step. Convergence is also dependent on such numerical techniques as smoothing the pressure in the axial direction using a relation of the form

$$P_{\text{new}_{i,j}} = P_{i,j} + \alpha(P_{i-1,j} + P_{i+1,j})$$

where $P_{i,j}$ represents the pressure at the ith axial node and jth pitch node. This is carried out for each node after each time step. The smoothing factor α depends on the particular grid and on the conditions. The selection of an "optimum" value is a trial-and-error process which can be quite costly. A good value was found to be about 0.1 for the present case.

Figure 4 shows the effect of smoothing on the number of iterations required to reach the final stationary solution. The reference property is taken as the nondimensional axial velocity component at the trailing edge on the suction side. Comparison shows that smoothing of the pressure reduced the calculation time by 1/8, taking into account the extra work required to smooth the pressure.

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External/Base Burning for Base Drag Reduction at Mach 3

J.E. Hubbartt* and W.C. Strahle†
Georgia Institute of Technology, Atlanta, Ga.

Introduction

EXPERIMENTS have shown that base burning can result in significant base drag reduction at supersonic speeds with good fuel efficiency.[1-6] Since efficiency decreases with increasing base pressure, the application of pure base burning seems to be limited to base drag reduction (i.e., to base pressures near or below the freestream pressure). It is known that net base thrust is possible using external burning.[7,8] However, since base burning expands the wake gases and drastically reduces the wake momentum flux, external burning in combination with base burning offers the best promise for achieving base thrust. In fact, there is some experimental evidence that combined external and base burning may be more efficient for base drag reduction than base burning alone.[5] On the other hand, it has been shown recently, using a simplified analysis for the case of net base thrust, that combined external and base burning is not attractive from a fuel usage point of view.[9] Additional experiments are needed in order to evaluate the potential of combined external and base burning.

For several years the authors have been engaged in studies related to understanding and developing base and/or external burning.[6-8,10,11] The purpose of the Note is to disclose recent results of tests with combined base and external burning using pure hydrogen as the fuel.

Test Facility

The blowdown-type test facility simulates the base flow for an axisymmetric projectile at Mach 3. A schematic of the test section is shown in Fig. 1. The hollow cylindrical model is supported in the ducting upstream of the nozzle throat, virtually eliminating support effects. Hydrogen and instrumentation leads are ducted into the model through the four support struts. The hydrogen is at ambient temperature. The stagnation temperature of the tunnel air flow drifts downward from about 10 to −20°C during a typical run. The stagnation pressure of the tunnel flow is maintained at about 7000-mm Hg by a pressure regulator.

Three base configurations were used for the tests reported herein. These are shown in Fig. 2. The top panel shows the base injection configuration used for pure base burning. This configuration is shown installed in the schematic of Fig. 1. It used a porous sintered-metal base plate for axial injection of a uniform stream of hydrogen. The other two panels show the configurations used for combined base and radial injection. One configuration uses a channel and the other, a step, as flameholders around the six equally spaced jet nozzles. The nozzles are constant diameter orifices drilled radially inward into the hollow centerbody. Both of these configurations are also fitted with sintered-metal base plates for simultaneous axial injection into the near wake.

The combustible mixture in the near wake was ignited by a consumable pyrotechnic igniter attached to the base. Combustion in the channel flame holder was initiated separately by a coating of pyrotechnic compound in the channel.

Results and Discussion

The test results are presented in Fig. 3, where the fuel specific impulse is plotted against the increase in base force due to burning (i.e., the change in base force due to injection

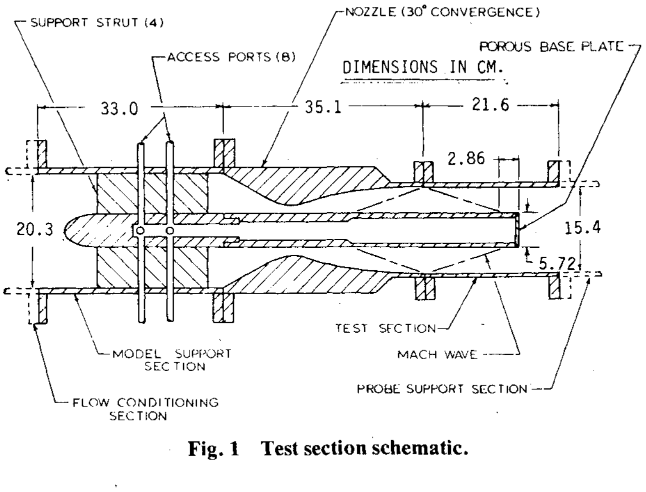

Fig. 1 Test section schematic.

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*Professor of Aerospace Engineering, School of Aerospace Engineering. Member AIAA.

†Regent's Professor, School of Aerospace Engineering. Associate Fellow AIAA.

and burning). This base force due to burning is expressed in percent of the base drag without injection and burning. Thus, at the 100% level, all base drag is eliminated by burning. The specific impulse is the ratio of the base force due to burning to the fuel mass flow rate.

Figure 3a shows results for the pure base burning mode using base injection only. Since the results are highly repeatable, only a portion of them has been included in this figure. The specific impulse is nearly 12,000 s for a 50% reduction in base drag. It is important to emphasize that this is about twice that obtainable with a sophisticated ramjet at the same operating conditions. The specific impulse decreases to 3000 s at a 90% reduction in base drag.

Results for combined base and radial injection, both with the channel and step flame holders, are shown in Fig. 3b. The line representing the base injection data of Fig. 3a is included for reference. The results of Fig. 3b are for two jet orifice diameters (1.0 and 1.9 mm) and ratios of jet-to-base mass flow rates from about 0.3 to over 4.0. The corresponding ranges in jet Mach number and jet-to-freestream velocity ratio, based on reversible jet expansion to the freestream static pressure, are from 1.0 to 3.1 and 2.0 to 4.2, respectively. No attempt is made to associate the data points with the specific jet orifice diameter, mass flow ratio, and/or jet Mach number, since the results are characterized more by scatter than specific trends. It should be noted that only three of the data points are for a base thrust condition (i.e., base force due to burning exceeds the base drag without burning).

The results for combined base and radial jet injection, in contrast with those for base injection only, scatter significantly. In general, the specific impulse, with a given base drag reduction, is lower than that for base injection. Nevertheless, specific impulse values slightly higher than those for base injection only were obtained. These high values cannot be attributed to wind tunnel interference since the base pressure is less than the freestream pressure and the wave emanating from the base is an expansion wave, which undoubtedly decreases the base pressure upon reflection and intersection with the wake. Hence, the results here are believed conservative at low base pressure levels. It is thought that the large data scatter with radial injection is due to differences in the combustion which was marginal for the low pressure and low temperature environment. In fact, ignition was extremely erratic and many tests were aborted because it was apparent that ignition was not accomplished either in the base, in the flameholder around the jets, or in both. It was not always possible to determine if ignition was fully successful or if all jets were burning. However, the high performance points of Fig. 3b were visually identified with good combustion in the jet flameholders and are believed to be due to good combustion. Therefore it is concluded from these results that combined base and external burning of the fuel can be competitive and perhaps slightly better than base burning alone for base drag reduction. This concurs with the two-dimensional wind tunnel test results of Ref. 5 and suggests that external burning coupled with base burning may also be practical for providing base thrust.

It has been determined that the three data points of Fig. 3b which provided base thrust have been influenced by wind tunnel wall effects. Pitot and static pressure surveys along the wake centerline showed that the wake was still subsonic at the point where the reflected compression wave created by the elevated base pressure intersected the wake. Thus, a portion of the base pressure increase with burning must be due to this reflected compression and the measured results are probably optimistic. The base pressure rise reported in Ref. 5 with combined base and external burning is much lower than that obtained in the present facility. It is probable that their results were also influenced by tunnel effects. However, they used an open tunnel, in which case, the compression wave created at the base reflects from the free boundary as an expansion wave which then interacts with the subsonic wake to reduce the base

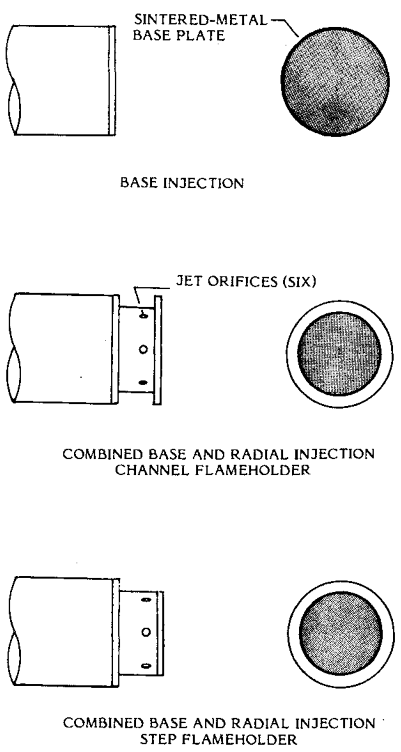

Fig. 2 Base configurations.

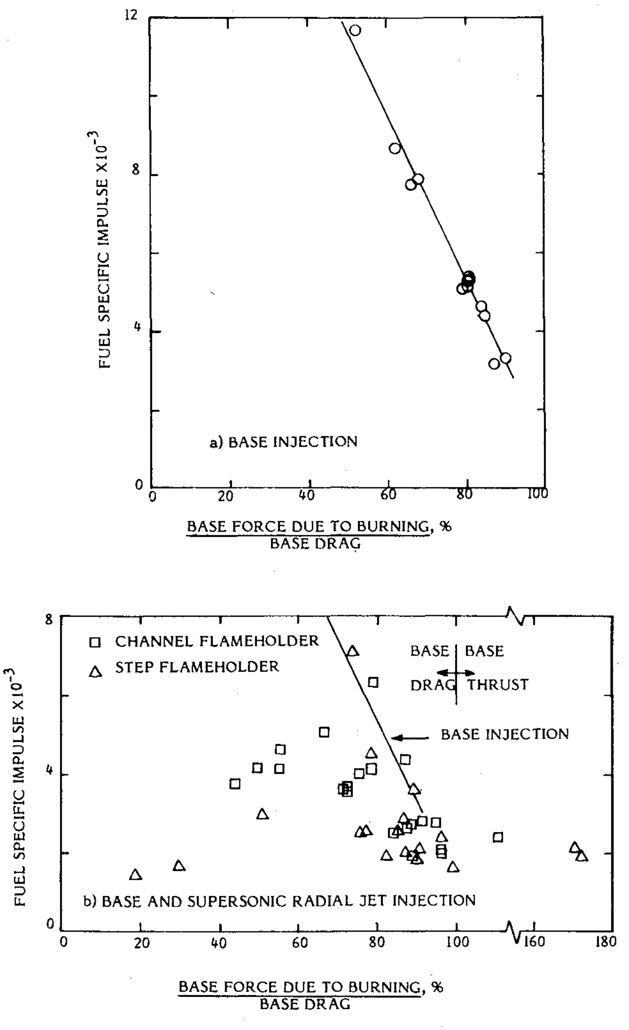

Fig. 3 Performance results.

pressure and, thus, the fuel efficiency. It can only be concluded that these small scale facilities cannot be used to accurately evaluate the potential of combined base and external burning for producing base thrust. This mode of operation is sufficiently promising to justify either free flight tests or burning tests in a large scale wind tunnel with a more favorable environment for combustion.

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