Factors influencing the burning characteristics of electrically controlled solid propellant with various metal content

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1 Introduction

The application of conventional solid propellants is limited such as inability to control the thrust. In order to overcome the drawback, electrically controlled solid propellant (ECSP) has gain continuously focused nowadays. ECSP, which is new type of the solid propellant, uses the electric potential difference as a source of ignition. With this ignition characteristics, therefore, the combustion of the ECSP was only held when the external voltage was applied to the propellant. Furthermore, with this multiple on and off characteristics, ECSP also has advantages for its operation on various trajectories by adjusting its burning rate. Additionally, ECSP is being easy to store because of its insensitivity for sparks and flame. Due to the above advantages during operation, many of previous work tried to determine the burning characteristics of ECSP.

The conventional solid propellant system has been used in wide range of applications [1, 2]. However, ECSP is able to cover all the advantages of the conventional solid propellant, and have additional merit in terms of burning rate control as per the application. There are many ingredients that can be included in ECSPs, resulting in a variety of ECSP compositions being studied. Sawka et al. [3] studied the burning characteristics of several ECSPs such as ammonium nitride (AN) and hydroxyl ammonium nitride (HAN)-based ECSPs. Gobin et al. [4] changed the composition of polyethylene oxide (PEO)/lithium perchlorate (LP)/ammonium perchlorate (AP) included in the propellant, and confirmed the effect of composition on the burning characteristics. Especially, HAN-based ECSPs have been widely introduced in formal investigations, due to their low toxicity and high-performance. Bao et al. [5] analyzed a few parameters affecting burning characteristics during the overall burning process, including the ignition and extinguishment process. Hiatt et al. [6] investigated the effect of flame exposure on the HAN-based ECSPs, by measuring the mass loss of the propellants. Bao et al. [7] analyzed the effect of nano sized particles on electric conductivity and burning characteristics. However, HAN-based ECSP has a significant disadvantage such as hygroscopicity, HAN absorbs the moisture from the atmosphere making it soft and having poor mechanical properties. Thus, LP-based ECSP has been considered as an alternative in this work, which is relatively free from hygroscopicity. Gnanaprakash et al. [8] analyzed decomposition characteristics of LP-based ECSP, and found the effect of external varying electric power on the combustion of ECSP samples. Li et al. [9] studied the effect of electrode area ratio by varying material and polarity of electrode. Due to the growing interest towards ECSP, LP-based ECSP has not been investigated yet widely, as compared to the HAN-based ECSP. In this study, therefore, LP-based ECSP was selected as a measurement target to discover the overall burning characteristics of ECSP.

The flame temperature could be considered as one of the important parameters for analyzing burning characteristics. To measure the flame temperature during burning process, multi-wavelength pyrometry technique was adopted at the point measurement. Weismiller et al. [10] adopted two different types of pyrometry to investigate both of averaged temperature and temperature distribution of nano-thermite.

In this study, the burning characteristics of metalized LP-based ECSP was analyzed. In this time, tungsten (W) was used as a metal additive for ECSP. Addition of metal particles to the ECSP compositions alters the burning rate characteristics of ECSP, which was strongly correlated with thrust generation. Thus, several measurement techniques were introduced to discover overall detailed burning characteristics of ECSP.

2 Methodology

Each of components included in the ECSP, such as LP, polyvinyl alcohol (PVA), W, glycerol, and boric acid (H_3BO_3), should be added with a sequential order. For this study, LP (Alfa Aesar Ltd., purity of 99%) was used as an oxidizer, meanwhile PVA (Sigma-Aldrich Ltd., over 99% hydrolyzed, 146,000-186,000 of molecular weight) was used as fuel and binder. Also, each of glycerol and boric acid was used as plasticizer and crosslinking agent. In this study, the different compositions of ECSP were considered to investigate the effect of metal additive, by changing the W content. Detailed weight ratios of each samples were listed in Table 1.

Table 1: Weight percent of components included in ECSPs.

Sample	H_2O	LP	PVA	W	Glycerol	H_3BO_3
M5 (W 5%)	50.63	27.37	10	5	5	2
M15 (W 15%)	44.14	23.86	10	15	5	2

The combustion experiments were carried out by fixing the ECSP samples between upper and lower electrodes as shown in Fig. 1. The upper and lower electrodes were connected to the positive and negative electrodes of the power supply (1 kV and 1 A), respectively. 300 V of electric potential difference was applied to the samples through the electrodes. Both of two electrodes were made of molybdenum (Mo) and had a same size of 20 mm x 10 mm x 5 mm. During the combustion experiments, electric signals were measured by installing a voltage probe (Hantek, T3100) and current probe (Tektronix, A622). These probes were directly connected to the oscilloscopes ((1) Tektronix, TBS1052B-EDU, bandwidth: 50 MHz, sampling rate: 1 GS/s; (2) Teledyne, WaveSurfer 3104z, bandwidth: 1 GHz, sampling rate: 4 GS/s), and the exact timing alignment was achieved due to this connection. Additionally, photodiode was installed in front of the samples, and used to measure the ignition time and burning by acquiring the luminous signals from the ECSP samples. Furthermore, the high-speed imaging technique was conducted to confirm the burning rates of the samples and define the flame location by using a high-speed camera (Vision Research, V711 Phantom, repetition rate: 1000 Hz) and 105 mm single lens (Nikon, NIKKOR). A manual MATLAB code was used to calculate the burning rate, determining the flame region in each time step. In addition, customized optical pyrometry system was designed and adopted to measure the flame temperature. In the pyrometry setup, spectrometer (Dongwoo Optron, MonoRa320i), intensified charge coupled device (ICCD, Andor iStar), fiber optics (Ocean optics, QP200-2-UV-BX), and an achromatic doublet (Thorlabs, MAP10100100-A) were used to compose the experimental setup. Also, the measurement point was fixed at 1.15 mm above the bottom electrode.

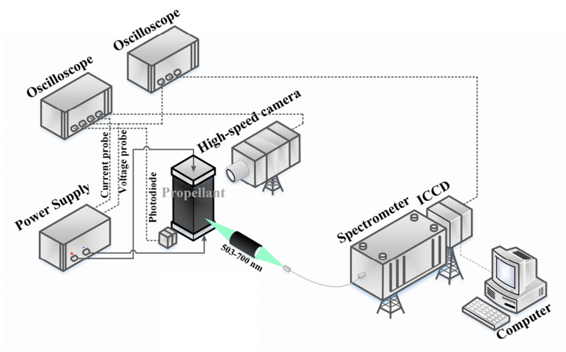

Figure 1: The experimental apparatus for the burning test of ECSP.

3 Experimental results

3.1 The effect of burning phase transition

Figure 2 shows the sets of electric signals during the combustion process of M5 and M15. When the external voltage was applied to ECSP samples, the internal current followed to increase with such delay. After that, the time when the internal current increased to the maximum, the propellant started to burn as recognized with the signals from the photodetector. Thus, the time when the photodetector first detected signal could be considered as the ignition time (T_{ign}). After the propellant was ignited, the internal current remained as almost constant level. In this period, the voltage signal shows the lower value than the applied 300 V. The voltage signal recovered the initial value of 300 V at the same time as the current dropped toward zero. Starting at this time, the difference in signal aspects was noticeable. The transition time was determined as a time when the trend of electric signals changed rapidly. The time period from T_{ign} to T_{trans} was defined as the transient burning phase ($\Delta t_{transient}$). After T_{trans}, the voltage reached at the maximum of 300 V, and the internal current increased linearly until the burning process was over at the end of the combustion process (T_{end}). At this time, the time period from T_{trans} to T_{end} was designated as the steady burning phase (Δt_{steady}). It was clearly observed that these burning phases strongly affected the burning characteristics of the propellant.

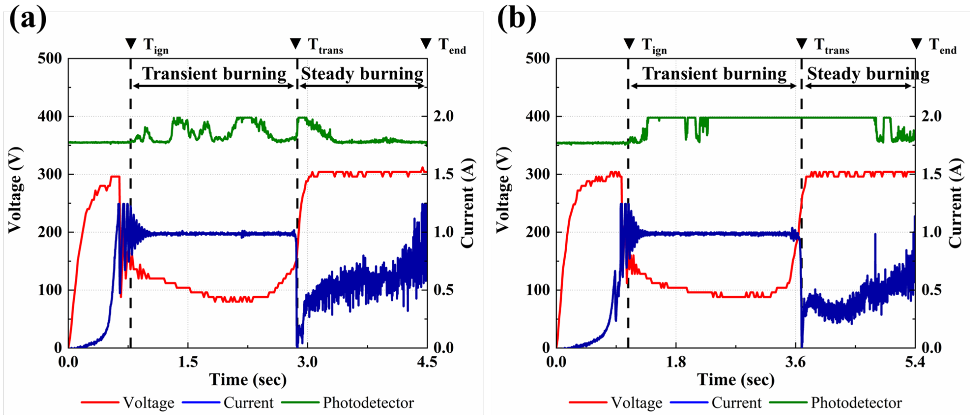

Figure 2: The electric signals for (a) M5 and (b) M15.

Figure 3 (a) and (b) shows sets of sequential burning images for each of M5 and M15 ECSPs, respectively. During the transient burning phase, which is corresponds to the time before T_{trans}, flames were mainly detected on the front and rear surfaces of the propellant, not on the interface between the upper electrode and top surface of the propellant for both of Fig. 3 (a) and (b). In contrast, in the steady burning phase, the flames at the top surface of the propellant could be detected, and the combustion which was accompaning the propellant regression was dominant because of this flame zone. In Fig. 4, in this time, the remaining length of the propellant and the regression was calculated. Rapid regression of propellant length was started just after the transition time, and the continuous regression was found since that time in both of the cases.

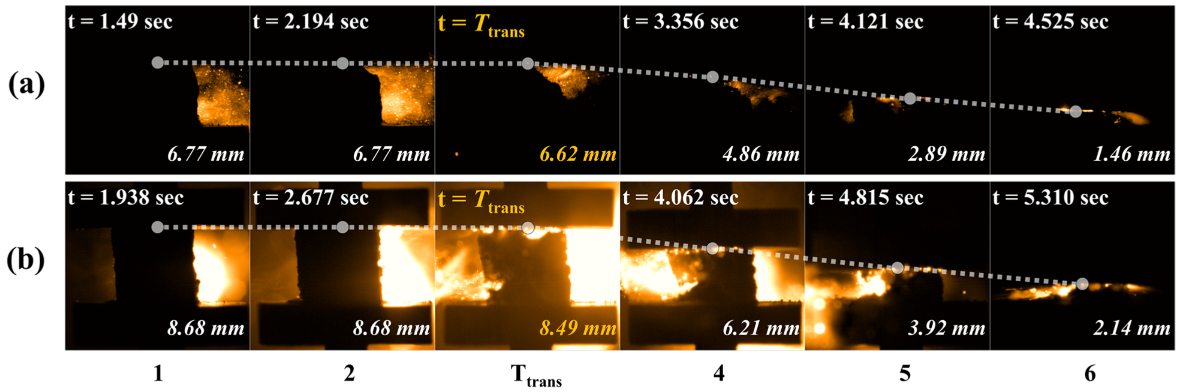

Figure 3: Sequential burning images of (a) M5 and (b) M15 ECSP during combustion process.

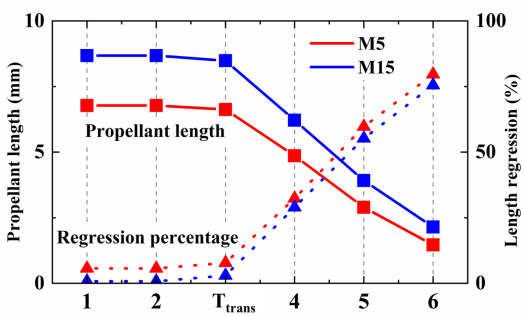

Figure 4: Propellant length and regression distribution for selected images.

3.2 The effect of metal addition.

Figure 5 displays the temporal distribution of temperature during burning at the selected point. Measuring the temperature during the burning process is important for estimating the thrust. Also, the effect of metal addition on the propellant was clearly seen. In short, temperature decreased as the metal content of ECSP increased. Calculted average flame temperatures were 1788.93 K and 1630.85 K for M5 and M15, respectively. About 9% of the average temperature was decreased, as the metal content increased from 5% to 15%. The major cause of decrease in the flame temperature could be considered as the oxidation of W. Increased heat delivered from flame to the metal particles could be one of the major cause for the reduction of flame temperature at higher metal containing propellant. Thus, the lower temperature was measured from the M15, compared to M5.

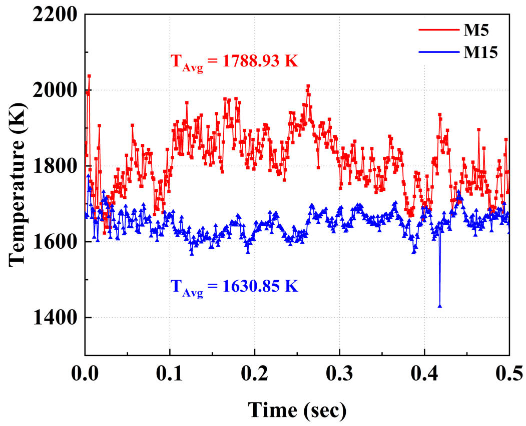

Figure 5: The experimental apparatus for the burning test of ECSP.

To understand the burning performance of the solid propellants, burning rate should be determined. Figure 6 shows the calculated volumetric burning rate during steady burning phase. To enhance the reliability of the experiment, six burning rates of ECSPs were calculated at each case of metal content. There was noticeable difference in burning rate about metal content. For higher metal containing propellant shows the higher burning rate. As the metal content increased 5% to 15%, burning rate also increased by 59.43%. In the previous study [8], burning rate of non-metalized propellants was considered. All of the metalized propellants show the higher value than non-metalized case.

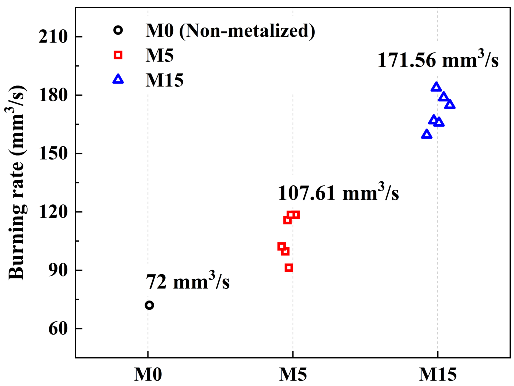

Figure 6: The experimental apparatus for the burning test of ECSP.

4 Discussion

It was clearly found that the burning phase transition and metal addition strongly influenced the burning characteristics of ECSP. In transient burning phase, regression of the propellant height was negligible. However, in the steady burning phase, continuous downward regression was observed and this implies that the performance test of the ECSP should be considered in this burning phase. Only 7.7% and 2.9% of the propellant height was decreased during the transient burning phase, meanwhile the rest of propellant height decreased in the steady burning phase. Moreover, the burning hot spots was formed at the various point on the front and rear surface of propellants in the transient burning phase. However, in the steady burning phase, the burning region was only formed at the interface between the top surface of the propellant which was connected with the upper electrode.

In addition, the effect of the metal addition was clearly seen by investigating the temperature distribution and burning rate. All of the metalized ECSP burned faster than the non-metalized ECSP.

Among the metalized propellant, higher burning rate was detected for the higher metal containing ECSP. In terms of the temperature, lower temperature was measured as the metal content increased. These differences could be cause by the oxidation and the heat absorption of the metal particles.

5 Conclusion

In this study, the factors which influence the burning charactersitics of ECSP and the overall burning characteristics of metalized ECSP were experimentally analyzed. The burning phase could be classified into two phases; transient and steady burning phases. The clear difference of burning characteristics between the burning phases could be observed by electric signal analysis and high-speed imaging. Almost of the propellant height decreased at the steady burning phase and the linear lincrease in the internal current could be confirmed. In addition, metal addition affected to the flame temperature and burning rate, which were directly correlated with thrust generation. For higer metal containing propellants, the lower flame temperature and higher burning rate could be extracted. Thus, to analyze the molecular change at the phase transition could be our future work.

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