EFFECT OF SURFACE PROPERTIES ON SHOCK WAVE REFLECTION

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ABSTRACT

In the reflection of shock waves off a surface von Neumann's theory assumes compressible and inviscid flow. It also assumes the reflecting surface to be perfectly smooth, non-porous, and adiabatic. It is found to be accurate for a wide range of regular reflection patterns and limited to very strong shocks in the case of Mach reflection. However experiments have shown that regular reflection persists beyond the theoretical limit. It has been postulated that this is due to the development of a viscous boundary layer behind the reflection point, an explanation now well accepted. However, the assumption of an adiabatic wall has persisted over many years. An experiment has been devised where two inclined surfaces on either side of a symmetry plane and impacted by a propagating shock wave normal to the plane would show any differences in reflection behaviour, if they were equally smooth but of different conductivities. Tests were conducted at incident shock Mach numbers from 1.30 to 1.59, and shock incidence angles of 20 to 55 degrees with a copper surface on one side and a glass surface on the other. Detectable differences in reflection geometry were established in most cases, indicating a possible small influence on reflection patterns.

INTRODUCTION

When a plane shock wave strikes a surface two reflection patterns are identified: regular and irregular reflection [1]. A very common type of irregular reflection is known as Mach reflection. The typical profiles for reflection off a plane wedge are shown in Fig. 1, where I is the incident shock, R the reflected shock, and M, termed the Mach stem, joining their intersection to the surface. Two-shock theory uses standard oblique shock analysis in a steady frame of reference fixed in the reflection point with the boundary condition that the flow behind the reflected wave is parallel to the wall. Three shock theory analyses the steady flow in a frame of reference fixed at the intersection of the three shocks, termed the triple point, with the boundary condition for the flow passing above and below this point to be in the same direction and have the same pressure. Since the velocities and temperatures are different this results in a shear layer, denoted S in the figure. The theory assumes the flow and wave topology to be self-similar in time as the incident wave moves up the wedge, and thus in the case of Mach reflection the trajectory of the triple point will be a straight line passing through the leading edge of the wedge. The application of the theory together with experimental results for a very weak incident wave is shown in Fig. 2.

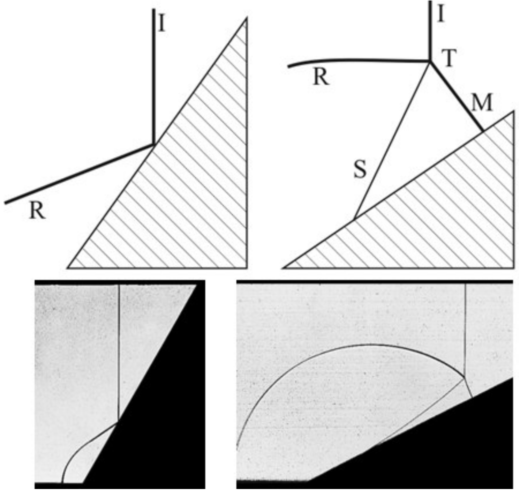

Figure 1 Regular and Mach reflection patterns

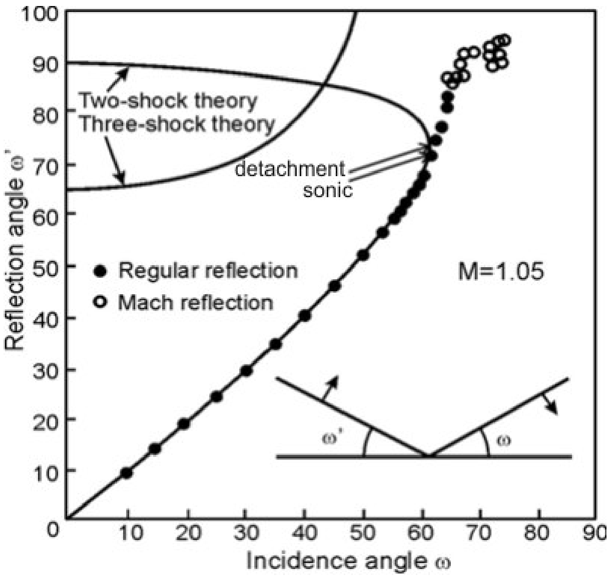

Figure 2 Theory and experiment for a weak shock

The persistence of regular reflection beyond the theoretical limit, known as the detachment condition, has come to be known as the von Neumann Paradox. Hornung and Taylor [2] suggested that it could be due to the development of the viscous boundary layer on the wall immediately behind the reflection point, due to a negative displacement thickness in the reflection point frame of reference. To demonstrate this they conducted a number of experiments in a shock tube and by changing the upstream density effectively increased the Reynolds number thereby reducing the effects of viscosity. These results were then extrapolated to infinite Reynolds number and showed their hypothesis to be valid. An alternate approach by Barbosa and Skews [3] reflected two identical independent waves off each on a plane of symmetry which then acts as an equivalent surface matching the assumptions of the theory because it removes the no-slip boundary and all properties are the same on either side. This demonstrated, within experimental accuracy, that transition in the wave pattern corresponds to the theory.

The majority of shock reflection studies do not even consider the thermal properties of the reflecting surface or whether there can be heat transfer across it. There are a number of studies on the effect of wall roughness which will not be considered here. However, in some of the studies, both numerical and experimental, it has only been assumed that the surface is isothermal. This assumption probably arises from an early boundary layer analysis by Mark [4], where the surface temperature rise caused by the passage of the shock was estimated to be extremely small. Details of some of the effects are given in a comprehensive study by Henderson et al. [5], although their work concentrates more on transition conditions between regular and Mach reflection. The work was for an incident shock Mach number of 2.33 in Argon. A particularly interesting example is for the gas and the isothermal wall to be initially at a temperature of 273K, the maximum temperature of the compressed gas then becoming about 1400 K. The gas in the boundary layer is thus strongly cooled near the surface, and its density increases by a factor of more than 4.

An interesting experimental study is that of van Netten et al. [6] for incident shock Mach number of 1.3 on a 30 degree wedge. The wedge has a cavity just under the surface into which liquid nitrogen was poured. Once boiling ceased the surface temperature was measured, with a thermocouple, to be about -179°C. A thin Mylar sheet was placed over the surface to limit condensation and was removed immediately prior to firing the shock tube. For hot wall tests the wedge was heated with a blow torch as uniformly as possible to a temperature of 110 °C.

Significant effects were found on the triple point trajectory angle with, in many cases, the Mach reflection erupting from the surface at a position along the wedge rather than at the leading edge as would be expected for a self-similar pseudo-steady flow. This has also been found to be the case for flows with a viscous boundary layer effect for wedge angles near transition. One concern with the above tests is whether the temperature of the gas above the wedge is uniform before the shock arrives, due to convection influences.

None of the above investigations examined the influence on the shock topography, being primarily interested in the triple point trajectory and the reflection transition conditions.

It is this thermal effect that prompted the current investigation, accepting that the effects would be small. In initial studies done in a standard shock tube with a fixed wedge the surface properties of the wedge were simply changed, but lack of sufficiently high reproducibility in shock Mach number did not allow firm conclusions to be drawn. The current experiment avoids this issue by returning to the benefits of using a symmetry plane.

EXPERIMENTS

An experiment has been devised where two inclined surfaces on either side of a symmetry plane, and impacted by a propagating shock wave normal to the plane should show any differences in reflection behaviour if they were detectable within experimental accuracy. Both surfaces need to experience the incident shock wave at the same incidence angle as well as identical initial conditions. The hardware developed is shown in Fig. 3.

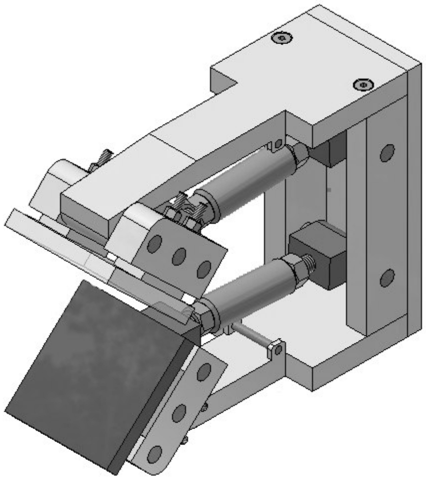

Figure 3 Adjustable test-piece holder

It consists of a heavy and robust structure to hold the two surface specimens. The surfaces can be adjusted in angle using a collar with a left-and-right-hand thread which is held in place with locknuts. Provision is made for attachment of tension springs (not shown) to account for any backlash, notwithstanding that very tight tolerances were maintained in the rotating members. The assembly is the same width as the shock tube so the wave interaction is two-dimensional. The specimens are attached to the rig so that their leading edges are in the same plane as the approaching shock wave. Their inclination is set with a digital inclinometer to an angle better that 0.1 degree.

The test pieces used were glass on the one side and copper on the other. The specimens were 10mm thick and 80mm long. Thermal conductivities are 1.05 W/mK and 401 W/mK respectively [7]. The copper was polished to a mirror finish in a metallurgical engineering laboratory and surface roughness tests performed in the direction of shock wave propagation in a tester with a resolution of 0.001μm. Five values were taken for each test piece and the surface roughness values down the length of the specimen taken as shown in the table below, giving average values of 0.013 and 0.079μm for the glass and copper. This is substantially below the value regarded as being hydraulically smooth in shock wave testing and having no effect on the reflection pattern [1].

Material	Glass	Copper
Position 1	0.013	0.075
2	0.016	0.152
3	0.012	0.044
4	0.014	0.055
5	0.011	0.071
Average μm	0.013	0.079

Table 4.1: Surface roughness test results

Visualisation was performed using a conventional Z-configuration shadow photography system with a continuous light source. Imaging was with a Photron camera at a frame rate of 75000 fps and shutter speed of 1μs. It unfortunately has limited spatial resolution of 320x264 pixels thereby compromising measurement accuracy.

RESULTS

The glass test piece is located on the right hand side of the image and the copper test piece on the left hand side. Typical results for both regular and Mach reflection are given in Fig. 4.

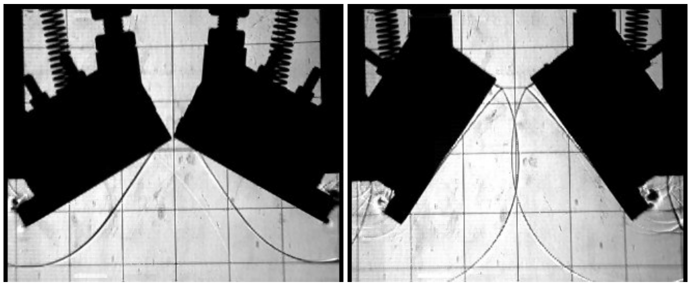

Figure 4 Regular reflection on the left and Mach reflection on the right.

There is a grid of wires adjacent to one of the shock tube windows, unfortunately not perfectly aligned for purposes of accurate measurement. Two images were extracted from the video for each test, one at earlier times and one later on. It was found that the reflection was not entirely pseudo-steady, or self-similar in time, as was expected. Images were imported into a CAD (Computer Aided Design) package, zoomed in, and measurements taken for the later time case, when the pseudo-steady situation should be forming. Shock waves were about three pixels wide and lines were positioned within them and measurements of angles read off from the software. For regular reflection the reflection angle was measured with respect to the surface, and for Mach reflection that between the incident and reflected waves.

It was found that the angles measured at early times were different from those at later times. This lack of self-similarity corresponds to the findings of Henderson and of van Netten where they showed Mach stem eruption away from the corner, in the one case near transition and in the other due to thermal effects from the wall. For the current tests data was taken when the shock is close to the highest point since the above references indicate that self-similarity is approached at later times.

Some typical results are given below. Equivalent wedge angle=(90°- incidence angle). In all cases glass results are shown with a diamond and copper results with a square. In all cases, measured wall angles on both sides did not vary by more than 0.01°.

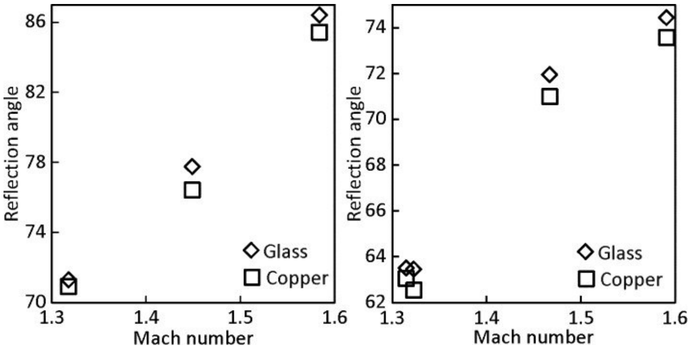

Figure 5 Mach reflection data. Left plot for a shock incidence angle of 50.62° and right plot for 55.53°.

It is noted that for all cases the reflection angle for the glass surface is slightly larger than that off the copper surface, indicating a slight difference in reflected shock wave strength. Notwithstanding the consistency in these results the difference between the two cases is small, about 1° for the higher Mach numbers. This is slightly above the estimate of maximum measurement error of less than half a degree. The issue of improving resolution in future is discussed below.

Some regular reflection data is given in Fig. 6. As for the Mach reflection case, differences at low Mach numbers are much smaller but otherwise the angles for the glass surface are consistently higher than for the copper surface. Interestingly tests at a small incidence angle of 20° gave contrasting results which will need to be confirmed from higher resolution tests when small angles are involved.

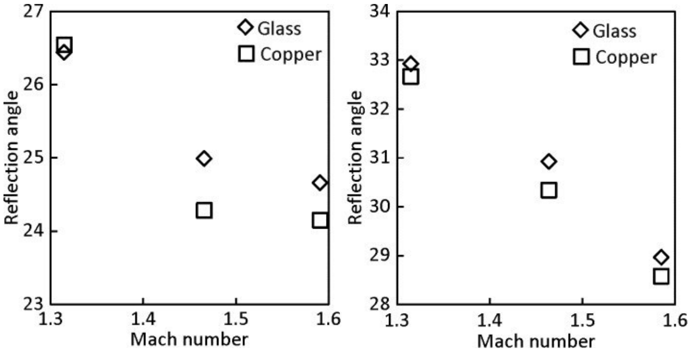

Figure 6 Regular reflection data. Left plot for incidence angle of 30.35°and right plot for 35.73°.

One interesting case is shown in Fig. 7. The interpretation from the video indicates that it is a regular reflection but there is no solution from theory for the particular wedge angle and Mach number tested, suggesting that it may be a Mach reflection with a short Mach stem which cannot be resolved. This is a common problem in attempting to establish transition conditions. However close examination of the image does indicate that there is a shear layer very close to the wall, particularly on the glass surface. With this assumption of it being a Mach reflection the angle data is similar to other Mach reflection cases.

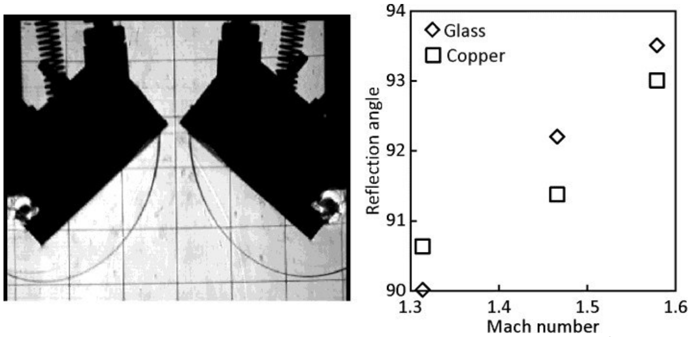

Figure 7 Tests for an incidence angle of 42.50°.

Thus, in general, the indications from these consistent comparisons are that there is an effect on shock wave reflection due to the thermal properties of the wall. However the effect indicated is too small so as to reach a positive conclusion and higher resolution tests are needed as mentioned below.

In seeking some qualitative indications it is instructive to examine the propagation back out of the cavity between the surfaces. The returning wave system, although complex, is propagating back through the gas which was heated by the incident wave and is thus at an even higher temperature. This suggests another way of testing. It would be necessary for the surface profiles of the surfaces to be completely symmetrical, particularly the angles, the leading and trailing edges to be directly opposite each other, and the external geometry to also be the same to avoid external perturbations to influence the flow. Two cases to explore this concept are given in Fig. 8. These show the incident wave entering at the leading edge showing excellent entry conditions as regards symmetry. The middle row of images shows the waves emerging at the test piece trailing edge, again with an indication of symmetry considering the limited resolution in the image. The last row shows the reflected wave systems emerging from the leading edge plane and it is notable that in both cases the main wave is propagating faster on the right hand surface than on the left hand side, indicating a difference in the basic propagation behaviour. Further testing which much tighter control on the test piece dimensions and conditions will be needed to confirm this effect.

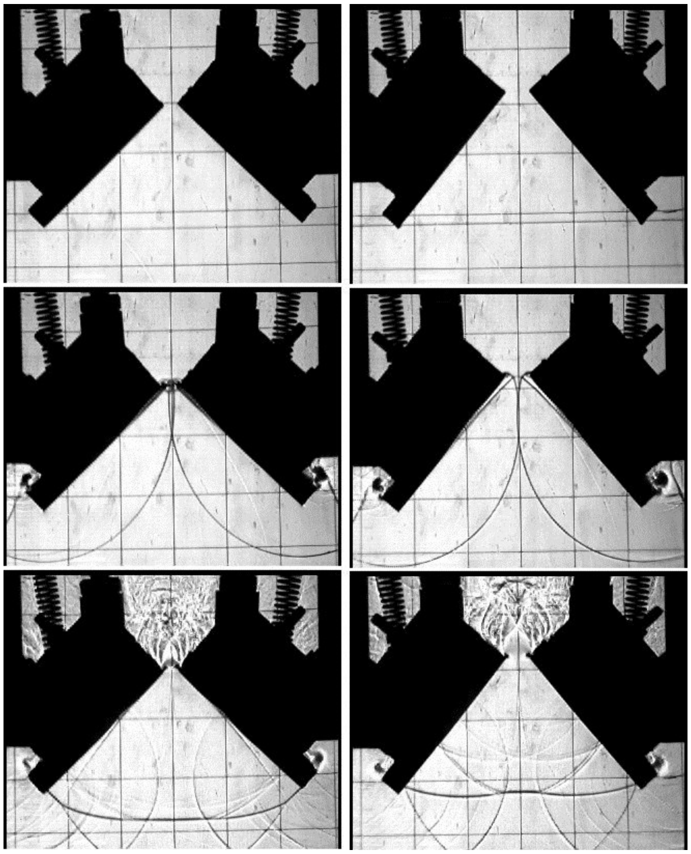

Figure 8 Reflected wave system from the cavity.

CONCLUSIONS

Preliminary tests to determine whether wall conductivity can have an influence on shock reflection topography were conducted. Consistent and repeatable results indicate that this is so, but with the indications that the effects are small due to the tests being limited by the scale of the experiment and limited camera resolution. Therefore experiments with much longer surfaces, and imaging at much higher resolution, are planned in order to clarify if a firm conclusion of an effect may be established.

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