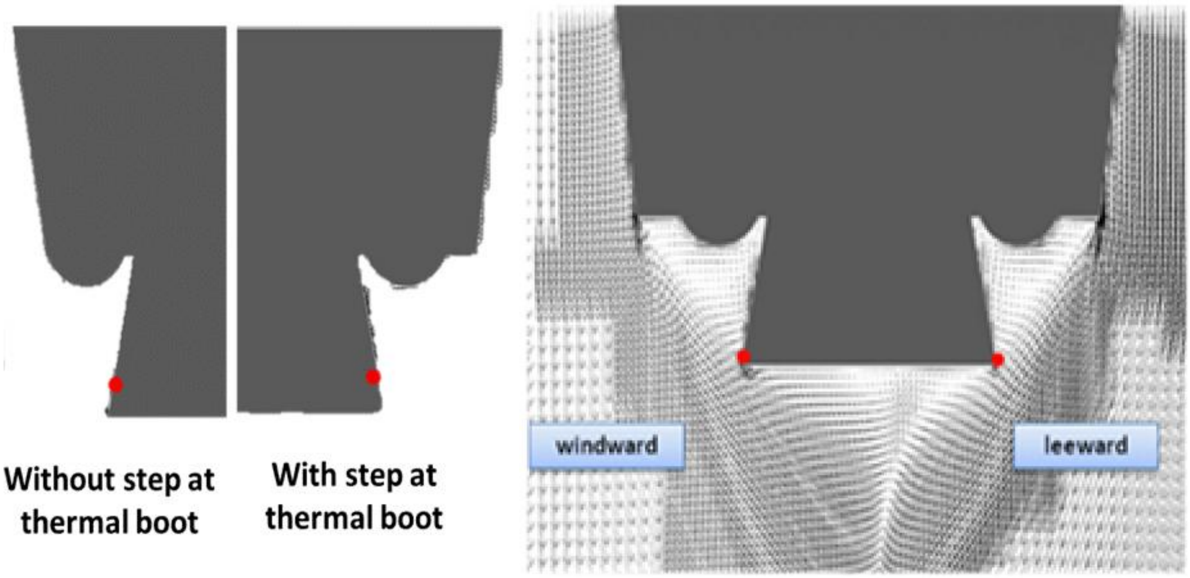


Figure 4: Variation of overall C_A and $C_{N\alpha}$ with Mach number



a) b)

Figure 5: a) Geometry of boat-tail before and after the addition of step at the thermal boot
b) Flow field around conical boat-tail (d=0.75 D) at M=1.20

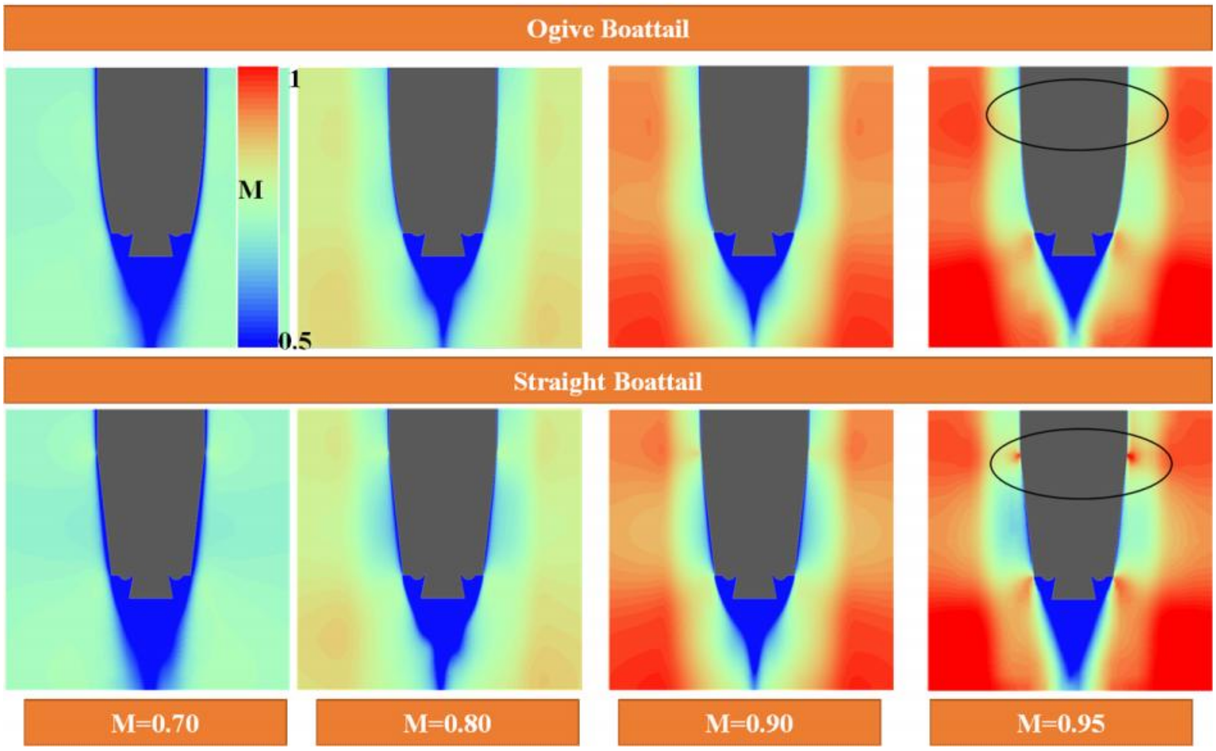


Figure 6: Mach palette over the boat-tail for cone and ogive boat-tails

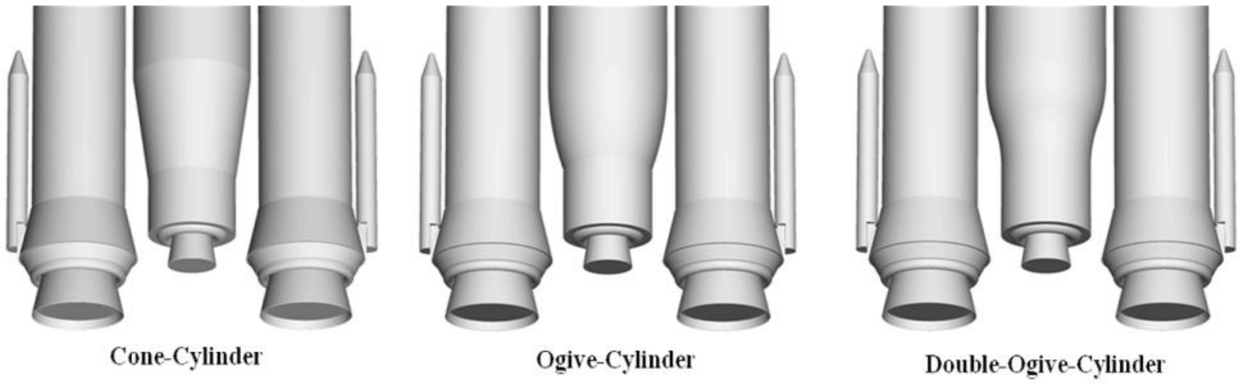


Figure 7: Cone/ogive-cylinder configurations studied

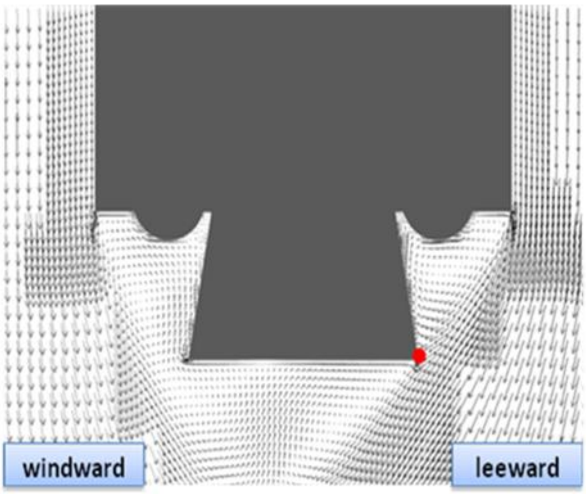


Figure 8: Flow field on the double-ogive-cylinder configuration at M=1.20

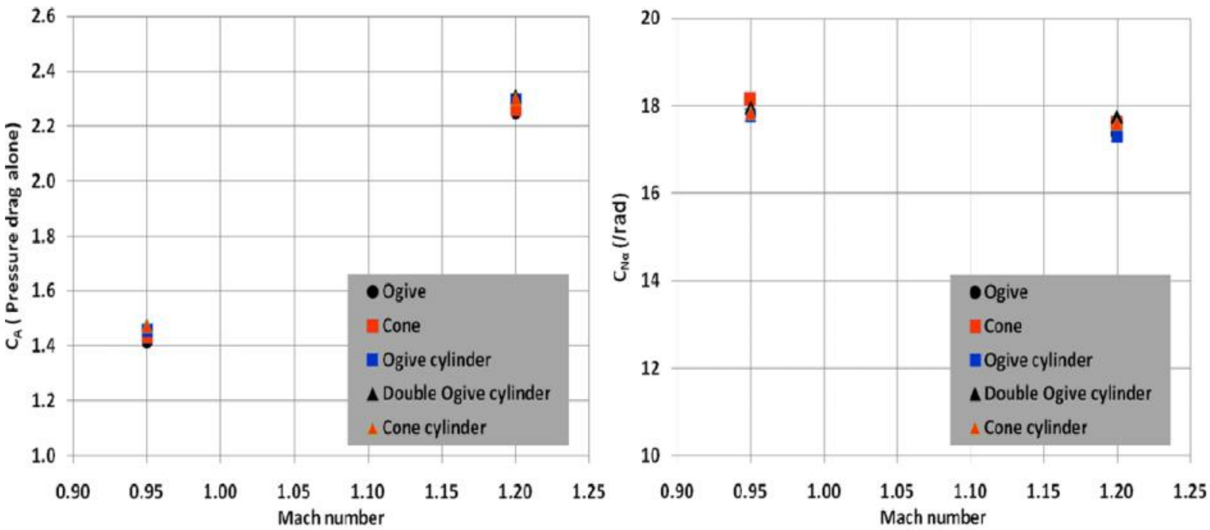


Figure 9: Variation of overall C_A and $C_{N\alpha}$ with Mach number

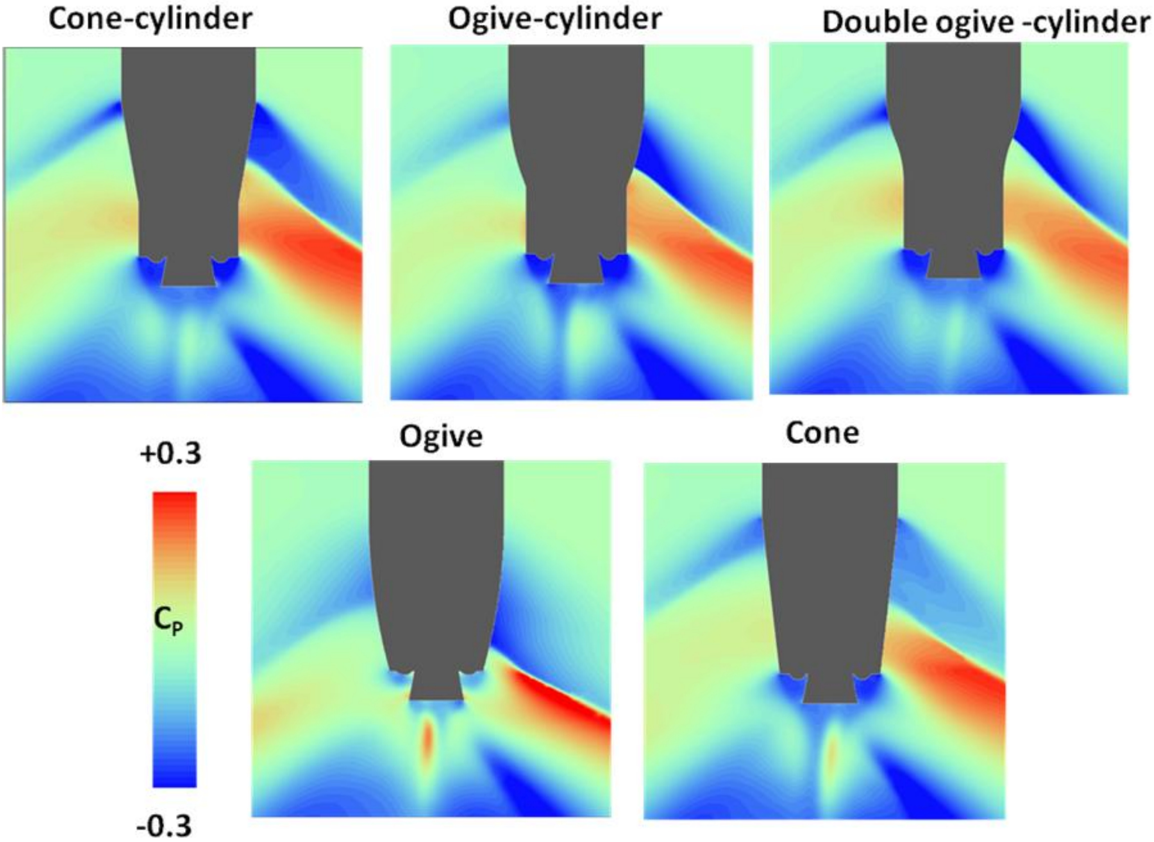


Figure 10: Pressure palette on base of shallow cone/ogive and ogive-cylinder configurations, M=1.20