Figure 3 contains photographs of samples, burned at 600 psia, of the same propellant as seen in Fig. 1. The bubble formation on the AP crystal shown in Fig. 3a is typical of structures that have been observed in studies of AP deflagration using single crystals,[8] and has been interpreted as indicating that the surface of the AP is covered by a thin molten layer. Gases formed from the decomposition within the molten layer expanded during rapid depressurization causing the bubble formation as the AP "froze." Indeed it would be difficult to explain the bubble-like structure without assuming the existence of a liquid state. Similar types of structures are evident in Fig. 2 and 4 as well as the majority of the samples studied. The volcano-like structure seen in Fig. 2a and 2d, and the vented structure shown in Fig. 2c also indicate that subsurface reactions have taken place within the liquid portion of the AP prior to quench.

By mechanically stressing the quenched samples it was possible to break the AP-binder bond, thereby releasing the AP particles, as seen in Fig. 3b–d. The unreacted surfaces of the AP particles which were in the binder, and the sharp edges of the resulting craters seem to indicate that no subsurface or interfacial reactions took place between the binder and the AP particles.

In order to explore a possible effect of binder-type on the surface structure, a propellant containing a CTPB binder was tested at pressures of 200, 500, and 600 psia. Results from the tests at 600 psia are shown in Fig. 4 and are typical of the results obtained at the other pressures (at the lower pressure the oxidizer particles protruded above the binder to a greater height). Figure 4a again indicates that the surface of the AP crystals was molten and that subsurface reactions resulted in gas liberation within the molten phase. The photograph seen in Fig. 4d seems to indicate that interfacial reactions did not occur at the CTPB-AP interface.

Conclusions

1) Previous observations that AP crystals protrude above the binder at low pressures and are recessed at high pressure were verified.

2) The polyurethane binder melts during burning to the extent that at higher pressures, where the oxidizer particles are recessed, the molten binder is able to flow over the AP crystals providing an explanation for the self-extinguishment of polyurethane propellants at high pressure.

3) Interfacial or subsurface heterogeneous reactions between the AP and binder were not apparent at all pressures for either the PU or the CTPB propellants. However, at low pressures where the AP protruded above the binder, there appeared to be an undermining of the AP crystals in the PU propellant but not in the CTPB propellant.

4) The AP crystals were observed to form a thin, surface melt and undergo subsurface reactions in the molten phase with in-depth liberation of gas resulting in bubbles and volcano-like fumaroles.

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Ion Density Profile across a Shock in a Partially Ionized Gas

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IT is very important to investigate a shock structure in a partially ionized gas in relation to the problem of a vehicle in an ionosphere. In order to investigate whether ions follow the Rankine-Hugoniot relation in a partially ionized gas, an ion density profile across a shock has been measured with the Langmuir probe technique in a plasma jet wind tunnel,[1] and the experimental result has been compared with the theoretical one. Schematic diagram of the measurement configuration is shown in Fig. 1. Measured profiles of ion density across the shock and in the free stream are shown in Fig. 2, which shows that the ion density upstream of the shock decreases due to the effect of recombination or diffusion and that the ion density behind the shock does not increase up to the value given by the Rankine-Hugoniot relation. Assuming that all particles have the same velocity u_1 upstream of the shock and that u_1 is constant, the relation between $1/n_i$ and z/u_1, where n_i is the ion density and z the distance along the flow, can be obtained from Fig. 2 as shown in Fig. 3. The following equation can be obtained easily from Fig. 3:

$$1/n_i = (\eta z/u_1) + K \quad (K\text{: constant}) \tag{1}$$

where η is the coefficient of the ion density decay. Equation (1) shows that the ion density decreases with time in the recombination type, but, when $\eta z/u_1$ is very small, the relation between $1/n_i$ and $\eta z/u_1$ is approximately linear even in the diffusion-type decay. Equation (1) leads us to the following

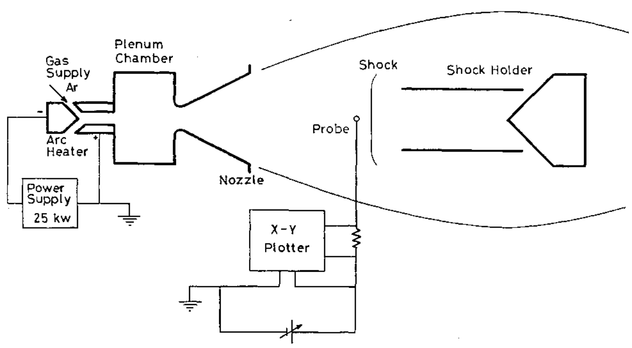

Fig. 1 Schematic diagram of measurement configuration.

Received May 29, 1969; revision received October 27, 1969.

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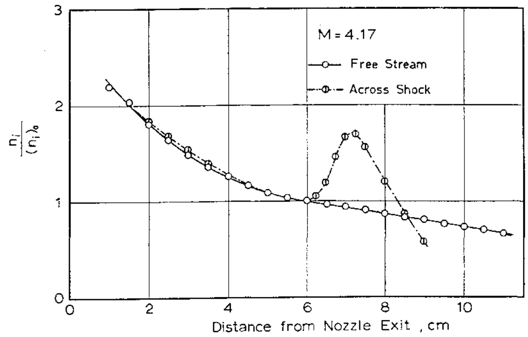


Fig. 2 Profiles of ion density in freestream and across shock.

equation:

$$d(n_i u_1)/dz = -\eta n_i^2 \tag{2}$$

We assume that η is constant without regard to the existence of the shock and that it takes the value in the free stream. Assuming that $u_a = u_i = u_e = u$ holds even in the shock, Eq. (2) is rewritten as follows:

$$d(n_i u)/dz = -\eta n_i^2 \tag{3}$$

In a partially ionized gas, the flow of the atoms can be considered to be unaffected by the charged particles. Therefore, $d(n_a u)/dz = 0$ holds. From this equation and Eq. (3),

$$(dn_i/dz) - (n_i/n_a)(dn_a/dz) = -(\eta/n_{ao}u_o)n_a n_i^2 \tag{4}$$

where subscript o denotes the upstream reference state. The reference point is chosen as the point where the decrease of the upstream ion density counterbalances the increase of it due to the compression produced by the shock. Namely, at this point, the gradient of the ion density vanishes. Equation (4) has the boundary conditions that $n_a = n_{ao}$, $n_i = n_{io}$ and $dn_i/dz = 0$ at $z = z_0$. Using nondimensional quantities $\nu_i' = n_i/n_{io}$, $\nu_a = n_a/n_a(-\infty)$, and $\xi = z/L$, where L is the maximum slope thickness of the atom shock, the solution of Eq. (4) is obtained as follows:

$$\nu_i' = \nu_a \Big/ \frac{\eta n_{io} L}{u_1} \int_{\xi_0}^{\xi} \nu_a^2 d\xi + \nu_{ao} \tag{5}$$

where ν_{ao} is the value of ν_a at $\xi = \xi_o$ and $u_o = u_1/\nu_{ao}$. The atom density profile is given by Mott-Smith's solution, $\nu_a = 1 + 3\beta/(1 + e^{-4\xi})$ in which $\beta = (M^2 + 1)/(M^2 + 3)$. The value of ξ_o can be determined as follows.

From Eq. (4) and the boundary conditions, the following relation is obtained:

$$(1/n_{ao})(dn_a/dz)_o = \eta n_{io}/u_o \tag{6}$$

Using Mott-Smith's solution in Eq. (6),

$$[\exp(-4\xi_o)]^2 + 2(1 + 3\beta - 6u_1\beta/\eta n_{io}L)\exp(-4\xi_o) + (1 + 3\beta)^2 = 0 \tag{7}$$

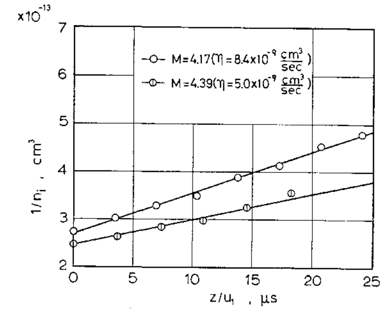
From Eq. (7) ξ_o can be estimated. Thus, the ion density profile across the shock can be obtained from Eq. (5).

Figures 4a and 4b show the comparisons between the experimental and calculated results. The ratios of the maximum ion density to the minimum one are tabulated in Table 1. The calculated results agree very well with experimental results in the ratio of the maximum ion density to the minimum one. Hence, it is clear that, if the ion density decay does not exist, ions follow the Rankine-Hugoniot relation in the density. Since the values of η are very large in comparison to the recombination coefficient[3] obtained for the condition similar to the present condition, it is expected that the ion density decay results from diffusion.

Table 1 Ratio of the maximum ion density to the minimum ion density

M	experiment	calculation	Rankine-Hugoniot
4.19	$1.65 \sim 1.87$	1.75	3.42
4.39	$2.07 \sim 2.42$	2.35	3.46

Fig. 3 $1/n_i$ as a function of z/u_1.



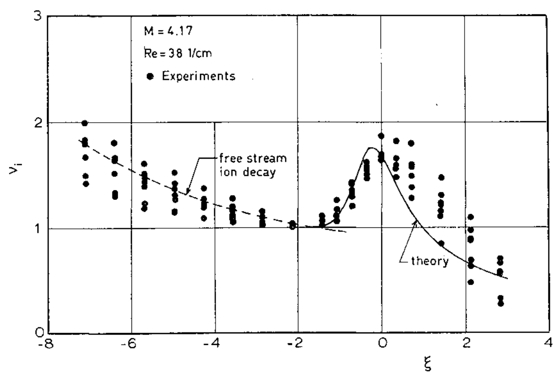


Fig. 4a Comparison between experimental result and calculated one of ion density profile. Re_1 = 38 1/cm, $n_{i0} = 4 \times 10^{12}$ 1/cm³, $n_{a1} = 1.1 \times 10^{15}$ 1/cm³, T_{e1} = 3000 °K, T_{a1} = 370 °K, L = 7.0 mm.

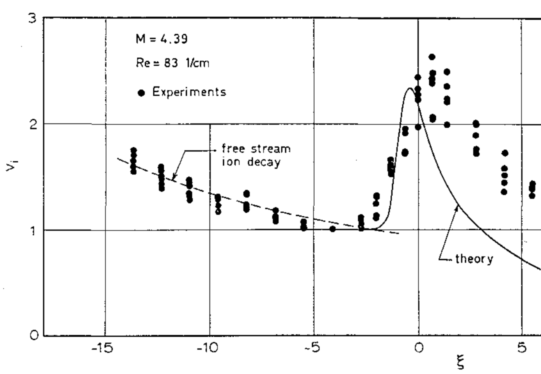


Fig. 4b Comparison between experimental result and calculated one of ion density profile. Re_1 = 83 1/cm, $n_{i0} = 4 \times 10^{12}$ 1/cm³, $n_{a1} = 2.0 \times 10^{15}$ 1/cm³, T_{e1} = 3400 °K, T_{a1} = 280 °K, L = 3.6 mm.

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