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Combustion of Mixed Fuels

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Introduction

STUDIES on the ignition characteristics and performance parameters of a liquid propellant system having nitric acid as an oxidizer and the mixture of Hydrazine + ethyl alcohol as mixed fuel have been reported earlier.[1] To have a more comprehensive picture, additional and supplementary combustion studies on the system were undertaken particularly in view of the fact that the mixed fuel can be used in external combustion engines like Stirling engine. These studies are reported in the present communication.

Experimental

Materials

Anhydrous hydrazine was prepared by dehydrating hydrazine hydrate as described earlier.[2] Ethyl alcohol was prepared by purifying absolute alcohol in the usual manner.[3]

1) *Measurement of mass burning rate:* Mass burning rate was determined by a specially designed burner which consisted of two glass tubes *A* and *B*, the diameter of *A* being 1 cm. The tubes *A* and *B* were connected by polythene tubing. *B* was used for burning, and the diameter of *B* could be varied. *A* had a bent portion in the upper part and a side-tube attached with a burette; the side tube was maintained at the same level as the tip of *B*. Fuel could be introduced into *A* with a known rate, and the excess of the fuel overflowing through the side-tube could be measured. The tip of *B* was ignited, and the amount of fuel consumed in air at different time intervals could be measured.

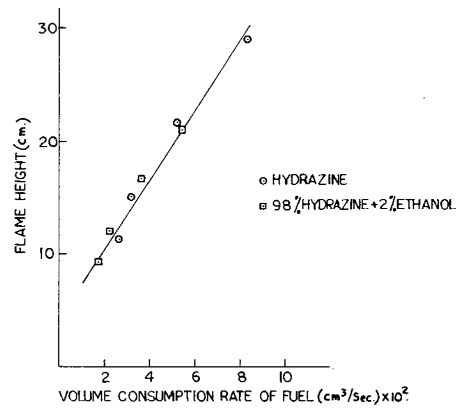

Fig. 1 Test of Eq. (3)

Burning rate studies were also made in N_2O_4/NO_2 oxidizing atmosphere by enclosing the burner with a Pyrex glass tube (6 cm. i.d.) which was flushed with NO_2. NO_2 was prepared by the usual laboratory method.[4] The results were plotted against time. A linear plot was obtained from which the mass burning rate was calculated. The data are given in Table 1.

2. *Measurement of flame height:* Flame height was measured visually with the help of a metallic scale placed behind the flame. A number of measurements were made during each run and the average values of the flame heights are plotted against volume consumption rate as shown in Fig. 1.

3) *Measurement of temperature profile:* Temperature of the flame at various points was recorded potentiometrically with the help of Chromel-Alumel thermocouple having bead diameter ~1.5 mm the cold junction of which was placed in melting ice. For measuring the temperature distribution in the liquid phase a modification was made in the burner design so as to allow the thermocouple junction to be moved up and down inside the tube. Results are plotted in Fig. 2.

III. Discussion

According to Spalding the rate of pool burning and vessel diameter are related as follows.[5]

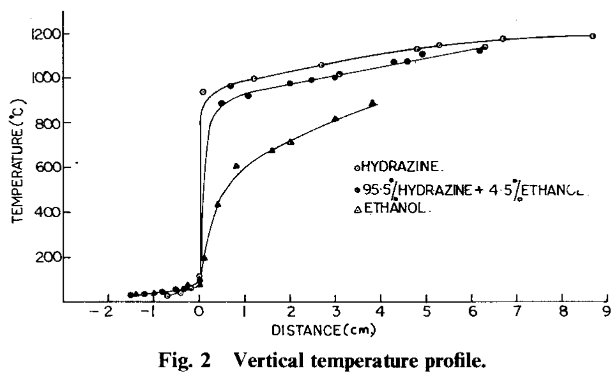

Fig. 2 Vertical temperature profile.

Received October 11, 1974. Our thanks are due to the Ministry of Defence and Council of Scientific and Industrial Research for supporting the investigation.

Index categories: Fuels and Propellants, Properties of; Liquid Rocket Engines; Combustion Stability, Ignition and Detonation.

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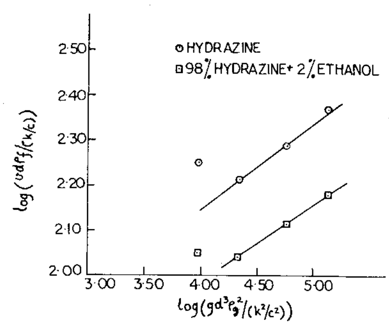

Fig. 3 Test of Spalding's equation, Eq. (1).

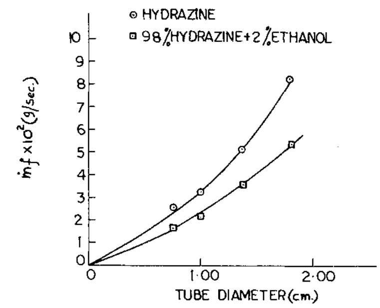

Fig. 4 Variation of mass burning rate with tube diameter.

Table 1 Mass burning rate of mixed fuels—hydrazine + ethyl alcohol

	$\dot{m}_f$ (g/sec)							
	Oxidizing atmosphere: air ($\%\,N_2H_4$)					Oxidizing atmosphere: N_2O_4/NO_2 ($\%\,N_2H_4$)		
Tube diameter (cm)	100	98	92	83.6	0.0	100	98	92
0.75	0.026	0.017	...	...	...	...	...	...
0.99	0.032	0.022	0.020	0.012	0.005	...	...	...
1.37	0.052	0.036	...	...	...	0.083	0.051	0.041
1.81	0.083	0.054	...	...	...	...	...	...

$$v d \rho_f/(k/c) = A B^{3/4}[g d^3 \rho_g{}^2/k^2/c^2]^n \tag{1}$$

where v is the linear burning rate; d is the vessel diameter; ρ_f and ρ_g are the densities of liquid and atmospheric gas, respectively; k and c are the thermal conductivity and specific heat of gas, respectively; g is the gravitational constant; B is the transfer number; and A and n are the empirically adjusted constants.

Since other quantities occurring in Eq. (1) are constants, a log-log plot of Reynolds number, which corresponds to the left-hand side of the previous equation and the Grashof number (the term in bracket in the right-hand side), should give a straight line. Such a plot is given in Fig. 3. Burning rate values at lower diameter fall above the curve. This discrepancy is probably because as the diameter of the tube is decreased, the steady-state combustion becomes more and more difficult. Under limiting conditions, irregular ejection of the liquid from the fuel surface was actually observed.

The results can also be analyzed in terms of the theory of Godsave[6] which, however, strictly holds for droplet burning. In the present experiment the geometry of the burning surface is maintained and fixed by a controlled supply of fuel in the burning zone, whereas in the model of Godsave, the droplet diameter decreases with time. As suggested by Godsave

$$\dot{m}_f = \frac{4\pi k}{C_p} \, \frac{\ln[1 + C_p(T_c - T_1)/H_v]}{(1/r_1) - (1/r_c)} \tag{2}$$

where $\dot{m}_f$ is the mass burning rate; k and C_p are the thermal conductivity and specific heat of the fuel vapor, respectively; r_1 and r_c are the radii of droplet and combustion surface, respectively; T_c and T_1 are the flame and liquid droplet temperatures, respectively; and H_v is the heat of vaporization of the liquid fuel.

According to the previous equation $\dot{m}_f$ would depend linearly on d, the droplet diameter, provided the ratio r_1/r_c remains constant at all diameters. The results plotted in Fig. 4 show that this is not so, suggesting that r_1/r_c changes with the diameter of the tube.

Table 1 shows that $\dot{m}_f$ decreases with the increase in the percentage of ethyl alcohol in the mixed fuel. The lower value in the case of mixed fuel is because the combustion of ethyl alcohol essentially occurs in the vapour phase, and part of the thermal energy from the flame front is used up in the vapourization of ethyl alcohol. Ethyl alcohol will vapourize preferentially because of a lower boiling point and lower heat of vapourization. On account of this, the surface temperature would be decreased because of endothermic vaporization. This in turn would reduce the flame temperature. Lower flame temperature are observed experimentally as is clear from Fig. 2. That is why the observed ignition delays are longer in mixed fuels, and the calculated flame temperatures are lower.[1] Burning rate in N_2O_4/NO_2 atmosphere was found to be more than its corresponding value in air, as is clear from Table 1.

Comparative study of temperature distribution along the flame has been made, and the results (see Fig. 2) show that the flame temperature of the mixed fuel is always lower than the flame temperature of hydrazine as expected. The relationship between flame height and volume consumption rate in open tanks has been investigated by Atallah.[7] According to him, for pans less than 3 cm diam,

$$L = 0.153\,(Q\theta/D) \tag{3}$$

where L is the flame height, Q is the volume consumption rate, θ is a dimensionless parameter, and D is the diffusion coefficient. Equation (3) suggests that the flame height should be proportional to the volume consumption rate which we find to be the case, as is clearly shown in Fig. 1.

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