ANALYSIS OF FLOW FIELD ACROSS BLUNT FIN WITH DIMPLES –EXPERIMENTATION

Wg Cdr Muthu kumara samy Sekaran[1] ,B. Achu Naik[2]

Vel Tech Dr RR & Dr SR Technical University, 42, Avadi Veltech Road,

Chennai, 600 062,India

e mail: sekaran.muthu@gmail.com Moble: +91 98401.05664

Abstract

Experimental studies are made on the hemi – cylindrically blunted fins for Mach 2.2 to examine the effect of dimples on shock wave / boundary layer interaction. Flow field details around hemi – cylindrically blunted fin has been captured using oil flow visualization, measurements of static and total pressures and the lambda shock has been captured by shadowgraphy. Configuration indicate nonstart. The effect of the number of holes, hole diameter and height of the blunt fin on the separation region has been investigated.

Keywords:- Fins, Dimples, shadowgraphy, oil flow visualization, lambda shock wave, boundary layer

Nomenclature

D	= diameter of hemi – cylindrical blunt fin
t	= thickness of blunt fin
H	= height of blunt fin
d	= diameter of holes
L	= length of blunt fin
n	= number of holes
S_1	= primary separation line
S_2	= secondary separation line
S_3	= tertiary separation line
X_w	= attachment line

1.Introduction

The interaction of shockwave and surface boundary layer is a very complex phenomena which occurs on the high speed aerospace vehicles because of protrusion, control surface etc. This phenomenon may result in the loss of control effectiveness owing to flow separation or in loss of structural integrity owing to severe local heating.

The extent of separation depends on the body geometry e.g. height 'H', leading edge diameter 'D', local surface area in form of dimples holes and angle of attack 'α'. The incoming flow is characterized by its Mach number 'M_∞', Reynolds number 'Re_∞', and the thickness of the boundary layer.

Shock – wave / boundary-layer interaction is a critical area of research for the development of all future aerospace systems as they are ubiquitous in high-speed aerodynamic flows. The extraordinary pressure and thermal loads in the regions of shockwave boundary layer interaction poses a wide variety of problems including damage like rapid fatigue to aero-structures and associated protection systems, inlet flow distortion and engine nonstart, all of which could have adverse consequences. The shock wave boundary layer interaction occurs when a high – speed flow passes over an infinite blunt fin mounted on a surface as shown in Fig. 1. The fin bow shock causes the boundary layer to separate from the surface ahead of the fin, resulting in a separated-flow region composed of horseshoe vortices near the surface, and a lambda – type shock pattern ahead of a fin. The shock wave emanating from the separated-flow region (separation shock) impinges on the fin bow shock, and causes intense heating and high pressure locally around the fin leading edge.

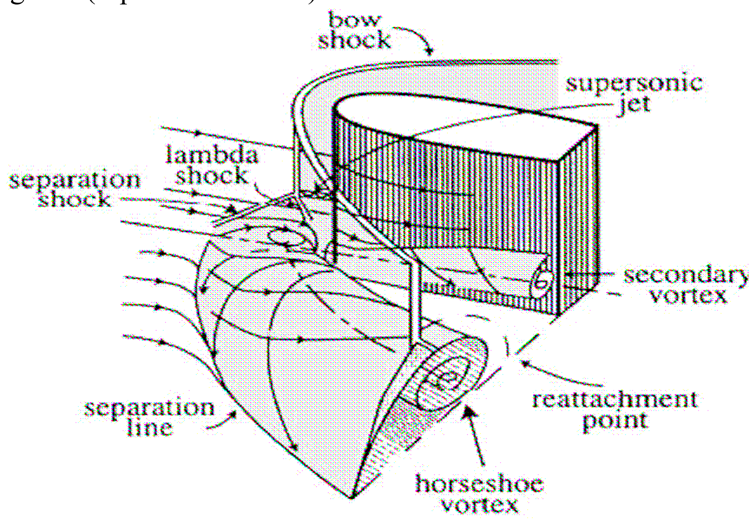


Fig. 1 Schematic of the 3D flow around the blunt fin

C. Lada and K. Kontis[1] studied on control effectiveness of dimples on the glacing shock wave turbulent boundary layer interaction produced by a series of hemi-cylindrically blunted fin at Mach number 0.8 and 1.4 at angles of sweep 0^0, 15^0, 30^0, and 45^0. The passive control technique used a series of 2 mm diameter, 1 mm deep indents drilled across the hemi-cylindrical leading edge at angle 0^0, 45^0, and 90^0. A substantial decline in the scale of interaction, and an overall increase of the intensity of the pressure levels in the whole interaction region on the side-connecting wall were observed with increasing number of holes. C. Lada, C. Wong[2] performed a series of experiments on blunt fin at transonic flow. They observed for blunt fins dimples at 45^0 at Mach 0.8 and 1.4 the effect was to bring about a substantial decline in the scale of the interaction on both the fin surface of the pressure levels in the whole interaction region was attenuated by the leading edge sweep.

S. Becker and h. Lienhart[3] studied the structure of the flow field around three-dimensional obstacles by using different kinds of flow visualization techniques and Laser Doppler Anemometry (LDA) system. A. Van Dijk and H. C De Lange[4] studied the flow around the cubic obstacle in a rectangular channel at subsonic flow condition. The result shows that when increasing the Mach number the far upstream separation point and the far downstream attachment point distance increasing. F. K. Lu and G. S. Settles[5] show that the kerosene lampblack mixtures for visualizing surface flows of swept shock boundary-layer interaction has been extended through the use of ground colored chalk contrasting colors enable different regions of the interaction surface to be clearly visualized. K. R. Srinivasan and E. Loth[6] found that all the control devices gave rise to larger lambda shocks than far the base line solid wall. S. B. Verma[7] has conducted experiment on application of laser-Schlieren technique. To study shock-wave boundary layer interactions flow fields, he found that measure time-dependent voltage signals representative of the fluctuating density gradient field.

The present experiment is intended to obtain the overall flow field details around a hemi – cylindrically blunt fin for a Mach number of 2.2 with adoption of dimples, holes on the apex of blunt fin for reducing the shock wave / boundary layer interaction. Studies are also made to characterize the flow field by varying height of blunt fin.

2.Geometrical Details of Blunt fin

A hemi – cylindrical blunt fin adopted in the present study is similar to the geometry reported by Priyank[8] , which was design Mach number 2.2. The dimensional details of the blunt fin are presented in fig. 2. The holes of 2 mm diameter were made on the apex of the blunt fin to reduce the shock wave / boundary layer interaction, and to see more effectiveness of holes on shock wave / boundary layer interaction the diameter of holes was increased to 4 mm. Even though surface roughness has a major impact on this shock wave / boundary layer interaction , for this study we have kept the surface roughness issue aside, and compared the various parameters with the same level of surface smoothness.

For Blunt fin with holes (F-aa-bb-cc-dd)

F- Single fin, aa-thickness, bb- height, cc- number of holes, dd-diameter of hole

Identification No.	Length (L)	Thickness (t)	Height (H)	Diameter of hole (d)
F12120000	45	12	12	0
F12120102	45	12	12	2
F12120202	45	12	12	2
F12120204	45	12	12	4
F12120204	45	12	12	4
F12180204	45	12	18	4
F12240204	45	12	24	4

Identification No.	Length (L)	Thickness (t)	Height (H)	Diameter of dimple (d)
1DF0204	45	12	12	4
2DF0204	45	12	12	4

3.Experimental Details

The experiments were performed using the Supersonic Wind Tunnel at Birla Institute of Technology, Mesra, Ranchi as in Ref Fig 3. It is a blow down type wind tunnel having test section size of 50mm X 100mm and Mach number ranging from 1.5 to 3.0. Fig. 3 shows the photograph of supersonic wind tunnel.

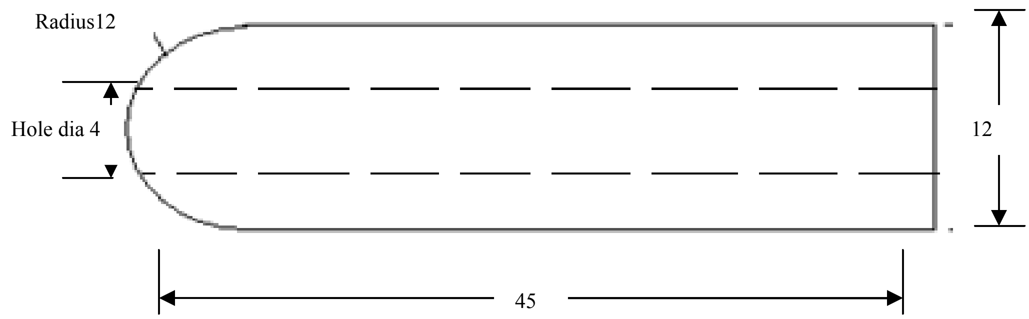


Fig. 2 Geometrical Details of blunt fin (dimensions in mm)

A model, as per the dimensions given in Fig. 2 was fabricated on lathe machine which ensured the dimensional accuracy 0.1 mm. The overall length of the model was 45 mm and width of 12 mm. different arrangements are made for flow visualization and static pressure measurement. A typical photograph of models presented in Fig. 4 which shows different models of blunt fin.

Fig. 3 Photograph of supersonic Wind Tunnel

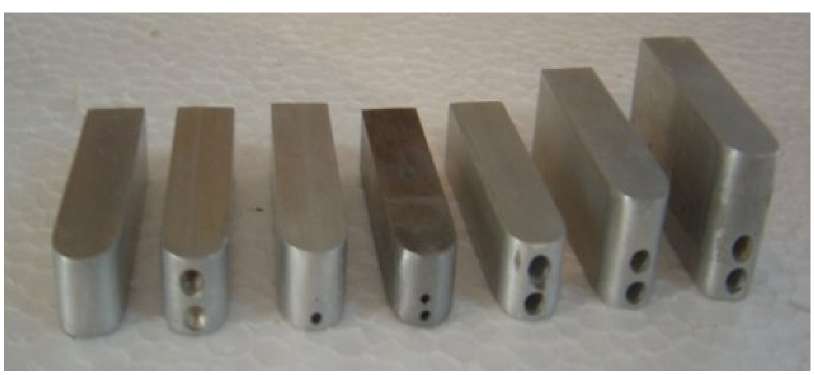


Fig. 4 photograph of different types of blunt fin

3.1Oil flow method

Flow visualization was conducted in order to determine the upstream influence and separation line locations so that the pressure ports could be properly positioned. A mixture of titanium dioxide (TiO_2), lubricating oil and oleic acid in suitable ratio has been used. Lubricating oil was added to give viscous nature to the mixture and oleic acid to give better dispersion of mixture. The mixture was sprayed on the base plate with the model mounted over it and the tests were performed in order to get the streak lines. The surface streak lines forms on the base plate after stabilized run of the tunnel. Flow visualization carried out using oil flow technique consisted of the base plate painted in black to provide a good photographic contrast. The test was conducted at a stagnation of 30 psig and Mach number 2. 2. The plate was taken out of window and the flow field obtained on the surface was captured using digital camera for further analysis. The base plate was made as thin as possible so that it doesn't affect the flow field.

3.2 Static pressure method

The measurement of the static pressure was done using the 28- channel mercury manometer and pressure scanner. Pressure tapping were made flush with surface plate where steel tubes of 1. 3 mm diameters were connected. Connection of steel tubes with the manometer was done using polythene tubes. The static pressure distribution along the centerline of the fin was obtained using the static pressure tapping provided on the surface plate. A 28- channel mercury manometer was employed to capture the data from the pressure tapping. The pressure taps were made flush with the plate surface. These ports were connected to manometer using polythene tubes.

$$C_p = \frac{2}{\gamma M_\infty^2}\left(\frac{P_x}{P_\infty} - 1\right)$$

Where P_x = respective pressure port numbers P_∞ = atmosphere pressure

Fig. 5 Photograph of the model used for pressure measurements with pressure ports

3.3 Shadowgraph pictures method

Shadowgraph technique in standard Z-type optical arrangement was employed in order to study the shock pattern ahead of the blunt fin. A monochromatic light source is used to pass through a slit and is reflected back through a concave mirror to the test section. The reflection is made such that the whole test section glass window is covered and it passes to another concave mirror placed on the other side of the tunnel. The reflected light through the mirror is captured through high-speed photography which shows the density variation across the body. The models were mounted in the centre of the section using proper sting and connecting rod and the test were made at a stagnation pressure of 30 psig and Mach Number 2. 2. The image obtained on the screen was captured using a Digital SLR camera (Model: Sony DSLR A100K)

4. RESULTS AND DISCUSSION

In general the strong bow shock wave associated with blunt fins (shock generators), introduces radical changes in the flow field structure.

4.1 Effect of Dimples on shock wave / boundary layer interaction

Figures 7a-c shows the effect of dimples located at zero degree across the hemi-cylindrical blunted leading edge. For the case F12120000, the flow field is symmetrical. For the no-dimple case, there is evidence of at least three separation lines and two attachment lines on the side wall of the blunt fin. By introducing the dimples on the blunt fin, the scale of interaction increases locally. However their effect seen in the oil flow visualization is minimal/ negligible. Comparing the Fig. 7a and b the primary separation(S_1) distance ahead of the fin apex remain constant for the cases F12120000 and 1DF0204, whereas for the case 2DF0204 primary separation(S_1) distance increase very slightly. Fig. 13 shows the effect of dimples on the centerline pressure distribution on blunt fin models. It has been seen from the graph that Cp value starts increasing from X/ D = -4. 3 where the flow separation takes place and reaches to maximum value 0.16 and then start decreasing. As flow approaches to blunt fin leading edge, the Cp value again starts increases to a value of 0. 66. As observed from the graph, the dimples on the frontal face of the fin have very slight effect on the centerline pressure distribution. And hence the effect can be treated as negligible at Mach 2. 2. Although further study is required by varying the diameter and depth of dimple. Fig. 7a and b shows the effect of dimples on the shock wave/ boundary layer interaction. It has been seen that, there is a very slight effect of dimples on the scale of shock wave/ boundary layer interaction. The effect is negligible for the cases 1DF0204 and 2DF0204.

4.2 Effect of number of holes on shock wave / boundary layer interaction

A substantial decline in the scale of interaction has been observed after a through hole of 2 mm dia. was made on to the blunt fin leading edge. It has been observed from the graph in Fig. 9 that the scale of interaction, Xs/ D for 1 hole was 1. 87 and for no holes case was 1. 85 which clearly show the slight decreas X_w the primary separation line (S_1). In order to see the effect of increase in number of holes, 2 holes were drilled on the leading edge face, which on experiments revealed that the primary separation distances are further decreasing and S_1/ D = 1. 64. For this case consequently decreasing the scale of shock wave boundary layer interaction along the vicinity of fin as shown in Fig. 7a, d and e. It clearly indicates that increase in the number of holes weaken the shock ahead of the fin. It has been observed from the graph in Fig. 14 that the Cp values does not vary much along the centerline for the cases F12120000 and F12120102, whereas in the case of F12120202 the maximum value of Cp is 0. 51, which indicates that flow through the holes helps in reduction of pressure level. It has been observed that as the number of holes increases on the blunt fin leading edge, the Cp value decreases. In wake region there is no major change in Cp value.

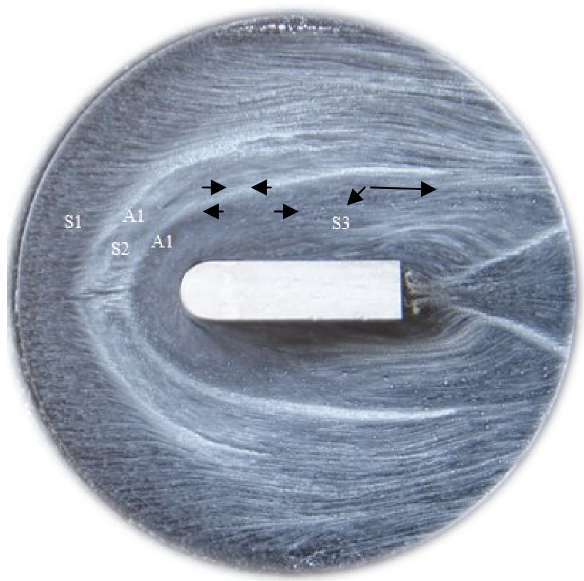
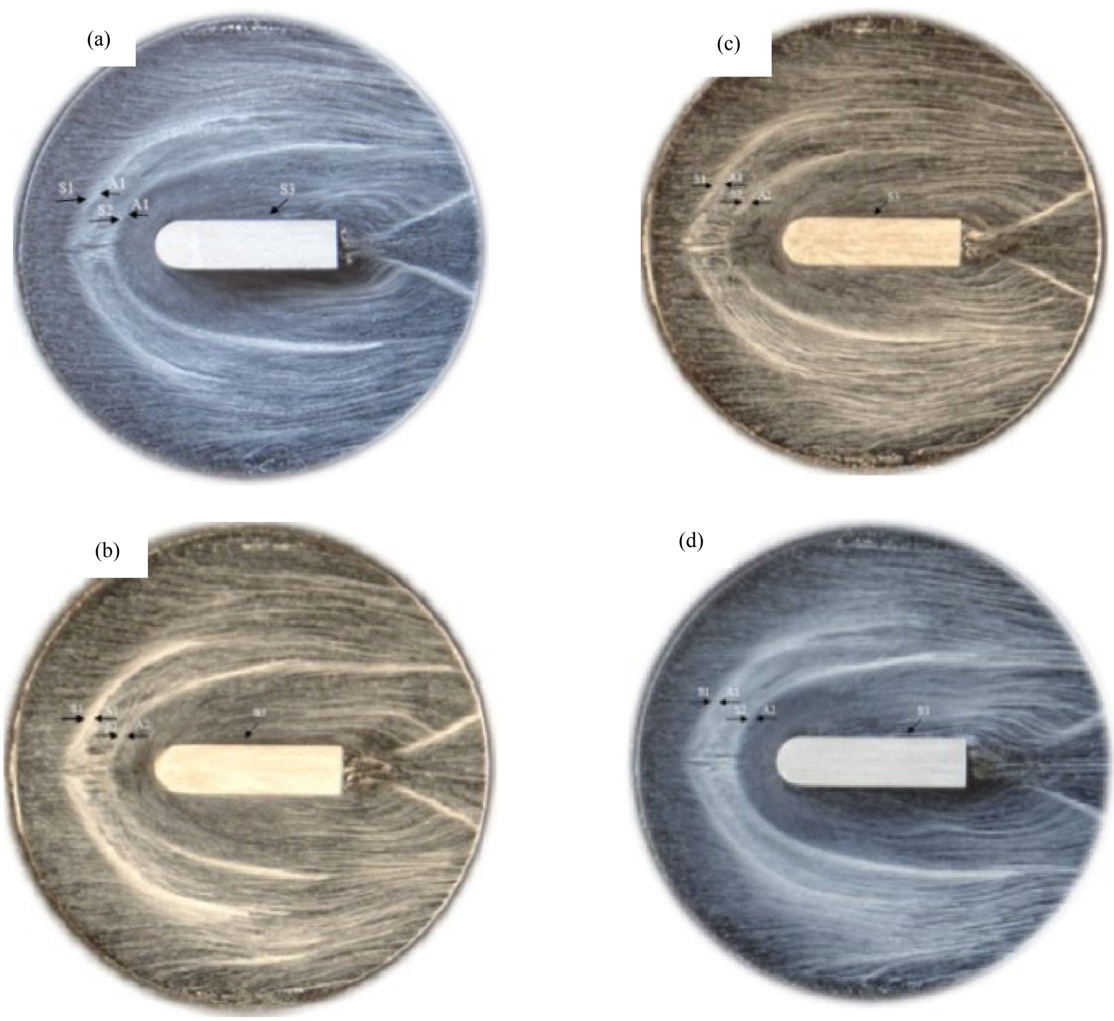


Fig. 6 Photograph showing the oil flow visualization across blunt fin



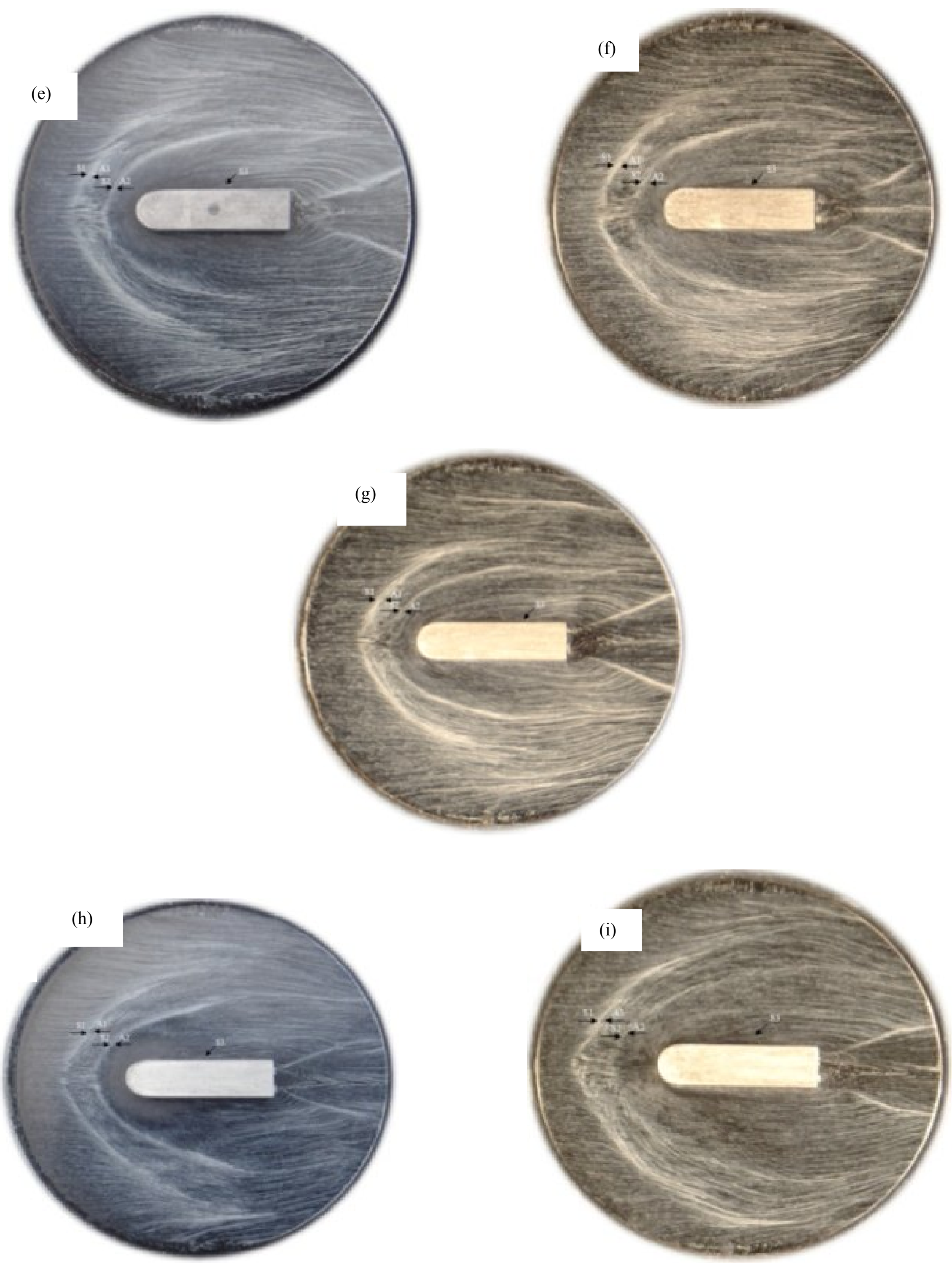


Fig. 7 Surface flow topology at Mach = 2.2; **a** no- dimples case; **b** one dimple case; **c** two dimples case; **d** one hole of 2mm dia. case; **e** two holes of 2mm dia. case; **f** one holes of 4mm dia. case; **g** two holes of 4mm dia. and 12mm height of blunt fin case; **h** two holes of 4mm dia. and 18mm height of blunt fin case.

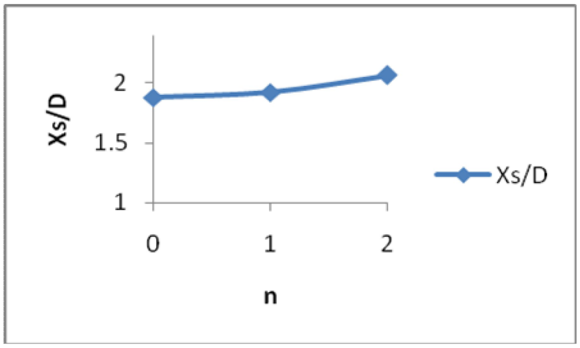


Fig. 8 Variation of separation length with dimples

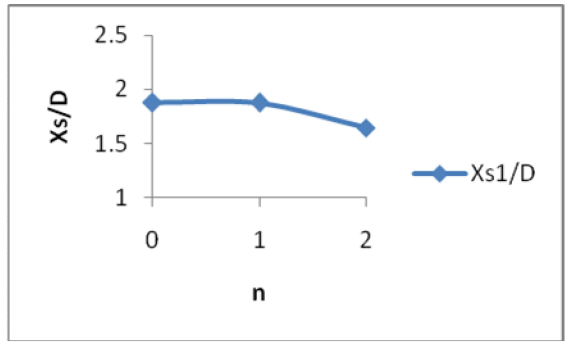


Fig. 9 Variation of separation length with number of n holes

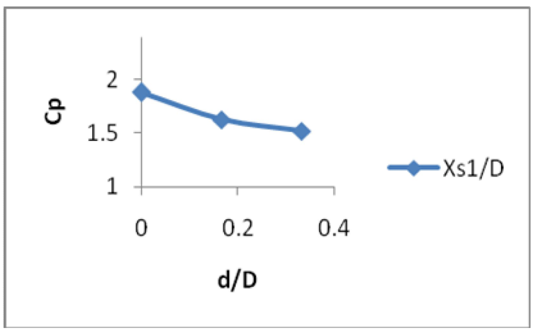


Fig. 10 Variation of separation length with diameter of holes

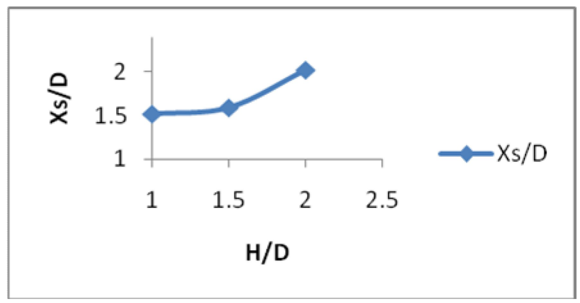


Fig. 11 Variation of separation length with height H of blunt fin

4.3 Effect of diameter of hole on shock wave / boundary layer interaction

Figures 7a, e and g shows the effect of diameter of hole on blunt fin leading edge. For the case of F12120204 the primary separation line (S_1) reduction is more when compared to F12120000 and F12120202. And also in lateral separation line(Ys) reduction was seen. From Fig. 7a, e and g, it has been observed that the diameter of the holes play vital role in the shock wave/ boundary layer interaction. Fig. 15 shows the graph plotted for Xs/ D vs d/ D keeping D, H, and n constant. It shows that as diameters of the holes are increased, the separation line distance decreases. As the roughness of the surface increases, the local pressure level decreases, it strengthens adverse pressure gradient which results in the decrease of static pressure level. From Fig. 15 it has been observed that, as the diameter of the holes increases the Cp value decreases. So for the case of F12120204 the Cp is value is less than other cases.

Figure 17a, d and e shows that, the effect of diameter of the hole on shock wave/ boundary layer interaction. For cases of F12120202 and F12120204, it is observed that as the diameter of the holes increases the scale of shock wave/ boundary layer interaction increases. For the case of F12120202, the length of shock has increased, compare to other two cases. For the case of F12120204 shock length has reduced due to increase of scale of shock wave/ boundary layer interaction.

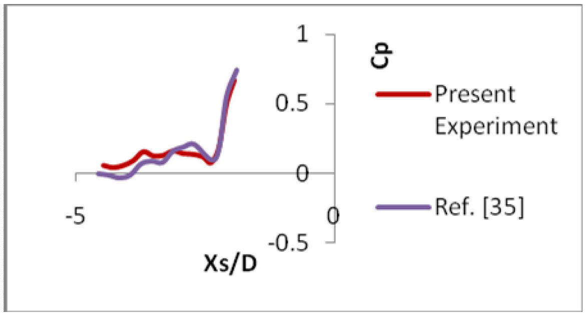


Fig. 12 Comparison of experimental and ref.9 along the centerline of F12120000

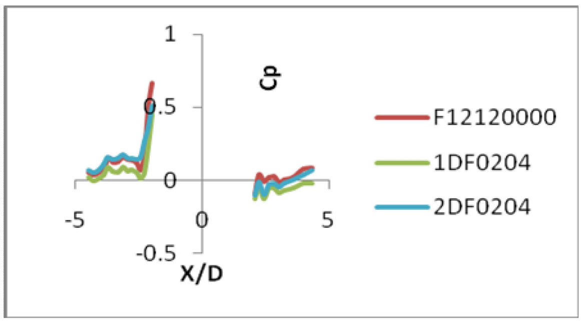


Fig. 13 Centerline pressure measurements by varying number of dimples

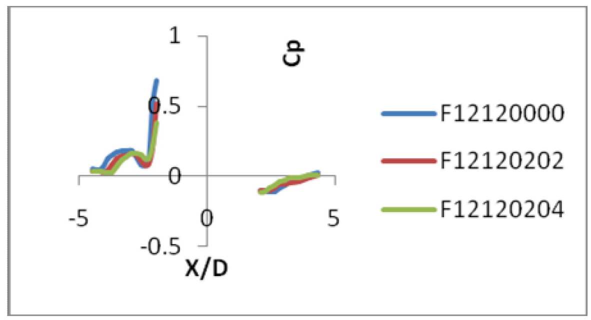


Fig. 15 Centerline pressure measurements by diameter of holes

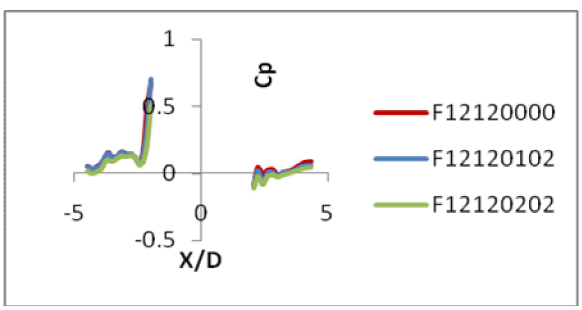


Fig. 14 Centerline pressure measurements by number of holes

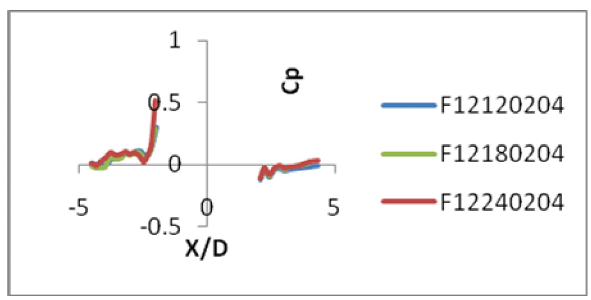


Fig. 16 Centerline pressure measurements for fin equal D, d and varying H

4.4 Effect of blunt fin height on shock wave / boundary layer interaction

Figures 7g, h and i show the effect of height on blunt fin with constant D, d and n. It has been observed from Fig. 7g, h and i the primary separation line(Xs_1) and lateral separation line(Ys) increases as the height of blunt fin is increased. As seen in Fig. 11 it has been observed that Xs/ D for case of F12120000 are 1. 5 and with increase in H/ D i. e. for H/ D of 2, Xs/ D increase to 2. 2. Indicating that the effect of holes becomes lesser with the increase in height. Fig. 16 shows the effect of height of blunt fin at the centerline pressure distribution for varying height of 12 mm, 18 mm and 24 mm blunt fin models. It has been observed that there is significant variation in Cp value along the centerline of the models. A cp value in the case of F12240204 is much higher along the centerline than other two models. It has been seen that as the height of blunt fin increased, the region of interaction increases. In the wake region there is not much change in Cp value for cases of F12180204 and F12240204. For the case of F12120204, Cp value is less when compared to other two cases models.

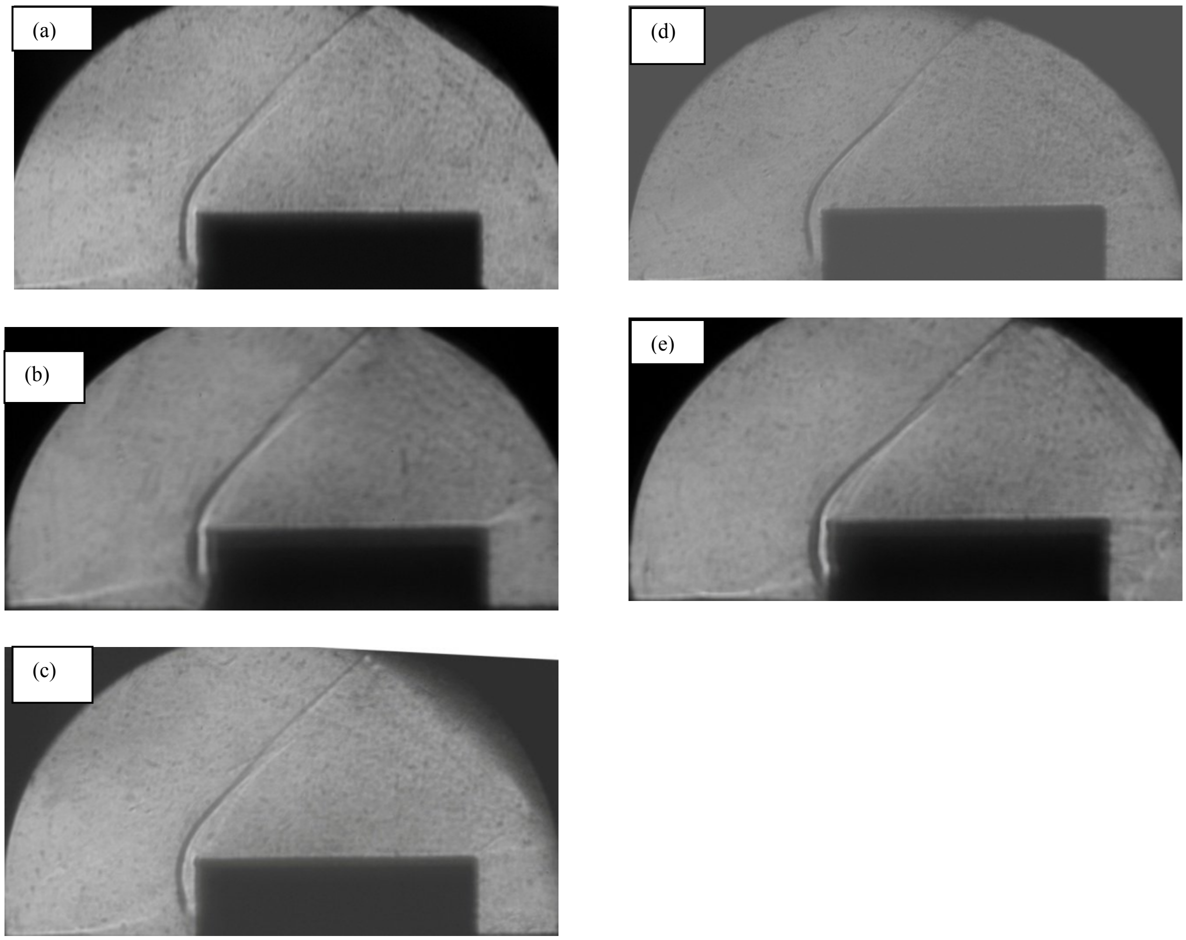


Fig. 17 Shadowgraphy pictures at M = 2.2 for the blunt fin case; **a** - no- dimple case; **b** - two dimples case; **c** - one hole of 2mm dia. case; **d** - 2 holes of 2mm dia. case; **e** - 2 holes of 4mm dia. case.

5. Conclusions

In the present investigation an effort has been made to study the complex flow field phenomena across the blunt fins and to reduce the pressure level and drag on the body. To obtain the results, experiments have been carried on the blunt fins at M=2.2 The experiments consisted of oil flow visualization, static pressure measurements and shadowgraph. Effects of various parameters such as dimples, effect of number of holes, diameter of holes and height of fins have been obtained. There may be other issues related to other mechanisms which may be housed inside the leading edges, the study may pave way for a possible solution to reduce the drag to a considerable extent and also reduce the pressure level at the leading edges.

A number of important conclusion has been drawn from present investigations that are summarized below:

1. Based on oil flow visualization, it has been observed that dimpled drilled on the leading edge has a negligible effect on to the extent of separation.
2. Experiments performed revealed that the holes drilled through the blunt fin models helped in reducing the separation distances as well as the pressure level at the leading edge.
3. Shadowgraph photograph showed that the lambda shock formed weakens with increase in the diameter of the holes drilled on the blunt fin.

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