Burning and Flameholding Characteristics of a Miniature Solid Fuel Ramjet Combustor

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The objective of this research was to characterize the combustion and flameholding limits in solid fuel ramjet combustors of particularly small size (10 mm i.d.). The main combustion characteristics, as well as the specific effects resulting from the special size range, are pointed out. Several hundred static tests were performed with three different fuel types, polymethylmethacrylate (plexiglass), polyethylene, and polybutadiene. Air inlet temperatures of 800 K, 520 K, and room temperature were tested to simulate flight Mach numbers of 3, 2, and low subsonic, respectively. All three fuels exhibited very good flameholding capability at the higher air temperature (800 K). The flammability limits decreased at 520 K and became very narrow at room temperature. The flameholding capability also deteriorated with decreasing combustor size. The flow-reattachment distance, coinciding with the maximum fuel regression rate zone, was shown to be proportional to the inlet step height and was independent of fuel type and port-flow Reynolds number.

Nomenclature

A = area
d = diameter
F = thrust
G = mass flux
H = step height
k = thermal conductivity
M = Mach number
m = exponent
$\dot{m}$ = mass flow rate
n = exponent
p = pressure
Q = heat capacity (sensible enthalpy)
$\dot{Q}$ = heat loss rate
$\dot{q}$ = heat flux
Re = Reynolds number
$\dot{r}$ = fuel regression rate
T = temperature
V = volume
x_r = reattachment distance

Subscripts

a = air
in = air inlet
min = minimum
p = port
rz = recirculation zone
t = nozzle throat
w = wall

Superscript

$\bar{}$ = mean

Introduction

THE ramjet engine is a simple air-breathing propulsion system using the aerodynamic compression principle. It may be suitable for a variety of missions in the supersonic flight speed range, demonstrating energetic advantages (much higher specific impulse) over rockets and simplicity compared to turbojet engines. Solid fuel for such an engine is usually a hollow cylinder attached to the inside wall of the combustion chamber, and the incoming air flows through its port. This configuration simplifies the engine by avoiding the fuel storage, feeding, and injection systems. A schematic diagram of a solid fuel ramjet (SFRJ) combustor presenting the main geometry, combustion, and flow features is shown in Fig. 1. The SFRJ is basically a dump combustor. As a result, the flowfield includes several distinct zones: a recirculation separated-flow region at the head-end of the combustor followed by a reattachment zone; and a redeveloping boundary layer further downstream, where a diffusion flame between the decomposing fuel gases and the air takes place.

Small-scale SFRJ combustors may be considered for certain missions, especially for self-propelled projectiles. In addition, increased fuel burning rates are expected from smaller port diameters for the same flow conditions. Nevertheless, even though there have been indications that different burning characteristics may be expected in the small-size range,[1,2] only minimal data on motors having diameters smaller than 30–40 mm can be found in the literature.[3,4]

The objective of this research was to characterize experimentally the combustion and flameholding envelope in particularly small-size combustors (10 mm i.d.). Effects of inlet air temperature, fuel type, and relative step height on the flammability limits and fuel regression rate were investigated. Combustor-size influence on flameholding capability was demonstrated.

The flameholding mechanism in the SFRJ is based on the sudden expansion of the incoming air (see Fig. 1). The flow

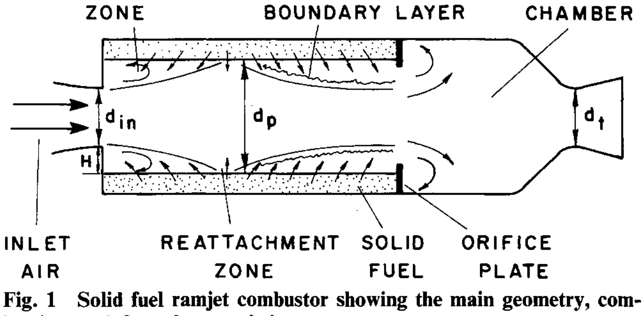

Fig. 1 Solid fuel ramjet combustor showing the main geometry, combustion, and flow characteristics.

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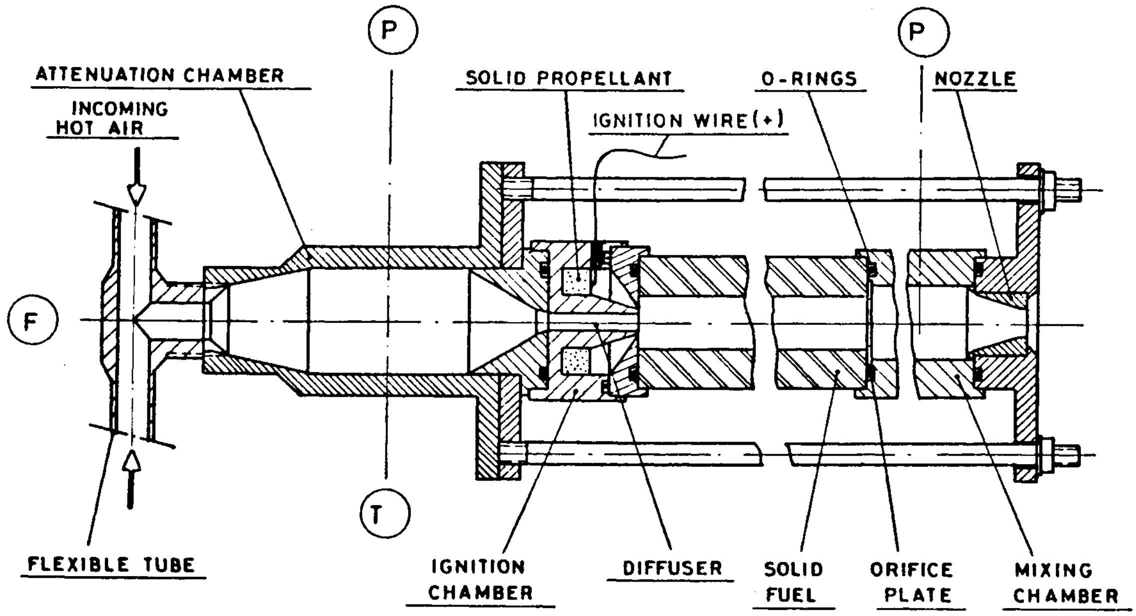


Fig. 2 Test combustor.

recirculation zone formed serves as a hot gas body, often fuel rich, of relatively low flow velocities. The inlet step acts like other bluff-body-type flameholders. Flameholding analyses[5,6] developed for premixed combustors consider the existence of the recirculation zone essential for flame stabilization. Models requiring, for example, equality between characteristic residence and chemical times (expressed by the so-called first Damköhler similarity group) lead to a linear proportion between the blowoff velocity and the flameholder size for similar pressures and fuel/air ratios. Experimental data reported by DeZubay[7] generally agree with this trend. In the case of the SFRJ, the recirculation zone length has been found to be proportional to the step height.[2,8] Hence, larger step heights generate larger recirculation zones with a better flame-stabilizing effect. Nevertheless, from an operational standpoint, small step heights are advantageous, as they allow larger amounts of solid fuel to be placed in a given combustion chamber. Thus, the knowledge of the flameholding limits in terms of the minimum step heights required for sustained combustion is important design information. Some other factors are also known to affect flameholding capability. Higher flow velocities in the combustor port narrow the stable combustion envelope, whereas higher inlet air temperatures increase the flame stabilization.[1,2] It has also been indicated that the smaller the motor size, the more difficult establishing a self-sustained combustion becomes.[2]

Experimental System and Procedure

The static test system is described in detail in Refs. 3 and 4. A specially built 30-kW electric heater and water-cooled three-way valve provided the necessary controllable hot, high-pressure pure airflow rates (as high as 40 g/s). The combustor is shown in Fig. 2 along with the solid-propellant igniter and the modular air injector (air inlet), permitting testing with different inlet diameters. The air injector consisted of a converging section (half-angle 30 deg) downstream of a 20-mm-diam plenum chamber, followed by a 20–26 mm-long cylindrical section. No measurements were taken of the pressure and velocity distributions or turbulence level at the inlet. Inlet, as well as port, Reynolds numbers (above 50,000) indicate the turbulent nature of the flow. In the present tests, fixed initial geometry (i.e., 10 mm i.d. and 70 mm long) fuel grains were used. The combustor included an aft-mixing-chamber, 40 mm long and 14 mm i.d., located downstream of the fuel grain, and an orifice plate 9–10 mm i.d., between the fuel grain and the mixing chamber. Inlet air pressure and temperature, airflow rate, chamber pressure, and thrust were measured continuously during the tests.

Three different hydrocarbon (HC) polymeric fuel types, polymethylmethacrylate (PMMA, plexiglass), polyethylene (PE), and a polybutadiene/polystyrene (PB/PS) mixture (approximately 3/1) at three air inlet temperatures, 800 K (simulating flight Mach number of 3 at sea level), 520 K ($M = 2$), and room temperature, were investigated. Numerous (about 300) motor-firing tests were conducted.

Flameholding limits were obtained from "go/no-go" type tests, i.e., tests exhibiting sustained combustion were considered within the flameholding envelope, whereas those resulting in no ignition were considered out of the flameholding limits.

Average fuel regression rates (in respect to time and axial location) were calculated from the overall fuel mass loss during the combustion. Local regression values were obtained from direct measurements of the local port diameter after burnout. These measurements also revealed the axial location of maximum regression. Short burn-time tests (typically 2 s) were conducted in order to minimize the variations of the port diameter and cylindrical shape during combustion.

Results and Discussion

Flameholding Limits

It is common to describe the flameholding envelope of an SFRJ engine (defined by the conditions necessary for stabilized, self-sustained combustion) in terms of the ratio of the fuel-port area to the air-inlet area, A_p/A_{in} (representing the step height), and the ratio of the fuel-port area to the nozzle-throat area, A_p/A_t (representing the gas-flow velocity inside the combustor).[1,2] This approach is, in essence, a different way to represent the two main parameters used in other analyses.[5–7] Pressure was kept at an intermediate range (0.3–1 MPa), where its effect is less pronounced than at lower values. Inlet air temperature was used as a parameter and exhibited a significant influence.

Figure 3 shows the flameholding limits obtained with PMMA fuel at two inlet air temperatures, 800 and 520 K. Similar tests were also conducted with two other fuels, PE and PB/PS, and included air at room temperature as well. Figure 4 summarizes on one plot the flameholding limit results for all fuels tested with the inlet air temperature as a parameter.

As shown in Figs. 3 and 4, all three fuels exhibited very good flameholding capability at the higher air temperature (800 K). Port-to-inlet-area ratios larger than 1.2–1.8 (depending on the fuel type) enabled self-sustained combustion, even for $A_p/A_t = 1$. For sufficiently large A_p/A_t ratios, stable combustion could be obtained for $A_p/A_{in} = 1$, namely, for zero step height. This result, in essence, indicated that there are almost no practical limitations for systems operating at inlet air temperatures of 800 K and above. Similar general behavior was reported by Schulte[2] for larger combustors (120 mm i.d.) employing polyethylene at about 870 K and chamber pressures of 0.25–0.6 MPa. Yet, Fig. 4 shows that the polybutadiene-based fuel, PB/PS, exhibited better flameholding capability both in respect to the step height as well as the port-to-nozzle-throat area ratio. This may be because of the higher regression rates of this fuel compared to others, resulting in richer fuel/air mixtures at the recirculation region.

One should note that flameholding, and even autoignition of the fuel because of high inlet temperatures, do not necessarily guarantee high combustion efficiency. It has been demonstrated, however, that in this test system, good combustion efficiency (90% in the average) may be ensured by including a mixing plate and an aft-mixing-chamber.[3,4]

Significant deterioration in the flameholding capability was observed at the lower air temperature (520 K). Tests performed with inlet air at room temperature (290 K) revealed even narrower flammability limits associated with step heights, which may be impractically large. These trends with the inlet air temperature agree well with flameholding theories. Higher temperatures increase reaction rates and shorten the characteristic chemical times. Hence, as implied by the first Damköhler number, higher blowoff velocities, as well as the need for smaller step heights, are expected. Notably, PMMA flameholding capability was particularly inferior at

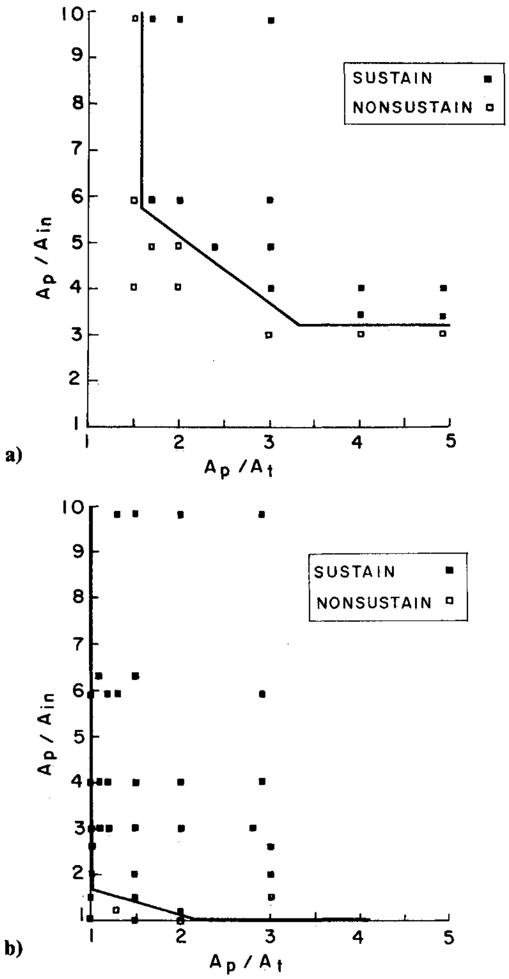


Fig. 3 Flameholding data of PMMA at two (total) air inlet temperatures: a) 520 K and b) 800 K.

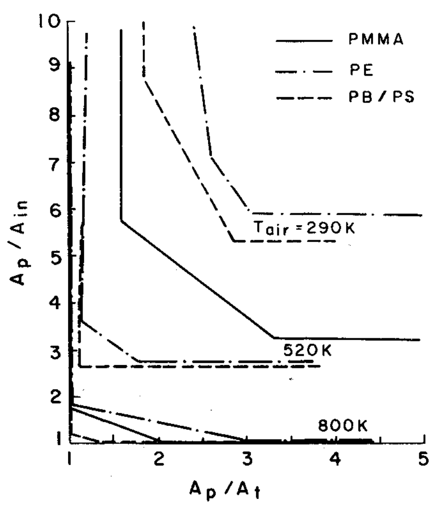
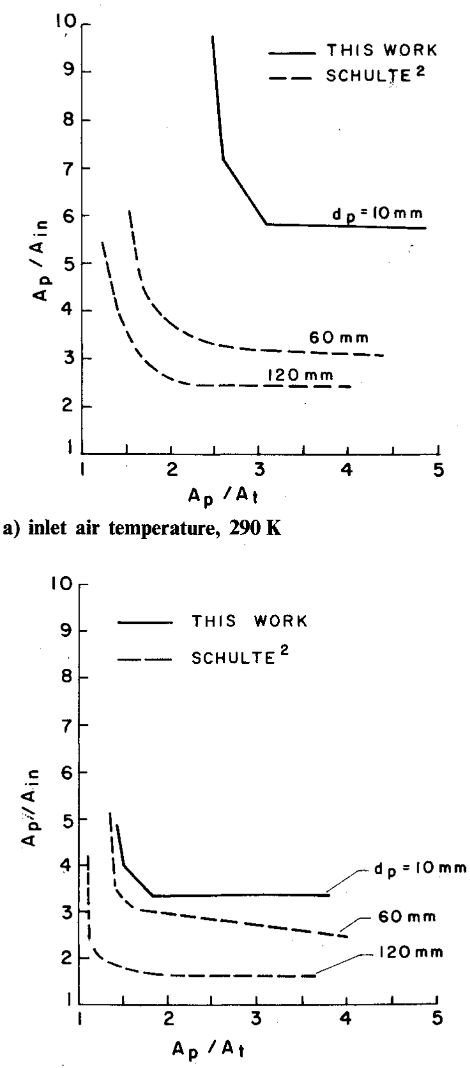


Fig. 4 Flameholding limits for PMMA, PE and PB/PS as a function of inlet air temperature.



a) inlet air temperature, 290 K

b) inlet air temperature, 470 K

Fig. 5 Combustor-size effect on flameholding of polyethylene.

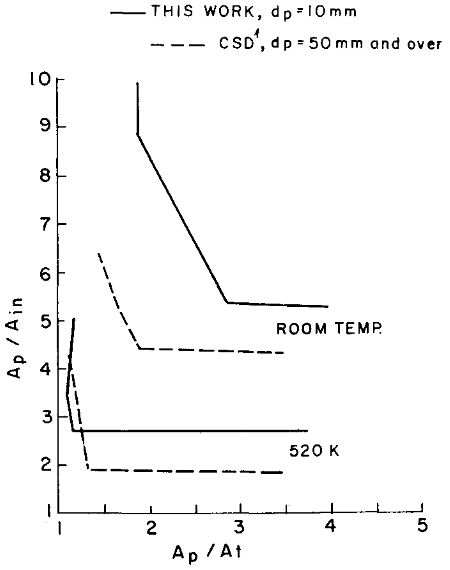
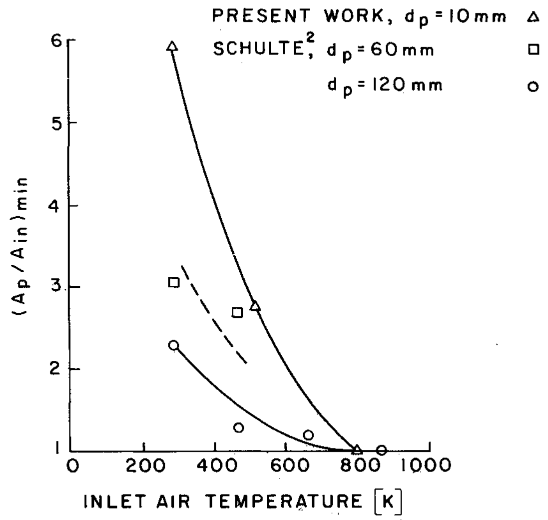
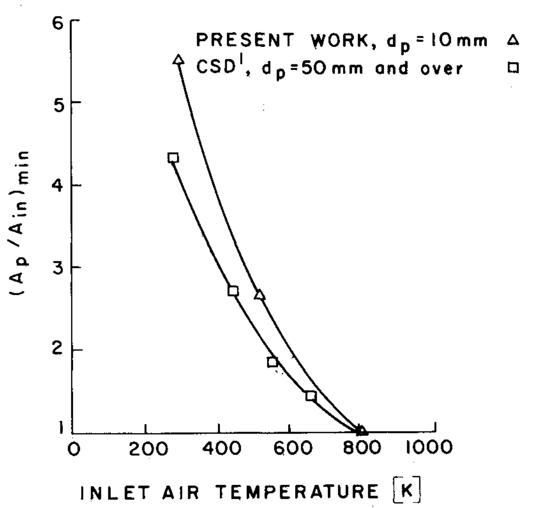


Fig. 6 Combustor-size effect on flameholding of polybutadiene-based fuels.



a) polyethylene



b) polybutadiene

Fig. 7 Inlet air-temperature effect on the minimum port-to-inlet-area ratio for sustained combustion.

low temperatures. At room temperature, it was impossible to get ignition of PMMA, even for port-to-inlet-area ratio of 9. One may speculate that such behavior is a result of two main reasons. First, the relatively low regression rates and the high

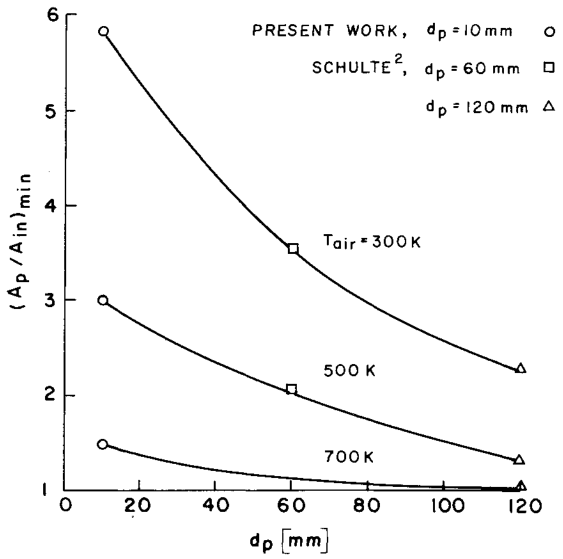


Fig. 8 Combustor-port-diameter effect on the minimum port-to-inlet-area ratio (fuel polyethylene).

value of stoichiometric fuel/air ratio of PMMA (0.121) compared to regular HC fuels result in leaner mixtures at the recirculation zone, as indicated by the overall fuel/air ratios. Second, the heat of combustion of PMMA in air is about 30% less than that of the other HC fuels tested.

The data gathered in these miniature SFRJ combustors permitted comparison with data available on larger combustors.[1,2] Figure 5 compares the flameholding limits of polyethylene in 10-mm, 60-mm, and 120-mm diam combustors at 470 and 290 K, approximately, and at similar pressures. A similar comparison is made in Fig. 6 for polybutadiene-based fuels using data reported by the Chemical Systems Division of United Technologies (CSD)[1] for large combustors. Reference 1 presents only size and pressure ranges rather than exact values (i.e., 50–270 mm port diam and 0.15–3.8 MPa, approximately).

It is now possible to demonstrate the air-temperature and combustor-diameter effects on the flameholding capability by presenting the minimum inlet step required for sustained combustion in different conditions. Figure 7 shows the variation of the minimum A_p/A_{in} ratio required with the inlet air temperature for different combustor sizes. Figure 8 reveals the effect of the combustor size on the minimum step height required at different air temperatures. From Figs. 7 and 8, one can see the significant effect of the inlet air temperature on the flameholding capability, particularly in the low-temperature (low Mach number) range. The temperature influence diminishes for high inlet air temperatures and becomes almost insignificant above 800-900 K, corresponding to flight Mach numbers of 3 and above at sea level. This observation is reflected by the fact that at this inlet air temperature, the minimum possible port-to-inlet-area ratio of 1 (i.e., zero step height) is reached. Note that the same behavior is observed for both PE- and PB-based fuels. Furthermore, the combustor size has a very prominent effect on the flammability limits at the lower air-temperature range. This effect was found to diminish, just like the temperature effect at the high air-temperature range, i.e., at high flight Mach numbers. For combustor diameters between 10 and 120 mm, the size effect almost vanishes for air temperatures higher than about 900 K.

The effect of combustor size (and also to some extent the air temperature) on the flameholding capability are believed to be associated with the following general mechanism. Besides the need for a low flow velocity zone, an important factor in the flameholding mechanism may be the heat capacity (i.e., the total sensible enthalpy) in the recirculation zone. This sensible enthalpy provides an "anchor" and continuous reignition source for the flame in the combustor volume. Obviously, the heat capacity and, hence, the anchoring capability of the recirculation zone decrease with decreasing the step height because of the decreasing volume of the recirculation zone. In addition, the heat content is affected by the balance between the rate of energy added to the recirculation zone and the rate of heat loss.

Energy is added to the recirculation zone by heat transfer, particularly from the exothermic reactions in the shear layer at the interface between the recirculation zone and the inlet airstream, and by the heat generation by chemical reactions within the recirculation zone itself. Heat is lost from the recirculation zone primarily by forced convection to the wall (particularly when dealing with HC fuels exhibiting low radiative combustion). Obviously, the heat capacity of the recirculation zone is higher for higher air temperatures, as the basic energy level of the gases is then higher. (In the extreme case of a very high inlet air temperature, this in itself may be sufficient to maintain combustion in the chamber.)

Changing the combustor size causes changes of the heat balance in the recirculation zone. For smaller port diameters, deterioration of the flameholding capability is a result of the smaller ratio between the heat capacity and the rate of heat loss, which in turn is the result of the smaller ratio between the recirculation zone volume and the wall surface area.

One can reach this conclusion by a simple analysis as follows: for geometric similarity conditions (constant A_p/A_{in}), the step height is proportional to the port diameter. Because the recirculation zone length was found to be proportional to the step height,[2,8,9] then

$$V_{rz} \propto d_p^3 \tag{1}$$

For a given gas temperature in the recirculation zone,

$$Q_{rz} \propto d_p^3 \tag{2}$$

In the case of a similar heat flux to the wall, the total heat loss $\dot{Q}_w$ from the recirculation zone is proportional to the wall area A_w (outer surface), which is relative to d_p^2. Hence, the ratio between the heat capacity and the heat loss is

$$Q_{rz}/\dot{Q}_w \propto d_p^3/A_w \propto d_p \tag{3}$$

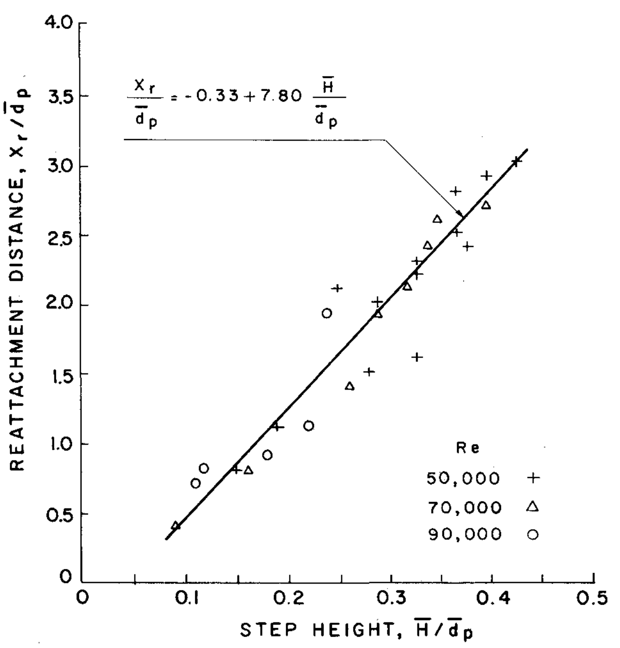


Fig. 9 Correlation between the reattachment distance and the step height (polybutadiene-based fuel at air temperature of 800 K).

namely, the smaller the combustor diameter, the smaller the ratio between the heat capacity and the heat-loss rate.

The situation can be shown to be even more sensitive to the port diameter. The heat flux was shown to be approximated by[3,4]

$$\dot{q} \propto G^n d_p^{n-1} \tag{4}$$

When comparing combustors operating at the same mass flux (G) conditions, taking into account the different surface area, one gets

$$\dot{Q}_w \propto d_p^{1+n}, \qquad G = \text{const} \tag{5}$$

hence,

$$Q_{rz}/\dot{Q}_w \propto d_p^{2-n}, \qquad G = \text{const} \tag{6}$$

Since n is expected to be smaller than 1, Eq. (6) expresses an even stronger effect of the combustor port diameter on the flameholding capability than Eq. (3). In the particular case of $n = 2/3$ reported by Krall and Sparrow,[9] it implies

$$Q_{rz}/\dot{Q}_w \propto d_p^{4/3}, \qquad n = 2/3 \tag{7}$$

The Reattachment Distance

The reattachment distance x_r determines the recirculation-zone length and, hence, plays a role in the flameholding phenomena. It has been shown that the reattachment point coincides with the local maximum heat-transfer rate to the wall in nonreacting flows at no-blowing situations.[9] Although some change in the nature of the recirculation zone is expected in the presence of wall blowing,[10] one can assume that the reattachment point in SFRJ combustors coincides with the maximum fuel regression rate location. This point was used to determine the reattachment distance.

Normalizing the reattachment distances and the step heights to the port diameter enables the comparison of motors of different sizes. In the following analyses, the average values of the step height and the port diameter during each test were used. Note that because of the step-height increase during the motor operation, the reattachment point tends to move downstream. Hence, this movement may cause some scattering in the results and may introduce some uncertainty as to the exact conditions (e.g., step height and port diameter) corresponding to the measured reattachment location.

The study examined the effect of different parameters on the reattachment distance. The effect of the port Reynolds number was studied by holding other parameters, such as fuel type and inlet air temperature, constant. Figure 9 displays the dependence of the reattachment distance on the step height for polybutadiene-based fuel with air temperature of 800 K at different port Reynolds numbers. This figure does not indicate any pronounced effect of Reynolds number on the reattachment distance. The same conclusion can be reached from correlations of other fuels and other air-temperature conditions. Figure 10 displays about 100 test points obtained from a variety of test conditions, including different fuels and various air temperatures over a range of Reynolds numbers. One can see that there is no distinct influence of any of these parameters on the correlation between the normalized reattachment distance and the mean step height. The best-fit straight line can be approximated by

$$x_r/\bar{d}_p = -0.64 + 9.24\bar{H}/\bar{d}_p \tag{8}$$

However, most experimental data would be placed within the range

$$6\bar{H}/\bar{d}_p \le x_r/\bar{d}_p \le 9\bar{H}/\bar{d}_p \tag{9}$$

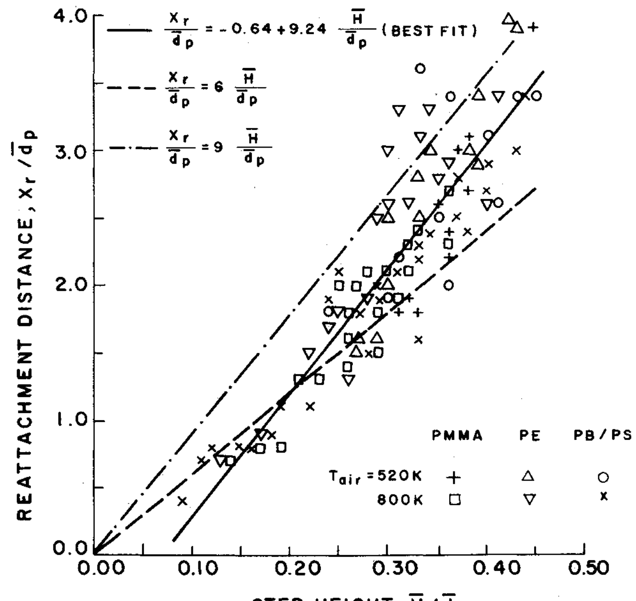


Fig. 10 Reattachment distance vs step height at a variety of test conditions.

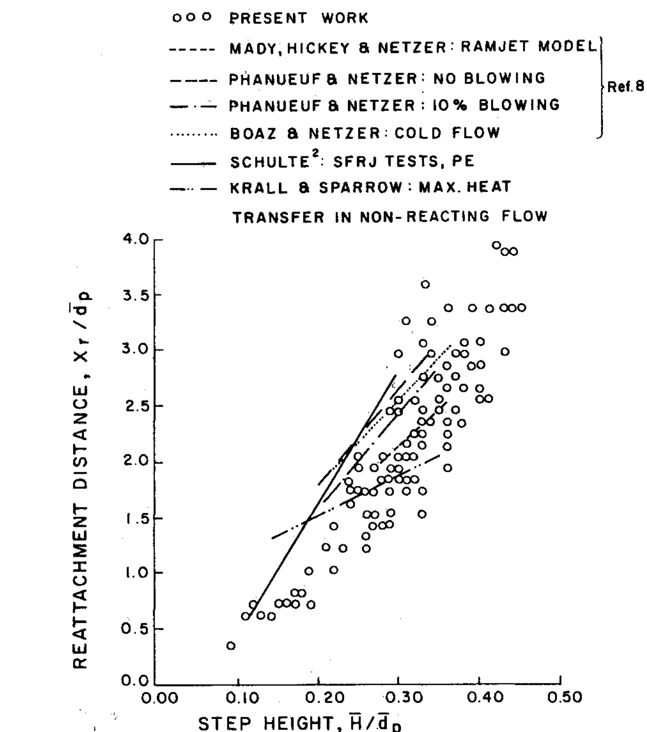


Fig. 11 Experimental data on the normalized reattachment distance vs the normalized step height.

in accordance with other investigations.[2,8,9,11] A comparison between this work and other investigations is given in Fig. 11. The general trend is similar, indicating that there is no appreciable size effect on the reattachment distance correlation. The very wide range of results obtained in the present work (almost the entire possible range) should be noted.

Fuel Regression Rate

Besides the commonly used correlations between the average fuel regression rate $\dot{r}$ and the air mass flux G in the combustor port, the effect of several other parameters was investigated.

Chamber pressure was found to have practically no measurable effect on the fuel regression rate for pressures of 0.3–1.0 MPa approximately. This behavior was typical for all

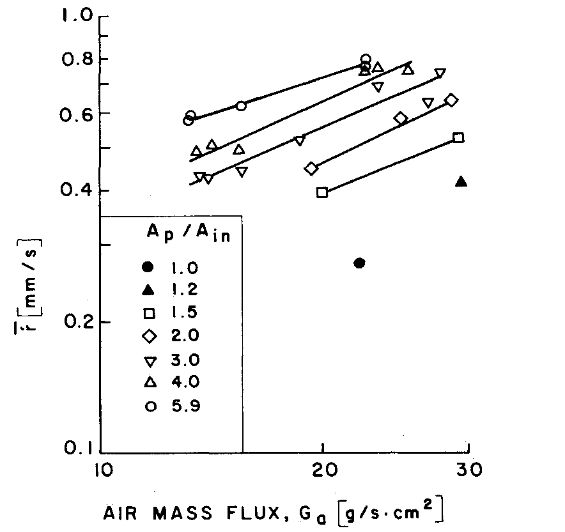


Fig. 12 Average regression rate vs air mass flux at different port-to-inlet-area ratios (fuel PMMA and air temperature 800 K).

Table 1 Effect of inlet air temperature on regression rate results for different fuels at fixed air mass flux of 20 g/(s·cm²) and the same initial geometry

Fuel type	Initial A_p/A_{in}	Regression rate $\dot{r}$, mm/s Inlet air temperature 520 K	800 K	m
PE	3.0	0.32	0.48	0.94
	4.0	0.34	0.52	0.97
	5.9	0.46	0.68	0.91
PB/PS	4.0	0.66	1.00	0.96
	5.9	0.80	1.20	0.94

conditions of inlet air temperatures and fuel types. Other investigations in larger motor diameters did reveal some pressure effect.[2,8]

Inlet air temperature, on the other hand, was found to have appreciable effect on $\dot{r}$. Presuming that the temperature effect for fixed-geometric and mass-flux conditions influences the regression rate as follows,

$$\dot{r} \propto T^m \tag{10}$$

the exponent m was found to be of the order of 0.9–1.0 for the different fuels tested (see experimental data in Table 1). Note that the value of m was extracted from tests at only two temperatures, 520 and 800 K. Thus, one cannot confirm the validity of Eq. (10). Also note that m appeared to be rather high compared to data obtained from larger motors.[2,8] One might relate this high value, at least in part, to the somewhat different heat-transfer regime in small vs large combustors and to the effect of the relative increase in port diameter during the test on the "apparent" measured exponent value, as was found for the G exponent. Detailed discussion on this issue is included in Ref. 4. Also, because of the larger relative heat losses in smaller combustors, initial air temperature plays a more significant role in the heat transfer to the wall.

Study on the effect of step height on the fuel regression rate revealed a consistent increase of the mean regression rate with increasing the step height for combustors of equal initial port diameter and grain length. Figure 12 shows the dependence of the mean fuel regression rate (in respect to time and length) on the mean air mass flux, with the initial port-to-inlet-area ratio (representing different step heights) as a parameter. Similar correlations were made for each of the three fuels tested at two different temperatures, 520 and 800 K.

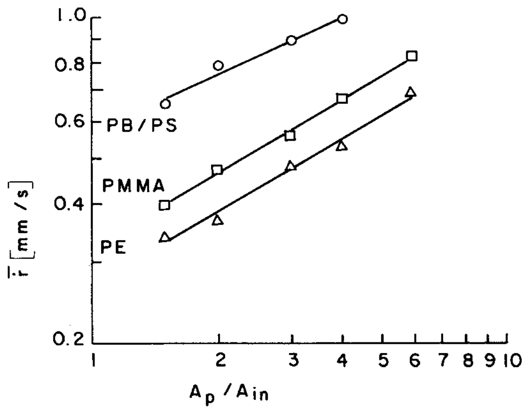


Fig. 13 Average regression rate vs port-to-inlet-area ratio (fixed air mass flux 20 g/s · cm² and temperature 800 K).

The weighted average of the slope of all individual curves plotted on a log-log scale could be approximated by the following correlation based on about 100 data points:

$$\dot{r} \propto G^{0.9} \tag{11}$$

A similar unusually high exponent has already been indicated in previous work,[4] where a value of $n \cong 1$ correlated the experimental data. It was then discussed that miniature SFRJ port diameters tend to yield "apparent" exponents, which may be higher than the fundamental values associated with the heat-transfer mechanism. Interestingly, no pronounced effect of the step height on the regression rate exponent n has been detected.

Figure 13 shows the dependence of the average regression rate on the initial port-to-inlet-area ratio for the three fuels at fixed air mass flux of 20 g/(s · cm²). Prominent effect of A_p/A_{in} on $\dot{r}$ was found:

$$\bar{\dot{r}} \propto (A_p/A_{in})^{0.5}, \qquad G = \text{const} \tag{12}$$

This effect may be related to the specific heat-transfer regime in the separated recirculation flow zone resulting from the inlet sudden expansion. Krall and Sparrow[9] found experimentally a similar effect on the peak heat-transfer rate (corresponding to the reattachment zone) in nonreacting, no-blowing flow conditions. Their correlation was approximated by

$$Nu_{\max} \propto (A_p/A_{in})^{0.33} \tag{13}$$

Combining the different effects investigated in the present work yields the following empirical regression rate correlation for the specific 10-mm-port-diam SFRJ combustor:

$$\bar{\dot{r}} \,\tilde{\propto}\, G^{0.9-1.0} T_a^{0.95} (A_p/A_{in})^{0.5} \tag{14}$$

Concluding Remarks

The miniature (10-mm-port-diam) SFRJ combustor tested revealed some combustion and flameholding characteristics peculiar to this special size range along with more general phenomena.

Although the general characteristics of the flameholding behavior in this work were found to be generally similar to those of larger motors, a clear trend of deteriorating flameholding capability with decreasing the combustor size was observed, especially at low inlet air temperatures (corresponding to low supersonic Mach number range).

The regression rate behavior exhibits significant effects of the air mass flux, inlet air temperature, and port-to-inlet-area ratio (i.e., step height). These effects were found to be more pronounced in the miniature motor than in large-size combustors.

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