AIAA 80-0280R

Mach 3 Hydrogen External/Base Burning

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Experimental studies of base pressure manipulation for an axisymmetric model at Mach 3 with cold gas injection and burning are described. Air, nitrogen, helium, and hydrogen are used for cold gas injection tests. Burning tests use hydrogen subsonically injected either radially upstream of the base plane or axially through a porous base plate. These modes of injection yielded base burning that is efficient for base drag reduction. Base burning is also combined with external compression, simulating external burning to show that the separate effects are additive.

Nomenclature

A_b	= model base area
I	= injection mass flow parameter, Fig. 8
I_{sp}	= specific impulse, Fig. 8
M	= Mach number
$\hat{M}$	= molecular weight
$\hat{M}_a$	= air molecular weight
$\dot{m}_{\text{bleed}}$	= injection mass flow
p_1	= freestream static pressure
p_b	= base pressure
p_{b0}	= undisturbed base pressure
V_1	= freestream velocity
ρ_1	= freestream density

Introduction

BURNING, either in the near wake (base) or in the freestream adjacent to the near wake (external), can provide significant base drag reduction for projectiles operating at airbreathing altitudes. The coupling of attractive performance values with hardware simplicity makes this a particularly interesting propulsion concept.

The feasibility of base burning to efficiently reduce base drag has been established.[1-5] Experience shows, however, that the maximum base pressure with this mode of operation approximately equals the freestream pressure and that efficiency decreases with increasing base pressure. Base pressures higher than the freestream pressure are possible using external burning[6,7] and combined external and base burning.[5] However, it is now thought that combined external and base burning offers the greater promise for achieving base thrust efficiently.

For several years the authors have been engaged in fundamental studies related to understanding and developing base and/or external burning. Theoretical results have been reported in Refs. 6 and 7. Experimental results of cold flow tests simulating flow phenomena with base and external burning for a Mach 3 axisymmetric body have been reported in Refs. 8 and 9. The purpose of this paper is to report on additional results from the continuing experimental program. Presented are the effects of base bleed, base burning, and combined base burning and simulated external burning on the base pressure. Performance is also expressed in terms of a specific impulse based on the increase in base force and the injectant flow rate.

Test Facility

The blowdown-type test facility was designed to simulate the base flow for a projectile at Mach 3 and a Reynolds number, based on the base diameter, in excess of 3×10^6. Test section details are shown in Fig. 1. The hollow cylindrical model is supported in the ducting upstream of the nozzle where $M = 0.07$. This virtually eliminates support effects. Gases, for base injection, and instrumentation leads are ducted into the model through the four support struts. The gases enter the model at ambient temperature. Base pressure is evaluated as the average of five pressures measured on the base plate. Tunnel flow is not heated and stagnation temperature drifts downward from about 10 to $-20°$C during a typical run. Several pressures are measured on the model and tunnel surfaces to ascertain that flow conditions are repeated from tests to tests. A computer based data acquisition system controls testing and data retrieval.

Results and Discussion

Cold Gas Base Injection

The model was fitted with a porous sintered-metal base plate for uniform base injection and tests were run injecting air, nitrogen, helium, and hydrogen, covering a wide range in molecular weights. These gases were injected axially into the near wake at ambient temperature, at subsonic speeds, and with negligible momentum flow rates. Figure 2 presents variations in base pressure elevation and specific impulse with mass flow rates for nitrogen, helium, and hydrogen injection. The mass flow rate of injected gas for a given base pressure rise varies almost directly with the gas molecular weight. With hydrogen, relatively high values of specific impulse are obtained with significant reductions in base drag.

Correlations of the base flow data are shown in Fig. 3. The scatter of the data in the present results is probably within the accuracy of the data. The relevant flow parameter is the mass flow parameter I times the molecular weight ratio to the 0.8 power. This molecular weight correction factor was first suggested by Bowman and Clayden[10] and, later, by Freeman and Korkegi[11] on the basis of base injection tests with axisymmetric projectiles. Their data, reformulated in the present form, are included in Fig. 3 for comparison. Lewis and Chapkis[12] correlated two-dimensional base flow data for nitrogen and helium using a volume flow parameter. This parameter, which corresponds to I times the molecular weight ratio, does not satisfactorily correlate the axisymmetric data.

The results of Freeman and Korkegi and the present results differ significantly even though the test Mach numbers are

Presented as Paper 80-0280 at the AIAA 18th Aerospace Sciences Meeting, Pasadena, Calif., Jan. 14-16, 1980; submitted Jan. 31, 1980; revision received Nov. 24, 1980.

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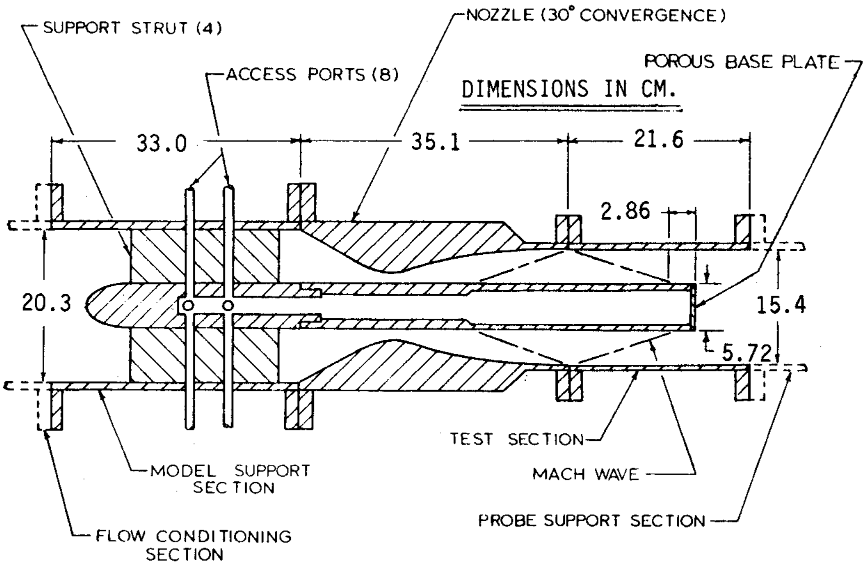

Fig. 1 Test section schematic.

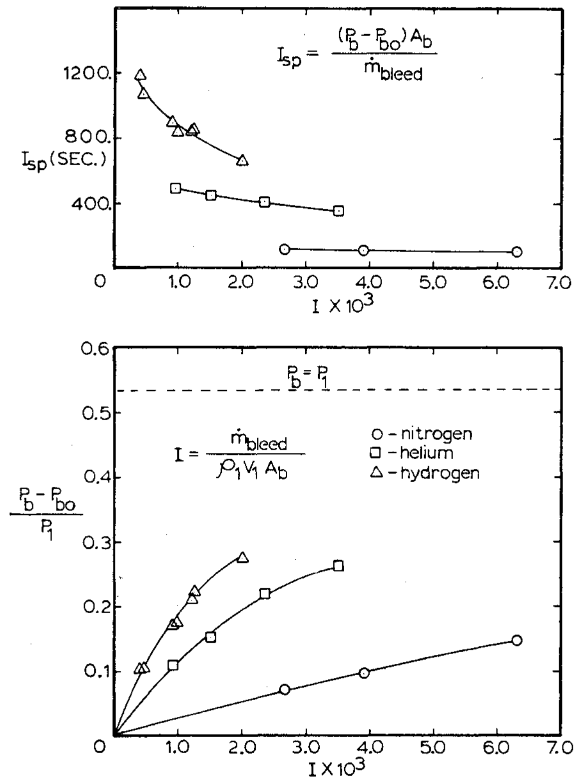

Fig. 2 Base pressure rise and specific impulse for cold gas injection.

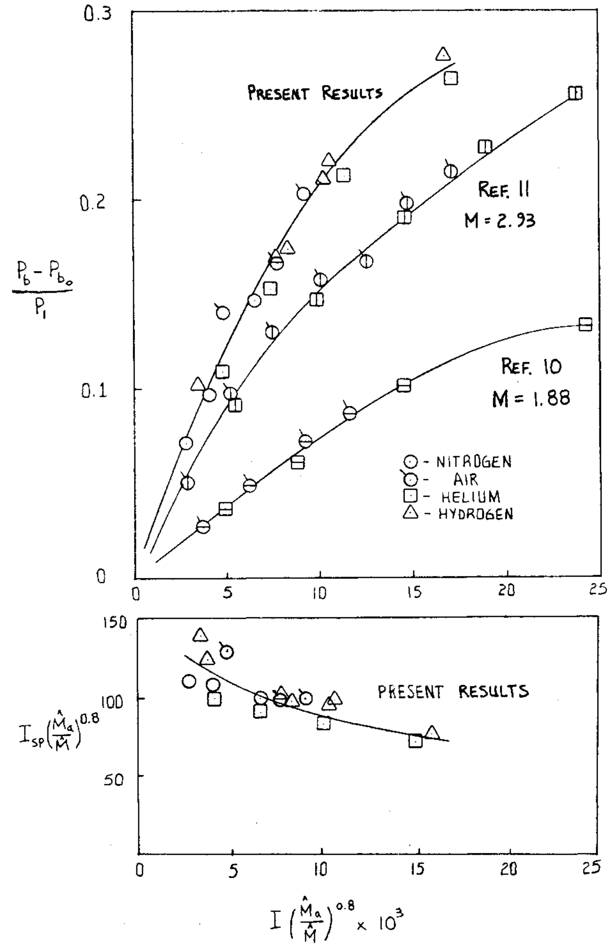

Fig. 3 Correlation of cold gas injection results.

nearly the same. This might be attributed to the differences in test configurations. They tested a strut supported projectile complete with rifling ring in a wind tunnel.

Base Burning

Gaseous hydrogen, ducted into the model at ambient temperatures, was used as the fuel for base burning tests. Attempts at base region ignition with a 6000 V ac spark source were unsuccessful due to the low temperatures and pressures. Ignition was accomplished using cured pyrotechnic compound paste fired by an embedded, electrically-heated, nichrome filament. The final igniter configuration, utilizing a consumable base mounted sting, is shown in the top panel of Fig. 4. After ignition, combustion was sustained by tabs of catalytic platinum gauze attached to the base. Ignition and burning were observed through the plexiglas tunnel ducting enclosing the base region of the test model. The luminosity of the pale blue hydrogen flame was enhanced by periodic injection of small amounts of salt water into the tunnel flow upstream of the base.

For base injection rates greater than $I \approx 4 \times 10^{-4}$ the visible combustion region extends four or five diameters downstream of the base plane while remaining attached to the base. For lower injection rates the luminous region diminishes in size and intensity and is closely confined to the base. Observation of igniter flare particle paths and pitot-static pressure

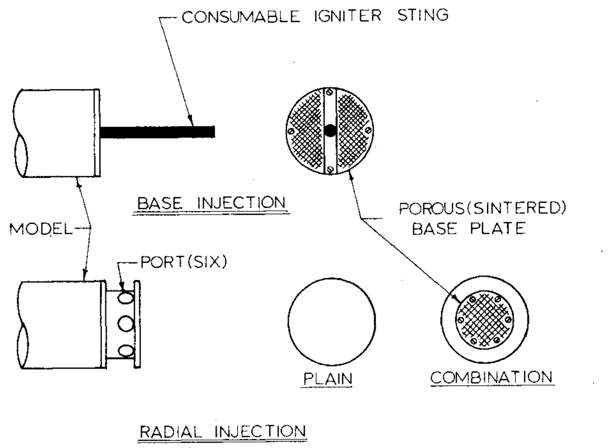

Fig. 4 Ignition and fuel injection configurations.

measurements with burning indicated that, even at high injection rates for which nearly all base drag is eliminated, a recirculation region persists in the wake. This recirculation mixes the fuel and oxidizer in the wake core. Temperature measurements in the wake with platinum-platinum 10% rhodium thermocouples showed that combustion exists throughout the visible conical region. These measurements show further that burning extends into the shear layer. Temperatures approaching the thermocouple useful limit of 1600°C were only encountered within two or three model radii of the base for even the highest injection rates attempted. This value is significantly below the stoichiometric flame temperature for hydrogen.

Four fuel injection configurations were tested. Three of these are shown in Fig. 4. The base injection configuration (top panel) uses a porous sintered-metal base plate for axial injection of a uniform stream of hydrogen. The radial injection configuration (lower left panel) uses six equally spaced radial ports recessed in an annular channel. The channel provided a recirculation cavity for ignition and flame retention. It was lined with the pyrotechnic for ignition. Platinum gauze was mounted in the channel for flame retention. The combination configuration (base plate shown at lower right) uses the radial injection configuration with the plain base plate replaced by a porous base plate to permit combined radial and axial injection. The fourth configuration (not shown) provides for radial slot injection. Spaces were inserted between the plane base plate and the cylindrical forebody to yield a 0.64 cm (¼ in.) wide peripheral slot immediately upstream of the base plane.

Burning results for subsonic base injection, radial slot injection, and radial jet injection are shown in Fig. 5. For comparison, the figure includes cold flow base injection results. Results are the same for radial slot injection and for base injection. Visual observations of the burning zone also revealed that both of these modes of injection yield pure base burning. The lower portion of the figure shows that base pressure rises with increased hydrogen injection and asymptotically approaches freestream pressure. The diminishing returns of increased injection, however, are reflected by the rapid decline of specific impulse values shown in the upper portion of the figure. Nevertheless, a significant reduction in base drag at impressive values of I_{sp} have been demonstrated. For example, these tests show an 80% reduction in base drag with $I_{sp} = 5000$ s and a 50% reduction with $I_{sp} = 12,000$ s. For comparison, the I_{sp} of a Mach 3 ramjet operating in the same freestream environment with an equivalence ratio of about 0.5 would be in the range from approximately 5000 to 6000 s, depending upon the design sophistication.

Results of base burning tests with hydrogen at lower freestream Mach numbers have been reported by Townend and Reid[2] and Baker et al.[1] Townend and Reid tested a strut supported projectile at Mach 2.14 in a wind tunnel. They used

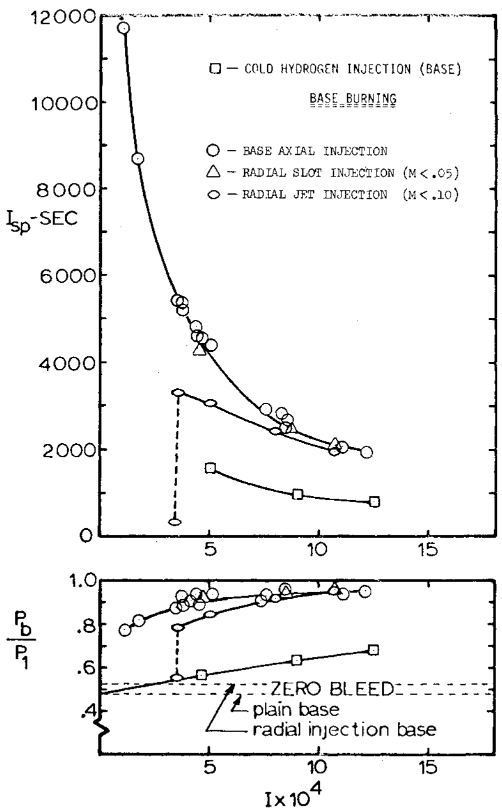

Fig. 5 Base burning performance.

radial slot injection and report base pressures higher than the freestream pressure. I_{sp} values computed from their results are approximately 4400 and 2700 s with 85 and 100% base drag reduction, respectively. These values are comparable with the present results. Baker et al. tested a strut supported projectile at Mach 1.6 in a free jet. They used base injection through multiple nozzles. I_{sp} values computed from their results are approximately 4100 and 1300 s with 50 and 75% base drag reduction, respectively. These indicate that performance decreases significantly nearer $M = 1$. This trend is also indicated by the cold flow results of Fig. 3.

As shown in Fig. 5, performance with subsonic radial injection through discrete nozzles is somewhat lower than that with base or radial slot injection. Observations of the flame indicated that this mode of operation more resembled base burning with direct base injection than external burning with discrete plume combustion in the freestream. Furthermore, analysis showed that jet penetration into the freestream must be small. Perhaps the reduced performance is due to some combustion occurring farther out in the wake shear flow (i.e., some external burning effect). However, it is felt that this is probably due to flow asymmetries created by the discrete jets. Previous cold flow tests[8] have demonstrated adverse effects of such asymmetries.

Combustion tests were attempted using supersonic injection to effect external burning. Both the radial injection configuration and the combined radial and base injection configuration (Fig. 4) were used. With these conditions, it was not possible to obtain ignition and/or sustained combustion except when the hydrogen flow rate was so high that combustion extended downstream into the tunnel ducting causing pressure increases that clearly influenced the base pressure.

Combined Base Burning and External Compression

Base burning using base injection was combined with external compression, designed to simulate external burning, to determine if these two effects are additive. Compression sections I, II, and IV, described in Ref. 8, were used for these tests. Compression sections I and II impose axisymmetric

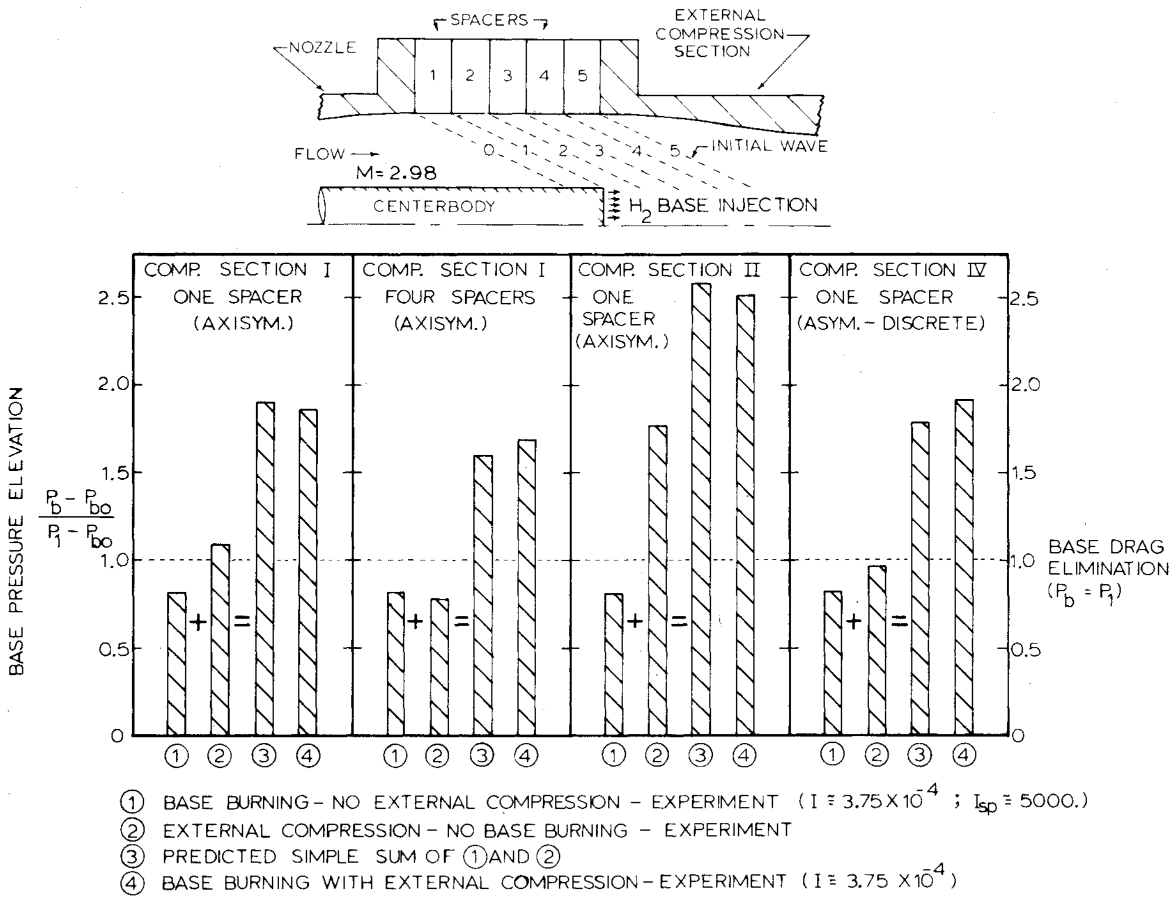

Fig. 6 Combined base burning and simulated external burning.

compression on the near wake which, in the absence of base injection, eliminate base drag and produce base thrust, respectively. Compression section IV imposes an asymmetric compression that simulates compression due to six combustion plumes in the freestream. Compression sections II and IV are designed with the same cross-sectional area distribution, simulating the same volume displacement in external burning.

The first two panels (left to right) in Fig. 6 show that the combined effect of simultaneous base and simulated external burning with compression section I is nearly the sum of the individual contributions. The third panel reinforces this finding for the alternate test section. In all three cases the base pressure was boosted above freestream static pressure yielding a condition of base thrust. Panel three, in fact, shows an instance in which the base thrust is sufficiently high to eliminate all drag on a well designed vehicle.

The last panel in Fig. 6 shows the results using simulated discrete external burning. Once again, the measured base pressure with base burning and compression is very close to the simple sum of the individual experimental values. Comparison of panels three and four confirm earlier findings that the application of external burning in discrete plumes diminishes the base pressure boost obtained with axisymmetric burning; however, a condition of base thrust is still demonstrated for this case.

Schadow and Chieze[13] determined from two-dimensional, planar Mach 2 wind tunnel tests that the two base pressure rise mechanisms associated with external burning of a solid propellant and base injection of an inert gas can be superimposed. More recently,[4] however, they found from Mach 2 tests of an axisymmetric model burning a solid propellant that the base pressure with combined external and base burning was less than that with base burning alone. They speculate that this is probably due to external burning limiting the oxygen entrainment into the base region.

Conclusions

1) The relevant flow parameter for correlating base pressure data for supersonic axisymmetric bodies with cold gas base injection is the injection mass flow parameter times the freestream to gas molecular weight ratio to the 0.8 power.

2) Base burning with subsonic radial slot or axial injection of hydrogen can reduce significantly the base drag at efficiencies comparable with or better than that of a ramjet. Near elimination of base drag appears to be an upper limit and can only be achieved with heavy penalties in I_{sp}.

3) Subsonic radial injection of hydrogen through discrete nozzles resulted in base burning with a lower efficiency than that for axial base injection.

4) The combined effect of base burning and external compression simulation external burning is very nearly the sum of the individual contributions. Additional tests are needed to determine the efficiency of producing base thrust with combined base and external burning.

Acknowledgments

This research was supported entirely by the Air Force Office of Scientific Research, Contract F49620-78-C-0003. The authors express their gratitude for the continuing sponsorship of this work.

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