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Base Burning Performance at Mach 3

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Experimental results are reported concerning base drag reduction of a Mach 3 axisymmetric body using base burning and combined preburning and base burning. Hydrogen is used as the fuel. For base burning alone, hydrogen is diluted with N_2, He, and CO_2 to simulate practical values of the injectant total heating value. For combined preburning and base burning hydrogen diluted with N_2 and CO_2 is preburned with O_2 before the fuel-rich products are injected into the wake. It is shown that the diluents do not change the performance and that combined preburning and wake burning is far superior to base burning alone. Furthermore, high values of specific impulse are achievable with most of the base drag eliminated.

Nomenclature

A_b = model base area
I_{H2} = hydrogen injection parameter, $\dot{m}_{H_2}/\rho_1 V_1 A_b$
I_{SP} = specific impulse, $(P_b - P_{b0})A_b/\dot{m}_I$
I_{SPH2} = hydrogen specific impulse, $(P_b - P_{b0})A_b/\dot{m}_{H_2}$
$\dot{m}_{H2}$ = hydrogen mass flow rate
$\dot{m}_I$ = total injection mass flow rate
M = Mach number
P_1 = freestream static pressure
P_b = base pressure
P_{b0} = undisturbed base pressure
Q_R = effective fuel heating value, $Q_{RH_2}\dot{m}_{H_2}/\dot{m}_I$
Q_{RH2} = hydrogen heating value, 1.21×10^5 J/g
T_0 = stagnation temperature
V_1 = freestream velocity
Y_i = mass fraction of species i
ρ_1 = freestream density

Introduction

THERE are many conceivable missions for bodies in supersonic flight where drag reduction would be beneficial. One component of drag, base drag, is usually a significant fraction of the overall drag, especially for bluff-base bodies. The base flow is especially amenable to modification by base burning, and base drag may be substantially eliminated by such means.[1-5] This may be done with extremely high values of fuel specific impulse by using atmospheric air in the burning process.

Substantial work at this laboratory has been carried out using pure H_2 as a fuel in both base burning and exernal burning modes of operation. In reality, H_2 is not generally a viable candidate as a fuel from the systems viewpoint. Also, in many cases it would be desirable to generate the "fuel" in a gas generator prior to atmospheric injection. In such a case hot, fuel-rich gases would be the injectant. This paper is concerned with base burning operations with more realistic "fuels."

Here the H_2 is mixed with the diluents CO_2, He, and N_2 prior to injection to investigate the effects of molecular weight and effective fuel heating value. Then the diluent is augmented with O_2 and part of the H_2 is preburned with the O_2 prior to injection. This is the case of fuel-rich hot gases with various diluents. Again, the effects of molecular weight and fuel heating value are investigated. The goals are an understanding of the processes involved in the base flow phenomena and generation of performance data in such a system.

Test Facility

The blowdown-type test facility was designed to simulate the base flow for a bluff-base, axisymmetric projectile at Mach 3 with a fineness ratio of about 6.[1,6] The stagnation pressure in the test section was held constant at about 9.3×10^5 Pa by a pressure regulator. The tunnel flow was not heated and the stagnation temperature drifted downward from about 280 to 250 K during a typical 5 min run. The Reynolds number based on the model diameter was about 4.5×10^6.

Test section details are shown in Fig. 1. The hollow cylindrical model extends through the wind-tunnel nozzle and is supported by four streamline struts in the ducting upstream of the nozzle where the Mach number is 0.07. This virtually eliminated support effects since the dynamic head at the struts was only 0.35% of the difference between stagnation and static pressures in the test section. Gases for base injection and instrumentation leads were ducted into the model through the support struts. Base pressure was evaluated as the average of four or five pressures measured on the base plate. Also, pressures were measured on the model forebody and tunnel surfaces to ascertain that the flow conditions were repeatable. For some tests, traversing probes were inserted into the wake to measure pressures and temperatures. The probes were supported downstream of the base by a two degree-of-freedom actuator. Tests showed that the probes had no effect on base pressure. A computer-based data acquisition system

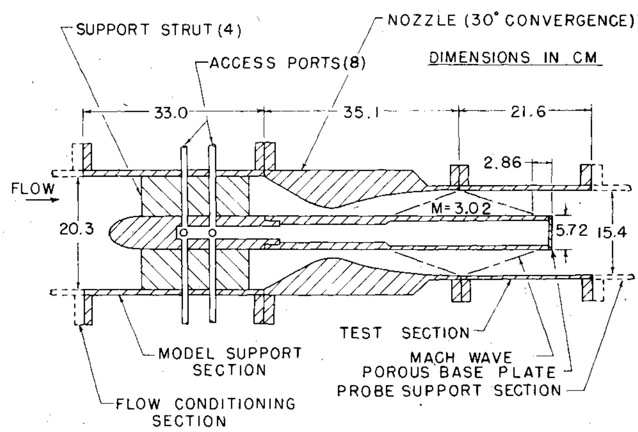

Fig. 1 Base burning test section schematic.

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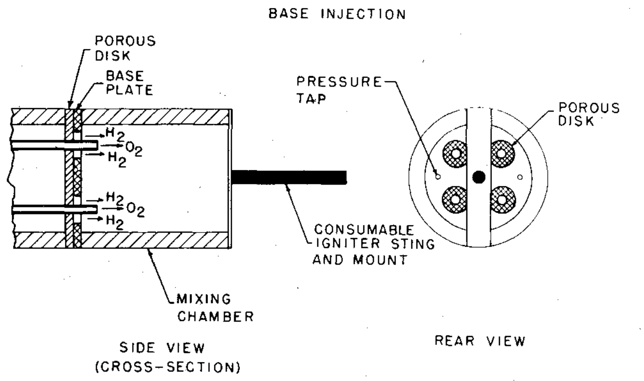

Fig. 2 Base configuration for preburning and wake burning.

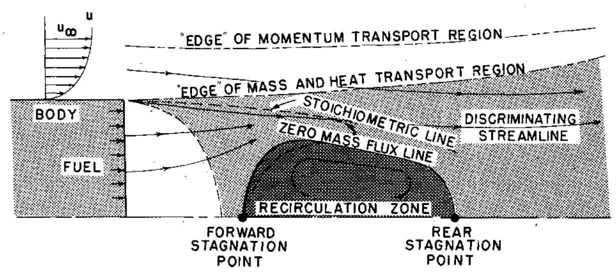

Fig. 3 Flow model for base burning.

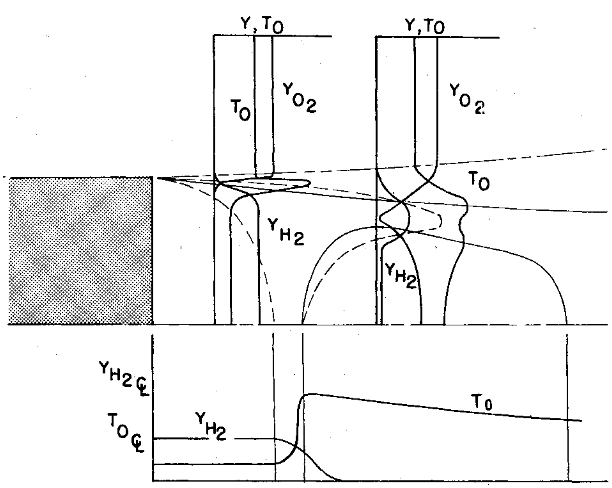

Fig. 4 Illustrative temperature and species profiles for base burning.

controlled the testing and retrieved the data. All pressure data were normalized by the tunnel stagnation pressure which was measured almost simultaneously to minimize drift effects.

Two base configurations were used for these investigations. The plane base configuration shown in Fig. 1 has a 0.32 cm thick sintered metal base plate. This was used for the base burning tests in which hydrogen diluted with inert gases was injected into the wake. The hydrogen and diluent flow rates were measured by a sharp-edged orifice and a rotameter, respectively, and then thoroughly mixed before being introduced into the model. The second base configuration is shown in Fig. 2. This was used for the combined preburning and wake burning tests. As shown, pure oxygen is supplied to the front of the preburner via four tubes passing through the centerbody and the porous base plate. Hydrogen premixed with inert gases is supplied through the hollow centerbody and the porous base plate. This mixture is constrained by the solid base plate to annular jets surrounding the oxygen jets. The large pressure drop across the porous disk distributes the diluted hydrogen equally to the four annuli. The oxygen flow rate is measured by a rotameter and distributed equally to the four jets by identical oxygen supply tubes.

Ignition is accomplished by a consumable igniter sting attached to the downstream end of the base.[1] Figure 2 shows the igniter attached to the preburning base configuration. The igniter support strap is constructed of aluminum which melts soon after combustion begins.

Results

Description of the Flowfield

Although conceptually simple in principle, base burning operates upon an exceedingly complex flowfield. Consequently, the reasoning process involved in determining the causes of performance changes with changes in operating variables is a bit tortuous. As an aid in understanding the flowfield phenomena, Figs. 3 and 4 are shown. These figures present the flowfield description as currently understood. The structure is consistent with what had been learned from 1) extensive pitot and static pressure probing in cold flow [6]; 2) limited pressure and temperature probing in hot flow, with and without diluents[7]; 3) cold-flow analysis with gas injection[8]; 4) hot-flow analysis[9]; and 5) visual observation.

The recirculation zone shown in Fig. 3 was always present at the low injection rates used in these experiments. It is, of course, possible to "blow off" this zone with a sufficiently high injection rate.[10] Here, the recirculation zone plays an important role in momentum, heat, and mass transport and it also provides a convenient view of what determines the base pressure achieved. That is, viewing the rear stagnation point, it is true by definition that the flow must stagnate here so that the streamline approaching the point develops a sufficiently high stagnation pressure to, in fact, stagnate. This pressure is produced by the static pressure plus the dynamic head, which is influenced by static pressure and Mach number. If the Mach number is reduced on the streamline, a lower stagnation pressure is produced so that the static pressure is increased (base pressure goes up). The Mach number in these combusting flows is primarily influenced by the speed of sound; a temperature increase on the stagnation streamline will yield a base pressure increase.

This view of the cause of base pressure changes is not inconsistent with the, perhaps, more common view of a viscous subsonic-supersonic throat which occurs further downstream.[8,9] With heat addition the core of the wake becomes hotter and the Mach number goes down. It takes a longer distance downstream for the shear forces to raise the centerline gases to Mach 1. That is, the viscous throat moves downstream. The focusing of the wake is reduced and the streamlines come off of the body trailing edge with less inward turning. Hence, the base pressure rises. The authors prefer looking at the stagnating streamline, however, since it is in this region of the flow that most of the combustion process is taking place and where the flowfield details are more readily apparent. Also, the reversed flow ahead of the stagnation point supplies oxygen to the combustion zone.

Shown in Fig. 4 is a typical set of hypothesized oxygen, hydrogen, and stagnation temperature profiles. The profiles presume that there is some diluent in the H_2 but no oxidizer in the diluent and, consequently, no precombustion. The variables studied are the diluent type and precombustion vs cold injection. In the case of no combustion at all (the cold mass addition case), prior studies had shown a strong effect of injectant molecular weight on base pressure.[1] As an example, low molecular weight reduces the density and, consequently, the dynamic head on the stagnating streamline. As a result, the lower the injectant molecular weight is, the higher the base pressure. In the burning case, however, the heating effect far outweighs any mass addition effect and the injectant mass flows used are substantially below those used when pure mass addition was studied. Consequently, the mass addition effect is weak.

Consider, then, what might be expected if the H_2 rate is fixed and one introduces diluent flow in the reacting case. At the stoichiometric line, since the stoichiometry demands a high O_2/H_2 mass ratio, the temperature will be reduced over that with pure H_2. However, the temperature drop is not much because the primary diluent is the N_2 in the air, not that carried with the H_2. This mild temperature drop would tend to drop the base pressure. On the other hand, the stoichiometric line will move inward so the temperature maximum will be closer to the stagnating streamline and its temperature will rise. This increases the base pressure. Counter to this effect is the fact that the shear layer, being denser, will have higher mixing rates. This effect increases the velocity and dynamic head on the stagnating streamline, tending to drop the base pressure. This last effect should be more pronounced as the diluent molecular weight is increased. On the other hand, the molecular weight effect in the pure mass addition case goes counter to this. The result of these four competing processes is that there will probably be little change in the base pressure under the cited conditions. This is confirmed experimentally later in this paper.

Next, consider what might happen if O_2 is preburned with H_2 before injection. Consider the case with H_2 being in excess so that there is additional combustion with the air. Now the injectant comes out hot and the recirculation zone and stagnating streamline will be hotter than if they had to rely on diffusion from the stoichiometric line. At a fixed H_2 rate with an increasing O_2 rate, the base pressure should rise. Generally, the mixing rates should drop because of a hotter shear layer, which should augment the base pressure rise. Therefore, a reactive "diluent" should increase performance. This is generally in accord with the findings described below.

Summarizing, any diluent reduces the effective heating value of the fuel (H_2 + diluent being the overall fuel). At a fixed H_2 flow rate, increasing the inert diluent should have little effect on base pressure. Of course, the I_{SP} performance will suffer because the total mass flow rate is increasing. On the other hand, if the inert diluent is replaced by a reactive diluent, the base pressure should rise; while the overall I_{SP} would fall, it would not fall as fast as with an inert diluent.

Base Burning Results

Figures 5-7 present the performance results for pure base burning. Figure 5 shows the effect of the hydrogen injection rate on the base drag reduction and the specific impulse based on the hydrogen flow rate only. Included are results for injection of pure hydrogen and hydrogen diluted with N_2, He, and CO_2 so as to yield effective fuel heating values in the practical range of 20,000-25,000 J/g. The results for pure hydrogen injection are from Ref. 1 and, as noted there, compare well with those reported by Townsend and Reid[3] for radial slot injection but are somewhat higher than those reported by Baker et al.[4] for base injection through multiple nozzles. The results of Fig. 5 show that the addition of the diluent and the molecular weight of the diluent have no significant effect. Thus, the performance is determined by the heat release of the hydrogen combustion, as argued in the previous section.

A more useful presentation of the data is a plot of specific impulse scaled by the fuel heating value vs the base drag reduction, as shown in Fig. 6 for the case of pure-hydrogen injection. Here, a reference fuel heating value of 20,000 J/g has been used to normalize the heating value of pure hydrogen. In this case, the scaling of I_{SP} is not significant since there is no diluent. These results are presented simply to establish a reference case with pure-hydrogen injection, to illustrate the scatter in the data for this reference case, and to show that the data are well represented by a straight line. A similar presentation for all of the data with diluted hydrogen is in Fig. 7. Here, the specific impulse and the fuel heating value are based on the total injection mass flow rate. The data cover effective fuel heating values from 10,000 to 60,000 J/g.

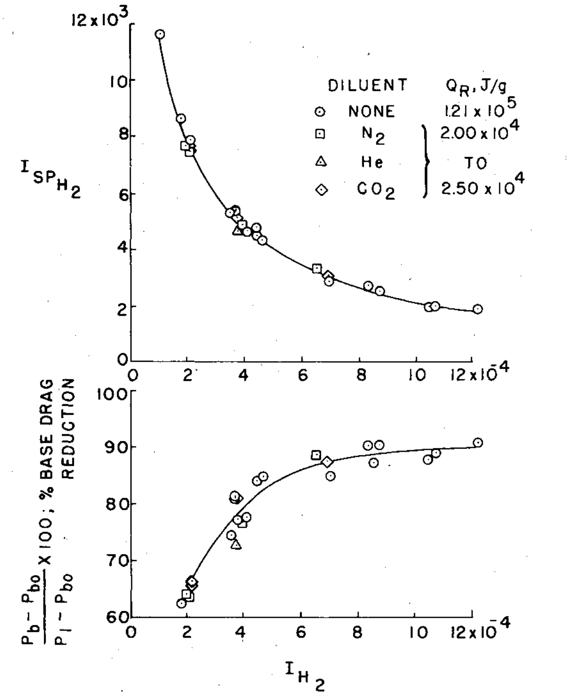

Fig. 5 Base burning performance results with and without diluted H_2.

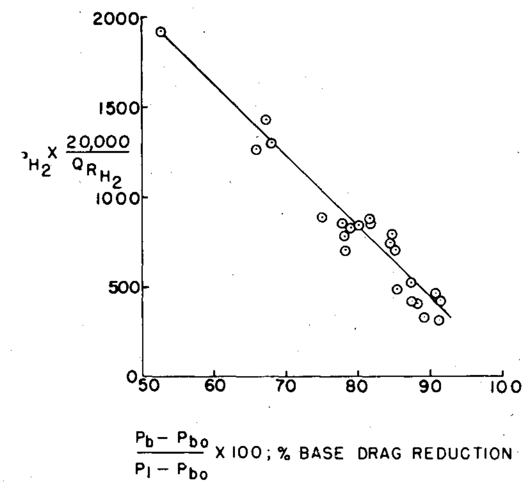

Fig. 6 Base burning performance results with pure H_2.

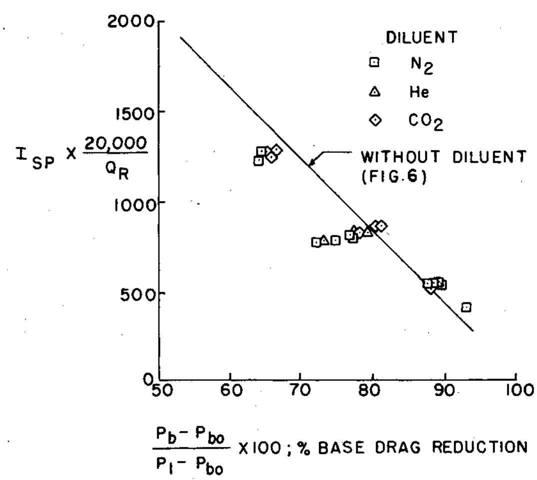

Fig. 7 Base burning results with diluted H_2 $10{,}000 \leq Q_R \leq 60{,}000$.

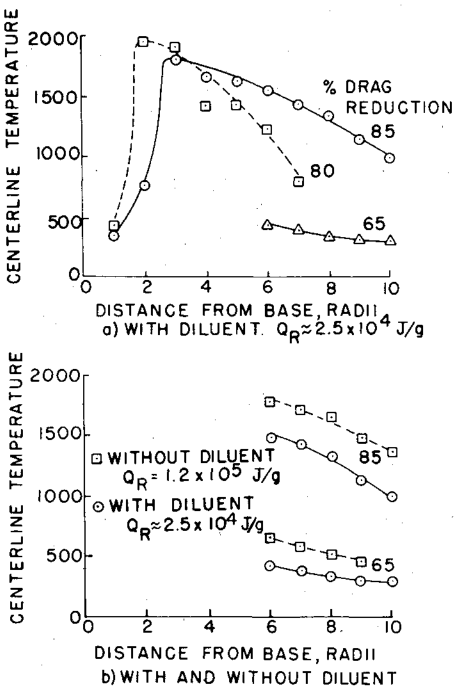

Fig. 8 Centerline temperature profiles for base burning, CO_2 diluent.

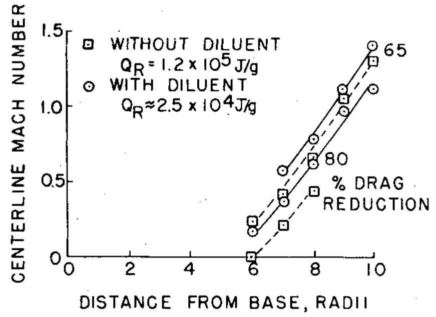

Fig. 9 Centerline Mach number profiles for base burning, CO_2 diluent.

The reference line from Fig. 6 with pure-hydrogen injection is included. These results do indicate that the diluent may slightly reduce the performance at the lower values of base drag reduction. However, the effects are small and in general the differences are within the scatter shown on Fig. 6. Thus, it is concluded that the primary determinant of the performance is the total heat dump rate into the wake.

Some temperature traverses on the wake centerline are shown in Fig. 8. The upper plot presents temperature profiles for three base pressure levels (i.e., total heat dump rates). In each case the hydrogen is diluted with CO_2 so as to yield an effective heating value of about 25,000 J/g. These results show that the maximum temperature on the centerline occurs close to the base plane. Oxygen could not be supplied to this combustion zone so near the base by simple diffusion directly from the freestream. Hence, recirculation must exist so that the combustion zone receives oxygen from the forward flow induced by recompression. The location of the maximum temperature shifts downstream as the base pressure rises with the increasing hydrogen flow rate and, correspondingly, the recompression weakens. Downstream of the temperature peak the gas mixture is oxygen rich and the temperature drops rather rapidly due to mixing with the freestream air. Figure 8b compares temperature profiles for pure-hydrogen injection with those for diluted-hydrogen injection. The temperature

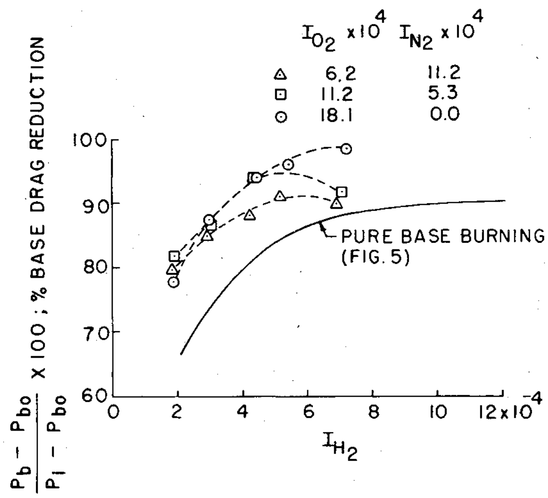

Fig. 10 Preburning and base burning performance results, N_2 diluent.

reduction with diluent cannot be accounted for by the dilution effect alone. Thus, to account for the difference the mixing rates must be increased because of the diluent.

Wake centerline Mach number profiles evaluated from measured temperature and pitot static pressures are shown in Fig. 9. From these results it appears that if the base drag reduction is less than 80% and $Q_R = 25{,}000$ J/g the wake becomes supersonic within 9.5 radii downstream of the base. Since the wave emanating from the base and reflecting from the wind-tunnel wall will intersect the wake at this location, this represents the boundary for interference free flow. For higher values of the base drag reduction and Q_R, the results are conservative since an expansion wave will decrease the base pressure. However, the wave is weak for these higher base pressures and the effect must be small. The results of Fig. 9 also indicate that the rear stagnation point moves downstream about one base radius as the base drag reduction is increased from 65 to 80%.

Combined Preburning and Base Burning Results

The preburner base configuration of Fig. 2 was tested both without injection and with base burning using pure-hydrogen injection to determine if the preburner affected base pressure. Without injection, the measured base pressure was only 1% higher than that for the plane base configuration (Fig. 1). This small change in P_{b0} is within experimental accuracy. Nevertheless, this higher value of P_{b0} has been used in the following results for preburning. With pure base burning the specific impulse was also in agreement with the plane base results of Fig. 5 for the same hydrogen flow rate. Thus, it is evident that the preburner base configuration does not influence the performance.

Figures 10 and 11 present the performance results for combined preburning and base burning using N_2 as the diluent to reduce the effective heating values. Figure 10 shows the effect of hydrogen injection rate on the base drag reduction. Data are shown for three runs distinguished by an increasing O_2 flow rate and a decreasing N_2 flow rate so as to maintain a nearly constant $O_2 + N_2$ flow rate. For comparison, the curve from Fig. 5 for pure base burning is included. The base pressure is significantly increased by preburning in accordance with the earlier arguments from flow model details. The data for the two lowest O_2 flow rate runs show an optimum hydrogen flow rate. The performance reduction after this optimum apparently is due to hydrogen cooling as the H_2 flow rate is increased for constant O_2 and N_2 flow rates. A maximum is not reached in the run with the highest O_2 flow rate which yields a peak base pressure approximately equal to the freestream pressure. Also it should

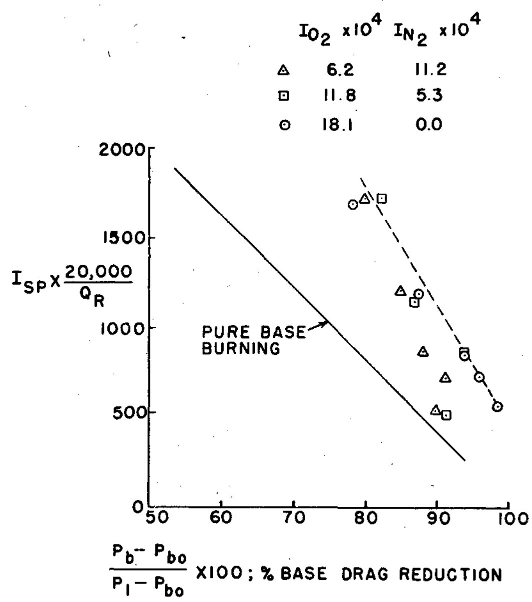

Fig. 11 Preburning and base burning performance results, N_2 diluent.

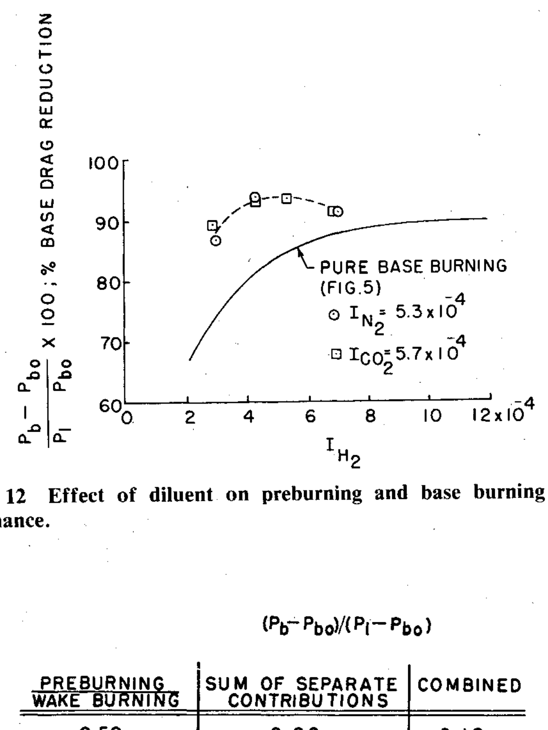

Fig. 12 Effect of diluent on preburning and base burning performance.

$(P_b - P_{bo})/(P_l - P_{bo})$

PREBURNING / WAKE BURNING	SUM OF SEPARATE CONTRIBUTIONS	COMBINED
0.52	2.06	2.18
3.0	1.95	1.83
2.9	2.00	2.07
0	1.79	1.92

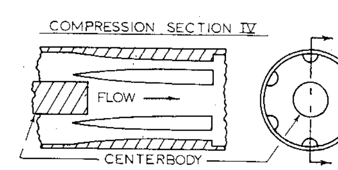

Fig. 13 External compression combined with preburning and base burning.

be noted that the base pressure elevation apparently approaches a limit with the increasing O_2 flow rate, that is, as the ratio of preburning to wake burning is increased. The results of Fig. 10 cover a range in effective fuel heating values of about 17,000-35,000 J/g. The lowest value corresponds to the lowest I_{H_2}. The heat release ratio of preburning to wake burning at the lowest I_{H_2} is about 0.35-2.4 and at the highest I_{H_2} is about 0.15-0.5. The limiting base pressure is apparently reached when this ratio is about 0.5.

The results of Fig. 10 are recast in terms of the scaled I_{SP} vs base drag reduction in Fig. 11. The pure base burning line is from Fig. 6. The low data points correspond to small preburning to base burning heat release ratio for which the pure base burning limit is approached. The dashed line approximates the best performance for combined preburning and base burning. With base drag reduction greater than 80%, preburning can at least double the I_{SP}. Furthermore, impressive values of I_{SP} are obtainable with large drag reductions for practical total fuel heating values and splits between preburning and wake burning. In fact, the performance is as good or better than ramjet performance.

Figure 12 compares results for preburning and wake burning using CO_2 and N_2 as diluents. These data again show that the molecular weight has no significant effect on the performance.

An attempt was made to compare the present results with the hot-gas injection results of Ref. 11. However, the tests of Ref. 11 were at much lower equivalent fuel heating values and yielded low base pressure rises with sharp optimums caused by the injection method. Therefore, direct comparisons are not possible. Extrapolations of their results indicated high performance, which is consistent with the present preburning results.

Finally, preburning and base burning were combined with external compression, designed to simulate external burning, to determine if these effects were additive. Compression section IV described in Ref. 6 and shown schematically in Fig. 13 was used for these tests. This compression section uses symmetrically located half-bodies of revolution to simulate the blockage of six jet plumes burning in the freestream. As shown in Fig. 13, combining external compression with burning results in a base pressure rise that is essentially the same as the sum of the separate contributions. This is shown to be the case for preburning to wake burning heat release ratios of 0-3 and for base thrust levels sufficient to overcome the forebody wave drag of a typical Mach 3 projectile. Thus, it is highly desirable that tests be made with real external burning combined with preburning and wake burning. At the present time the efficiency of this mode of operation is unknown.

Conclusion

Pure base burning performance with hydrogen fuel is determined by the hydrogen flow rate and, thus, the total heat dump rate into the wake independent of the diluent used to reduce the effective heating value of the injectant. This means that the specific impulse for pure base burning is inversely proportional to the heating value of the injectant. Combined preburning and base burning with hydrogen fuel yields considerably higher values of specific impulse than base burning alone, apparently as a consequence of higher wake-core temperatures which reduce the pressure rise required to stagnate the flow. This is also independent of the diluent used to reduce the effective heating value of the injectant. Impressive performance is obtainable with combined preburning and base burning. For example, 90% of the base drag can be eliminated with specific impulse greater than 1000 using an effective fuel heating value of 20,000 J/g. Finally, the base pressure rise resulting from combining preburning and wake burning with external compression, simulating external burning, is nearly the sum of the separate contributions.

Additional tests are needed to determine the efficiency of combining external burning with preburning and wake burning.

Acknowledgments

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References

[1]Hubbartt, J.E., Strahle, W.C., and Neale, D.H., "Mach 3 Hydrogen External/Base Burning," *AIAA Journal,* Vol. 19, June 1981, pp. 745-749.

[2]Schadow, K.C. and Chieze, D.J., "Experimental Investigation of Combined Base Injection and External Burning," *AIAA Journal,* Vol. 16, Oct. 1978, pp. 1074-1089.

[3]Townsend, L.H. and Reid, J., "Some Effects of Stable Combustion in Wakes Formed in a Supersonic Stream," *Supersonic Flows, Chemical Processes, and Radiative Transfer,* edited by D.B. Olfe and V. Zakkay, Macmillan Co., New York, 1964, p. 137.

[4]Baker, W.T., Davis, T., and Matthews, S.E., "Reduction of Drag on a Projectile in a Supersonic Stream by the Combustion of Hydrogen in the Turbulent Wake," Johns Hopkins Univ., Applied Physics Lab, Rept. CM-673, June 4, 1951.

[5]Ward, J.R., Baltakis, F.P., and Pronchick, S.W., "Wind Tunnel Study of Base Drag Reduction by Combustion of Pyrotechnics," U.S. Army Ballistic Research Laboratories, Rept. 1745, Oct. 1974.

[6]Neale, D.H., Hubbartt, J.E., Strahle, W.C., and Wilson, W.W., "Effects of External Compression on an Axisymmetric Turbulent Near Wake," *AIAA Journal,* Vol. 16, Sept. 1978, pp. 940-947.

[7]Strahle, W.C. and Hubbartt, J.E., "Base and External Burning for Propulsion," AGARD 58th Symposium on Ramjets and Ramrockets for Military Application, Oct. 1981.

[8]Mehta, G.K. and Strahle, W.C., "A Theory of the Supersonic Turbulent Axisymmetric Near Wake Behind Bluff Base Bodies," *AIAA Journal,* Vol. 15, Aug. 1977, pp. 1059-1060.

[9]Schetz, J.A., Billig, F.S., and Favin, S., "Approximate Analysis of Base Drag Reduction by Base and/or External Burning for Axisymmetric Supersonic Bodies," AIAA Paper 80-1258, June 30-July 2, 1980.

[10]Neale, D.H., Hubbartt, J.E., and Strahle, W.C., "Effects of Axial and Radial Air Injection on the Near Wake With and Without External Compression," *AIAA Journal,* Vol. 17, March 1979, pp. 301-303.

[11]Clayden, W.A. and Bowman, J.E., "Cylindrical Afterbodies at $M=2$ with Hot Gas Injection," *AIAA Journal,* Vol. 6, Dec. 1968, pp. 2429-2431.