Fuel Regression and Flame Stabilization Studies of Solid-Fuel Ramjets

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An experimental investigation of solid-fuel ramjets (SFRJ) has been performed in order to determine the fuel regression behavior and flame stability limits. In order to investigate the fuel regression for various flight speeds and altitudes, chamber pressure, air mass flux, and inlet temperature have been varied over a wide range. The flame holding studies with a sudden-expansion dump combustor were aimed at minimizing the ratios of fuel port to nozzle throat area and fuel port to injector area. The standard fuel in this study was polyethylene (PE), whereas hydroxylterminated polybutadiene (HTPB) fuel was also investigated in a limited number of tests.

Nomenclature

A	= area
D	= diameter
$G_{air} = \dot{m}/A_3$	= air mass flux
h	= flameholder step-height
L	= length of fuel grain
L_r	= length of recirculation zone
M	= Mach number
$\dot{m}$	= air mass flow
p_c	= combustion pressure
$\dot{Q}_{con}$	= convective heat flow
$\dot{Q}_{rad}$	= radiative heat flow
$\bar{\dot{r}}$	= average regression rate
T_{tot}	= total temperature

Subscripts

2	= flameholder inlet
3	= fuel port
5	= nozzle throat

Introduction

IN order to be considered a serious alternative propulsion system, a Solid Fuel Ramjet (SFRJ) must operate within the flammability limits over the expected operating envelope of altitudes and Mach numbers. An advantage of the SFRJ is its potential for several different applications because of its inherent operational simplicity. Its performance is known to be comparable to that of liquid-fuel ramjets and ducted rockets. However, the mechanism of flame stabilization in the recirculation zone, flame propagation throughout the combustor, and the turbulent diffusion flame within the redeveloping boundary layer downstream of the reattachment point are still not well understood.

An impression of the complex nature of the flowfield in the dump combustor can be gained from the sketch of Fig. 1. Behind the rearward facing step, the recirculation causes intense mixing of fuel, air and, hot combustion products. Thus, the stabilized flame in the recirculation zone can propagate throughout the combustor. A minimum step-height is required to achieve sustained combustion. This minimum step-height is essentially dependent on the inlet air mass flow and temperature. It is highly desirable to know the limits of stable operation since inlet conditions change over a wide range during flight missions. Also, missile design engineers are interested in minimizing the required step-height in order to maximize pressure recovery, increase fuel loading and, thus, range. Combustion studies pertinent to flame stabilization have been reported by different authors.[1,2]

Another point of interest for the recirculating flowfield is the variation of the recirculation zone length with changes in the flameholder step-height. Although no true reattachment point can be defined because of mass addition from the solid fuel walls, it is possible to create a zone where effective reattachment does occur. With increasing step-height the length of the recirculation zone increases. Our own experimental results are compared with experimental and theoretical data of other authors.[2-4]

The second important combustion zone can be described by a turbulent diffusion flame within the redeveloped boundary layer downstream of the reattachment point. Fuel vapors from the surface and oxygen-rich gases from the core flow diffuse from opposite sides into the boundary layer. This diffusion-controlled flame is sustained by the hot combustion products of the recirculation zone, which are partly mixed with the incoming core flow. The amount of vaporized fuel is determined by the convective and radiative heat transfer from the diffusion flame to the fuel surface. The dominant parameters for the heat transfer or total amount of vaporized fuel are the air mass flux, chamber pressure and, air inlet temperature. Heat transfer occurs mainly by convection, but radiative heat transfer is not negligible, especially when large amounts of soot are formed near the solid fuel surface.[1,5,6] The solid fuel regression rate is, therefore, strongly influenced by different flight conditions. Some data have been published on the regression behavior in SFRJ,[4,7] but data are lacking for higher air inlet temperatures and mass fluxes.

Experimental Hardware

The connected-pipe test facility is shown in Figs. 2 and 3. The air flow system and air heater are designed to simulate a range of flight conditions up to flight Mach numbers of 3.3 at sea level and Mach 4 for heights between 10 and 25 km. With the help of the high-pressure air, hydrogen, and oxygen supply systems, it is possible to heat air with flow rates up to 5.5 kg/s, attaining a maximum temperature of 900 K. The hydrogen/oxygen air heater consists of ten burners which are distributed on the circumference. By choosing the number of burners, a wide range of power can be realized. The maximum amount of water vapor in the air on account of combusting hydrogen and oxygen is about 6% of the total mass flow. Oxygen is replenished, so that the amount of oxygen is kept constant at 23% of the total air mass flow for all inlet air

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temperatures. After igniting the hydrogen/oxygen air heater, a desired constant air inlet temperature at ramjet inlet is reached in between 1 and 2 s.

The experimental ramjet motor consists of four main sections: the step insert section (flameholder), the solid fuel grain, the afterburner chamber, and the nozzle. The length of the fuel grain (L) can be varied up to 1 m. With different flameholder inserts and nozzles, ratios of grain port to flameholder area between 1 and 5 and ratios of grain to nozzle throat area between 1 and 4 can be investigated. For ignition of the solid fuel, either a pyrotechnic (mixture of aluminum and teflon powder) or a H_2/O_2 spark torch igniter is used.

The air heater and the ramjet motor are mounted on a thrust stand as shown in Fig. 3. For test interpretation, the air, hydrogen, and oxygen flows are measured by sonic nozzles. Pressures are measured upstream and downstream of the flameholder and at the end of the fuel grain and afterburner chamber; whereas, the air inlet temperature is measured by thermocouples. The measuring locations are indicated in Fig. 2. A typical burning time for the investigations in this study was between 30 and 40 s.

Test Results and Discussion

The intent of this effort, as noted in the Introduction, was to conduct a parametric study of the solid fuel regression behavior and the flameholder blow-off limits in order to supply a broad research data base.

Length of the Recirculation Zone

A series of combustion tests was evaluated to determine the length of the recirculation zone behind the step inlet. The location of the reattachment point can be determined after a test

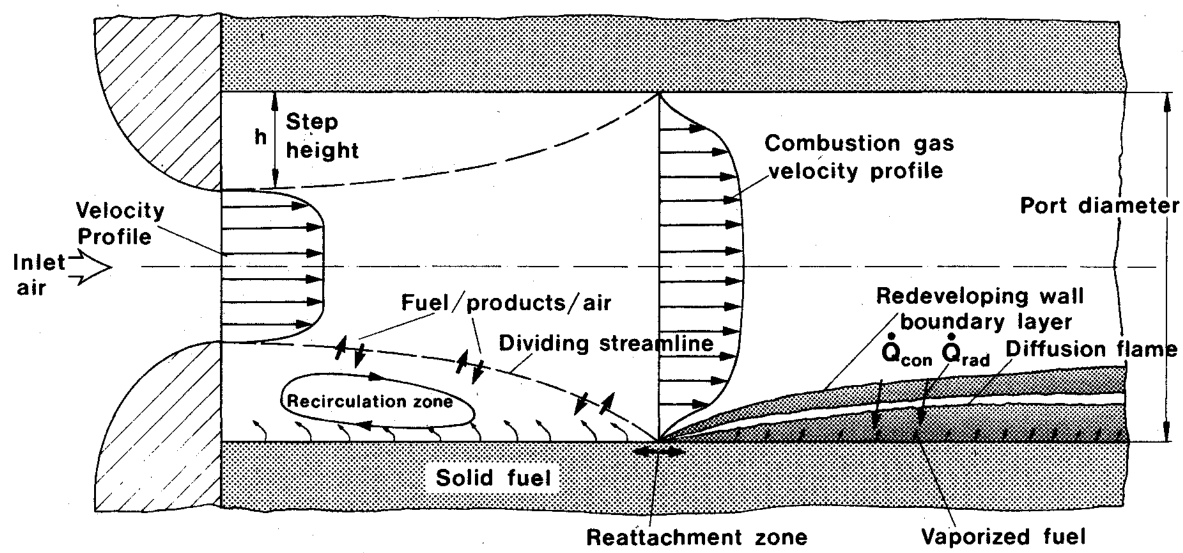

Fig. 1 Schematic illustration of SFRJ dump combustor flowfield.

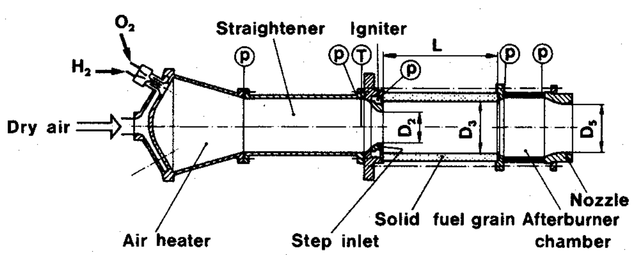

Fig. 2 Schematic of SFRJ and air heater.

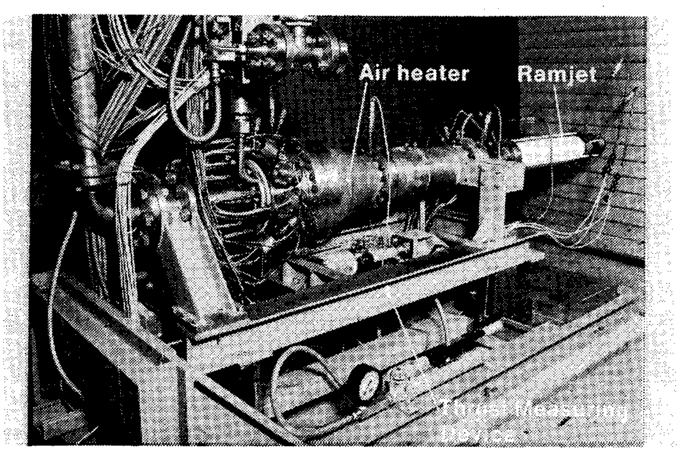

Fig. 3 Photographic view of test hardware.

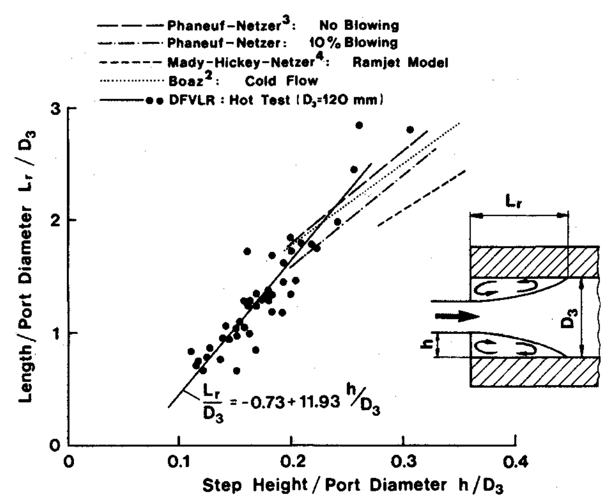

Fig. 4 Reattachment locations for axisymmetric flows.

Table 1 Regression rate approximation for PE/AIR

	Empirical power law	Constant	Motor size D_3, mm
Fig. 5	$\dot{r} = 0.008 \cdot p_c^{0.28} \cdot T_{2,tot}^{0.50}$	$G_{air} = 25.0$	60
Fig. 6	$\dot{r} = 0.013 \cdot p_c^{0.26} \cdot T_{2,tot}^{0.42}$	$G_{air} = 36.0$	120
Fig. 7	$\dot{r} = 0.066 \cdot p_c^{0.39} \cdot G_{air}^{0.26}$	$T_{2,tot} = 673$	120

Note: $\dot{r}$(mm/s)/p_c(bar)/$T_{2,tot}$(K)/G_{air}(g/cm^{2}s).

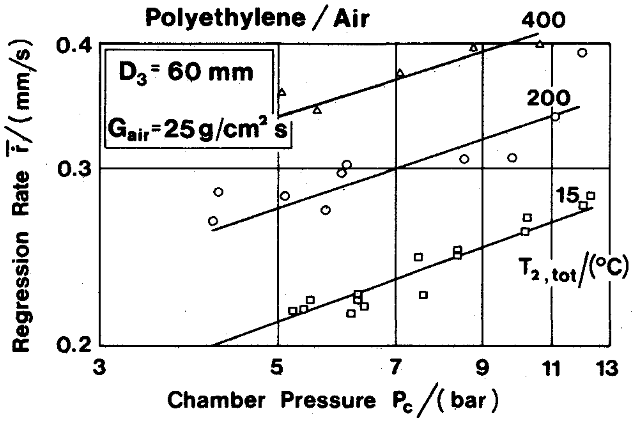

Fig. 5 Regression rate vs chamber pressure for various air inlet temperatures.

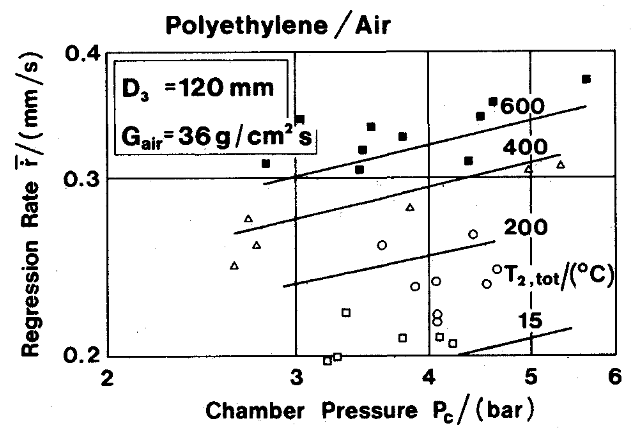

Fig. 6 Regression rate vs chamber pressure for various air inlet temperatures.

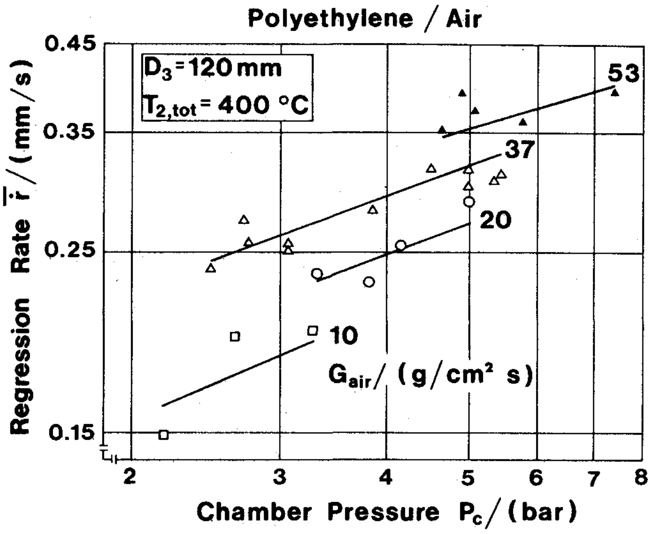

Fig. 7 Regression rate vs chamber pressure for various mass fluxes.

run because the markings of the flow pattern on the polyethylene fuel surface are preserved. With increasing step-height, the reattachment point moves downstream as shown in Fig. 4, where the step-height and the length of the recirculation zone is nondimensionalized by the port diameter. A linear approximation of 44 data points resulted in the expression $L_r/D_3 = -0.73 + 11.93\ h/D_3$. The relatively large scatter of the data points is due to the fact that the point of transition from the recirculation zone to the redeveloping boundary layer is not always plainly evident on the fuel surface. The results of other investigations are included in Fig. 4 for comparison. Other authors[2,3] have investigated nonreacting flows. The experiments with 10% blowing and the ramjet model by Netzer et al.[4] show somewhat shorter recirculation zone lengths for the same step-heights than the nonreacting flow results. For step-height to port diameter ratios smaller than 0.2, this study indicates a tendency toward smaller recirculation zones in comparison to the results of other authors. Cold flow studies typically showed a ratio of $L_r/h = 8$ to 9, whereas in this study a ratio of 6 to 9 was found.

Regression Rate

For the fuel regression rate study, different parameters were investigated. The rate of decomposition of the solid fuel mainly depends on the combustion pressure, air mass flux and air inlet temperature. The average regression rate was determined by weighing the fuel grain prior to and after each run.

Figures 5 and 6 show plots of the regression rate vs the chamber pressure and different air inlet temperatures with air mass flux held constant. The indicated fuel port diameter is the initial port diameter. The regression rate can be approximated by an empirical power law

$$\bar{\dot{r}} = a \cdot p_c^b \cdot G_{air}^c \cdot T_{2,tot}^d$$

The results of this approximation for the two investigated ramjet sizes is presented in Table 1. The power law is valid only for the data reported, and extrapolations should be done with caution. The influences of pressure and air inlet temperature in Figs. 5 and 6 are similar. By comparing the regression rates of the two different engine sizes, the additional effect of the port diameter becomes obvious. The fuel port diameter of 60 and 120 mm led to a variation in the regression rate of the order of $\bar{\dot{r}} \simeq D_3^{-0.23}$. With increasing port diameter, the regression rate decreases if all other influence parameters are held constant. This may be caused by a diminished heat transfer to the fuel surface due to an increased flame distance to the surface with growing fuel port sizes. A somewhat larger effect of the port diameter on the regression rate is reported in Ref. 8. However, they used a polybutadiene fuel (in contrast to the polyethylene used in this study) over a range of engine diameter between 100 and 260 mm. Figure 7 presents data obtained by varying the air mass flux with air inlet temperatures held constant. The power law approximation for the regression results in chamber pressure had larger influence than mass flux (Table 1).

Regression rate studies[4,7] with a polymethylmethacrylate (PMMA) fuel reported a stronger influence of mass flux $\bar{\dot{r}} \sim G_{air}^{0.38-0.41}$ and a weaker influence of air inlet temperature $\bar{\dot{r}} \sim T_{2,tot}^{0.34}$, whereas the pressure influence is reported by $\bar{\dot{r}} \sim p_c^{0.29-0.51}$. Only a rough comparison is possible because of difference in range and configurations.

Flameholding Limits

An experimental investigation has been conducted to appraise the stable operating range of a SFRJ. The combustion or flameholding limits were investigated for different air inlet temperatures, various ratios of fuel port area to nozzle throat area (A_3/A_5) and fuel port area to flameholder area (A_3/A_2). In Fig. 8 stable and unstable ranges for four different air temperatures are shown. Stable ranges can be defined as supercritical area ratios with sustained combustion after ignition, whereas unstable ranges or subcritical cases (shaded area, Fig. 8) represent blow-off conditions for any given temperature. With increasing air temperature the stable operating range is extended. At an air temperature of 600 °C, the required flameholder step-height goes to zero and the conditions of self-ignition are satisfied. The tests to determine the flameholding limits were conducted by starting with a stable operating condition for the area ratios for a given air inlet

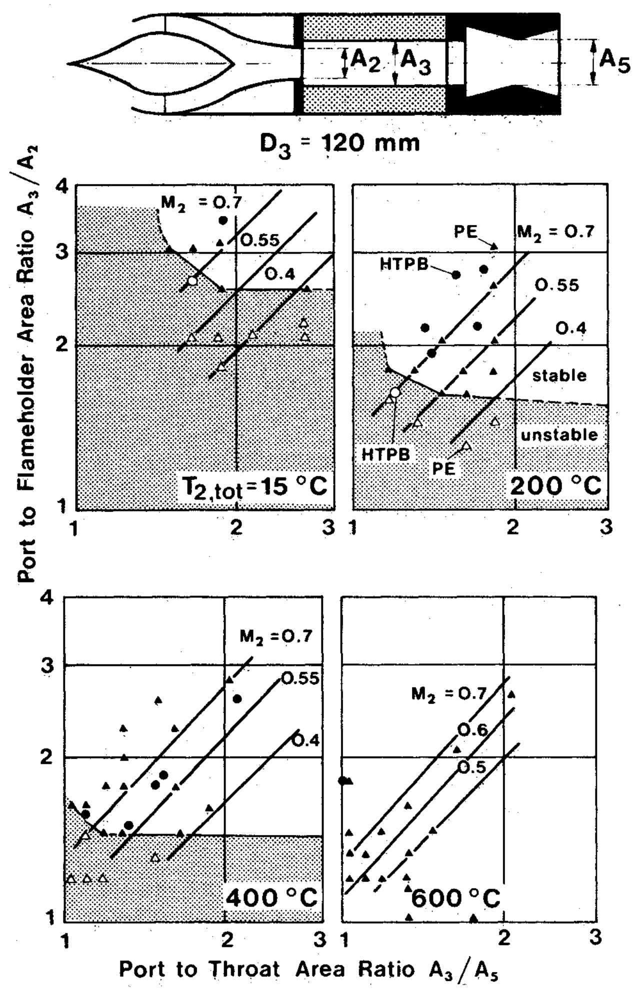

Fig. 8 Effect of air inlet temperature on flameholding limits (shaded area = unstable operation).

temperature. Then the nozzle throat and flameholder area ratio was reduced until stable combustion was no longer possible. Combustion termination was characterized by blow-off after burnout of the igniter. Flameholder and nozzle were changed step by step by keeping the flameholder Mach number M_2 constant. The majority of the tests were conducted with a polyethylene fuel. A limited number of tests with another hydrocarbon fuel (HTPB) were made and similar behavior seemed to prevail. These tests show that the flameholding limits are not very sensitive to changes in the fuel, although more experiments are necessary to verify this conclusion.

The initial port diameter for the fuel grain of all data points in Fig. 8 was about 120 mm. Preliminary experiments with a smaller motor size ($D_3 = 60$ mm) showed deviating flameholding limits, in so far as the area ratios A_3/A_2 and A_3/A_5 necessary for flame stabilization increased for decreasing fuel port diameters. For air inlet temperatures of 15 and 200 °C a comparison of the flameholding limits of the two motor sizes are shown in Fig. 9. This trend is in accordance with results for a smaller combustor.[8]

Summary

For two different ramjet sizes, an experimental study of the regression rate of a polyethylene fuel showed a similar behavior over a wide range of air inlet temperatures, mass fluxes, and chamber pressures. The dependance on mass flux

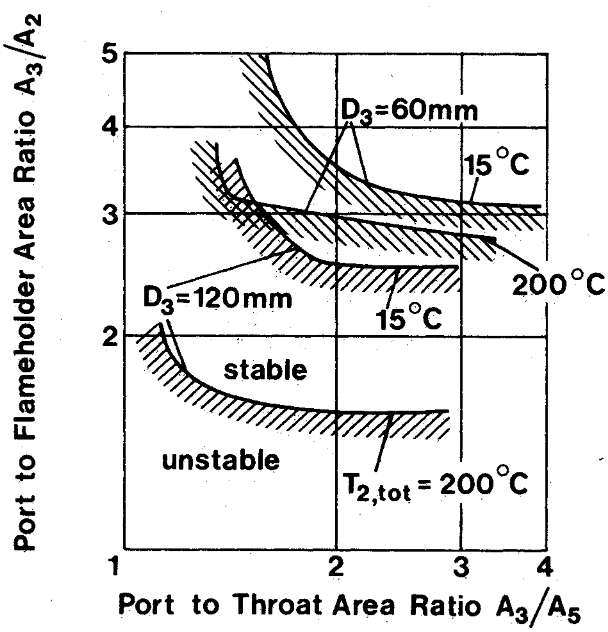

Fig. 9 Comparison of flameholding limits of two motor sizes.

and chamber pressure is somewhat weaker than on air inlet temperature. With increased port diameter of the solid fuel grain, the average regression rate is reduced because of a diminished heat transfer to the wall.

The length of the recirculation zone increases approximately linearly with the inlet step height and was found to be 6-9 step-heights long.

For a polyethylene fuel, the flameholding limits could be represented by expressing the ratios of port to flameholder area and port to nozzle throat area as a function of air inlet temperature. With increasing air inlet temperature the stable operating range is found to exend. Thus, fuel loading can be increased and flameholder pressure losses are reduced. Since with increased fuel loading and decreased pressure losses the motor performance can be improved, the flameholding limits play an important role in designing a ramjet motor.

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