# Investigation of Flow Field Inside a Mixed Compression Rectangular Air Intake for Different Cowl Shape at Different Back Pressures at Mach 2.0 and 2.2.

S K Vutukuru [1*], R K Mishra[2], S K Yadav 3, Gopinath B4 and Rajesh T R 5

1 1-4Department of Aerospacel Engineering, MVJ college of Engineering and Technology, Bangalore
5Department of Mechanical Engineering, Gopalan College of Engineering, Bangalore
* Correspondence: vshravankoundinya1989@gmail.com;

**Abstract:** The flow field around and inside of air intake has been a topic of intensive research because of the complex physics of the intake and also the drag over the intake was realized to contribute significantly to the overall drag of the flying vehicle. The main purpose of the air intake in most of the flying vehicles is to supply controlled amount of air tothe combustion chamber for good engine performance. In the present work three different cowl shapes were consid- ered for a mixed compression rectangular intake designed at Mach 2.2 (clean cowl) and compared with two other cowl shapes V-Notched [90$^0$] and pointed cowl along with different back pressures and their pressure recovery at the intake exist section. The cowl shape showed significance change in the pressure distribution over the ramp surface and also change of cowl shape helped overcome the phenomenon of intake "unstart" condition.

**Keywords:** start, unstart, pointed cowl.

## 1. Introduction

Intake is an essential part of an air breathing engine for the reason that a desired mass flow, low distortion flow is provided to the engine at all flight operating conditions at supersonic flow regimes and also the pressure recovery loses to be minimized. It is therefore important to analyze the flow field in and outside the air intake. In the present report three different cowl shapes were used and compared at Mach 2.0 and 2.2 along with different back pressures at the exit section of the intake model. The comparison was so chosen because the two cowl shapes V-Notch and pointed showed starting and better pressure recovery atoff design intake conditions [1-2]. A better pressure recovery was obtained for pointed cowl at higher Mach compared to V-notch cowl [1]. By comparing the three intakes a better understanding of cowl shape importance, performance could be obtained.

Adopting bleed and cowl bending for the suppression of unstart phenomenon at supersonic speeds was carried out and it was realized that a air bleeding of 1.8% reduced the problem of unstart [3]. Further also the starting characteristics with cowl deflection were analysed and realised that the cowl defection is comparable to a 2.8% bleed and is another possibility to start the Intake [4]. Different cowl deflections to analyse and capture the flow field with and without free exit flow was performed. There was a reduced separation with increased cowl deflection angle. An improvement in pressure recovery was observed for 2$^0$ cowl deflection [5]. Cowl shape and cowl location for a hypersonic Mach number was performed. It was observed that better mass recovery was observed for increase in the cowl plate length. Further for every 10mm increase in the cowl length plate a recovery of 5-10% was noted [6]. Intake height, boundary layer thickness are the two main criteria for the total pressure recovery at Mach 6[7]. Starting characteristics problem in a variable geometry and movable cowl for a hypersonic intake was performed and it was inferred that a rotation of $15.7^{0}$ is needed and brought back to normal position after an unstart condition for the intake [8]. A good air flow was captured and a pressure recovery of 55% for a compression ratio of 14.8 through a rectangular to elliptical shape transition [9]. Drag coefficient reduction on two quasi axis symmetric scramjet models were observed at Mach 6 & Mach 8. This decrease of drag coefficient increased with increase in Mach numbers [10]. An increased in pressure recovery was observed with increase in duct internal contraction ratio [11]. Effect of external and internal side wall compression along with the different contraction ratios for the scram jet inlet performance. There was an increase in the compression ratio of the inlet by additional side wall compression [12]. Three different type of inlets with different cowl length ratios of 0337, 0.439 and 0.547. At the zero angle of attack and at low Mach and mass flow the long cowl flow separation over the forward portion remained for Mach 0.79 and but for short cowl there was negative pressure peaks near the leading edge [13]. The effect of cowl position, Reynolds number and vortex generators for hypersonic air intake was studied. It was observed that rising the cowl there was increase in the separation region inside the cowl and reducing the Reynolds number resulted in the increase of boundary layer displacement thickness [14]. At Mach 6, movable cowl and aft plug was deployed for the two-dimensional scramjet engine. Intake starting steadily improved with varying increasing Reynolds number and also with aft plug position[15]. Static pressure was measurement for a three-dimensional side wall compression with leading edge sweep angles of $30^{0}$ and $70^{0}$ at Mach 6 to know the intake performance parameters. The intake was found to start and remained started during the tests[16]. Flow field around a supersonic air intake with a notched cowl was tested experimentally for different Mach other than the design Mach of 2.2. The flow inside the duct accelerated and the acceleration increased with increase in notch angle[17].

## 2. Materials and Methods

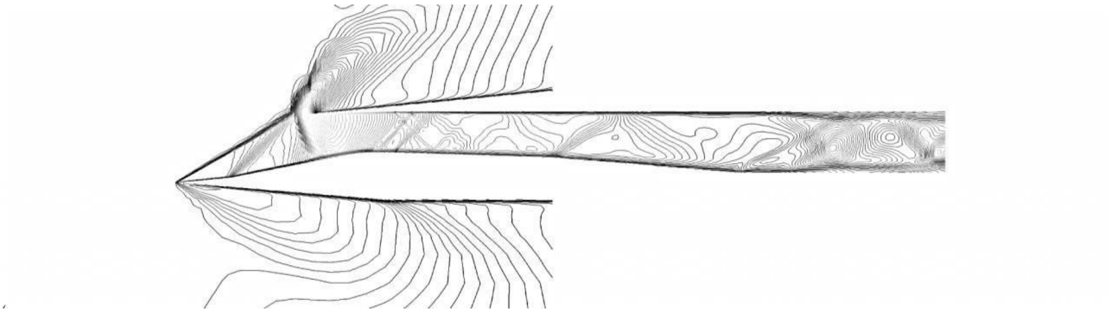
All the computations were performed by using the ANSYS FLUENT. Initially the geometry was modelled in solid works and then imported into GAMBIT where domain and meshing has been done. Turbulence intensity of 0.5 %, No slip condition at the boundary walls and corresponding value of y+ 25. Minimum spacing at the walls remained 0.15mm in the y direction. A total of 345800 cells (structured mesh) and all the residuals converged for $10^{-5}$.

Experiments were performed in an intermittent blow wind tunnel where a high speed of 2.2 Mach through a C-D nozzle could be achieved.

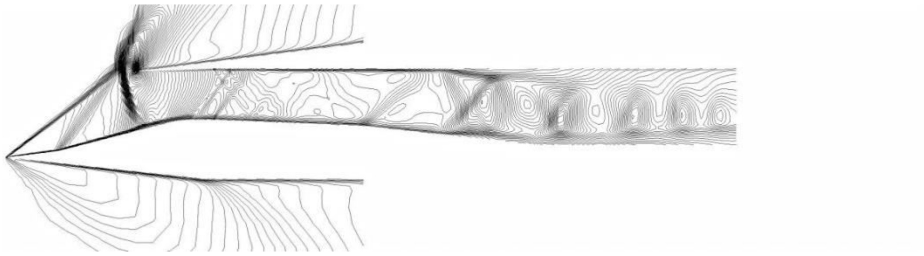
## 3. Results

All computations were carried out with the stagnation pressure or total pressure of 342615 Pa. k-ω turbulence model was used. The static pressure at the exit was 43787.75 Pa corresponding to Mach 2.0 and 32041.92 Pa for Mach 2.2 at the exit respectively. The static pressure at the exit was increased, the same has been experimentally tested with a conical plug. The presence as well as the location of the normal shock depended of the static pressure at the exit of the intake. For simulation the presence of the shock is analysed through density contours along the ramp centre line.

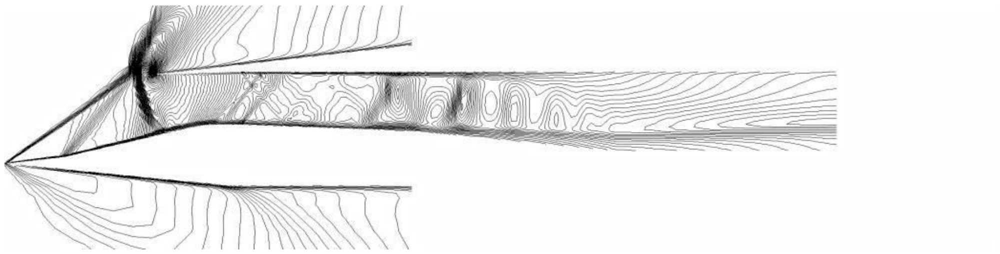
Density contours along ramp centre line for clean cowl model at Mach 2.0 for different back pressuresis shown in Fig.1. The figure 1 clears show that the intake has un started with a normal shock at the entry of the intake.



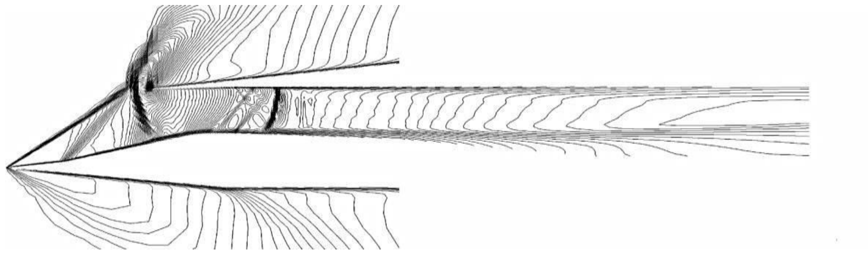
(a) Density contour along ramp centre plane for a back pressure of $Pe/P_{inf}=2.5$.



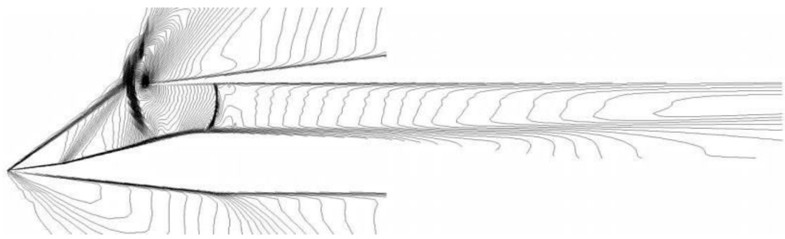
(b) Density contour along ramp centre plane for a back pressure of $Pe/P_{inf}=3.5$



(c)Density contour along ramp centre plane for a back pressure of $P_e/P_{inf}=4.5$.



(d) Density contour along ramp centre plane for a back pressure of $P_e/P_{inf}=5.5$.

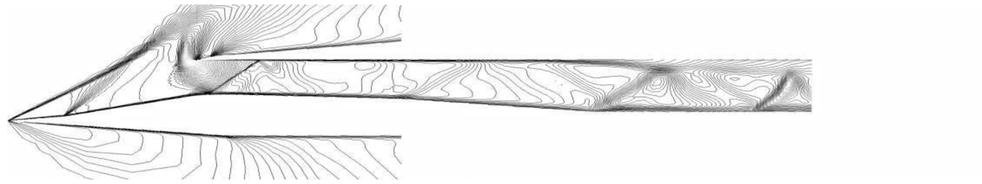


(e) Density contour along ramp centre plane for a back pressure of $P_e/P_{inf}=5.68$.

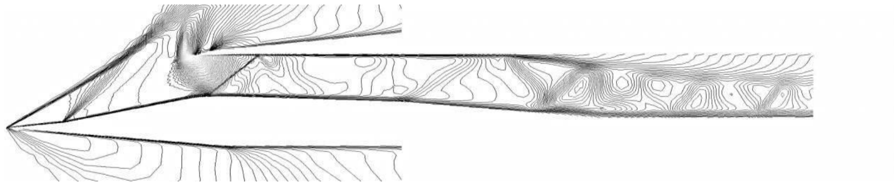
Fig.1 Density contours for clean cowl at different back pressure in terms of ratio $P_e/P_{inf}$

The normal shock inside the intake was observed only at a back pressure ratio of $P_e/P_{inf}$ =4.5. Below a back pressure of $P_e/P_{inf}$ =4.5 the shock observed to be swallowed. The position of the normal shock varied with change in back pressure.

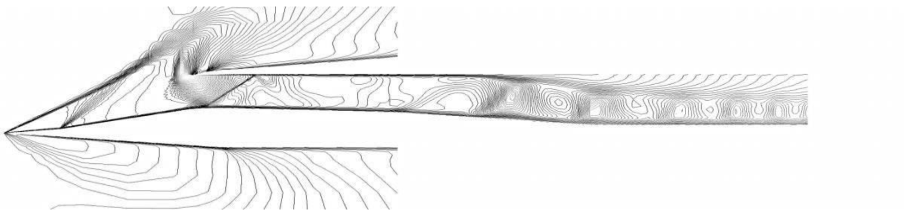
Density contours for the V-Noch cowl ($90^0$) at ramp centre plane at Mach 2.0. is shown in the figure 2. It is to be noted that the intake has started and there are shock reflections under the cowl lip (V -Notched cowl).



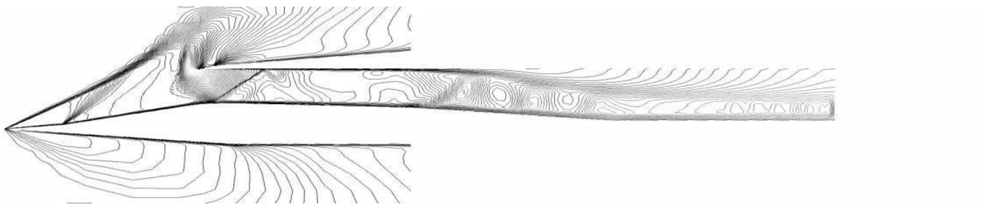
(a) Density contour along ramp centre plane for a back pressure of Pe/Pinf =2.5.



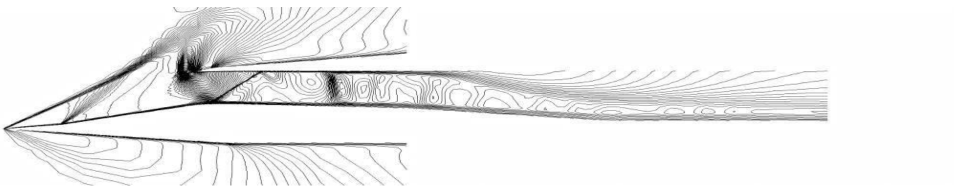
(b) Density contour along ramp centre plane for a back pressure of Pe/Pinf =3.0.



(c) Density contour along ramp centre plane for a back pressure of Pe/Pinf =3.5

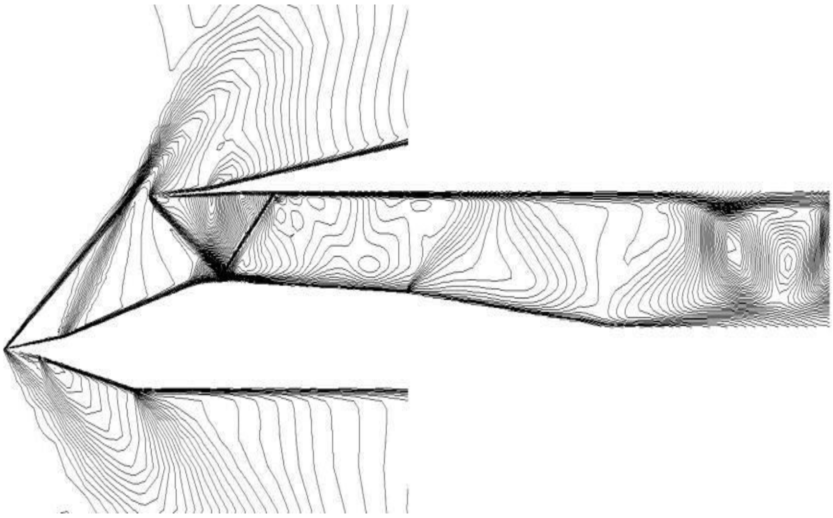


(d) Density contour along ramp centre plane for a back pressure of Pe/Pinf =4.0

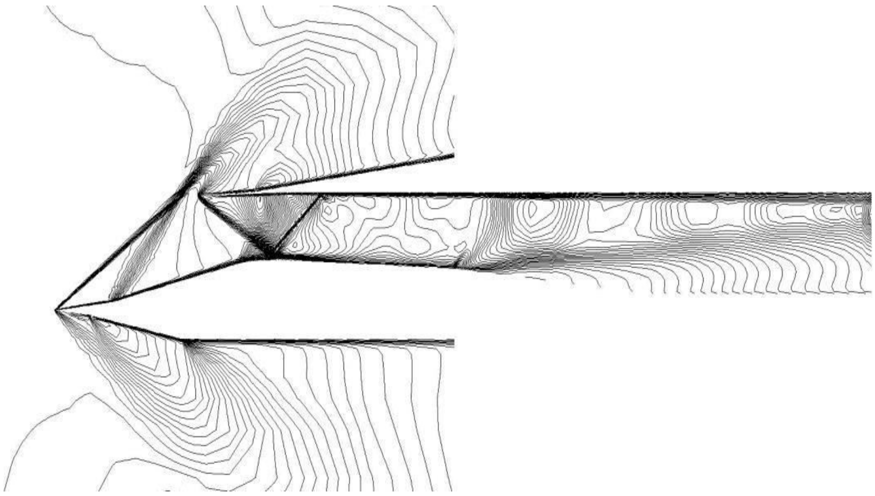


(e) Density contour along ramp centre plane for a back pressure of Pe/Pinf =4.5.

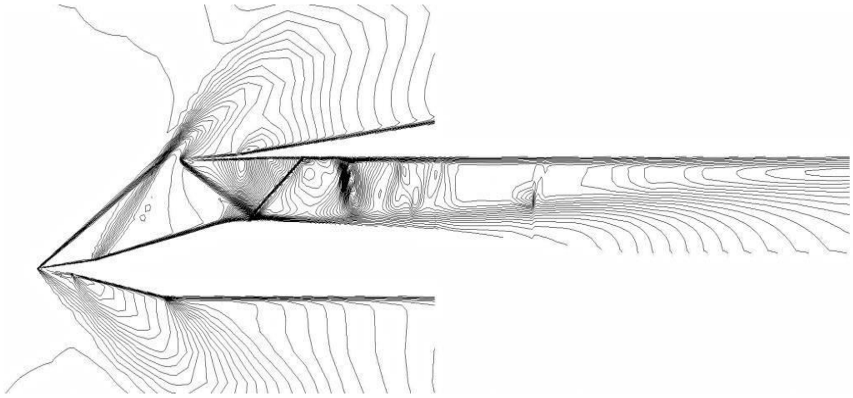
Figure. 2 Density contours for V-notch cowl ($90^0$) at different back pressure in terms of ratio $P_e/P_{inf}$



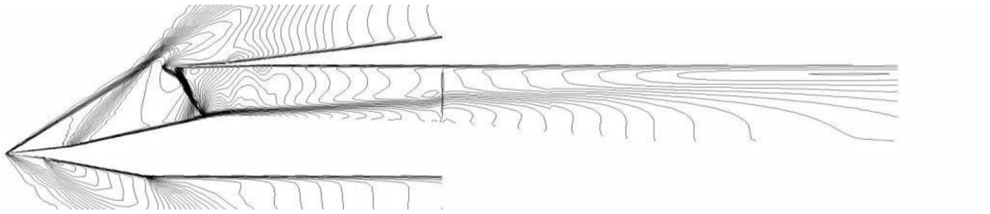
(a) Density contour along ramp centre plane for a back pressure of Pe/Pinf =2.5.



(b) Density contour along ramp centre plane for a back pressure of Pe/Pinf =3.5.



(c) Density contour along ramp centre plane for a back pressure of Pe/Pinf =4.5.



(d) Density contour along ramp centre plane for a back pressure of Pe/Pinf =5.5.

Figure. 3. Density contours for pointed cowl ($90^0$) at different back pressure in terms of ratio $P_e/P_{inf,}$

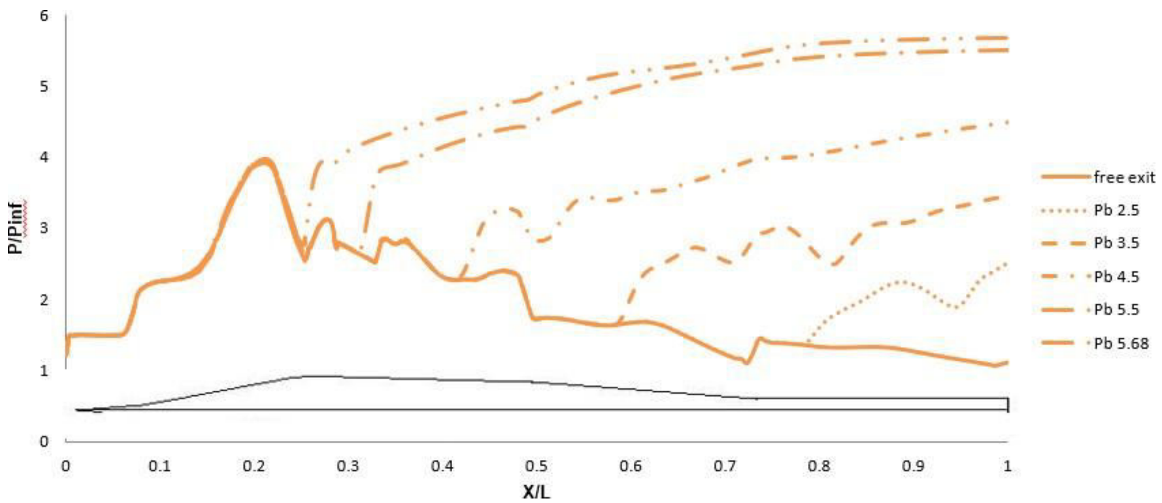



**Figure 4. Static pressure distribution along ramp centre plane for clean cowl air intake.**

The static pressure distribution along the ramp centre line for the v-notch cowl (90⁰) is as shown in the figure 5. The graph corresponds to the change in static pressure for the v-notch cowl intake.

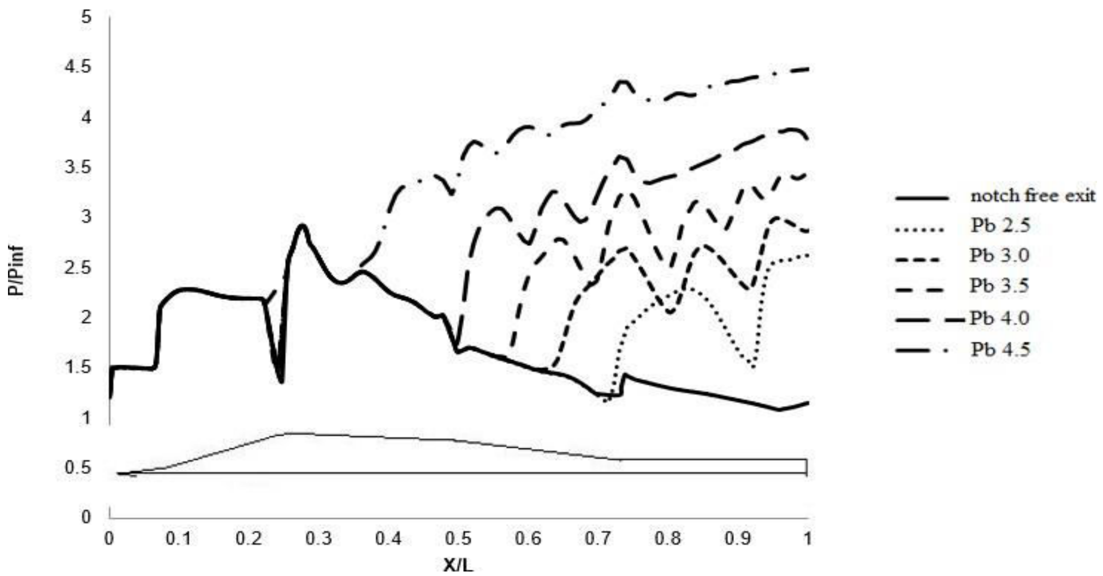
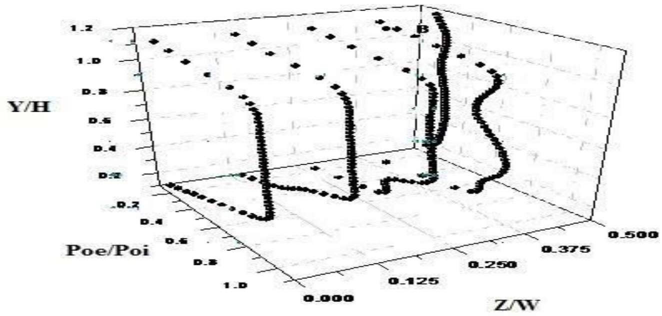


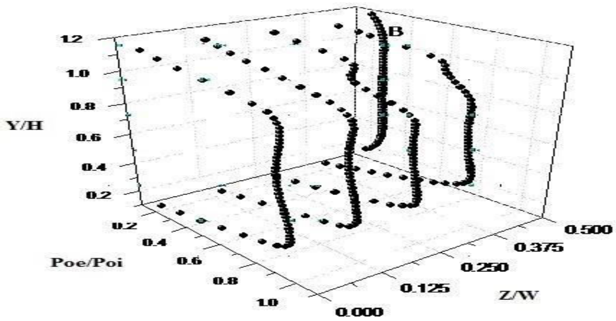

**Figure 5. Static pressure distribution along ramp centre plane for V-notch cowl (90⁰).**

It is to be noted that the shape of cowl had changed the static pressure distribution on the ramp surface and also the back pressure ratio influenced the position of shock mainly the normal shock. The appearance of shock for all the three intakes models depended on back pressure and cowl shape. The starting of intake was also based upon the cowl shape. The static pressure distribution for the pointed cowl was mentioned along the ramp surface was discussed[1].

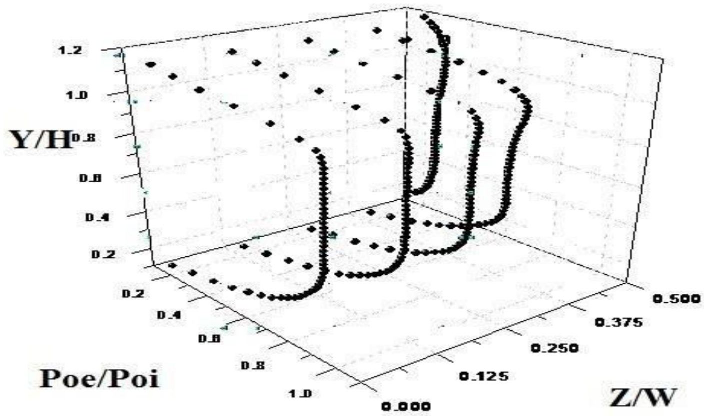
Total pressure recovery at the exit for the three different intakes is shown in the figure 6 at Mach 2.0 and for pointed and notched cowl in the figure 7.




**(a) Clean cowl**

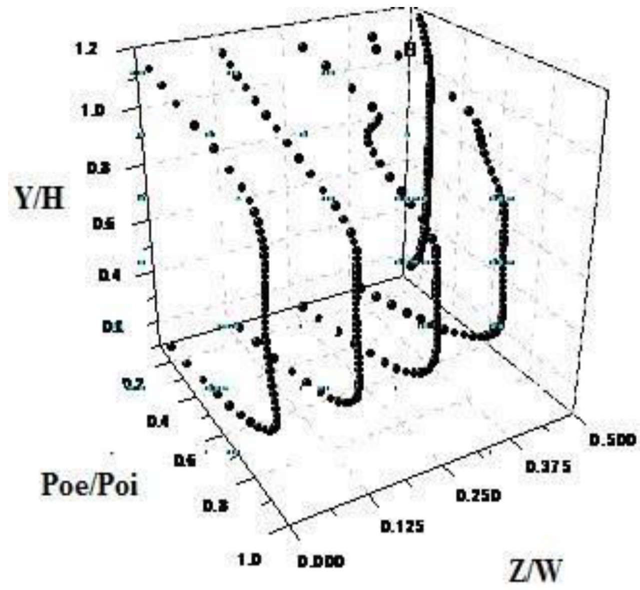



**(b) Notch cowl**

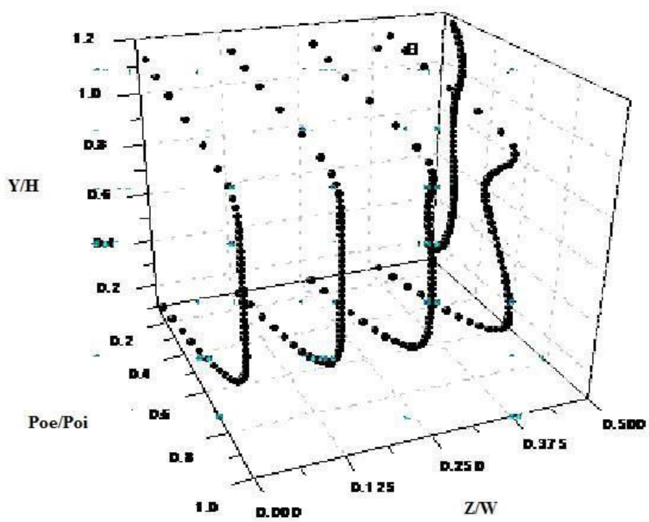



**(c) Pointed cowl**

**Figure 6. Total pressure distribution at the intake exit plane at various Z/W locationsacross the width at Mach 2.0 .**




**(a) Notched cowl intake**




**(b) Pointed cowl intake**

**Figure 7. Total pressure distributions at the intake exit plane at various Z/Wlocations across the width at Mach 2.2.**

Table 1: Total pressure ratios at the intake exit at Mach 2.0

**(a) Clean cowl intake**

| location of the exit plane | | Maximum value of total pressure ratio ( $P_{oe}/P_{oi}$) |
|---|---|---|
| X/L | Z/W | |
| 1 | 0 | 0.97 |
| 1 | 0.125 | 0.97 |
| 1 | 0.25 | 0.97 |
| 1 | 0.375 | 0.93 |
| 1 | 0.5 | 0.28 |
| | | Average value 0.824 |

**(b) Notch cowl intake**

| location of the exit plane | | Maximum value of total pressure rati( o $P_{oe}/P_{oi}$ ) |
|---|---|---|
| X/L | Z/W | |
| 1 | 0 | 0.98 |
| 1 | 0.125 | 0.98 |
| 1 | 0.25 | 0.98 |
| 1 | 0.375 | 0.97 |
| 1 | 0.5 | 0.28 |
| | | Average value 0.84 |

**(c) Pointed cowl intake**

| location of the exit plane | | Maximum value of total pressure ratio( $P_{oe}$ $/P_{oi}$ ) |
|---|---|---|
| X/L | Z/W | |
| 1 | 0 | 0.97 |
| 1 | 0.125 | 0.97 |
| 1 | 0.25 | 0.95 |
| 1 | 0.375 | 0.88 |
| 1 | 0.5 | 0.29 |
| | | Average value 0.812 |

**Table 2: Total pressure ratios at the intake exit at Mach 2.2.**

**(a) V-Notch cowl:**

| location of the exit plane | | Maximum value of total pressure ratio( $P_{oe}/P_{oi}$) |
|---|---|---|
| X/L | Z/W | |
| 1 | 0 | 0.952 |
| 1 | 0.125 | 0.956 |
| 1 | 0.25 | 0.960 |
| 1 | 0.375 | 0.936 |
| 1 | 0.5 | 0.232 |
| | | **Average value 0.807** |

**(b) Pointed cowl:**

| location of the exit plane | | Maximum value of total pressure ratio ( $P_{oe}$ / $P_{oi}$ ) |
|---|---|---|
| X/L | Z/W | |
| 1 | 0 | 0.974 |
| 1 | 0.125 | 0.970 |
| 1 | 0.25 | 0.966 |
| 1 | 0.375 | 0.946 |
| 1 | 0.5 | 0.229 |
| | | **Average value 0.817** |

It can be inferred from the above table that the pointed cowl would give better pressure recovery at the exitof the intake for higher Mach that is at Mach 2.2 and at lower Mach the V -notched cowl $90^0$ is efficient.

## 4. Discussions

It could be analyzed from the Figures 4 and Figure 5 that the back pressure for the clean cowl is more to bring the normal shock to the entry of the inlet duct. The rise and fall of the static pressure plot along the ramp surface is due to shock and shock reflections respectively along the ramp surface center line. The notched cowl or a pointed cowl remain as an alternative for the intake model to get it started at Mach numbers lower than the designed Mach. The clean cowl has the highest-pressure recovery at Mach 2.2 dueto its design Mach condition when compared to any other type of intake at Mach 2.2. The pressure recovery increased with the increase in Mach number for the pointed cowl Intake model.

## 5. Conclusions

1. There exits start and unstart condition for the air-intake and these conditions of the start and un-start are dependent on the back pressure at the exit section of the intake.
2. With the change in the back pressure at the exit of the intake the position of the shock changed.
3. For the design Mach the pressure recovery is the highest where the shocks are reflected at the cowl lip and terminated by weak normal shock.
4. For a given rectangular intake, to make the intake start at lower Mach number the cowl lip should be either a pointed cowl or a V Notched cowl $90^o$.

## References

1. Urbahs, A., Das, S., Vutukuru, S.K. and Carjova, K. (2017) Investigation of Flow Field around PointedCowl at Mach 2.0. Transport and Aerospace Engineering, 5, 75-82.

2. Vutukuru, S. , Das, S. and Urbahs, A. (2018) Study of Flow Field inside a Rectangular Air Intake with Pointed Cowl for Different Back Pressures at Mach 2.2. *World Journal of Engineering and Technology*, **6**,575-584.

3. Das ,S, and Prasad ,J.K. ,"Unstart Suppression and Performance Analysis of Supersonic Air intakeAdopting Bleed and Cowl Bending" ,Journal of institution of engineers (India),Vol91,march 2010 ,pp.27-35.

4. Das, S and Prasad J.K "Starting Characteristics of a Rectangular Supersonic Air Intake with Cowl Deflection", Aeronautical Journal, Vol114, may 2010, pp177189.

5. Das, S and Prasad J.K,"Effects of Cowl Deflection Angle in a Supersonic Air Intake", Defence Science Journal ,Vol 59 ,no 2 march 2009 ,pp99-105.

6. Mahapatra, D and Jagadeesh, G ,"Experimental Investigation of Cowl Shape and Location on Intake Characteristics at Hypersonic Mach Number" ,26th international symposium on shock waves ,Gottingen ,Germany 2009 ,pp.607 -612 .

7. Goldberg ,T.J and Heffner J .N," Starting Phenomena for Hypersonic Intakes with Thick Boundary Layers at Mach 6", NASA Technical note ,NASA TN D -6280 August 1971.

8. Cubbage J.M," Effect of Nose Bluntness and Controlled Roughness on the Flow on two Hypersonic Intake Centre Bodies without Cowling at Mach 5.98" ,NASA Technical Report ,july 1965,pp.1-64.

9. Smart M...K,"Experimental Testing of a Hypersonic Intake With Rectangular to Elliptical Shape Transition ", Journal of Propulsion and Power ,Vol 17 no 2 ,March -April 2001 ,pp276-283.

10. Katsuyoshi Tanimizu, D. J. Mee and R. J. Stalker, "Comparison of Drag Measurements of Two Axisymmetric Scramjet Models at Mach 6" , 16th Australian Fluid Mechanics Conference ,2-7 December 2007.

11. EL Goldsmith,"Effect of Internal Contraction, Initial Rate of Subsonic Diffusion and Cowl and Centrebody Shape on the Pressure Recovery of a Conical –Centre body intake at supersonic speeds", Aeronautical research council ,Reports and Memoranda .1962 ,R&M NO 3204 ,LONDON .

12. Oliver M.Hohn and Ali Gülhan ,"Experimental Investigation On The Influence Of Side Wall Compression On The Flowfield Of A Scramjet Inlet At Mach 7" .,17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference ,11-14.april2011,San Francisco ,California.
13. Richard J.Re and william K.Abeyounis ,"Wind Tunnel Investigation Of Three Axisymmetric Cowls Of Different Lengths At Mach Numbers From 0.60 to 0.92" ,NASA Technical Memorandum 4488, September ,1993.
14. Rowan J.G & Smart ,M.K ,"Design Of Modular Shape Transitioning Inlets For A Conical Hypersonic Vehicle ",in proceedings of the 48th AIAA Aerospace Sciences Meeting ,USA,2010,1-15.
15. Holland ,S.D .,"Wind Tunnel Blockages And Actuation Systems Test Of A Two Dimensional Scramjet Intake Unstart Model at Mach 6",NASA Technical Report 109152,November 1994 ,pp1-42.
16. Robert W.Cubbison ,Edward T.Meleason ,and David F.Johnson ,"Performance Characteristics From Mach 2.58 to 1.98 of An Axisymmetric Mixed Compression Inlet System With 60 percent Internal Contraction", NASA Technical Research Memorandum ,lewis Research Center ,Cleveland Ohio ,TM X - 1739 ,February 1969.
17. V.Jagadeesh Babu ,"Investigation of Flow Field Around a Supersonic Air Intake with Notched Cowl",M.E Thesis ,Department of Space and Rocketry ,Birla Institute of Technology ,Mesra,Ranchi,2011.