AIAA JOURNAL
Vol. 35, No. 11, November 1997

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Experiments on Oblique Shock Interactions with Planar Mixing Regions

D. R. Buttsworth* and R. G. Morgan†
University of Queensland, Queensland 4072, Australia
and
T. V. Jones‡
University of Oxford,
Oxford OX1 3PJ, England, United Kingdom

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.

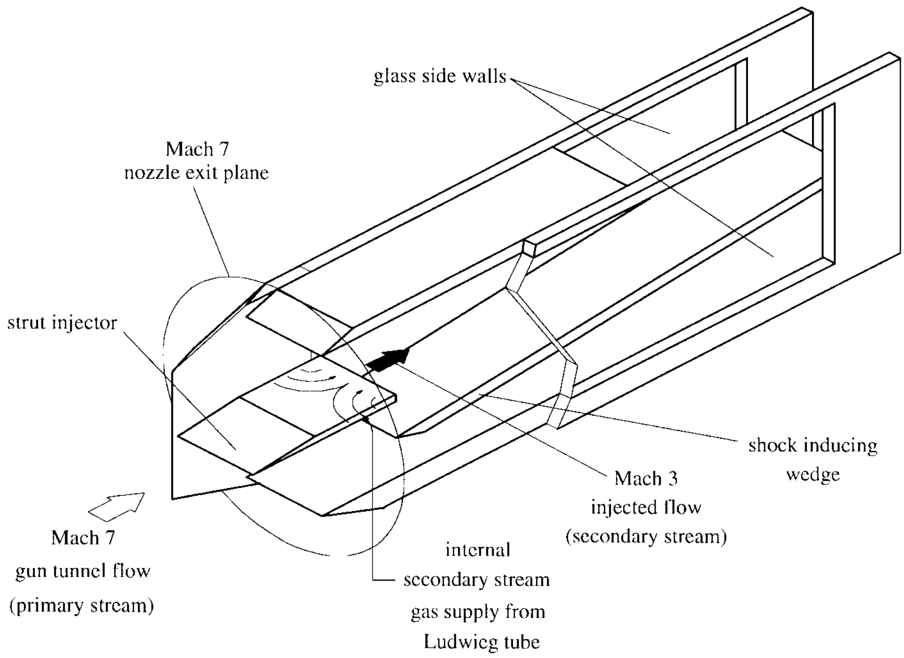
Mach number distributions, e.g., Fig. 3a, were calculated from pitot pressure measurements (reported in Ref. 11) by assuming the static pressure across the mixing region was constant and equal to the undisturbed freestream value. The analytical shock–mixing region interaction solution[9] was coupled 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

Received Sept. 13, 1996; revision received March 25, 1997; accepted for publication April 7, 1997.

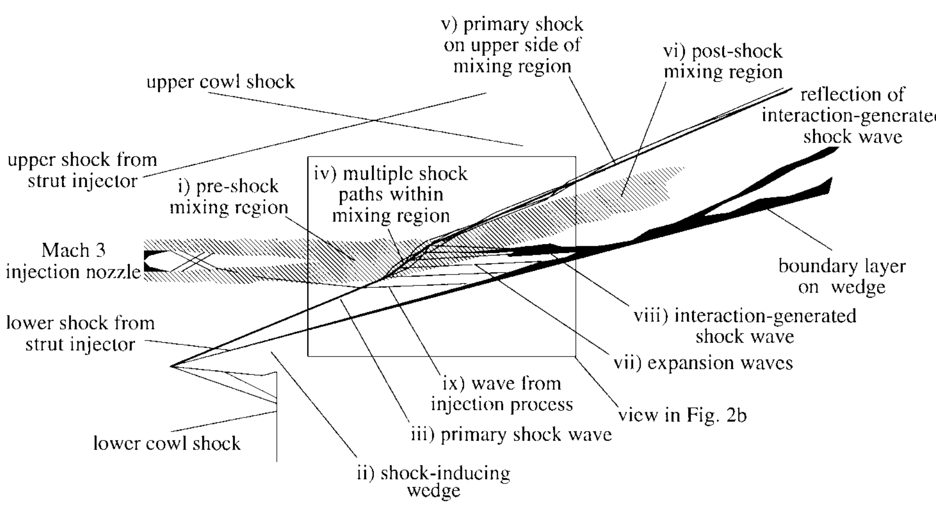
*Postgraduate Student, Department of Mechanical Engineering; currently Associate Lecturer, Faculty of Engineering and Surveying, University of Southern Queensland, Queensland 4350, Australia. Member AIAA.
†Associate Professor, Department of Mechanical Engineering.
‡Professor of Turbomachinery, Department of Engineering Science, Parks Road. Member AIAA.

Table 1 Estimated flow parameters

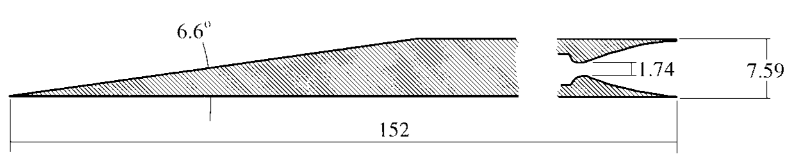
Parameter	Primary stream	Secondary stream Case 1	Case 2	Case 3	Case 4
M	7.11 (±0.04)	3.2 (±0.1)	3.2 (±0.1)	3.2 (±0.1)	3.2 (±0.1)
T, K	71 (±4)	93.1 (±5)	93.1 (±5)	93.1 (±5)	93.1 (±5)
p, kPa	1.58 (±0.06)	1.58 (±0.06)	1.58 (±0.06)	1.58 (±0.06)	1.58 (±0.06)
u, m/s	1220 (±30)	1300 (±100)	1050 (±80)	850 (±50)	640 (±30)
R, J/kg/K	297	1300 (±100)	800 (±60)	530 (±30)	297



a) Three-dimensional sketch with foreground side wall partially cut away

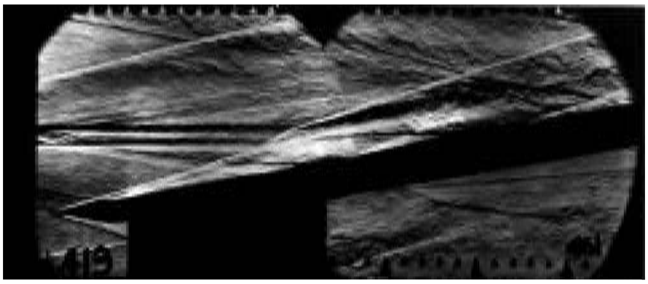


b) Side view illustrating some of the flow features

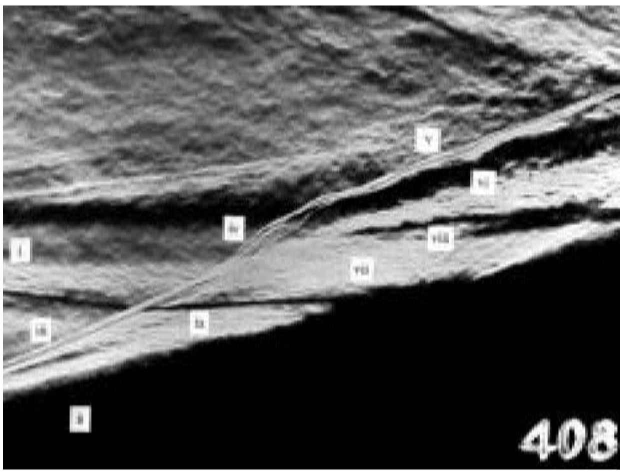


c) Details of the strut injector (dimensions in millimeters)

Fig. 1 Illustration of the model used in the experiments.



a) Composite image for 10-deg wedge, case 4



b) Details of interaction for 15-deg wedge, case 2

Fig. 2 Examples of schlieren images (refer to Fig. 1b for interpretation of features).

the shock-inducing wedges to include the displacement effects of the boundary-layer growth. For each case, the flow turning angle was chosen so that the MOC shock calculation matched the average shock angle observed in the primary stream below the mixing region.

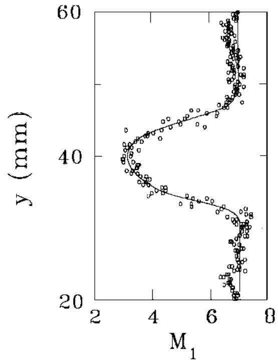
The analysis provides a reasonable estimate of the experimental shock trajectory (Fig. 3b). However, in the 10- and 15-deg-wedge cases, the displacement of the shock wave on the upper side of the mixing region was underpredicted by the MOC calculations. In the 5-deg case, there is good agreement between the theoretical predictions and the experimental results on the upper side of the mixing region; however, this agreement only arises because the theoretical prediction lies above the experimental results on the lower side of the mixing region. Therefore, it is concluded that, in general, the theoretical model underestimates the shock displacement associated with the mixing region interaction.

Static Pressure Distribution

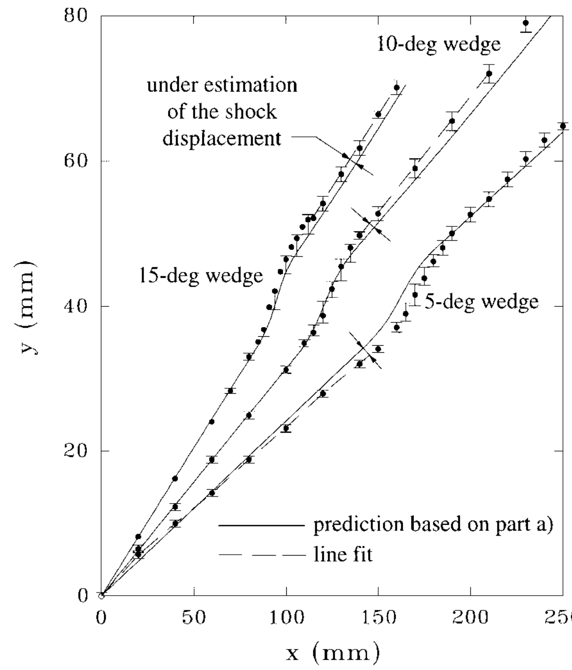
Static pressure measurements and MOC predictions for the 15-deg wedge case 1 experiments are given in Fig. 4. The dip in static pressure arises because, typically, expansion waves are reflected as an oblique shock enters regions of decreasing Mach number and compression waves are reflected as the oblique shock enters regions of increasing Mach number.[9] The shock wave generated by the coalescence of the reflected compression waves (feature viii in Fig. 1b) reaches the wedge upstream of the location indicated by the MOC prediction (Fig. 4) because it was treated as a disturbance traveling along the trajectory of the leading compression wave in the MOC calculations.

Shock Interaction Process

From the schlieren photographs, measurements were made of the total thickness of the mixing region, both with and without shock impingement (Fig. 5). The broken lines in Fig. 5 were obtained by multiplying the mixing results without shock impingement (the solid lines) by a shock compression factor derived from the theoretical inviscid interaction analysis.[13] Obtaining a consistent measurement of the total mixing region thickness from the schlieren images became difficult in some instances where wave effects coincided with the edge of the mixing region. Nevertheless, the differences between the theoretical predictions and experimental measurements appear significant.



a) Preshock Mach number distribution at $x = 130$ mm



b) Shock trajectory results

Fig. 3 Case 4 experiments.

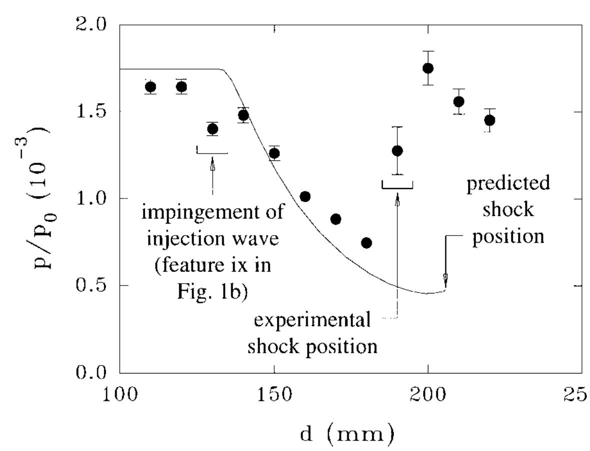


Fig. 4 Static pressure measurements on the 15-deg wedge for the case 1 conditions (symbols) and prediction from the MOC calculations (line).

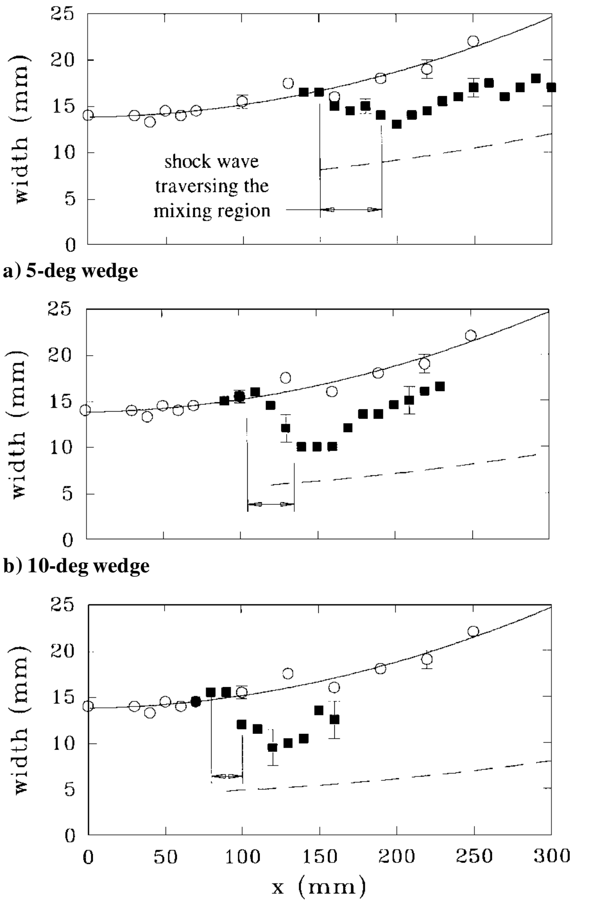


Fig. 5 Measurements and predictions of the mixing region widths from the case 4 schlieren images: ○, no shock impingement; □, shock impingement; ——, curve fit for no-shock-impingement experimental data; and – – –, theoretical prediction for postshock region based on inviscid compression model.

Conclusion

Schlieren measurements indicate that the interaction of the oblique shock waves and planar mixing regions in the present study is an unsteady, nonplanar event. No significant differences in the interaction processes were revealed by the schlieren visualization of the four mixing cases. Static pressure measurements on the shock-inducing wedge were predicted reasonably well with the steady, planar interaction analysis. The steady shock trajectory analysis was also in reasonable agreement with the schlieren measurements; however, there was a tendency to underpredict the shock displacement associated with the shock wave's traverse of the mixing region. The increased shock displacement relative to the theoretical predictions is consistent with the appearance of postshock mixing regions that are significantly wider than the inviscid predictions. These effects might be related to additional mass entrainment into the mixing region; however, additional quantitative measurements are needed to examine this possibility and clarify the role of unsteady and nonplanar effects.

Acknowledgments

The authors wish to thank the Defence Research Agency (DRA Farnborough) for providing the financial support of the gun tunnel facility. The first author gratefully acknowledges the financial assistance of the British Council through a Post Graduate Research Bursary. We also wish to thank T. M. Cain and N. A. Morris for their assistance during the experimental program.

References

[1]Menon, S., "Shock-Wave-Induced Mixing Enhancement in Scramjet Combustors," AIAA Paper 89-0104, Jan. 1989.

[2]Gilreath, H. E., and Sullins, G. A., "Investigation of the Mixing of Parallel Supersonic Streams," International Symposium on Air Breathing Engines, ISABE Paper 89-7060, Sept. 1989.

[3]Sullins, G. A., Gilreath, H. E., Mattes, L. A., King, P. S., and Schetz, J. A., "Instabilities in Confined Supersonic Mixing Layers," International Symposium on Air Breathing Engines, ISABE Paper 91-7096, Sept. 1991.

[4]Hyde, C. R., Smith, B. R., Schetz, J. A., and Walker, D. A., "Turbulence Measurements for Heated Gas Slot Injection in Supersonic Flow," *AIAA Journal*, Vol. 28, No. 9, 1990, pp. 1605–1614.

[5]Shau, Y. R., and Dolling, D. S., "Exploratory Study of Turbulent Structure of a Compressible Shear Layer Using Fluctuating Pitot Pressure Measurements," *Experiments in Fluids*, Vol. 12, 1992, pp. 293–306.

[6]Waitz, I. A., Marble, F. E., and Zukoski, E. E., "Investigation of a Contoured Wall Injector for Hypervelocity Mixing Augmentation," *AIAA Journal*, Vol. 31, No. 6, 1993, pp. 1014–1021.

[7]Yang, J., Kubota, T., and Zukoski, E. E., "Applications of Shock-Induced Mixing to Supersonic Combustion," *AIAA Journal*, Vol. 31, No. 5, 1993, pp. 854–862.

[8]Vasilev, V. I., Zakotenko, S. N., Kraskeninnikov, S. J., and Stepanov, V. A., "Numerical Investigation of Mixing Augmentation Behind Oblique Shock Waves," *AIAA Journal*, Vol. 32, No. 2, 1994, pp. 311–316.

[9]Buttsworth, D. R., "Interactions of Oblique Shock Waves and Planar Mixing Regions," *Journal of Fluid Mechanics*, Vol. 306, Jan. 1996, pp. 43–57.

[10]Cain, T. M., "An Experimental Study of Underexpanded Jets," D.Phil. Thesis, Dept. of Engineering Science, Univ. of Oxford, Oxford, England, UK, 1991.

[11]Buttsworth, D. R., Morgan, R. G., and Jones, T. V., "A Gun Tunnel Investigation of Hypersonic Free Shear Layers in a Planar Duct," *Journal of Fluid Mechanics*, Vol. 299, Sept. 1995, pp. 133–152.

[12]Buttsworth, D. R., and Jones, T. V., "A Fast-Response Total Temperature Probe for Unsteady Compressible Flows," American Society of Mechanical Engineers, ASME Paper 96-GT-350, June 1996.

[13]Buttsworth, D. R., "Shock Induced Mixing and Combustion in Scram-Jets," Ph.D. Thesis, Dept. of Mechanical Engineering, Univ. of Queensland, Queensland, Australia, 1994.

[14]Morris, N. A., "An Experimental and Computational Study of Moderately Under-expanded Rocket Exhaust Plumes in a Co-flowing Hypersonic Stream," D.Phil. Thesis, Dept. of Engineering Science, Univ. of Oxford, Oxford, England, UK, 1995.

P. R. Bandyopadhyay
Associate Editor

Monte Carlo Analysis of the Hysteresis Phenomenon in Steady Shock Wave Reflections

G. Ben-Dor,* T. Elperin,† and E. Golshtein‡
Ben-Gurion University of the Negev,
Beer-Sheva 84105, Israel

Introduction

THE shock wave reflection phenomenon was first studied by Ernst Mach. More than a hundred years ago, he recorded experimentally two different shock wave reflection configurations, a regular reflection (RR) and a Mach reflection (MR). Intensive research of the reflection phenomenon of shock waves was reinitiated in the early 1940s by von Neumann. Since then, it has been realized that the MR wave configuration can be further divided into more specific wave structures.[1]

The analytical models for describing the RR and the MR wave configurations were initiated by von Neumann. They are known as the two- and three-shock theories, respectively. Both theories make use of the conservation equations across the oblique shock waves together with appropriate boundary conditions.

Received Feb. 20, 1997; revision received Aug. 5, 1997; accepted for publication Aug. 14, 1997.

*Professor and Dean of Faculty of Engineering Sciences, Pearlstone Center for Aeronautical Engineering Studies, Department of Mechanical Engineering, P.O. Box 653.

†Professor, Pearlstone Center for Aeronautical Engineering Studies, Department of Mechanical Engineering, P.O. Box 653.

‡Ph.D. Student, Department of Mechanical Engineering, P.O. Box 653.