Port Size Effects on the Combustion of PVC Plastisol - O_2 (Gas) System

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Nomenclature

D_p = port diameter of the fuel grain, mm
D_o = outer diameter of the fuel grain, mm
G_{ox} = oxidizer mass flux, gm/cm^2-sec.
L = length of the fuel grain, cm
$\dot{m}_f$ = rate of fuel mass consumption, gm/sec.
$\dot{m}_{ox}$ = rate of oxidizer mass flow, gm/sec.
$\dot{r}(x)$ = local regression rate at x, mm/sec.
$\bar{\dot{r}}$ = average regression rate, mm/sec.
x = distance along the length of the fuel grain, cm.

Introduction

THE hybrid propulsion system has emerged as a potential propulsion technique because of its handling ease, safety, simplicity, on-off capability and thrust and thrust vector control adaptability. Many theoretical models have been forwarded for the combustion of hybrid system. Marxman and Gilbert[1] proposed an idealized aerodynamic flat plate model similar to that of turbulent diffusion flame where combustion takes place in the turbulent boundary layer and verified the results experimentally. Marxman, Wooldridge, and Muzzy[2] extended the regression rate equation given earlier to combustion of a cylindrical grain. Smoot and Price[3] also proposed a regression rate theory using a cylindrical moael neglecting the radiation effects. Numerous experimental work has also been carried out to test the validity of the average regression rates given by the previous theoretical calculations for various polymers and carboneous fuels with gaseous oxygen.

The reported data, however, lacks in describing the phenomenon of combustion along the length of the grain. This Note describes an investigation of the local regression rate along the length of the grain and its dependence on port sizes and L/D_p ratio. The combustion of a fuel grain of fixed length and outer diameter has been studied for constant mass flow rate of oxidizer and constant duration of burning. The port diameters have been varied so as to give L/D_p ratio from 8 to 48. PVC-Plastisol has been chosen as fuel because of its good mechanical and chemical properties and similar average regression rate under identical oxidizer mass flux.[4]

Experimental Set up and Test Procedure

Experiments have been carried out with static motor using grains of 24 cm length and 50 mm o.d. with port diameters ranging from 5 mm to 30 mm. A schematic diagram of the experimental set up has been shown in Fig. 1.

A pyrotechnic igniter with an ignition delay of 0.2 sec. was used to initiate combustion. Oxygen was injected through an orifice of 3 mm diameter with the help of a solenoid valve soon after the initiation of combustion. The injection pressure was maintained at 35 kg./cm^2 to give an oxidizer mass flow rate of 15.4 gm/sec ($\pm 3\%$) during each experimental run. All the tests were conducted for a fixed duration of combustion of 10 sec.

Local regression rates along the length of the fuel grain at an interval of 1 cm were determined by accurately measuring the unburnt web thickness with a micrometer (least count = 0.0001 mm). The fuel grain was accurately weighed before and after the test and mass consumption rate was determined by the difference of the weights, assuming a constant rate of consumption. The average regression rate was computed from weight loss and average port area during each test.

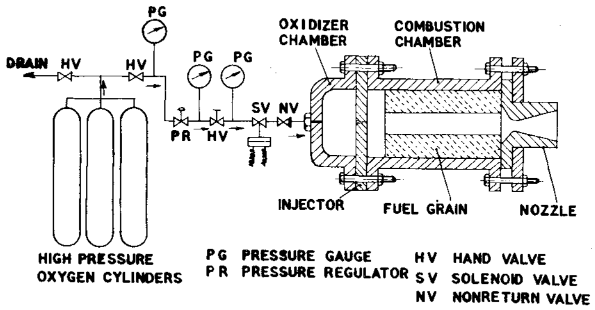

Fig. 1 Schematic diagram of experimental set-up.

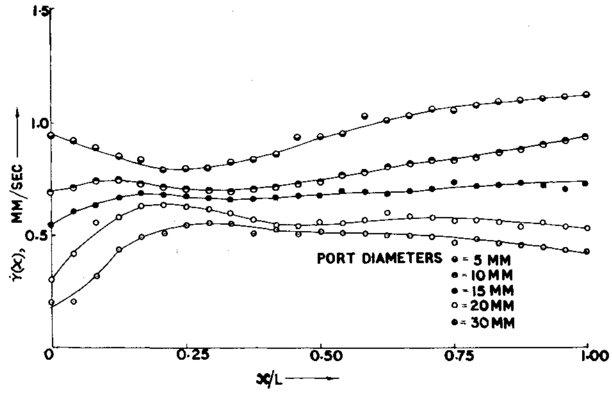

Fig. 2 Variation of local regression rates for various port diameters.

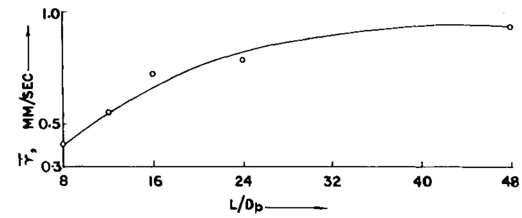

Fig. 3 Variation of average regression rates with port diameters.

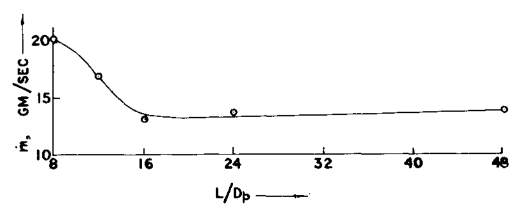

Fig. 4 Variation of fuel mass consumption rates with port diameters.

Results and Discussion

The local regression rates for different port sizes are shown in Fig. 2. The curve for 5 mm port diameter shows a good

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agreement with those obtained by Marxman et al.[2] for Plexiglass-O_2 system for the same duration of burning. However, the curve is flattened in case of 10 mm port diameter grain and a maximum regression rate is observed at $x/D_p \approx 3.5$ after which the regression rate is approximately constant. The curves for higher port diameters also show a similar trend.

The average regression rates for different port diameter grains are shown in Fig. 3. It is clearly indicated that the regression rate increases considerably as the L/D_p ratio increases. This is in agreement with the theoretical results,[2] where the fuel regression rate depends upon the oxidizer mass flux. For the same rate of oxidizer mass flow, the oxidizer mass flux decreases as the port area increases.

The fuel mass consumption rate for different port diameters have been presented in Fig. 4. The rate of fuel consumption is approximately constant for L/D_p ratio range of 16 to 48. This may be explained by the tendency of hybrid combustion in a stoichiometric ratio which depends upon the oxidizer mass flow rate. For higher port diameters, that is L/D_p ratio less than 16, the rate of heat transfer from the flame zone increases by increase of port surface area resulting in higher fuel mass consumption rate.

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Optimum Exhaust Velocity for Laser-Driven Rockets

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RECENT computer studies† of payload transfers from low Earth orbit to synchronous orbit and return via laser-driven rocket propulsion have shown that trip time reaches a minimum as specific impulse is varied. These minimums were obtained for constant exhaust-jet power and specified payload mass. The computations were based on the perigee-propulsion laser drive described in Ref. 1. The present Note shows that such minimums occur for all missions and that the optimum specific impulse is primarily determined by the mission difficulty. More generally, this optimum specific impulse maximizes payload kinetic energy achievable with a fixed jet power and propulsion time. These optimums differ from those obtained for low-thrust propulsion systems with on-board power.

The laser-driven rocket, in which remotely generated laser power is used to heat propellant,[2] belongs basically to the class of specific-impulse limited propulsion systems (Type I of Ref. 3) if difficult (high $-\Delta v$) missions are being considered. For more modest missions, however, specific impulses below the maximum achievable may well be optimum. The observed minimization of trip time as specific impulse is varied can be demonstrated from the basic rocket equation:

$$m_p/m_0 = 1 - e^{-\Delta v/v_j} \tag{1}$$

where Δv is the required velocity increment, determined by the mission, v_j is the exhaust jet velocity, m_p is propellant mass, and m_o is the initial mass. Equation (1) is valid for impulsive-thrust increments in gravitational fields or for any constant v_j thrust period in field-free space. For raising payloads in the Earth's gravitational field via laser-driven rockets, neither the impulsive-thrust nor the field free condition really applies very accurately, but the Δv in Eq. (1) can nevertheless be regarded as an effective mission-difficulty measure (of the order of 8 to 15 km/sec for the round trip to synchronous orbit). The total impulse needed for a given mission can increase by as much as a factor of two as thrust/mass ratio decreases.[4] But in the range of values possible for a particular propulsion system, the range of total impulse (and hence effective Δv) is quite small; hence Δv can be considered to be independent of v_j.

To express Eq. (1) in terms of propulsion time T_p and exhaust-jet power P_j we can write

$$m_o = m_{\text{pay}} + (1+k)m_p \tag{2}$$

$$m_p = \dot{m}_p T_p \tag{3}$$

$$\dot{m}_p = \frac{F}{v_j} = \frac{Fv_j}{v_j^2} = \frac{2P_j}{v_j^2} \tag{4}$$

$$P_j = \tfrac{1}{2}\dot{m}_p v_j^2 = \tfrac{1}{2}Fv_j \tag{5}$$

where m_{pay} is payload mass, $\dot{m}_p$ is propellant flow rate, F is thrust, and k is the ratio of propulsion system mass (including tankage) to propellant mass.

Introducing Eqs. (2-4) into Eq. (1) and solving for T_p yields

$$T_p = \frac{\alpha v_j^2}{2}\;\frac{1-e^{-\Delta v/v_j}}{(1+k)e^{-\Delta v/v_j} - k} \tag{6}$$

where $\alpha = m_{\text{pay}/P_j}$. For $k \ll 1$ (a reasonable approximation) Eq. (6) becomes

$$T_p = \frac{\alpha(\Delta v)^2}{2}\left[\frac{v_j}{\Delta v}\right]^2 (e^{\Delta v/v_j} - 1) \tag{7}$$

Assume that α and Δv are independent of v_j; then differentiation of Eq. (7) yields the following result for minimizing T_p as function of v_j:

$$e^x(2-x) = 2 \tag{8}$$

where $x = \Delta v / v_{j,\text{opt}}$.

The solution of Eq. (8) (other than $x=0$) is $x = 1.594$, or

$$v_{j,\text{opt}} = 0.627 \quad \Delta v \tag{9}$$

Thus the optimum v_j is directly proportional to Δv, and is independent of other variables. This result is simpler than that obtained for systems with onboard power sources (electric propulsion), for which optima depend on the specific mass of the power plant.[5] Using Eq. (9) in Eq. (7) yields:

$$T_{p,\min} = 0.773 \;\; \alpha(\Delta v)^2 \tag{10}$$

For the satellite raising mission ($\Delta v \approx 8$ to 15 km/sec), Eq. (9) yields optimum specific impulse in the range 500 to 1000 sec.

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