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INTERACTION OF AN INCIDENT CONICAL SHOCK WITH A BOUNDARY LAYER ON A FLAT PLATE

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ABSTRACT

The paper reports an experimental investigation on the interaction of an incident conical shock wave with a turbulent boundary layer. Half-cones of angles ranging from 14° to 40° were used. The experimental techniques utilised were the surface flow visualization and the Schlieren and shadowgraph photography. The results show that the interaction of an incident conical shock wave with the turbulent boundary layer on a flat plate is of three-dimensional nature. Boundary layer separation was found to depend on the freestream Mach number, the cone angle, the cone length, and on the height of the cone above the plate.

INTRODUCTION

Shock wave and boundary layer interaction occur in supersonic engine intakes, control surfaces and flow over wings. The interaction affects the performance of these components. Understanding of the interaction will enable more accurate prediction of the complicated nature of flows resulting from such interactions.

An important but as yet not fully explored problem is that of interaction between an incident conical shock and a two-dimensional boundary layer on a plane surface. As far as the authors are aware, Panov's (1968) is the only study which has investigated this problem experimentally but that too is quite limited.

As part of the investigation, flow visualization studies comprising surface oil flow visualization technique, Schlieren and shadowgraph photography were carried out to survey the flow field. This paper presents these results and discusses the interaction phenomenon in terms of these results.

EXPERIMENTAL ARRANGEMENT

The experiments were carried out in a blow down supersonic wind tunnel of cross section 155 mm x 90 mm at a Mach number M = 2.0 and freestream unit Reynolds number of 30×10^6 m^{-1} and 58×10^6 m^{-1}.

The models were half-cones with angles ranging from 14° to 40°. The cone base diameter was 20 mm. The flat plate which spanned across the test section was 269 mm long, 150 mm wide and 9 mm thick with a 6° leading edge [Figure 1]. The two-dimensional turbulent boundary layer thickness on the plate varied between 2.2 mm to 2.4 mm in the region of interaction.

Preliminary investigations using flow visualization techniques were carried out with 20°, 30° and 40° half-cones mounted at heights of 30 mm, 45 mm and 60 mm. The half-cones were positioned in the stream-wise direction in such away that the shocks interacted with the flat plate boundary layer at the same location, thus providing a constant boundary layer thickness at the beginning of the interaction with all the cones.

After these preliminary investigations, detailed studies were then made with half-cones of angles ranging from 14° to 26° all mounted at a height of 30 mm above the flat plate.

The volumetric breakdown of the oil-pigment mixture for the surface flow visualization was three parts light mineral oil, two parts titanium dioxide and a few drops of of oleic acid. Both the shadowgraph and the Schlieren methods (Magi, 1990) had identical optical arrangement with the exception that a knife edge was introduced for the latter.

DISCUSSION OF RESULTS

Three-dimensional separation

McCabe (1966) studied swept shock wave/boundary layer interaction with a sharp unswept fin. He adopted Maskell's (Crabtree et al.,1963) separation criterion which is that separation line must be an envelope of the limiting streamlines upstream of the shock as shown in Figure 2. This figure reproduced from McCabe is a schematic representation of the oil flow patterns, showing separated boundary layer on the side wall at a Mach number of 1.96 when a wedge in a plane perpendicular to the wall was used to create the shock. The oil filaments do not break away from the wall at separation, but instead turn approximately parallel to the shock and run together to form an envelope along the separation line.

In Maskell's model of three-dimensional separation, two basic components are free shear (or vortex) layers and bubbles as shown in Figure 4. The surface of separation encloses fluid which is not part of the main stream but is carried along with the body. The bubble formation requires the existence of one singular point S, where the behaviour of the flow is the same as near a separation point in two-dimensional flow. The limiting streamlines on the surface of the solid body join the line of separation tangentially.

First Series of Experiments

Figure 4a is a typical Schlieren photograph showing the interaction with a conical shock. It is a half cone with 30° angle and is 45 mm above the flat plate. The head of the expansion from the base of the cone interacts and weakens the shock. Prior to the interference of the expansion wave, the shock is straight. The position where interference first begins depends on the cone angle and height. Shocks also originate from the top and the bottom of the leading edge of the support and, the cone-rod retaining screw.

It is observed that above the flat plate, there is a thin and lightly shaded layer which is in fact the boundary layer. A fairly dark area appears on top of it. The existence of this dark area can be explained as follows. Due to the interaction of the side wall boundary layer which is of considerable thickness with the plate boundary layer at the junction where the flat plate meets the side wall, the density gradient at this corner is no longer normal to the light. The light passing through this intersection is being deflected. Since the camera was focused on the centre plane of the tunnel, the displaced image of the irregular density gradient is captured.

The weakened shock strikes the boundary layer. The boundary layer grows in thickness at the region of interaction. Reflection which is in the forms of expansion and compression, is characterised by a four-wave confluence type (Henderson, 1966). The separation of the boundary layer could be identified by the small hump just downstream of the rear leg of the bifurcated structure. Due to the growth of the boundary layer, the main-stream flow is now deflected towards the wall and brought back parallel to the wall at a short distance downstream accomplished by a system of compression waves which appear downstream of the interaction. Figure 4b shows the various details.

Figure 5 depicts surface oil flow field on the flat plate for a cone of 40° mounted at a height of 30 mm. The boundary layer has separated as indicated by the upstream limiting surface streamlines running parallel to the shock to form an envelope along the separation line.

Surface streamlines originating from the line of reattachment travel in both upstream and downstream directions. Reverse flow occurs between the separation line and the reattachment line. The area of the separation region decreases away from the line of symmetry. This is probably due to flattening out and eventual disappearance of the surface of separation at some distance away from the line of symmetry. It is then followed by a complete turn around of the flow in the boundary layer brought about by the opposite flow direction of the external streamlines.

The wake shock and interaction of the incident shock with the boundary layer on the side wall of the tunnel are also seen at the bottom of this photograph.

A summary of the preliminary study is tabulated and shown in Figure 6. There is no separation of boundary layer for all the three cones mounted at a height of 60 mm above the flat plate. For the other two mounting heights, the length of separation increases with cone angle. Shock wave angles both at the cone and at the shock wave-boundary layer intersection were also measured. These data show that in all cases with the exception the 20° cone at a height of 30 mm, expansion waves originating from the base of the cone have interacted with the incident shock.

The non-dimensional lengths l/h of the separated region at the line of symmetry are plotted against the cone angles mounted at various height and this is shown in Figure 7. The curves could be extrapolated to show that separation would occur with cones of approximately 15° and greater at heights of 30 mm and 45 mm. In order to study further the interaction of incident conical shock and the boundary layer without the influence of the expansion waves on the incident shock, investigations were then carried out with half-cones of angles ranging from 14° to 26° all mounted at a height of 30 mm above the flat plate.

Second Series of Experiments

Figure 8 (Teh and Gai, 1992) shows oil-flow patterns obtained on the flat plate when a 14° half-cone mounted at a height of 30 mm was used to generate the shock. The deflections of the surface streamlines are sudden in the vicinity of the line of symmetry and they tend to be gradual away from it. There is no deflection at the line of symmetry. Away from the line of symmetry, the deflection initially increases to a maximum and then decreases.

The associated Schlieren photograph is shown in Figure 9. The expansion waves originating from the base of the cone interacts with the reflected shock. The dark area above the boundary layer is still present. Downstream of the reflected shock, there exists a region of interaction of the expansion waves and the reflected wave system. The recompression process lasts further downstream compared to Figure 4a.

The structure of the incident shock and the reflected shock at the boundary layer takes the form of a 'V' which is considerably thicker than the boundary layer. Incidentally, the top of 'V' happens to coincide with upper surface of the dark area. Both the incident shock and the reflected shock seem to begin refracting from here. This gives the notion that the thickness of the boundary layer stretches from the flat plate to the upper surface of the dark area. In fact, any attempt to quantify the observation in the region of interaction would be erroneous due to the three-dimensional nature of the flow field. The strong density gradient in the spanwise direction creates an inhomogeneous refractive field.

Figure 10 (Teh and Gai, 1992) shows oil-flow patterns obtained on the flat plate with a 17° half-cone. All the surface streamlines after the shock originate from the the vertex of the shock trace. The boundary layer has just separated as indicated by the upstream limiting surface streamlines running parallel to the shock to form an envelope along the separation line.

Figure 11 is a Schlieren photograph showing the conical shock patterns for a 21° cone. Expansion waves originating from the base of the cone not only interacted with the whole of the reflected shock but their front is beginning to interact with the incident shock. Although the boundary layer has separated as indicated by surface oil flow photograph, it cannot be seen distinctly here.

CONCLUSIONS

The experimental investigation has shown that the interaction of an incident conical shock wave with the turbulent boundary layer on a flat plate is of a three-dimensional nature.

The strength of the incident shock on the boundary layer depends the freestream Mach number, the cone angle, the cone length, and on the height at which the cone is supported above the plate.

Depending on the cone angle and the height at which the cone is mounted above the flat plate, expansion waves originating from the base of the cone were observed to interact with both the incident and reflected shocks or with the reflected shock.

For the flow with a Mach number of 2.0, the boundary layer starts to separate with the shock generated by a 17° half-cone mounted at a height of 30 mm above the plane boundary layer.

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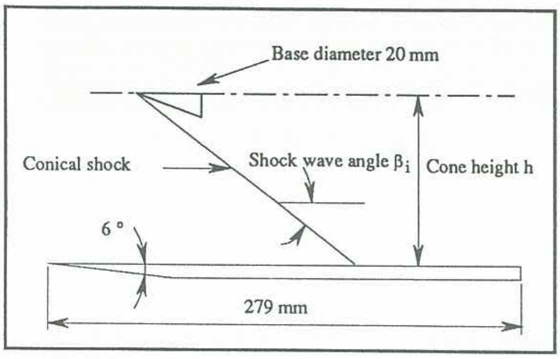

Figure 1 Experimental Arrangement

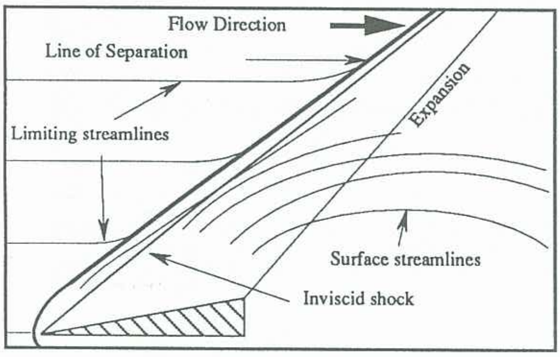

Figure 2 Separated Boundary Layer
Oil Flow Pattern (McCabe 1966)

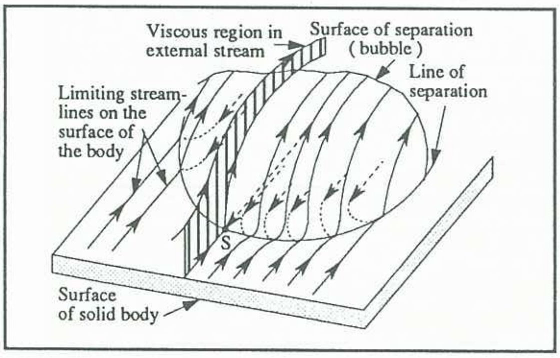

Figure 3 Separation in Three Dimensions
(Crabtree 1963 et al)

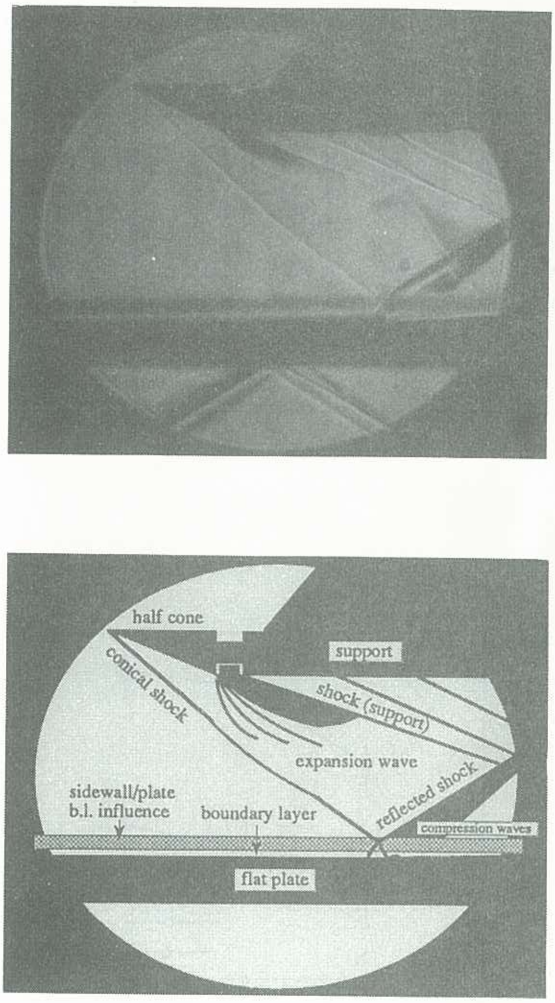

Figure 4 FlowField of Conical Shock
(a) Schlieren Photograph, (b) Schematic Representation
Cone Angle 30°, Cone Height 45 mm

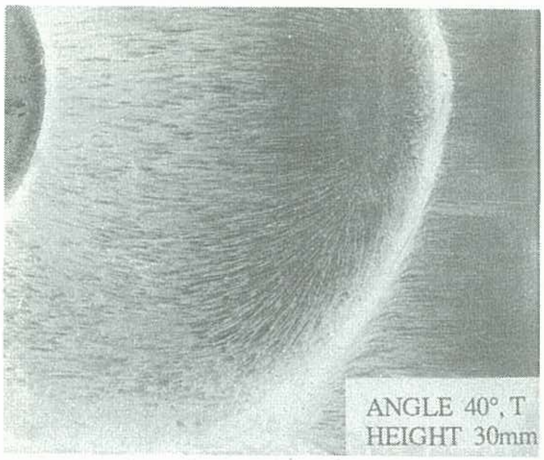

Figure 5 Oil Flow Pattern
Cone Angle 40°, Cone Height 30 mm

Cone Height (mm)	Angle h (°)	Non-dim. Separation length l / h	Wave angle at cone (°)	Boundary layer-Shock Intersection (°)	Influence of Expansion Wave on Shock
30	20	0.183	39.6	39.6	No
	30	0.250	49.5	48.4	Yes
	40	0.267	62.5	47.0	Yes
45	20	0.044	38.9	38.2	Yes
	30	0.111	46.5	41.5	Yes
	40	0.133	63.0	42.3	Yes
60	20	Nil	39.3	37.7	Yes
	30	Nil	46.9	34.0	Yes
	40	Nil	63.0	37.3	Yes

Figure 6 Preliminary Study
Data from Flow Visualization

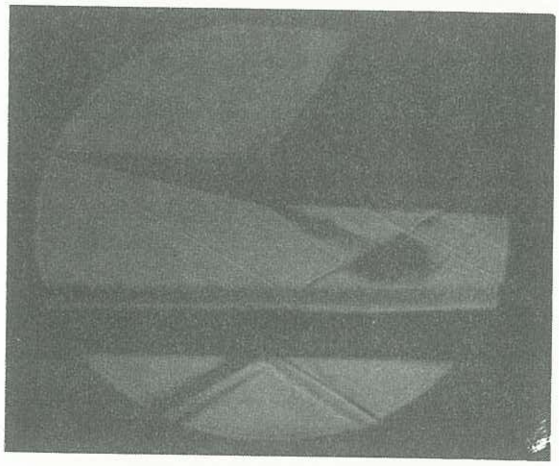

Figure 9 Schlieren Photograph
Cone Angle 14°, Cone Height 30 mm

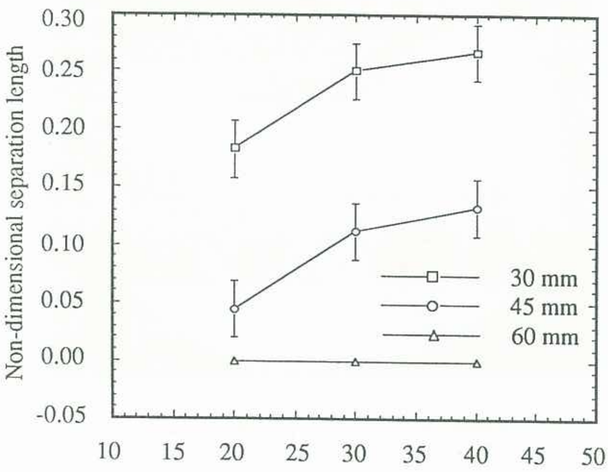

Figure 7 Lengths of Separated Region
for various cones at different height

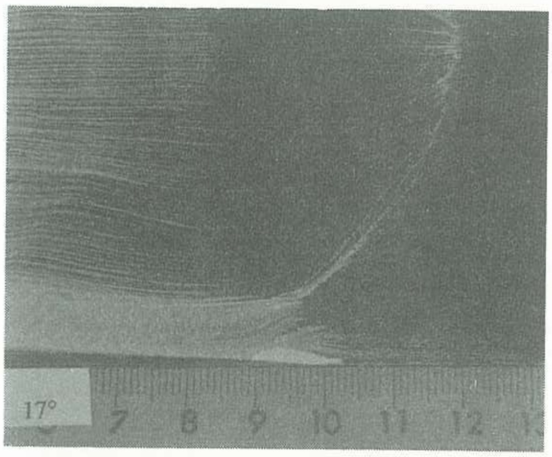

Figure 10 Oil Flow Patterns, Cone Angle 17°,
Cone Height 30 mm (Teh and Gai , 1992)

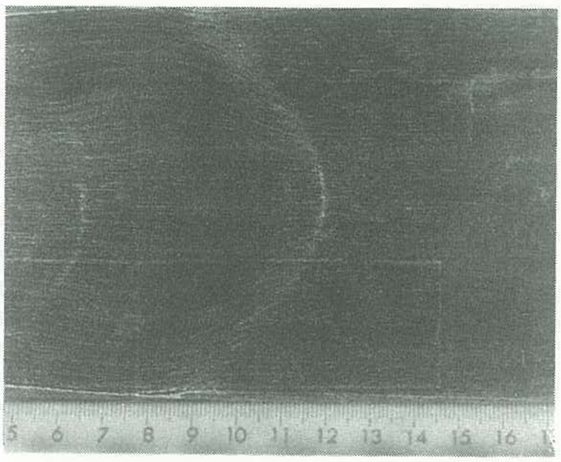

Figure 8 Oil Flow Pattens, Cone Angle 14°,
Cone Height 30 mm (Teh and Gai, 1992)

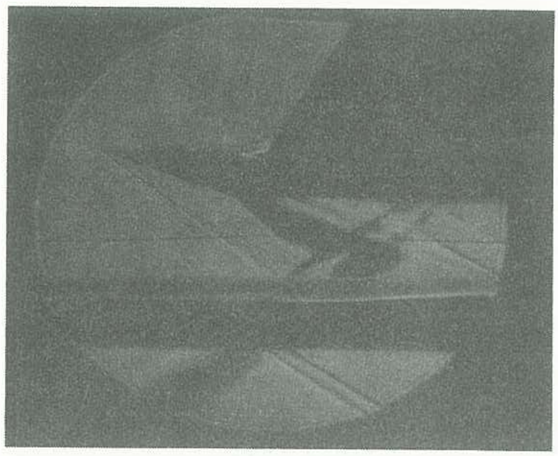

Figure 11 Schlieren Photograph
Cone Angle 21°, Cone Height 30 mm