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SHOCK INTERACTIONS WITH HYPERSONIC MIXING LAYERS - STEADY FLOW ANALYSIS AND EXPERIMENTS

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ABSTRACT

Interest in scramjet powered flight has led to the study of shock induced mixing and combustion effects. To provide further understanding of phenomena associated with shock induced mixing and combustion, an experiment investigating the interaction of shock waves and a mixing region was undertaken. Hydrogen was injected parallel to a co-flowing stream of nitrogen, from the base of a central strut injector. Pitot pressure measurements were taken within the mixing region. After the pitot rake was removed, static pressure measurements were made downstream of the shock wave mixing layer interaction on the surface of 3 different shock inducing wedges. The flow was turned through angles of 5, 10, or 15 degrees with these wedges. Theoretical calculations of the static pressure were performed using a shock interaction model based on the time average flow properties, and the results from the pitot survey. Agreement between the theoretical model and experimental results was reasonable, but more data is required to fully validate the shock interaction model, and to demonstrate its usefulness in understanding the processes of shock induced mixing.

INTRODUCTION

If hypersonic flight using scramjet (supersonic combustion ramjet) propulsion is to be realized, the problem of significantly enhancing supersonic mixing and combustion must be solved. The scramjet is an airbreathing concept which requires the injection of fuel (usually hydrogen) into the high speed air stream entering the engine. The fuel is resident within the engine for only short periods of time and must mix and burn rapidly in order to produce the required thrust. Unfortunately, supersonic flow is not conducive to rapid mixing. It has been known for some time that mixing can be profoundly influenced by compressibility effects (Papamoschou and Roshko, 1988). Therefore, methods to enhance the mixing rates in supersonic flows are currently being sought.

The impingement of shock waves on mixing regions has received some attention as a candidate method for improving the mixing in supersonic streams. Varying degrees of shock induced mixing augmentation have been observed in recent supersonic mixing layer experiments (e.g., Hyde et al., 1990, Sullins et al., 1991, and Roy, 1991). Based on a survey of previous literature, Kumar et al. (1989) state that through the interaction of turbulence and shock waves, the turbulence and mixing may be amplified by a factor of 2 to 5. Numerical studies of their own (presented in the same paper) suggest that an oscillating shock wave may also provide efficient mixing enhancement. However, fluctuations in either the pre-shock flow or the shock itself are not essential for mixing augmentation. Jacobs (1992) experimentally demonstrated the mixing enhancement resulting from shock wave impingement on a cylindrical gas region of lower density. Additionally, it is well known that vorticity is generally discontinuous across a shock wave in steady compressible flow (e.g., Hayes, 1957).

It is evident therefore that the passage of a shock wave may influence mixing through modifications to both the fluctuating and steady flow properties. Fluctuations associated with the interaction process have been dealt with previously (e.g. Kumar et al., 1989), however, there is a paucity of research treating the interaction process on a time average level. Therefore, the true influence of the fluctuating flow properties cannot be fully assessed. In the current study, theoretical modelling of the interaction process is achieved using a simple steady flow shock interaction analysis. It is felt that a steady flow analysis of a shock mixing region interaction provides a useful benchmark for assessing the influence of unsteady turbulence effects, and gives good physical insight into the shock propagation process. Experimental investigations of shock wave interactions with mixing regions were performed using a central strut injection model, in conjunction with a shock tunnel facility.

INTERACTION MODEL

The current interaction model is based on steady flow properties ahead of the shock wave. No interaction between fluctuating quantities and the shock is treated with this approach. A stable oblique shock wave generated by a straight wedge, which does not decelerate the flow to subsonic velocities, is assumed. Since mixing typically occurs slowly under supersonic conditions, a non-uniform distribution of properties is likely within a supersonic mixing layer. The mixing region ahead of the shock wave is treated as unidirectional with a uniform pressure, and is modelled using the distribution of the steady Mach number alone. A constant value for the ratio of specific heats is also assumed to exist across the mixing region. Modelling of the shock wave is achieved using the Rankine-Hugoniot relations (Liepmann and Roshko, 1957).

Consider the situation depicted in Fig. 1a. By employing the conditions of matched pressure and flow direction on either side of the dividing streamline, it is possible to derive an expression describing the propagation of the shock wave in the variable Mach number region. This expression takes the form,

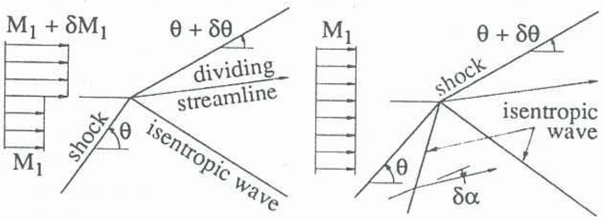
$$\frac{\partial\theta}{\partial M_1} = f_1(M_1, \theta) \quad (1)$$

The function $f_1(M_1, \theta)$ is analytic, but quite complicated and will not be further detailed in the current paper. The Mach number distribution ahead of the shock is the initial factor causing the shock wave to change direction. However, further shock curvature may arise due to the nonuniform pressure field behind the shock resulting in isentropic waves impinging on the shock wave from behind, Fig. 1b. In this case, the equation which describes the effect on the shock wave shape takes the form,

$$\frac{\partial\theta}{\partial\alpha} = f_2(M_1, \theta) \quad (2)$$

Again, the function of M_1 and θ is analytic, but will not be further defined in the current paper. If the distribution of Mach number and the strength of the waves impinging on the shock from behind are known, the shock wave shape through the mixing region may be calculated. The change in shock direction will then be given by

$$d\theta = f_1(M_1, \theta)\, dM_1 + f_2(M_1, \theta)\, d\alpha \quad (3)$$



a) Primary shock curvature. b) Secondary curvature effects.

Fig. 1 Shock wave interaction model.

A method of characteristics solution was used to implement Eqn (3). Calculations begin with the solution of the Rankine-Hugoniot shock relations at the leading edge of the shock-inducing wedge. The Mach number distribution, the wedge angle, and the ratio of specific heats are the only parameters necessary for solution of this problem. Steps of equal size are taken across the Mach number distribution, and Eqn (3) is employed at each calculation point on the shock wave to find the new shock angle.

EXPERIMENT

Facility

An experiment investigating reflected waves generated by the oblique shock as it passes through the mixing region (with the general arrangement given in Fig. 2) was performed in the T4 free piston shock tunnel facility at the University of Queensland (Stalker and Morgan, 1988). A contoured nozzle, nominally designated "Mach 5," was used to accelerate the stagnated test gas to the required flow conditions. For the present experiments, the tunnel was operated using an argon driver at a volumetric compression ratio of 60 with a 2 mm mild steel primary diaphragm. The shock tube was filled with nitrogen to 100 kPa. An example of the stagnation pressure signals recorded at this condition is presented in Fig. 3. A relatively low enthalpy condition was chosen for the present study (Table I), so that the velocity of the shock tunnel and the injected streams would be approximately equal. It was thought that matched velocities would simplify description of the mixing region, and that the shock interaction process for such a region would be amenable to solution via the steady flow interaction model. At this condition, a conservative estimate (Gourlay, 1992) based on the analysis of Stalker and Crane (1978) suggests that 3 ms of test time should be available prior to driver gas contamination.

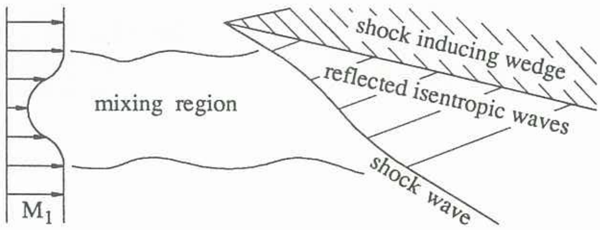


Fig. 2 Schematic of experimental arrangement.

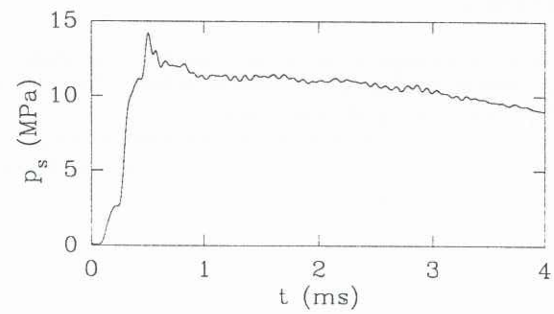


Fig. 3 Example of shock tube stagnation pressure.

An estimation of the flow conditions generated by the tunnel was achieved through a two stage calculation process. From the shock tube filling conditions, the measured shock speed and stagnation pressure, the conditions at the end of the shock tube (the nozzle supply conditions) were calculated with a equilibrium shock tube calculation, ESTC (McIntosh, 1968). These conditions were then used in a nonequilibrium nozzle flow calculation, NENZF (Lordi et al, 1966). The nozzle flow expansion calculation was continued until the measured pitot pressure was reached.

Table I Initial primary and secondary stream conditions.

Parameter	Primary Stream (nitrogen)	Secondary Stream (hydrogen)
H_0 (MJ/kg)	3.05	4.24
M	6.42	2.68
p (kPa)	3.18	5.13
u (km/s)	2.33	2.24
T (K)	317	121
ρ (kg/m^3)	0.0338	0.0102

Model and Instrumentation

A rectangular duct, 164 mm high and 80 mm wide (Fig. 4) was located at the nozzle exit plane. Hydrogen was injected through a contoured nozzle (Fig. 5) from the base of a central strut which had a thickness of 5.38 mm. The hydrogen was supplied to the injector by a Ludwieg tube and fast acting valve combination (Morgan and Stalker, 1983). An asymmetric design for the leading edge of the strut injector was chosen to facilitate spillage of the shock away from the primary shock inducing wedge. Using gas dynamic relations, the pressure mismatch caused by the asymmetry of the strut was estimated to be less than 0.1 %. The contoured nozzle was designed using a method of characteristics. During the experiments, attempts were made to match the static pressure of the injected flow with that of the shock tunnel flow. To this end, a pitot rake was set up at the exit of the injector nozzle, and the Ludwieg tube was fired at a number of different filling pressures without running the shock tunnel. Using the area ratio of the nozzle, and the average pitot pressure over the nozzle distance surveyed, Fig. 6, a condition was chosen which approximately matched the calculated static pressure supplied by the shock tunnel. However, on re-examination of the results, it was found that the injection condition was probably under-expanded (see Table I).

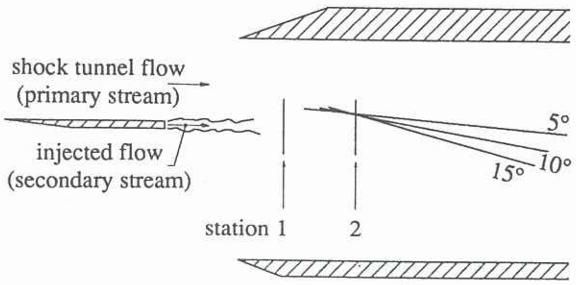


Fig. 4 Experimental model.

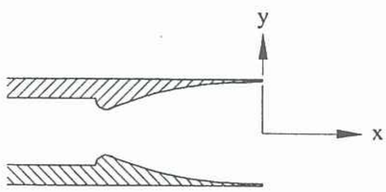


Fig. 5 Sketch of the injector nozzle.

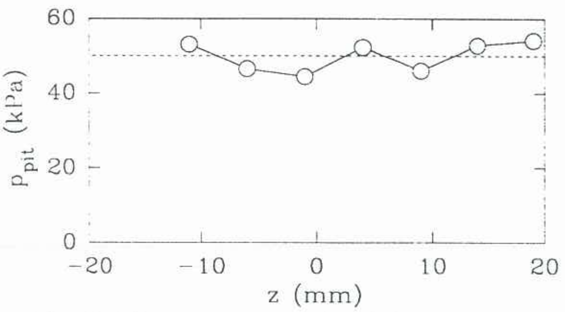


Fig. 6 Pitot pressure at exit of injector nozzle.

Three different wedges were employed to compress the mixing region through 5, 10, and 15 degrees. Eleven pressure transducers were mounted on each of the wedges, in two streamwise rows 4 mm either side of the centreline of the wedge. The transducer spacing along both rows was 8 mm. To investigate the distribution of flow properties, a 7 probe pitot rake with a 5 mm spacing between the probes, was utilized.

RESULTS

Pitot Survey

Two pitot surveys at the stations shown in Fig. 4 were made over a number of runs. (An example of the pitot pressure histories obtained from the probe are presented in Fig. 7.) To implement the model of the interaction process, a knowledge of the Mach number distribution ahead of the shock is necessary. The assumption of a constant static pressure across the width of the pitot survey permits easy calculation of a Mach number distribution from the measured pitot pressures using the Rayleigh supersonic pitot relation (Liepmann and Roshko, 1957). The Mach number distributions calculated from the pitot pressures are presented in Fig. 8. The value of static pressure assumed for the Mach number calculations was 3.18 kPa (the static pressure in the undisturbed primary stream). This is a reasonable assumption since, at the second station, the pressure was calculated to be within 3 % of 3.18 kPa across the width of the survey, for the initial mismatch of pressures given in Table I.

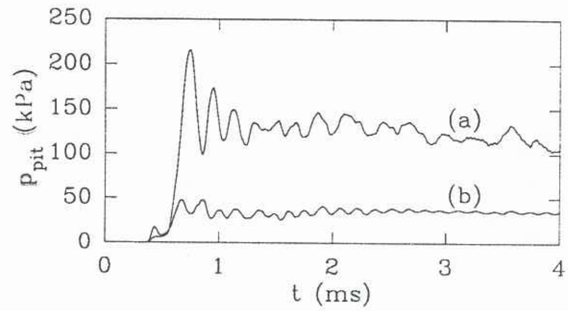


Fig. 7 Sample pitot pressure signals from a probe a) in the shock tunnel flow, and b) near the centre-line of the injected flow.

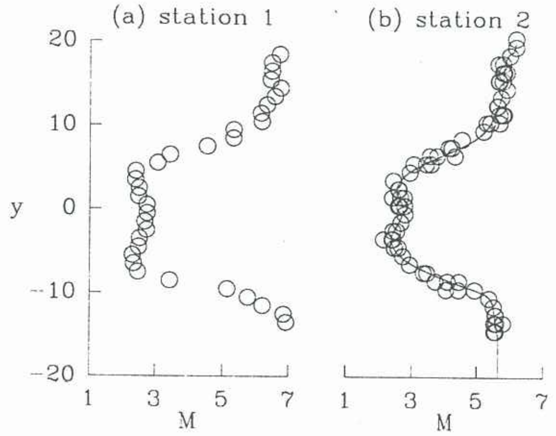


Fig. 8 Calculated Mach number distributions from pitot pressure results.

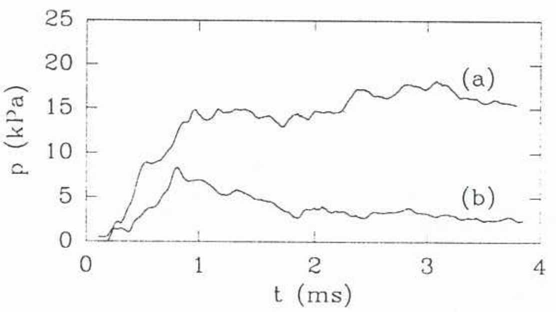


Fig. 9 Static pressure signals from the transducer midway along the matrix, 10 degree case. a) injector removed, shock tunnel flow only. b) shock tunnel plus injected flow.

Static Pressure

In order to test the shock interaction model, measurements of the pressure along the 5, 10 and 15 degree turning angle wedges were obtained. Signals from the transducer midway along the transducer matrix in the 10 degree wedge are presented in Fig. 9. For each of the transducers, results obtained with hydrogen injection (e.g. Fig. 9b) were normalised using the signals obtained with the injector removed (e.g. Fig. 9a). Normalization in this manner, provides a degree of compensation for non-uniformities present in the nozzle flow and arising through shock wave boundary layer interactions. The mean levels for the 11 normalized signals over a time period from 2 ms to 3 ms (for the time base displayed in Fig. 9) are presented in Fig. 10. The standard deviations of each signal over the same time interval are represented by the bars given in Fig. 10.

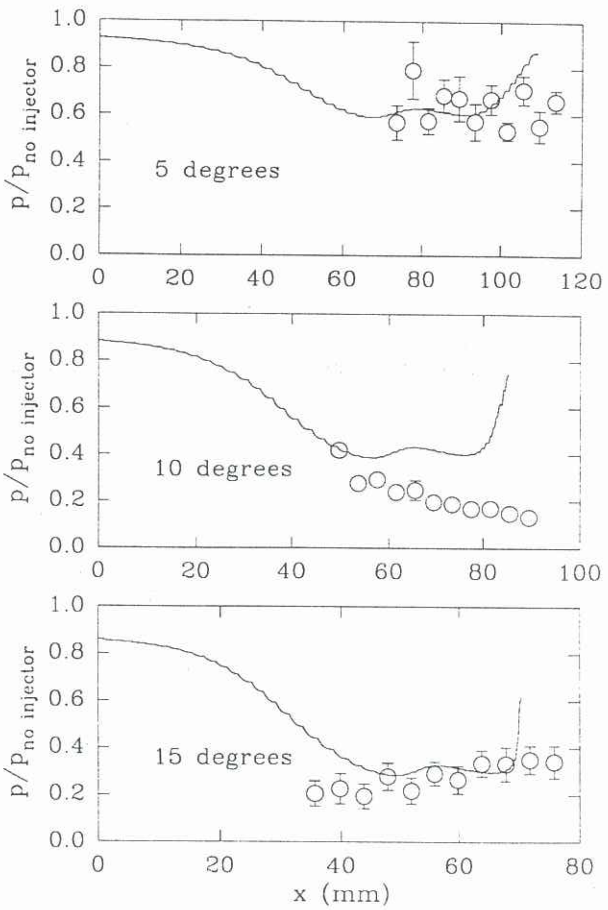


Fig. 10 Normalized static pressure results. ⏀ = experimental results. ⌒ = results from theoretical model.

By assuming the Mach number distribution (Fig. 8b) inferred from the pitot pressure at station 2, the appropriate wedge turning angle, and that $\gamma = 1.4$, it was possible to apply the shock interaction model. The solid lines given in Fig. 10 are the results from the model, calculated using the method of characteristics solution described briefly in a previous section.

CONCLUSIONS

Examination of Fig. 10 indicates that there appears to be some agreement between the theoretical model and the experimental results. Unfortunately, the experimental Mach number distribution was much broader than anticipated, resulting in a clustering of transducers near the bottom of the dip in the pressure distribution. The lowest pressure experienced on the wedge is in reasonable agreement with the theoretical model, except for the 10 degree turning angle case. The current interaction model is limited to conditions of uniform pressure and flow direction ahead of the shock wave. Furthermore, the Mach number distribution used in the theoretical model was obtained from a single streamwise location (station 2, Fig. 4), whereas the mixing region would have developed over the length required for the shock to traverse the mixing layer. More data will be required to validate the current model and assess the influence of fluctuating properties on the interaction process.

Further experiments are planned in which attempts will be made to more closely match the static pressure in each stream. The development of the mixing layer will be closely monitored using the pitot rake at a number of streamwise locations. In addition, the distribution of the transducers in the shock inducing wedge will be altered in an attempt to detect the spacial form of the changes in static pressure.

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