HYBRID ROCKET MOTOR EXPERIMENTS

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Delft/Rijswijk, The Netherlands
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SUMMARY

This report is a survey of experimental results obtained by burning polymethylmethacrylate and polyethylene with oxygen and mixtures of oxygen and nitrogen in a small hybrid rocket motor. These results may be used as a guideline for test programs to be set up to investigate the combustion behaviour in Solid Fuel Combustion Chambers.

This project is sponsored by the Technology Foundation (Stichting voor de Technische Wetenschappen STW) and the Management Office for Energy Research (Stichting Projectbeheerbureau Energie Onderzoek).

In addition money and manpower are made available by a special funding from Delft University of Technology (Beleidsruimte), while also manpower and computer facilities are provided by the Department of Aerospace Engineering Delft, Delft University of Technology and the Prins Maurits Laboratory TNO. This latter laboratory also provides the project with funding.
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NOMENCLATURE

Roman Symbols

A - area
a - coefficient
b - coefficient
c* - characteristic velocity
d - diameter
F - thrust
G - mass flux
L - length
M - molecular weight
m - mass flow
p - pressure
R_o - universal gas constant
r - regression rate
T - temperature
t - time
V - volume

Greek Symbols

ΔM - weight loss
ϕ - mixture ratio
ρ - density

Superscripts

(\bar{C}) - average
(\cdot)^0 - initial
(\cdot)^e - final
m - mass flux exponent
n - pressure exponent
Subscripts

a  - ambient
b  - burning
c  - combustion chamber
d  - diameter
ext - extinguishment
f  - fuel
hy - hydrogen
i  - injection chamber
ign - ignition
ox - oxygen
p  - pressure
stoi - stoichiometric
t  - throat
v  - valve
w  - wall
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   (c) 1.41 MPa ≤ p ≤ 2.0 MPa.
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1. INTRODUCTION

Solid Fuel Combustion Chambers may find application as propulsion units, as gas generators by burning coal and as a means of obtaining clean combustion of waste material. To investigate the flow and combustion processes in a Solid Fuel Combustion Chamber (SFCC), a research project was initiated three years ago. This research can be divided into a theoretical and an experimental part. For the latter a special test facility is being constructed. However, at the time the research was started a small test facility for hybrid rocket motors was available. As the flow and combustion processes are similar to those occurring in an SFCC, experimental results obtained from hybrid rocket motors test runs may guide in the development of an experimental program for the SFCC.

This report presents experimental results with a laboratory scale hybrid rocket motor using either polymethylmethacrylate (PMMA) or polyethylene (PE) as a fuel and gaseous oxygen or mixtures of oxygen and nitrogen as oxidizer. The main purpose of this investigation concerned the regression rate behaviour as a function of various parameters. In addition the characteristic velocity has been determined and compared with theoretical values.

Chapter 2 describes the hybrid rocket motor test facility. Data reduction of the experiments is presented in Chapter 3.

The experimental results are discussed in Chapter 4 and conclusions are given in Chapter 5.

2. HYBRID ROCKET MOTOR TEST FACILITY

The hybrid rocket motor test facility consists of the following components:

i. a hybrid rocket motor
ii. a thrust stand
iii. a gassupply system
iv. a control system
v. a data acquisition system.

These components are discussed below.
2.1. The hybrid rocket motor

The fuels used, polymethylmethacrylate (PMMA) and polyethylene (PE), do not react hypergolically with oxygen or mixtures of oxygen and nitrogen. An ignition system is therefore required. For this purpose hydrogen gas is supplied to the motor for a short time in combination with the oxidizer employed for the specific test run. Ignition takes place by means of a spark plug. The heat generated gasifies the surface of the fuel and the fuel gases react with the remainder of the oxidizer.

Once this gasification process is taking place, the hydrogen supply is stopped and combustion will continue as long as oxidizer is supplied to the fuel grain. The ignition time normally lasted approximately 0.2 s for experiments with pure oxygen to 0.7 s for an oxidizer consisting of 40% oxygen and 60% nitrogen (by weight). The ignition time for experiments with PMMA and mixtures of 21% oxygen and 79% nitrogen (by weight) was considerably longer and lasted about 7 s.

After shut down of the oxidizer supply combustion ceases and the motor is purged with nitrogen gas for about 15 s to clear it from combustion products and fuel gases.

Figure 1 is an exploded view of the hybrid rocket motor, showing all its components. The motor consists of the following parts (the numbers behind the components refer to Fig.1):
Figure 1. Exploded view of the hybrid rocket motor.
- an injection chamber (1) with needle valves for hydrogen (2) and oxidizer (3) supply
- a spark plug (4) to ignite the motor
- a connection for a pressure transducer (5) for the measurement of the injection pressure
- the fuel grain (6), either PMMA or PE
- an aft mixing chamber (7)
- a nozzle (8), which is interchangeable so as to allow for various test conditions
- a connection for a pressure transducer (9) for the measurement of the pressure in the secondary combustion chamber
- three rods and bolts (10) to hold the fuel grain between the injection chamber and the aft mixing chamber

In some cases, use has been made of a diaphragm at the forward end of the fuel grain in order to create a sudden expansion of the flow entering the bore of the fuel grain.

All metal parts are made of stainless steel, except for the aft mixing chamber, the nozzle and the diaphragm which are made from copper.

The needle valves which are mounted on the injection chamber allow for a manual adjustment of the mass flow of the hydrogen and oxidizer entering the injection chamber. Later on during the test
series these needle valves were replaced by others that were mounted in the gas feed lines.

The pressure transducers that have been used together with their main characteristics are listed in Table 1.

Table 1. Pressure transducers employed and their characteristics.

<table>
<thead>
<tr>
<th>Location</th>
<th>Manufacturer</th>
<th>Type</th>
<th>Pressure range (MPa)</th>
<th>Sensitivity (pC/MPa)</th>
<th>Time constant (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection chamber</td>
<td>Kistler</td>
<td>701A</td>
<td>0 - 25</td>
<td>780</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Aft mixing chamber</td>
<td>Kistler</td>
<td>701A</td>
<td>0 - 25</td>
<td>770</td>
<td>1,000,000</td>
</tr>
</tbody>
</table>

2.2. The fuel grain

The fuel grains were made of PMMA and PE. Some properties of PMMA and PE are given in Table 2. The theoretical performances of PMMA and PE with oxygen and mixtures of oxygen and nitrogen are given in Figures 2 and 3. For reasons of comparison, the performances of PMMA and PE with air are given in these Figures as well. The results are obtained by using the NASA-SP 273 computer code(2). The fuel grains are cylindrical, the length and the outer diameter being 300 mm and 70 mm respectively. Some test runs with PE and oxygen however employed fuel grains with a length of about 120 mm.
Figure 2. Theoretical performance of PMMA with oxygen, mixtures of oxygen and nitrogen and air. (a) temperature versus mixture ratio.
Figure 2b. Characteristic velocity versus mixture ratio.
Figure 3. Theoretical performance of PE with oxygen, mixtures of oxygen and nitrogen and air. (a) Temperature versus mixture ratio.
Table 2. Properties of PMMA and PE(1).

<table>
<thead>
<tr>
<th></th>
<th>PMMA</th>
<th>PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular formula</td>
<td>(C₅H₈O₂)ₙ</td>
<td>(C₂H₄)ₙ</td>
</tr>
<tr>
<td>Molecular weight</td>
<td>(kg/kmol)</td>
<td>100.12</td>
</tr>
<tr>
<td>Density</td>
<td>(kg/m³)</td>
<td>1180</td>
</tr>
<tr>
<td>Melting point</td>
<td>(K)</td>
<td>433 - 473</td>
</tr>
<tr>
<td>Heat of combustion</td>
<td>(MJ/kg)</td>
<td>26.2</td>
</tr>
<tr>
<td>Standard heat of formation (kJ/mol)</td>
<td>-430.5</td>
<td>-58.6</td>
</tr>
</tbody>
</table>

2.3. The thrust stand

Figure 4 is an exploded view of the thrust stand. The thrust stand is a horizontal installation. This implies that the reaction forces due to the varying weight of the motor and the thrust are orthogonal and hence do not affect each other. As there is only one force link, forces due to thrust misalignment cannot be measured. To measure the thrust, the hybrid rocket motor is mounted on the upper beam (2) of the thrust stand, which in turn is connected to the frame (1) by means of two elastic hinges (4) that can only transmit forces in vertical, but not in horizontal direction. The horizontal force, the thrust, is transmitted to the frame (1) via a piezo electric force link (3). Characteristics of this force link are presented in Table 3. By means of an adjustable bolt (5) the force link can be preloaded. The thrust stand allows for fuel grains of different length, up to a maximum length of 0.35 m. Figure 5 shows in detail how the force link connects the upper part of the thrust stand to the frame. Figure 6 shows the thrust stand with the hybrid rocket motor.
Figure 4. Components of the thrust stand.

Table 3. Characteristics of the piezo-electric force link.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Force range (kN)</th>
<th>Sensitivity (pC/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kistler</td>
<td>9301A</td>
<td>± 2.5</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Figure 5. Detail of the force link, mounted on the thrust stand.

Figure 6. The hybrid rocket motor mounted on the thrust stand.
2.4. The gas supply system

Figure 7 is a diagram of the gas supply system. For the hybrid rocket motor, normal industrial gases are used which are supplied in industrial gas bottles.

The array of the hydrogen buffer consists of four bottles with a capacity of 1 l each and the oxidizer buffer consists of two bottles with a capacity of 50 l each and one bottle with a capacity of 10 l. Before a test run these bottles are filled from the supply to a required pressure level. For experiments with diluted oxygen, the oxidizer buffer bottles were filled with both oxygen and nitrogen in such a way that a specific mixture ratio could be obtained.

Between the buffer bottles and the feed lines to the hybrid motor adjustable pressure reducers have been installed. The pressure reducer in the oxygen line can be adjusted continuously from the control room, as to allow for a varying oxidizer supply during a test when necessary. During the test series described in this report, the oxidizer mass flow however was kept constant. Solenoid valves in the gas supply lines can be opened and closed from the control room. Check valves prevent back flow of the gases from the rocket motor into the feed lines.
Figure 7. The gas supply system.
$t_1, t_2$ and $t_3$ are preset and adjustable
$0 < t < t_1$ ignition phase
$t_1 < t < t_2$ operational phase
$t_2 < t < t_3$ purging with nitrogen

Figure 8. The operational sequence.

2.5. The control system

The hybrid rocket motor system is operated from a control room. The sequence of events that is necessary to start, operate and stop the motor is schematically shown in Figure 8. As all times involved are rather short, this sequence of events is automatically controlled from a control panel. The duration of each event, namely ignition phase ($t_1$), operational phase ($t_2$) and purge phase ($t_3 - t_2$) are adjusted by means of timers. To warn people in the vicinity of and on the test location of the occurrence of a test run, sirens are also initiated from this control panel.
2.6. **Data acquisition**

Before, during and after a test run many variables have to be measured in order to obtain information about the performance of the rocket motor.

The system allows for pressure measurement in the injection chamber and in the aft mixing chamber and for thrust measurement during a test run.

In addition other variables are measured before and after a test run:

- primary and secondary oxidizer pressure
- primary and secondary hydrogen pressure
- ambient temperature and pressure
- nozzle - throat and - exit diameter
- mass and dimensions of the fuel grain.

Post combustion fuel port diameter measurements were made to determine local regression rates. As shown in Figure 9 a stand for making these measurements was built so that the maximum and minimum port diameters at ten millimeters intervals could be quickly and accurately measured.

![Figure 9. Stand for measuring port diameters.](image-url)
The electrical signal from the two pressure transducers and the force link are recorded by the following equipment:

- Analogue tape recorder
  Honeywell, model 101

- Ultraviolet recorder
  SE Labs (EMI) Ltd, SE oscillograph 3006/DL with galvanometers type B3300

- AD converter
  manufactured by PML, max. sample frequency 10 kHz

- Digital tape recorder
  Kennedy, model 9700

The UV recordings only served for a quick, first look analysis. The signals recorded by the digital tape recorder were directly used as an input for computerized data reduction. The analogue signals from the Honeywell tape recorder were used as back up and for replay in some cases of unexpected events. The sample frequency was 1000 Hz for every signal.

3. DATA REDUCTION

The digital data as recorded on magnetic tape have been read by the PDP11/45 computer system of the Prins Maurits Laboratory. For the data analysis a special computer code has been developed. From the pressure time history in the injection chamber, the pressure time history in the aft mixing chamber and the thrust time history, the ignition and burnout time are calculated. They are denoted by \( t_{\text{ign}} \) and \( t_{\text{ext}} \) respectively. In general the values obtained for the ignition time for the three traces correspond very well; the same applies for the values obtained for the burnout time.

The burning time, \( t_b \), however is obtained from the pressure history in the aft mixing chamber and is calculated as follows:

\[
    t_b = t_{\text{ext}}, p_c - t_{\text{ign}}, p_c
\]
The mean pressure levels in the injection chamber and in the aft mixing chamber, $p_i$ and $p_c$ respectively are calculated according to:

\[
\frac{t_{ext, p_i}}{t_{ign, p_i}} = p_i(t) \, dt \\
\frac{t_{ign, p_i}}{t_{ext, p_i} - t_{ign, p_i}} = p_i
\]

and

\[
\frac{t_{ext, p_c}}{t_{ign, p_c}} = p_c(t) \, dt \\
\frac{t_{ign, p_c}}{t_{ext, p_c} - t_{ign, p_c}} = p_c
\]

while the mean thrust level, $\bar{F}$, follows from:

\[
\frac{t_{ext, F}}{t_{ign, F}} = F(t) \, dt \\
\frac{t_{ign, F}}{t_{ext, F} - t_{ign, F}} = F
\]

The oxidizer mass flow, $m_{ox}$, is calculated from the pressure drop in the buffer vessels:

\[
m_{ox} = \frac{\left[ p^o_{ox} - p^e_{ox} \right] \cdot M_{ox} \cdot V_{ox}}{R \cdot T \cdot v_{ox}}
\]

where $M_{ox}$ stands for the molecular weight of the oxidizer:

\[
M_{ox} = \left[ \frac{0.875}{\alpha + 0.875} \right] M_2 + \left[ \frac{\alpha}{\alpha + 0.875} \right] M_n
\]
In this Equation, $\alpha$ is the nitrogen/oxygen mixture ratio (by weight) and 0.875 is the molecular weight ratio of nitrogen to oxygen.

The hydrogen mass flow, $m_{\text{hy}}$, is also calculated from the pressure drop in the hydrogen buffer vessels:

$$m_{\text{hy}} = \frac{\left(p_{\text{o, hy}} - p_{\text{hy}}\right)}{R \cdot T \cdot v_{\text{o, hy}}} \cdot \frac{M_{\text{hy}} \cdot V_{\text{hy}}}{t_{\text{o, hy}}}$$

The average fuel mass flow is determined according to:

$$m_\text{f} = \frac{\Delta M}{t_b}$$

The average mixture ratio, $\phi$, then follows from:

$$\phi = \frac{m_{\text{ox}}}{m_\text{f}}$$

The oxidizer-, fuel-, and total mass flux at ignition and burnout as well as the mean oxidizer-, fuel- and total mass flux during a test run are obtained in the following way:

$$G_{\text{ox}}^\circ = \frac{m_{\text{ox}}}{d_{\text{ox}}} \left[\frac{\pi - \bar{\alpha}}{4} \right]$$

$$G_{\text{ox}}^e = \frac{m_{\text{ox}}}{d_{\text{ox}}} \left[\frac{\pi - \bar{\alpha}}{4} \right]$$

$$\bar{G}_{\text{ox}} = \left[ G_{\text{ox}}^\circ + G_{\text{ox}}^e \right] / 2$$

$$G_{\text{f}}^\circ = \frac{m_\text{f}}{d_\text{f}} \left[\frac{\pi - \bar{\alpha}}{4} \right]$$

$$G_{\text{f}}^e = \frac{m_\text{f}}{d_\text{f}} \left[\frac{\pi - \bar{\alpha}}{4} \right]$$
\[ \bar{G}_f = \left[ \frac{G^o_f + G^e_f}{2} \right] \]

\[ G^o = G^o_{\alpha x} + G^o_f \]

\[ G^e = G^e_{\alpha x} + G^e_f \]

\[ \bar{G} = \left( \frac{G^o + G^e}{2} \right) \]

The regression rate was obtained by two different methods. The first method is based upon the mass loss of the fuel grain; the regression rate is simply calculated from:

\[ r_w = \sqrt{\frac{\text{o}^2 \cdot \frac{4 \cdot M}{\pi \cdot \rho_f \cdot \text{d} \cdot \text{o}}}{2 \cdot t_b}} \]

The second method is based upon the determination of the mean diameter of the conduit before and after a test run:

\[ r_d = \frac{\text{p} \cdot \text{d}^e - \text{p} \cdot \text{d}^o}{2 \cdot t_b} \]

In a few cases an instantaneous local regression rate has been measured by means of the ultrasonic pulse echo technique. This is reported elsewhere (3).

The characteristic velocity, \( c^* \), is calculated according to:

\[ c^* = \frac{\text{p} \cdot \bar{A} \cdot \text{t}}{m_{\alpha x} + m_f} \]
where:

\[ \overline{A}_t = \frac{\pi}{8} \left( \frac{o}{d_t} + \frac{e}{d_t} \right)^2 \]

4. EXPERIMENTS

Table 4 presents a list of the major series of tests, totalling over 150 experiments. Apart from these a few runs using wood and polystyrene as fuels were performed, but since these were isolated efforts, they will not be discussed. The first four series of experiments, covering about three quarters of the total, deal with hybrid rocket motors using pure oxygen. In the next series the oxygen content of the oxidizer was lowered systematically in order to investigate its influence on combustion behaviour. This seemed to be a logical step towards the study of combustion in solid fuel ramjets. In accordance with this goal a number of experiments with a flameholder, in the form of a rearward facing step at the entrance of the grain, were performed. Comparing them with similar runs in a configuration without a step, its influence was studied.

The variables investigated were the regression rate, \( r \), and the characteristic velocity, \( c^* \), as a function of oxidizer and total mass flux, pressure, geometry (length and initial diameter of the cylindrical bore), burning time and fuel type.
Table 4. List of experiments.

<table>
<thead>
<tr>
<th>Oxidizer</th>
<th>Fuel</th>
<th>Grain length (m)</th>
<th>Pressure range (MPa)</th>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>100% O₂</td>
<td>PE</td>
<td>0.3</td>
<td>0.3 - 1.9</td>
<td>no</td>
</tr>
<tr>
<td>100% O₂</td>
<td>PE</td>
<td>0.12</td>
<td>0.3 - 1.4</td>
<td>no</td>
</tr>
<tr>
<td>100% O₂</td>
<td>PMMA</td>
<td>0.3</td>
<td>0.2 - 2.3</td>
<td>no</td>
</tr>
<tr>
<td>100% O₂</td>
<td>PMMA</td>
<td>0.3</td>
<td>1.3 - 1.6</td>
<td>yes</td>
</tr>
<tr>
<td>80% O₂ + 20% N₂</td>
<td>PMMA</td>
<td>0.3</td>
<td>0.9 - 1.3</td>
<td>no</td>
</tr>
<tr>
<td>80% O₂ + 20% N₂</td>
<td>PMMA</td>
<td>0.3</td>
<td>0.6 - 0.7</td>
<td>yes</td>
</tr>
<tr>
<td>60% O₂ + 40% N₂</td>
<td>PMMA</td>
<td>0.3</td>
<td>0.9 - 1.2</td>
<td>no</td>
</tr>
<tr>
<td>60% O₂ + 40% N₂</td>
<td>PMMA</td>
<td>0.3</td>
<td>1.3 - 1.4</td>
<td>yes</td>
</tr>
<tr>
<td>40% O₂ + 60% N₂</td>
<td>PMMA</td>
<td>0.3</td>
<td>0.8 - 1.2</td>
<td>no</td>
</tr>
<tr>
<td>40% O₂ + 60% N₂</td>
<td>PMMA</td>
<td>0.3</td>
<td>0.8 - 1.1</td>
<td>yes</td>
</tr>
<tr>
<td>20% O₂ + 80% N₂</td>
<td>PMMA</td>
<td>0.3</td>
<td>0.8 - 1.7</td>
<td>yes</td>
</tr>
<tr>
<td>air</td>
<td>PMMA</td>
<td>0.3</td>
<td>0.7 - 1.3</td>
<td>yes</td>
</tr>
</tbody>
</table>

4.1. Data Interpretation

When reducing the data one is faced with the difficult question as to the best way for presenting the regression rate by some general law. In most of the measurements performed an overall regression rate was measured as is the case of most data reported in the literature. Marxman and coworkers\(^4\) noted already in 1963 that the regression rate in a cylindrical, perforated grain depends strongly on the particular port size and may change significantly with time as burning proceeds. Schmucker\(^5\) in his 1972 book lists a considerable number of expressions, proposed by different authors. The most popular are:

\[(1) \quad r = a G^m p^n \]

where \(G\) is the total mass flux and \(p\) the pressure in the chamber.

\[(2) \quad r = a G_{ox}^m p^n \]

when \(G_{ox}\) is the mass flux of the oxidizer. 

Barrère\(^6\) proposed
(3) \( r = a G^m p^n e^{q} \)

Wahlquist and Panelli\(^7\) put forward

(4) \( r = a G^m \left( \frac{1}{L^n} \right) + b \)

Here \( L \) is the length of the tube

Smoot and Price\(^8\) proposed three different laws, according to the magnitude of the mass flux:

\[
(5) \quad \begin{cases} 
    r = a G^{0.8} & \text{for low flux} \\
    r = \frac{ab G^{0.8} p^n}{a G^{0.8} + bp} & \text{for medium flux} \\
    r = a p^n & \text{for high flux} 
\end{cases}
\]

Each of these formulas gave fair agreement with the experimental results of the various investigators and it will be shown than they may be applicable to particular series of experiments performed in the present work, as will be pointed out in the discussion of the results.

As mentioned before, during the work on this SFCC project a method for measuring the instantaneous regression rate of the fuel was developed\(^3\) and it appears that with its help the physical mechanism underlying the combustion process may be understood, thus reconciling the various formulae proposed.

According to the results obtained (see Fig.10) it appears\(^9\) that after an initial period of about 3 s, during which the regression rate is abnormally high, a correlation of the type

(6) \( r = a G^m_{\text{ox}} \) with \( a = b p^n \)

represents faithfully the instantaneous regression rate.
Figuur 10. Regression rate of PMMA for combustion with oxygen determined by ultrasonic technique.

Since in the experiments the quantity held constant was the oxidizer mass flow, it becomes clear that the mass flux diminishes with time as burning proceeds and, therefore, there will be a difference in overall regression rate according to the burning time, the longer burning times corresponding to lower overall rates.

As for the initial very high regression rate, it should be remembered that the ignition was performed by using for a short time an oxygen–hydrogen mixture, which is much more reactive and will, therefore, affect the regression rate. One should therefore make use of eq. (6) only after approximately 3 seconds.
4.2. Experiments with polyethylene

28 experiments were performed with polyethylene as fuel and pure oxygen as oxidizer, using two fuel grain lengths, 0.12 and 0.3 m. The pressures were in a range between 0.3 and 1.9 MPa, most test runs lasted between 15.5 and 17.5 seconds, with two longer ones (close to 37 s). The initial bore diameter ranged between 18.8 to 40.8 mm, while the mass flux rates varied between 30 and 141 kg/m²s. The measured regression rate went from 0.20 to 0.42 mm/s. A compilation of the test conditions and the experimental results is given in Table 5.

A typical pressure-time diagram is shown in Fig.11. After an initial ignition peak of about 1.7 MPa, the pressure settles at 1.2 MPa and is steady. In some test runs combustion instability was observed.

Figure 12 shows experimental data of the regression rate versus the mass flux for the two grain lengths. One can observe that in both cases a pressure increase augments the regression rate; this effect is felt up to 1 MPa and is not seen for higher pressures. Comparing the regression rates for the shorter grain at 0.3 MPa with those of the longer grain at 0.4 MPa one can see that the first are higher. This is in agreement with eq. (4) and with results obtained by Wooldridge and Muzzy(10).

If one tries to correlate all the results for the two series of experiments according to eq. (1) the result is

\[ r_{0.3} = 0.0635 G^{0.36} p^{0.22} \text{ mm/s, and} \]
\[ r_{0.12} = 2.774 G^{0.32} p^{0.064} \text{ mm/s} \]

Here \( r \) is given in mm/sec, \( G \) in kg/m²s and \( p \) in MPa (these units will be used throughout). Figures 13 and 14 compare these correlations with the experimental data. The fact that the shorter specimen appears less pressure dependent is in accordance with the findings of Smoot and Price(8), since here the mass flux is somewhat lower.
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Figure 11. Typical pressure time history for combustion of polyethylene with oxygen.
Figure 12. Regression rate of PE/O₂, as a function of total mass flux. a) 0.3 m grain. b) 0.12 m grain.
Figure 13. Regression rate of PE/O₂. Grain length 0.3 m.
Figure 14. Regression rate of PE/O₂. Grain length 0.12 m.

The characteristic velocity is presented as a function of the equivalence ratio in Fig. 15. The continuous curve represents the theoretical value of $c^*$ (the 5% deviation limits are also shown). Although the results appear to have a very wide scatter, it is possible to understand their distribution, if one relates them to different types of experiments. It appears that the runs with the shorter grain have a low $c^*$; since the residence time of the gases in the chamber is short, it is probable that combustion is incomplete, so that only part of the energy is utilized. The experiments performed with the longer grain at low pressures (below 0.45 MPa) are also characterized by short residence times, since the density is low and the flow velocity high.
Figure 15. Characteristic velocity for PE/O$_2$ combustion as function of equivalence ratio.

On the other hand the runs corresponding to long burning times show clearly that the lower velocities due to the large port diameter favour complete combustion. In the case of high pressure runs (above 0.9 MPa) there is an increase in the number of collisions, which acts again favourably on the characteristic velocity. Although these are average values, the trends appear to be significant and to indicate potential advantages of using relatively high combustion pressure in solid fuel ramjets.
4.3. Experiments with plexiglas and oxygen

A large number of experiments (88) was run using pure oxygen and plexiglas. During these experiments the pressure ranged between 0.27 and 2.25 MPa, the combustion time was between 4.8 and 46 s, the initial diameter varied from 18.7 to 39.3 mm, with mean flux values between 31 and 321 kg/m² s. The measured regression rate went from 0.23 to 0.99 mm/s. Figure 16 shows a typical pressure-time diagram. After an initial peak of about 1.6 MPa, the pressure settles at 1.4 MPa and remains steady. In some test runs combustion instability was observed.

![Pressure-time diagram](image)

Figure 16. Typical pressure history for combustion of PMMA with oxygen.
The dependence of the regression rate on the burning time, mentioned before for PE/O₂, can be seen clearly in Fig.17 for three different pressure ranges. Due to the large range of burning times and the initial high regression rates, it was decided to analyze separately results for short times (around 5 seconds) and those for longer times. In each of these subdivisions runs were grouped according to the pressure. A compilation of the test conditions and the experimental results is given in Table 6. For different pressure ranges it was possible to obtain correlations of the type of eq.(1).

For the short burning times these were:

\[
0.41 \leq p \leq 0.51 \text{ MPa} \quad r = 0.138 \, p^{0.44} \, p^{0.89} \text{ mm/s}
\]
\[
1 \quad 1.4 \leq p \leq 2 \text{ MPa} \quad r = 0.050 \, p^{0.46} \, p^{0.85} \text{ mm/s}
\]
\[
1.4 \leq p \leq 2 \quad r = 0.173 \, p^{0.18} \, p^{0.74} \text{ mm/s}
\]
\[
p \geq 2 \text{ MPa} \quad r = 0.059 \, p^{0.34} \, p^{0.89} \text{ mm/s}
\]

Figure 18 compares the predictions with experimental results for the lowest pressure. The agreement is similar for the higher pressure ranges. It is interesting to observe that in all these relations there appears to be a strong influence of the pressure, whose exponent, n, is higher than that of the mass flux, m. This is in general agreement with the findings of Smoot and Price⁸, according to which the pressure influence is stronger for high mass flow; it may also be connected with pressure dependent reactions involving hydrogen, which is present in the initial stage.

Looking now at the results for longer times, one observes that for low values of the pressure (0.33 - 0.41 MPa) its influence appears much lower than that of the mass flux:

\[
r = 0.002 \, p^{1.03} \, p^{-0.03} \text{ mm/s} \quad \text{(see Fig.19a)}
\]

at higher pressures (0.8 - 1 MPa) the influence of the pressure increases:

\[
r = 0.021 \, p^{0.60} \, p^{0.40} \text{ mm/s} \quad \text{(see Fig.19b)}
\]
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Figure 17. Regression of PMMA/O₂ as a function of total mass flux.
(a) 0.4 MPa < p < 0.7 MPa
(b) 1.0 MPa < p < 1.4 MPa
(c) 1.4 MPa < p < 2.0 MPa.
PMMA / O₂; L = 0.3 m
0.41 MPa ≤ p ≤ 0.51 MPa
\( t_b = 5 \) s

Figure 18. Regression rate of PMMA / O₂. Short burning time.
0.41 MPa ≤ p ≤ 0.51 MPa.
Figure 19a. Regression of PMMA/O₂. Long burning times.
0.33 MPa ≤ p ≤ 0.41 MPa.
Figure 19b. Regression rate of PMMA/O₂. Long burning times. 
0.8 MPa ≤ p ≤ 1.0 MPa.
Figure 19c. Regression rate of PMMA/O₂. Long burning times. 1.41 MPa ≤ p ≤ 2.0 MPa.

At high pressures (1.41 – 2 MPa) the mass flux is again dominant:

\[ r = 0.025 \, G^{0.58} \, p^{-0.1} \, \text{mm/s} \]  
(see Fig.19c)

This can be compared with the results for polyethylene, shown in Fig.12.

As regards the characteristic velocity, this is plotted in Fig.20 as a function of the equivalence ratio. The results obtained are somewhat lower than the theoretical predictions, but it appears that only at the lowest pressures (0.27 – 0.33 MPa) the combustion is not complete, probably because of low residence time.
4.4. Experiments with plexiglas and mixtures of oxygen and nitrogen

42 experiments were performed with plexiglas and mixtures of oxygen and nitrogen in proportions 80/20, 60/40, 40/60 and 20/80. Most of the experiments in the first three series had a burning time of approximately 10 seconds, but a few were longer (27 s). In these series only 2 runs at each oxidizer composition had a step. In the last series all experiments had a step, since otherwise combustion could not be maintained, and the burning times were longer (27 to 69 s). The pressure varied between 0.6 and 1.7 MPa, and the mean flux rate between 42 and 168 kg/m² s. The initial bore diameter went from 18.8 to 42.5 mm. The regression rate range was between 0.163 and 0.451 mm/s without a step and reached 0.648 mm/s when there was a step. A compilation of the experimental conditions and the test results is given in Table 7.

Looking first at the series with 80% oxygen and 20% nitrogen and employing relation (1) a very strong pressure dependence appears to exist:

\[ r = 0.023 \, G^{0.51} \, p^{1.75} \, \text{mm/s} \]  
(see Fig.21a)

This is much lower for 60% oxygen and 40% nitrogen:

\[ r = 0.054 \, G^{0.38} \, p^{0.09} \, \text{mm/s} \]  
(see Fig.21b)

and goes up again for 40% oxygen and 60% nitrogen:

\[ r = 0.027 \, G^{0.51} \, p^{0.59} \, \text{mm/s} \]  
(see Fig.21c).
Figure 20. Characteristic velocity of PMMA with oxygen as a function of equivalence ratio.
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Figure 21a. Regression rate of PMMA for combustion with mixtures of oxygen and nitrogen. 80% oxygen and 20% nitrogen.
Figure 21b. Regression rate of PMMA for combustion with mixtures of oxygen and nitrogen. 60.6% oxygen and 39.4% nitrogen.
Figure 21c. Regression rate of PMMA for combustion with mixtures of oxygen and nitrogen. 40.6% oxygen and 59.4% nitrogen.

The instantaneous regression rate that was measured ultrasonically can be correlated by equation (6)

\[ r = b d_{\text{ox}}^m \]

with \( b = a p^n \). Table 8 gives the pertinent data which are also shown in Fig. 22. There is clearly a difference between the local value of the regression rate and its average.

As regards the characteristic velocity, it appears to be generally close to the calculated value, as shown in Fig. 23.
Table 8. Regression rate coefficient and exponents for tests with PMMA and various oxidizers.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Oxidizer</th>
<th>Chamber pressure (MPa)</th>
<th>Equivalence ratio (-)</th>
<th>b¹)</th>
<th>m¹)</th>
</tr>
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<tbody>
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<td>PMMA</td>
<td>100% O₂</td>
<td>1.227</td>
<td>0.61</td>
<td>0.1000</td>
<td>0.2888</td>
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<tr>
<td>PMMA</td>
<td>80% O₂ + 20% N₂</td>
<td>1.255</td>
<td>0.78</td>
<td>0.6800</td>
<td>0.3554</td>
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<tr>
<td>PMMA</td>
<td>62% O₂ + 38% N₂</td>
<td>1.123</td>
<td>0.72</td>
<td>0.0209</td>
<td>0.6052</td>
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<tr>
<td>PMMA</td>
<td>42% O₂ + 58% N₂</td>
<td>0.823</td>
<td>1.23</td>
<td>0.0074</td>
<td>0.3027</td>
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</table>

¹) \( r = b \frac{G^*}{\dot{m}_{ox}} \) where \( r \) in mm/s and \( \dot{G} \) in kg/m²s.

Figure 22. Regression rate of PMMA for combustion with pure oxygen and N₂-O₂ mixtures determined by ultrasonic technique.
Figure 23a. Characteristic velocity for combustion of PMMA with mixtures of oxygen and nitrogen as a function of equivalence ratio. 80% oxygen and 20% nitrogen.
Figure 23b. Characteristic velocity for combustion of PMMA with mixtures of oxygen and nitrogen as a function of equivalence ratio. 60% oxygen and 40% nitrogen.
Figure 23c. Characteristic velocity for combustion of PMMA with mixtures of oxygen and nitrogen as a function of equivalence ratio. 40% oxygen and 60% nitrogen.

4.5. The influence of a rearward facing step

15 experiments were performed using a rearward facing step. These included burning times from 6.5 to 69 seconds and mean pressures between 0.6 and 1.7 MPa. The mass flux rates were between 61 and 209 kg/m²s; the initial burning diameter varied from 18.6 to 26 mm. The fuel was in all cases plexiglass, while the oxidizer went from pure oxygen to mixtures containing 20% oxygen and 80% nitrogen. The data are given in Table 9, from which one sees that the mean regression rate had a wide range - from 0.18 to
0.99 mm/s. If one compares the regression rates obtained with those expected for similar conditions when there is no step, one finds that the latter are considerably lower. This and the fact that for 20% oxygen combustion occurs only with a step are attributed to the enhanced mixing and the higher combustion intensity caused by recirculation of the flow generated behind the step.

The influence of the step on the regression rate appears to be more pronounced when there is more oxygen; this is understandable, since it is only the oxygen that effects the combustion. This effect of a step has been observed and reported by earlier investigators (11,12,13). A further interesting fact observed is that immediately behind the step the regression rate is appreciably higher than in other parts of the grain, creating a concave profile, as shown in Fig.23, instead of the usual flat one. This phenomenon was also reported by Gany and Timnat (12).

As regards the influence of a step on the characteristic velocity, it appears that if the flow is subsonic at the step, the measured value is below the calculated one (see Figs.23 and 25), while for choked conditions at the chamber inlet, c* is higher than the calculated value.
Table 9. Effect of step on regression rate.

<table>
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<tr>
<th>Oxygen constant</th>
<th>h/d_p initial</th>
<th>h/d_p final</th>
<th>t_b (s)</th>
<th>( \dot{G} ) (kg/m^2s)</th>
<th>( \ddot{p} ) (MPa)</th>
<th>( \ddot{r} ) (mm/s)</th>
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</thead>
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Test H820618-1

Figure 24. Grain profile behind a step.
Figure 25. Characteristic velocity for the combustion of PMMA with 20% oxygen and 80% nitrogen as a function of equivalence ratio and step height.

5. CONCLUSIONS

About 150 test runs have been performed burning polyethylene and plexiglas as fuels with oxygen or mixtures of oxygen and nitrogen as oxidizer in a hybrid rocket motor. The experiments took place in the pressure region between 0.3 MPa and 2.5 MPa.

The following conclusions are reached:

1. The regression rate of polyethylene and plexiglas is affected by the mass flux, the geometry of the fuel and the chamber, the pressure level and the composition of the oxidizer.
2. Two types of empirical relations have been found to be useful; the first being:

\[ r = a G^m p^n \]

and the second

\[ r = b G^m \]

where

\[ b = a \varphi^n \]

3. The range of the values of the regression rate lies between 0.18 mm/s and 0.99 mm/s.

4. A rearward facing step has a noticeable effect on the combustion behaviour. First it increases the mean regression and secondly it changes the profile of the burned fuel grain.

5. The effect of pressure on the regression appears to be stronger at low pressures.
   For polyethylene no pressure effect was noticeable above 1 MPa while for plexiglas this tends to disappear at 2 MPa.

6. The characteristic velocity depends not only on the mixture ratio but also on the residence time of the combustion gases.
6. REFERENCES


7. ACKNOWLEDGMENTS

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