SYNCHRONOUS SHOCK WAVE EMERGENCE FROM INTERSECTING DUCTS

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ABSTRACT

Various studies have been conducted on the dynamics of the flow field resulting from the emergence of a shock wave from a duct. These studies have included differences in duct cross-section and even the interaction of shock waves from several tubes simultaneously. However, the simple case of two shock waves of similar strength emerging from orthogonal ducts, such as might be the case in the event of a blast in HVAC ducting, has not been well considered. In this study a shock tube was bifurcated to produce two waves of equal strength and close synchronisation which could then interact in an open test section. It was found that a complex reflected shock wave system forms where the two shock waves interact. This interaction was visualised using high-speed shadowgraph at a speed of 75 000 frames per second for incident shock wave Mach numbers of 1.15, 1.3, and 1.4. Related to these shock waves are the vortex lines shed at the diffraction edges, which are strongly influenced by the close proximity near the shared corner and show significant narrowing as a result. When the two shock waves are not perfectly synchronised, there is also a slipstream which develops from the shared corner and, for strong shock waves, a vortex structure bound by the shear layer. The exact shape of this vortex structure is still being interrogated. A complementary numerical study using the commercial code, ANSYS Fluent, to understand the topology of the shock waves and vortices produced better was undertaken though this also requires further refinement. Another interesting feature noted in the case of unsynchronised shock wave interaction is jetting from between the shear layers produced by the irregular reflection of the two shock waves from each other and also the possibility of a Kelvin-Helmholtz instability of the shear layer, which is not nominally plane unlike in previous observations thereof.

INTRODUCTION

A shock wave is a discontinuity which arises in supersonic flows to enforce a geometric boundary condition. Since information in a fluid propagates at the local speed of sound, supersonic flows (or fluids in which bodies travel supersonically) the flow cannot smoothly adjust to the presence of a a body and must be deflected suddenly. The shock wave causes this shift though with a decrease of stagnation pressure and increase in entropy. The directly observed effect of a travelling shock wave is an increase in the static pressure, density, and static temperature of a fluid and induced motion in the direction of travel of the shock wave.

While shock waves normal to a flow are commonly studied, shock waves that are inclined to the flow, or oblique shock waves, are more common since it is these waves which form to adjust a supersonic flow to the presence of a corner. Oblique shock waves occur at the leading edges of supersonic objects ranging from bullets to aircraft. When these waves interact with a surface, they must be reflected to meet the continuity condition at the surface such that mass cannot emerge from or disappear into the surface. This reflection can adopt two basic forms: regular and irregular (or Mach) reflection.

A schematic of the regular reflection of an oblique wave is shown in Figure 1. This type of reflection is characterised by the location of the reflection point on the surface of reflection, similar to the geometric reflection of light from a mirror. The inclination of the incident wave, *i*, to the surface will induce the fluid to flow at an angle away from the surface. Since this would violate continuity, the reflected wave, *r*, arises to change the trajectory of the flow to parallel to the reflecting surface again. It should be noted that unlike the geometric reflection of light, the angle of the reflected to the surface does not match that of the incident wave but is rather related by an non-linear equation

NOMENCLATURE

Table 1. NOMENCLATURE

M	[-]	Mach number

Subscripts

i	Incident wave
m	Mach stem
r	Reflected wave
$shock$	Shock wave
sl	Shear layer

to that angle and the strength of the incident wave, represented by the Mach number (M_{shock}).

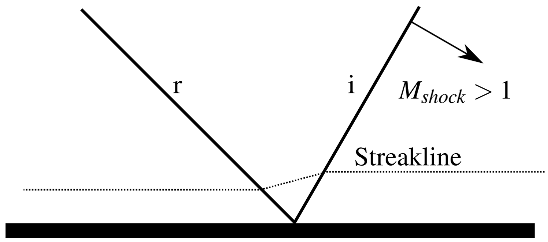

Figure 1. Schematic of regular reflection

By contrast a schematic of a Mach reflection is shown in Figure 2. This type of reflection arises when the angle of the incident wave to the reflecting surface is very shallow. This results in the flow deflected upward to an extent that no single reflected wave can exist which will turn the flow back parallel to the the surface. The reflection point therefore moves away from the surface and a connecting shock wave, referred to as the Mach stem (m), forms. The Mach stem is perpendicular to the surface and generally strong. The Mach stem meets the reflection point of the incident and reflected waves, which is now referred to as the triple point. Although theoretically the Mach stem is flat and normal to the surface, it has been experimentally observed that there is some curvature of the Mach stem at the triple point.

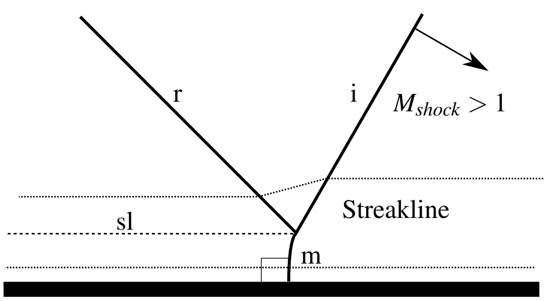

Figure 2. Schematic of irregular, or Mach, reflection

As a result of the differing shock wave interactions for particles above and below the triple point (through the incident and reflected waves above and through only the Mach stem below), the fluid behind the triple point has different states. While the fluid is at the same pressure, the speed, density, and temperature of the fluids differs and so a contact surface between the two fluids arises. This surface is referred to as a shear layer since the difference in velocity between the fluid above and below the contact surface differs. Since Mach stems may be too small to view in the early stages of these reflections, the presence of a shear layer is used as an indicator of the transition of a shock wave reflection from regular to Mach reflection. It must be noted that the shear layer here is drawn as parallel to the reflecting surface but that it most often occurs inclined toward the surface.

Another interaction of shock waves which commonly occurs is diffraction. This is the process whereby a moving shock wave is forced to pass over a convex corner i.e. the surface turns away from the shock wave. As described by Skews [1], the shock wave will curve around the corner and the momentum of the flow behind the shock wave will induce a vortex to form at the corner. For corner turn angles up to 255°, the strength of this vortex will depend on the corner angle. Beyond this angle the vortex strength is constant. A general schematic is shown in Figure 3.

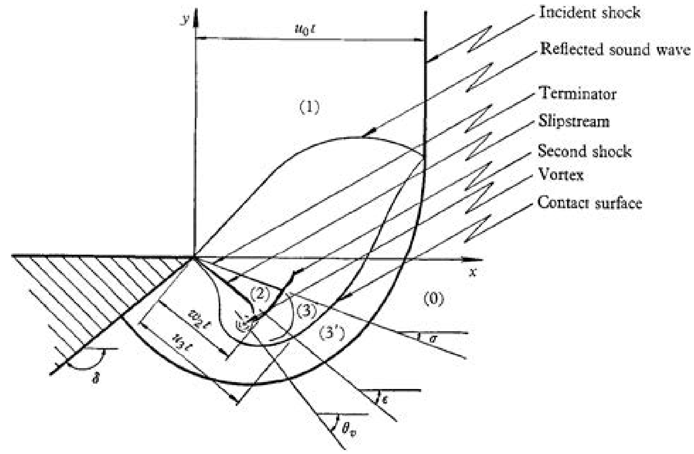

Figure 3. Schematic of the region behind a normal shock that has diffracted over a corner [1]

The passage of plane shock waves in ducts has been a subject of study for decades in the field of gas dynamics. Notionally these waves could arise by various means including: ingestion of exterior moving shock waves generated by aircraft, or as a result of explosions (either accidental or intentional). Such studies have typically focused on the emergence of these shock waves from the open end of a shock tube. Arguably the first study of this sort by Elder and de Haas [2] looked at the dynamics of the flow produced by a plane shock wave emerging from a cylindrical shock tube. Parameters such as the vortex ring convection speed and diameter were measured and related to the tube diameter.

However, in most practical installations rectangular ducting is used and so the case of a shock wave emerging from the end of a shock tube with a rectangular or square cross-section is of greater interest. A study by Jiang, Onodera, and Takayama [3] considered the case of a plane shock wave emerging from a shock tube with a square cross-section. This was visualised experimentally by holographic interferometry and was also modelled computationally. In this case, the vortex loop formed with an initially fairly uniform cross-sectional area and with an approximately square shape when viewed in the longitudinal direction. As this vortex propagated, the axis of the square section changed by 45° and there was significant thickening of the vortex core along the straight edges of the vortex loop.

The majority of these studies considered only the case of a single shock wave emerging from a single duct. However, the more general case would be of several shock waves interacting

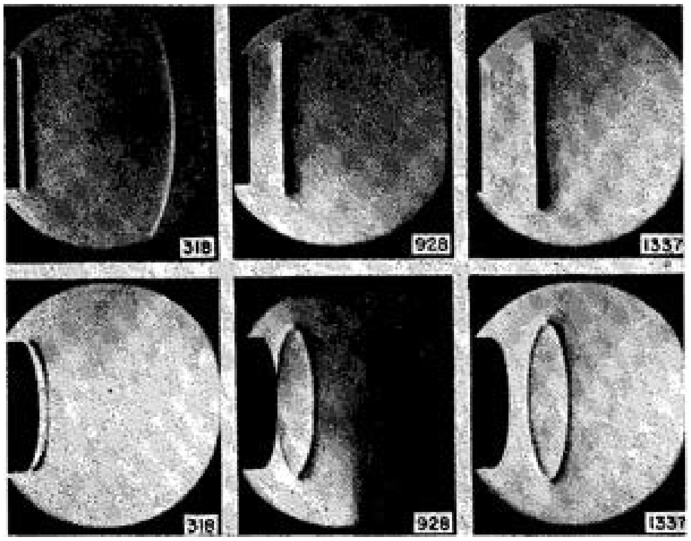

Figure 4. Schlieren images of shock wave and vortex ring at the exit of a cylindrical shock tube [2]

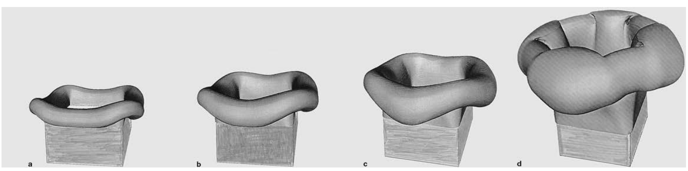

Figure 5. Computational images of the vortex loop and jet boundary developing from the end of a square cross-section shock tube [3]

as a result of emergence from various ducts. Barbosa and Skews [4] constructed a shock tube with two orthogonal ducts driven by a single shock wave source. This allowed for the study of synchronised shock waves of equal strength at corners of various angles. By making small modifications to the shock tube arrangement, a delay could be introduced in the arrival of one of the shock tubes at the test section and hence a study of unsynchronised shock wave interaction. The most significant feature to be expected from such a flow field would be the interaction of the later shock wave with the vortex shed from the diffraction corner by the earlier shock wave. The later shock wave undergoes a complex interaction with spiral vortex shed by the first shock wave after reflecting off of the diffracted first shock wave. Several shock wave reflection points exist in the field and the vortex develops adjacent regions which are alternately sub- and supersonic as a result of this interaction. A holographic interferogram of such an interaction is shown in Figure 6.

While the study by Barbosa and Skews did consider the interaction of two shock waves at the exits of two tubes, the flow field was constrained by the test section windows to be effectively two-dimensional. However, the diffraction of two shock waves into a larger volume at a common edge would be the most general case that could be considered.

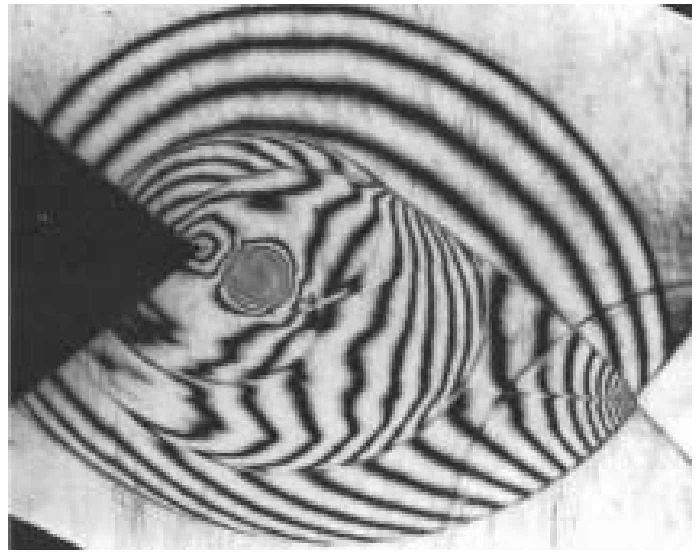

Figure 6. Holographic interferogram of the shock wave-vortex interaction for unsynchronised shock waves of equal strength at a common corner [4]

EXPERIMENTAL APPARATUS

The test section of the bifurcated shock tube used by Barbosa and Skews has been replaced with an open section in which there are plates normal to the axis of each of the tubes which extend away from the exit so that the flow is bounded by the exit planes of each tube. The test section geometry used in this study, in which the two sock waves meet at an orthogonal corner, is shown in Figure 7.

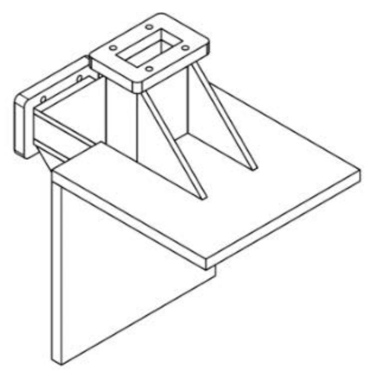

Figure 7. Test section used

The flow field was visualised using high-speed shadowgraphy capturing using a Photron FastCam SA5-775k operating at a speed of 75 kfps (thousands of frames per second).

COMPUTATIONAL MODEL

The flow field was also modelled using the commercial code ANSYS Fluent 15.0. The domain consisted of two lengths of duct and a diffraction domain bounded by walls and an outlet boundary. The symmetry plane defined by the longitudinal centre planes of the two tubes was used to reduce the size of the computational domain. The model comprised approximately 2.5 million cells with an average quality of 0.82. An implicit, density-based solver with an AUSM formulation was used and Green-Gauss cell-based with a third-order MUSCL spatial discretisation scheme was used. The model was computed as inviscid. The distibution of cells, ranging in size from 0.5 mm to 20 mm, is shown in Figure 8.

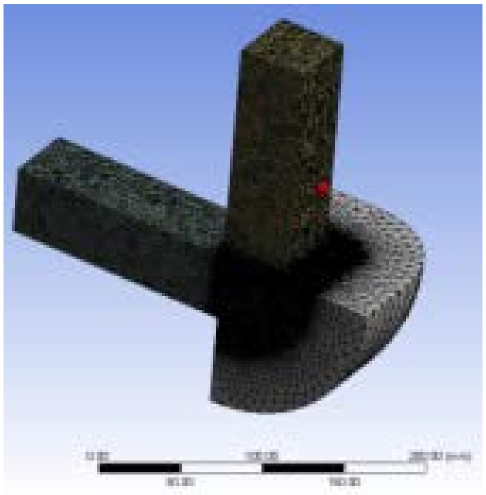

Figure 8. Initial mesh for CFD model

RESULTS

The results presented will first be described in detail for the case of a Mach number of 1.15. Thereafter the results for the Mach numbers of 1.3 and 1.4 will be contrasted. In the first frame of Figure 9 the shock waves have just arrived at the exits of each of the tubes. There is a slight mis-synchronisation of approximately 1.5 *µs* evident by the visible wave at the tube exit along the left edge of the frame. That first wave has visibly diffracted over the bottom edge of that tube as well as logically having diffracted over the edges that are vertical in the direction of visualisation and the upper edge, which is within the upper tube.

In the second frame the vortex shed along the outer (bottom) edge of the lower tube can be seen though the vortex lines along the vertical edges are not yet visible. The second shock wave has exited from the upper tube and exhibits similar behaviour. The two shock waves appear to be undergoing a regular reflection at this time. A weak interaction can also be seen to the right of the shock wave interaction as a results of the diffracted first shock wave interacting with the approaching second shock wave.

In the third frame the vortex shed over the outer (right) edge of the top tube is now visible and the vortex line shed along the outer (left) edges of the bottom tube can now be seen. The vortex appears to taper toward the common corner but that line also appears to bend near the bottom edge of the tube.

In the fourth frame the reflected shock waves have passed through the diffraction vortices and the vortex tube boundaries along all edges are visible now. The reflection between the two incident shock waves has also changed to a Mach reflection, indicated by the short shear layers emanating from the two triple points and the flat Mach stem between the reflected waves.

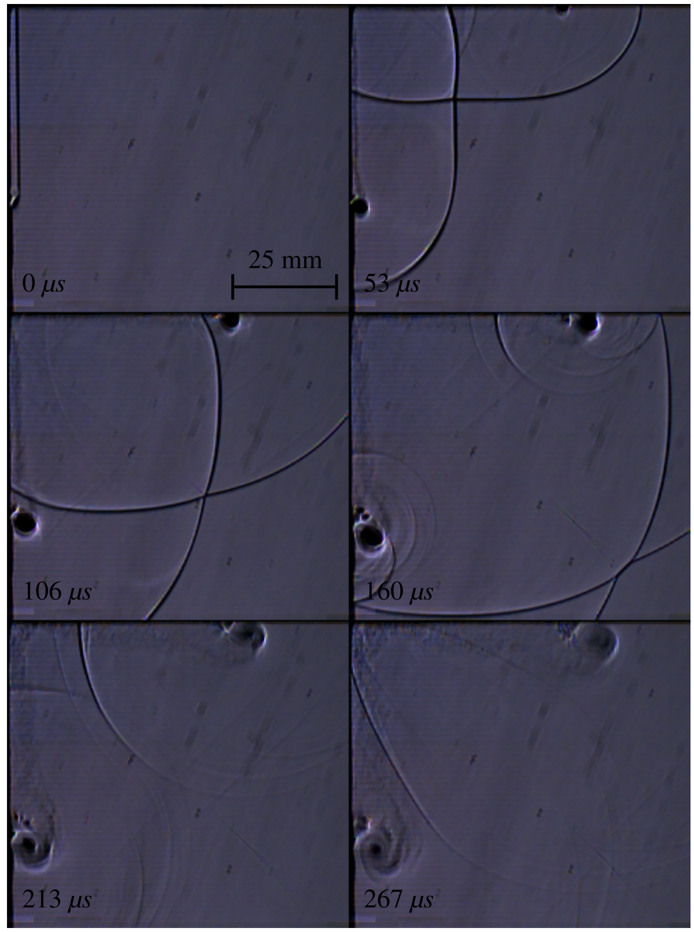

Figure 9. Shadowgraphs of flow development for a nominal incident Mach number of 1.15

In the fifth frame the Mach reflection has propagated out of the field of view. Reflected shock waves from the shock wave-vortex interactions are also propagating back toward the common edge. The structure of the vortices shed at the edges aligned with the visualisation axis can now be discerned. The reflected shock waves from the shock wave-vortex interactions are approaching the common corner though, oddly, the strengths appear quite different. The vortex boundaries for the portions of the vortices shed on the edges normal to the visualisation axis show a clear taper toward the common corner and there is a bending of their axes away from the same corner that can just be seen in that region.

In the final frame the vortices are detaching from the diffraction edges and convecting into the flow field. The strength of the vortices appears to be diminishing already while the reflected shock waves from the shock wave-vortex interactions seem to be having a negligible effect on the vortices. The most noticeable difference in the results for the Mach 1.3 incident shock wave strength, in Figure 10, is the clear Mach reflection as ev-

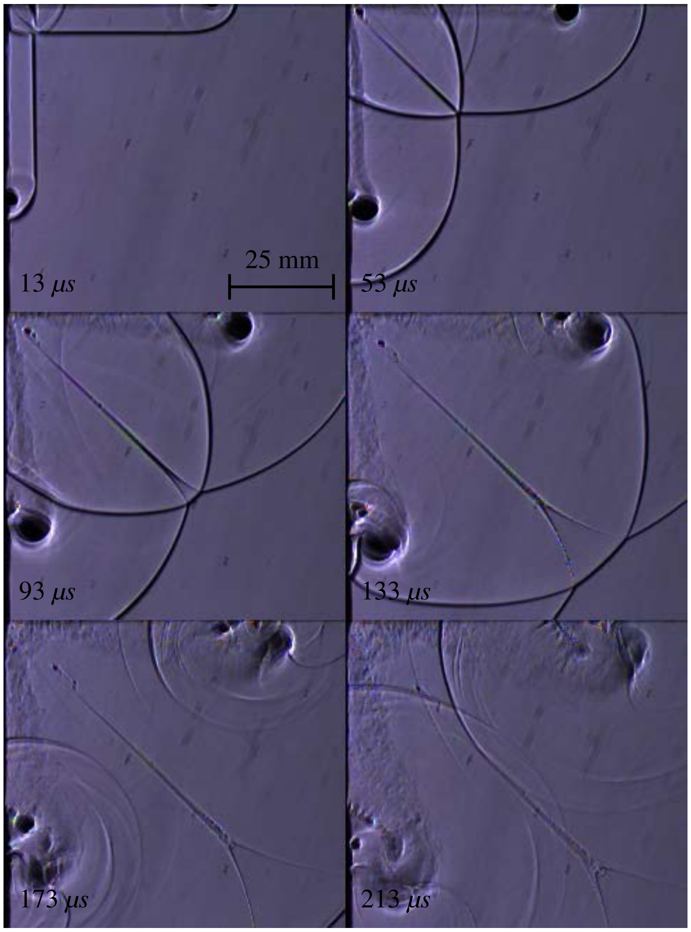

Figure 10. Shadowgraphs of flow development for a nominal incident Mach number of 1.3

ident from the shear layers in the first frame. The Mach stem remains quite short and only becomes discernable in the third frame. Thereafter it widens quite rapidly and the shear layers adopt a Y-shaped pattern as a result.

In the second frame a vortex can also be seen near the base of the shear layer ”Y”. This vortex was originally produced by the diffraction of the first wave at the exit (again a difference estimated at about 2 μs but in this case the top wave arrived first) which has then been forced out into the visible flow field by the flow induced by the shock wave. Of particular interest is that the shear layers seem to terminate in this vortex and that it appears to be bound to travel along the centreline between these two. The latter aspect could also be explained by that centreline being the common surface between the two jets exiting each tube.

This vortex is also of interest because a vortex line cannot terminate in free space. This suggests then that what appears to be a single vortex line may be a vortex loop with a very high aspect ratio or that this vortex must somehow interact with the main vortices associated with the main diffraction edges. Unfortunately it is not possible to determine this from the experimental images captured though the smaller dark spot farther along the shear layers in frames 4 and 5 of this series suggest that the former is a likely description of the flow field. This raises the question of how this loop would form before separating from the corner. It is possible that this would happen through the interaction with the vortex shed by the diffraction of the second shock wave into the other tube.

Another feature of interest in this series is the jetting in the final frame away from the corner between the two shear layers. This is visible as the small ”bubble” between the two arms of the Y-shaped shear layer. This behaviour is similar to that seen in [5].

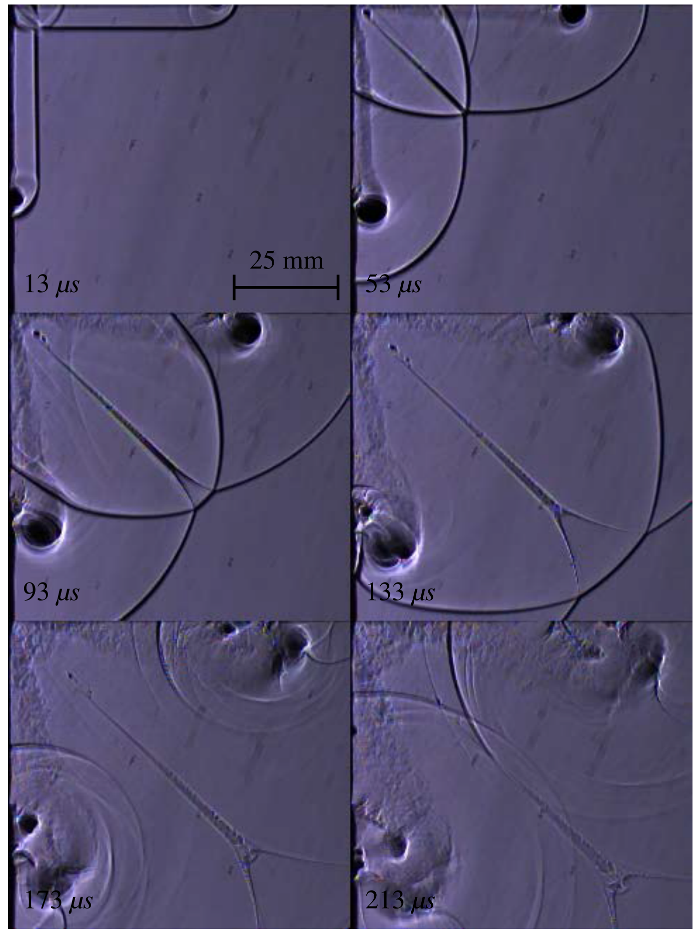

Figure 11. Shadowgraphs of flow development for a nominal incident Mach number of 1.4

Similar features to those seen in the Mach 1.3 results are visible in the Mach 1.4 results. The few differences of note are the earlier incidence of inter-layer jetting and stronger jetting visible in the last frame of the series as well as the more clearly pronounced vortex profiles. The interaction between the originally normal vortex lines at the common corner shows more pronounced deformation but the turbulent boundaries of these vortices make it difficult to describe their shapes more clearly.

In order to better understand the flow field due to the limitations imposed by the visualisation system features of the flow field were visualised using different techniques from the computational model. An example of this is given in Figure 12.

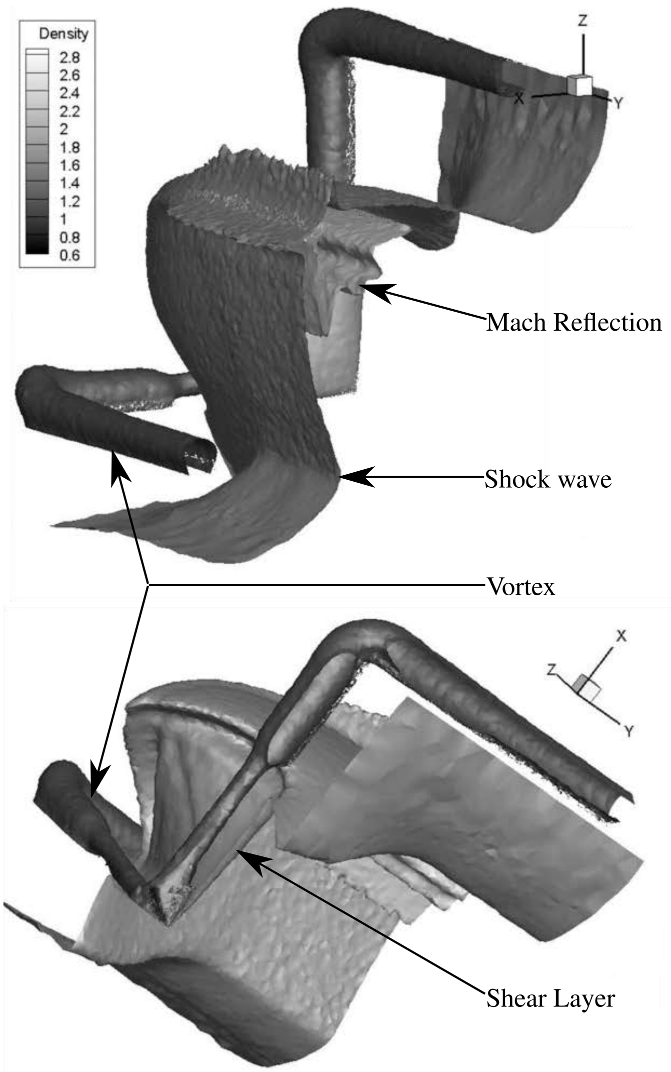

Figure 12. Isopycnic surfaces for a nominal incident Mach number of 1.15 20 μs after shock arrival at the common corner

In this figure the vortex loops and shock surface can be seen. A thickening of the vortex loops near the common corner is visible at this early stage while the vortex tubes do seem to taper toward the corner. The rest of the vortex tubes appear to be quite uniform in cross section. This bears out the consistent profile of the vortex lines viewed along the axis in the experimental images.

Of more interest here is the shape of the shock reflection region. Since the shock waves diffract outward at the ends of the common corner, the reflection pattern seen in the experimental images would be that along the visualisation axis but the shock waves could form a different reflection pattern at surfaces inclined to the visualisation axis and so the reflection pattern between the two shock waves could vary between regular and Mach reflection. Unfortunately such detail does not seem to have been resolved by the current computational model. Due to time constraints only synchronised models could be run and similar limitations were found in those results. None of the features attributed to unsynchronised arrival of the shock waves, most especially the vortex loop at the base of the shear layers, could thus be verified.

CONCLUSION

The interaction between shock waves propagating in orthogonal ducts has been studied experimentally and computationally. While the experiments indicate interesting features, including shear layer jetting and Mach reflection, issues with exact synchronisation of the arrival of the two shock waves remain. The constraint of the visualisation by the system geometry also limits the features that can be definitively described from those images.

An attempt to improve the understanding of the flow field through detailed computational modelling has produced some interesting results but significantly higher resolution of weaker features is needed to be able to confirm the experimental results.

ACKNOWLEDGMENT

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