A Preliminary Study on Triggering Lightning with Transient Flames

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ABSTRACT

Both laboratory and field experiments to study the possibility of triggering lightning with a transient solid-propellant-produced flame have been carried out. Laboratory experiments show that a flashover could be triggered by the kind of flame between plane-plane electrodes subjected to DC high voltage at much lower electric field than that of the corresponding spontaneous breakdown. Furthermore, we found that by adding a small amount aluminum into the propellant, the electric conductivity of transient flames could be improved by 30 times and the flashover electric fields could be reduced by 40% compared with those without adding Al. By using the propellant with an addition of Al, we carried out field experiments to trigger an upward leader from a 26 m high tower in the beginning of 1998. Three flames were fired during a weak thunderstorm and all these flames produced appreciable electric field changes at ground, indicating that the flames could play a similar role as the wire used in rocket-triggered lightning.

Key words : Lightning, Transient Flame, Triggered Lightning

1. Introduction

It is well known that the lightning discharges frequently cause electric faults in power transmission in Japanese Hokuriku area. To solve this problem, several active lightning protection methods of triggering lightning discharges artificially to make safe areas, such as wire-rocket method (Horie et al., 1982), laser triggering methods (Shindo et al., 1993; Wang et al., 1994; 1995), water jet methods (Takaki et al., 1993), have been under study in Japan. Only wire-rocket method has been used successfully in triggering lightning. In Japan, the wire-rocket triggered lightning experiment has been carried out continually for more than 20 years in Hokuriku area since 1977, and on average, the successful rate of triggering has reached 60%. However, due to the unexpected fly of both rocket and wire, it is very difficult to apply this method nearby a power transmission line for lightning protection. We have proposed to use a transient propellant-produced flame to trigger lightning [Watanabe et al., 1996]. In the present study, we have carried out several laboratory experiments to develop a new propellant to improve the effect of the transient flame on triggering discharges. Using the new developed propellant, we have also carried out field experiments from Jan. 16 to Feb. 16 of 1998. This paper is to report our experimental results.

2. Laboratory Experiments and Results

2.1 Measurements of Flame Conductivity

Based on the knowledge of wire-rocket triggered lightning technique, to trigger a lightning with a flame, besides the intense environmental electric field the flame should have not only a high speed of expansion but good conductivity as well. To meet these requirements, we tried to produce transient flames by firing a kind of double-base propellant (D.B.: Nitro-glycerin and Nitro-cellulose 1:1) mixing with some metal composite such as Aluminum (Al), Nitro-cesium (Cs), Nitro-kalium (K), and Nitro-natrium (Na). The mixing ratio of the D.B. to each of the metal composite is 10 : 1. The flame conductivity is measured with an electric circuit shown in Figure 1. As seen in this figure, one probe (Probe1) is subjected to a DC voltage of -200 V and another probe (Probe2) is grounded through a 10 k Ω resistor. As a flame extends upward and connects these two probes with a spatial interval of 6 cm, the electric current should flow in the circuit. The conductivity of the flame is obtained through measuring the voltage over the 10 k Ω resistor by an oscilloscope (input impedance : 1M Ω). Figure 2 shows the conductivity versus time for the different metal composites, where D.B. represents the case of only propellant, and Al, K, Na and Cs represent the cases of D.B. mixing with Al, K, Na and Cs, respectively. The time 0 is the ignition time of the flames. From this figure, the propellant with addition of Al could produce a flame which has the largest conductivity among all the cases, being a value about 30 times larger than that in the case of D.B. from the time 25 ms after the ignition with a duration of more than 60 ms.

Table 1 lists the ionization potentials and the combustion heats of K, Na, Cs and Al. There are no big differences in their ionization potentials. However, great differences are found in their combustion heats. The larger the combustion heat of the metal, the higher the conductivity of the flame which is produced by the metal-adding propellant. It appears that aluminum could release much more combustion heat energy to create more ions by frequent ionization than the other metals studied. In addition, the time for the conductivity to reach a stable high value from the flame ignition is about 25 ms in the case of Al, while those in the other cases are all around 50 ms. Apparently, the D.B. + Al is the most suitable composite propellant for triggering lightning.

2.2 Laboratory Experiment

Fig.1 The electric circuit for measuring the electrical conductivity of transient flames.

Fig.2 The electrical conductivity of transient flames versus time for different metal composites.

To investigate the effect of flames in triggering discharges, laboratory experiment have been carried out. In these experiments we apply first high DC voltage between two plane electrodes, one being a Rogowski plane electrode (upper) with a diameter of 1 m and the other being a square plane electrode (lower) with a size of $2 \times 2 \text{ m}^2$. Then we introduce transient flames through a hole at the center of the lower electrode by firing composite propellant underneath. In all of our experiments, the negative high voltages were applied on the upper electrode. As reported by Watanabe et al(1996) transient flames are capable of triggering discharges between the electrodes. We measured the time lag of the ignition of the discharge from the firing of the flame (we call it the "discharge delay time") and the applied voltage for both the D.B. and D.B.+Al cases. The results are shown in Figure 3, where the lowest flashover electric field is the critical electric field just under which flashovers could never be triggered. As evident in this figure, the lowest flashover electric field for D.B.+Al is about 40% lower than that for D.B. propellant. Both are greatly lower than the air breakdown electric field of about $3 \times 10^5 \text{ V/m}$ in ideal plane-plane electrodes, indicating that the transient flame has significant effect on triggering discharges. In the case where the applied electric field is 90 kV/m, the discharge delay time for D.B.+Al is about 10 ms, much shorter than that for D.B. propellant, a value of about 35 ms. These two facts indicate that it is easier to trigger a discharge between plane-plane electrodes with a flame produced by D.B.+Al than by only D.B..

3. Field Experiment

3.1 Field Experimental Setup

Field experiment was carried out at the top of Takeyama Mountain of Mikata, Fukui, from Jan. 16 to Feb. 16 of 1998. The altitude of the mountain is about 200 m. Based on the laboratory experimental results, we chose D.B.+Al propellant to produce flames in

Table.1 Comparison of the ionization potential and the combustion heat of various metals.

Name of Composite	Ionization Potential (V)	Combustion Heat (kcal/g)
Cs	3.87	38
K	4.33	4.33
Na	5.14	49.7
Al	5.98	199.6

Fig.3 The flashover electric fields versus the time elapse of a flashover from the firing of transient flames for D.B. and D.B.+Al propellants.

Fig.4 A map of the field experimental setup.

our field experiment. Special rocket engine was designed to produce a kind of long flames which could extend to 6 m in a period of about 10 ms with a duration of about 70 ms. Figure 4 shows the experimental setup. Ten such rocket engines were located at the top of a 26 m high tower. With a laser ignition system inside a small observation room located about 70 m from the tower, we can ignite each rocket engine through optical fibers connecting to the engines. A Rogowski Coil was mounted around the tower feet to measure the current (if any) flowing through the tower. The electric signal from the Rogowski Coil was transmitted to a recording system inside the observation room by a E/O-O/E optical link system. Besides the current measuring system, a high speed digital photo-diode observation system (ALVS3.5) with a speed of 10^4 frame/sec, a slow antenna (bandwidth 5 Hz $\sim$ 5 MHz), a field mill (DC $\sim$ 100 Hz), and a corona current measuring system (3 m high above ground) were also employed in the experiment.

3.2 Field Experimental Results

Three rocket engines were fired when a thunderstorm was overhead on Feb. 8, 1998. Figure 5 shows the electric fields measured at the ground level by the field mill around the time when the rocket engines were fired. Three flames were fired at a local time of 12:53 (Fire 1), 13:17 (Fire 2) and 13:26 (Fire 3), under the ground electric fields of about -2.4 kV/m, 2.3 kV/m and 3.2 kV/m, respectively.

Figure 6 shows the electric field changes due to the three flames. The field changes were recorded by a slow antenna at a distance of 35 m from the tower feet. The slow antenna system can operate at a time resolution from 80 ns to 50 ms with either internal or external trigger and can record up to 2 Mega-words for each event with up to 100% pre-trigger. The time resolution used in this study was 80 ns, and the resulting total recording time per event was 160 ms with 120 ms pre-trigger interval. The slow antenna system was set on external trigger mode, and its triggering signal is obtained from the high speed camera system ALVS3.5. As shown in Figure 6, the electric field changes due to the flames 1, 2 and 3 at 40 ms after firing the flames reached 150 V/m, -178 V/m and -334 V/m, respectively. This means that the transient flames could produce positive

Fig.5 The ground electric field around the firing of transient flames on Feb. 8, 1998.

Fig.6 Electric field changes produced by flames fired on Feb. 8, 1998.

electric field changes under negative thunderstorm electric field but negative changes under positive one. This is very similar to the case in rocket-wire triggering lightning technique. No electrical current was recorded through the tower feet, suggesting the current (if any) is not appreciable.

Figure 7 shows an example of the length of transient flame versus time obtained from ALVS3.5 recordings. The mean length of the three flames is about 6 m, and the mean expansion velocity is about 500 m/s. This expansion velocity is apparently larger than the ion drift velocity under the high electric field which can be expected at the top of the tower [Wang et al., 1995].

4. Concluding Remarks

Laboratory experiments confirmed the significant discharge triggering effect of a transient flame. Flames produced by firing D.B.+Al propellant have higher conductivity and lower triggering flashover electric field than those flames produced by firing other kind of composite propellants, indicating the D.B.+Al is the best propellant for triggering discharges with flames.

Three 6 m long transient flames were produced from the top of a 26 m high tower by firing D.B.+Al propellant at the electric fields of -2.4 kV/m, 2.3 kV/m and 3.2 kV/m at ground. The electric field changes due to the flames recorded at a distance of 35 m from the tower foot are 150 V/m, -178 V/m and -334 V/m, respectively. No main discharges were observed. The flame expansion velocity that we observed is about 500 m/s. All these results further indicate that transient flames are capable of penetrating possible corona sheath and initiating a leader like the upward moving wire in rocket-triggered lightning technique under suitable thunderstorm conditions. We will continue our field experiments in future.

Fig.7 One example of flame height versus time.

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(Received May 24, 1998; revised July 2, 1998;
accepted July 30, 1998)