rent must dissociate the molecular propellant, and during that process the plasma remains at low temperature corresponding to its dissociative energy absorption. As a consequence, most of the discharge current flows downstream region when the molecular propellant is used.

Acknowledgment

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References

[1]Uematsu, K., Morimoto, S., and Kuriki, K., "MPD Thruster Performance with Various Propellants," *Journal of Spacecraft and Rockets*, Vol. 22, No. 4, 1985, pp. 412–416.

[2]Uematsu, K., Mori, K., Kuninaka, H., and Kuriki, K., "Effect of Electrode Configuration on MPD Arcjet Performance," JSASS/AIAA/DGLR 17th International Electric Propulsion Conference, IEPC84-11, Tokyo, Japan, 1984.

[3]Kagaya, Y., Yokoi, Y., Tahara, H., and Yoshikawa, T., "Thrust Performance and Current Distribution in a Quasisteady MPD Arcjet," JSASS/AIAA/DGLR 17th International Electric Propulsion Conference, IEPC84-31, Tokyo, Japan, 1984; see also Toki, K., Kuriki, K., and Sumida, M., "Multichannel Two-Dimensional MPD Arcjet," AIAA Paper 87-1000, May 1987.

[4]King, D. Q., "Magnetoplasmadynamic Channel Flow for Design of Coaxial MPD Thrusters," Ph.D. Thesis, Princeton Univ., Princeton, NJ, 1981.

[5]Subramaniam, V. V., and Lawless, J. L., "Onset in Magnetoplasmadynamic Thrusters with Finite-Rate Ionization," *Journal of Propulsion and Power*, Vol. 4, No. 6, 1988, pp. 526–532.

[6]Martinez-Sanchez, M., "The Structure of Self-Field Accelerated Plasma Flows," AIAA Paper 87-1065, May 1987.

[7]Toki, K., Kuriki, K., and Sumida, M., "Multichannel Two-Dimensional MPD Arcjet," AIAA Paper 87-1000, May 1987.

[8]Neynaber, R. H., Marino, L. L., Rothe, E. W., and Trujillo, S. M., "Scattering of Low-Energy Electrons by Atomic Hydrogen," *Physical Review*, Vol. 124, No. 1, 1961, pp. 135,136.

[9]Frost, L. S., and Phelps, A. V., "Rotational Excitation and Momentum Transfer Cross Sections for Electrons in H2 and N2 from Transports Coefficients," *Physical Review*, Vol. 127, No. 5, 1962, pp. 1621–1633.

[10]Lin, S. C., Resler, E. L., and Kantrowitz, A., "Electrical Conductivity of Highly Ionized Argon Produced by Shock Waves," *Journal of Applied Physics*, Vol. 26, No. 1, 1955, pp. 95–109.

Sensitivity of Shock/Shock Interactions to Upstream Variations

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Introduction

CURRENT plans for a transatmospheric vehicle, such as has been proposed for the National Aerospace Plane (NASP), depend on the design of weight-saving engine-integrated air-frames, in which the external vehicle surfaces act as the engine compression surface, and the aftbody would serve as the engine nozzle. It is generally assumed that the inlet will be designed so that its bow shock just contacts the cowl lip of the engine on design, although operating at this condition in steady state may not be possible.[1] One type of shock interaction that may occur when the bow shock contacts the shock formed on the engine cowl is known as the type IV shock interaction.

The type IV shock/shock interaction may result in localized regions of extremely high heating rates on the cowl of a hypersonic air-breathing engine. This work examines the effect that upstream variations have on the shock/shock interaction which results when a vehicle's inlet bow shock intersects with the engine's cowl bow shock. It is shown that slight perturbations in upstream conditions can have large effects on the type IV shock/shock interaction flowfield. The sensitivity of the flowfield to changes in various upstream parameters is presented, from which corresponding design rules for hypersonic inlets can be developed.

Previous analytical, experimental, and computational work has addressed the problem of shock/shock interactions.[2–9] The work presented here is an analytical study that considers how changes in freestream conditions, as described by the Mach number, and changes in the vehicle geometry, as described by changes in the vehicle bow shock deflection angle, influence the angle of the transmitted shock. This transmitted shock is a result of the vehicle's inlet bow shock intersecting the engine cowl bow shock, as shown in Fig. 1. This is of interest because, if the transmitted shock angle is strongly influenced by small changes in the upstream conditions, then it is likely that the entire interaction region will also be affected, along with the point of maximum heating on the cowl lip.

Results

In order to assess the significance of each upstream flow variable on the type IV interaction flowfield, a parametric study was done by solving the two-dimensional Rankine-Hugoniot relations. The effect of changes in freestream Mach number M_∞, incident shock angle β_i, and the cowl bow shock angle β_b, on the transmitted shock angle β_t were studied. The analytical approach has been to examine the sensitivity of the transmitted shock angle to changes in one parameter while holding the other two parameters constant.

Transmitted Bow Shock Angle Versus Mach Number

Varying Cowl Bow Shock Angles

For this study a constant inlet deflection angle of 10 deg was assumed. The results are shown in Fig. 2a. It is seen from

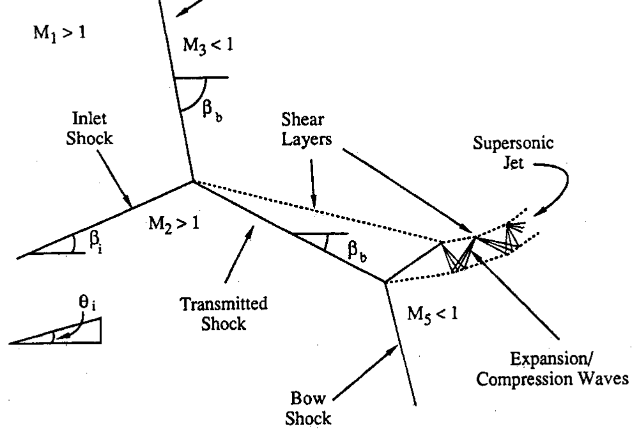

Fig. 1 Diagram of the type IV interaction.

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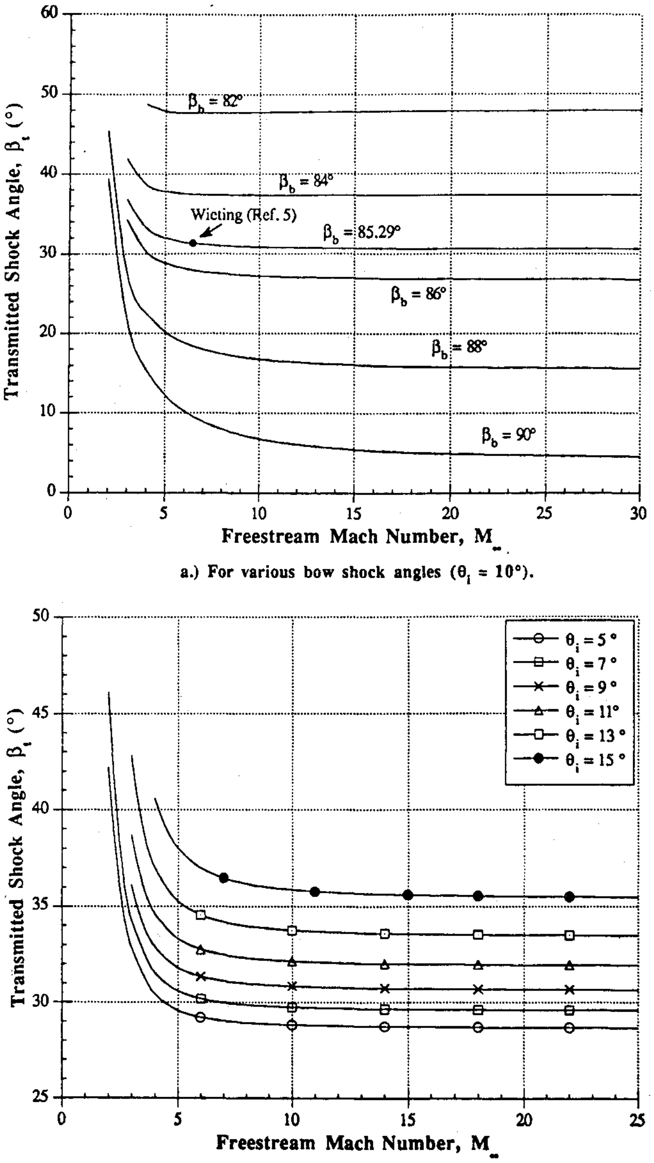
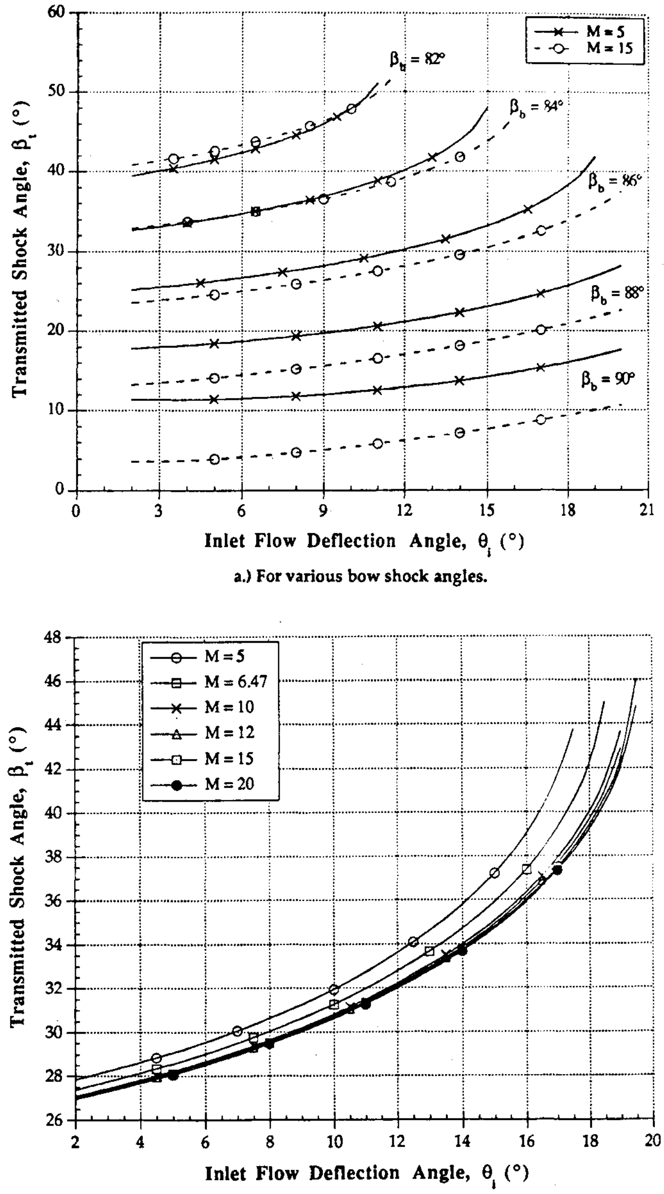


a.) For various bow shock angles (θ_i = 10°).

b.) For various inlet deflection angles (β_b = 85.29°).

Fig. 2 Effect of freestream Mach number on transmitted shock angle.



a.) For various bow shock angles.

b.) For various freestream Mach numbers (β_b = 85.29°).

Fig. 3 Effect of inlet deflection angle on transmitted shock angle.

Fig. 2a that at high M_∞, $M_\infty > 10$, changes in M_∞ have little effect on β_t, independent of β_b. However, note that for low M_∞, $2 < M_\infty < 10$, small variations in M_∞ can result in large variations in β_t.

Varying Inlet Deflection Angles

In this study it was assumed that cowl bow shock angle is held at a constant 85.29 deg which was extracted from the work of Wieting.[5] This corresponds to a "rubber" forebody which would allow the inlet shock to strike the cowl bow strike at the same location as upstream conditions are changed. Figure 2b shows the results from the parametric study. Notice from Fig. 2b that at the higher freestream Mach numbers, as M_∞ changes, β_t is by and large unaffected. However, at low supersonic Mach numbers, slight variations in M_∞ result in large variations in β_t. From Fig. 2b it is also seen that there exists a large range of M_∞ in which β_t will not change. In addition, notice that for a constant change in θ_i, β_t does not change proportionally.

By comparing Figs. 2a and 2b it is noticed that at large freestream Mach numbers, small changes in M_∞ will not affect the transmitted shock angle β_t. However, at low supersonic freestream Mach numbers, slight changes in M_∞ will strongly affect β_t.

Transmitted Shock Angle Versus Inlet Deflection Angle

Varying Bow Shock Angles

When a hypersonic vehicle is in flight, the inlet deflection angle θ_i may change, either by changes in angle of attack or by variable inlet geometry. The effect that a change in θ_i has on β_t for constraints set by β_b at two design Mach numbers (M_∞ = 5 and M_∞ = 15) were studied. These two cases are represented in Fig. 3a.

Notice in Fig. 3a that a change in θ_i is accompanied by a change in β_t. The exception to this is for very small θ_i and for large β_b. Second, the change in β_t is a minimum, for any specific β_b or M_∞, when θ_i is smallest. That is, as the inlet deflection angle, θ_i, changes for higher values of θ_i, the amount that β_t changes is correspondingly larger. As an example, consider the case of M_∞ = 5 and β_b = 86 deg. A change from θ_i = 3 deg to θ_i = 4 deg gives a change in β_t of 0.36 deg. However, a change from θ_i = 17 deg to θ_i = 18 deg gives a change in β_t of 2.16 deg. This should not be surprising, since the same trend is evident when one analyzes the relationship between Mach number, shock deflection angle, and shock wave from classical oblique shock wave theory.[10]

Comparing the two Mach number cases, observe that for the higher Mach number case the amount of deflection of angle β_t is less for a specific β_b than for the corresponding β_b in the lower Mach number case.

Varying Freestream Mach Numbers

It will most likely be the case that when a hypersonic vehicle changes its flight Mach number it will also be changing its angle of attack, thus changing θ_i. The effect that changes in θ_i have on β_t at fixed M_∞ is shown in Fig. 3b.

First note the familiar result that at high M_∞ the effect that a change in θ_i has on β_t becomes relatively independent of the flight Mach number. In addition, note the general trend that, at large θ_i, a slight change in θ_i has more of an effect on β_t than for smaller θ_i. It is also shown in this plot that, over all probable flight Mach numbers and all probable inlet deflection angles of a transatmospheric vehicle, the transmitted shock angle can vary by as much as 20 deg for ratio of specific heats, γ, equal to 1.4.

Conclusions

This work has shown that whenever the inlet bow shock strikes the cowl bow shock near its stagnation region the transmitted shock angle will be very sensitive to small upstream variations. It was also noticed that, as the freestream Mach number increased, the shock/shock interaction exhibits a Mach number independence, in that the variations in the transmitted shock angle become less dependent on Mach number variations as the Mach number increases. On the contrary, at small supersonic freestream Mach numbers, small changes in the freestream Mach number and small changes in inlet deflection angle result in large changes in the transmitted shock angle.

In order to minimize the motion of the transmitted shock angle over a large range of flight Mach numbers the inlet deflection angle should be as small as possible; at large inlet deflection angles, θ_i, small changes in θ_i have a strong effect on the transmitted shock angle.

There remains a question as to the source of the unsteadiness associated with the type IV supersonic jet. This unsteadiness may be attributed to freestream disturbances or from the dynamics associated with the jet itself. This work suggests that upstream disturbances may be amplified in the shock/shock interaction region, producing "apparent" unsteadiness, although it is probable that the jet unsteadiness is due to a coupling of these two effects.

References

[1]Lewis, M. J., Surline, Y., and Anderson, J. D., Jr., "An Analytical and Computational Study of Unsteady Shock Motion on Hypersonic Forebodies," AIAA Paper 90-0528, Jan. 1990.

[2]Lind, C. A., and Lewis, M. J., "The Effect of Shock/Shock Interactions on the Design of Hypersonic Inlets," AIAA Paper 90-2217, July 1990.

[3]Lind, C. A., "The Effect of Inlet Flow Variations on the Type IV Shock/Shock Interaction on a Hypersonic Inlet," M. S. Thesis, Univ. of Maryland, 1990, Rept. UM-AERO 90-36.

[4]Holden, M. S., Wieting, A. R., Moselle, J. R., and Glass, C., "Studies of Aerothermal Loads Generated in Regions of Shock/Shock Interaction in Hypersonic Flow," AIAA Paper 88-0477, Jan. 1988.

[5]Wieting, A. R., "Experimental Study of Shock Wave Interference Heating on a Cylindrical Leading Edge," Ph.D. Dissertation, Old Dominion Univ., 1987; also NASA TM-100484, May 1987.

[6]Nowak, R. J., Holden, M. S., and Wieting, M. S., "Shock/Shock Interference on a Transpiration Cooled Hemispherical Model," AIAA Paper 90-1634, June 1990.

[7]Edney, B., "Anomalous Heat Transfer and Pressure Distributions on Blunt Bodies at Hypersonic Speeds in the Presence of an Impinging Shock," FFA Rept. 115, Aeronautical Research Institute of Sweden, 1968.

[8]Klopfer, G. H., and Yee, H. C., "Viscous Hypersonic Shock-on-Shock Interaction on Blunt Cowl Lips," AIAA Paper 88-0233, Jan. 1988.

[9]Prabhu, R. K., Stewart, J. R., and Thareja, R. R., "Shock Interference Studies on a Circular Cylinder at Mach 16," AIAA Paper 88-0233, Jan. 1988.

[10]Anderson, J. D., Jr., *Modern Compressible Flow with Historical Perspective*, 2nd ed., McGraw-Hill, New York, 1990.

Influence of Metal Agglomeration and Heat Feedback on Composite Propellant Burning Rate

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Introduction

THE combustion behavior of metals, particularly aluminum, in solid propellants has been studied extensively.[1] Most studies have aimed at understanding the agglomeration and ignition mechanisms with the hope of being able to reduce the extent of agglomeration at the propellant surface and thereby improve combustion efficiency.[2] Another aspect of metal combustion in solid propellants that has not received as much attention is the influence of the metal behavior on the burning rate of the propellant. While some progress has been made in this area, the role of metal combustion on propellant burning rate is still not clearly defined.

Metal addition affects several propellant properties that can influence the burning rate. Metal staples and wires embedded in propellants have the effect of increasing the propellant thermal conductivity in the direction normal to the regressing surface, which increases burning rate. Metal addition can also change the propellant stoichiometry and, thus, burning rate, depending on what ingredients the metal replaces in the formulation. Another factor associated with metal addition that may alter the burning rate is oxidation of the metal. Either slow or fast oxidation of the metal agglomerates as they reside on or near the surface of the propellant will tend to increase the propellant burning rate by transferring heat to the propellant.[1,3] Another way metals can affect burning rate is through the inert heating (or heat sink) effect. Until they ignite and move out of range of the hot AP/binder flames near the propellant surface, metal agglomerates can act as a heat sink, siphoning off energy from the primary AP/binder flames that otherwise would have gone to increase the burning rate of the propellant.[3,4] Radiative feedback from burning metal droplets can also enhance the burning rate. Recently, Ishihara et al.[5] used fiber optics to measure radiative feedback and microthermocouples (5-μm wire) to measure conductive heat feedback in AP/HTPB/Al propellants. Their results showed that with 20% Al loading at 1 MPa, radiation accounted for 26% of the total heat feedback.

Procedure

In this study, propellants were formulated varying only the metal content and type of metal. The AP-binder mass ratio

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