Rocket Plume (N_2O_4/MMH) Impingement on Aluminum Surface

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Introduction

THE combustion of bipropellant motors under high-altitude conditions using dinitrogen tetroxide and hydrazine fuels has been reported to result in the formation of nonvolatile residues. The partial oxidation of the fuel is particularly evident during the pulse mode operation of the motor where high-combustion temperatures are not attained. Two major problems resulting from the use of these restartable space environmental engines are the contamination[1–3] of vehicle surfaces from bipropellant rocket exhaust products and the occurrence of large transient ignition overpressures,[4] which could have deleterious effects on engine operation. The latter results from the sudden detonation of the combustion residues which had accumulated on the rocket chamber wall. Both problems result from the incomplete combustion of the oxidizer and the fuel. The major product from the partial oxidation of hydrazine type fuels by N_2O_4 has been identified as fuel nitrates.[5–9]

Although the chemical nature of the combustion residues has been studied by several investigators, no information is available on the particle size and distribution of residues in the plume. In this study, a polished aluminum bar was placed in the plume of a N_2O_4-monomethylhydrazine (MMH) bipropellant motor during pulse mode firings under high-altitude conditions to obtain the imprint of residues striking the metal surface at very high velocity.

Experimental

A Marquardt 22-lb-thrust motor was installed in a horizontal position in a vacuum chamber. Two aluminum (6061-T6) bars were placed 1.8 in. apart in a vertical position 4 ft from the nozzle exit, as shown schematically in Fig. 1. Orifices (0.5 in. diam) had been drilled in the front piece at 4.5-in. intervals. The front surface of the second bar had been polished to a mirror finish. This permitted examination of the imprint on the polished surface resulting from the impact of the combustion residue leaving the nozzle at very high velocity during the firings and traveling through the orifices. The orifices were numbered 1–6 from top to bottom, the first being directly in the rocket nozzle centerline. Filter papers were placed behind orifices 3 and 6 in an attempt to absorb the liquid products.

The motor was fired with a pulse width of 16.5 msec and an off-time of 20 sec. The injector head temperature was controlled at 60°, 40°, and 80° ± 5°F with 571, 596 and 603 pulses fired at these temperatures, respectively. The tests were conducted at an initial altitude of above 400,000 ft, and degradation took place to no lower than about 230,000 ft. When the injector head temperature or the pressure in the vacuum chamber reached these predetermined limits, the firings were stopped to either cool the injector or to pump down the system before the test was resumed.

At the conclusion of the test, the chamber was purged with nitrogen and the aluminum bars were quickly placed in a polyethylene bag until ready for analysis (within one week). Inspection of the polished bar showed that impingement of the exhaust products at high speed caused erosion of the metal, leaving circular imprints behind the orifices.

Infrared and differential thermal analyses were carried out on the exhaust products found on the aluminum bar. Electron photomicrographs were taken on the imprints formed on the polished metal surface by the high-speed impact.

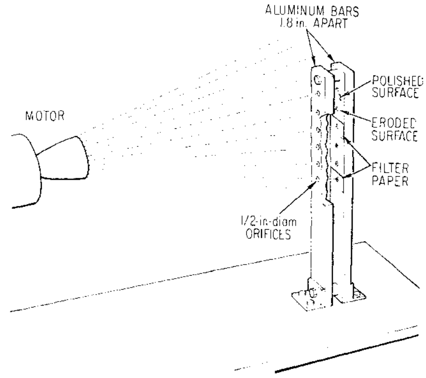

Fig. 1 Schematic of aluminum bars inserted in N_2O_4-MMH rocket plume.

Results and Discussion

By far, the largest quantity of material (amber-colored liquid deposit) was found behind orifice 1 corresponding to the geometric center of the plume. A pool of material had formed on this surface, and an excess had started flowing down (~2.5 in.) the vertical surface. The spatter from the impingement of the exhaust products striking the metal surface at high speed can be seen in Fig. 2. Upon washing the contaminants from the metal with water, a circular imprint remained on the surface, whereas the spattered area remained completely unmarked. Thus, it is clear that the markings were not caused by chemical reactions taking place between the exhaust products and the aluminum, but rather resulted from the high-velocity impact of the combustion residues.

The surface behind orifice 2 contained considerably less material than 1. Large amber-colored droplets (~0.03 in. diam) possibly resulting from the coalescing of many smaller droplets, could be observed. Again, on washing, a circular shaped eroded surface was left. The filter paper placed behind orifice 3 had a tannish discolored area where the exhaust materials impinged on the paper. However, no

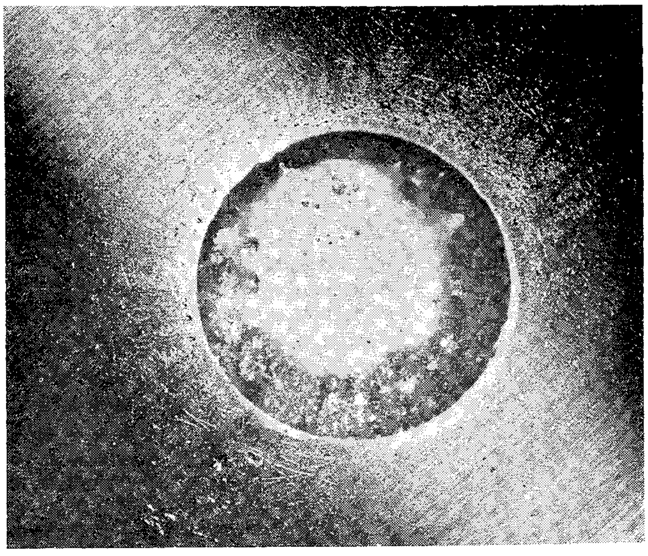

Fig. 2 Surface of aluminum bar behind orifice 1.

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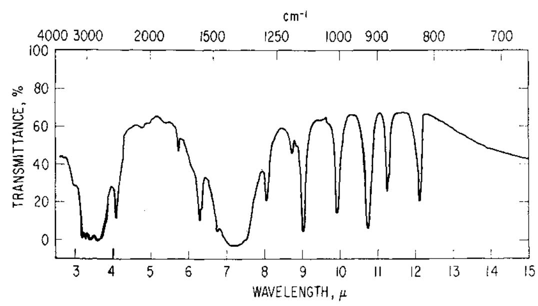

Fig. 3 Infrared spectrum (KBr disc) of N_2O_4-MMH combustion residue. It is identical to that for MMH-HNO_3.

visual damage to the paper could be observed, and the polished metal surface beneath the paper was untouched. Apparently, the thickness of the paper (Whatman No. 1) was sufficient to cushion the impact of the high speed particles and prevent their penetration to the polished surface. An increase in filter paper weight before and after the firings was 11.2 mg. The surface behind orifice 4 was somewhat similar to that of 2, which showed two or three droplets of materials. The overall quantity of material behind 4, however, was found to be less.

A marked difference was observed between the surfaces behind orifices 4 and 5. The surface behind orifice 5 remained essentially untouched although few craters were observed when viewed under high magnification. The combustion residues (liquids and/or solid particles) in the exhaust during the firings, therefore, were confined inside an area forming a cone. This "particle cone" with the apex located somewhere in the combustion chamber is considerably smaller than the total plume, which includes all exhaust products. Whereas the particle cone would be expected to be relatively insensitive to changes in altitude, the gaseous plume volume would show considerable fluctuation with changes in pressure in the test chamber. Further, it is of little value to discuss specific plume boundaries during firings where the pulse width is of such short duration (in this case 16.5 msec), since the plume is expanding and collapsing during the opening and closing of the injector valves.

The liquid products which were found on the front aluminum bar were removed, and the material was analyzed by an infrared spectrum taken on a potassium bromide disc. The spectrum, thus obtained and shown in Fig. 3, proved to be identical to that of MMH-HNO_3 found as combustion residues in other N_2O_4/MMH motor firings.[4,9] Further confirmation was made by comparison with MMH-HNO_3 synthesized by the treatment of MMH with equimolar solution of dilute nitric acid and the removal of water under reduced pressure. A differential thermal analysis (DTA) was also run on the liquid nonvolatile exhaust products.

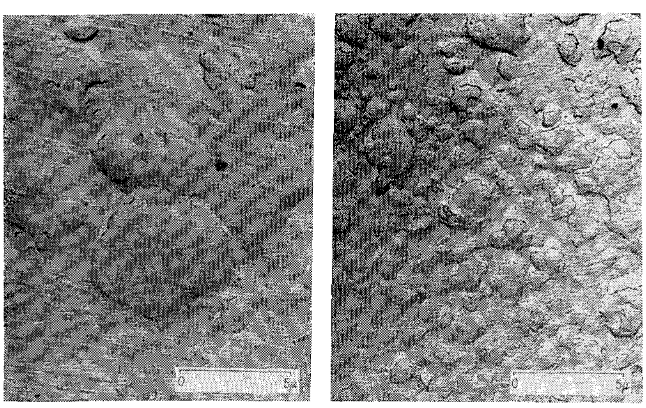

Fig. 4 Photomicrographs of aluminum surfaces behind orifices 1 and 4, respectively.

It showed an exotherm at 270°C and was similar to a DTA curve for pure MMH-HNO_3.

A closer observation of the metal bars showed that the imprints behind orifices 2, 3, and 4 were offset from the holes in the front bar. The extent of offset of the imprints was directly proportional to the direct line of sight to the rocket motor, indicating that the products were expelled in a straight line from the nozzle. For protection of sensitive space vehicle surfaces from direct contamination, one may assume that the combustion residues result from a point source in the motor and travel in a straight line. However, surfaces protected by a barrier or external to the plume were not completely free from contamination. For example, an extremely thin film of material was found over the entire area of the polished aluminum bar, which became very noticeable on removal of the filter papers. This film, however, could have resulted from the recirculation of the exhaust products in the test chamber after each firing and may not be deposited in actual space conditions.

If the exhaust products striking the polished aluminum bar at high velocity did erode the surface, it is difficult to understand why a thin sheet of paper was capable of offering complete protection of the surface. Perhaps these results are an indication that the impinging materials in the exhaust of the N_2O_4/MMH motor of the current study are liquids. Solid products would be expected to leave craters after penetration of the paper, whereas gaseous combustion products would be incapable of eroding the metal surface even on direct impact. A behavior intermediate between the solids and gases may be expected for liquid products. They may possess sufficient force to form craters during direct impingement, yet be unable to penetrate the paper without losing the bulk of their energy. Further, the kinetic energy of the liquid particles on striking the paper (particularly if the surface is rough relative to the size of the particles) is dissipated over a large surface area.

The qualitative observation of the aluminum bar has shown that the highest concentrations of the combustion residues were found in the center region of the plume. The relative quantity of material decreased on moving outward from the center, and a negligible amount of material was found beyond the particle cone.

In Fig. 4 are shown the photomicrographs taken on the replicas prepared from representative aluminum surfaces behind orifices 1 and 4 on an electron microscope. The mounds which appear in the photographs, therefore, are actually pits or craters on the metal surface presumably caused by the impact of the combustion residues. The size of the residues may be inferred from the crater size. The typical larger craters corresponding to imprints behind orifices 1 and 4 are estimated to be $6\mu(\sim 2.3 \times 10^{-4}$ in.) and $2\mu(\sim 0.8 \times 10^{-4}$ in.), respectively. The craters found behind orifice 2 were slightly smaller than those found behind orifice 1. Thus, the craters, and hence the exhaust particles, are considerably smaller in the periphery than in the center of the plume. The larger craters in the core of the plume may have resulted from the fact that the larger particles leaving the combustion chamber through the narrow restriction of the rocket nozzle are less likely to be deflected toward the outer edge of the plume than smaller particles. Further, it can be seen that the craters are more numerous in the periphery than in the center. It is difficult to understand why more particles were found in the outer edges of the plume unless droplets of residues are coalescing to form fewer but larger particles in the core. An alternative explanation is the fragmentation of the large droplets into smaller ones. Since all particles had approximately the same velocity, the smaller particles having less momentum were more readily pushed outward (for example, by pressure gradient) to the periphery of the particle cone. A complete understanding of these results, however, is not possible at this time.

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Approximate Far-Field Flow Description for a Nozzle Exhausting into a Vacuum

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Nomenclature

A = area
B = empirical factor defined by Eq. (2)
d = diameter
K = shaping constant defined by Eq. (13)
M = Mach number
n = shaping term exponent
r = radial distance from nozzle
γ = ratio of specific heats
θ = angle from nozzle axis to streamline
θ_m = limiting streamline angle
ρ = density

Subscripts and superscripts

$*$ = nozzle throat conditions
ch = chamber conditions
o = axis conditions

Introduction

APPROXIMATE calculation techniques for use in describing the flow pattern of gas exhausting through a nozzle into a vacuum can be useful when time and/or facilities do not allow for use of more accurate method-of-characteristics solutions. In addition, as indicated by Hill and Draper,[1] the use of method-of-characteristics solutions at distances beyond a few hundred exit radii is often unsuccessful because of program limitations. A method for far-field approximation of the complete flowfield was sought which would be sufficiently accurate, at least for preliminary design, while providing rapid results by use of hand calculations. Initial assessment of the problem led to a solution which combined the technique developed by Sibulkin and Gallaher[2] for axial density decay with the suggestion of Albini[3] for Mach number angular distribution. The method was only moderately successful. However, significant improvement was achieved by the addition of a "shaping" term and the imposition of the continuity and momentum relationships on the flow.

Initial Approximation

At large distances from the nozzle, the streamlines appear to be straight radial lines emanating from a common source. The mass flux, ρu, therefore, varies as $1/r^2$. Since at large r the velocity is constant (equal to u_{max}), the density varies inversely with the square of the distance from the nozzle. The density decay can, therefore, be expressed as

$$\rho_o/\rho_{ch} = B(d^*/r)^2 \tag{1}$$

where B is approximated by[2]

$$B \cong [5(1 - \cos\theta_m)]^{-1} \tag{2}$$

The Mach number angular distribution was expressed in Ref. 3 as

$$\lim_{r\to\infty}\left[\frac{M_o}{M}\right] = \cos^{1/2}\left(\frac{\pi}{2}\frac{\theta}{\theta_m}\right) \tag{3}$$

Equations (1) and (2) together with the isentropic relation for ρ_o/ρ_{ch} result in the following expression for the axial Mach number

$$M_o = [2/(\gamma - 1)]^{1/2}\{[5(r/d^*)^2(1 - \cos\theta_m)]^{\gamma-1} - 1\}^{1/2} \tag{4}$$

In the far field, however,

$$[5(r/d^*)^2(1 - \cos\theta_m)]^{\gamma-1} \gg 1 \tag{5}$$

Therefore,

$$\lim_{r\to\infty}[M_o] = [2/(\gamma - 1)]^{1/2}[5(1 - \cos\theta_m)]^{(\gamma-1)/2}(r/d^*)^{\gamma-1} \tag{6}$$

The complete Mach field can be defined by combining Eqs.

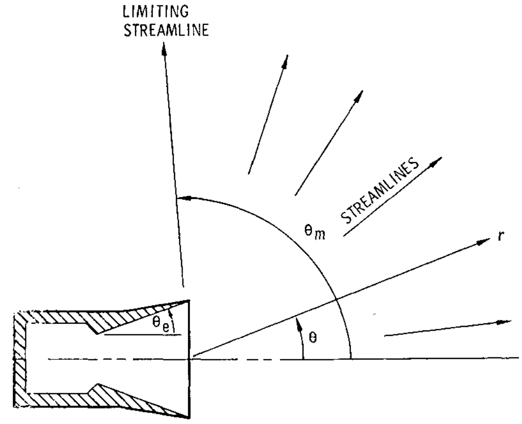

Fig. 1 Schematic representation of a nozzle exhausting into a vacuum.

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