Another promising feature of these systems is evident by their flame temperatures. The nature of the plots of chamber temperature with O/F ratio, presented in Fig. 2, is closely similar to that of the specific impulse plots. The flame temperatures calculated at chamber pressure, 30 atm, are quite high, being on the order of 3000 K and comparable to those obtained with potential systems such as UDMH-HNO_3.[8]

As expected, the performance parameters of the various TCH-HNO_3 systems are of the same order. However, a close inspection of the data reveals that the p-dimethylaminobenzaldehyde derivative-HNO_3 system yields the highest I_{sp} and flame temperature among the various systems based upon mono-TCH. The reason for this could be the relatively low average molecular weight of its combustion products. Having the highest formula weight, it has the lowest percentage of sulphur, consequently, it will produce the lowest amount of sulfur-containing products; thereby reducing the average molecular weight. A similar conclusion may be drawn by comparing the performance parameters of the mono- and bis-acetone thiocarbonohydrazones-HNO_3 systems. The apparently superior parameters of the bis-derivative-HNO_3 system could be attributed to the relatively smaller percentage of sulfur that the bis-derivative has, as compared to the monoanalog.

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Combustion Related to Solid-Fuel Ramjets

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Introduction

As the second stage of a medium- or long-range missile, the solid-fuel ramjet (SFRJ) is a viable alternative to a rocket. The combustion process in a SFRJ is similar to that in hybrid rockets, with the exception that the freestream contains a relatively low oxidizer in the SFRJ. Bartel and Rannie[1] introduced the concept of SFRJ and modeled the combustion process both experimentally and theoretically. The regression rate data on tubular carbon block in a turbulent airstream exhibited the familiar dependence on the mass flux G as $G^{0.8}$. Boaz and Netzer[2] carried out experimental investigations in a range of chamber pressure p with PMMA as the fuel. They obtained the regression rate law as, $\dot{r} = cp^{0.51}G^{0.41}T^{0.34}$. Schadow et al.[3] obtained radial and axial profiles of the temperature and species concentration in this setup. The airstream was heated to 550 K to simulate the actual condition in a ramjet. The experimental results of Schadow et al.[3] were reproduced by the theoretical model of Netzer.[4,5] Mady el al.[6] investigated the effect of port flow rate and bypass flow rates on the combustion mechanism and efficiency. When the airflow was totally through the fuel port, the regression rate could be expressed in the form, $\dot{r} = 0.0043p^{0.29}G^{0.38}$; but when part of the airflow was bypassed, the expression changed to $\dot{r} = 0.0016\,p^{0.42}G^{0.003}$. The heat-transfer mechanism has been argued to be convection dominated in the former case, but radiation dominated in the latter. Subsequent work by Hewett and Netzer[7] showed that the expression obtained for the case with bypass airflow could have been in error.

The convective theory of boundary-layer combustion of Marxman et al.[8] yields a burning rate expression of the type $\dot{r} = a_0 G^n p^m B^{0.23}$. The index n would be 0.8 for turbulent flow and 0.5 for laminar flow in the port of the fuel grain. Although most of the hybrid rocket results are indeed correlated in the form of $G^{0.8}$, it has been contended that it could as well be 0.5. The results on the SFRJ indicate values closer to 0.5 than to 0.8. The pressure sensitivity of the regression rate is weak as given by the theory and arises through chemical kinetics and radiation effects. But, experiments using SFRJ seem to indicate a stronger dependence. The present work is aimed at enriching the experimental data in this area and examining these aspects of the SFRJ.

Experimental

The setup used for the present experiments is shown schematically in Fig. 1. The airflow from the blower is taken through a control valve, a "flow straightner," and a calibrated venturimeter to the combustion chamber containing the tubular fuel blocks. Preliminary experiments showed that a diaphragm at the inlet with a resulting recirculation zone is essential for stabilizing the flame. In the present work, the weight loss method is adopted to derive the fuel regression data. A number of blocks with the same initial diameter (40 mm i.d.) are burned through different burn times and the corresponding weight losses are measured. The ignition was through a solid propellant piece glued on the inner surface of the fuel blocks. Quenching was effected by purging with nitrogen.

Initial attempts with blocks of pure fuel-like rubber and polyester were in vain since both ignition and sustainance of

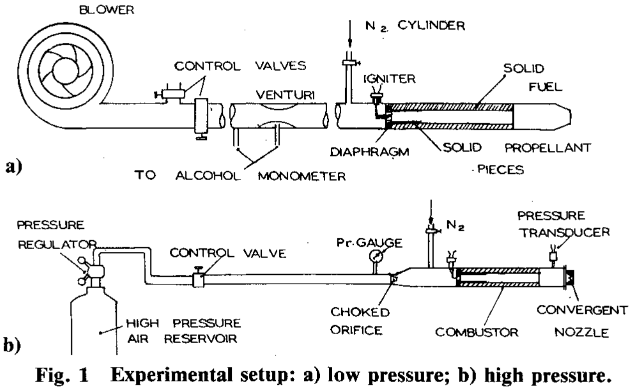

Fig. 1 Experimental setup: a) low pressure; b) high pressure.

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Table 1 Experimental results from low-pressure setup ($r_0 = 20$ mm, $\rho_f = 1.15$ g/cm^3, $p = 0.93$ atm)

Sl. no.	$\dot{m}_a$, g/s	$G_{ox,0}$, g/cm$\cdot^2$	t_b, s	L, cm	Values of $a'(\times 10^3)$ for $n=0.5$	$n=0.8$
1	31.2	2.48	22	34.0	6.89	5.43
2	31.2	2.48	22	32.5	6.57	5.16
3	21.8	1.74	34	33.6	6.94	5.87
4	25.6	2.04	32	32.7	6.60	5.56
5	21.8	1.74	33	26.1	6.72	5.62
6	36.0	2.87	16	36.3	6.80	5.09
		Mean			6.756	5.45 $(\times 10^{-3})$
		Standard Deviation			0.138 (2.69%)	0.294 $(\times 10^{-3})$ (5.384%)

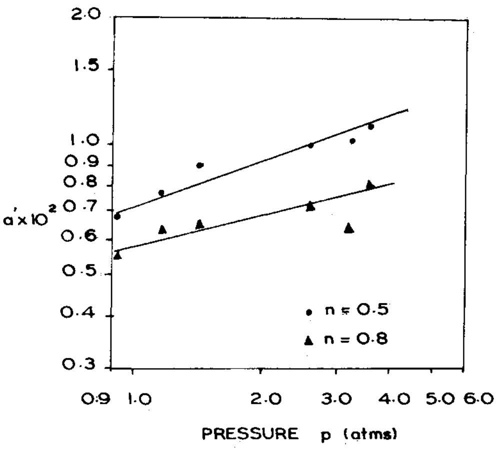

Fig. 2 a' **vs** p **for pressure sensitivity of regression rate.**

combustion proved difficult. Then, a small percentage of ammonium perchlorate (AP)—a standard oxidizer in solid propellants—was mixed with the polyester. The final set of blocks, which exhibited smooth ignition and combustion, contained 25% AP. It may be noted that this combination is too fuel rich to burn as a solid propellant at the low pressures relevant to the SFRJ.

The experiments to estimate the pressure sensitivity of regression rate were conducted in a smaller high-pressure setup using a smaller motor (shown in Fig. 1b) and fuel blocks 15 mm in diameter. The airflow rate and pressure are measured with a choked orifice and a strain gage pressure transducer respectively.

Results and Discussion

The weight loss W_L vs time t_b data from the experiments are used to derive the regression rate $\dot{r}$ dependence on the oxidizer mass flux G_{ox} and pressure p restricting to the usual form

$$\dot{r} = aG_{ox}^n p^m \tag{1}$$

given by the convective theory. Therefore, it is presumed that the small amount of solid oxidizer contained in the fuel blocks does not give rise to any premixed flame and that combustion proceeds in the diffusion flame formed in the boundary layer. The task, then, is to obtain the values of the constants a, n, and m for combustion of AP-filled polyester in air.

At any given pressure, writing

$$\dot{r} = a' = G_{ox}^n \, (a' = ap^m) \tag{2}$$

the weight loss of a tubular grain with time can be expressed as

$$\frac{(2n+1)}{r_0} a' G_{ox,0}^n t_b = \left(1 + \frac{W_L}{\pi r_0^2 L \rho_f}\right)^{n+½} - 1 \tag{3}$$

where r_0 is the inner radius of the fuel block, L its length, and ρ_f the fuel density. Subscript 0 refers to the initial condition.

The validity of a laminar flow correlation ($n = 0.5$) can be checked by verifying if W_L varies linearly with $G_{ox,0}^{0.5} L t_b$. But such a simple plot is not possible to test the turbulent flow proposition ($n = 0.8$).

Alternatively, for a given value of n (0.5 or 0.8), Eq. (3) can be used to compute a value of a' for each experimental point of W_L vs t_b. If the values of a' obtained in this manner for all data points are nearly equal, the corresponding value of n can be treated as appropriate. Table 1 summarizes the results of such an analysis. With a lower standard deviation, the results favor the $n = 0.5$ case, but the difference between the two cases is so small that no definite conclusion can be drawn.

Similar calculations can be done with the data obtained from high-pressure setup. Figure 2 is a logarithmic plot of a' ($=$ const p^m) vs p. Once again, the two cases of $n = 0.5$ and 0.8 are equally good. Corresponding values of the pressure index m are 0.36 and 0.26, respectively. The pressure index seems close to the values reported in the literature (0.3-0.5). However, in the present experiments, the ammonium perchlorate impregnated in the fuel blocks might be giving rise to certain reactions of premixed type that exhibits greater pressure sensitivity. The effect of AP in fuel blocks is also seen in the magnitude of the regression rate. While the $\dot{r}$ for PMMA/air at atmospheric pressure is reported[6] to be 6.2×10^{-3}cm/s at the same G_{ox} level ($G_{ox} = 2.11$ g/cm$\cdot^2$/s), polyester/25% AP gives about 9.6×10^{-3} cm/s. Since the properties of the fuel do not seriously alter the regression rate, it can be said that the presence of AP has enhanced the regression rate by a factor of 1.5.

It may be pertinent, at this stage, to draw attention to an aspect of the convective theory of boundary-layer combustion, namely, the regression rate variation with the transfer number B, which varies considerably from the O_2/fuel environment of a hybrid rocket to the air/fuel in a SFRJ. The value of the mass transfer number B for PMMA/oxygen is 9.81 and that for PMMA/air about 1.66. The regression rate of PMMA measured by Marxman et al.[8] in O_2 flow is 8.89×10^{-3} cm/s. When this figure is scaled by $(B_{air}/B_{O_2})^{0.23}$, i.e., $(1.66/9.81)^{0.23}$, one obtains the regression rate in the airflow at the same mass flux and pressure as 5.91×10^{-3} cm/s. This compares favorably with the value 6.2×10^{-3} cm/s. measured by Mady et al.[6] A similar thermochemical calculation (detailed in Ref. 8) would yield, for the present case of polyester/25% AP in air, a value of $B = 1.88$ if the dissociative sublimation of AP is assumed to be endothermic. The corresponding regression rate of the polyester/25% AP blocks in the hybrid mode should have been 6.1×10^{-3} cm/s if the $B^{0.23}$ law holds for this grain. The measured regression rates are much higher. If the AP surface processes are exothermic as the recent works[9] suggest, the effective heat of vaporization for the fuel blocks would be lower, resulting in an increase in B and thus the estimated regression rate. All of these results warrant a more extensive examination of this particular mode of combustion wherein a partially oxidizer-filled fuel block burns in a flowing stream of oxidizer.

Conclusions

The experiments have demonstrated that at low inlet air temperatures, smoother ignition and sustained combustion can be achieved by dispersing a small percentage of solid oxidizer in the fuel matrix. A flame-holding mechanism would still be necessary. For the polyester/AP air combination, the regression rate can be expressed as $\dot{r} = 0.0068 G_{ox}^{0.5} p^{0.36}$; a slightly different expression with 0.8 as the index of G_{ox} can be nearly as good. Both the pressure index and the regression rate dependence on B call for further examination of this mode of combustion.

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