Technical Notes

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Experiments on Oblique Shock Interactions with Planar Mixing Regions

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Introduction

EXPERIMENTAL studies using supersonic mixing configurations have revealed varying degrees of shock-induced mixing augmentation.[1–3] Increases in turbulent activity through shock impingement have been observed[4]; however, it appears that such changes in turbulent activity do not necessarily translate into sustained mixing augmentation downstream.[5] Theoretical and experimental studies indicate that mixing augmentation can be sustained by the interaction of an oblique shock wave with a discrete fuel jet, which induces significant streamwise vorticity.[6,7] However, in a numerical study of shock-induced mixing augmentation of square fuel jets,[8] it was found that the major contribution to the mixing augmentation was actually from the vorticity amplification associated with the shock-induced convergence of the jet rather than the induced streamwise vorticity.

To investigate the influence of shock compression on the development of the postshock mixing region, an inviscid analysis describing the steady interaction of an oblique shock wave and a planar mixing region was developed.[9] This model can be used to estimate parameters such as the shock trajectory, the strength of waves reflected from the interaction process, and the postshock vorticity. The present work examines the application of the inviscid interaction model in a hypersonic configuration and focuses on the details of the shock wave–mixing region interaction process.

Experimental Apparatus

Gun Tunnel Facility

The present experiments were conducted in the University of Oxford gun tunnel facility.[10] The gun tunnel was operated with the Mach 7 contoured nozzle (throat of 19.1-mm diam, exit of 211-mm diam), using nitrogen as the test gas. The nozzle reservoir pressure remained constant (to within ±3%) for approximately 25 ms (the test time) and all of the data were obtained during this period. A Ludwieg tube supplied gas mixtures of hydrogen and nitrogen to the strut injector (Fig. 1). This Ludwieg tube was operated such that the injection pressure was constant (to within ±2%) for the duration of the 25-ms test time.

Table 1 provides estimates of the primary and secondary stream flow parameters based on various pressure and temperature measurements described in Ref. 11. The primary stream temperature and velocity presented in Table 1 are based on experimental total temperature measurements[12] and are slightly lower than anticipated (in Ref. 11) due to cooling effects within the gun tunnel barrel, which were not included in the original estimates.

Planar Duct Model

A planar duct (164 mm high, 80 mm wide) with a central strut injector and a shock-inducing wedge was located at the exit of the Mach 7 gun tunnel nozzle, as shown in Fig. 1. The central strut injector had a small contoured Mach 3 nozzle, which was coupled to the Ludwieg tube. The Mach 3 nozzle was designed (using a method of characteristics) to produce an approximately parallel flow at the exit plane of the strut injector. The strut injector had an asymmetric profile (Fig. 1c) to avoid strong pressure disturbances generated by the injector impinging on the shock-inducing wedge. Inviscid calculations indicated that the asymmetric geometry of the strut injector's leading edge would not induce measureable differences in the primary stream flow properties on either side of the injection nozzle.[13]

Instrumentation

Schlieren photographs were obtained using a horizontal knife edge system with an argon jet light source, which had a spark duration of approximately 0.1 μs. Pitot pressure measurements were obtained using a probe (having an external diameter of approximately 1.6 mm) that traversed the mixing region during the test time.[14] Static pressures were measured at 10-mm intervals on the 15-deg shock-inducing wedge using a subminiature piezoresistive device that was located in recessed holes, each with an orifice diameter of approximately 1 mm.

Results

Shock Trajectory

Examples of the schlieren images obtained are given in Fig. 2. It appears that shock surface ripples are generated as the shock interacts with the mixing region. These ripples (which appear as multiple shock paths on the schlieren images) persist into the freestream on the upper side of the mixing region. Repeated schlieren images of the same mixing case and cinematographic results indicate that the shock surface ripples are an unsteady feature. Hence, the observed shock wave–mixing region interaction process has both unsteady and nonplanar components.

Mach number distributions, e.g., Fig. 3a, were calculated from pitot pressure measurements (reported in Ref. 11) by assuming the static pressure across the mixing region was constant and equal to the undisturbed freestream value. The analytical shock–mixing region interaction solution[9] was coupled with a method of characteristics (MOC) code[13] to calculate the shock trajectory and the postshock flow based on the experimentally derived preshock Mach number distributions. For the case 4 flows, the MOC results are compared with the experimental measurements (from the schlieren images) in Fig. 3b. The wedge angles specified in the MOC calculations were slightly higher than the nominal turning angles of

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