Full-Scale ZAP Rocket Motor Firings

A total of 19 full-scale motors with nylon/phenolic nozzle throat inserts were statically test fired. The performance of the nylon/phenolic throat inserts was satisfactory; however, two distinct groupings of erosion rates could be established. Because of limited funding the material was not fully characterized for this program and more than one lot of material was used. However, the material performance within each group was very uniform, and there was no evidence of any spalling or chunking. Apparently, the thermochemical or mechanical response for each "group" of material is sufficiently different to produce measured difference in regression. Additional analysis would be required to ascertain the cause for the difference in performance. Selected material property measurements and perhaps a theoretical model of material behavior would be needed to make the differences predictable.

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Rocket Combustion Stability Monitoring by Temporal Radiometry

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Discussion

The diagnosis of combustion instability in rocket engines requires knowledge of the frequency, amplitude, and phase of the chamber pressure variations. The measurement techniques usually relied upon to obtain these data employ high-frequency response pressure transducers and/or accelerometers, or, in specially designed transparent chambers, streak photography. Although the more meaningful measurements are obtained with flush-mounted chamber pressure transducers, this measurement is difficult, if not impossible, to obtain on tubular-walled chambers, and such a transducer is often the time-limiting component in workhorse chambers. Feed system measurements and accelerometers often do not give a true reflection of the pressure oscillations in the combustion chambers, or may be difficult to interpret.

The use of temporal or a.c. radiometry allows the determination of chamber pressure oscillations without physical attachment of measurement equipment to the engine, since the radiometer may be situated at any convenient distance from the test stand. The concept of a.c. radiometry is not new (see, e.g., Ref. 1). In the past few years, however, several fundamental guides to successful employment of the technique have been established so that reliable, semiroutine measurements can be obtained.

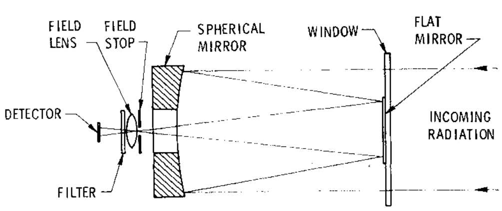

Fig. 1 Schematic of radiometer optical system.

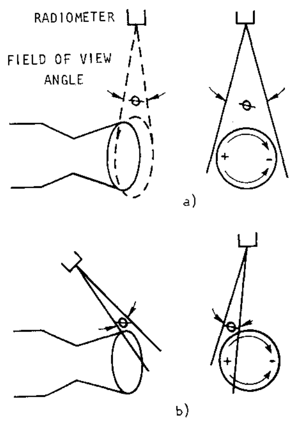

Fig. 2 Effect of radiometer field of view.

Frequency analysis of the time-varying radiation from rocket plumes has shown that this radiation is of two types: 1) a continuous frequency distribution, possessing an f^{-n} dependence caused by random processes, and 2) discrete frequencies caused by oscillations in combustion chamber pressure. Measurements made on engines using a variety of propellants have shown excellent agreement between a.c. radiometry and flush-mounted, high-speed pressure transducers, both in frequency and in spatial phasing.

A typical a.c. radiometer consists of an optical system to focus electromagnetic radiation from the engine exhaust plume onto a detector, a field stop to limit the field of view (FOV) of the radiometer to a particular spatial region of the exhaust, and spectral filters that allow only selected wavelengths to reach the detector (Fig. 1). An uncooled PbSe detector is used to monitor near infrared (1–6μ) radiation, and a photomultiplier tube is used to monitor ultraviolet or visible radiation. The detector output is usually recorded at several levels of amplification on separate channels of an FM tape recorder to provide accuracy over a wide intensity range. Typical frequency response is as high as 20,000 Hz. Other channels of the tape may be used for timing information and other desired measurements. Primary data reduction is carried out on a commercial frequency analyzer. The reduced data consist of a "sonagram" displaying frequency and relative intensity as a function of time. Wave forms and phase relationships may be studied with a conventional oscilloscope.

The field stop is used because if the radiometer FOV was such that both high and low regions of radiation intensity are viewed simultaneously, the integrated a.c. intensity may be zero. For example, if the radiometer views the entire plume (as in Fig. 2a), only the radial and longitudinal acoustic modes may be detected, because the tangential modes will be effectively integrated at any instant of time. To observe tangential modes, only a small portion of the nozzle exit (along the edge of the plume) is viewed (Fig. 2b). To identify all possible acoustic modes, it may be necessary to have as many as

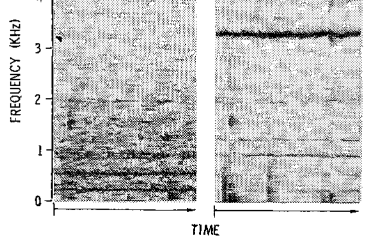

Fig. 3 Sonograms of radiometer (10° FOV) and pressure transducer data.

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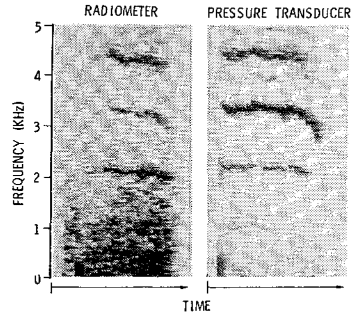

Fig. 4 Sonograms of radiometer (3° FOV) and pressure transducer data.

seven radiometers simultaneously viewing different portions of the plume. However, two or three are usually considered adequate. If the plume is optically thin (very transparent), it may be possible for a radiometer to "see" completely through the plume. Thus, a symmetrical view through the center of the plume would not likely detect a radial mode since the integration includes the entire plume. Therefore, the factors of opacity (at a particular wavelength) must be considered in data interpretation. In fact, in optically thin plumes, the effect may be an apparent doubling of the instability frequency.

Although the mechanism whereby chamber pressure oscillations are exhibited in the exhaust radiation is not precisely known, it is not difficult to arrive at phenomenological explanations. A pressure oscillation in the combustion chamber would produce an oscillation in density and temperature of the gaseous species in the chamber. The frequency of this oscillation is presumably preserved as the gases travel out the nozzle, and brightness fluctuations are thereby produced in the exhaust. Another explanation is that chamber pressure oscillations vary equilibrium compositions, via reaction rates and local mixture ratio, sufficiently that the effects persist into the engine exhaust. Exhaust brightness fluctuations can also be caused by propellant feed system oscillations producing mixture ratio variations of the same frequency. No thorough study of these mechanisms has been carried out.

Results

The type of information obtainable from a.c. radiometry will be demonstrated by summarizing the results of four typical investigations.

The first project was carried out on test firings of a rocket motor equipped with a baffled injector and burning N_2O_4/Aerozine 50 propellant.[2] The motor could be bombed or pulsed unstable. Initially, the radiometer FOV included the entire nozzle exit region (approximately 25 cm) and was perpendicular to the flow axis. With this arrangement, as can be seen in the sonogram of Fig. 3, identical combustion frequencies are present in both the pressure transducer and radiometer data except for the 3500 Hz second-tangential mode. (The pressure variations of this mode were spatially distributed entirely within the radiometer FOV.) On a later run, the radiometer was arranged to view an injector baffle compartment through the nozzle. Initially, a 6° FOV was used (10 cm at the baffle compartment), and the second tangential mode was barely detected by the radiometer, since the 10-cm FOV nearly covered the baffle compartment and allowed the high- and low-pressure regions to be integrated to zero signal level. The FOV was then decreased to 3°, corresponding to a view diameter of less than 5 cm, and all combustion frequencies were detected (Fig. 4).

In the second study, two a.c. radiometers were used to observe the exhaust from the rectangular nozzle of a motor

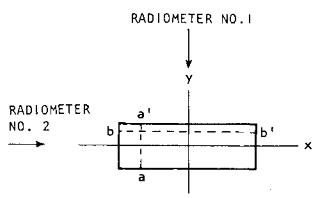

Fig. 5 Schematic of mode detection for rectangular nozzle.

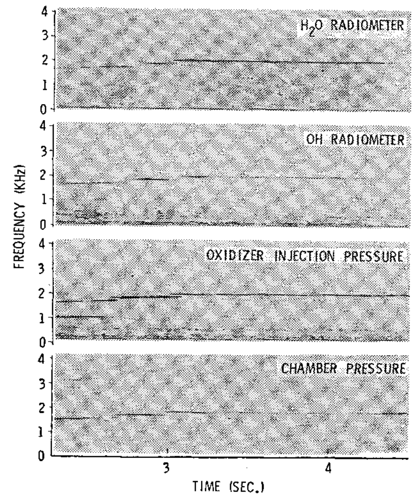

Fig. 6 Sonograms of radiometer and pressure transducer data for aerospike engine.

burning the propellant URFNA/UDMH.[3] The FOV was perpendicular to the chamber axis at the nozzle exit plane, and the angles of view of the two radiometers were displaced 90° from each other (Fig. 5). Radiometer 1 was capable of recording a transverse instability aa' as it moved up and down the y axis, and it would not detect bb' moving back and forth on the x axis because bb' was always in the FOV and the radiometer would not see any change in radiance. In a similar manner, radiometer 2 was sensitive to bb' and insensitive to aa'. The exhaust was calculated to be optically thick, and thus each radiometer would see into the exhaust only a short distance and there would be no frequency doubling effect. Any oscillation that was seen by both radiometers would be a longitudinal mode. Unfortunately, for evaluation of the technique, the motor was quite stable. Only one brief period of instability occurred at the start of one test, and it was seen with equal intensity by both radiometers, indicating a longitudinal mode.

The third study was carried out during static tests of the 250 klb-thrust LO_2/LH_2 aerospike rocket engine.[4] The exhaust was viewed just below the nozzle exit plane by two radiometers located 400 ft from the test stand. One radiometer monitored OH radiation, the other monitored H_2O emission, and each had an 8-cm-diam FOV at the exhaust. Radiometer data, along with data from conventional pressure transducers monitoring oxidizer injection pressure and chamber pressure, are shown for a portion of a typical test in Fig. 6. During the first second of the data slice shown, chamber pressure was gradually increased from 550 to 800 psi and both continuous and discrete frequency shifts occurred.

In the fourth study, a.c. radiometry was used to identify the instability modes present in an experimental, high-thrust H_2/O_2 engine. Two radiometers filtered to monitor H_2O ra-

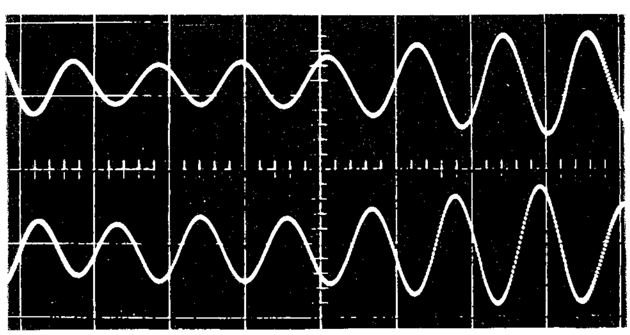

Fig. 7 Phase relationship for radiometers viewing opposite sides of the H_2/O_2 engine exhaust.

diation viewed opposite edges of the exhaust from a site about 70 ft from the engine, and the resulting sonagrams showed that both radiometers observed the same frequency (1750 Hz). Phase analysis was accomplished via a dual-beam oscilloscope, and Fig. 7 shows that the two radiometer signals were 180° out of phase. This indicates a tangential rather than radial mode of instability.

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Comparison of Predicted and Measured Low-Density Plume Impingement Effects

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Nomenclature

C_H = Stanton number
C_m = molecular thermal speed
$\mathfrak{M}$ = molecular mass
$\dot{N}$ = molecular collision rate
P_w = pressure
$\dot{q}$ = heat flux
R = gas constant
Re = Reynolds number
S = molecular speed ratio
T = temperature
v = directed velocity
x = distance along streamline
γ = ratio of specific heats
δ = geometric scale factor
η = number density
θ_i = impingement angle
λ = mean free path
ρ = density
σ^2 = molecular collision cross section

Subscripts

ex, f = exit and flight, respectively
i,j,m = incident, jet, and modeled, respectively
o,w,∞ = total, wall, and ambient, respectively

Introduction

THE behavior of freely expanding plumes has received considerable attention. Aerodynamicists have investigated the behavior of sonic orifices as sources for molecular beams or as primary sources of test gas for conventional flow measurements in high Mach number/low-density flow experiments.[1–3] However, the details of flowfields impinging on surfaces placed in a near-free molecular flow are difficult to determine for well defined flowfields and virtually impossible for rarefied freely expanding jets. The details of such noncontinuum expansion are the subject of current research.[4–6] The work presented was done to define loads and heat transfer to the Saturn V/S-IVB J-2 engine during orbital operation of an oxygen-hydrogen burner engine. The most critical parameter was the heating rate to the J-2 engine, which needed to be defined to insure engine restart capability.

To achieve flowfield simulation, M_{ex}, T_0, Re_{ex} should be matched, the nozzle must be duplicated, and geometry should be duplicated. (The latter two relate to the effect of the nozzle boundary layer.) By simulating flowfield M's and local unit Re's, flowfield Knudsen numbers are duplicated. Duplication of flow chemistry is impossible unless the actual combustion gases are used. Since this normally involves the release of H_2, which cannot be readily pumped cryogenically, test gases must be used that can be condensed with 20° to 30°K helium cryogenic surfaces. As a result, the γ and $\mathfrak{M}$ of the test gas normally will not be the same as the flight gas. Finally, T_0/T_w should be held fixed to duplicate the behavior of the hypersonic flow near the surface.

Simultaneous simulation of M, T_0, and Re can be achieved either by a full-scale test or by a reduced scale with increased density. For a scaled condition,

$$\rho_f/\rho_m = \delta\ \mathfrak{M}_f\sigma^2{}_m/\mathfrak{M}_m\sigma^2{}_f \tag{1}$$

where δ is the geometric scale factor. To assure a similar limiting velocity, T_0 must be duplicated.

Plume Limitations

Several facility-generated problems can arise in low-density, noncontinuum expansions.[4–7] Of special concern is the permeation of ambient molecules into the stimulated flowfield.

Several regimes can be recognized in a rarefied plume. Near the origin for a continuum source (i.e., $\lambda^* \ll r^*$, where the flow is sonic) the flow will be completely controlled by collisions between molecules in the jet. Some dissipation will be present due to viscous stresses in the jet, but they will not significantly alter the velocity, and the increase in gas temperature can be neglected, since the increase in random kinetic energy will be much less than the average directed kinetic energy. The second regime is that portion of the flow in which collisions with static ambient gas occur with the same frequency as collisions between jet molecules. Here the external gas will begin to scatter the plume molecules causing a degradation of the plume flow properties. Finally, after the jet has expanded to an extremely low density, collisions with the ambient gas will be more important than between jet molecules. This essentially two-fluid model of the gaseous expansion assumes that the ambient

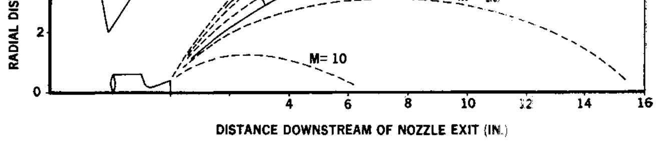

Fig. 1 Nitrogen plume flowfield from method of characteristics solution.

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