ELECTRICAL IGNITION OF NEW ENVIRONMENTAL-FRIENDLY PROPELLANTS FOR ROCKETS AND SPACECRAFTS

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Abstract

Monopropellant hydrazine is today widely used as propellant for missiles and spacecrafts. Hydrazine is however highly toxic. ADN-based liquid monopropellants seems to be a promising alternative to hydrazine, being substantially easier to handle, giving a 10 % higher specific impulse, and up to 60 % higher density-impulse, compared to hydrazine. This paper presents the results from electrical ignition experiments of liquid ADN-based propellants were the propellant is resistively heated by conducting an electric current through the propellant. Due to local phenomena close, or on the surface, of the electrodes, the required electric energy for ignition is small. The limited amount of energy required for ignition shows that this type of ignition method can be used in a flying vehicle as a missile or a spacecraft where strong weight and volume requirements apply.

I. INTRODUCTION

Hydrazine is today widely used as monopropellant for missile and spacecraft propulsion [1]. However, during the last years, increased efforts have been made to find a substitute to hydrazine due to its toxic nature [2, 3]. Its toxicity requires costly safety measures during handling and testing of spacecrafts. A less toxic monopropellant will thus offer substantial cost savings. One type of monopropellants proposed is ternary solutions based on an oxidizer salt dissolved in a fuel/water mixture [4, 5]. This type of monopropellants is sometimes referred to as “green” monopropellants. Water is added to liquefy the propellant if the fuel is not able to dissolve all the oxidizer required. As oxidizer salt, ammonium dinitramide (ADN, NH₄N(NO₂)₂) has been used in the study presented here. Two promising fuels have been identified and propellants with them have been formulated. The propellants are denoted FLP-105 and FLP-106 [6]. The propellants have been characterised [7] and their physical properties, as a function of temperature, is given in Table 1. Furthermore, the specific impulse of the FLPs is approximately 10 % higher compared to hydrazine. For small propulsion systems the density-impulse is an important quality measure. Due to the high density of FLP, the density-impulse for FLP-105 is approximately 60 % higher compared to hydrazine.

Table 1. Propellant properties as functions of temperature [7]. All temperatures T in °C.

<table>
<thead>
<tr>
<th>Monopropellant</th>
<th>FLP-105</th>
<th>FLP-106</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass density, ρ (10³ kg/m³)</td>
<td>1.426 - 8.4·10⁻⁴ T</td>
<td>1.378 - 8.2·10⁻⁴ T</td>
</tr>
<tr>
<td>Specific heat capacity, c_p (kJ/kgK)</td>
<td>2.19 + 5·10⁻⁴ T</td>
<td>2.40 + 6·10⁻⁴ T</td>
</tr>
<tr>
<td>Conductivity, σ (S/m)</td>
<td>4.24 + 0.179·T + 5.2·10⁻⁴·T²</td>
<td>7.55 + 0.255·T + 5.2·10⁻⁴·T²</td>
</tr>
</tbody>
</table>

One important aspect in the development of new monopropellants is the ignition. The state of the art hydrazine thrusters use catalytic ignition, which is reliable and simple. To replace hydrazine, ADN-based monopropellants must be as easy to ignite. One disadvantage with the ADN-based monopropellants is the high combustion temperature, which is 700 – 900 °C higher compared to hydrazine. The current state of the art hydrazine catalyst (Shell 405) cannot withstand such high temperatures [5]. This, and the fact that hydrazine and ADN-based liquid propellants are very different both physically and chemically, require development of new ignition methods, or new catalysts. The ignition temperature of the FLP is in the range of 150 to 200 °C depending on the test method and the heating rate [7].

Three different methods of heating the propellant to the ignition temperature have been identified:

- Pyrotechnic (by forming hot gases using a solid energetic material which in turn will heat the propellant)
- Thermal conduction (by spraying the propellant on a hot object which in turn is heated by electric means)
- Resistive (ADN is a salt and thereby possesses a relatively high electric conductivity. This means that an ADN-based monopropellant can be resistively heated)

When using pyrotechnic ignition the number of ignitions will be equal to the number of pyrotechnic devices. Pyrotechnic ignition is thus not suitable for multi-pulse mode operations. In a missile or a satellite the amount of electric energy available are limited. In both thermal conduction ignition and resistive ignition, electric...
energy is the main energy source. Heating the propellant by thermal conduction is expected to require more electric energy compared to resistive heating since, in the latter case, only the propellants itself needs to be heated. Thus, the latter is to prefer. This work is concentrated upon an investigation about the possibilities of resistive ignition of ADN-based monopropellants.

II. EXPERIMENTAL ARRANGEMENT

An experiment arrangement for the electrical ignition of the liquid propellant was designed and constructed. Figure 1 shows a schematic picture of the experiment arrangement with the pulsed-power supply, sample holder, anode, cathode and diagnostics.

![Figure 1. Schematic picture of the experimental set-up.](image)

A tube made of PMMA (Plexiglas), with the dimensions (inner diameter x height) Ø9 x 30 mm was used as sample holder. The sample holder was glued to the bottom plate, made out of stainless steel, over the cathode. The anode and the cathode were hemispherically-tipped and made out of stainless steel, with a diameter of 8 mm, or of aluminium, with a diameter of 2.2 mm. The anode, fixed to the top plate made of plastic, was placed so the half-spherical portion of it was in contact with the liquid propellant in the sample holder. An open gap existed between the tube and the anode. The height of the arrangement is about 150 mm and its diameter is about 120 mm.

The pulsed-power supply (PPS) used consisted of a 67 µF capacitor bank with a nominal voltage of 30 kV, which at full voltage can store 30 kJ. The system was monitored by remote control, from which charging, dumping and triggering was performed. In the ignition experiments presented here, the charging was limited to 6 kV, corresponding to 1.2 kJ.

The current through the sample was measured by a current probe (Pearson 1423) and the voltage across the sample was measured by a voltage divider (Tektronix P6015A). Standard nylon optical fibres were pointed at the sample and connected to the oscilloscope via opto detectors. In some experiments, a high-speed video camera (Photron APX) was used.

III. CIRCUIT ANALYSIS

A. Equivalent electric circuit

The equivalent electric circuit of the test set-up is shown in Figure 2. The pulsed-power supply and the connecting wires are represented by the RLC-elements with the following values: \( R = 30 \, \text{mΩ}, \, L = 1.1 \, \text{µH} \) and \( C = 67 \, \text{µF} \). The propellant sample is the load, which is designated \( R_s \). The propellant sample is heated by the current and thereby its resistance varies in time.

![Figure 2. The equivalent electric circuit of the test set-up.](image)

The RLC-components are the capacitance, the inductance and the resistance of the pulsed-power supply and its connections. \( R_s \) is the resistance of the propellant sample.

B. Modelling of sample resistance and temperature

If assuming uniform heating of the sample, the sample resistance and the sample temperature can be estimated by the following.

The volume of the sample is a cylinder with radius \( r \) and height \( h \). Thus, its cross-sectional area is \( A = \pi r^2 \) and its volume is \( V = \pi r^2 h \). The resistance \( R \) of the sample in the axial direction is given by

\[
R = \frac{h}{\sigma(T) A}
\]

where \( \sigma(T) \) is the temperature-dependent electric conductivity of the sample material as given by Table 1.

If all dissipated electric power in the sample is used to increase the sample temperature, the sample temperature increase is given by

\[
\frac{dT}{dt} = \frac{UI}{c_p(T)m}
\]

where \( U \) is the voltage across, and \( I \) the current through, the sample, and \( c_p \) is the temperature-dependent specific heat capacity of the sample material as given in Table 1. The mass \( m \) of the sample is given by

\[
m = \rho(T)V
\]

where \( \rho \) is the temperature-dependent mass density as given in Table 1.
C. Simulation results

The main idea is to increase the temperature of the sample to its ignition temperature, which lower limit is about 150 °C. Figure 3 shows the simulated sample resistance and sample temperature for an applied voltage of 4 kV, with sample properties of FLP-105, where the ignition temperature is not reached. The dimension of the sample holder was Ø9x30 mm and the distance between the anode tip and the cathode tip was 25 mm. For this sample size, it is required to discharge a PPS charged to about 4.8 kV (0.77 kJ) to increase the sample temperature to above 150 °C.

![Figure 3. Typical simulated results.](image)

IV. EXPERIMENTAL RESULTS

Figures 4 and 5 show typical results from one experiment, where the pulsed-power generator was charged to 4 kV, the propellant was FLP-105, the dimension of the sample holder was Ø9x30 mm and the distance between the anode tip and the cathode tip was 25 mm.

Figure 4 shows the voltage, current, opto signals and the derived dissipated energy, (integration of voltage times current). The optical signal at about 0.6 ms indicate the initial ignition of the propellant, whereas the steep rise and saturation of the optical signal at 1.5 ms is defined as full ignition of the propellant sample. The dissipated energy for the initial ignition was about 100 J and for the full ignition 180 J. The pulsed power supply continues to deliver current through the electrical conducting plasma, i.e. the burning propellant. Figure 5 shows the current and the derived resistance (voltage divided by the current).

![Figure 4. Typical measurement results.](image)

![Figure 5. Typical measurement results, continued.](image)

V. DISCUSSIONS

The sequence of the events is interpreted in the following way, where mainly the typical result presented in Figures 4 and 5 are used together with the high-speed video recordings. The sample is heated by the current forced through it. The light signal from the optical fibres indicates that the propellant is ignited. It is not possible to identify the initial ignition in the voltage and current signals. From the high-speed video recordings, one can see that the initial ignition first starts at the lower electrode (the cathode), followed by ignition at the upper electrode (anode). The ignition front travels from the lower electrode towards the upper one. Since the sample holder is open at the upper electrode, the internal pressure forces the propellant out of the sample holder at the upper electrode, thus creating a burning plume. After a certain time, the ignition front reaches the upper electrode and a full ignition occurs, saturating the optical fibre measurements. This full ignition is not possible to identify in the voltage measurement, and can barely be detected in the current measurement. Finally, a steep current increase and a sudden drop in voltage are observed, indicating that an arc discharge has short-circuited the electrode gap. Such a breakdown is not observed in all cases. This interpretation of the sequence events is consistent with the observations made in studies of ignition of liquid propellant in gun technology [8, 9].

It was expected that the propellant would be heated uniformly until it reached the thermal ignition temperature. Due to heat losses to the surrounding, the highest temperature would be found in the middle of the sample, and it was thus expected that the ignition would be initiated in the very centre of the propellant. Thus, the electric energy needed to obtain ignition would approximately be equal to the energy needed to raise the bulk temperature to the ignition temperature. However,
the result shows that the ignition was initiated close, or on
the surface, of the electrodes, and the electric energy
required was only a fraction of what was expected.
Apparently, some local phenomena at the electrodes are
responsible for the ignition.
Local phenomena that cause the ignition are
favourable, since it requires a minimum of bulk material.
The smaller amount of propellant that is electrically
heated, the less electric energy is needed. If the initial
amount of propellant is too small, ignition might be
impossible due to heat loss to the surrounding. Once the
propellant has ignited in a rocket combustion chamber, a
large amount of chemical energy is released. If the initial
amount of propellant ignited is large enough, it will in
turn ignite the following propellant entering the
combustion chamber, and thus sustained combustion will
be achieved. The minimum amount of propellant that
must be electrically ignited to achieve sustained
combustion must be determined experimentally, together
with minimum amount of required electric energy.

VI. CONCLUSIONS

ADN-based liquid propellants have been successfully
ignited by resistive heating. The required energy was
substantially less than expected, thus giving great
potential for minimizing the power supply. The ignition
was not due to uniform heating of the sample. Instead, the
ignition seemed to be locally initiated at the electrodes.
Fast ignition, less than 2 ms, was obtained. The limited
amount of energy required for ignition shows that this
type of ignition method can be used in a flying vehicle as
a missile or a spacecraft where strong weight and volume
requirements apply.

VII. ACKNOWLEDGEMENTS

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Figure 6. High-speed video pictures, frame rate
20 000 fps.