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Investigation of Flow Field Around the Pointed Cowl Air Intake at Mach 2.0

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***Abstract* – Experiments and computational studies were carried out to get an understanding of the flow field around a rectangular supersonic intake with pointed cowl shape. Experiments include quantitative pressure measurements and flow visualization studies by using schlieren techniques. The effects of the presence of various cowl shapes on ramp surface have been obtained computationally at Mach 2.0. The experiments were carried out only for the pointed cowl. Schlieren Photographs were taken. Three-Dimensional simulations were made by using FLUENT at supersonic speed. The details of the experiments and computations are discussed.**

***Keywords* – Cowl, intake, Mach, pointed cowl, schlieren.**

I. INTRODUCTION

Air Intake has been the topic of active research over the years. The need to supply controlled amounts of air to the combustion chamber requires to ensure the quality and quantity of air entering the combustion chamber. In order to implement this objective a thorough understanding of the flow phenomena is essential. In supersonic inlets the flow field in and around the intake becomes highly complex due to several flow interactions. The drag induced by the air intake gives a significant part to the overall drag of the vehicle. Hence the characteristics of the air intake have to be investigated at the early stages of development to optimize the design of the vehicle. Over the past half century, a lot of research has been done on various factors which influence air-inlet flow fields. From the literature it is clear that cowl geometry plays an important role in the performance of the air intake. In the present study, cowl shape effects for a rectangular intake are evaluated and experimentally tested. Three different shapes of cowl where taken up and compared computationally. The experiments were performed only for the pointed cowl shape.

II. STATE OF THE ART TECHNOLOGY

A summary of theoretical, experimental and computational studies performed by various researchers on different types of air -inlet is presented in this section.

Air intake adopting bleed and cowl bending for unstart suppression and performance was carried out by Das and Prasad [1]. Investigation over inviscid flow condition led to the start of the intake and turbulent flow led to the unstart condition. It was observed that the bleeding of 1.8 % of air alleviates the unstart problem. They concluded that a definite increase in performance and flow quality by cowl bending and adopting bleed. Staring characteristics for intake with cowl deflection were also studied by Das and Prasad [2], concluded that cowl defection could be thought of an alternative to the bleeding for the intake model. Two dimensional simulations corresponding to different cowl bending studied by same authors [3] concluded that the increase in cowl deflection angle increased the performance for the intake model with pressurized exit and small deflection led to good pressure recovery.

Experiments on cowl shape and intake characteristics at hypersonic speeds were performed by Jagadeesh and Mahapatra [4]. Good mass recovery (5 % to 10 %) was observed with increase in cowl plate length up to 10 mm.

The effects of wall temperature, cowl bluntness, cowl length, boundary layer thickness on the starting phenomenon of intake at Mach 6.0 were studied by Goldberg and Heffner [5]. They concluded that wall cooling is the most important for the start of the intake, and also pressure recovery did not depend much on the Reynolds number.

Nose bluntness and controlled roughness on the flow was investigated by Cubbage [6] at Mach 5.98 and it was concluded that nose bluntness and roughness have only small influence on surface pressure.

A three-dimensional computational analysis of hypersonic intake was reported by Smart and White [7]. It was concluded that losses due to shock detachment on the cowl leading edge influence the characteristics of overall flow at the exit of the intake.

Studies on intake at hypersonic speeds with the help of a moving cowl were performed by Donde [8]. It was concluded that the cowl needs to be rotated by an angle of 15.70 and then it should be brought to the desired position for starting the intake after its unstart.

Studies on intake with rectangular to elliptical shape transition at Mach 6.2 were performed by Smart [9]. The intake could capture 96 % of available air flow and 55 % of the total pressure was recovered for 14.8 ratio of compression.

Studies on subsonic diffuser shape on the internal contraction ratio, pressure recovery and also cowl on a conical centre body angle 250 were performed by Goldsmith [10], studies were designed for Mach 2.46 and experiments performed at Mach 2.48. The conclusion was that pressure recovery increased for the increased internal duct contraction ratio and also increase in the internal angle of the cowl, for a given internal contraction ratio of the Duct.

Ianson and Stolley [11] studied the effects of Reynolds number, cowl position and presence of vertex generators on a two-dimensional hypersonic intake. They concluded that Reynolds number reduction led to an increase in the boundary layer thickness, but there was little effect on the intake flow.

Studies on 3-D side wall compression for the leading edge sweep angles of 300 and 700 at Mach 6.0 by Holland [12] were investigated to account for the geometric parameter effects on the intake performance. The parameters were cowl position and leading edge sweep angle. For each configuration, the intake was found.

Computations on 3-D hypersonic intake at Mach 8 as well as experiments were performed by Renairtz et al. [13]. Only a single outer compression ramp was used and side wall compression effects were discussed. It was concluded that the intake in combination of the isolator is able to generate the required flow conditions for stable supersonic combustion with the help of a central strut injector.

Experiments on large scale 2-dimensional with a mixed compression were performed by Wong et al. [14]. The variable inlet model was taken with a design Mach 3.0 and studied at transonic speeds and varying Reynolds number. The report discussed the effects on engine face total pressure performance on the throat boundary layer bleed, vertex generators for the ramp at transonic speeds and cowl positions. It was concluded that the 1-D inviscid theory is inadequate for the prediction of drag due to the viscous effect on the ramp surface.

Rectangular to elliptical shape transition for 3-D hypersonic intake was studied by Smart [15]. Apart from swept leading edges a highly significant notch cowl was used to allow for self-starting at high ramjet take over speeds.

The flow field over the pointed cowl (90°) intake model is not investigated. The previous research attempts in this field have never come across any research on the pointed cowl model for a rectangular intake. In this paper, an attempt is made to investigate and analyse the characteristics of the intake model with the pointed cowl (90°) and a good comparison with the existing intake models is made. It is made sure that the intake model is physically realizable.

III. Research Methodology

Experiments were performed by using the supersonic wind tunnel facility available in the department of space engineering and rocketry, Birla Institute of Technology, Mesra, Ranchi. The test -section size of the wind tunnel is 50 mm × 100 mm, and it has removable side windows. This is an intermittent blow-down type wind tunnel, which makes use of compressed air stored in the external reservoir with maximum capacity of 30 m^3 and maximum pressure storage capacity of 300 psi. An air drier is used between the compressor and reservoir to remove moisture from air. A settling chamber settles down the air before it enters into the wind tunnel nozzle. The stored air is released using an electronic solenoid valve through pneumatic operations to the settling chamber and finally expanding through a C-D nozzle at the test section. The run time of the wind tunnel depends on stagnation pressure and Mach number, which can go up to 60 seconds. In this study, a typical run time of 10 to 20 seconds was used. For the present study nozzle block is corresponding to Mach 2.0.

Computations were performed by using ANSYS FLUENT CFD. The geometry was made in GAMBIT and Meshed, defining the boundary conditions for the model. A K-ω turbulence model was used. A free stream turbulence intensity of 0.5 % was specified at the inlet. No slip condition was imposed at the boundary walls. The minimum spacing at the walls in Y-direction was at the order of 0.15 mm, which corresponds to $y+$ value of 25. A total of 345 800 number of cells, structured mesh and the residuals were converged to 10^{-3}.

IV. Results and Discussion

Experimental and computational studies were carried out to get an understanding of the flow field around the rectangular supersonic intake with pointed cowl shape. The experiments include quantitative pressure measurement and flow visualization studies using schlieren techniques. The effects of presence of various cowl shapes on the ramp surface have been obtained computationally at Mach 2.0. The experiments were carried out only for the pointed cowl shaped intake at Mach 2.0. The schlieren photographs were taken. Three-dimensional simulations were made by using FLUENT at supersonic speed. The details of the results obtained through experiments and computations are discussed in this chapter.

Three-dimensional computations were carried out on the supersonic air intake with clean cowl, notch cowl (90°) and pointed cowl (90°). The computations were made without and with back pressures for all the three types of cowl intake. The viscous computations are discussed in detail in the following sections.

A. Pointed Cowl (90°) Intake Model Free Exit at Mach 2.0

The density contour is shown in the Fig. 1. The shocks emanating from the first and second ramps can be seen very clearly. The shock impingement is on to the cowl lip. The reflected shock from the cowl tip impinges on the ramp surface downstream of the shoulder. The shock reflections could be seen inside the intake duct showing a "start" condition.

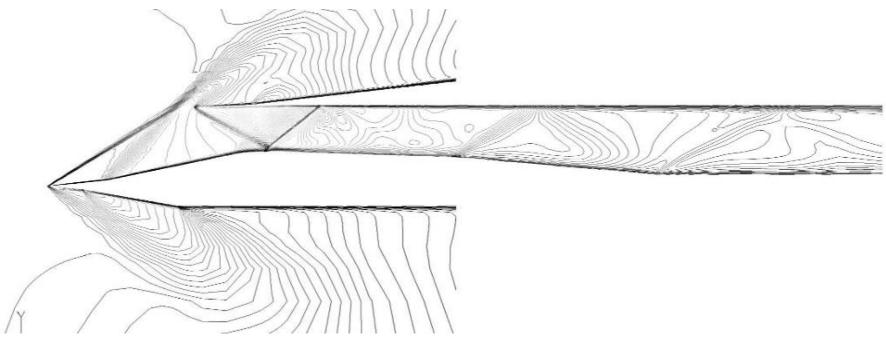

Fig. 1. Density contour along the centre plane of the ramp for pointed cowl [90°] intake model.

B. Comparison of the Results for Different Cowl Configurations

Fig.2 provides a comparison of various intake ramp surface pressure distributions. The pressure is constant along the first ramp in all the cases. For the clean cowl, there is an increase in pressure over the second ramp which is due to bow shock (peak pressure value), hence there is a huge spillage. A drop in peak pressure value seen for both notch and pointed cowl is due to the weakening of the cowl shock. There is a sudden decrease in pressure at the shoulder of the intake due to the expansion corner. A smaller peak value in case of pointed cowl model indicates that the cowl tip shock on the ramp has moved downstream compared to the notch cowl intake model.

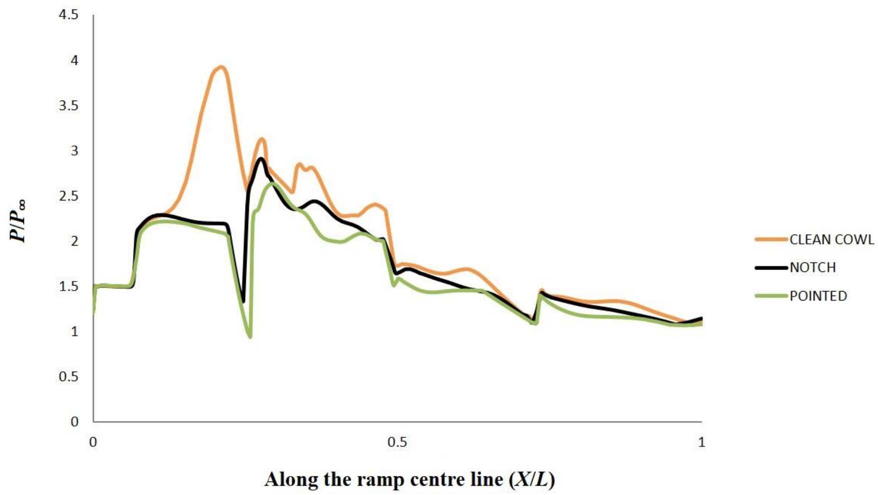

Fig. 2. Pressure distribution along the ramp centre plane (X/L) for different cowl shapes.

At Mach 2.0, the notched cowl intake gave a good pressure recovery of 84.0 % and the pointed cowl pressure recovery was only 81.2 % which was lower than the clean cowl intake model giving 82.4 %. It was observed that for all three intake models the maximum value of the total pressure ratio at the centre plane and at the side wall plane is found to be 0.97 and 0.29 for the pointed cowl model. Further computational results are

C. Computational Results for Pressurized Exit for Pointed Cowl (90°) at Mach 2.0

The computations for the intake with back pressures are made to simulate the engine operating conditions. With a typical back pressure, a normal shock enters the intake duct and interacts with the surface boundary layer. This interaction leads to massive flow separation on the walls of the intake. A similar grid and solver settings were adopted for pressurized exit as it was used for the free flow computations. The only difference is the specification of the exit pressure corresponding to the back pressure.

The back pressure is applied in terms of exit static pressure ratio P_e/P_∞. This ratio is gradually increased from 2.5 to 5.7 to bring the shock near to the throat region. It was observed that for the pointed cowl intake, the normal shock is expelled out of the intake throat at $P_e/P_\infty = 5.5$ and stands at the intake entry plane showing a sub- critical operation of the intake. A critical condition is seen for $P_e/P_\infty = 4.5$. Fig. 3 shows the ramp pressure distribution for different back pressures at the exit plane for Mach 2.0. It could be seen that there is no pressure difference compared to the free exit flow up to $X/L = 0.76$ for the back pressure ratio of $P_e/P_\infty = 2.5$. Beyond $X/L = 0.76$, the pressure gradually increases and reaches a value of 2.44 at the exit. With further increase in the pressure, the normal shock forms and moves to the upstream location and at $P_e/P_\infty = 4.5$ the normal shock is seen at the near throat region and the location is around $X/L = 0.28$. Fig. 4 shows the centre plane density contour for the back pressure for the pointed cowl $P_e/P_\infty = 4.5$.

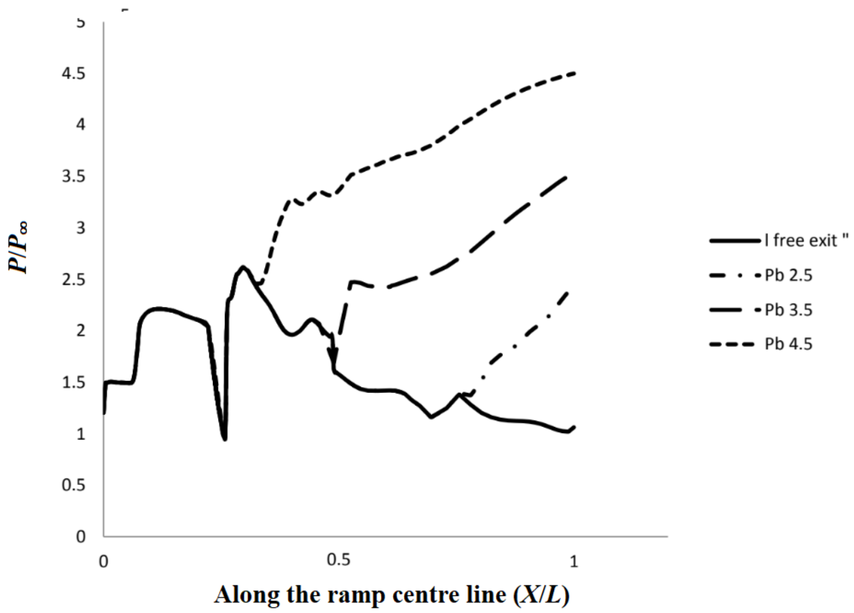

Fig. 3. Ramp pressure distribution for different back pressures at the exit plane for the pointed cowl at Mach 2.0 along the ramp Centre line (X/L).

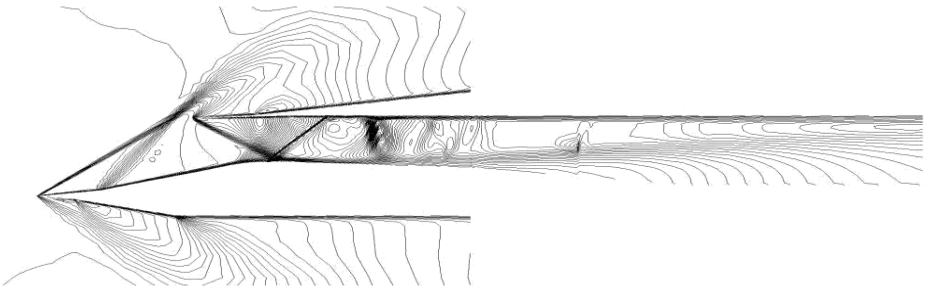

Fig. 4. Density contour at the centre plane for a back pressure for the pointed cowl at $P_e/P_\infty = 4.5$.

D. Experimental Results for Pressurized Exit for Pointed Cowl (90°) at Mach 2.0

All the experiments have been performed in an intermittent blow down supersonic wind tunnel at a free stream Mach 2.0 with a typical run time of 20 s and a stagnation pressure range of 30 psig which was measured by using a pressure sensor. Schlieren flow visualization was adopted to investigate the external and internal shock patterns. Static pressure and total pressure were measured at identified locations. The results obtained are discussed in the following sections.

Flow visualization was performed using the schlieren technique. The objective of the visualization was to obtain the effect of cowl geometry on the intake flow, effect of cowl leading edge angle as well as the effect of the throttle on the flow field.

The schlieren photograph of supersonic intake with the pointed cowl for the free flow at Mach 2.0 is shown respectively in the Fig. 5. Metal side plate pointed intake model shows two compressive ramp shocks, as well as shock on cowl lip condition is also clearly visible at Mach 2.0. Though internal shock reflections could not be seen, their presence was evident through the experimental results.

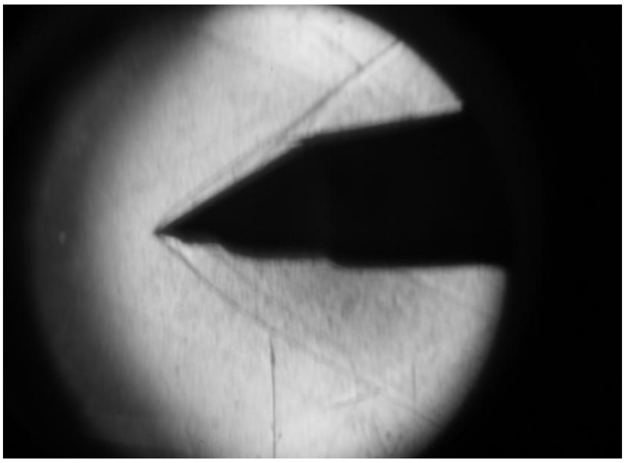

Fig. 5. Schlieren flow visualization photograph over the intake model at Mach 2.0.

Static pressure measurements were performed at 5 different locations (1 on the first ramp, 4 on the second ramp, 2 on the throat/isolator, 5 on first diffuser, 2 on the second diffuser and 1 on the third diffuser) along the centre line of the ramp surface. The static pressure measurements are made only on the ramp surface to get the effect of the cowl geometry. The static pressure is non-dimensionalised with the free stream pressure.

The surface static pressure distribution was evaluated over the ramp surface at Mach 2.0. For the Mach 2.0 at X/L = 0.1, sudden rise in pressure is due to the ramp shock. The maximum pressure value is obtained at X/L = 0.3 location. Fig. 6 shows comparison of experimental and computational results.

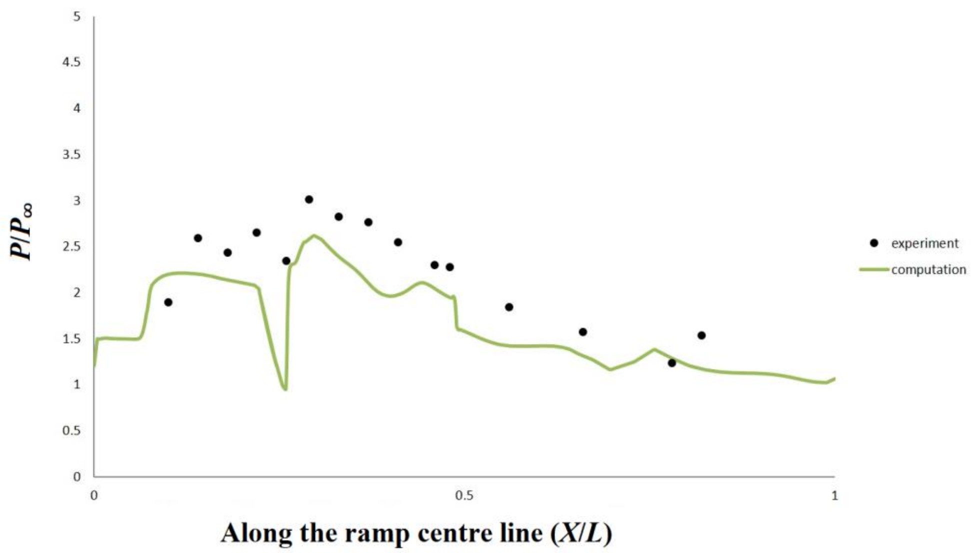

Fig. 6. Measured pressure along the ramp surface for pointed cowl (90°) intake Model for Mach 2.0 along ramp centre line (X/L).

V. Conclusion

In the present investigation, experiments and computations were performed to obtain the flow field characteristics of a supersonic intake designed for Mach 2.0. The experiments include flow visualization by using the schlieren techniques and measurement of static pressures. Three dimensional simulations of the flow field by using the FLUENT has been made. To capture the flow field, k-ω turbulent model was adopted to capture the flow field. The experiments were made for the pointed cowl model at Mach 2.0. The studies were made with the pointed, clean and notch cowl models and the effect of these cowl models on the intake has been obtained.

The following important observations were made from the results obtained the through experiments and computations.

In the presence of either the notch cowl or pointed cowl, the intake showed the starting nature at off design conditions. This starting of intake was observed evident from the schlieren, density contours and pressure distribution on the ramp surface. The static pressure measurements confirmed that the pressure rise inside the duct is due to the cowl presence and changed with an increase in Mach number. The increase in Mach number resulted in good pressure recovery for the pointed cowl model. The pressure recovery has increased for the notched cowl at low Mach numbers and, while at high Mach numbers this pressure recovery was good only for the pointed intake.

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