SOME ASPECTS OF STEADY-STATE PROPELLANT COMBUSTION AS RELATED TO DYNAMIC COUPLING MECHANISMS

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INTRODUCTION

In the analysis of solid-propellant combustion instability it is useful to understand the structure of the reaction zone in order to perform proper modeling. This presentation is concerned with three aspects of composite propellant flame structure; namely, a thick or extensive reaction zone, the presence of surface reactions and velocity dependency of the linear regression rate. It is concluded that two of these items may be of importance in determining the response of a burning propellant to an acoustic disturbance. Inclusion of these factors may be successful in bringing calculated response factors into agreement with experimental measurements. This discussion is presented within the framework of discussing some of the realities of the reaction zone in order to provide direction for future theoretical activity.

THICK REACTION ZONE

Diagnostic measurements of the flame zone structure of composite solid propellants have been carried out over the

past several years with some degree of success. The resulting data and the implications regarding reaction zone behavior now begin to form a consistent picture. In reference 1 the presence of CN radiation was used as an indicator of the reaction zone, based on the knowledge that this particular species could result only from a reaction between the binder and oxidizer. Also, the CN radiation in some premixed flames has been shown to be limited to the reaction zone with possible weak extensions into the burned gases. By combining the spectral emission of the propellants and a mercury light source which served as a tracking device, the reaction zone thickness, the position of onset of CN radiation, and the position of maximum CN radiation were determined. The reaction zone at 1 atmosphere (1.01×10^5 N/m^2) was found to have a thickness of 2000 microns and hence is not a zone of negligible dimension, as assumed in most of the response analyses. Measurements over the pressure range of 1 to 20 atmospheres indicate a thickness of 2000 to 1000 microns (2×10^{-3} m) (ref. 2). Temperature measurements of the gas phase have also been made. In reference 3 a servo system was employed to maintain the burning propellant surface at a fixed position, and the gas phase temperature was measured optically using the sodium D-line reversal technique. The results indicated that at a fixed position above the pro-

pellant surface the temperature varied from the lower limit of accurate temperature measurement, 1800° K, to the adiabatic flame temperature of the propellant, 2200° K. These fluctuations occurred at any position above the surface over a range of 100 to 800 microns ($1x10^{-4}$ to $8x10^{-4}$ m) and over a pressure range of 115 to 215 psia ($7.9x10^5$ to ;4/75x10^5 N/m^2). The size of the temperature measuring zone was 60 by 40 microns ($6x10^{-5}$ to $4x10^{-5}$ m). The temperature variations are undoubtedly caused by the receeding surface which is heterogeneous in nature (small oxidizer particles embedded in a fuel matrix) which gives rise to alternate streams or pockets of oxidizer and fuel vapors. It was concluded, on the basis of the temperature measurements, that the diffusion and mixing of varying fuel and oxidizer streams is limiting the reaction so that the reaction zone becomes spread out over a fairly wide zone.

The interpretation given these previous results is that the reaction zone is of the order of 1000 microns ($1x10^{-3}$ m) in thickness with continuous reaction occurring between fuel and oxidizer components. The behavior is not that of a premixed gas flame but rather a diffusion or mixing limited flame. Hence although the relaxation time associated with the local gas phase burning is short relative to the wave time and other processes (mass transport and heat conduction),

the diffusion or mixing of the fuel-oxidizer vapors may not be so. Hence the mixing time can introduce a significant time delay and must be considered as a time dependent quantity in the feedback loop. The existence of a thick reaction zone therefore has a profound influence on the form of the analytical equations used for determining the propellant response. Inclusion of this more realistic description of the flame zone may yield a satisfactory fit of the available experimental data. Whether the thick reaction zone concept will cause a shift of the response curve to different frequencies and yield a larger maximum value remains to be evaluated.

ENERGY FLUX TO THE PROPELLANT SURFACE

The optical temperature measurements of reference 3 indicate that values close to the adiabatic flame temperature occur within 100 microns ($1x10^{-4}$ m) of the burning propellant surface. The spectrographic observations in reference 1 show the onset of the reaction zone occurs at about 70 microns ($7x10^{-5}$ m) above the surface. The results of Sutherland's measurements (ref. 5) showed that the active reaction zone occupies only 100 microns ($1x10^{-4}$ m) or less adjacent to the propellant surface. Penzias, however, obtained values close to 800 microns ($8x10^{-4}$ m) before adiabatic flame temperature is reached. It is noted that all of these measurements suffer inaccuracies either due to optical limitations or nonunique-

ness (due to spatial variations as discussed in ref. 3) of the thermocouple measurements. However, one may estimate the energy flux from the propellant gases back to the solid propellant surface for a range of temperature gradient values, assuming a one-dimensional temperature profile. Using various values for the vertical distance, δ, above the propellant surface at which the flame temperature is reached, a thermal conductivity of 0.0002 cal/cm sec ^{o}C (83.6 J/m sec ^{o}K) and a 2000^{o} C (2000^{o} K) temperature gradient the heat flux was calculated as shown in figure 1. Since approximately 200 cal/gr (8.4×10^{8} J/kg) are required to vaporize the solid (ref. 6), which has a density of 2 gr/cm^{3} (2×10^{3} kg/m^{3}), some 400 cal/sec cm^{2} (16.7×10^{9} J/sec m^{2}) are required to maintain a burning rate of 1 cm/sec (1×10^{-2} m/sec). According to the curve in figure 1 this means δ would be 10 microns (1×10^{-5} m) in thickness, appreciably lower than any measurements have indicated. Allowing a conservative estimate of δ equal to 50 microns (5×10^{-5} m) reveals that only 80 cal/sec cm^{2} (33.4×10^{8} J/sec m^{2}) would be available at the propellant surface which is some 20 percent of the energy required. Obviously, additional heat sources are required to sustain the deflagration. The most evident source is the exothermic reaction involved in ammonium perchlorate decomposition. Estimates of the energy flux, based on thermocouple measurements and a heat balance (ref. 7) run approximately 130 cal/gr (5.4×10^{8} J/kg). The possibility of surface reac-

tions between oxidizer and binder constituents at or below the surface have also been postulated as an additional energy source, reference 8. However, no experimental evidence exists to justify the presence of these condensed phase reactions. Extinguished samples of oxidizer-binder sandwiches show no hint of interfacial reactions (refs. 9 and 10). Hence, it must be concluded that energy flux from the burning propellant gases and the exothermic decomposition of ammonium perchlorate provide all the energy required for sustaining the burning of the propellant. It appears, therefore, that in order to accurately represent the combustion behavior in analytical terms, the energy terms should contain both a surface component and a gas phase conductive term. The inclusion of a term arising from surface or subsurface reactions of fuel and oxidizer constituents does not appear to be justified.

VELOCITY COUPLING

Recent efforts to further the understanding of solid propellant combustion instability has indicated the importance of considering the effects of both pressure and velocity coupling mechanisms (refs. 11 to 15). Velocity coupling may arise through flow reversal which may give rise to the occurrence of in-phase energy addition. The effect is a nonlinear one due to rectification of the velocity response during flow reversal, shown in figure 2(a). Velocity coupling may also

arise in the presence of mean flow without reversal; provided propellant erosivity occurs. Theoretical analyses of velocity coupling has proceeded either employing a threshold erosivity (ref. 11) or a mean flow effect (refs. 12 and 13) leading to in-phase energy addition as shown in figure 2(b).

Both linear and nonlinear calculations indicate the profound influence of velocity effects on the response value and stability limits. Experimental data obtained to date lend credance to the importance of velocity coupling; references 14 and 15.

CLOSURE

Inclusion of the concept of a thick reaction zone, the presence of energy sources in the gas and at the solid phase and the dependency of regression rate on velocity in addition to pressure are considered tantamount in the analytical formulation of the acoustic response of composite solid propellants containing ammonium perchlorate. The extensive or thick zone implies that the premixed treatment is invalid and a realistic mixing or diffusion zone is required. Hopefully, reasonable agreement between theoretical pressure response and experimental data will be achievable without a complete accounting for all the complexity of the decomposing surface structure. The remaining task will then be the inclusion of velocity coupling.

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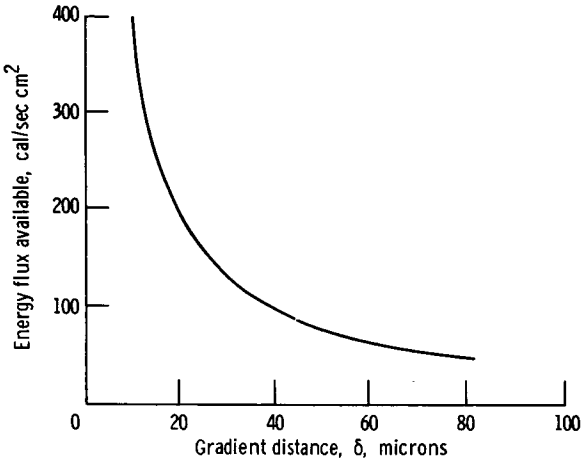

Figure 1. Energy flux to burning surface.

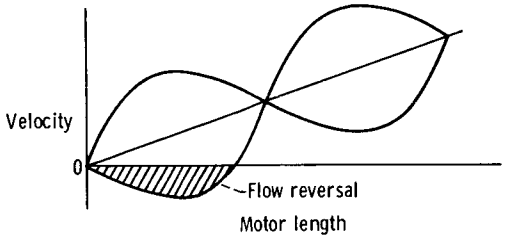

Figure 2a. Head end flow reversal in presence of high amplitude oscillation (ref. 13).

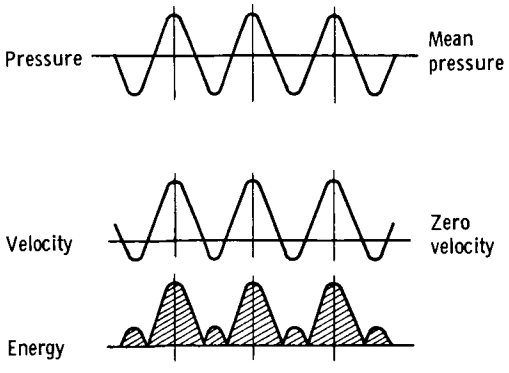

Figure 2b. In-phase energy addition due to mean velocity.