Active Interruption of Motor Combustion for Ammonium-Perchlorate Composite Propellant

By Yosuke MEICHIN¹⁾ and Masafumi TANAKA¹⁾

¹⁾ National Defense Academy, Yokosuka, Japan

(Received June 30th, 2017)

Most of solid propellants have difficulty in controlling magnitude of their thrust or stopping their operation arbitrarily. Some solid propellants show a unique property of self-quenching in intermediate pressure range. This property could be utilized for the realization of actively controlled solid propellant rocket motor. However, little is known about the mechanism of this self-quenching phenomenon. In this paper, a simulation model of this phenomenon is developed and the simulation results are compared with the experiment results to determine the mechanism of this self-quenching phenomenon. The simulation results are in good agreement with the experiment results by assuming self-quenching phenomenon has stochastic nature and by selecting proper parameters.

Key Words: Solid Propellant, Rocket Motor, Combustion Interruption, Modeling & Simulation

Nomenclature

A_b	: area of burning surface
A_o	: area of outlet
a	: pre-exponential factor in Vieille's law
c_D	: discharge coefficient
c_p	: specific heat at constant pressure
c_v	: specific heat at constant volume
$\dot{H}$	: enthalpy flow rate
$iSQPR$	: intermediate self-quenching pressure range
M_W	: molecular mass
m	: mass
$\dot{m}$	: mass flow rate
n	: pressure index
p	: pressure
p_{cr}	: critical pressure
R_0	: universal gas constant
r	: burning rate
T	: temperature
T_d	: AP decomposition temperature
t	: time
U	: internal energy
V	: volume
σ_{iSQPR}	: standard deviation of iSQPR
γ	: specific heat ratio
μ_{iSQPR}	: average of iSQPR
ρ	: density of solid propellant
τ	: time delay of combustion to pressure
ω	: mass fraction of inert gas
Subscripts	
c	: chamber
comb	: combustion gas
d	: downstream
e	: environment

f	: flame
g	: generation
High	: high mode
i	: input
ign	: ignition of solid propellant
inert	: inert gas
Low	: lower limit or low mode
n	: time step
o	: output
s	: gas storage
Up	: upper limit
vc	: start of valve closing
vo1	: start of first stage valve opening
vo2	: start of second stage valve opening
0	: initial

1. Introduction

Solid propellant rocket motors have been used in many propulsion systems for their reliability and storability. While solid propellant rocket motors have these merits, they have difficulty in controlling magnitude of their thrust or stopping operation arbitrarily. As a result, most solid propellant rocket motors have been operated under their pre-programmed thrust-time properties, and this has been limiting the utilization of solid propellant rocket motors.

On the other hand, some ammonium perchlorate (AP) and hydroxyl-terminated polybutadiene (HTPB) based composite propellants show a unique combustion characteristic of self-quenching in some MPa intermediate pressure range.¹⁾ Figure 1 schematically shows the relations between chamber pressure p_c and mass flow rates of such propellants burned in a choked chamber. In Fig. 1, two curves, mass generation rate curve and mass discharge rate curve, are drawn and two equilibrium points of mass generation rate and mass discharge rate appear.

One equilibrium point at lower p_c is “low mode” of combustion and the other equilibrium point at higher p_c is “high mode” of combustion.^{2,3)} A pressure range where mass generation rate becomes 0 is called “intermediate self-quenching pressure range”, or iSQPR, which has lower limit iSQPR_{Low} and upper limit iSQPR_{Up}. At low mode, oscillatory combustion, repeats of stop and restart of combustion, or mass generation, is achieved. In contrast, stable combustion is achieved at high mode.

Fig. 1. Mass generation rate curve and mass discharge rate curve for self-quenching solid propellant, and “low mode” and “high mode” of combustion.

This self-quenching property could be utilized for the realization of active thrust controlled solid rocket motors. Tanaka et al. demonstrated an active combustion interruption method of a solid propellant rocket motor with inert gas injection.⁴⁾ In their proposed method, a solid propellant was burned at low mode, inert gas was injected into a combustion chamber to hold p_c in iSQPR, and combustion interruption was accomplished.

However, little is known about the detailed mechanism of this self-quenching phenomenon. In this paper, our objective is to get better knowledge about this phenomenon. To accomplish this objective, we did combustion interruption experiments of solid propellant with inert gas injection, developed a simulation model, and compared the simulation results and the experiment results to validate the developed model.

2. Experiments

Four experiments (Exp. 1 ~ 4) were conducted. Table 1 shows conditions of these experiments. Nitrogen (N_2) and Helium (He) were used as inert gas. Exp. 1 and 2 were inert gas injection experiments without combustion, and Exp. 3 and 4 were combustion interruption experiments with inert gas injection. In the following subsections, details of a solid propellant, an experiment apparatus, experiment procedures, and experiment results are discussed.

Table 1. Conditions of experiments.

Exp.	Inert gas	Combustion	p_{s0} (MPa)	p_{c0} (MPa)	T_{s0} (K)	T_{c0} (K)
1	Nitrogen	No	9.17	0.10	307	300
2	Helium	No	9.60	0.10	300	300
3	Nitrogen	Yes	11.6	0.10	302	306
4	Helium	Yes	11.6	0.10	301	301

2.1. Solid propellant

The solid propellant used for these experiments contained 73 % AP oxidizer and 27 % fuel binder in total grain mass and was not metalized. The crystalline AP particles had a unimodal distribution in diameter of 15 μm . The fuel binder consisted of 73.1 % HTPB, 19.8 % dioctyl adipate (DOA), and 7.1 % isophorone diisocyanate (IPDI) in total binder mass. Table 2 shows other parameters of this propellant. Pre-exponential factors and pressure indexes were determined from results of strand burner experiments. Specific impulse was calculated under conditions of ratio of chamber pressure to environment pressure 40, optimum expansion, and frozen flow using CEA.⁵⁾

The end-burning grain was 77 mm in diameter and was partitioned into 21 sectors by squarely crossed Bakelite plates as shown in Fig. 2. Previous studies indicate the partitioning is necessary to extinguish combustion with inert gas injection.

Table 2. Parameters of solid propellant.

Name	Symbol	Value	Unit
Pre-exponential factor (Low mode)	a_{Low}	3.05	mm/s·MPa ⁿ
Pressure index (Low mode)	n_{Low}	0.49	-
Pre-exponential factor (High mode)	a_{High}	2.44	mm/s·MPa ⁿ
Pressure index (High mode)	n_{High}	0.66	-
Specific impulse	I_{sp}	196	s

Fig. 2. Partitioned solid propellant grain.

2.2. Experiment apparatus

Figure 3 shows our apparatus for combustion interruption experiment of solid propellant with inert gas injection and Table 3 shows parameters of this apparatus.

Fig. 3. Apparatus for combustion interruption experiment.

Table 3. Parameters of experiment apparatus.

Name	Symbol	Value	Unit
Gas storage volume	V_s	4.60	ℓ
Chamber volume (before ignition)	V_c	430	$\text{m}\ell$
Gas injection inlet diameter	D_i	4.0	mm
Graphite nozzle throat diameter	D_t	3.5	mm

The combustion chamber contains the solid propellant grain and equips a gas injection inlet, sensors for pressure and temperature measurement, and a graphite nozzle for gas exhaust. The temperature sensor is type R (Platinum Rhodium -13% / Platinum) thermocouple. A hot-wire igniter powered by a 12 V DC battery ignites the solid propellant grain with support of small boron/potassium nitrate pellets. The chamber head end is made of transparent acryl plate. This transparent acryl plate and translucent propellant grain allow to observe light emitting burning surface from the back of the burning surface with a high-speed camera. This high-speed camera takes a picture every 1 ms.

The gas injection system is composed of a gas storage, a ball valve, a check valve, a stepping motor, and a control PC. The ball valve controls gas flow between the gas storage and the chamber. The check valve prevents high temperature combustion gas from flowing into the gas storage. The stepping motor drives the ball valve based on a pre-programmed sequence stored in the control PC. This valve controlling sequence features a 2-stage valve opening scheme to prevent p_c from going beyond iSQPR and combustion from reaching high mode, while it allows the simulation model to be simplified. The gas storage equips the same pressure and temperature sensors as the chamber equips. These sensors are connected to an amplifier, and a data logger records data from the amplifier.

2.3. Experiment procedures

All experiments had almost the same procedures except ignition of a solid propellant was done or not. Detailed procedures are described below.

- 1) Load the solid propellant grain with the hot-wire igniter, and attach the sensors and the gas injection inlet in the chamber.
- 2) Pressurize the gas storage to specified pressure with inert gas.
- 3) Ignite the solid propellant (Exp. 3 and 4 only).
- 4) Manually judge whether combustion reached low mode or not, based on value of p_c (Exp. 3 and 4 only).
- 5) Manually trigger gas injection.

2.4. Experiment results

2.4.1. Inert gas injection without combustion

Figures 4 and 5 show results of Exp. 1 and 2, inert gas injection experiments without combustion, respectively. The time of the start of the first stage valve opening, t_{v01} , is at time origin of both figures. The time of the start of the second stage valve opening, t_{v02} , and the time of the start of the valve closing, t_{vc} , of both figures are at 0.6 s and 1.6 s, respectively. Environment pressure, p_e , is atmospheric pressure, 0.1 MPa. Table 1 shows values of initial gas storage pressure, p_{s0} , initial chamber pressure, p_{c0} , initial gas storage temperature, T_{s0} , and initial chamber temperature, T_{c0} .

Both figures clearly show the 2-stage valve opening scheme and steep rises of chamber temperature T_c at t_{v01} and t_{v02} and steep fall of T_c at t_{vc} .

Fig. 4. Histories of pressure and temperature of Exp. 1, N_2 injection without combustion.

Fig. 5. Histories of pressure and temperature of Exp. 2, He injection without combustion.

2.4.2. Combustion interruption

Figures 6 and 7 show results of Exp. 3 and 4, combustion interruption experiments with inert gas injection, respectively. Pictures of burning surface taken with the high-speed camera are also shown in these figures. t_{v01} and t_{v02} of both figures are at 0.0 s and 0.6 s, respectively. In Exp. 3, the time of the ignition of the solid propellant, t_{ign} , is at -2.5 s and t_{vc} is at 2.3 s. In Exp. 4, t_{ign} is at -2.6 s and t_{vc} is at 1.6 s. p_e is atmospheric pressure, 0.1 MPa. Table 1 shows values of p_{s0} , p_{c0} , T_{s0} , and T_{c0} .

Both figures clearly show oscillatory nature of low mode and steep falls of T_c at t_{v01} and t_{v02} . Value of iSQPR_{Low} for this solid propellant is about 3.0 MPa and this value is consistent with previous studies. Pictures during steep falls of T_c , not shown here, indicate combustion interruptions were accomplished by gradual decrease of the number of burning sectors, not by simultaneous quenching of all sectors.

Figure 6 shows p_c of Exp. 3 was kept well above iSQPR_{Low} during entire valve opening period, a good condition for combustion interruption. This is confirmed by a picture indicating combustion interruption was completely accomplished soon after t_{v02} . In contrast, Fig. 7 shows p_c of Exp. 4 was not kept well above iSQPR_{Low}. As a result, the picture in the middle shows one sector of the partitioned grain continued burning even after t_{v02} . Rapid depressurization at t_{vc} caused combustion interruption.

Fig. 6. Histories of pressure and temperature, and pictures of burning surface of Exp. 3, combustion interruption with N_2 injection.

Fig. 7. Histories of pressure and temperature, and pictures of burning surface of Exp. 4, combustion interruption with He injection.

3. Modeling and Simulations

In this section, we develop a simulation model of self-quenching phenomenon and perform simulations. Details of this model and these simulations are discussed in the following subsections.

3.1. Modeling

Basic assumptions of this model are listed below.

- 1) Every gas is perfect gas.
- 2) Every thermodynamic process is isentropic process.
- 3) Every solid propellant specific parameter such as burning rate characteristic, combustion temperature, and molecular mass of combustion gas, etc. has given value.

This model has 2 routines, namely, the gas phase routine and the burning surface routine. The gas phase routine simulates transfers of mass and energy, and the burning surface routine simulates generations of mass and energy in the chamber.

3.1.1. Gas phase routine

Figure 8 shows a schematic diagram of the gas phase routine. The gas phase routine has 3 elements, the gas storage, the chamber, and the environment, and it simulates the transfers of mass and energy between these elements.

The gas storage and the chamber have 5 properties, pressure p , volume V , internal energy U , mass m , and temperature T . The environment is a boundary condition of this model and has one property, p , which never changes throughout a simulation.

Fig. 8. Schematic diagram of gas phase routine.

In this model, the transfers of mass and energy between the gas storage and the chamber, and, the chamber and the environment are considered first. When considering an element, the gas storage or the chamber, mass flow rate from this element to the downstream element is

$$\dot{m} = A_o \sqrt{\frac{2\gamma_n p_n^2 M_{W,n}}{(\gamma_n - 1) R_0 T_n}} \left\{ \left(\frac{p_{d,n}}{p_n} \right)^{\frac{2}{\gamma_n}} - \left(\frac{p_{d,n}}{p_n} \right)^{\frac{\gamma_n + 1}{\gamma_n}} \right\}, \quad (1)$$

when pressure of the downstream element p_d is greater than critical pressure p_{cr} , or

$$\dot{m} = A_o c_D p_n, \quad (2)$$

when p_d is less than p_{cr} . In these equations, p_{cr} and c_D are

$$p_{cr} = p_n \left(\frac{2}{\gamma_n + 1} \right)^{\frac{\gamma_n}{\gamma_n - 1}},$$

$$c_D = \sqrt{\frac{\gamma_n M_{W,n}}{R_0 T_n} \left(\frac{2}{\gamma_n + 1} \right)^{\frac{\gamma_n + 1}{\gamma_n - 1}}}.$$

Enthalpy flow rate from this element to the downstream element is

$$\dot{H} = c_{p,n} \dot{m} T_n. \quad (3)$$

Then, mass, internal energy, temperature, and pressure of this element at next time step are

$$m_{n+1} = m_n + (t_{n+1} - t_n)(\dot{m}_i + \dot{m}_g - \dot{m}_o), \quad (4)$$

$$U_{n+1} = U_n + (t_{n+1} - t_n)(\dot{H}_i + \dot{H}_g - \dot{H}_o), \quad (5)$$

$$T_{n+1} = \frac{U_{n+1}}{c_{V,n+1} \left(\frac{m_{n+1}}{M_{W,n+1}} \right)}, \quad (6)$$

$$p_{n+1} = \frac{m_{n+1} R_0 T_{n+1}}{M_{W,n+1} V}. \quad (7)$$

In the chamber, mixing of inert gas and combustion gas can occur. Therefore, changes of gas properties must be considered. Mass fraction of inert gas of this element at next time step is

$$\omega_{n+1} = \frac{\omega_n \{m_n - (t_{n+1} - t_n)\dot{m}_o\} + (t_{n+1} - t_n)\dot{m}_i}{m_{n+1}}. \quad (8)$$

Then, specific heat at constant volume, specific heat at constant pressure, molecular mass, and specific heat ratio of this element at next time step are

$$c_{V,n+1} = \omega_{n+1}c_{V,inert} + (1 - \omega_{n+1})c_{V,comb}, \quad (9)$$

$$c_{p,n+1} = \omega_{n+1}c_{p,inert} + (1 - \omega_{n+1})c_{p,comb}, \quad (10)$$

$$M_{W,n+1} = \frac{1}{\frac{\omega_{n+1}m_{n+1}}{M_{W,inert}} + \frac{(1 - \omega_{n+1})m_{n+1}}{M_{W,comb}}}, \quad (11)$$

$$\gamma_{n+1} = \frac{c_{p,n+1}}{c_{V,n+1}}. \quad (12)$$

Gas properties of the other elements never change.

3.1.2. Burning surface routine

The burning surface routine simulates the generations of mass and energy from combustion of solid propellant in the chamber and adds generated mass and energy to the chamber element of the gas phase routine.

The burning surface routine has 2 stages. At first stage, burning rate of solid propellant is calculated. And at second stage, mass generation rate and enthalpy generation rate are determined. For details, burning rate is

$$r = a_{Low}p_c^{n_{Low}}, \quad (13)$$

when p_c is less than $iSQPR_{Low}$, or

$$r = a_{High}p_c^{n_{High}}, \quad (14)$$

when p_c is greater than $iSQPR_{Up}$, or otherwise

$$r = 0. \quad (15)$$

Mass generation rate and enthalpy generation rate are

$$\dot{m}_g = \rho r A_b, \quad (16)$$

$$\dot{H}_g = \frac{c_{p,comb}\dot{m}_g T_f}{M_{W,comb}}. \quad (17)$$

The burning surface routine is the key to simulate self-quenching phenomenon. However, little is known about combustion of solid propellant. Therefore, several assumptions are made in this routine. They are listed below.

- 1) The burning surface is partitioned into 21 sectors, same as the actual solid propellant grain. Each sector has its own values of A_b and $iSQPR_{Low}$.
- 2) Sectors are independent each other; r and $iSQPR_{Low}$ are calculated at each sector, and no flame propagation exists between sectors.
- 3) Each sector completely stops the generations of mass and enthalpy when p_c is in $iSQPR$.
- 4) $iSQPR_{Low}$ is calculated at every sector and at every time step. It follows a normal distribution with average $\mu_{iSQPR,Low}$ and standard deviation $\sigma_{iSQPR,Low}$, that is, its value is in range of $\mu_{iSQPR,Low} \pm \sigma_{iSQPR,Low}$ with 68 % probability.
- 5) Value of p_c used to judge condition of 3) has delay of time τ .
- 6) Combustion is completely extinguished when T_c is less than AP decomposition temperature T_d .
- 7) Total mass generation rate and enthalpy generation rate are sum of those of each sector.

These assumptions are confirmed by the following experimental observations. The partitioned grain repeats flickering independently in each sector in low mode. Bakelite-made partitioning plates survive motor combustion. The

quenched surface is not flat but shows a bumpy aspect. Some statistical approach will be allowed for modeling. Assumption 6) will be backed up through the previous investigation that the average low mode pressure was dependent on the surrounding combustion gas temperature.⁶⁾

3.2. Simulations

The model discussed in Section 3.1 was executed on Microsoft Excel using its macro feature. Four simulations (Sim. 1 ~ 4) were performed. Their results are shown in Section 4. Sim. 1 and 2 are inert gas injection simulations without combustion and correspond to Exp. 1 and 2, respectively. Sim. 3 and 4 are combustion interruption simulations with inert gas injection and correspond to Exp. 3 and 4, respectively. In every simulation, p_e was set to atmospheric pressure, 0.1 MPa. And p_{s0} , T_{s0} , t_{v01} , t_{v02} , and t_{vc} were set to be same as the corresponding experiment. p_{c0} and T_{c0} of Sim. 1 and 2 were also set to be same as the corresponding experiments. And p_{c0} , T_{c0} , and other parameters of Sim. 3 and 4 are shown in Table 4.

Table 4. Parameters of combustion interruption simulations.

Name	Symbol	Value	Unit
Initial chamber pressure	p_{c0}	3.0	MPa
Initial chamber temperature	T_{c0}	1550	K
Flame temperature	T_f	1550	K
Average of $iSQPR_{Low}$	$\mu_{iSQPR,Low}$	3.0	MPa
Standard deviation of $iSQPR_{Low}$	$\sigma_{iSQPR,Low}$	0.75	MPa
AP decomposition temperature	T_d	513	K
Time delay of combustion to pressure	τ	50	ms

In this paper, p_{c0} was set to $\mu_{iSQPR,Low}$, and $\mu_{iSQPR,Low}$ was set to average of p_c when combustion occurred in experiments. T_{c0} was set to T_f , and T_f was set to average of T_c when combustion occurred in experiments. And T_d was set to crystal transition temperature of AP. Values of $\sigma_{iSQPR,Low}$ and τ were selected to fit the simulation results to the experiment results.

4. Comparison of Experiment and Simulation

In this section, the simulation results are shown and are compared with the corresponding experiment results to validate the developed model and to get better knowledge of self-quenching phenomenon of solid propellant.

4.1. Inert gas injection without combustion situation

Figures 9 and 10 show results of Sim. 1 and 2, and compare them with the results of Exp. 1 and 2, the inert gas injection without combustion situation, respectively. Both figures show the simulation results are in good agreement with the experiment results. Pressure curves are well matched, while temperature curves are less matched, especially for the He injection situation.

The reason for this discrepancy is inexistence of thermal conduction between gas and surroundings in this model. In experiments, the temperature curves recovered to environment temperature quickly, indicating thermal conduction between gas and surroundings has non-negligible effect on temperature.

From these comparisons, it is proved that the gas phase routine of this model has enough accuracy for simulations of self-quenching phenomenon.

Fig. 9. Comparison of pressure and temperature histories of Sim. 1 (broken lines) and Exp. 1 (solid lines), N_2 injection without combustion.

Fig. 10. Comparison of pressure and temperature histories of Sim. 2 (broken lines) and Exp. 2 (solid lines), He injection without combustion.

4.2. Combustion interruption situation

Figures 11 and 12 show results of Sim. 3 and 4, and compare them with the results of Exp. 3 and 4, the combustion interruption with inert gas injection situation, respectively. Figure 11 shows the result of Sim. 3 is in good agreement with that of Exp. 3. In contrast, Fig. 12 shows the result of Sim. 4 is quite different from that of Exp. 4, especially for p_c and T_c .

Fig. 11. Comparison of pressure and temperature histories of Sim. 3 (broken lines) and Exp. 3 (solid lines), combustion interruption with N_2 injection.

The reason for this discrepancy is use of T_c , temperature of

gas, in this model to judge whether AP decomposition stops or not, that is, combustion is terminated or not. Temperature of gas, especially He, falls faster than temperature of solid propellant itself. Therefore, combustion interruption of Sim. 4 was accomplished sooner than Exp. 4.

Combustion interruptions of experiments and simulations were caused by gradual decrease of the number of the burning sectors, not by simultaneous quenching of all sectors. This tendency of the simulation results comes from the assumption of stochastic nature of burning surface. This implies some stochastic processes play an important role in self-quenching phenomenon of solid propellant.

Fig. 12. Comparison of pressure and temperature histories of Sim. 4 (broken lines) and Exp. 4 (solid lines), combustion interruption with He injection.

5. Conclusion

In this paper, combustion interruption experiments were conducted and a simulation model was developed to get better knowledge about the self-quenching phenomenon of solid propellant.

The simulation results are compared with the experimental results. Most simulation results are in good agreement with the experimental results with the assumption of stochastic nature of burning surface. This implies some stochastic processes play an important role in this phenomenon.

However, there is difference between the simulation result and the experiment result in the combustion interruption with He injection situation. This discrepancy comes from lack of details of a condensed phase of a solid propellant in our simulation model. And there is a possibility of stochastic nature of burning surface comes from the condensed phase. Therefore, we will continue development of this simulation model to include the condensed phase of the solid propellant.

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