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# Combustion Control of Solid Rocket Motors by Polytetrafluoroethylene Sublimates

Takeshi Tachibana*
*Kyushu Institute of Technology, Sensuicho, Tobata 804, Japan*
and
Hideyuki Horisawa† and Itsuro Kimura‡
*Tokai University, Hiratsuka, Kanagawa 259, Japan*

**This article proposes a new concept of combustion control of solid propellants in relatively small thrust levels. In this method two different types of propellants, called main charge and pilot charge, are used, and the main charge should be combustible only with the help of the flow of the heated pilot gases. Production of heated pilot gases is initiated and interrupted by the on-off of dc arc discharges along the pilot charge surface. The dc power input will control the production rate of the pilot gases, which in turn will alter the consumption rate of the main charge. As the pilot charge, polytetrafluoroethylene and solidified ammonium perchlorate (AP) were used. As the main charge, fuel-rich and non-self-combustible hydroxyterminated polybutadiene/AP/titanium composite propellants were used. Our test motor showed quick response of initiation, interruption, and good regulation of combustion rates by input dc power. The mass consumption rate of the main charge was nearly proportional to the mass flow rate of the pilot gases. Typical values of the former and the latter rates were 0.2 and 0.02 g/s, and specific impulse and thrust were about 230–280 s and 0.45–1.1 N, respectively, at 1 kW of discharge.**

## Nomenclature

$D$ = nozzle throat diameter, mm
$F$ = thrust, N
$G$ = discharge gap distance, mm
$I_{arc}$ = arc discharge current, A
$I_{sp}$ = specific impulse, s
$M_m$ = mass consumption rate of main charge, g/s
$M_p$ = mass sublimation rate of pilot charge, g/s
$P_a$ = ambient pressure, atm
$P_c$ = chamber pressure, atm
$R_c$ = arc-current control resistance, Ω
$V_{arc}$ = arc discharge voltage, V
$V_s$ = dc arc source voltage, V
$W_{arc}$ = arc power, W

## Introduction

EXPERIMENTAL work was conducted to examine the feasibility of a combustion control concept for solid propellant rocket motors in relatively small thrust levels. In this method the control of combustion, including the initiation and interruption, of the propellant is made by hot pilot gases flowing through the burning port. The pilot gases are produced by means of dc arc discharges along the surface of some sublimation substances, called pilot charge, and the generation rate is controlled by changing the electrical input $W_{arc}$. Accordingly, the propellant, called main charge, is expected to burn with the help of the flows of pilot gases. In such a concept, both the main charge and pilot charge should not be self-combustible. We chose fuel-rich hydroxyterminated polybutadiene/ammonium perchlorate (HTPB/AP) and hydroxyterminated polybutadiene/ammonium perchlorate/titanium (HTPB/AP/Ti) as main charges, and polytetrafluoroethylene (PTFE) and AP as pilot charges.

The authors previously reported on the part relating to the production and its controllability of PTFE sublimates by dc arc discharges.[1] It is shown there that the sublimation rate of PTFE by dc arcs is nearly proportional to the electrical input power, and the mass consumption per unit electrical energy is about $2 \times 10^{-5}$ kg/kJ. In the present study, this technique is used as the generation and its rate control device of the heated pilot gases.

The main propellant grains selected here, which are being examined as candidates of solid propellants for ducted rocket, have fairly fuel-rich compositions. It is observed by separate experiments that they do not burn without the aid of external heat under some limited chamber pressures.[2] Saderholm et al.[3] had also reported on combustion characteristics of fuel-rich AP propellants that burn only when exposed to flowing gases (at around 1500 K and 10–60 atm), and extinguish when flow stagnates. Their report offered us some useful information on the point of interaction of fuel-rich propellants with pilot hot gas flows.

As the pilot charge, AP solidified from powder was also used, in addition to PTFE used previously. Since both PTFE and AP are sublimation substances and are expected to emit oxidizing agents, it is anticipated that the combustion of the fuel-rich main charges can be controlled with the aid of PTFE- or AP-sublimate flows, especially at high temperature like in this case.

## Experimental Results

Figures 1 and 2 show a photograph of the rocket motor and its configuration, and the size and disposition of propellants (pilot charge and main charge) used in this experiment. dc arc discharges, which stand between the electrodes, (+) and (−) in the figure, are started by a high frequency and high voltage initiator (10 kV, 3 MHz modulated with 100 Hz), connected in parallel to the main dc power source ($V_s$ = 0–440 V). The power level of the arc discharges influences the generation rate of the pilot gases. This control circuit is shown in Fig. 3, and some typical arc discharge trends are shown in Fig. 4.

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*Associate Professor, Department of Mechanical Engineering. Member AIAA.
†Research Assistant, Department of Precision Mechanics.
‡Professor, Department of Aeronautics and Astronautics. Member AIAA.

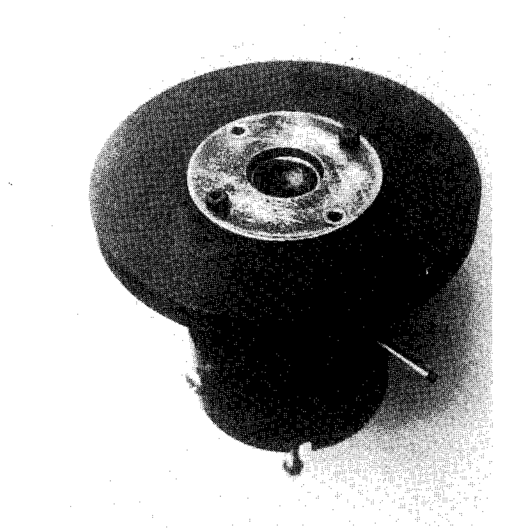

**Fig. 1 Photograph of the rocket motor used.**

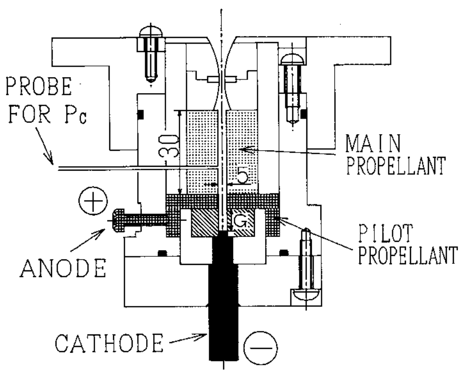


**Fig. 2 Disposition of electrodes and propellants.**

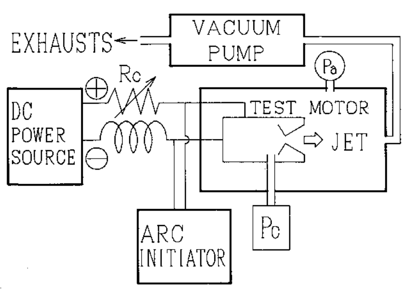


**Fig. 3 Schematic of the experimental setup. An arc initiator is used only in the ignition stage, which is less than 0.1 s. A power source voltage $V_s$ higher than $V_{arc}$ gives easier ignition and more stable dc arcs.**

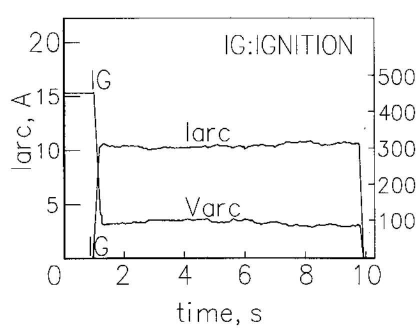


**Fig. 4 Sample trends of discharge current $I_{arc}$, and voltage $V_{arc}$. Main charge: HTPB/AP = 50/50, pilot charge: PTFE, $D$ = 2 mm, discharge gap $G$ = 9 mm, $P_c$ = 5 atm.**

Two kinds of pilot charges, PTFE and AP, were tested here. The mass sublimation rate of pilot charge per unit of electric power $M_p/W_{arc}$ was about 0.02 g/(s kW) in the case of PTFE, and about 0.04 g/(s kW) in the case of AP, regardless of the input power in the range of the values used, 0.3–2 kW. For instance, the mass consumption of PTFE in 10 s by 0.5-kW discharge is only 0.1 g, whereas the initial mass of PTFE is about 5 g.

The main charge has a configuration of internal burning and is 30 mm long. The initial port diameter is 5 mm. The combustion of the main charge is initiated, maintained, interrupted, and restarted by the control of the pilot gas flows, and the magnitude is dominated by the flow rates. The nozzle of the motor has a throat of diameter $D$ = 1.7–2.0 mm, and the area ratio is 50. These values are selected to attain objective chamber pressures around 2–8 atm.

Table 1 shows the pilot and main charges used in the present experiment and their properties. Three kinds of main charges were used in this work. Similar kinds have been tested for ducted rockets, and more details can be found in Ref. 2 and elsewhere. It is observed that they are not self-combustible under less than 6–8 atm, and the addition of titanium (Ti) lowers the non-self-combustion limits.

Figures 5a and 5b show the results for the relation of the mass generation rate of pilot gases $M_p$ (g/s), and of the main charge $M_m$ (g/s), vs dc discharge power $W_{arc}$ (W). The corresponding chamber pressures $P_c$ are also shown in Fig. 5. The ambient pressure $P_a$ is kept lower than 0.03 atm by pumping out the exhaust gases throughout the experiment. In this experiment, $W_{arc}$ is controlled by the change of $R_c$ through $I_{arc}$, which uniquely determines $V_{arc}$. The results indicate that both $M_p$ and $M_m$ are nearly proportional to $W_{arc}$, and $P_c$ increases accordingly. Since $M_p$ is smaller by about one figure

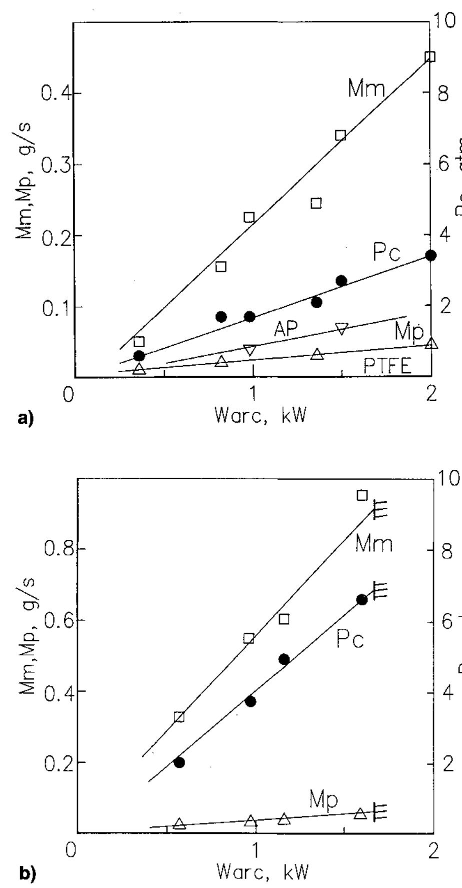


**Fig. 5 Relation between discharge power $W_{arc}$ and gas generation rates ($M_p$, $M_m$) for different combinations of pilot and main charges: a) $M_m$: HTPB/AP = 50/50, $M_p$: PTFE or AP and b) $M_m$: HTPB/AP/Ti = 40/50/10, $M_p$: PTFE, $D$ = 2 mm.**

**Table 1 Pilot and main charges used**

| | | | | |
|---|---|---|---|---|
| Pilot charge | Heat of formation, kJ/kg | PTFE $(C_2F_4)_n$ −7940 | AP $NH_4ClO_4$ −2520 | |
| Main charge | HTPB/AP/Ti (%Wt.) | 50/50/0 | 40/50/10 | 30/50/20 |
| | $I_{sp}$,[a] s | 171 | 178 | 185 |
| | non-self-combustion limit, atm | 8 | 7 | 6 |

[a]Values when pressure ratio is 20.

**Table 2 Estimated performance at $W_{arc}$ = 1 kW**

| Main charge | HTPB/AP = 50/50 | | HTPB/AP/Ti = 40/50/10 | |
|---|---|---|---|---|
| Pilot charge | PTFE | AP | PTFE | AP |
| $M_p$, g/s | 0.02 | 0.04 | 0.02 | 0.04 |
| $M_m$, g/s | 0.22 | 0.22 | 0.56 | 0.56 |
| $I_{sp}$, s | 272 | 253 | 228 | 223 |
| Thrust, N | 0.45 | 0.49 | 1.10 | 1.15 |

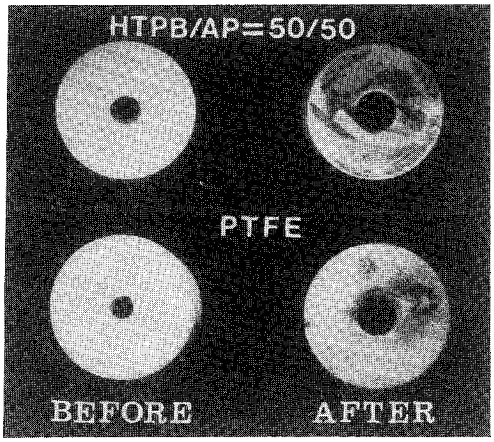


**Fig. 6 Photograph of propellants before and after use.**

compared to $M_m$, the chamber pressure depends mainly on $M_m$. $M_m$ was larger when a main charge with 10% Ti included was used than without.

Throughout this work, prompt ignition and interruption of combustion were observed without fail by the on-off of dc arc discharges: there was a very quick response of the gas emission from the nozzle to the initiation of discharges (less than 0.1 s of delay), and a relatively rapid response of interruption of combustion by the discharge cutoff (hardly more than 0.5 s of delay). When a main charge with 20% Ti (HTPB/AP/Ti = 30/50/20) was used, however, interruption of combustion was impossible, because $P_c$ went higher than 6 atm, the non-self-combustion limit of this propellant in the case $D$ = 2 mm. Also, the case with 10% Ti (HTPB/AP/Ti = 40/50/10) in higher discharge energy (about 1.6 kW) showed continuous combustion in a short span of time (about 1 s), even after discharge cutoff. The corresponding chamber pressure was near 7 atm, which is the border toward the self-combustible region.

Since the main propellants used here are burned in the non-self-regressive range, the combustion mechanism would be different from that of ordinary self-regressive propellants. Therefore, the results obtained so far have not yet revealed the influence of the chamber pressure on $M_m$ and $M_p$, and so more investigations are planned to be carried out; some information on the mechanism will be obtained by further experiments and study on the diagnostics of the exhaust gases. Photographs of propellants before and after their use are shown in Fig. 6, which shows that the inner surfaces are regressed nearly uniformly. However, the microscopic nonuniformity and the increase of the port area with the lapse of time (nonsteadiness) are important issues for accurate combustion control. These aspects are to be examined with characteristics of combustion response and better choice of propellants in our further study.

Table 2 shows estimated values of thrust levels of the test motor in some typical cases. It shows relatively low specific power (about 1 W/mN) and high thrust compared with those of resistojets or arcjets. Although this work is still in the stage of investigation on the feasibility of combustion control, and we are not sure yet what thrust level should be aimed at, this type of motor could be a good candidate for an electrical thruster in the Newton class. For any type of electric propulsion systems, weight reduction of power supply equipment is a common concern. Since propellants are stored in solid form in this system, it offers some advantage in storability and weight-saving.

## Conclusions

The concept of combustion control of solid propellants with the help of high-temperature pilot gases produced by dc arc discharges was experimentally examined. From the preliminary work conducted so far, it turned out to be that the expected mechanism of combustion control functioned successfully when HTPB/AP = 50/50 or HTPB/AP/Ti = 40/50/10 was selected as the main charge (for main thrust), and PTFE or AP as the pilot charge (for pilot flow gases). Since most proposed combustion control of solid propellants is by liquid injection or gas-operated plasma jet,[4] this method is unique in the sense that neither liquid nor gas containers are necessary.

At this moment the specific impulse is not high enough due to an inappropriate oxidizer/fuel ratio. More experiments in a different configuration, e.g., by sandwiching stratified AP (oxidizer) in the main propellant or with longer main propellants, are planned to be conducted to maintain a higher specific impulse or thrust levels.

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